CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Characterization of Waste Plastic as Construction Material for Selected Building Products in Housing

by

Aaroon Joshua Das

A dissertation submitted in partial fulfillment for the degree of Doctor of Philosophy

in the

Faculty of Engineering
Department of Civil Engineering

2025

Characterization of Waste Plastic as Construction Material for Selected Building Products in Housing

By

Aaroon Joshua Das

(DCE 191002)

Dr. George Wardeh, Professor

Cerge-Pontoise University, France

(Foreign Evaluator 1)

Dr. Mizan Ahmad, Senior Lecturer

Curtin University, Bentley, Australia

(Foreign Evaluator 2)

Dr. Majid Ali

(Research Supervisor)

Dr. Majid Ali

(Head, Department of Civil Engineering)

Dr. Imtiaz Ahmad Taj

(Dean, Faculty of Engineering)

DEPARTMENT OF CIVIL ENGINEERING

CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY

ISLAMABAD

2025

This effort is dedicated to

The ***Poverty Affected People*** *who will*

avail benefit from this research

My Loving Parents, Wife, Daughters

and Son

who are prayerful, proud and happy for each

milestone I achieve in life and patiently beared

the long hours I spent working on research

My Supervisor

for his vision, knowledge and persistent

concerns, which guided me to complete this

work

CAPITAL UNIVERSITY OF SCIENCE & TECHNOLOGY
ISLAMABAD
Expressway, Kahuta Road, Zone-V, Islamabad
Phone:+92-51-111-555-666 Fax: +92-51-4486705
Email: info@cust.edu.pk Website: https://www.cust.edu.pk

CERTIFICATE OF APPROVAL

This is to certify that the research work presented in the dissertation, entitled "**Characterization of Waste Plastic as Construction Material for Selected Building Products in Housing**" was conducted under the supervision of **Dr. Majid Ali**. No part of this dissertation has been submitted anywhere else for any other degree. This dissertation is submitted to the **Department of Civil Engineering, Capital University of Science and Technology** in partial fulfillment of the requirements for the degree of Doctor in Philosophy in the field of **Civil Engineering.** The open defence of the dissertation was conducted on **October 20, 2025**.

Student Name : Aaroon Joshua Das (DCE191002)

The Examination Committee unanimously agrees to award PhD degree in the mentioned field.

Examination Committee :

(a)	External Examiner 1:	Dr. Muhammad Yaqub Professor UET, Taxila
(b)	External Examiner 2:	Dr. Rao Arsalan Khushnood Associate Professor TIP, Islamabad
(c)	Internal Examiner :	Dr. Muhammad Usman Farooqi Associate Professor CUST, Islamabad

Supervisor Name : Dr. Majid Ali
Professor
CUST, Islamabad

Name of HoD : Dr. Majid Ali
Professor
CUST, Islamabad

Name of Dean : Dr. Imtiaz Ahmed Taj
Professor
CUST, Islamabad

Author's Declaration

I, **Aaroon Joshua Das** hereby state that my PhD dissertation titled **"Characterization of Waste Plastic as Construction Material for Selected Building Products in Housing"** is my own work and has not been submitted previously by me for taking any degree from Capital University of Science and Technology, Islamabad or anywhere else in the country/abroad.

At any time if my statement is found to be incorrect even after my graduation, the University has the right to withdraw my PhD Degree.

(Aaroon Joshua Das)

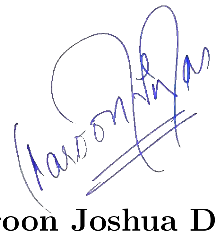
Registration No: DCE 191002

Plagiarism Undertaking

I solemnly declare that research work presented in this dissertation titled **"Characterization of Waste Plastic as Construction Material for Selected Building Products in Housing"** is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been duly acknowledged and that complete dissertation has been written by me.

I understand the zero tolerance policy of the HEC and Capital University of Science and Technology towards plagiarism. Therefore, I as an author of the above titled dissertation declare that no portion of my dissertation has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled dissertation even after award of PhD Degree, the University reserves the right to withdraw/revoke my PhD degree and that HEC and the University have the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized work.



(Aaroon Joshua Das)

Registration No: DCE 191002

List of Publications

It is certified that following publication(s) have been made out of the research work that has been carried out for this dissertation:-

Journal Article

1. **Das, A. J.** and Ali, M. (2025). "Prospective Use and Assessment of Recycled Plastic in Construction Industry. Recycling, 10(2), 41.
   https://doi.org/10.3390/recycling10020041 "
2. **Das, A. J.** and Ali, M. (2025). "Sustainable Development and Assessment of Low-Strength/High-Toughness Recycled Plastic Rebars for Structural Elements Under Light Loads. Sustainability, 17(11), 4997.
   https://doi.org/10.3390/su17114997."
3. **Das, A. J.** and Ali, M. (2025). "Multiscale Evaluation of Recycled Plastic Corrugated Panels for Sustainable Construction. Buildings 15(14), 2423.
   https://doi.org/10.3390/buildings15142423"

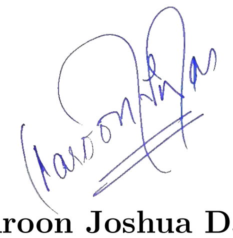
Conference Proceeding

1. **Das, A. J.** and Ali, M. (2021)."Recycling of waste plastic with least effects to the environment: A Review" *In proceedings of International Conference on Innovations in Energy Engineering and Cleaner Production, Silicon Valley, California USA (29-30 July 2021)*
2. **Das, A. J.** and Ali, M. (2021). "Energy Absorption capabilities of recycled-plastic reinforcing bars for earthquake resistant housing construction." *In proceedings of Australian Earthquake Engineering Society Conference. (25th – 26th November, 2021)*
3. **Das, A. J.** and Ali, M. (2021)."An overview on different corrugated sheets from manufacturing to housing element" *In proceedings of International Conference on Advances in Engineering, Architecture Science and Technology, Turkey (15th – 17th December 2021)*

4. **Das, A. J.** and Ali, M. (2021). “An overview on different reinforcing bars from manufacturing to strengthening element” *In proceedings of International Conference on Civil Engineering for Sustainable Development, Bangladesh. (10th – 12 February 2022)*

5. **Das, A. J.** and Ali, M. (2022). “Flexural Capacity of Recycled Plastic Corrugated Sheet” *In proceedings of 1st International Conference on Advances in Civil and Environmental Engineering, University of Engineering and Technology Taxila, Pakistan. (22nd and 23rd February 2022)*

6. **Das, A. J.** and Ali, M. (2022). “Mechanical and microstructure properties of recycled polystyrene for use in construction,” *Proc. 3rd IMCEET-2025 Conf.*, 29th April 2025.



(Aaroon Joshua Das)
Registration No: DCE 191002

Acknowledgement

I would like to express my deepest gratitude to my father, Engr. Donald Das, and my mother, Mrs. Marian Angelica Das, for their unconditional love, prayers, and lifelong support. Their constant encouragement has been the foundation of my personal and academic success. To my wife, Mrs. Mehreen, who had been giving unwavering support, understanding, and immense patience throughout this journey. Your encouragement has been a beacon of strength in difficult times. My heartfelt affection also goes to my lovely daughters, Anisha and Eliza, and my son, Ryan, your smiles, warmth, and innocent affection have brought light and joy even in the most challenging moments of this research.

The most special indebtedness goes to my research supervisor, Prof. Dr. Majid Ali, for his valuable guidance, hidden directions (which he allowed me to explore), pearls of wisdom, and unique style of motivation during hard times. His amazingly timely feedback, patience, persistence, and untiring efforts, through emails, text messages, and personal interactions were instrumental in pushing me beyond my perceived limits. His mentorship has profoundly shaped this dissertation and my academic growth.

I would like to thank all colleagues who helped me, and I acknowledge Mr. Junaid, Mr. Shehryar, Mr. Farrukh Hameed, Mr. Uzair, Mr. Syed Arsalan Ali, Mr. Musawar, Mr. Maqsood, Mr. Sagheer Ahmed Rana, Mr. Qasim, Mr. Asim, Mr. Asif and not the least Mr. Prince Rasif for their helpful assistance in lab work and spending long hours with me during my research work. Special acknowledgment to my brother Mr. Ephraim and my family for the financial and administrative support provided during the research phase. This untiring help and constant support of all will remain with me throughout my life.

(Aaroon Joshua Das)

Registration No. DCE 191002

Abstract

The intensifying global plastic waste crisis has created a pressing demand for innovative, sustainable materials in the construction sector. Recognizing the environmental threat posed by post-consumer thermoplastics and the lack of scalable structural applications for recycled plastics, this research introduces a novel pathway for converting waste plastic into durable, low-cost construction products. The core motivation lies in mitigating landfill overflow and pollution while creating circular, eco-efficient construction alternatives. This study aims to develop and validate structural elements namely recycled plastic rebars and corrugated panels using mechanical recycling techniques, primarily targeting HDPE, PP, and their blends. Distinct from earlier studies that limited recycled plastics to secondary additives, this work explores their direct use as full-profile construction components under load-bearing conditions. The novelty of this doctoral investigation is rooted in its integrated approach that spans material processing, empirical modeling, and prototype-scale validation, offering practical solutions to structural needs in modular housing and infrastructure systems.

The methodology comprised a multi-phase experimental protocol. A total of 140 thermoplastic samples were sorted, shredded, and extruded into test specimens. These were subjected to mechanical testing tensile, flexural, shear, and compressive loading across 35 specimens per test as per ASTM standards. Advanced characterization methods including Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA), Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD) were applied to determine chemical structure, thermal stability, and morphological integrity. In 4, full-scale recycled plastic rebars were developed in three diameters (12 mm, 19 mm, and 25 mm) and tested, given the absence of standard protocols for plastic reinforcement bars. Additionally, corrugated panels (600 mm × 450 mm × 12 mm) made from rHDPE and rPP were evaluated for dynamic properties, impact strength, watertight performance, and field-scale slab behavior. Empirical equations were developed to model performance parameters, and energy absorption and toughness were quantified to assess resilience under simulated service conditions.

The findings establish that recycled HDPE and PP composites can perform effectively as structural elements under light to moderate loads. Ribbed rPP rebars with 25 mm diameter achieved peak tensile loads of 12.2 ± 0.6 kN and toughness indices exceeding 19, validating their use in boundary walls and modular panels. Corrugated panels made from rHDPE exhibited superior stiffness and flexural strength (peak loads >1.9 kN), while rPP panels showed high ductility and retained more than 50% of their original strength under repeated impacts. Dynamic testing highlighted effective damping properties, with rPP excelling in longitudinal modes. Water leakage tests on overlapping corrugated panels confirmed their impermeability, making them suitable for cladding and roofing. These outcomes affirm the viability of recycled plastic-based materials for sustainable construction and advocate for their integration into policy, code development, and industry standards. It is recommended that future work may explore other building items such as hollow and solid blocks, their mechanism as a structure, durability in real-world environments, and scalability through industrial collaboration.

Keywords

Recycled HDPE; Recycled PP; Polymer rebars; Corrugated panels; Light-load structures; Sustainability; Circular economy; Empirical modelling.

Contents

List of Figures

List of Tables

Abbreviations

C	Compression
DEMF(IP)	In-plane Flexural Dynamic Elastic Modulus
DEMF(OOP)	Out-of-plane Flexural Dynamic Elastic Modulus
DEML	Longitudinal Dynamic Elastic Modulus
F	Flexural
FTIR	Fourier Transform Infrared Spectroscopy
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
MS	Maximum Stress
PEA	Peak Energy Absorption
PET	Polyethylene Terephthalate
POL	Polyolefin
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
R	Recycled
r-PVC	Recycled Polyvinyl Chloride
rHDPE	Recycled High-Density Polyethylene
rPP	Recycled Polypropylene
RFF(IP)	In-plane Flexural Resonance Frequency
RFF(OOP)	Out-of-plane Flexural Resonance Frequency
RFL	Longitudinal Resonance Frequency
SAM	Samicanite
S	Shear

T	Tensile
TEA	Total Energy Absorption
TGA	Thermogravimetric Analysis
TI	Toughness Index
uPVC	Un-plasticized Polyvinyl Chloride
V	Virgin
XRD	X-ray Diffraction
YS	Yield Stress

Symbols

ξ_L	Longitudinal Damping
ξ_F(IP)	In-plane Flexural Damping
ξ_F(OOP)	Out-of-plane Flexural Damping
Au	Gold
Ca	Calcium
Ti	Titanium
Cl	Chlorine
Si	Silicon
Fe	Iron
Al	Aluminium
Na	Sodium
Mg	Magnesium
K	Potassium
Cr	Chromium
S	Sulfur
Sr	Strontium
Ta	Tantalum
Mo	Molybdenum
Ne	Neon
τ	Shear stress (MPa)
γ	Shear strain
$P_{\max}$	Maximum applied load
$\sigma_{\max}$	Maximum (normal) stress
$\varepsilon_{\max}$	Maximum (normal) strain

Chapter 1

Introduction and Research Framework

1.1 Prologue

The 21st century faces an escalating environmental dilemma plastic waste. As global plastic production surpasses 400 million tons annually, improper disposal and inefficient recycling have led to massive accumulations of plastic waste in landfills, oceans, and urban landscapes. Thermoplastics such as high-density polyethylene (HDPE) and polypropylene (PP), widely used in packaging, domestic goods, and industrial applications, form a significant portion of this waste stream due to their high volume and slow degradation rate. While plastic offers versatile and durable properties during its usable life, its persistence in the environment has become a major ecological and health concern. The construction industry, although responsible for a substantial portion of global material consumption, has only marginally engaged with post consumer plastic as a primary resource. Existing applications remain limited to non-structural roles such as aggregates, fillers, or insulation materials far from exploiting the full potential of recycled polymers in functional building components. This research emerges in response to the dual global challenge of plastic waste management and sustainable infrastructure development. It aims to investigate and demonstrate the structural viability of recycled plastic through the design, fabrication, and testing of full-scale products such as corrugated panels and plastic rebars. By transforming waste into value-added construction materials, the study not only addresses environmental degradation but also offers a cost-effective, scalable solution for housing and infrastructure, particularly in resource constrained or disaster affected regions. Grounded in the principles of circular economy and sustainable development, this doctoral work bridges the gap between waste recovery and construction innovation. It contributes to the vision of converting urban waste liabilities into engineering assets enabling greener cities, resilient structures, and more inclusive communities.

1.2 Research Motivation and Problem Statement

On the behest of knowing that there are environmental concerns produced by plastic. The problem of un-manageability and lack of understanding has evolved to produce a huge health risk. The nature of this material is not absolute and can be synthesized. This notion has led to motivate the author to use waste material and to make useful plastic. As a part of this goal,in this doctoral study, development of plastic corrugated panels and rebars from waste plastic is focused. Thus, the problem statement is as follows

The thermoplastic waste (as a solid waste) is producing environmental concerns and unwanted landfills. It may be noted that complete range of building product (like blocks, corrugated panels, rebars etc.) developed from recycled plastic are not available in the market and their details properties are not assessed. It is worth to mention that there is no literature available as such for manufacturing of building products from waste plastic assessing its use in sustainable construction. The reason can be the environmental or economical aspects. Construction industry is only using waste plastic as filler, coarse or fine aggregate in cementitious composites, components of asphalt, insulation or others but not for complete building components. The optimized recycling for construction industry can provide a sustainable solution. There is an idea proposed of using recycled plastic for complete building products e.g. interlocking blocks, corrugated sheets, rebars, for mortar free interlocking structure. Different products are already in market which are produced from recycled thermoplastic still almost 80–90% waste plastic is going to landfill. The shortcomings, if any, in such development is also a worthy knowledge for *researchers. Thus, the conversion of waste plastic to recycled plastic having engineering properties (toughness, corrosion free, impermeability) for possible building products like Corrugated panels and rebars needs attention with least effect to environment and long termed economy. In this doctoral work, development of recycling method, Corrugated panels and rebars are specifically focused.*

1.2.1 Research Questions

1. How can the direct application of post-consumer high density polyethylene HDPE and polypropylene PP in structural elements help mitigate the environmental impacts of plastic waste accumulation?

2. What is the feasibility of transforming recycled thermoplastics into structurally competent construction materials using mechanical extrusion techniques?

3. To what extent do recycled high density polyethylene HDPE, polypropylene PP, and polyolefin blends retain their chemical integrity and generate low emissions during processing for sustainable construction applications?

4. How can recycled plastic rebars be engineered to withstand structural loads in light-duty construction applications?

5. What influence do surface texture and cross-sectional dimensions have on the mechanical performance of extruded recycled plastic rebars?

6. How do the failure modes and microstructural characteristics of rHDPE and rPP rebars affect their suitability for use as primary reinforcement materials?

7. How do recycled high density polyethylene HDPE and polypropylene PP corrugated panels perform under flexural, impact, and dynamic loading typical of roofing and cladding applications?

8. What are the dynamic mechanical properties of recycled plastic panels under in-plane and out-of-plane resonance conditions?

9. How effective are recycled plastic corrugated panels in providing water-tightness and mechanical stability when used in overlapping structural assemblies?

1.3 Overall Goal of the Research Program and Specific Objectives of this PhD Thesis

The overall Goal of the Research Program is to develop earthquake resistant houses i.e., interlocking structures using recycled plastic structural elements (e.g. Blocks, panels, rebars etc).

The specific aims of this doctoral study is as under

- To establish the feasibility of converting post-consumer thermoplastics, primarily HDPE and PP, into construction-grade materials through controlled mechanical recycling, with emphasis on minimizing environmental impact and validating their mechanical and microstructural integrity for use in housing and infrastructure.
- To develop and characterize recycled-plastic rebars from rHDPE and rPP through optimized extrusion, assessing their mechanical strength, ductility, and surface morphology to determine suitability as corrosion-free reinforcements for light-load, mortar-free structural systems.
- To design and evaluate recycled-plastic corrugated panels produced from rHDPE and rPP for roofing and wall applications, determining their flexural, impact, and dynamic performance, and establishing empirical correlations between mechanical responses to support predictive design for sustainable modular construction.

1.4 Scope of Work and Study Limitations

The scope of work for the current study includes

1.4.1 Recycling and Material Preparation

- Collection, identification, and segregation of post-consumer thermoplastics, primarily high-density polyethylene (HDPE) and polypropylene (PP), from municipal waste streams.

- Development of a mechanical recycling and extrusion setup to convert the sorted polymers into recycled pellets and structural forms under controlled temperature and emission-monitored conditions.
- Characterization of recycled polymers through mechanical testing (tensile, flexural, shear, and compression) and microstructural analyses (FTIR, SEM, TGA/DSC, and XRD) to evaluate their physical integrity, thermal stability, and suitability for construction use.

1.4.2 Development and Evaluation of Recycled-Plastic Rebars

- Fabrication of recycled HDPE (rHDPE) and recycled PP (rPP) rebars in plain and ribbed profiles using extrusion technology.
- Assessment of their mechanical behaviour under tensile, shear, and compressive loading, in comparison with ASTM A615 guidelines for steel rebars.
- Examination of surface morphology and fracture mechanisms using SEM and XRD to correlate geometry, crystallinity, and strength.
- Benchmarking of rHDPE/rPP rebars against conventional steel, GFRP, and bamboo reinforcements to classify their performance for light-load, mortar-free, and corrosion-free applications such as boundary walls and modular units.

1.4.3 Fabrication and Testing of Corrugated Panels and Prototype Slab

- Manufacturing of corrugated polymer panels using recycled HDPE and PP to evaluate their structural feasibility for roofing and wall cladding systems.
- Comprehensive testing including flexural strength, impact resistance, and dynamic behaviour (ASTM E1876) to determine stiffness, damping, and energy absorption characteristics.

- Validation of water-tightness and full-scale performance through prototype slab testing under ponding and flexural loading conditions.
- Establishment of empirical relationships between flexural and impact strength for predictive modelling of composite performance in light-load structures.

1.4.4 Analytical Modelling

- Formulation of empirical models linking mechanical performance parameters such as load capacity, toughness, and stiffness to design dimensions.

1.4.5 Sustainability, Standardization, and Broader Integration

- Examination of environmental benefits through emission control during processing and potential life-cycle advantages of recycled polymers.
- Identification of gaps in existing codes, standards, and policy frameworks regarding the structural use of recycled plastics.
- Recommendation of future strategies for code-level adoption, standardization, and sustainable implementation of recycled-plastic components in the construction industry.

The study limitations include

- The region of study to recover plastic waste would be Islamabad.
- No other use shall be drawn from waste plastic recycling.
- In consideration to the equipment availability the material properties shall be assessed.
- The mechanical properties of recycled plastic, Rebars and corrugated panels were assessed as per availability of testing equipment.

- Long-term durability factors (UV degradation, creep, and thermal aging) were acknowledged but not experimentally addressed, as they require extended exposure periods and specialized equipment beyond the timeframe of this research.
- Empirical modeling was employed to capture indicative relationships between properties; however, full statistical validation and benchmarking against external datasets were not feasible within the current research scope.
- The study primarily concentrated on establishing mechanical performance correlations and, therefore, did not extend to comparative analysis with conventional construction materials. This omission was intentional to maintain focus on recycled polymer systems within the available research scope.
- Long-term durability aspects such as UV degradation, creep resistance, and environmental aging were recognized but not experimentally investigated, since these require prolonged exposure regimes and specialized equipment that exceeded the timeframe and resources of the present work.
- The empirical model developed to relate impact and flexural strength serves as a preliminary framework; however, its predictive capability remains limited without broader benchmarking and statistical validation.
- The actual emission values, benchmark comparisons, or life-cycle assessment (LCA) details were a limitation in this study
- The equipment required for quantification of environmental assessment was not available and can be assessed in future research.

1.4.6 Rationale Behind the Variable Selections

For recycling waste plastic and assessment of material properties

- Material Selection (HDPE, LDPE, PP, HIPS, Polyolefin, Samicanite, Virgin PE) These were chosen to represent a broad range of thermoplastics from municipal waste and to assess individual and blended performance [1].

- Blending Ratios Experimental blending of LDPE, Sam and PP with HDPE aimed to improve ductility and energy dissipation.
- Testing Variables Tensile, shear, flexural, and compressive strengths were selected for comprehensive mechanical profiling. Thermal (TGA), chemical (FTIR), and microstructural (SEM) characterizations were performed to confirm material stability and recyclability.
- Phase 1 involved recycling and characterization of HDPE/PP; Phase 2 applied the materials in developing rebars and corrugated panels for sustainable construction.[2, 3]

For Rebars

- Material Type (rHDPE, rPP) These were selected based on their prevalence in MPW and favorable mechanical processing characteristics. rPP's extrusion consistency and toughness made it suitable for ribbed rebar production.
- Rebar Dimensions (12 mm, 19 mm, 25 mm) Standard structural diameters were chosen to align with industry norms and allow for comparative performance analysis.
- Surface Configuration (Plain and Ribbed) Surface texture directly influences bond behavior with masonry or modular units. Ribbing enhances mechanical interlock and toughness.
- Testing Variables Tensile strength, toughness index, and energy absorption were selected to evaluate load-carrying behavior and deformation capacity. SEM and XRD were used to analyze failure modes and crystallinity.

For Corrugated Panels and prototype slabs

- Material Selection (rHDPE and rPP) These thermoplastics are abundant in municipal waste streams and offer contrasting properties—rHDPE provides higher stiffness and strength, while rPP offers better impact resistance and ductility. Their combination allows for a comparative evaluation of mechanical and dynamic behaviors.

- Panel Geometry The corrugated profile (600 mm × 450 mm × 12 mm) was selected to enhance flexural rigidity and mimic practical roofing and wall cladding systems.

- Testing Variables Flexural strength, energy absorption, and damping characteristics were selected to assess load-bearing potential and vibration behavior. Water ingress tests were included to verify real-world performance in roofing/cladding.

1.5 Brief Methodology

In the first phase of the research, the feasibility of converting post-consumer thermoplastic waste mainly HDPE, LDPE, PP, HIPS, and polyolefins into usable construction-grade materials was thoroughly evaluated. The waste plastics were sourced from municipal streams, cleaned, shredded, and processed through controlled mechanical extrusion. A total of 166 samples were fabricated and subjected to standard mechanical testing to assess tensile (ASTM D638), flexural (ASTM D790), shear (ASTM D732), and compressive behavior. Additionally, thermal (TGA), chemical (FTIR), and morphological (SEM) analyses were conducted to determine material recyclability, structural integrity, and emission output during processing, validating the sustainability of the recycling technique. In the second phase, recycled plastic rebars were developed through extrusion using rHDPE and rPP in various diameters (12 mm, 19 mm, and 25 mm) and surface configurations (plain and ribbed). Mechanical testing was performed in accordance with ASTM A615 to evaluate their tensile strength, toughness, and energy absorption capacity. To improve mechanical consistency, performance-enhancing additives and compatibilizers were incorporated during production. Fracture behavior and crystalline structure were studied through SEM and XRD analysis. A polynomial-based empirical model was further formulated to predict tensile behavior under different conditions, supporting the advancement of standard design practices for recycled plastic reinforcements. The third phase involved the fabrication and performance assessment of corrugated plastic panels using rHDPE and rPP, with standardized dimensions of 600 mm × 450 mm × 12 mm. The panels were evaluated for flexural behavior (ASTM D790), dynamic stiffness (ASTM E1876), and impact resistance through drop-weight and pendulum tests. To validate real-world applicability, prototype slab systems using overlapping joint configurations were installed and tested under simulated service conditions for roofing and wall cladding purposes. Structural durability and water ingress resistance were assessed, and material performance was confirmed using SEM and XRD. The empirical correlation between flexural strength and impact durability provided additional insight into the panels' reliability for modular, low-cost construction systems.

1.6 Research Impact on Industry

1.6.1 Research Novelty / Uniqueness

This doctoral research presents a pioneering approach in the field of sustainable construction materials by developing full-scale, structurally viable building products entirely from recycled thermoplastics. Unlike previous studies that primarily explored the use of plastic waste as fillers, aggregates, or insulation components, this work positions recycled plastic as a standalone structural material in the form of corrugated panels and recycled plastic rebars. Key Novel Aspects Include

- First-time Development of 100% Recycled Plastic Corrugated Panels and Rebars - The study introduces a first of its kind framework for converting post-consumer thermoplastics (HDPE and PP) into structural-grade components corrugated panels and rebars demonstrating their potential as standalone construction materials rather than as filler or aggregate substitutes.

- Integration of Mechanical Recycling with Structural Engineering - It establishes a direct link between recycling processes and structural performance, integrating low-emission mechanical recycling with engineering design to develop durable, corrosion-free, and reusable materials suitable for modular and mortar-free assemblies.

- Empirical Modeling and Multiscale Validation - The research develops empirical models and analytical correlations to predict tensile, flexural, and impact behaviour of recycled-plastic components, providing a quantitative foundation for future design and performance assessment of polymer-based structural elements.

- Targeted Application in Mortar-Free, Interlocking Plastic Structures - Through a multiscale evaluation approach, the study connects microstructural characteristics (FTIR, SEM, XRD, TGA) with macroscopic mechanical responses, demonstrating how crystallinity and morphology influence overall load-bearing capacity.

- Contextual Relevance for Developing Countries - The work presents a sustainable and context-specific innovation, offering a replicable method to transform municipal plastic waste into functional construction materials that address both environmental and socioeconomic needs of developing regions.

1.6.2 Research Significance and Benefit

This research holds significant relevance in the context of global environmental sustainability and the growing demand for affordable, durable construction materials. By introducing recycled plastic as a structural-grade material, the study bridges critical gaps between plastic waste management, materials engineering, and low-cost infrastructure development.

1.6.2.1 Environmental Significance

The project directly addresses the pressing challenge of plastic pollution by converting post-consumer thermoplastics into high-value construction products. This not only diverts waste from landfills and water bodies but also reduces the carbon footprint associated with the production of traditional materials like steel and cement.

1.6.2.2 Engineering and Scientific Contribution

The research contributes to the scientific understanding of how recycled HDPE, PP, and their blends behave under structural loads. It provides empirical models, material characterizations, and performance benchmarks that serve as a foundation for future studies and industry standards on recycled plastic construction materials.

1.6.2.3 Economic and Social Benefit

By utilizing readily available municipal plastic waste and low-energy manufacturing processes, the developed products offer a cost-effective alternative for construction, especially in resource-constrained or disaster-prone regions. This supports housing initiatives for low-income communities and promotes local economic activity through plastic waste valorization.

1.6.2.4 Industrial and Technological Advancement

The study introduces a scalable production method for recycled plastic corrugated sheets and rebars, providing opportunities for existing plastic recycling industries to diversify into the construction sector. It lays the groundwork for the development of green, prefabricated infrastructure systems compatible with modular design trends.

1.6.2.5 Policy and Development Impact

The findings support policy frameworks aimed at promoting sustainable construction, plastic reuse, and climate-resilient infrastructure. They provide credible evidence for integrating recycled plastic into national building codes, public procurement standards, and international sustainability certifications.

1.6.3 Practical Implementation

The outcomes of this research present several promising practical applications for the construction and materials industry, especially in regions seeking sustainable, low-cost, and modular construction solutions. The use of recycled plastic materials, processed through mechanical extrusion and molded into structural components, offers a scalable path toward reducing environmental pollution and addressing material shortages in civil infrastructure.

- **Roofing and Cladding Systems** Corrugated panels fabricated from recycled HDPE and PP demonstrated strong mechanical integrity under flexural and impact loading. These panels can be effectively used for roofing and vertical cladding in housing, temporary shelters, and industrial sheds. Their lightweight nature and water resistance make them ideal for disaster-prone and remote areas.

- **Modular Mortar-Free Construction** The development of ribbed and plain plastic rebars provides a sustainable alternative to conventional steel reinforcements in light-load structural applications. These rebars can be incorporated into mortar-free, interlocking plastic block systems for constructing boundary walls, partitions, and modular housing units, thereby reducing construction time and labor costs.

- **Prefabricated Construction Units** Given their repeatable strength and resistance to corrosion and moisture, both corrugated panels and plastic rebars are suitable for prefabricated construction modules. These units can be deployed in disaster relief efforts, emergency housing, and remote settlements where access to conventional materials is limited.

- **Urban Infrastructure and Furniture** Recycled plastic components can be utilized in constructing street furniture, fencing, pedestrian walkways, and urban installations. Their weathering resistance and ease of molding into various forms make them practical for such non-load-bearing yet durable applications.

- **Water-Resistant and Corrosion-Free Applications** Due to their impermeability and non-corrosive nature, the recycled plastic panels and rebars are well-suited for humid environments and areas exposed to saline conditions. Applications include underground ducts, rural sanitation structures, and coastal fencing.

1.6.4 National and Global Impact with Emphasis on SDGs Relevance

In Pakistan, the exponential rise in plastic waste, particularly in urban and peri urban areas, poses severe threats to environmental health and public infrastructure.

A large proportion of unmanaged plastic ends up clogging drainage systems and contaminating freshwater bodies. This research contributes to Diverting plastic waste from landfills and water streams, thereby reducing urban flooding and waterborne contamination. Supporting the development of low-cost, disaster-resilient housing, especially in underserved and flood-affected regions. Strengthening the local recycling ecosystem by introducing construction applications as a high-value market for recycled polymers.

The methods and findings of this research are universally applicable, particularly for developing and climate-vulnerable nations struggling with both housing shortages and plastic pollution. By converting waste into durable building components, the work promotes sustainable resource use and pollution mitigation on a global scale.

Alignment with Sustainable Development Goals (SDGs)

- **SDG 9 – Industry, Innovation and Infrastructure**
  The research introduces innovation in material science and supports the development of green manufacturing systems capable of producing structural-grade recycled components.

- **SDG 11 – Sustainable Cities and Communities**
  The use of lightweight, recyclable, and weather-resistant panels and rebars supports safer, greener, and more affordable housing and infrastructure solutions.

- **SDG 12 – Responsible Consumption and Production**
  The project promotes sustainable material cycles by transforming municipal plastic waste into useful structural components, reducing the dependency on virgin raw materials.

1.6.5 Research Challenges

Despite its promising outcomes, this research encountered several technical, logistical, and methodological challenges that highlight the complexity of developing structural-grade materials from recycled plastics. Addressing these challenges was essential to ensure the reliability, scalability, and sustainability of the proposed solutions.

1.6.5.1 Variability in Waste Plastic Feedstock

One of the foremost challenges was the inconsistency in the composition, quality, and cleanliness of municipal plastic waste. Variations in polymer types, degradation levels, and contamination introduced unpredictability during processing, affecting extrusion quality and mechanical performance.

1.6.5.2 Absence of Standardized Protocols for Recycled Plastic Products

There are no universally accepted testing standards specifically designed for recycled plastic-based construction products such as rebars and corrugated panels. This posed difficulties in benchmarking performance and required adaptations of existing standards (e.g., ASTM A615, D790) to non-conventional materials.

1.6.5.3 Additive Selection and Compatibility

Enhancing the structural properties of recycled plastics necessitated the use of compatibilizers and additives. Selecting the appropriate formulations that balanced toughness, ductility, and environmental stability while remaining cost-effective required extensive experimental iterations.

1.6.5.4 Extrusion and Manufacturing Consistency

Maintaining uniform flow, shape retention, and cooling during mechanical extrusion of complex geometries (such as ribbed rebars and corrugated panels) posed engineering challenges. Minor deviations in temperature, pressure, or feed rate often impacted material homogeneity and product strength.

1.6.5.5 Scaling from Laboratory to Field Applications

While laboratory scale testing demonstrated the feasibility of the recycled products, replicating these results at full scale especially under field conditions required prototype fabrication and real-world stress simulation, which was both resource-intensive and time-sensitive.

1.6.5.6 Perception and Market Acceptance

Another barrier was the hesitation from industry professionals and potential users to accept recycled plastic as a reliable structural material. This cultural and psychological resistance emphasizes the need for awareness, demonstration projects, and code development.

1.6.5.7 Environmental, Safety, and Risk Management

Though mechanical recycling is environmentally favorable, maintaining safety during plastic melting and extrusion (e.g., emissions, odor, thermal hazards) required strict monitoring and risk mitigation measures to ensure a safe working environment and compliance with environmental standards.

1.6.6 Ethical and Management Considerations Including Risk Management

This research was carried out with a commitment to ethical responsibility, environmental stewardship, and effective management practices. The handling of waste materials, engagement with informal recycling channels, and experimental processing all necessitated a careful approach to uphold safety, sustainability, and ethical integrity.

1.6.6.1 Ethical Sourcing and Community Involvement

The plastic waste used in this study was sourced through registered municipal waste handlers and local recycling units, ensuring that no unregulated or harmful material streams were exploited. Informal waste pickers and collection agents were engaged through ethical channels to avoid exploitation and to promote inclusivity. No human or animal testing was involved at any stage, and no hazardous chemicals were used that would endanger public health or violate environmental protocols.

1.6.6.2 Environmental Responsibility

Mechanical recycling was intentionally chosen over chemical methods due to its lower environmental impact and reduced emission profile. All processing activities were carried out in well-ventilated environments with continuous monitoring of emissions. Waste residues from the extrusion process were minimized and reprocessed where feasible, in line with zero-waste principles.

1.6.6.3 Research Safety and Lab Risk Management

During plastic shredding, heating, and extrusion, operational risks such as thermal hazards, inhalation exposure, and mechanical injuries were proactively managed. Standard operating procedures (SOPs) and personal protective equipment (PPE) were strictly enforced. Fire extinguishers, ventilation systems, and thermal monitoring devices were maintained to mitigate accidental risks.

1.6.6.4 Data Integrity and Reproducibility

All experimental procedures followed international testing standards (ASTM) to ensure scientific integrity and reproducibility. Proper documentation, repeat trials, and calibration of testing equipment were ensured. No data manipulation or omission occurred, and all findings are transparently presented with supporting raw results and statistical treatment.

1.6.6.5 Project Management and Compliance

The research adhered to institutional research protocols and ethical review standards. Milestones were tracked using structured project management tools to ensure timely progress, resource optimization, and accountability. All procurement and laboratory practices complied with university and governmental safety regulations.

1.6.6.6 Social Impact and Transparency

The study recognizes the broader societal implications of promoting recycled plastics in construction. It strives to promote transparency, sustainability, and public awareness by advocating for low-cost, environmentally responsible building alternatives particularly for communities with limited access to durable and affordable housing.

1.6.7 Research Deliverable, Sales and Marketing Potential

Deliverables include recycled waste plastic prototypes of corrugated panels and rebars, empirical data, and performance models. The research holds commercialization potential in prefabricated construction markets, especially for disaster-resilient housing.

1.7 Dissertation Layout

This doctoral dissertation is systematically organized into six comprehensive chapters, each contributing to the overarching goal of promoting sustainable construction through the utilization of recycled plastic materials. The progression of chapters is designed to establish the theoretical foundation, present critical analysis, and offer empirical validation of recycled plastic-based alternatives for structural applications in the construction sector.

Chapter 1 – Introduction This chapter introduces the research background, environmental motivation, and challenges associated with plastic waste management. It defines the research problem (Section 1.2), outlines the research aim and specific objectives (Section 1.3), and highlights the novelty, industrial impact, and sustainability relevance (Sections 1.4 to 1.6). A brief methodology (Section 1.5) and this thesis layout (Section 1.7) conclude the chapter.

Chapter 2 – Literature Review Provides a critical review of existing recycling techniques, mechanical behaviour of thermoplastics, and structural applications of plastic-based composites. Section 2.2 discusses perspectives on plastic recycling, while Sections 2.4 and 2.5 identify existing research gaps and justify the need for full-scale recycled plastic structural components.

Chapter 3 - Prospective Use and Assessment of Recycled Plastic in Construction Industry Describes the collection, classification, and extrusion of recycled HDPE, PP, and polyolefin waste (Section 3.2). Standardized mechanical tests and analytical techniques such as FTIR, SEM, and TGA are employed (Section 3.3) to assess mechanical performance and recyclability. Environmental sustainability is validated through emission profiling and economic feasibility analysis (Section 3.4).

Chapter 4 – Assessment of Recycled Plastic Rebars for Light Loads Focuses on the fabrication of recycled plastic rebars in different diameters and textures (Section 4.2). Tensile testing under ASTM A615 (Section 4.3), microstructural examination via SEM and XRD (Section 4.4), and development of empirical models (Section 4.5) are presented. The chapter establishes the load-bearing potential of rHDPE and rPP rebars for light structural use.

Chapter 5 – Multiscale Evaluation of Recycled Plastic Corrugated Panels for Sustainable Construction Covers the design, fabrication, and testing of corrugated panels (Section 5.2), including flexural (ASTM D790), impact, and dynamic resonance tests (ASTM E1876) in Section 5.3. Section 5.4 evaluates prototype slab performance under service conditions, while Section 5.5 correlates flexural capacity with impact durability. Section 5.6 presents the overall structural and functional assessment.

Chapter 6 - Conclusion and Recommendations This final chapter summarizes the research outcomes (Section 6.1), confirms that the aims and objectives have been met (Section 6.2), and offers practical recommendations (Section 6.3) for further standardization, field implementation, and industrial adoption of recycled plastic-based construction systems.

Chapter 2

Literature Review

2.1 Introduction

The increasing accumulation of plastic waste has emerged as one of the most critical environmental challenges of the 21st century, posing severe risks to terrestrial and marine ecosystems, public health, and sustainable urban development. Despite global awareness and policy initiatives, an overwhelming proportion of post consumer plastic especially thermoplastics such as high density polyethylene (HDPE), polypropylene (PP), and low density polyethylene (LDPE) continues to end up in landfills, oceans, and incineration plants, leading to long term ecological degradation. With projections indicating a potential doubling of plastic waste by 2050 if current trends persist, the need for innovative, large scale recycling strategies has never been more urgent. Plastic recycling, particularly through mechanical and chemical means, has been identified as a key mitigation strategy to address this crisis. However, the potential of recycled plastics has largely remained untapped in primary structural applications, especially in the construction sector. While prior research has explored the incorporation of recycled plastics as fillers, aggregates, or insulation materials, these approaches offer limited contribution to the structural integrity or scalability of green construction practices. Given the durability, chemical resistance, and moldability of thermoplastics, there exists significant potential for their transformation into structural grade construction materials. The current study aims to address this gap by evaluating the use of recycled HDPE, PP, and their blends in manufacturing full scale corrugated panels and reinforcement bars (rebars) for morta rfree interlocking construction systems. Unlike conventional approaches, this research investigates recycled plastic not merely as a supplement but as a standalone construction material, suitable for load bearing and impact resilient components. To establish the viability of this approach, the study integrates multi scale testing including tensile, shear, flexural, and compression analysis alongside advanced material characterization techniques such as Scanning Electron Microscopy (SEM), XRay Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Thermogravimetric Analysis (TGA). Additionally, environmental and safety assessments during the recycling process ensure alignment with sustainability goals and minimal ecological impact. This chapter presents a detailed review of the state of the art in plastic waste recycling, highlighting current practices, material properties, environmental implications, and the transformative potential of thermoplastics in construction. The review further identifies key gaps in knowledge and technological limitations, laying the foundation for the novel contributions made through this research. This chapter provides a comprehensive overview of the perspectives, processes, and advancements in plastic recycling with a focus on its integration into construction materials. Section 2.2 reviews the fundamentals of plastic recycling from multiple viewpoint identification, methods, and environmental implications establishing the theoretical foundation for material recovery and reuse. Subsequent sections (2.3–2.4) synthesize global research on the manufacture and utilization of recycled plastic rebars and corrugated panels, illustrating their potential as sustainable alternatives for lightweight and eco-friendly construction. Together, these sections bridge the knowledge gap between waste-plastic recycling techniques and their practical implementation in structural applications.

2.2 Perspectives of Plastic Recycling from Various Aspects

Plastic pollution has emerged as a pressing global issue, with rising levels of waste accumulating both on land and in oceans, posing severe threats to ecosystems and hu man health. Recent studies have demonstrated that the improper disposal of plastics into landfill sites and marine systems significantly increases toxic substances in terrestrial and freshwater environments[4]. Without intervention, the accumulation of plastic waste is projected to rise dramatically by 2050. Recycling plastic waste has been identified as one of the most effective strategies to mitigate its detrimental effects on the environment [5].

Thermoplastics, highlighted in various studies, have potential applications in construction due to their durability and chemical properties [6]. However, the contamination of plastic waste at different stages of its life cycle exacerbates environmental hazards, making sustainable waste management a critical area of focus.The sources of waste plastic are packaging, agriculture, construction and demolition, automotive industry, municipal waste, and electrical and electronic waste [7]. A study by [8] showed that the plastic waste recycling rate of Asian countries is unsatisfactory. A compilation presented in Table 1 shows the statistical trend of waste produced in different areas of Asia. China has a recorded highest waste generation crossing 49 Mt in 2018, followed by India, which has more than 17.5 Mt. Pakistan has 1/3rd of this quantum, equating to around 5.5 Mt or so. These numbers signify to proceed this potential quantum of waste plastic for recycling [8]. Suppose this level of consumption is brought together with some essentials and lucrative recycling in the construction industry. In that case, it will provide a sustainable solution with impacts on the environment, society, and the economy.

Plastic waste and its trade in Asia face challenges regarding their environmental and economic implications, and mitigation policies are required in a broader context [9]. Waste that ends up in landfills, oceans, and natural environments is greatly reduced by plastic recycling. Recycling conserves raw materials and, thus, decreases the need for extracting and processing virgin materials. Additionally, plastic recycling is more energy efficient than producing new plastics from raw resources, creating economic benefits and employment for the recycling industry. Nevertheless, the great majority of plastic waste is still sent to landfills, where it can take centuries to decompose. Plastics are not biodegradable: they break down into micro plastics, which embed in the soil, water, and air. The focus of research has been on micro plastics, which have become global pollutants, entering water, sea, and even air ecosystems. The opportunities assessed in solid waste management and plastic recycling highlight that the country's shift towards more sustainable waste management measures and its exploration of the possibility of forming efficient recycling systems is a need that suits regional requirements [10]. Marine wildlife is under threat from plastic pollution in marine environments. Animals ingesting or becoming entangled in plastic waste can cause injury or death. According to [11], more than 800 marine species have been documented to interact with plastic debris. This has resulted in the formation of large debris patches in oceans, including the Great Pacific Garbage Patch, which is composed of millions of tons of floating waste. These marine debris patches not only harm aquatic life but also affect ecosystems and lead to biodiversity loss. A study was conducted that applies life cycle assessment (LCA) to look at the environmental impacts of

Table 2.1: Total Plastic Waste (TPW) (2016–2018) by Country.

Country	**TPW (2016)**	**TPW (2017)**	**TPW (2018)**
China	49.04	49.19	49.71
India	17.48	17.58	17.66
Japan	10.95	11.07	11.19
Turkey	6.13	6.21	6.28
Thailand	5.85	5.88	5.96
Pakistan	5.30	5.40	5.51
Korea, Rep.	4.40	4.39	4.38
Vietnam	3.28	3.29	3.30
Iran, Islamic Rep.	3.20	3.19	3.24
Saudi Arabia	2.97	3.05	3.11
Indonesia	2.74	2.95	3.10
Philippines	2.53	2.58	2.61
Malaysia	2.45	2.60	2.65
Singapore	1.19	1.22	1.24
Israel	1.02	1.02	1.03
Yemen Rep.	0.91	0.92	0.93
Sri Lanka	0.54	0.55	0.56
Mongolia	0.46	0.46	0.46
Tajikistan	0.35	0.36	0.36
Qatar	0.24	0.24	0.25
Turkmenistan	0.16	0.16	0.16
Brunei Darussalam	0.05	0.05	0.05

recycling PET bottles that have been split into fibers. It offers a detailed comparison of the energy consumption and emissions of the processes used for producing recycled and virgin PET [12]. The incineration and burning of plastic waste are other methods of plastic waste management. This is most efficient where there are no spaces for land filling or where there are no facilities for recycling. However, fumes are released during this process, like dioxins and furans, which are carcinogenic, and these are released as gases when plastics are incinerated. Human respiratory health can be badly affected, and humans are very vulnerable to these fumes that develop from burning plastics. This becomes a part of the larger environmental problems of air pollution and climate change. Many regions face deadly smog, which causes visual impairment, with an increase of traffic accidents occurring due to this futile and non healthy gaseous environment. This has become important for policymakers who are seeking to reduce the environmental footprint of plastic waste management, as sustainable alternatives to incineration are sought after.

The impact of energy, environmental, and economic factors on plastic waste recycling encourages the development of ways to increase global recycling rates for all multidisciplinary aspects [13] in order to reduce plastic consumption, encourage biodegradable alternatives, and adopt circular economic principles to help decrease plastic waste. Global collaborations among researchers, policymakers, and industries are striving to come up with new ways to manage the problem of plastic pollution. These efforts are working towards a sustainable future where plastic use and recycling go hand in hand. By understanding the challenges and opportunities facing plastic recycling, society can build better waste management systems and promote environmentally responsible consumption practices [14].

Among the most used plastics in different sectors are high density polyethylene (HDPE), polypropylene (PP), High Impact Polystyrene (HIPS), and Low Density Polyethylene (LDPE) because of their distinct characteristics and widespread use. Since it has a high strength to density ratio and chemical resistance, HDPE is used in making bottles, pipes, and other containers. PP is used in packaging, automotive parts, and household items due to its toughness, flexibility, and heat resistance. The above mentioned properties also make HIPS a popular material in the electronics, automotive, and packaging industries because of its impact resistance and machinability. This lightweight and flexible plastic is used in films, plastic bags, and food packaging and LDPE is a very popular plastic in the market because of its light weight and flexibility. These plastics are produced in large quantities around the globe because they are durable, recyclable, and suitable for different applications [15].Figure 2.1 illustrates the performance of thermoplastics. The synthesis cost increases when the performance level increases

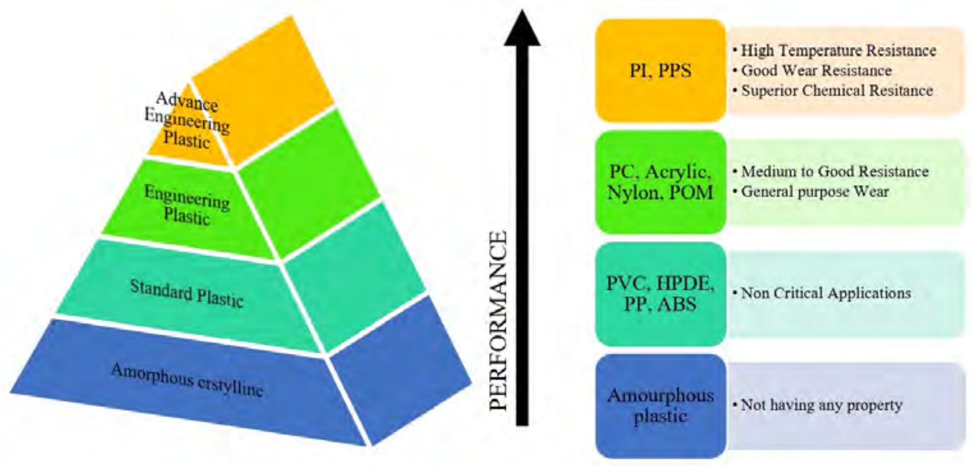


FIGURE 2.1: Temperature as a function of different thermoplastic [16]

The construction industry has explored various methods to repurpose plastic waste into valuable building materials. Researchers have discussed [17, 18] the use of plastic waste in producing construction items through mechanical extrusion and secondary recycling. The products are formed after remolding the plastic into desired shapes. AI based sorting mechanisms are also taking a boom in the market, which is very efficient and quick, which adds value to the mechanical extrusion system. Complex algorithms are developed which improvise the sorting mechanism [19]. Chemical recycling is a more energy efficient process capable of expanding recycling capabilities to previously non recyclable polymers. Chemical recycling involves the destruction of plastics to their molecular levels and then making other forms of polymeric material or virgin material [20]. This also suggests that the pyrolysis process, which converts plastic waste into fuel products, could be a viable solution to the plastic waste crisis [21]. This method does not make the products required for construction, it just removes impurities or converts the polymers to its basic plastic. However, further research is needed to improve the efficiency and scalability of these processes. Actionable points for technological advancement, stakeholder collaboration, and policy interventions are in discussion in different research for these issues [22]. The growing need for affordable housing in rapidly urbanizing areas has further motivated efforts to re purpose waste plastic in construction. As cities grow, more people end up in informal settlements because many cannot afford the right conventional housing materials. Costs of construction materials are high because they are in their raw and new form. The use of recycled or raw plastics is cost efficient and reduces costs while promoting green building practices [23]. Plastics are chemically inert, which makes them durable and resistant to environmental exposure. Using waste plastics in construction could help decrease the demand on landfill sites and support a circular economy that rewards recycling.

Plastic materials could be a source of affordable housing for low income communities based on repurposed plastics for building materials. But these solutions need a planned approach based on scientific work to overcome the problems of material collection, processing, and the longevity of plastic based construction elements. In the current market, about 19.70% of the virgin plastic is used in the construction industry for purposes like panels, ceilings, doors, and other finishing items that are not load bearing. This is because steel and concrete are still the materials of choice for structural applications because of their strength, despite ongoing research into the potential use of plastic waste as a fine aggregate substitute in concrete mixtures. The strength of the mix does not improve with this substitution, but it does provide a more sustainable method of reducing plastic waste. Plastic waste has also been considered for pavement construction, presenting a novel approach to managing waste materials in infrastructure projects. This work will make novel contributions with the focus on developing new ways of managing waste plastics, especially on improving the efficiency of the recycling process. The local waste plastic materials that are being recycled in Pakistan are without any proper technological insight, and the inert challenge to address the environmental pollution is also not being taken into consideration.

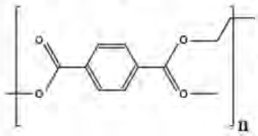
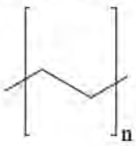
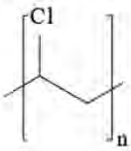
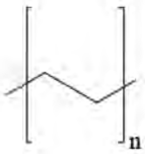
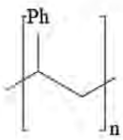
Previous studies predominantly investigated recycled plastic as an additive in concrete composites, roads, and various applications. In contrast, this study explores its viability as a standalone material for structural products. It is important to note that the gas emission monitoring during the extrusion process showed that there was a minimal environmental impact and, therefore, supports the proposed recycling strategy. It is shown that the construction industry's use of recycled plastics has several environmental benefits and, therefore, presents an alternative to the disposal of plastics in landfills and promotes the circular economy. These materials could, therefore, be used to produce durable eco friendly construction products such as blocks, panels, rebars, and other components after adding some chemicals to the recycled plastics to enhance their mechanical properties. These findings, therefore, reveal the capacity of recycled plastics to assist in the solution of the problems of the waste management of plastics and sustainable construction. The production of cost effective and resource efficient building materials is possible through the recycling of waste plastics and, thus, this research contributes to the global effort of environmental conservation and sustainable development.

Plastic recycling methods are generally divided into mechanical and chemical approaches, each presenting specific benefits and drawbacks. Mechanical recycling, which involves physical reprocessing of waste plastics, is comparatively inexpensive and generates a lower carbon footprint, making it suitable for large scale waste reduction initiatives. A limitation of this route is the common issue of down-cycling, where the recycled material loses some of its original properties, resulting in reduced mechanical strength or product quality and restricting its use to lower value applications such as pallets or plastic lumber [24]. In contrast, chemical recycling through processes such as pyrolysis, solvolysis, or enzymatic depolymerization can break polymers down to yield high-purity monomers or polymer precursors similar in quality to virgin materials [25] . This allows the production of higher value items, including automotive and electronic components [24]. However, the disadvantage of chemical pathways lies in their significant energy requirements, dependence on advanced facilities, and, when fossil-based energy is used, a questionable environmental profile. For construction applications, mechanical recycling is more consistent with the circular economy model, as it repurposes plastic waste into functional forms with minimal processing. Chemical recycling, though promising in terms of material recovery, has not yet been widely scaled for producing bulk construction components. In this thesis, mechanical recycling by extrusion is selected deliberately, as it offers a balance of practicality, cost-efficiency, and reduced environmental impact. Its advantages in scalability and lower emissions strengthen its potential as a viable pathway for transforming plastic waste into innovative and sustainable construction materials.

2.2.1 Plastic Identification for Waste Plastic Recycling

Plastics are diverse materials that are categorized by their chemical composition and physical properties to define the kind of plastic for effective recycling and utilization. The main categories are thermoplastics and thermosetting plastics. Thermoplastics can be remelted and reshaped and, thus, are suitable for recycling. Thermosets cannot be remelted because of their cross linked polymer structure [14]. Plastics can also be classified based on their chemical nature and availability for recycling and their use, as follows: PET, HDPE, PVC, LDPE, PP, PS, and ABS are the most common plastics encountered in municipal waste. These plastics are not only central to consumer and industrial products but also have great potential for use in civil engineering applications, such as infrastructure and construction materials. The SPI classification is used to describe the different types of recyclable plastics in Table 2.2. The first category, polyethylene terephthalate (PET), is easily recycled because of its impermeability and solvent resistance and hence is used in the packaging of food and beverages. The density of PET lies within the range of 1.38–1.40 g/cm^3, and it has good transparency and heat resistance [28]. Another kind of widely recycled plastic is highdensity polyethylene (HDPE), which has a waxy surface, semi flexibility, and good chemical resistance. It is used for containers, pipes, and other household goods, with a density of 0.93 to 0.97 g/cm^3. Polyvinyl Chloride (PVC) is famous for its transparency, chemical resistance, and stability but is often criticized for its difficulty to recycle. Its density is 1.10–1.45 g/cm^3, but there are concerns about the chemical transformation during the recycling process [29]. The above mentioned Low Density Polyethylene

TABLE 2.2: Recyclable plastic and properties as per society of plastic industry [26, 27].

SPI symbol/ Code	Structure	General Properties of the Material	Recyclable?	Density (gm/cm^3)
Polyethylene terephthalate: PET				
1 PETE		Impermeable ability: Good Solvent resistance, Hard, Clear, Microwave Transparency, High heat resistant	Widely recycled	1.38-1.40
High-Density Polyethylene: HDPE				
2 HDPE		Impermeable ability: Excellent Chemical repellent Strong, Semi-flexible Waxy surface	Widely recycled	0.93-0.97
Polyvinyl Chloride: PVC				
3 V		Excellent transparency Chemical repellent, Rigid, Good against weathering, Impermeable ability is Good, Stable	It is often not recyclable; the only problem is the chemicals that might alter the polymer	1.10-1.45
Low-Density Polyethylene: LDPE				
4 LDPE		Waxy on surface, Flexible Good transparency, Impermeable ability: Good Low melting point	Not recycled, Fails under stress	0.91-0.94
Polypropylene: PP				
5 PP		Chemical Repellent, Hard, Flexible, High melting point, Translucent, Waxy on surface, Strong	Rarely recycled	0.90-0.92
Polystyrene: PS				
6 PS		Clear, Glassy, Rigid, Brittle, Hard, Good Clarity Fats and solvents can affect	Rarely Recycled	1.04-1.11 For Expanded Polystyrene 0.016-0.64
Others				
7 OTHER		Includes numbers 7-19 usually Polyamides, ABS, PC mixed polymers, etc	Not recycled due to diverse risk of contamination	varies

(LDPE) has very few recycling options because it is a flexible and transparent material with a low melting point and a density of 0.91 to 0.94 g/cm^3.

PP is a strong and chemically resistant plastic with a high melting point and is used in the automotive and industrial sector. However, the rate of recycling of PP is very low because of the intricate ways in which it breaks down. PS is available in its rigid and expanded form and has its characteristics of being brittle, having a glassy appearance, and good clarity. However, the density of the rigid forms of PS is between 1.04 and 1.11 g/cm^3, while that of the expanded forms is 0.016–0.64 g/cm^3. The other category is a group of mixed polymers, including polyamides, ABS, and PC, which are not usually recycled on account of contamination risks and their diversity of composition. These materials have restricted recyclability and are thus a barrier to the sustainability agenda in the plastics industry[4]. Overall, improving recycling methods and addressing contamination risks are crucial steps toward increasing the sustainability of plastic use.

The rising global concern regarding environmental sustainability has emphasized the need to manage plastic waste effectively by integrating recycling practices in various industries, particularly civil engineering. Plastics have become indispensable in modern construction due to their combination of lightness, durability, and resilience against environmental factors. One commonly used recyclable plastic is polyethylene terephthalate (PET), recognized for its strength, lightness, and moisture resistant properties. It effectively prevents gas and solvent permeation, which makes it a preferred choice for food packaging. PET finds extensive use in bottles, food containers, geotextiles, and as fibers for reinforcing concrete.

Civil engineering applications frequently employ PET to enhance concrete structures, improving their strength and resistance to environmental stresses. Recent studies, such as those conducted by [27], have demonstrated that PET fibers reduce water absorption in concrete, thus increasing its thermal insulation and making it suitable for road pavements and building insulation solutions. Additionally, PET is widely utilized in geotextiles to bolster soil stability and minimize erosion, contributing approximately 8% to the total municipal waste generated.

Another important material is high density polyethylene (HDPE), which is known for its durability and chemical resistance. It has a waxy texture and is very tight; therefore, it is used in construction in drainage pipes, detergent bottles, and plastic lumber. In civil engineering, the most popular applications of HDPE are in drainage systems, geomembranes, and landfill liners to prevent the leakage of hazardous waste. It is a very effective environmental safety measure, especially in landfill use as a strong barrier to prevent contaminant leakage. In addition, HDPE pipes are applied in water and gas distribution networks because of their high strength and resistance to corrosion. HDPE and all its variants make up about 30% of municipal waste.

Another well known plastic that is sensitive to flexibility and resistance against chemicals is Polyvinyl Chloride (PVC). It is rigid or flexible, depending on its form, and is used in pipes, flooring, and waterproof membranes. This makes it suitable for electrical cable insulation and other building applications because of its weather ability. However, the processing of PVC produces harmful chemicals as a by product. Therefore, researchers have also ventured into the investigation of sustainable methods for PVC recycling to reduce the adverse impact of PVC on the environment. PVC forms about 10% of the municipal waste and thus forms a large portion of the waste streams.

Low Density Polyethylene (LDPE) is a form of plastic that is flexible and moisture resistant and has a lower melting point and is used in plastic bags, wraps, and landfill liners. It is, therefore, suitable to use as protective films and vapor barriers in construction due to its durability and flexibility. LDPE can be successfully incorporated into asphalt modifications to improve the flexibility and lifespan of road surfaces, as reported by [5]. This plastic variant contributes about 30% of municipal waste, including other forms of polyethylene.

Polypropylene (PP) is another of the most widely used plastics in food packaging, concrete reinforcement, and geotextiles. It has good chemical, heat, and fatigue resistance and is, therefore, used in various industries. PP fibers in civil engineering enhance the crack resistance and the durability of concrete structures. PP has been found to enhance the service life and the performance of infrastructure projects, as [30] has shown, and PP is incorporated into concrete mixtures. About 19% of municipal waste is made up of PP, and it is still a valuable material in construction because of its versatility.

Polystyrene (PS), especially expanded (EPS), is widely used for insulation and lightweight aggregates in concrete. This is a rigid, brittle plastic with good clarity and excellent thermal insulating properties. PS is widely used in disposable cutlery, insulation panels, and as a lightweight filler in concrete. Recycled EPS is used in concrete mixtures to enhance the thermal performance and decrease the overall structural weight of buildings to make them more energy efficient. PS constitutes about 6% of municipal waste. Lastly, ABS is a kind of Acrylonitrile Butadiene Styrene, a highly durable and impact resistant plastic used in making automotive parts, toys, and modular construction panels. Its use in modular construction has been increasing because it is strong and easy to fabricate. Figure 2.2 illustrates

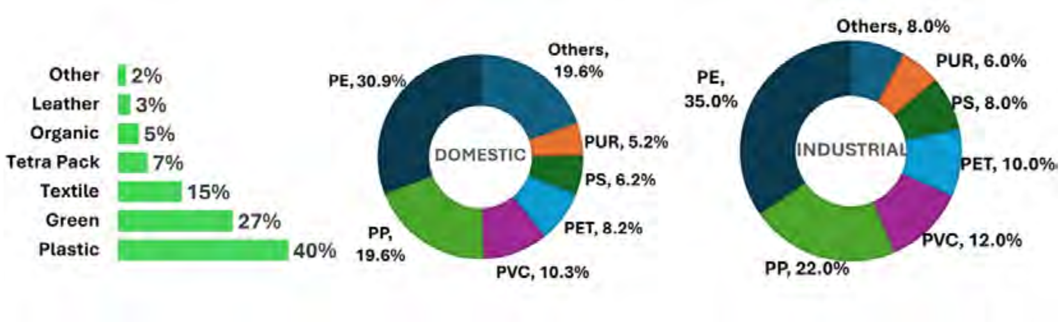


Figure 2.2: Representation of composition of waste: (a) different waste in municipal waste; (b) domestic bifurcation of plastic waste; and (c) industrial bifurcation of plastic waste[31, 32]

the distribution and composition of waste materials and plastics. (a) shows that plastic waste (40%) is the dominant category in municipal waste, followed by green waste (27%), textiles (15%), and smaller fractions of Tetra Pack, organic, leather, and other materials. (b) presents the overall composition of plastic waste in municipal waste, being 40% overall, with Polyethylene (PE) (30.9%) and polypropylene (PP) (19.6%) being the most abundant, followed by PVC, PET, PS, and PUR, while other materials make up 19.6%. Industrial waste is also of significance and is highlighted in (c). The plastic types from these make PE and its variants, HDPE and LDPE, good contenders for recycling; PP is another contender for recycling, as PE (35%) and PP (22%) dominate in the waste, along with contributions from PVC, PET, PS, PUR, and other minor components. The data emphasize the significant presence of PE, along with its variants, and PP in plastic waste, making them key candidates for recycling and sustainable material applications.

2.2.2 Waste Plastic Recycling Methods and Products

Waste plastic recycling methods and the products derived from these processes have become an essential focus in addressing global plastic pollution. As plastic waste continues to accumulate at an alarming rate, recycling offers a promising solution to reduce the environmental impact while generating valuable products for various industries. Recycling methods, including mechanical, chemical, and thermal recycling, have been extensively studied and improved to enhance the efficiency and quality of recycled plastics [31]. Each method offers unique advantages and produces specific products that contribute to the circular economy and sustainable development goals. Polymer recycling methods, including mechanical and chemical recycling, in the context of environmental sustainability are discussed in study. It also discusses the limitations and opportunities of current technologies in achieving a circular economy for plastics [20]. Mechanical recycling is the most used method. It starts with the usual collection of materials from waste; sorting it into its categories; cleaning, either through washing or screening; shredding, as per the extrusion machine sizes; and finally remolding the plastic waste into desired new products. The melting points, extrusion flow speed, and other changes are made as per the plastic type. It is highly employed for plastic packaging, bottles, and other containers, etc. The quality of the recycled material is found to decrease with multiple extrusions and over time due to the polymer chain scission and contamination. To overcome this, stabilizers and additives are used to improve the properties, improving their robustness as recycled plastic [32].

Chemical recycling is another method by which plastics are depolymerized or broken down into their monomeric components or other valuable chemicals through processes such as depolymerization, solvolysis, and pyrolysis. While mechanical recycling is capable of handling pure plastic types, chemical recycling can handle mixed and contaminated plastic waste to produce high quality raw materials that can be used to make new plastics. They are monomers, fuels, waxes, and solvents. Advancements in catalytic depolymerization to make chemical recycling more efficient and economically viable to recover valuable compounds from complex plastic waste streams have been reported in research [33]. For enhancing the reuse and recycling of waste management strategies, integrated approaches to effective resource utilization and sustainability are necessary [34]. Thermal recycling processes, such as pyrolysis and gasification, are methods used to break down plastic waste into energyrich products such as fuels, syngas, and char. Pyrolysis is a process which involves the heating of plastic waste in the absence of oxygen to produce pyrolysis oil, which can be further processed into various fuels or used as raw material to produce new plastics. Pyrolysis can be used for all kinds of plastics, including those that are not able to be recycled mechanically [35]. Gasification, a partial oxidation of plastic waste at high temperatures, produces syngas that can be used to make electricity or other chemicals and fuels. Thermal recycling is especially useful for dealing with nonrecyclable and contaminated plastic waste that would have otherwise been sent to the landfill. New technologies, including advanced solvent-based recycling and the enzymatic recycling of plastics are also being developed to enhance the efficiency and sustainability of the plastic recycling process. The solventbased recycling is a process of dissolving plastics in a solvent to separate the polymers from contaminants and additives. This produces high purity polymers, which can be reused to make new plastics. Enzymatic recycling, a more recent concept, uses enzymes to cut back specific plastic polymers into their monomers. However, the enzymatic recycling of PET (polyethylene terephthalate) and other polyesters has been found to be very efficient and produced highquality monomers that can be repolymerized into plastics of virginlike quality [36].

Another new method that is also coming up is electrochemical recycling, which uses electrolysis to tear down plastic polymers to their basic forms. This method is a clean and energy efficient way of recycling plastics with minimal or no hazardous products. In a study [31], the authors pointed out that electrochemical recycling is very efficient at converting plastic waste into useful chemicals and monomers, thereby reducing the impact on the environment and promoting sustainability. The products obtained from recycled plastics depend greatly on the type of recycling method employed. Lower value products, such as plastic lumber, pallets, and park benches, as well as packaging materials, are usually produced from the mechanical recycling process. Since chemical recycling can produce highpurity raw materials, it is possible to make highvalue products, such as automotive components, electronic housing, and medical devices. Other thermal recycling methods produce fuels and energy products that can be used in the place of fossil fuels, cutting carbon emissions and helping with energy sustainability [6].

Alongside conventional recycling techniques, innovative technologies, such as 3D printing with recycled plastics, offer new ways of creating customized and intricate products. Recycled plastics can be used in additive manufacturing to make high performance components for aerospace, healthcare, and consumer products and their potential. Researchers seek to enhance the mechanical properties and efficiency of recycled plastics for 3D printing by fine tuning material formulations and printing techniques. Optimization models for waste supply chains concentrate on strategic network designs to enhance recycling and waste management systems [37].

Composite materials from recycled plastics have better mechanical and thermal properties than conventional materials [38]. For instance, researchers have investigated the processing of composites from recycled PET and HDPE reinforced with natural fibers, glass fibers, or carbon fibers. Automotive parts, building materials, and consumer products are made from composite recycled materials, offering a green alternative to the virgin materials [27]. Although current recycling technologies and the diverse array of marketable products produced from recycled plastics are strong, there are still issues with scaling up these technologies to the necessary level to make recycling operations economically feasible.

Contamination, poor quality, and limited infrastructure pose a significant problem to the current lack of the widespread adoption of recycling practices. To overcome these challenges, researchers are looking into the development of new sorting technologies, automation, and efficient purification processes that can enhance the quality of the recycled products. In parallel with recycling of petrochemical plastics, researchers have also been developing bio-based polymers and composites for construction applications. Bio-based plastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), derived from renewable resources, offer biodegradability and reduced carbon footprint. However, their use in construction is still limited to non-structural or semi-structural components due to inherent limitations in durability and thermal stability. More promising are biocomposites – materials that combine natural fibers or agricultural waste with polymer matrices (either bio-derived or recycled plastics).

Numerous studies document biocomposites being used for interior building elements for instance, natural fiber polymer composites have been used to manufacture doors, window frames, ceiling panels, and even load-bearing components like beams and slabs [39]. Wood-plastic composites (WPCs), which often mix recycled plastic with wood flour or natural fibers, are already commercial for decking, cladding, and furniture, offering weather resistance and moderate strength. These bio- and natural fiber composites are attractive for their lightweight and sustainability; some even demonstrate mechanical properties comparable to synthetic composites [40].

To enhance the mechanical performance of recycled plastics, researchers have created hybrid composites by reinforcing them with fibers or fillers. Recycled polypropylene and HDPE have been combined with glass fibers, carbon fibers, and even textile waste fibers to produce rebars and panels with superior stiffness and strength. For example, carbon fiber-reinforced recycled HDPE can achieve flexural moduli above 5 GPa [39], significantly higher than plain recycled HDPE, indicating the potential for structural-grade materials when proper reinforcement is used. Hybrid approaches also extend to nano-fillers (like nanoclay or carbon nanotubes) to improve stiffness, or blending different types of plastics to enhance properties through compatibilization . While this thesis focuses on 100% recycled plastic without additives (to prove feasibility of the pure material), the literature suggests that future development of recycled plastic construction materials may involve such hybridization to meet higher structural demands.

Another branch of research aims to incorporate plastic waste into concrete and masonry [41, 42], forming what can be termed recycled polymer concrete. One approach is using shredded or pelletized plastic waste as a partial replacement for mineral aggregates in concrete. Studies have shown that replacing 5–15% of natural aggregate with waste plastic can decrease concrete density and improve impact resistance and thermal insulation [43]. However, plastic's lack of surface roughness and chemical bond with cement paste often leads to reduced compressive strength and modulus in the resulting concrete[44]. For instance, adding PET or HDPE particles tends to lower concrete's compressive strength by up to 20–50%, and may affect workability, unless special binders or treatments are applied [44]. To counteract these drawbacks, researchers have formulated polymer concretes where a polymer resin (sometimes derived from recycled plastics) entirely replaces Portland cement as the binding phase. Such polymer concretes can attain high strength and rapid curing; however, they are expensive and can creep under sustained loads. Notably, plastic aggregate concrete and polymer cement applications are more common in non-structural elements (like paving blocks, architectural features, or overlays) due to code limitations and variable performance. By highlighting these studies, we see a broader context the use of waste plastics in construction is being explored in many forms – from fully plastic structural units (the focus of this thesis) to mixed material systems like polymer mortars and fiber-plastic composites. Each approach addresses sustainability with different balances of strength, cost, and durability. This thesis complements that body of work by demonstrating how structural components can be made entirely from recycled plastics, thereby avoiding cement altogether and maximizing the usage of polymer waste.

2.2.3 Waste Plastic in the Construction Industry

The integration of plastic waste into the construction industry is a breakthrough. Sustainable building material tends to invoke environmental recovery. Recycled PET, HDPE, and LDPE are being assessed for use in the construction sector in applications like bricks, pavers, insulation materials, and lightweight concrete. The use of waste plastic aggregates as partial replacements for natural aggregates in concrete has been found to decrease the environmental hazards of conventional materials and enhance some features, such as the thermal insulation and durability of the concrete [45]. These usages present big challenges regarding the remolding and handling of recycled plastic in bulk quantum. Recent research has shown that incorporating plastic aggregates can reduce cement's workability, compressive strength, and durability due to the weak bonding between plastic and cement. However, findings on water absorption, shrinkage, and abrasion resistance remain inconsistent, with some studies indicating improvements when PET is used. Recently a comprehensive study has compared the performance of PET, HDPE, and PP under the same for curb construction.

One study study fills that gap by evaluating the mechanical and durability properties of plastic aggregate concrete and assessing its feasibility for curb applications [46]. Another study focuses on three types of recycled aggregates—recycled clay brick sand (RCBS), recycled glass sand (RGS), and recycled fine concrete aggregates (RFA)—loaded with nanoscale titanium dioxide (NT) to enhance the photocatalytic efficiency. The study only focuses on the recycling of aggregates but does not correspond to waste plastic [47]. The employability of waste in construction may lead to the production of more sustainable materials. Plastic lumber produced from recycled plastics is now used for decking, fencing, and even park benches, offering a durable and weather resistant alternative to traditional wood [27].

Innovations in 3D printing technology have also made it possible to create customizable building components using plastic filaments that are derived from waste materials to enhance both their design flexibility and resource efficiency. Even so, the problem of plastic waste dumping has not been eliminated by using recycled plastic materials in construction. Recent studies have also been aimed at improving the mechanical properties and the durability of enhanced plastic concrete, with some research suggesting that mixing different types of plastic waste can improve the strength and sustainability of the material [48]. This serves as a promising pathway to reduce plastic waste and promote a circular economy in the building sector by transforming plastic waste into construction materials [4, 49].

Table 2.3 presents an overview of various studies that used different types of plastic aggregates as replacements in construction materials through their diverse applications and replacement ratios. The LDPE has been used as a fine aggregate replacement in concrete mixtures, with replacement ratios that enhance the workability and reduce the density of concrete. HDPE has been incorporated to show its effectiveness in enhancing the durability of the concrete, reducing water absorption, and improving crack resistance. Polyethylene terephthalate (PET) has been used as a fine aggregate replacement and coarse aggregate replacement. These replacement levels, in research, have been up to 100% to enhance sustainability. The innovative ideas decrease the amount of waste material sent to landfill.

These studies collectively underscore the growing importance of integrating recycled plastics into construction materials to achieve sustainability goals in the building industry. Much research has also been done (annotated in the table) that uses plastic in road construction and soil stabilization. Different aspects have been compiled, such as mechanical benefits, PET incorporation, plastic integration, modification in asphalt, and generic uses of recycled mixed plastic. The gap identified is that it does not use plastic as the main material for products. This study will pave the way to developing recycled plastic waste as the main material for the construction industry. Recycled high density polyethylene (rHDPE) and polypropylene (rPP) blends have been extensively studied to assess their mechanical properties and their potential applications in various industries. The mechanical properties of rHDPE and rPP are influenced by processing conditions, blending ratios, and contamination from prior use. Table 2.4 is a depiction of different ratios of rHDPE with blends. Studies indicate that as the percentage of recycled polymer increases, the mechanical properties, such as tensile strength and Young's modulus, tend to degrade due to molecular chain scission and lower crystallinity [108]. Research [109] on PP:HDPE blends has shown that tensile properties degrade after multiple recycling cycles. The Young's modulus and yield strength of rPP:rHDPE blends were found to be lower than those of virgin polymer blends due to structural degradation during the recycling process. However, at rPP contents exceeding 75%, the yield strength of the recycled blends approached that of virgin materials. This decline in mechanical properties is primarily attributed to a reduction in crystallinity, molecular weight degradation, and the formation of imperfect crystalline structures. Moreover, blending techniques play a crucial role in mitigating mechanical property losses.

Table 2.3: Previous studies that used waste plastic in construction.

Waste Plastic Type	Purpose Used For	Matrix	Purpose	References
HDPE	FA, CA	Concrete	Additive	[50–53]
LDPE	FA, CA	Concrete	Additive	[51, 54–56]
PET	Fiber Strips	Concrete	Reinforcement	[49, 57–71]
NM	Filler Material	Concrete	Flexibility	[72–77]
Melamine Formaldehyde	Fiber Strips	Concrete	Reinforcement	[78]
PVC	Fiber Strips	Concrete	Flexibility	[79–81]
PET & PC	Fiber Strips	Concrete	Reinforcement	[64]
GFRP	Fiber Strips	Concrete	Reinforcement	[82, 83]
LDPE & PET	Filler Material	Concrete	Filler	[84]
ABS & PC	Filler Material	Concrete	Structural Support	[85]
PP	Fiber Strips	Concrete	Structural Support	[86, 87]
Mixed Plastics (various)	FA, CA	Asphalt	Durability	[88–91]
PE	Fiber Strips	Asphalt	Reinforcement	[92, 93]
PET	Filler Material	Asphalt	Flexibility	[94, 95]
PP	FA, CA	Asphalt	Durability	[96, 97]
HDPE	Fiber Strips	Asphalt	Durability	[98, 99]
PVC	Filler Material	Asphalt	Reinforcement	[100, 101]
PS	Filler Material	Asphalt	Flexibility	[102, 103]
LDPE	FA, CA	Asphaltic Concrete	Tensile	[90, 104]
PP	Fiber Strips	Soil	Soil Reinforcer	[105]
HDPE	Fiber Strips	Soil	Soil Reinforcer	[106]
PET	Filler Material	Soil	Soil Improvement	[107]

Table 2.4: Previous studies plastic blends of various plastic

Waste Plastic Type	**Mixed Proportion**	**Property Studied**	**References**
HDPE	100% HDPE	Tensile strength, elongation at break.	[108, 110]
PP	100% PP	Impact resistance, tensile modulus.	[108, 111]
HDPE + LDPE	Diff. proportion HDPE, LDPE	Ductility, impact strength.	[108, 112]
HDPE + PP	50% HDPE, 50% PP	Tensile strength, elongation, thermal stability.	[109]
HDPE + SAM (samicanite)	Diff. proportion HDPE, SAM	Wear resistance.	[113]
HDPE + POL (polyolefin)	60% HDPE, 40% POL	Elastic modulus, heat deflection temperature.	[114]
HDPE + V (virgin PE)	Diff. proportion HDPE, virgin PE	Stress cracking resistance, environmental resistance.	[115]
LDPE	100% LDPE	Tensile strength, environmental stress cracking.	[113]

The effects of compatibilizers such as maleic anhydride polypropylene (MAPP) on rPP:HDPE blends were investigated [110], and it was found that their addition significantly improved interfacial adhesion and tensile strength. This improvement was due to better stress transfer at the interface between PP and HDPE, thereby reducing the negative effects of immiscibility between the two polymers. The study [110] also focused on the longterm mechanical performance of rHDPE/vHDPE blends, revealing that blending virgin HDPE with recycled HDPE up to 70% recycled content maintained comparable tensile properties to virgin HDPE. However, increasing the recycled content beyond 70% led to significant reductions in mechanical performance, particularly in fatigue resistance. The study also found that different blending methods, such as powder mixing and extrusion, had a negligible effect on tensile performance. Morphological analyses using scanning electron microscopy (SEM) and atomic force microscopy (AFM) have demonstrated that higher proportions of rHDPE lead to phase separation at the nano scale level, which negatively impacts mechanical strength [113]. However, strategic processing techniques, such as controlled cooling rates and optimized mixing, can enhance mechanical performance by improving the homogeneity of the blend. A study on electron beam cross linking in HDPE/PU blends indicated that while crosslinking can improve thermal stability and mechanical properties, it significantly reduces elongation at break. However, optimized cross linking combined with compatibilizers resulted in a balance of tensile strength and ductility, making such blends suitable for high performance applications [114]. All these previous studies only focus on plastic generically but not for use in construction and assess only the properties of plastics. Detailed mechanical properties also need to be assessed for these types of plastic.

2.2.4 Environmental Aspects and Hazards of Waste Plastics

While waste plastic recycling offers several environmental benefits by reducing plastic pollution and conserving resources, there are also several environmental aspects and hazards associated with it that need to be addressed. The environmental implications of plastic waste recycling processes (mechanical, chemical, and thermal recycling) vary from reducing landfill waste to producing potential air and water pollutants. These aspects must be addressed to develop sustainable recycling systems that minimize harm to human health and the environment [31]. One of the major environmental issues of plastic waste recycling is the generation of toxic substances because of the recycling process. Plastics are melted and remolded through mechanical recycling and can emit volatile organic compounds (VOCs) and other hazardous air pollutants [5]. These emissions can also lead to air pollution and are bad for human health. Plastic additives, like flame retardants, stabilizers, and plasticizers, are also problematic as they can leach into the environment during recycling. The risks can also be reduced by ensuring proper ventilation and the use of filtration systems in recycling plants [33]. Chemical re-

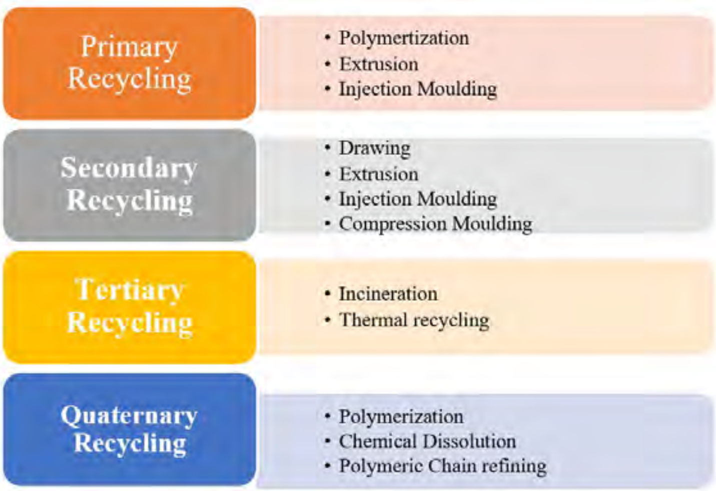


FIGURE 2.3: Classification of Recycling Methods for Thermoplastics

cycling processes that are based on breaking down plastics to their basic chemical components also have environmental issues. Although chemical recycling has the advantage of producing high quality recycled materials, it is an energy intensive process and can also produce hazardous byproducts. For instance, the depolymerization of plastics produces harmful chemicals that must be properly handled to avoid causing pollution [31]. Ways to improve catalysts and reactor designs to decrease the environmental footprint of chemical recycling processes are also being developed. Thermal recycling processes, including pyrolysis and gasification, are means of transforming plastic waste into fuels and other forms of energy. However, these processes are known to emit greenhouse gases (GHGs) and other pollutants, which contribute to climate change and poor air quality [34]. Emissions, such as carbon monoxide, nitrogen oxides, and particulate matter, are produced during the pyrolysis process and need advanced emission management systems to control them. The environmental impact of thermal recycling also depends on the efficiency of the process and the type of plastic waste that is being treated. Another crucial environmental aspect of waste plastic recycling is the potential contamination of water sources. Micro plastics are persistent pollutants that pose risks to aquatic ecosystems and human health, and the potential contamination of water sources is another significant environmental aspect of waste plastic recycling. To minimize water pollution, recycling facilities must implement effective filtration and wastewater treatment systems to prevent the discharge of micro plastics into the environment to prevent the release of micro plastics into water bodies during the collection, sorting, and washing stages of plastic waste. Another environmental challenge is the disposal of non recyclable plastic residues. Not all types of plastic waste are efficiently recyclable, and the residues left after recycling processes are often sent to landfills or incinerated. The land filling of plastic residues can leach toxic substances into the soil and groundwater, while incineration can emit harmful pollutants in the air. Strategies for sustainable waste management must also address the development of technologies to manage non recyclable residues and decrease their environmental impact [31].

Figure 2.4 is the scheme of this study intended to explore recycling plastics for structural construction materials, moving beyond their traditional use in concrete and roads. The approach is to assess and recycle municipal solid waste plastics for construction applications with complete recycled plastic products. It begins with the assessment of municipal waste collection, sorting, cleaning, and palettization as the initial recycling steps, as well as the role of plastics in construction. The waste plastic material assessment in this study stage involves a spot analysis using SEM and a material behavior evaluation using TGA and FTIR. The product manufacturing process includes the modification of mechanical extrusion setup and the preparation of mold, while also considering gas emissions and environmental hazards. The processed materials are further modified for future construction applications. This structured approach ensures an environmentally sustainable and

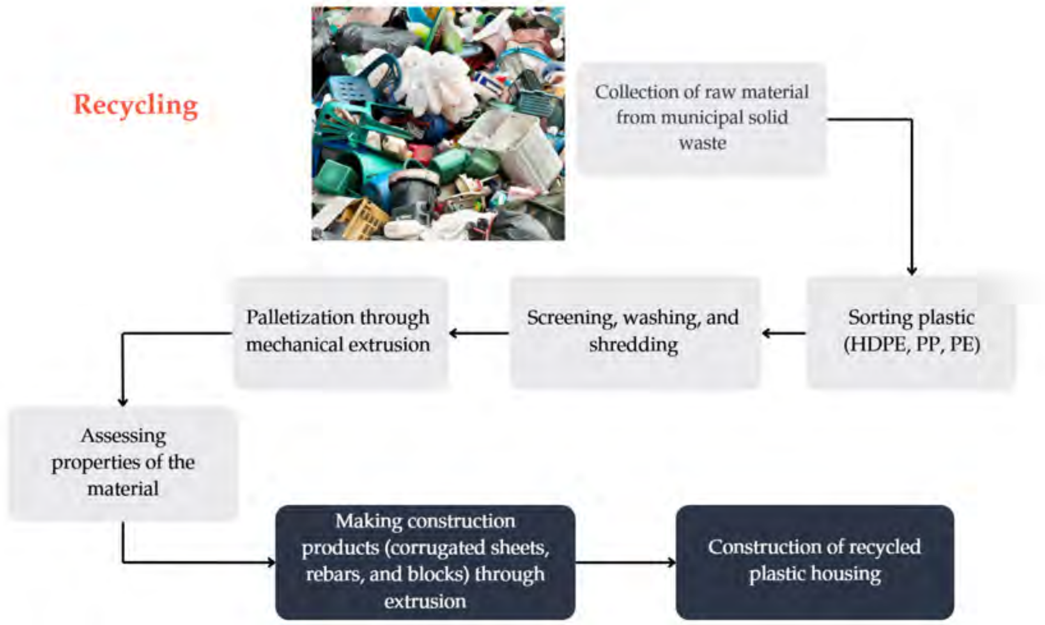


FIGURE 2.4: Flowchart to assess prospective use of recycled plastic in Construction Industry.

technically feasible method for recycling plastics into durable construction materials. Although environmental challenges are present, the advantages of plastic recycling outshine its disadvantages when done correctly. Recycling keeps plastic waste from entering the environment, conserves raw materials, and reduces the need to produce virgin plastic, which is an environmentally impactful process. The following are ways to minimize the environmental hazards of recycling, at the point of the recycling facilities: improving sorting technologies, cleaner production techniques, and circular economy principles should be adopted.

2.2.5 Recent Sustainable Material Innovations

In addition to recycling petrochemical plastics, researchers have increasingly focused on the development of bio-based polymers and composites for construction applications. Polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), derived from renewable feedstocks, are particularly appealing because of their biodegradability and reduced carbon footprint. However, their structural use remains limited due to inherent weaknesses in durability and thermal stability, confining them mainly to non-structural or semi-structural applications. More promising progress has been made with bio composites, which are produced by combining natural fibres or agricultural residues with polymer matrices, either bio-derived or recycled. These materials have been successfully used to manufacture doors, window frames, panels, and lightweight load-bearing members. Among these, wood–plastic composites (WPCs) are already widely commercialized for decking, cladding, and furniture. They offer weather resistance and moderate mechanical strength while being lightweight and sustainable, with some formulations achieving properties close to synthetic composites.

To address the relatively low mechanical performance of recycled plastics, hybrid composite approaches have been extensively studied. Reinforcing recycled polypropylene and HDPE with glass fibres, carbon fibres, or even textile waste fibres has been shown to produce rebars and panels with improved stiffness and strength. For instance, recycled HDPE reinforced with carbon fibres has demonstrated flexural moduli above 5 GPa, which is a significant improvement over plain recycled HDPE and indicates potential for structural-grade applications. In addition to fiber reinforcement, nano-fillers such as nano clays and carbon nanotubes have been explored for enhancing stiffness and long-term durability. Blending different plastics with compatibilizers has also been reported as a means of improving interfacial bonding and overall performance. While the present thesis deliberately restricts itself to the use of 100% recycled plastics without additives, these studies suggest that future advancements in structural applications may rely on such hybridization strategies to overcome performance limitations. Another strand of research has examined the incorporation of plastic waste into concrete and masonry. Shredded or pelletized plastics are commonly used as partial replacements for mineral aggregates in concrete mixes. Experimental studies have shown that substituting 5–15% of natural aggregates with plastic waste lowers concrete density and enhances impact resistance and thermal insulation. At the same time, the absence of surface roughness and chemical bonding between plastic particles and cement paste often results in reduced compressive strength and stiffness. For example, the inclusion of PET or HDPE particles has been observed to decrease compressive strength by as much as 20–50%, unless special surface treatments or binders are employed. To mitigate these limitations, polymer concretes have been formulated in which a polymer resin, sometimes sourced from recycled plastics, entirely replaces Portland cement as the binder. Although these mixes can deliver high strength and rapid curing, they remain costly and may be susceptible to creep under sustained loading. Consequently, plastic-aggregate concretes and polymer mortars are currently more common in non-structural uses such as pavers, overlays, and architectural elements.Collectively, these developments show that plastics, whether bio-derived, hybridized, or incorporated into cementitious systems, are being integrated into construction in diverse ways. Each approach balances trade-offs among strength, cost, durability, and sustainability. The present work builds upon this body of research by demonstrating that entire structural components can be produced exclusively from recycled plastics, thereby eliminating cement dependence and maximizing the valorisation of polymer waste within a circular economy framework.

2.3 A Glimpse on Need, Manufacturing and Utilization of Rebars from Existing Literature

2.3.1 Sustainable Rebars from Plastics

Plastic waste has become a critical environmental threat, with 79% found in landfills and marine environments in 2015, a figure projected to double by 2050 if current trends persist [116–118]. Recycling is widely endorsed as a key mitigation strategy, and the construction sector presents significant potential for large scale reuse [119]. Historically reliant on steel since Monier's 1867 patent, reinforcement bars are now evolving through materials like fiberrein forced polymers (FRP), bamboo, and coir fiber to address issues of cost and corrosion [120, 121]. Despite advantages such as light weight and corrosion resistance, FRP rebars suffer from brittleness and anisotropy under dynamic loads [120, 122], while bamboo and coir exhibit improved tensile and damping behavior in seismic settings[123, 124]. Recent research has introduced hybrid rebars incorporating waste plastics (e.g., PET, PVC) with glass fibers, enhancing both strength and sustainability [125, 126] . These innovations are increasingly used in mortarfree construction systems, where interlocking units replace cement joints, and recycled plastic rebars serve as lowcost seismic stiffeners [121]. Concurrently, microplastics pose rising health risks, with adults ingesting over 3,000 particles annually [127, 128]. Recycling is hampered by additive and heavy metal contamination, e.g., antimony from ewaste [129], yet solutions like micro factories, HDPE based reuse, and rPVC/rHIPS blends offer promise [130, 131]. Advances in mechanical, chemical, thermal, enzymatic, and electro chemical recycling are improving recovery efficiency and polymer purity, with applications extending from plastic lumber to aerospace components [132, 133]. These developments underscore the need for automation, improved sorting, and purification to scale up sustainable recycling systems [134].A recent study examined recycled polyethylene from used products and found that contamination and material inconsistency can affect its reuse in new production pro-cesses [135]. Plastics have gained increasing attention in construction due to their corrosion resistance, low weight, and long service life, making them suitable for use in non-load-bearing structural components. Their reusability aligns with circular eco-nomic goals, particularly as concerns grow over the environmental impact of post-consumer plastic-waste. Recent studies in Guayaquil, Ecuador, report that households generate approximately 1.64 kg of plastic waste per day, with HDPE and PP comprising around 20% and 10%, respectively [136, 137]. Despite their recyclability, large portions remain unrecycled due to limited infrastructure and source separation [136]. These findings underscore the need for targeted recovery strategies for PP and HDPE in urban waste management systems.

2.3.2 Eco-Friendly Rebar Solution

The construction industry is actively seeking sustainable reinforcement strategies to address the limitations of conventional steel rebars, particularly their susceptibility to corrosion in aggressive environments such as marine and coastal regions [138]. Although epoxy coated and stain lesssteel variants have improved corrosion resistance, their high cost has stimulated the search for alternatives. Fiber Reinforced Polymer (FRP) rebars, especially those made from glass, carbon, or aramid fibers, offer notable advantages including corrosion resistance, low weight, and reduced electromagnetic interference [120, 122]. Nevertheless, FRP rebars exhibit brittle failure modes and anisotropic behavior, limiting their application under dynamic and shear loading conditions [139]. Recent developments in hybrid FRP composites, integrating jute and coconut fibers, have enhanced flexural and impact performance, providing greener reinforcement options [123]. Bamboo has also emerged as a costeffective, renewable material for structural reinforcement, achieving satisfactory tensile strengths with proper treatment to mitigate biodegradability concerns [123, 140, 141]. Natural fiber ropes, such as jute, hemp, and coir, when chemically treated, have been effectively used to improve the ductility and seismic performance of concrete structures [124, 142]. Ferrocement strips, thin mortar composites reinforced with mesh or wires, have proven effective in flexural strengthening and crack control of slabs and walls [143]. Additionally, nearsurface mounted (NSM) techniques using steel wire strips have demonstrated substantial improvements in the shear capacity and ductility of retrofitted reinforced concrete beams [144]. Thermo Mechanically Treated (TMT) rebars, known for their high strength and superior seismic performance, remain widely used in earth quakeprone regions [145, 146]. Basalt Fiber Reinforced Polymer (BFRP) rebars, produced from volcanic basalt rock, are gaining attention due to their excellent corrosion, chemical, and thermal resistance properties, making them ideal for marine and repair applications [147]. In parallel, recycled plastic rebars developed from PET, HDPE, and polypropylene fibers present a sustainable and corrosion resistant alternative for noncritical applications, promoting circular economy principles [148, 149]. These diverse innovations collectively signify a shift towards eco efficient, resilient, and cost effective reinforcement strategies in modern construction practices.

2.3.3 Use of Rebars in Lightweight Construction

Mortar free construction, or dry stack masonry, is an emerging technique that eliminates the use of cement based mortar by utilizing precisely manufactured interlocking units such as concrete blocks, stabilized soil bricks, or recycled composites that fit together to ensure structural integrity through geometry and weight alone. This method offers numerous benefits, including faster construction, reduced material costs, and enhanced sustainability due to the absence of cement, which lowers carbon emissions.

It also provides superior seismic performance, as the flexibility between interlocked units allows for better energy dissipation during earthquakes, making it ideal for disasterprone regions and emergency shelters [150, 151]. Advanced block designs now incorporate features like tongue and groove or dovetail joints, improving load transfer, ease of assembly, and structural strength [152, 153]. Materials used in these systems include high strength concrete and recycled composites, and researchers have integrated insulation elements to enhance energy efficiency [143]. The use of locally sourced materials further supports sustainability by reducing transportation emissions and costs [154, 155].

Mortar free construction has proven adaptable for both temporary and permanent structures in residential, commercial, and emergency contexts, with studies confirming its resilience to environmental stressors and comparable performance to conventional masonry [149]. Additionally, it simplifies maintenance by allowing individual block replacement, reduces water ingress by eliminating mortar joints, and aligns well with green building initiatives. As urbanization increases and the demand for efficient, ecofriendly construction rises, mortarfree systems are poised to play a key role in the future of sustainable infrastructure development [155].

This study presents a pioneering approach by transforming municipal plastic waste, specifically HDPE and PP, into structural rebars for mortarfree construction. Unlike conventional studies that utilize recycled plastics as additives or fillers, this work develops fullscale, loadbearing rebars from waste polymers. A total of 48 rebar samples in three diameters (12 mm, 19 mm, 25 mm), both plain and ribbed, were fabricated through mechanical extrusion and subsequently tested. Due to the absence of standard methods for plastic rebars, tensile testing was conducted following ASTM A615 guidelines. FTIR analysis confirmed characteristic CH stretching and CH_3 rocking vibrations of the base polymers. XRD revealed distinct crystalline peaks of HDPE and PP, while SEM highlighted ductile tearing in HDPE and brittle fracture in PP. Mechanical results showed substantial tensile strength, with HDPE demonstrating better extrusion performance and recyclability. Earlier, plastic waste was used in minimal quantum in research as a sustainable solution. This is the first study to validate recycled plastic rebars as standalone elements for sustainable construction. The findings offer a viable, lowcarbon alternative to conventional steel reinforcement, reducing dependency on virgin raw materials. By employing mechanical extrusion and promoting the structural reuse of plastic waste, this research supports circular economy principles and contributes to sustainable material innovation, environmental resilience, and the broader goals of sustainable urban development.

2.4 Available Researches on Need, Manufacturing and Utilization of Corrugated Panels

Corrugated panels are intensely utilized for lowcost construction, originally devised in the 1820s by Henry Palmer to reduce construction costs using timber-framed, masonryfooted systems [156]. Over the decades, advancements like the Hatschek and Magnani processes enabled mass production of fibercement corrugated panels[157–159]. However, with global plastic waste surging, particularly HDPE and PP, sustainable alternatives have emerged, emphasizing the use of recycled plastic for construction components [158, 160, 161]. Mechanical recycling via extrusion has enabled the development of polymer based roofing sheets with adequate tensile and flexural properties [162].

These sheets, when fabricated using recycled plastic pellets, have shown high durability and thermal stability under various mechanical loads [163–165]. Their integration into construction materials also aligns with circular economic goals and reduces landfill pressure [166, 167]. Research further suggests that thermoplastics can be molded into panels, and sheets that meet structural demands [168, 169].

Recent field and lab studies validate their energy absorption, chemical resistance, and minimal gas emissions during processing [170]. Such applications represent a paradigm shift from concrete heavy, resource intensive roofing to lightweight, cost effective recycled alternatives[158, 171].The reported 25% efficiency corresponds to reduced thermal heat gain achieved by the low thermal conductivity of PP/HDPE (0.22–0.48 W/mK) and the insulating behaviour of corrugated geometry[172].

A broad review of corrugated sheet materials reveals a diverse range ranging from asbestos reinforced fiber cement to galvanized iron and newer polymeric compounds. Classical materials such as asbestos cement had high thermal and chemical resistance but faced health and environmental concerns, prompting research into PVA, cellulose, and synthetic fiber alternatives [157]. UPVC and polymer composite sheets, tested using FEM simulations and static load experiments, are being explored as viable replacements, offering fire resistance and structural reliability [174]. Even corrugated paper boards have seen optimization using sustainable design and simulation techniques for improved performance in packaging and building skins [158]. For metallic alternatives, corrugated steel sheets provide high load bearing capacity but face fatigue issues, especially at bolted lap joints under cyclic stress [164].

Roof systems comprising builtup and panel designs also vary significantly in impact resistance under hail or storm conditions, guiding material selection for resilient architecture [175]. Overall, the design of corrugated sheets today is strongly influenced by ecological imperatives, economic feasibility, and mechanical behavior under loading, leading to a transition toward recycled polymers and composites in roofing and enclosure systems [176]. Properties of corrugated panels, both static and dynamic, are pivotal in determining their application in realworld construction. Finite element modeling of UPVC hollow sheets confirms their capacity to withstand wind speeds up to 99 km/h and human installation loads [177]. Impact testing of roofing systems highlights how builtup panels behave differently under hail strike conditions, underlining the importance of ductility and surface resilience [178]. Fibercement sheets produced by the Hatschek process show anisotropic permeability patterns that influence vapor and gas transfer across roofing surfaces [179].

Structural shell models also show that corrugation enhances membrane stiffness while reducing inplane deformation, contributing to improved stability under buckling loads [180]. From a material science perspective, composite sandwich panels incorporating Kevlar, PP, and thermoplastic polyurethane demonstrate high flexural stiffness and improved failure mechanisms under loading [29]. Corrugated iron buildings, historically valued for their transportability and economy, now face conservation challenges, though the same principles are being revived through recycled plastic counterparts [156]. Modern applications of recycled plastic panels, produced via hot pressing and mechanical extrusion, exhibit minimal emissions, good interfacial bonding, and performance characteristics suitable for roofing, panel, or siding systems[160, 176]. These shifts suggest a growing preference for polymer-based corrugated systems capable of meeting structural and environmental standards simultaneously. Table A.18 presents a comparative overview of commonly used corrugated roofing materials, highlighting their advantages, limitations, and fixing methods. While galvanized and aluminium sheets are affordable and widely used, they suffer from corrosion and poor thermal performance. Fibre-cement, bitumen, and plastic sheets offer better resistance but are limited by brittleness, weight, or manufacturing constraints. This comparison underscores the need for durable, lightweight, and corrosion-free alternatives such as recycled polymer corrugated panels proposed in this research.

2.5 Identified Research Gap

Despite a growing body of literature on the reuse of plastic waste in construction, most studies have focused on the incorporation of plastic as a secondary additive such as filler material in concrete composites, coarse or fine aggregate substitutes in pavements, or insulation components. These applications, while useful, do not fully leverage the structural potential of recycled plastics. There is a notable lack of research on the use of 100% recycled thermoplastics (such as HDPE and PP) as primary materials for load bearing and modular construction components, including corrugated panels and structural rebars. Furthermore, existing research rarely integrates multiscale material characterization (e.g., SEM, XRD, FTIR) with structural performance validation under standardized mechanical testing protocols (ASTM D790, A615, etc.). Moreover, the absence of empirical models that relate the mechanical behavior (e.g., impact resistance, tensile strength, energy absorption) of recycled plastic products to their compositional or geometric parameters further limits the scalability and predictability of such materials in realworld applications. In terms of practical implementation, few, if any, studies have investigated the use of recycled plastic components in mortar-free, interlocking building systems, particularly in the context of lowcost housing or disasterrelief shelters in developing countries. The lack of commercially available building products such as recycled plastic rebars and corrugated panels combined with the absence of relevant design standards emphasizes the novelty and necessity of the current research. A meaningful assessment of recycled plastic construction products requires comparison with established materials such as steel, concrete, and timber. Conventional mild steel rebars (ASTM A615 Grade 40) typically deliver yield strengths around 280 MPa and a modulus of elasticity near 200 GPa. By contrast, recycled HDPE/PP rebars exhibit much lower tensile strength (approximately 20–30 MPa in this study) and significantly reduced stiffness, often only a few gigapascals. To meet equivalent performance targets, design adaptations are necessary, such as enlarging the cross-section or decreasing spacing within reinforcement meshes. Future studies can improve the analogy and enhance the properties of recycled plastic rebar strengths. Although weaker mechanically, recycled plastic rebars offer notable advantages in cost and sustainability. The feedstock, post-consumer plastic waste, is inexpensive, and extrusion is a relatively low-energy, modular process. In contrast, steel production depends on energy-intensive ore smelting and is subject to market volatility. Plastics also weigh about one-eighth as much as steel, simplifying transportation and handling, while their resistance to corrosion eliminates costly protective measures and long-term maintenance. The early cost modelling can be explored for future studies indicative of volume or weight replacement, in light-duty and non-critical applications, roughly the total life-cycle expense of recycled plastic components may be 30–40 % lower than that of steel. Added environmental benefits include reduced landfill demand and lower embodied carbon. These economic and ecological advantages explain the growing interest in recycled plastics as a structural resource for affordable housing and secondary infrastructure. However, for applications requiring high strength, hybrid composites or reinforcement strategies remain essential to bridge the performance gap with steel and fibre-reinforced polymers. Thus, the most realistic role for recycled plastics lies not in wholesale replacement of steel, but in delivering low-cost, corrosion-resistant solutions where lower strength is acceptable, but durability and sustainability are paramount.

2.6 Summary

This chapter comprehensively explored the various dimensions of plastic waste recycling, focusing on its environmental urgency, technological evolution, and emerging relevance to the construction industry. It highlighted how conventional approaches have predominantly utilized plastic waste as supplementary materials such as fillers, aggregates, or insulation rather than as principal structural components. The growing global interest in recycling HDPE, PP, LDPE, and other thermoplastics stems from their inherent chemical stability, mechanical strength, and recyclability, yet their direct application in fullscale structural construction remains largely under explored. The tensile, flexural, and shear responses are now correlated with crystallinity, fracture morphology, and thermal stability obtained from FTIR, XRD, and TGA results. This linkage highlights that higher crystallinity and compact molecular alignment in rPP contribute to increased tensile strength and stiffness, whereas the more amorphous structure of rHDPE enhances ductility and energy absorption. These interrelations provide a holistic understanding of how material composition and processing influence overall performance, thereby strengthening the scientific coherence of the study Through an indepth review of existing literature, the chapter established that while recycled plastics have demonstrated potential in roadways, pavements, insulation, and fiber reinforced composites, their deployment as stand alone building elements such as corrugated panels and rebars is limited and lacks standardized validation. Furthermore, limited integration of multiscale characterization techniques (SEM, XRD, FTIR, TGA) with standardized mechanical testing has restricted the optimization and predictability of recycled plasticbased products. Key gaps identified include the absence of empirical performance models, minimal focus on structuralscale recycled plastic components, and the lack of research addressing mortarfree, interlocking construction applications using such materials. These limitations signify both the novelty and necessity of the current study. The research presented in subsequent chapters aims to fill these voids by synthesizing recycled plastic products through mechanical extrusion, conducting comprehensive mechanical and microstructural evaluations, and proposing designready applications for lowcost, modular, and sustainable construction systems. In summary, the literature reveals a pressing need for standardized performance data and structural applications of fully recycled plastic materials. Prior studies, while demonstrating the feasibility of using waste plastics in construction, have largely been limited to non-structural uses or composite formulations. There is a noted lack of established testing protocols and design guidelines for recycled plastic structural elements [25, 181], as well as minimal exploration of 100% recycled plastic members under load. These gaps directly shape the approach of this dissertation.

Chapter 3

Prospective Use and Assessment of Recycled Plastic in Construction Industry

Related Article

1. **Das, A. J.** and Ali, M. (2025). "Prospective Use and Assessment of Recycled Plastic in Construction Industry". Recycling, 10(2), 41.

2. **Das, A. J.** and Ali, M. (2021). "Recycling of waste plastic with least effects to the environment: A Review" *In proceedings of International Conference on Innovations in Energy Engineering and Cleaner Production, Silicon Valley, California USA (29-30 July 2021)*

3. **Das, A. J.** and Ali, M. (2022). "Mechanical and microstructure properties of recycled polystyrene for use in construction," *Proc. 3rd IMCEET-2025 Conf.*, 29th April 2025.

3.1 Background

This study introduces innovative approaches to managing waste plastics, emphasizing improved recycling efficiency. In Pakistan, plastic recycling lacks technological insight and fails to address environmental pollution concerns. This research examines the potential of municipal plastic waste in the construction industry by developing structural elements with essential mechanical properties for housing. Previous studies on waste plastic alone have not completely analyzed all the parameters for use in the construction industry. Seven types of recycled plastics HDPE, LDPE, PP, polyolefin, samicanite, and virgin polyethylene (PE) were analyzed for identification, impurities, and mechanical, thermal, and structural properties. Comprehensive assessments using SEM, FTIR, and TGA provided insights into chemical composition, thermal stability, and impurity levels. A total of 140 samples were tested: 35 each for shear, flexural, tensile, and compression. Results indicate that HDPE exhibited superior tensile strength and shear resistance, making it suitable for structural applications. Blending HDPE with LDPE and PP enhanced ductility and energy absorption, while combinations with polyolefin and samicanite improved thermal stability. The SEM analysis of failure sur-faces revealed ductile tearing in HDPE and brittle failure in PP. Unlike previous studies that primarily explored recycled plastics as additives in concrete composites, soil stabilization, and roads, this research evaluates their viability as standalone structural materials for building products. Mechanical extrusion, being the most efficient process to reduce environmental hazards, was employed. The findings highlight the potential of recycled plastics in construction, offering an eco friendly alternative to landfill disposal while promoting a circular economy. By varying and assessing different blends, recycled plastics can be used to manufacture durable construction products, such as blocks, panels, and rebars. This research contributes to sustainable development by demonstrating the feasibility of cost-effective, resource efficient building materials derived from plastic waste.

3.2 Experimental Procedure

3.2.1 Recycling Through an Environmentally Friendly Approach

3.2.1.1 Collection of Raw Material and Material Identification

New developments in extrusion-based plastic recycling have greatly expanded the ability to transform waste plastics into useful materials in a more sustainable and efficient manner. New extrusion technology has resulted in the creation of machines that can handle a wider variety of post-industrial and post-consumer plastic waste than previous machines. They have also resulted in higher quality recycled products and less environmental pollution. Moreover, the integration of catalytic technologies into the extrusion process has shown promise in selectively upcycling plastic waste into valuable products.

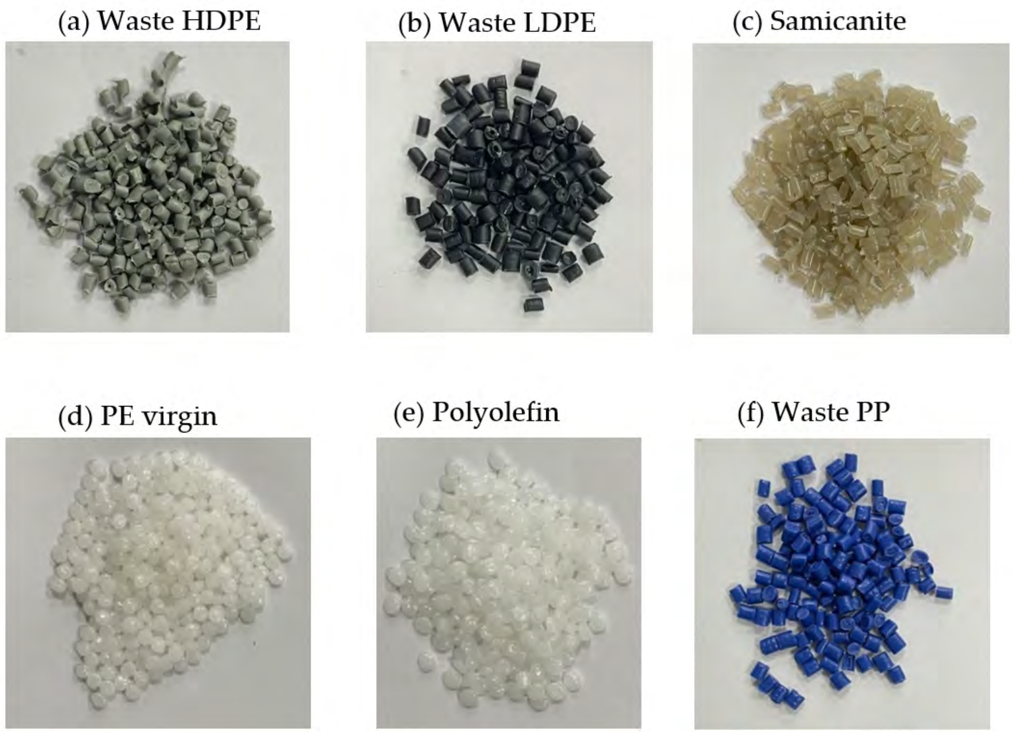


FIGURE 3.1: Pallets of different raw plastic materials analyzed for research.

The waste plastics were collected from municipal solid waste, and palletization was done in the first round after cleaning. The source materials were collected and sorted out from the waste as per their resin type; the same were cleaned with a simple water wash. Materials were sorted using RIC labels (2 HDPE, 5 PP) on waste plastic. Waste plastics were washed and dried before extrusion. The process was conducted under local exhaust ventilation; gas monitoring with the ST8900 sensor confirmed safe levels ($H_2S < 5$ ppm, $CO < 20$ ppm), and pallets were made for the second round of extrusion to make the desired mold as per the ASTM standards: D790 (flexural), D695 (compression), D732 (shear), and D638 (tensile). A further six modifications were drawn from waste materials, and the samples were studied for the same mechanical properties to investigate the effects of mixing. Out of the other plastics, HDPE was found to be better for the extrusion process than the other plastics, which is a major component in municipal waste. Other materials, which were locally available, were used to make variant mixes that were further assessed, and which were likely to vary the properties of the plastic; these included LDPE with HDPE, polyolefin with HDPE, samicanite pallets with HDPE, and HDPE with virgin material. These plastics were sought to economize the product and alter the properties for an efficient extrusion process. Figure 3.1 shows the different raw materials in the pallets that were formed after the first round of extrusion. FTIR, TGA, and SEM were used to assess the basic material properties, which are also shown in Figure 3.1.

a. SEM and the detection of impurities

The SEM analysis of raw waste plastic materials (Figure 3.2) was done, and waste HDPE plastic at a magnification of 250 µm revealed compositional variations in different regions. The spectrums were further analyzed for the composition of the material. Spectrum 2 in Figure 3.3 indicates the presence of impurities, with a composition of 93.3 wt.% carbon (C), 5.5 wt.% oxygen (O), 1.2 wt.% calcium (Ca), and 0.2 wt.% sodium (Na). In contrast, Spectrum 4 in Figure 3.3 showed a slightly different impurity profile, with 95 wt.% carbon (C), a significantly higher oxygen content at 33.6 wt.%, 0.9 wt.% calcium (Ca), and 0.4 wt.% chlorine (Cl). These differences suggest localized variations in the chemical composition, potentially due to surface contamination, additives, or environmental exposure.

The SEM in Figure 3.2 shows the details of waste LDPE plastic at a magnification of 100 µm, which revealed notable differences in chemical composition across regions. Spectrum 7 exhibited a diverse impurity profile, with 80.6 wt.% carbon (C), 13.6 wt.% oxygen (O), 4.4 wt.% calcium (Ca), 0.6 wt.% silicon (Si), 0.4 wt.% sodium (Na), 0.3 wt.% aluminium (Al), and 0.2 wt.% magnesium (Mg). However, in contrast, Spectrum 10 exhibited a pure composition of 100 wt.% carbon (C), with no detectable impurities or additives present. These results point to the surface chemistry of the LDPE sample being heterogeneous, due to contamination, additives, or pro-cessing conditions. At a magnification of 500 µm, the SEM image in Figure 3.2 of sami-canite showed a consistent chemical composition across different regions. Both Spectrum 2 and Spectrum 3 in Figure 3.3 were composed entirely of 100 wt.% carbon (C), with no detectable impurities or additives present.

This uniformity of the carbon structure is expected from a highly pure material with consistent processing, which is the case with samicanite.The SEM image of virgin polyethylene (PE) at 500 µm magnification showed the material to be highly pure in its composition over the examined areas. Both Spectrum 2 and Spectrum 3 in Figure 3.3 presented a uniform chemical profile of 100 wt.% carbon (C) with no detectable impurities or additional elements. This result points to the pris-tine nature of the virgin PE sample, indicating its high purity and proper material properties for applications that demand contamination-free material. At a magnification of 250 µm, the SEM profile of polyolefin showed slight variations in chemical composition across the examined regions. In Spectrum 2 of Figure 3.3, the composition of 93.3 wt.% carbon (C), 4.3 wt.% oxygen (O), and 2.4 wt.% titanium (Ti) indicates the presence of minor impurities or additives. Spectrum 3 has a composition of 96.2 wt.% carbon (C), 2.9 wt.% oxygen (O), and 0.9 wt.% titanium (Ti), and this shows a higher content of carbon and a lower content of titanium than Spectrum 2. These differences point to a variation in the sample, which might be due to the distribution of additives or surface treatment effects.

b. FTIR of Raw Material

Fourier Transform Infrared Spectroscopy (FTIR) is a method for analyzing the infrared spectrum of a sample to determine its chemical constituency. It measures the infrared spectrum of a sample and produces a spectral output that acts as a molecular "fingerprint". This technique is especially useful for organic and inorganic materials, including polymers, coatings, and composites. It is also used to identify the functional groups, such as hydroxyl, carbonyl, and amine, as well as their interaction in a material. This method is both qualitative and quantitative and can be used to determine the composition of the sample, as well as the amount present [182] FTIR was performed on all the plastic raw material samples in Figure 3.4. The waste HPDE has intense C–H stretching bands, together with

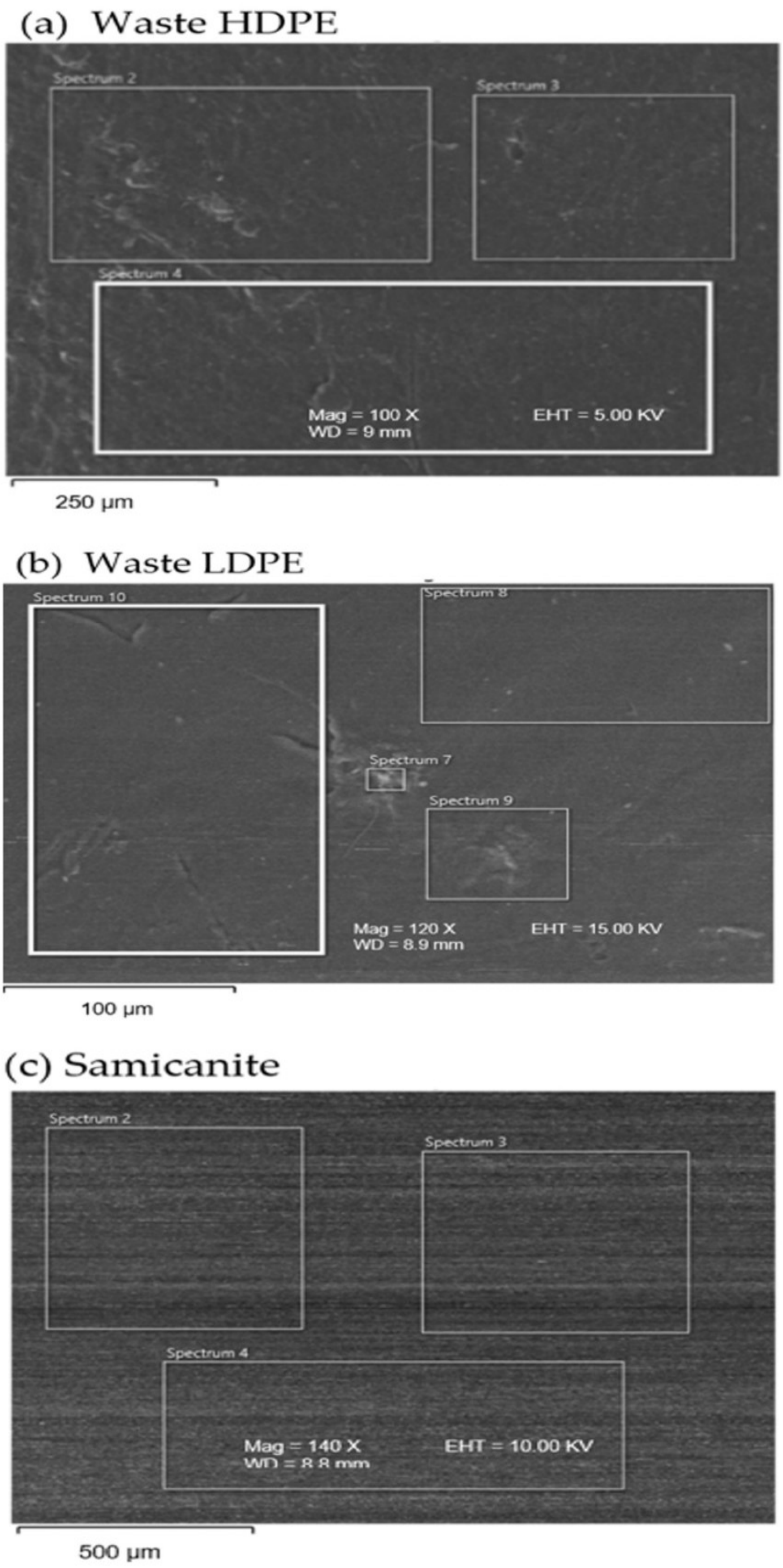


FIGURE 3.2: SEM images of different raw material pellets continued ...

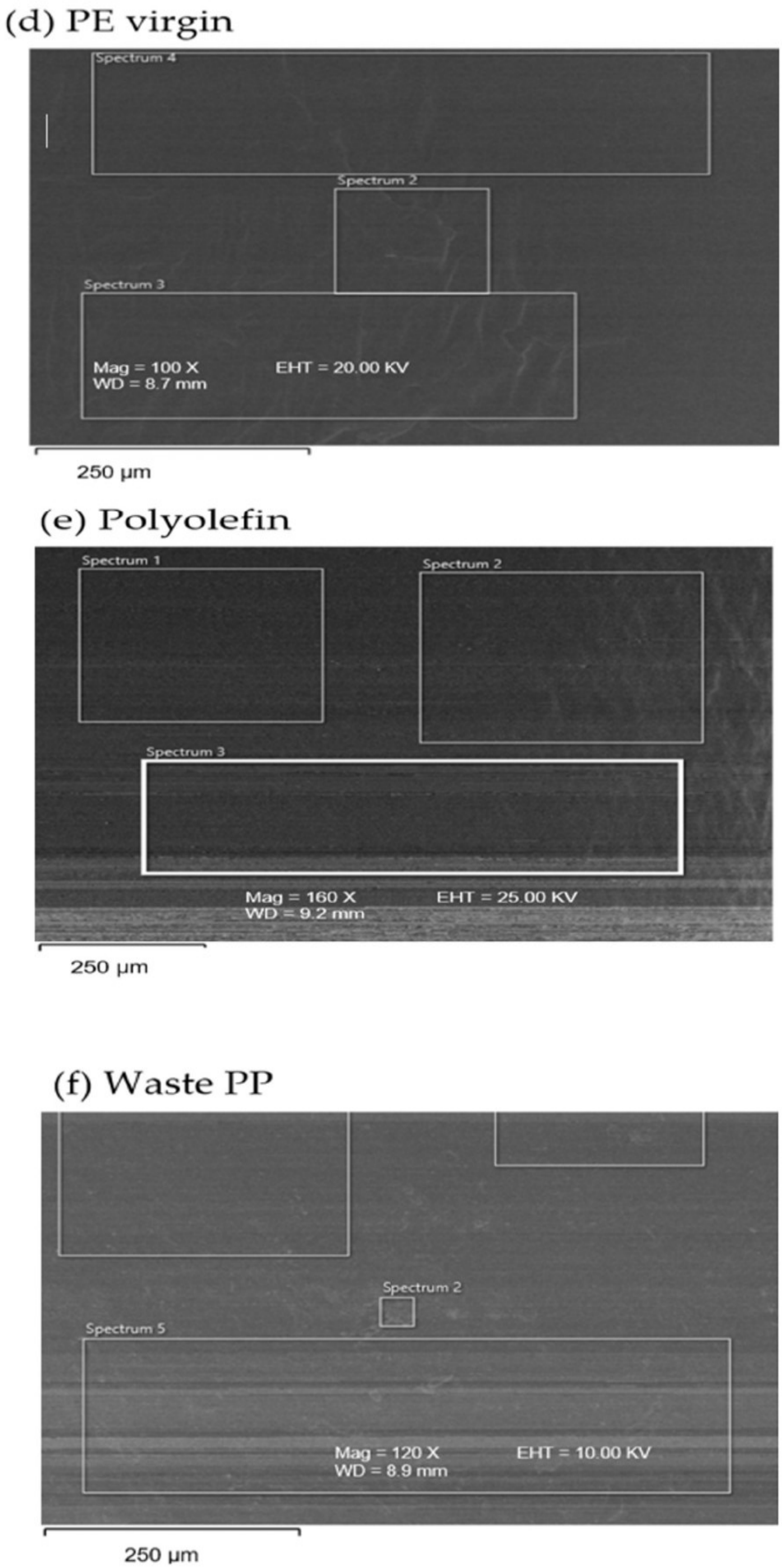


FIGURE 3.2: SEM images of different raw material pellets

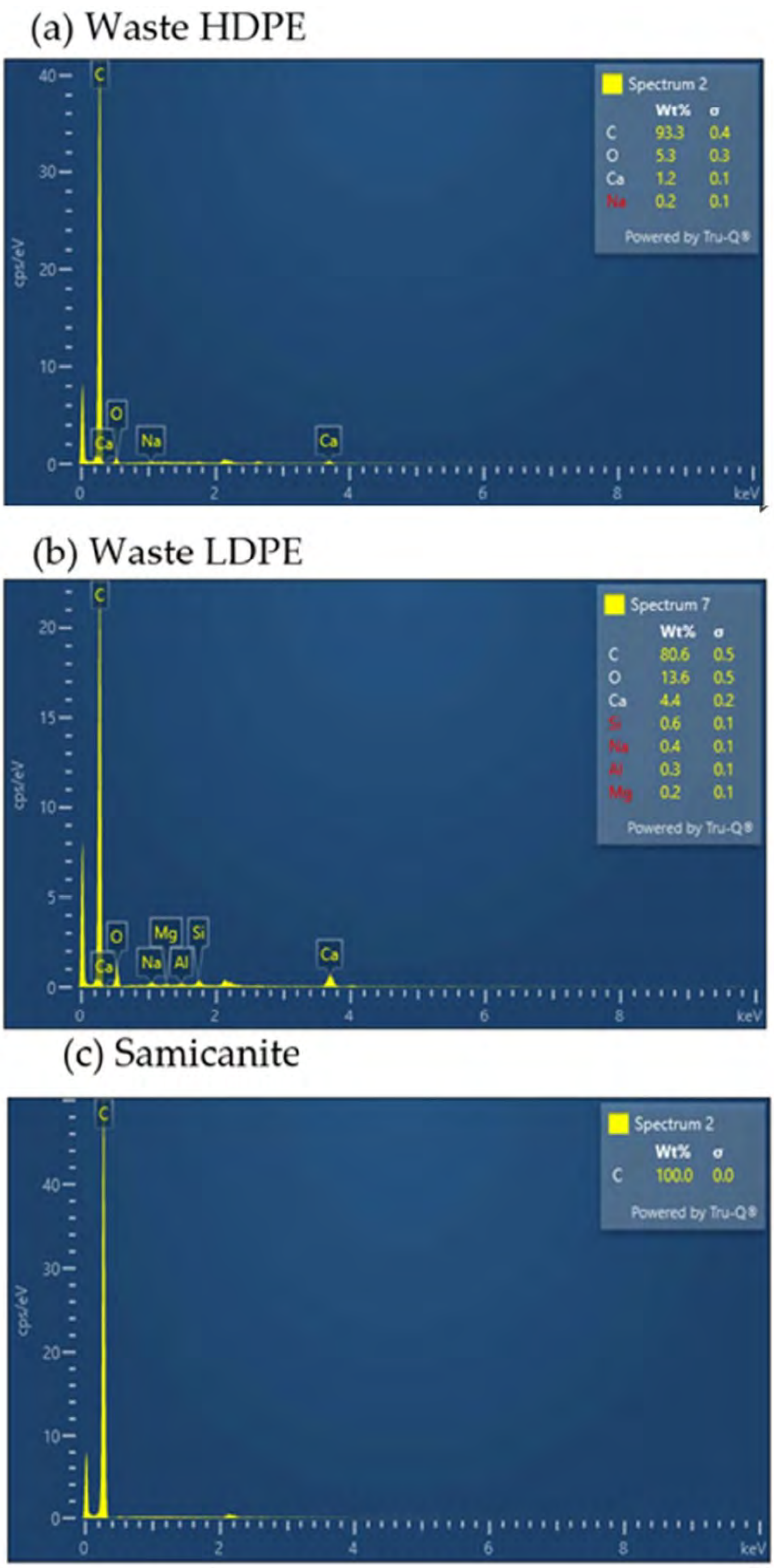


FIGURE 3.3: Spectra obtained from the SEM of different pallets showing the presence of different impurities in the collected material continued ...

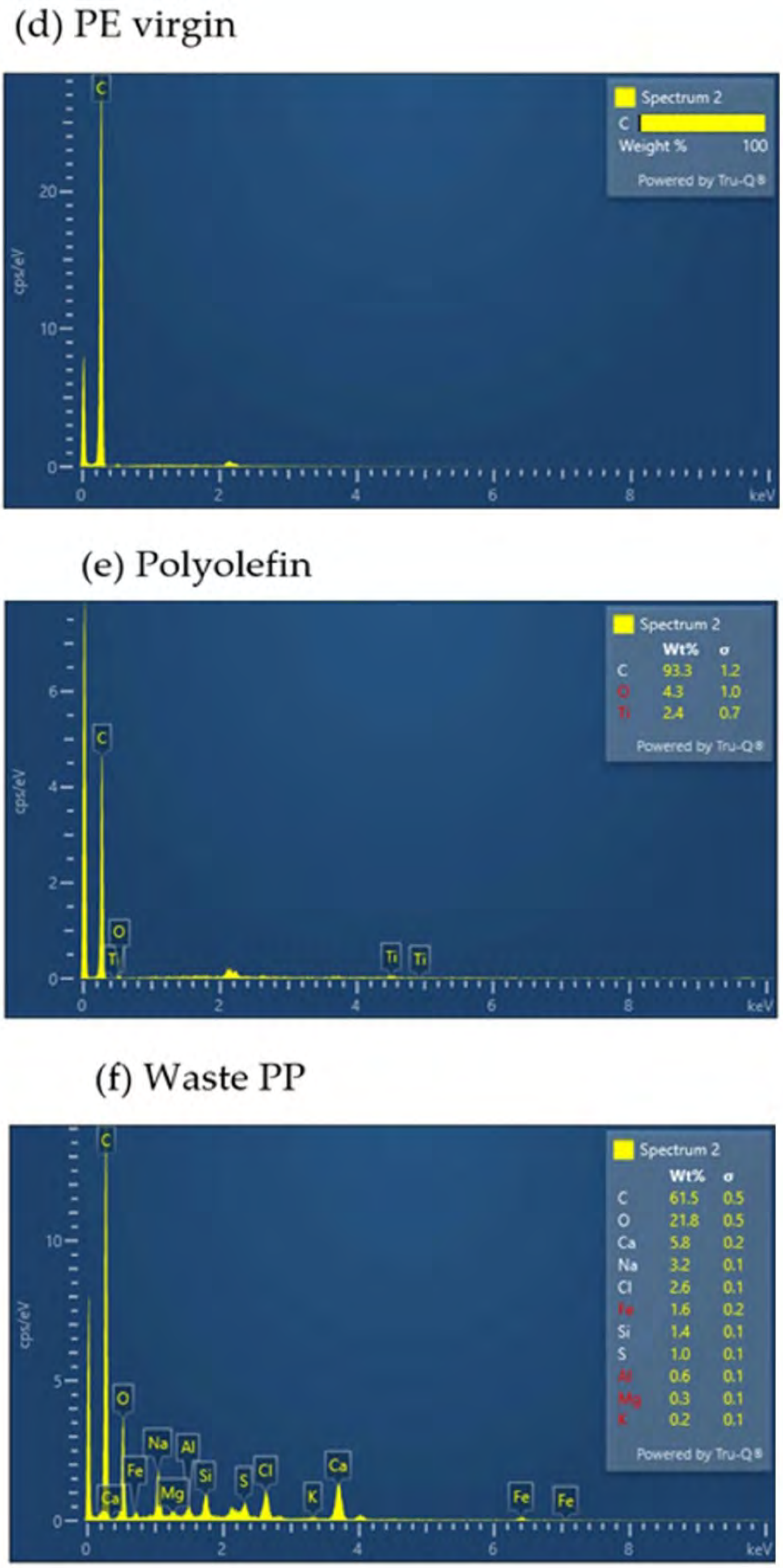


FIGURE 3.3: Spectra obtained from the SEM of different pallets showing the presence of different impurities in the collected material.

well-defined peaks in the carbonyl (C=O) region at about 1700 cm^{-1}, indicating that stabilizers or fillers have been used. The fingerprint region has several absorptions, which may be due to the material's composition or its processing.

This sample is most suitable for use in structural or packaging applications where the material needs to withstand the weather. The FTIR spectrum of the LDPE is characterized by the absorptions due to the hydrocarbon chain in the 2800–3000 cm^{-1} range. Other peaks in the 1000–1200 cm^{-1} region indicate the presence of oxygen-containing functions, which might be ethers or esters and are used to enhance the impact strength or service temperature of the material. This sample has easily reproducible intensity patterns that indicate that the material is homogeneous. FTIR spectra revealed mild oxidation (carbonyl and hydroxyl peaks), correlating with slight stiffness reduction but stable ductility. The FTIR spectrum of samicanite shows aliphatic absorptions and a secondary peak at about 1600 cm^{-1}, which may indicate the presence of aromatic structure or aromatics. The fingerprint region has strong and narrow peaks, which is characteristic of a good blend of polymer. This material has been developed to enhance its strength and heat resistance. Strong absorption in the carbonyl region at about 1700 cm^{-1} and C–H stretching peaks and a broad absorption indicate the presence of carbonyl-containing groups in the virgin PE.

The fingerprint region of this polymer shows that it is a well-ordered matrix with sharp peaks. This material is probably being used in applications where chemical and environmental resistance is of considerable importance. The spectrum for polyolefin highlights strong peaks in the aliphatic C–H stretching region. Moderate absorption in the 1100–1200 cm^{-1} range hints at oxygen-containing additives, such as fillers or processing agents. The material exhibits consistent intensity patterns, making it suitable for lightweight and flexible applications. The waste PP spectrum reveals strong hydrocarbon absorptions in the 2800–3000 cm^{-1} region and prominent peaks in the carbonyl region, suggesting the presence of esters or ketones. The fingerprint region is rich in detail, reflecting a highly tailored polymer composition. This material appears to be designed for specialized applications where chemical resistance and structural integrity are paramount.

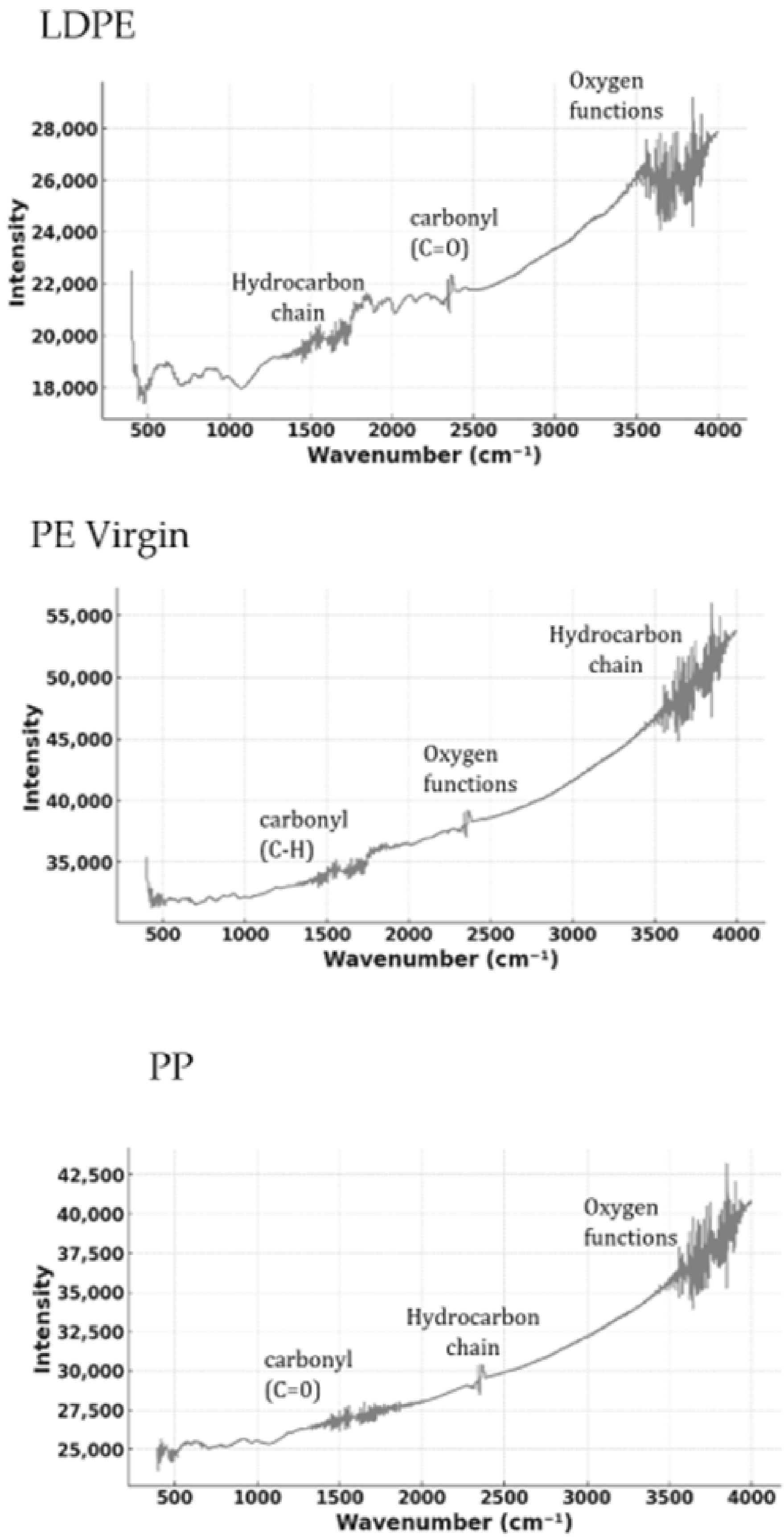


FIGURE 3.4: FTIR of different pallets showing absorption at different intensities in raw plastic materials continued ...

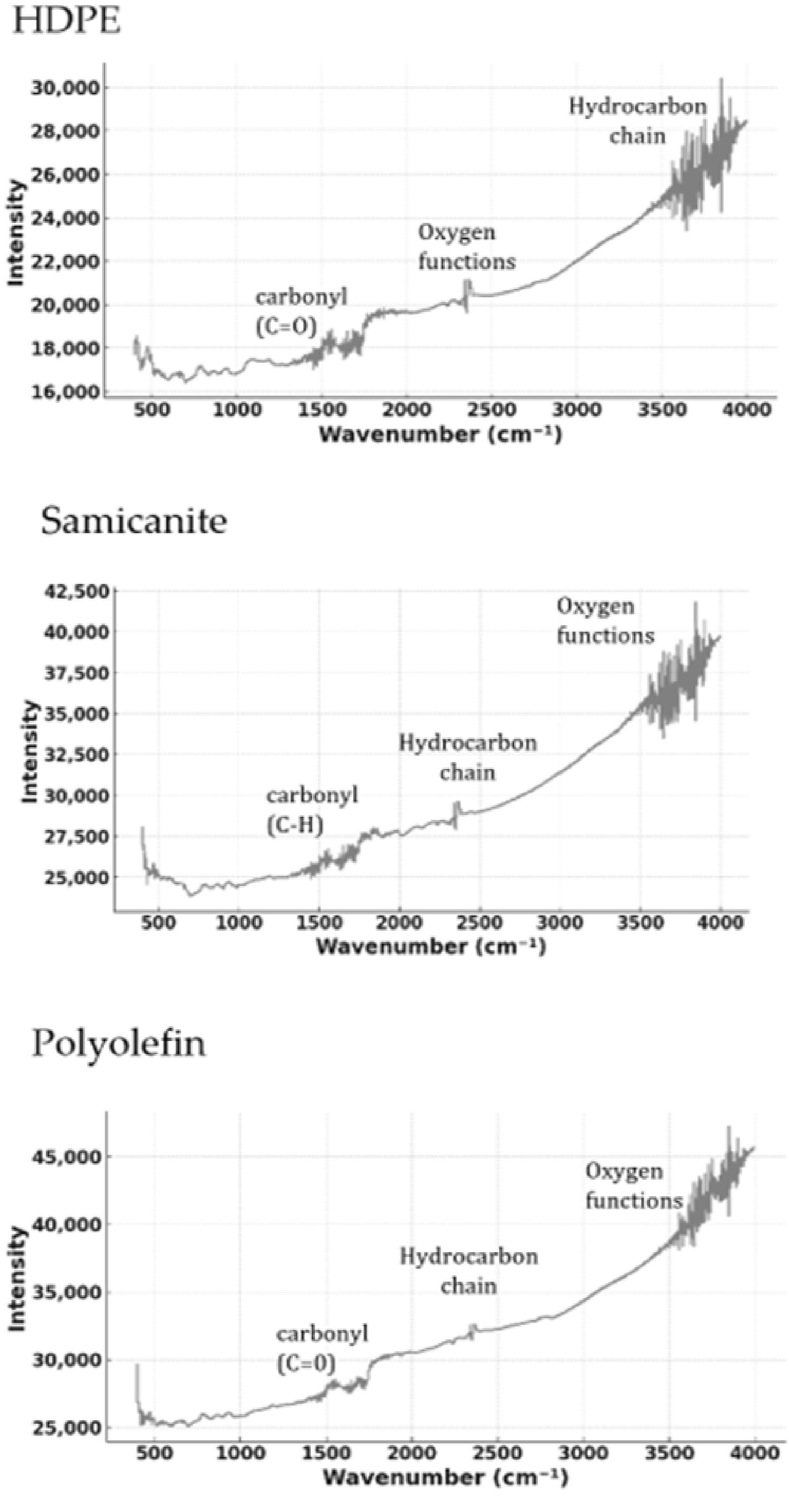


FIGURE 3.4: FTIR of different pallets showing absorption at different intensities in raw plastic materials

c. TGA and DSC of Raw Waste Plastic and Materials

In Figure 3.5, the TGA for one variant of waste HDPE provides an in-depth understanding of the material's thermal stability and decomposition behavior. For waste HDPE, the maximum weight observed was 3.09 mg at 240.50 °C, and the minimum weight was 3.03 mg at 124.09 °C, resulting in a weight loss of 0.07 mg. The Differential Scanning Calorimetry (DSC) analysis in Figure3.7 shows that the maximum heat flow was −13.13 mW at 126.64 °C, and the minimum heat flow was −35.36 mW at 242.04 °C. This information is critical for assessing the material's behavior under thermal stress and ensuring its suitability for applications requiring high thermal resilience. The small weight loss and the sharp heat flow peak confirm that the high thermal stability of the HDPE is very good for high-temperature applications.

The differentials show that there was almost no loss of mass, even at higher temperatures, which is consistent with the expected minimal degradation of the crystalline structure of the highlighted HDPE. This transition represents some phase change, like melting or crystallization, and it points to the material's thermodynamic behavior when it is being heated. Such information is valuable to understand the energy requirements and the stability of the material under specific conditions [5]. Weight-loss readings were rechecked; polymers exhibited ≤ 2 % loss up to 240 °C, confirming no degradation at 100 °C and validating thermal stability for extrusion. For waste LDPE, the maximum weight was 7.84 mg at 241.14 °C, and the minimum weight was 7.73 mg at 141.84 °C, with a weight loss of 0.11 mg. The maximum heat flow recorded was −9.90 mW at 142.62 °C, and the minimum was −34.45 mW at 242.16 °C. The wider heat flow peak and the greater weight loss are due to the amorphousness and the poor thermal stability of waste LDPE in comparison to HDPE, which is in agreement with its easy degradation at lower temperatures.

The broader heat flow peak and higher weight loss reflect LDPE's lower crystallinity and thermal stability compared to HDPE, corroborating its susceptibility to degradation at lower temperatures [31]. For samicanite, the maximum weight was 5.84 mg at 242.06 °C, and the minimum weight was 5.74 mg at 139.07 °C,

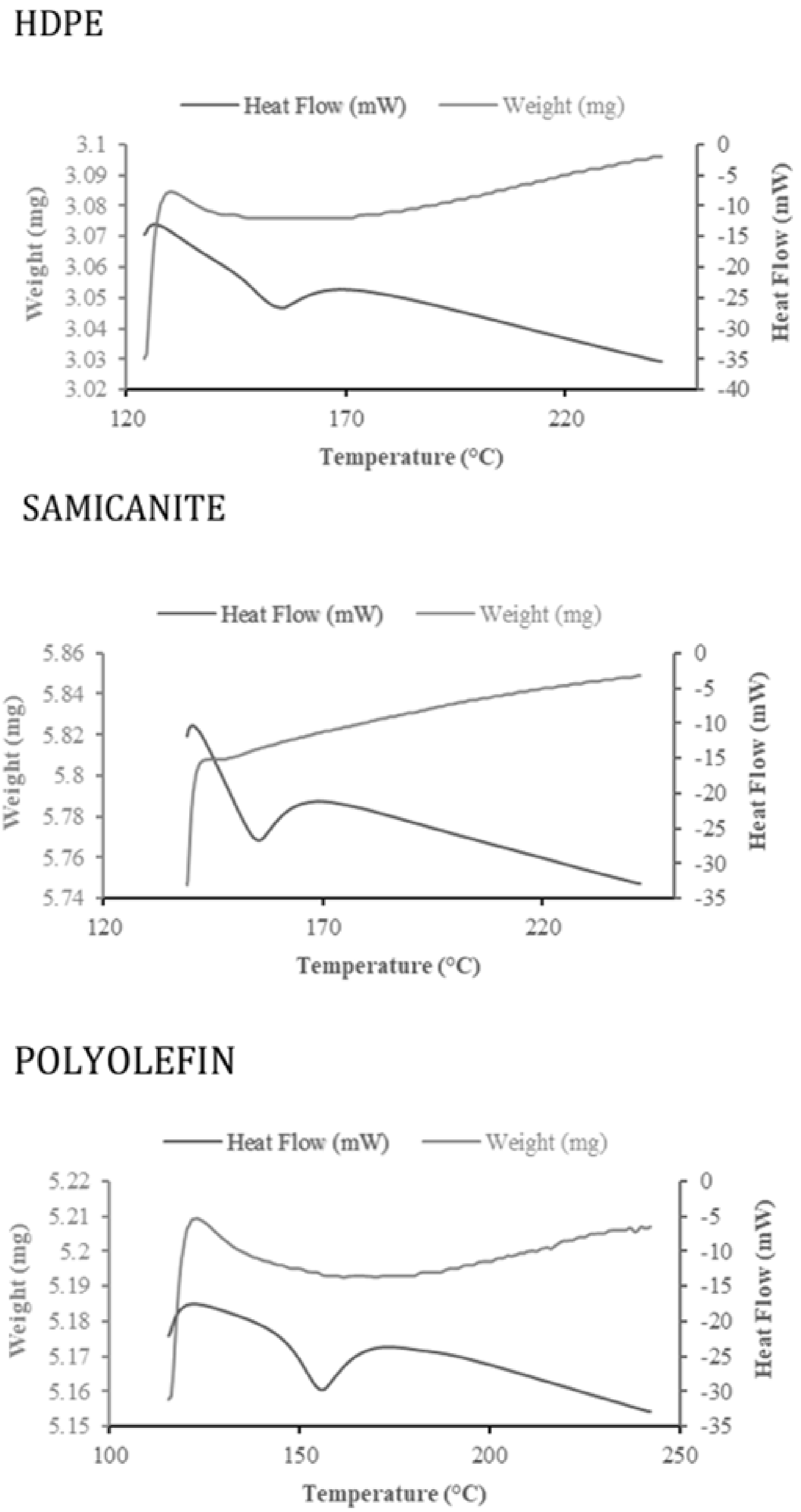
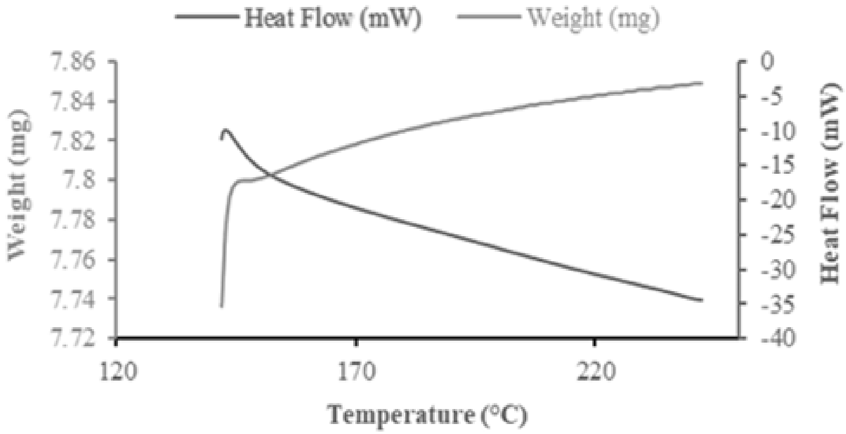
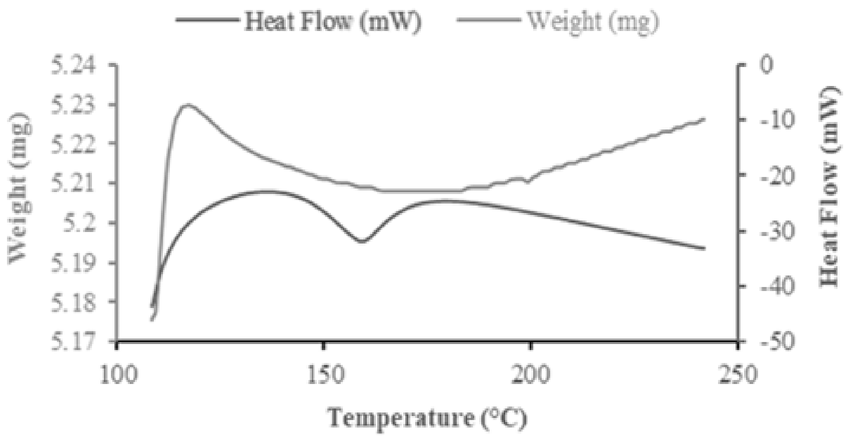


FIGURE 3.5: The TGA and DSC of different pallets, showing the behavior of the material during exposure to the extrusion temperature continued ...

LDPE



PE VIRGIN



PP

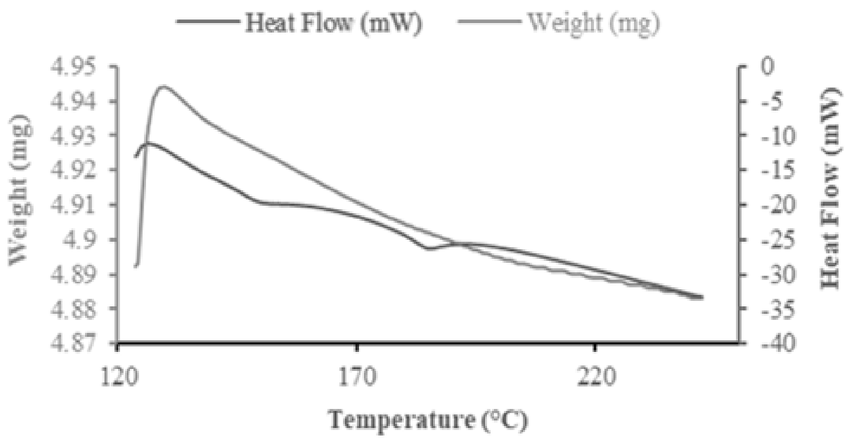


FIGURE 3.5: The TGA and DSC of different pallets, showing the behavior of the material during exposure to the extrusion temperature

with a weight loss of 0.10 mg. The maximum heat flow was −10.45 mW at 140.40 °C, and the minimum was −32.78 mW at 242.23 °C. The multi-step weight loss and distinct thermal transitions align with the composite nature of samicanite, suggesting degradation pathways involving volatiles and matrix breakdown, as discussed in research [5]. For virgin polyethylene, the maximum weight was 5.23 mg at 117.35 °C, and the minimum was 5.17 mg at 108.34 °C, with a weight loss of 0.054 mg. The maximum heat flow was −22.855 mW at 135.683 °C, and the minimum was −43.523 mW at 108.340 °C. The small weight loss and sharp thermal transitions indicate a high purity and consistent material performance, like HDPE [59]. For polyolefin, the maximum weight was 5.209 mg at 123.088 °C, and the minimum was 5.158 mg at 115.480 °C, with a weight loss of 0.052 mg. The maximum heat flow calculated was −7.490 mW at 121.685 °C, and the minimum was −32.947 mW at 242.158 °C. The moderate weight loss and multiple heat flow peaks highlight the blended nature of polyolefin, showing overlapping thermal events.

For waste PP, the maximum weight was 3.896 mg at 242.075 °C, and the minimum was 3.805 mg at 138.100 °C, with a weight loss of 0.091 mg. The maximum heat flow was −11.235 mW at 158.360 °C, and the minimum was −36.700 mW at 242.215 °C. The minimal weight loss and sharp melting peak around 160–170 °C indicate high crystallinity and excellent thermal stability, confirming its suitability for high-temperature environments. Table 3.4 shows the weight loss percentage of the raw plastic materials. Weight loss observed during Thermogravimetric Analysis (TGA) typically reflects the release or decomposition of materials due to heating, and its specific interpretation depends on the sample's nature and the temperature range in which the weight loss occurs. At low temperatures, typically below 150 °C, weight loss is often associated with the evaporation of absorbed or adsorbed moisture, indicating the presence of free or bound water within the sample. In the intermediate temperature range, between 150 °C and 400 °C, weight loss may be due to the release of volatile components, such as solvents, plasticizers, or unreacted monomers, which are common in polymeric and composite materials.

The temperature range was analyzed for the extrusion process being carried out for developing the products. Waste HPDE had the highest weight loss of 2.18% more than the other materials, which ranged from 1.01% in polyolefin to 1.78% in samicanite. The loss can be related to emissions of unhealthy gases. These gas emissions are at a very minimal range compared to the emission of unhealthy gases in other construction material processing, like calcination, which is commonly used in cement production and is associated with significant environmental impacts. Traditional calcination methods release substantial amounts of carbon dioxide, though innovative technologies, such as plasma-assisted decarbonization, show promise in reducing emissions. The optimization of calcination parameters in cement plants could mitigate environmental consequences, while still supporting industrial applications. Similarly, the potential for carbon capture and storage during calcination presents an opportunity for achieving negative emissions in energy-intensive industries. In contrast, recent advancements in polymer extrusion have focused on minimizing the release of harmful gases through precise temperature control and improved feedstock quality. Furthermore, it has been reported [183] that polyethylene processing emits comparatively fewer harmful gases than calcination, underscoring its relative environmental advantages. These findings collectively suggest that while emissions from polymer extrusion are minimal, ongoing efforts are crucial to enhance sustainability across all industrial processes for the construction industry.

Table 3.1: Thermal analysis results showing weight and heat flow parameters of different recycled plastic samples.

File Name	Weight (mg)		Weight (mg)	% Weight Diff	Heat Flow (mW)	
	Max (°C)	Min (°C)			Max (°C)	Min (°C)
Waste HDPE	3.10 (240.50)	3.03 (124.09)	0.07	2.18	-13.14 (126.64)	-35.37 (242.05)
Waste LDPE	7.85 (241.15)	7.74 (141.85)	0.11	1.45	-9.90 (142.62)	-34.45 (242.17)
Samicanite	5.85 (242.07)	5.75 (139.08)	0.10	1.78	-10.46 (140.41)	-32.79 (242.24)
PE Virgin	5.23 (117.35)	5.18 (108.34)	0.05	1.05	-22.86 (135.68)	-43.52 (108.34)
Polyolefin	5.21 (123.09)	5.16 (115.48)	0.05	1.01	-17.49 (121.69)	-32.95 (242.16)
Waste PP	4.94 (129.90)	4.88 (240.66)	0.06	1.25	-11.23 (126.31)	-33.34 (242.21)

3.2.1.2 Mechanical Extrusion Process

The extrusion machine had six heating coils with temperature monitoring thermocouples. These were automated by the controlling panel. The temperature ranges were from 100 °C and 200 °C were controlled to achieve the proper melted mix and desired flow to fill the mold. Figure 3.6 is a diagram of the extruder with an illustration of the areas of the setup used to prepare the molds. The study aims to determine the feasibility of recycled plastic blends for use in structural applications by analyzing their mechanical response. The mechanical extrusion method does not extensively emit harmful gases to the environment, and the weight loss of recycled plastic is very few. The method is more sustainable than the production of other construction products.

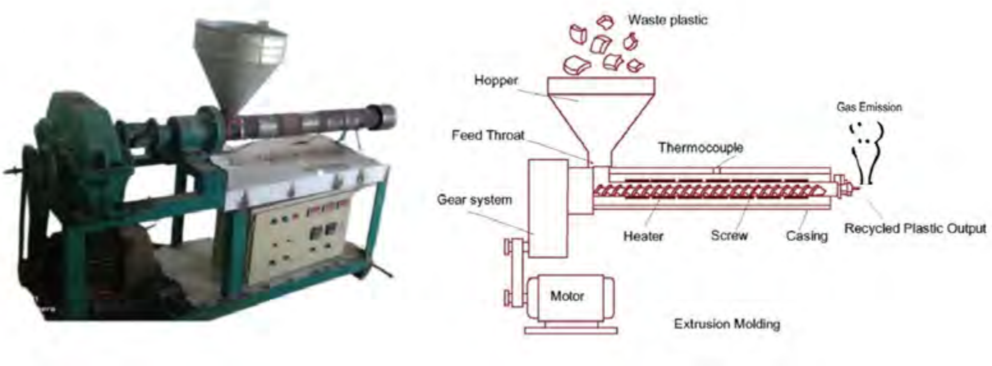


FIGURE 3.6: Single screw extruder setup.

3.2.1.3 Gas Emissions Detection and Monitoring

Given the high temperature melting of waste HDPE during the extrusion process, its environmental impact was assessed by monitoring gas emissions. A smart sensor (ST8900 model, Dongguan Wanchuang Electronic Products Co., Ltd, Dongguan City, China) was employed to measure and analyze the composition of emitted gases. This device could detect and quantify the oxygen level as the % Vol in the atmos-phere; carbon monoxide and hydrogen sulfide in ppm; and the lower explosive limits LELs of compounds such as methane, ethane, propane, butane, gasoline, petroleum gas, and turpentine as the % vol, as shown in Figure 3.6. The calibration was as per the manu-facturers' guidelines. The sensor was positioned near the extruder outlet to capture emissions during the extrusion phase, specifically when the material exited the setup. This ensured maximum gas emissions were accounted for. The recorded data were compared against the safety thresholds and exposure symptoms for humans, as outlined in the sensor's specifications manual. During the process of extrusion, all the samples showed emissions within safe limits, which is also mentioned in Figure 3.7.

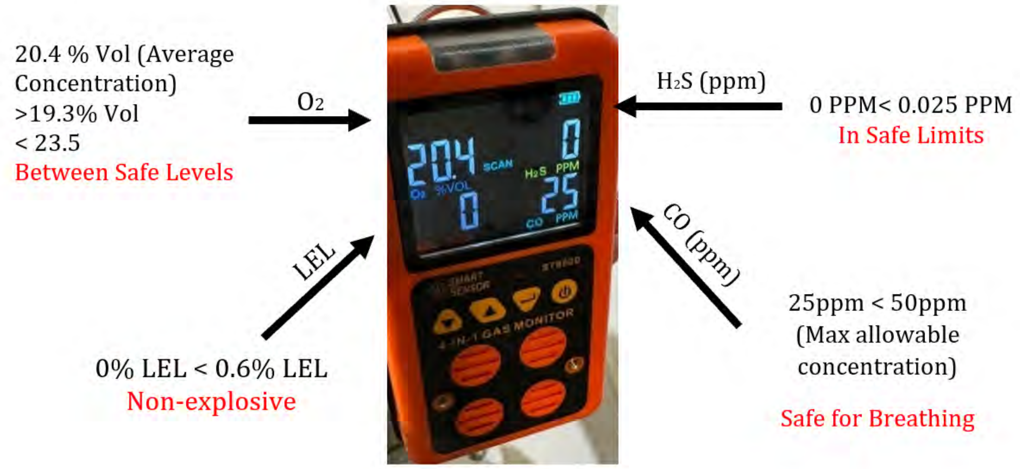


FIGURE 3.7: Multi-gas monitor (smart sensor) gas composition analyzer.

3.2.2 Preparation of Samples

The samples were developed after the second round of extrusion. The extruder was equipped with an electronic control panel to adjust the desired speed and temperature. The extrusion machine is kept in a closed moist free environment; the motor capacity is 900 revolutions per minute, and the gear reduced revolution capacity is 45–46 revolutions per minute. The extrusion speed was reduced by electronic speed controllers to 20–25 revolutions per minute for all the samples. With this speed, the recycled plastic extrude was workable. Considering the volume of the sample, properly sized were developed as dumbbell-shaped, beamlets, and squared prisms for each tensile, flexural, and shear sample, respectively. The compression samples were developed from an arrangement of piped sizers which developed rods in the desired length, and the diameter of the piped sizer was fixed. After getting an extruded length, the plane cutting of the rods of the desired samples of the compression cylinders were prepared. These molds were manually handled. The dye filling time was about 15 s for the shear samples, 21 s for the flexural samples, and for tensile samples, it was about 30 s. The compression samples' arrangement was designed in a way that can also be used for rebar manufacturing. The time taken was about 15 s for each section.

The average weight of the samples for rPP was 22 gms, 33 gms, 27 gms, and 67gms. For rHPDE, the average weights of the samples were 23 gms, 33 gms, 27 gms, and 68 gms for compression, flexural, shear, and tensile samples, respectively. The

TABLE 3.2: Material composition and number of mechanical test samples for different recycled plastic mixes.

Parameter	**Recycled Plastic Mixes**						
	rHDPE	**rPP**	**rHDPE + rPP**	**rHDPE + V**	**rHDPE + rLDPE**	**rHDPE + POL**	**rHDPE + rSAM**
Material content by weight							
rPP		**100%**	**50%**				
rHDPE	**100%**		**50%**	**50%**	**50%**	**80%**	**80%**
Other plastics (V, LDPE, SAM, POL)				**50%**	**50%**	**20%**	**20%**
Mechanical test samples							
Shear Test (S)	5	5	5	5	5	5	5
Flexure Test (F)	5	5	5	5	5	5	5
Tensile Test (T)	5	5	5	5	5	5	5
Compression Test (C)	5	5	5	5	5	5	5

other blends had similar average weights as for rHDPE. The extrusion screw was divided into 4 zones: feeding, compression, melt, and exit. The average temperature controlled by the thermocouple was 50–55 °C, 100–110 °C, 120–130 °C, and 120–135 °C in zones 1, 2, 3, and 4, respectively. A water bath was given for 3–5 min for the cooling of the samples. The samples were cast for mechanical testing, which included recycled waste HDPE, PP, a mix of HDPE and PP, a mix of samicanite and HDPE, a mix of LDPE and HDPE in two different proportions, a mix of polyolefin and HDPE, and a mix of virgin PE and HDPE. Five of each material were cast from a special mold prepared for samples. After a detailed analysis, the behavior of the samples was compiled. The details of the proportions are tabulated below in Table 5. The blends and plastics studied were framed in context to previous research, in Table 3.3. Special extended custom changes were made in the UTM for the test of mechanical properties, as per ASTM. Special molds were prepared for the extruded materials for testing, as per the ASTM standards, D790 (flexural) [184], D695 (compression) [185], D732 (shear) [186], and D638 (tensile) [187], as shown in Figure 3.8. The overall sample preparation summary is in Table 3.5. The table provides a detailed breakdown of the recycled plastic mixes, highlighting their material composition and mechanical testing to assess their suitability for construction applications. The materials include rHDPE, rPP, and various HDPE-based blends, such as rHDPE + rPP, rHDPE + V, rHDPE + rLDPE, rHDPE + POL, and rHDPE + rSAM. The composition varies, with rHDPE and rPP being 100% pure, while the blends contain 50-80% HDPE combined with other materials like PP, POL, and samicanite, as obtained from Table 3.3. To evaluate mechanical performance, shear, flexural, tensile, and compression tests were con-ducted. All the samples underwent and tensile tests, ensuring a comprehensive assessment of their load-bearing capabilities.

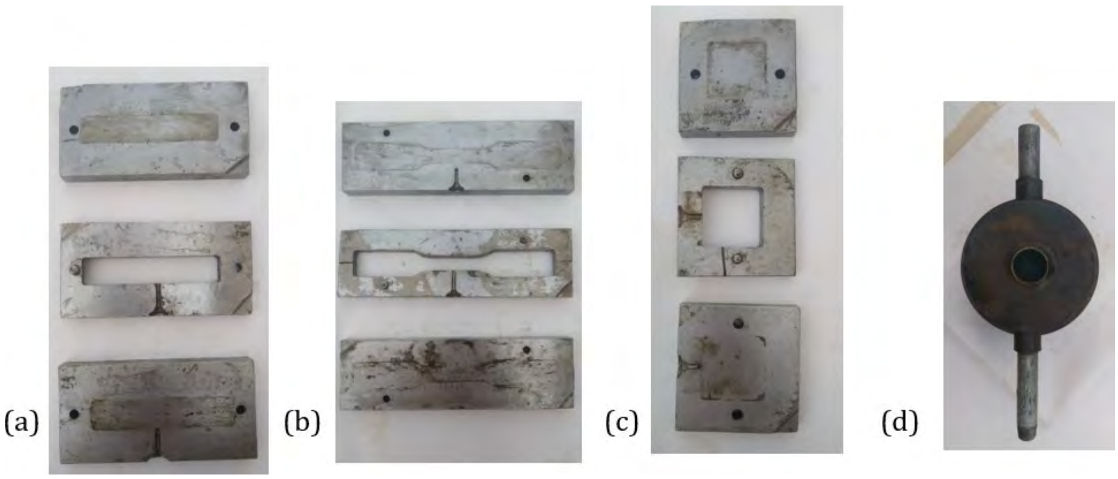


FIGURE 3.8: Molds for samples: (a) flexure mold, (b) tensile mold, (c) shear mold, (d) sizing mold for compres-sion sample.

3.2.3 Testing

3.2.3.1 Mechanical Testing

a. Shear
The Servo-Hydraulic Testing Machine had limitations in testing for compression, tensile, and flexural testing. The shear punch hole apparatus was made as per ASTM D732 (shear) for the testing of shear samples. The sample had a width of 50 mm, a length of 50 mm, and a thickness of 12.7 mm, as per the ASTM standard [186]. In this test, load and deflection graph values were obtained from which stress and strain graphs were developed. Shear total energy absorption, S-TEA, the shear toughness index, the shear maximum strength, SMS, and the shear yield strength,

SYS, were computed. These parameters provided valuable insights into the shear performance of the tested material, allowing for a comprehensive assessment of its mechanical durability and structural integrity under shear loading conditions. The custom test setup arrangements were developed as shown in Figure 3.9 for testing the mechanical proper-ties of recycled plastic.

b. Tensile

Tensile tests were performed as per the ASTM D638 samples. The samples were of dumbbell shape type III, as per the ASTM standard [187]. Additional grips were added for the sample, and the sample's length dimension for the narrow section was 57 mm, and the overall width was 29 mm, the thickness was 12.70 mm, and the gauge length was 50 mm. Load and deflection graphs were obtained. After developing the stress–strain curves, the tensile energy absorption, T-EA; tensile toughness index, T-TI; tensile maximum stress, T-MS; and tensile yield stresses, T-YS, were computed. Figure 3.9 shows the tensile test arrangement.

c. Compression

The compression samples, as per ASTM standard D695 [185], were tested to compute the compression total energy absorption, C-TEA; compression toughness index, C-TI; and compression maximum stress, C-MS. The values were obtained for cylinder samples of sizes 50 mm in height and 25.4 mm in diameter. The obtained values provide insights into the material's ability to absorb energy under compressive loads, its toughness characteristics, and its ultimate strength, which are critical parameters for evaluating mechanical performance in various structural applications. The compression testing arrangement is shown in Figure 3.9.

d. Flexure

The beamlets were tested for flexure, as per ASTM D790 [184], using a three-point load test. After developing the stress–strain curves, the flexural total energy absorption, F-TEA; flexural peak energy absorption, F-PEA; flexural toughness index, F-TI; flexural maximum stress, F-MS; and flexural yield stresses, F-YS, were computed. Plastic products are not exclusively used for construction materials, and ASTM standards with specific purposes are required for use in the construction industry. The flexural test arrangement is shown in Figure 3.9. All

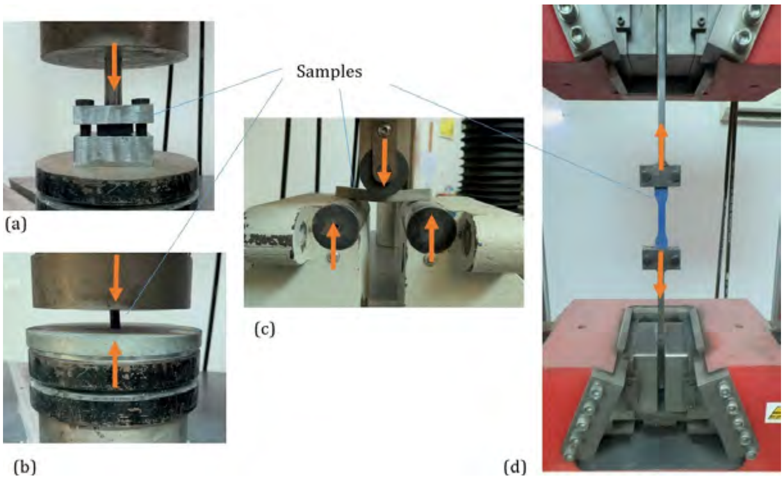


FIGURE 3.9: Custom test setup for (a) shear, (b) compression, (c) flexure, and (d) tensile tests.

mechanical tests in this study were conducted in line with relevant ASTM standards to ensure accuracy and comparability of results. Standards such as ASTM D638 (tensile properties), ASTM D790 (flexural properties), and ASTM D732 (shear) were selected because they are specifically tailored for plastics and therefore appropriate for evaluating recycled HDPE/PP at the small, standardized samples level. These standardized procedures incorporate the distinct behavior of polymers, such as viscoelasticity, strain-rate sensitivity, and elongation at break, by specifying specimen geometry, testing speeds, and the use of extensometers. While small, standardized samples level testing provides a rigorous and reproducible framework for establishing baseline mechanical properties, it is recognized that small specimens do not always capture the scale-dependent behavior of extruded members. To address this, the results obtained from ASTM tests were critically interpreted and later verified against product scale evaluations of rebars and panels. This two-stage approach ensures that the reported performance of recycled plastics is both scientifically reliable and practically contextualized for their intended structural applications.

3.2.3.2 Microstructure Analysis

a. SEM analysis

SEM helps identify physical imperfections, such as voids, material clustering, and microcracks, which weaken the structural integrity of the material. Voids, often caused by improper processing or trapped air, act as stress concentrators, leading to early failure under mechanical loads.Similarly, material clustering, where fillers or reinforcements aggregate unevenly, creates localized weak zones, reducing the overall strength of the material. SEM also reveals shear banding and microcracks, which propagate under stress and ultimately result in mechanical failure. SEM shows brittle fracture surfaces with sharp edges or ductile deformations with signs of fibrillation, helping determine whether the material failed due to inherent brittleness or structural weakening over time.

b. FTIR analysis

FTIR is crucial for detecting chemical composition changes that may have contributed to failure. FTIR reveals signs of crosslinking or polymer chain scission, both of which alter the material's mechanical properties, for the pre and post extrusion states of recycled plastic.

3.2.4 Optimization Procedure

The major content of waste plastics is PE-based. Recycled HDPE blends were used to assess the properties enhancements with the addition of materials like virgin HDPE, polyolefin, samicanite, and LDPE. Based on previous studies [115], the blends only impart marginal improvements. However, the products formulated for the construction industry need better performance and overall manageability. These materials impart rheological improvements, texture improvement, processibility, and improvements in the microstructure of HDPE. However, apart from these properties, the materials have an impact on the material properties of the material performance [114]. The recycling conditions studied are for developing construction materials from rHPDE, a major component in waste.

3.3 Results

3.3.1 Mechanical Performance of Recycled Plastic

3.3.1.1 Shear Behavior

Shear tests were conducted in line with the ASTM D732 specifications on the recycled plastics. The tests were carried out at a loading rate of 1.6 mm/min to determine the peak load (P_{max}), maximum strength (τ_{max}), maximum strain (γ_{max}), and energy absorption (E) of 35 samples. The stress–shear strain response of seven sets of distinct polymeric materials subjected to a punch hole test is shown in Figure 3.10; a specialized method for evaluating the shear properties of the materials is summarized in Table 3.6. The chart in Figure 3.10a represents the shear stress–shear strain behavior of recycled polymeric materials subjected to a punch hole test, providing insights into their mechanical response under shear-dominated loading conditions. Figure 3.10b shows the circular punch after failure.

The x-axis represents strain (γ), indicating the material's deformation as a ratio of change in length to the original length, while the y-axis represents stress (τ), measured in megapascals (MPa), representing the applied tangential force per unit area. Each curve corresponds to a specific recycled polymer blend or composition, highlighting differences in their elastic, plastic, and failure behavior.

The rHDPE (recycled high-density polyethylene) curve shows moderate peak shear stress and ductility, with a distinct elastic region, followed by yielding and plastic deformation before failure. This means that rHDPE has good strength and toughness for moderate punch resistance in structural applications. rHDPE + V has a similar shape to the curve of rHDPE, with a slightly lower peak stress but similar strain; this indicates that adding the V component does not greatly reduce the material's ductility. This blend may be useful in applications where the material will be subjected to shear loading and must be able to stretch slightly. In addition, rHDPE + rPP has a larger strain range with a lower peak stress, which indicates that it has good ductility and energy absorption for impact-resistant applications. The punch hole test of rHDPE + rSAM has the lowest peak stress and strain among all the blends, indicating that it has the weakest strength and deformation capacity. The weak mechanical response may be due to incompatibility or poor interfacial adhesion between rHDPE and rSAM, which renders it less useful for punch-resistant applications without further modification. rHDPE + POL has a peak stress that is moderate, and the stress decreases gradually after the yield point. This blend is most suitable for applications where the material will be subjected to shear loading and needs moderate mechanical properties. Lastly, rPP (recycled polypropylene) has the lowest peak stress but the highest strain capacity, which is a characteristic of ductile material. The material fails by extensive

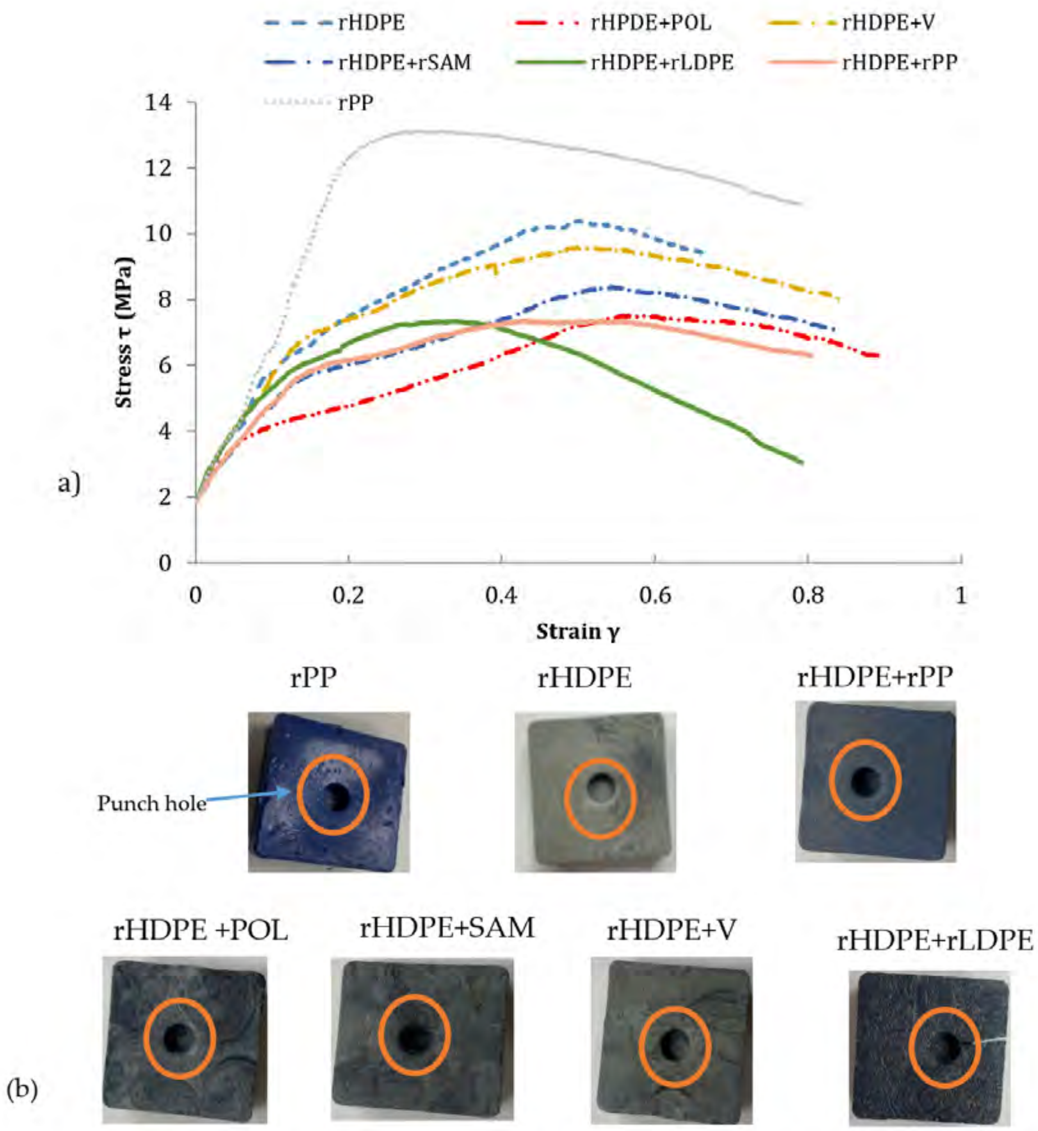


FIGURE 3.10: Shear behavior of recycled plastic. (a) Stress–strain curves; (b) punch holes phenomenon at peak loads on test specimens.

plastic deformation before failure, which shows its ability to absorb a lot of energy when subjected to shear loading and thus is suitable for use in flexible and impact damping applications, such as packaging or automotive parts. This chart shows the mechanical properties of recycled polymer blends under punch hole testing and how they are different. On the other hand, rPP is very ductile and tough, and thus it is most suitable for use in energy absorption applications. Intermediate blends, such as rHDPE+POL and rHDPE, have both high strength and high flexibility and can thus be used in applications with moderate mechanical properties. These results are helpful in choosing the material for a specific application that re-quires shear strength, toughness, and deformation properties.

The mechanical properties assessed include shear total energy absorption (S-TEA), the shear toughness index (S-TI), shear maximum stress (S-MS), and shear yield stress (S-YS); the results are compiled in Table 3.6 and Figure 3.11. The S-TEA for HDPE is in a range of about 5.43 kJ/m^3, showing moderate energy absorption during shear deformation. The S-TI for rHDPE is about 10.39 J, indicating good toughness under shear stress. This makes rHDPE resistant to cracking during deformation [188]. The S-MS for rHDPE is 10.39 MPa [188] [189]. The S-TEA of rHDPE + PL, S-TI, and S-MS are 5.38 kJ/m^3, 7.53 J, and 7.53 MPa, respectively, which are intermediate values like that of rHDPE. However, rHDPE + PL has slightly better energy absorption under shear stress [189]. The S-TEA for rHDPE + rPL is 7.53 J, indicating that it is moderately tough under shear deformation. The S-MS for rHDPE + PL is 7.53 MPa, showing that it has the strength of the order of that of rHDPE.

The S-TEA for rHDPE + V is 6.74 kJ/m^3, which is slightly higher than that of rHDPE and rHDPE + PL, showing that it has better energy absorption during shear deformation [189]. The S-TI for rHDPE + V is 9.59 J, indicating that it has higher toughness than rHDPE and rHDPE + PL [188]. The S-MS for rHDPE + V is 9.59 MPa, moderate in shear stress. The S-YS for rHDPE + V is 1.94 MPa, with good shear deformation before failure. The S-TEA for rHDPE + rSAM is 5.69/m^3, showing good energy absorption under shear stress. This composite has a moderate impact resistance [189]. The S-TI for rHDPE + rSAM is 8.39 J, indicating that it has moderate toughness and is thus suitable for applications to which moderate shear stress is applied [188]. The S-MS for rHDPE + rSAM is 8.39 MPa, with moderate shear strength. The S-TEA for rHDPE + rLDPE is 4.48 kJ/m^3, which is lower than those of rHDPE + V and rHDPE + rSAM, indicating that rHDPE + rLDPE has poor energy absorption under shear stress. The S-TI for rHDPE + rLDPE is 7.35 J, showing good toughness but poor crack propagation resistance compared to rHDPE + rSAM. The S-MS for rHDPE +

TABLE 3.3: S-TEA, S-TI, S-MS, and S-YS properties of recycled plastic mixes.

Parameter	**Recycled Plastic Mixes**						
	rHDPE	**rHDPE + rPOL**	**rHDPE + V**	**rHDPE + rSAM**	**rHDPE + rLDPE**	**rHDPE + rPP**	**rPP**
S-TEA (kJ/m^3)	5.43 ± 0.13 (9.96)	5.38 ± 0.03 (3.39)	6.74 ± 0.10 (8.15)	5.69 ± 0.10 (8.64)	4.48 ± 0.03 (4.84)	5.09 ± 0.09 (10.64)	8.69 ± 0.09 (5.06)
S-TI (J)	10.39 ± 0.63 (4.90)	7.53 ± 0.07 (14.40)	9.59 ± 0.03 (4.79)	8.39 ± 0.04 (7.25)	7.35 ± 0.01 (9.29)	7.38 ± 0.06 (15.47)	13.12 ± 0.04 (6.14)
S-MS (MPa)	10.39 ± 0.47 (6.14)	7.53 ± 0.95 (18.19)	9.59 ± 0.51 (7.28)	8.39 ± 0.39 (4.84)	7.35 ± 0.65 (12.40)	7.38 ± 0.45 (11.45)	13.12 ± 0.34 (5.43)
S-YS (MPa)	2.08 ± 0.06 (3.18)	1.85 ± 0.14 (8.60)	1.94 ± 0.01 (0.77)	1.89 ± 0.04 (2.07)	1.87 ± 0.25 (15.32)	1.84 ± 0.08 (5.40)	2.65 ± 0.02 (0.89)

Note: The values in parentheses represent CoV (%) values.

rLDPE is 7.35 MPa, moderate shear strength. The S-TI for rHDPE + rPP is 7.38 J, indicating moderate toughness. The S-MS for rHDPE + rPP is 7.38 MPa, meaning it has moderate shear strength. The S-TEA for rPP is 8.69 kJ/m^3, which reflects excellent energy absorption under shear deformation. The S-TI for rPP is 13.12 J, indicating excellent toughness. The S-MS for rPP is 13.12 MPa, indicating high shear strength. The S-YS for rPP is 2.65 MPa, showing good resistance to shear deformation. The CoV values of the shear parameters of the recycled plastic mixes are influenced by material composition, degradation, and processing conditions.

In the products, voids are also present due to gas accumulation in the extrusion process, and this influences the values mainly. rHDPE shows moderate variability, likely due to inconsistencies in molecular weight and contamination. rHDPE + rPOL has stable energy absorption but inconsistent stress properties, possibly due to phase separation. rHDPE + V has highly uniform yield stress, indicating good compatibility with virgin HDPE. rHDPE + rSAM shows relatively low CoV, suggesting good blend uniformity. rHDPE + rLDPE has high CoV in stress parameters due to mismatched crystallinity. rHDPE + rPP suffers from high variability, likely due to poor interfacial adhesion between HDPE and PP. rPP exhibits low CoV, particularly in yield stress, suggesting relatively consistent material properties with minor variations due to prior degradation. Overall, higher CoV values indicate material inconsistencies caused by differences in polymer compatibility, the presence of contaminants, processing conditions, and degradation effects due to extrusion.

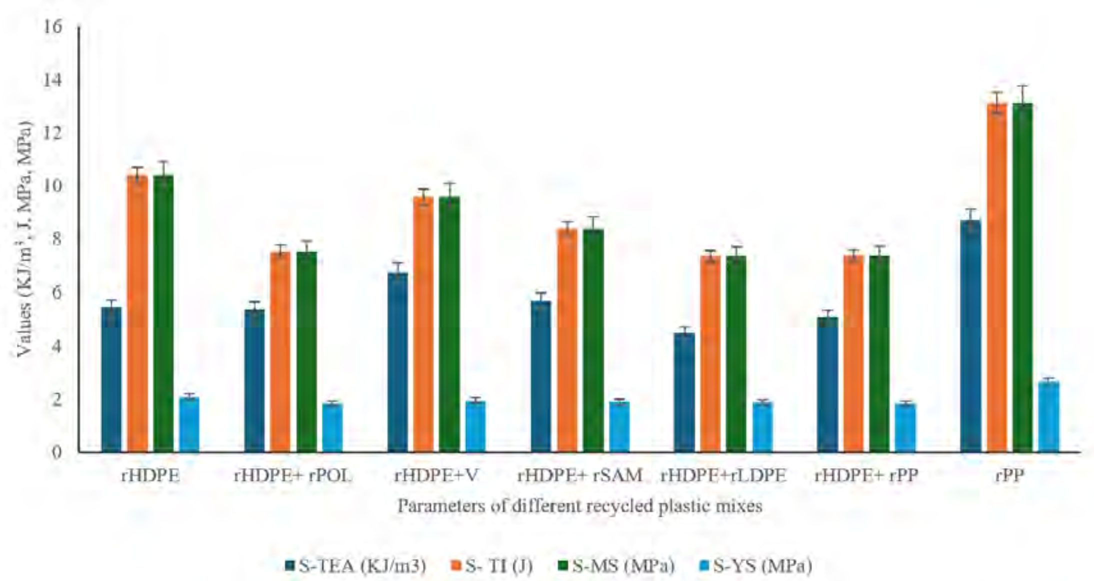


FIGURE 3.11: Graphical representation of S-TEA, STI, S-MS, and S-YS properties of recycled plastic mixes..

3.3.1.2 Flexural Behavior

Flexural tests were conducted in line with ASTM D790 specifications. The tests were carried out at a loading rate of 1.6 mm/min to determine the peak load (P_{max}), maximum strength (σ_{max}), maximum strain (ε_{max}), and energy absorption (E) of 35 samples. The stress–shear strain responses of seven sets of distinct polymeric materials subjected to a punch hole test are shown in Figure 3.12; a specialized method for evaluating the shear properties of the materials is summarized in Table 3.7. The flexural stress–strain curves provide a detailed analysis of seven distinct samples, each representing a unique combination of recycled polymers and additives under flexural loading. Strain (ε) is on the x-axis, which describes the material's deformation ratio, and flexural stress (σ) in megapascals (MPa) is on the y-axis, representing how much stress or deformation the material can withstand. Curves are included to illustrate the mechanical properties of the material depending on the material composition and the interaction between polymers and additives. This study presents a typical linear elastic region, followed by moderate peak stress and a subsequent plateau, indicating that the material exhibits both

Table 3.4: F-MS, F-YS, F-TEA, F-PEA, and F-TI properties of recycled plastic mixes. (The values in parentheses are CoV values.)

Parameter	**Recycled Plastic and Mixes**						
	rHDPE + rPP	**rHDPE + rSAM**	**rHDPE + rLDPE**	**rHDPE**	**rHDPE + POL**	**rPP**	**rHDPE + V**
F-TEA (kJ/m^3)	3.24 ± 0.28 (9)	13.66 ± 1.83 (13)	1.11 ± 0.50 (5)	12.80 ± 1.97 (15)	1.27 ± 0.18 (14)	45.74 ± 7.64 (17)	1.05 ± 0.13 (13)
F-PEA (J/m^3)	6.44 ± 0.69 (11)	9.82 ± 2.54 (26)	5.56 ± 0.06 (1)	50.79 ± 6.40 (13)	7.00 ± 1.97 (28)	208.81 ± 7.00 (3)	6.09 ± 1.31 (21)
F-TI (J)	3.45 ± 0.37 (12)	5.87 ± 1.52 (26)	1.15 ± 0.01 (1)	7.37 ± 0.93 (13)	1.39 ± 0.39 (29)	9.42 ± 0.32 (3)	1.15 ± 0.25 (28)
F-MS (MPa)	13.39 ± 1.21 (9)	34.61 ± 4.63 (13)	13.60 ± 0.06 (1)	25.83 ± 3.97 (15)	16.36 ± 1.91 (14)	22.23 ± 12.02 (17)	13.20 ± 1.60 (12)
F-YS (MPa)	13.12 ± 0.15 (1)	13.12 ± 2.00 (2)	12.98 ± 0.17 (2)	14.05 ± 0.16 (1)	13.36 ± 0.23 (1)	14.42 ± 0.12 (1)	12.92 ± 0.22 (2)

Note: values in parentheses are CoV (%).

strength and ductility. This suggests that blending these two recycled polymers enhances the flexibility of the material without compromising its structural integrity. The curve for rHDPE + rSAM, which contains samicanite (SAM), shows higher peak stress and a longer strain region, meaning that this material has high toughness and the ability to absorb energy. Samicanite appears to significantly reinforce the rHDPE matrix; hence, this blend is well-suited for applications requiring high durability and strain tolerance.

The curve for rHDPE + rLDPE has the lowest peak stress and the smallest strain range among all the blends and pure rHDPE. This indicates that rLDPE does not provide the same level of reinforcement as samicanite but instead increases the flexibility of the blend. The curve for 100% rHDPE shows a peak stress followed by a sharp decrease, which is characteristic of brittle failure. This implies that rHDPE has poor toughness and strain capacity and should be blended or modified to improve its mechanical performance. The rHDPE + POL blend that contains polyolefin (POL) has a peak stress that is moderately high with a slight bit of ductile behavior, which means that polyolefin improves the toughness and strain tolerance of the blend without sacrificing much strength. The rPP (stand alone polypropylene material) has a behavior very similar to that of the rHDPE+rPP blend, with a moderate level of ductility and a slightly lower peak stress. This means that although rPP is compatible with rHDPE, it does

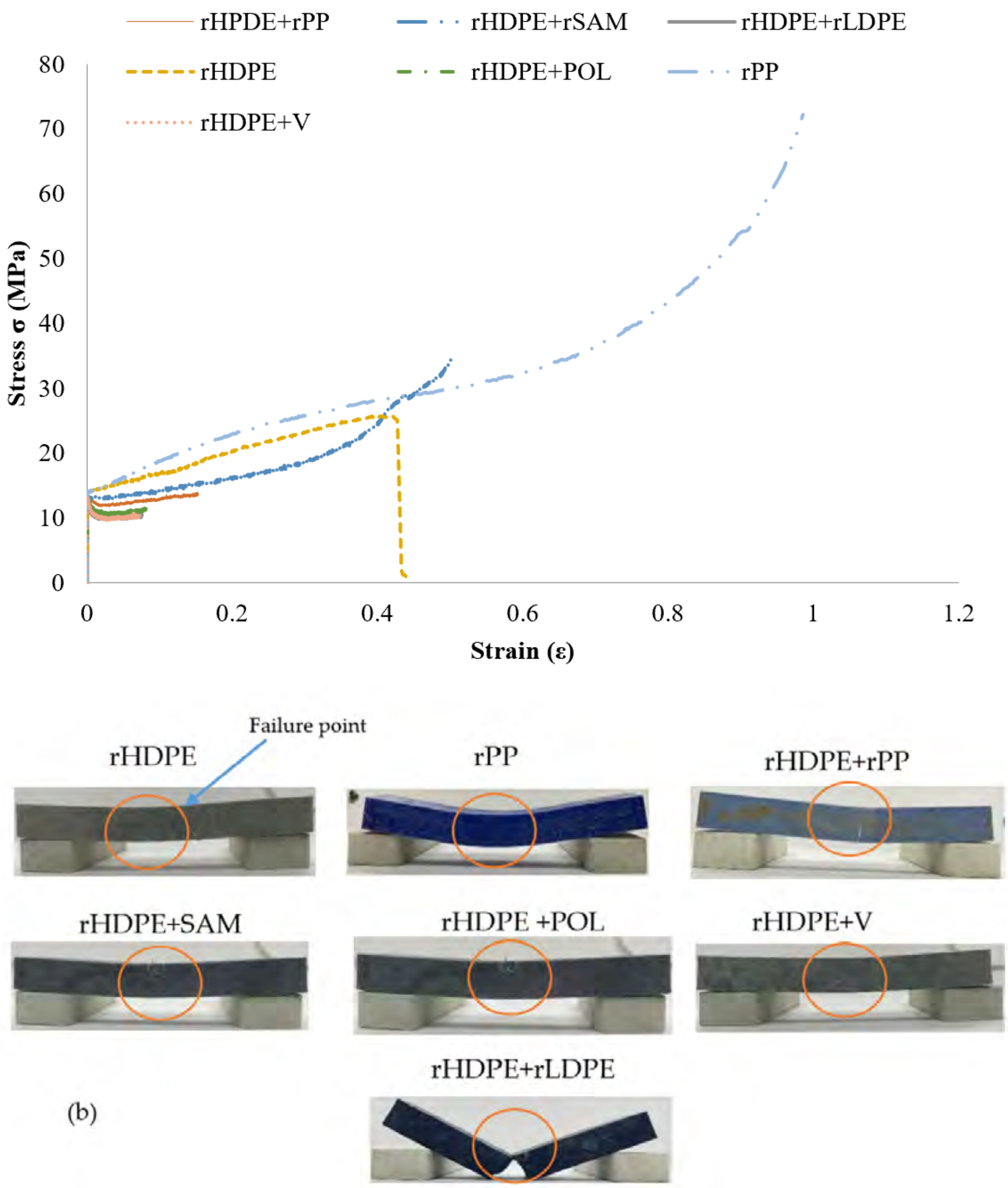


FIGURE 3.12: Flexural behavior of recycled plastic. (a) Stress–strain curves; (b) bending/failure phenomenon..

not make a significant contribution to the mechanical reinforcement. Finally, the rHDPE+V blend, represented by a dotted red line, exhibits the lowest peak stress and strain tolerance among the blends, suggesting that the additive contributes minimally to the material's overall mechanical enhancement. The detailed analysis examines the flex-ural properties of various recycled plastic composites, including HDPE + PP (polypropylene), HDPE + SAM (samicanite Pellets), HDPE + LDPE (Low-Density Polyethylene), HDPE + POL (polyolefin), PP (polypropylene), and HDPE + V (virgin material). The mechanical properties investigated include flexural total energy absorption (F-TEA), flexural peak energy absorption (F-PEA), flexural toughness index (F-TI), flexural maximum stress (F-MS), and flexural yield stress (F-YS), and are shown in Table 3.7 and Figure 3.13.

These properties are important to characterize the material's behavior under bending loads and to recommend the material for structural, impact-resistant, and flexible applications. The F-TEA for HDPE + PP is 3.24 kJ/m^3, which indicates that the material has a relatively low energy absorption capacity. Although this is a moderate value, it means that HDPE + PP is not very efficient for use in devices that need to absorb a large amount of energy when subjected to bending stresses. HDPE + PP would be appropriate for use in applications where energy absorption is not a critical factor. The F-PEA for HDPE + PP is 6.44 J/m^3 the material is of moderate toughness and absorbs some energy in the process of plastic deformation. It is not as good, however, as other composites, such as HDPE + POL or HDPE + SAM, in a high-stress environment. The F-TEA for HDPE + SAM is 13.66 kJ/m^3, which is much higher than that of HDPE + PP, indicating that HDPE + SAM has a very good energy absorption capacity. Studies have shown improvement in the mechanical properties of blends of HPDE [190]. The F-PEA for HDPE + SAM is 9.82 J/m^3, which means that it can absorb a large amount of energy when it is flexurally deformed. This increases its toughness and makes it suitable for high-impact applications. Of the composites evaluated, the F-TEA of HDPE + LDPE has the widest average range of 1.11 kJ/m^3. This implies that rather than employing this material in applications which demand a great deal of energy absorption or impact resistance, it should be used in the contrary scenario [191, 192]. Under a flexural loading energy absorption of HDPE + LDPE was moderate, with an F-PEA of 5.56 J/m^3; however, there was still a reasonable difference relative to a SAM or POL composite. As indicated by the value, the F-TI of HDPE + LDPE exhibits that the material has relatively lower toughness and is increasingly prone to cracking in the flexural and stress orientations, with the measurements of 1.15 J. The F-TEA for HI is 6.16 kJ/m^3, which shows that it has moderate energy absorption properties and is, therefore, suitable for applications that require a balance of rigidity and some degree of flexibility. The F-TEA for HDPE + POL is 45.74 kJ/m^3, the highest value among all composites, indicating that it has excellent energy absorption properties and is, therefore, suitable for applications that require high impact resistance and energy dissipation. The F-PEA for HDPE + POL is 208.81 J/m^3, which is excellent, and which shows that the composite can absorb a lot of energy before it fractures. The F-TI for HDPE + POL is 9.42 J, indicating that the material possesses very high toughness and very high resistance to crack propagation under bending stress [192]. Among all the composites tested, the F-MS of HDPE + POL is the highest, 72.23 MPa, thus making HDPE + POL one of the strongest composites with the best bending stress resistance. The F-YS of HDPE + POL is 14.14 MPa, which means that this composite can oppose the initial deformation under flexural stress. The F-TEA of PP is 45.74 kJ/m^3, which means that this material has an excellent

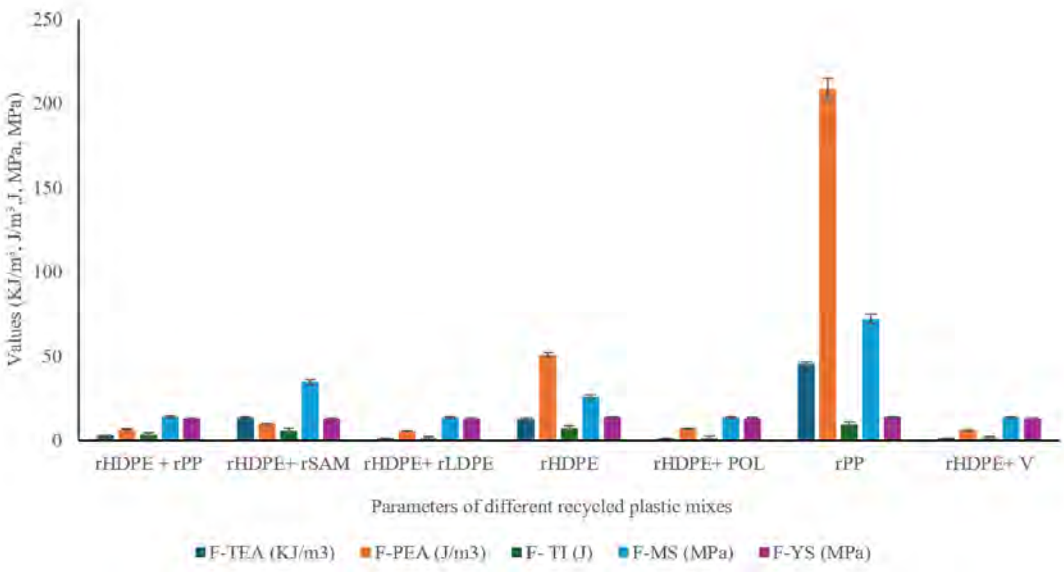


FIGURE 3.13: Graphical representation of F-MS, F-YS, F-TEA, F-PEA, and F-TI of recycled plastic.

energy absorption capacity, and, therefore, it is ranked among the best in energy dissipation. The F-PEA of PP is 208.81 J/m^3, which is a good sign of the plastic energy absorption capacity and is much higher than that of most other composites. The F-TI of PP is 9.42 J, and this indicates that it has a good resistance to crack propagation and is one of the toughest materials tested. The F-MS of PP is 72.23 MPa and thus has a high strength and a good bending stress resistance [192]. The F-YS of PP is 14.14 MPa, which means that it has a high resistance to initial plastic deformation under bending stress. The F-TEA of HDPE + V is 1.05 kJ/m^3, which is a low energy absorption, and thus it is not very efficient for high impact applications. The F-PEA for HDPE + V is 6.09 J/m^3, showing a moderate level of energy absorption. The F-TI for HDPE + V is 1.15 J, indicating lower toughness compared to other composites, like HDPE + POL. The F-MS for HDPE + V is 13.60 MPa, indicating moderate strength. The F-YS for HDPE + V is 12.92 MPa, showing a moderate level of resistance to deformation [189]. The CoV in the flexural properties of the recycled plastic mixes varies significantly based on the mate-rial composition and processing conditions. rHDPE + rLDPE shows the lowest CoV across all the parameters, indicating a highly uniform blend due to good polymer compatibility. rHDPE + rPP and rHDPE + rSAM exhibit moderate CoVs in energy absorption and toughness, suggesting controlled variability due to different polymer structures and impact modifiers. rHDPE and rPP show moderate-to-high CoVs in flexural strength, likely due to variations in crystallinity and prior degradation. rHDPE + POL and rHDPE + V have the highest CoV, particularly in energy absorption and toughness, indicating poor interfacial adhesion and phase separation. Overall, lower CoV values indicate consistent mechanical properties, while a higher CoV suggests material inconsistencies caused by polymer incompatibility, processing variations, and degradation effects.

3.3.1.3 Compression Behavior

Compression tests were conducted in line with ASTM D695 specifications. The tests were carried out at a loading rate of 1.6 mm/min to determine the peak load (P_{max}), maximum strength (σ_{max}), maximum strain (ϵ_{max}), and energy absorption of the 35 samples. The compression stress–strain behavior presented in the graph in Figure 3.14 showcases the mechanical performance of seven distinct polymer samples: rHDPE-V, rHDPE + SAM, rHDPE, rPP, rHDPE + rLDPE, rHDPE + POL, and rHDPE + rPP. Each sample represents a variation of recycled high-density polyethylene (rHDPE) or blends of polymers tailored to enhance specific properties. The behavior of these materials is critical for determining their applicability in industrial and structural applications, especially in the context of sustainable material development.

The rHDPE-V and pure rHDPE samples show moderate levels of stress and strain, reflecting the intrinsic properties of recycled HDPE, which is known for its rigidity and resistance to deformation under compressive loads. The linear elastic behavior at low strain levels transitions to a plateau indicative of yielding, a characteristic of semi-crystalline thermoplastics. These results align with the use of rHDPE in applications like rigid containers, pipes, and construction panels, where moderate strength and stiffness are sufficient. However, pure rHDPE lacks the enhanced flexibility or toughness required for more demanding applications. Incorporating samicanite (SAM) into rHDPE significantly increases the stress response, as seen in the rHDPE + rSAM curve, which outperforms pure rHDPE.

This improvement is due to the reinforcing effect of rSAM that probably increases the load transfer capability of the polymer matrix and decreases the probability of microcrack initiation under compression. Such composites are of great interest for load-carrying applications in structural elements and automotive parts [31]. The increased stress capacity also shows that the addition of fillers like SAM can effectively compromise between sustainability and high performance. Recycled polypropylene (rPP) has a distinct curve with lower stress values but a higher strain capacity than the rHDPE-based samples. This behavior is a result of the material's toughness and flexibility, which is less rigid than that of rHDPE. Due to its ductile nature, rPP is well-suited for applications involving the absorption of energy, such as packaging, automotive bumpers, and furniture [5].

Nonetheless, the inability to bear high stress may exclude it from structural use. The ductility and the strain-to-failure of the rHDPE are improved when it is blended with low-density polyethylene (LDPE) in comparison to pure rHDPE. This stress–strain curve of the rHDPE + rLDPE blend is nearer to an ideal curve than the curve of the pure rHDPE because rLDPE's flexibility improves the stiffness of the rHDPE. Such blends are useful for toughness and durability-based applications, like flexible piping, geomembranes, and industrial liners [35]. This synergy is important because it shows the potential to create materials with desired properties by blending polymers. The stress response of all the samples is higher for rHDPE + POL than for any other sample, indicating that this composite has the highest load-bearing capacity and stiffness. The rHDPE + POL composite is most suitable for high-performance applications where high mechanical strength is required, such as structural reinforcements and heavy-duty containers. The stress

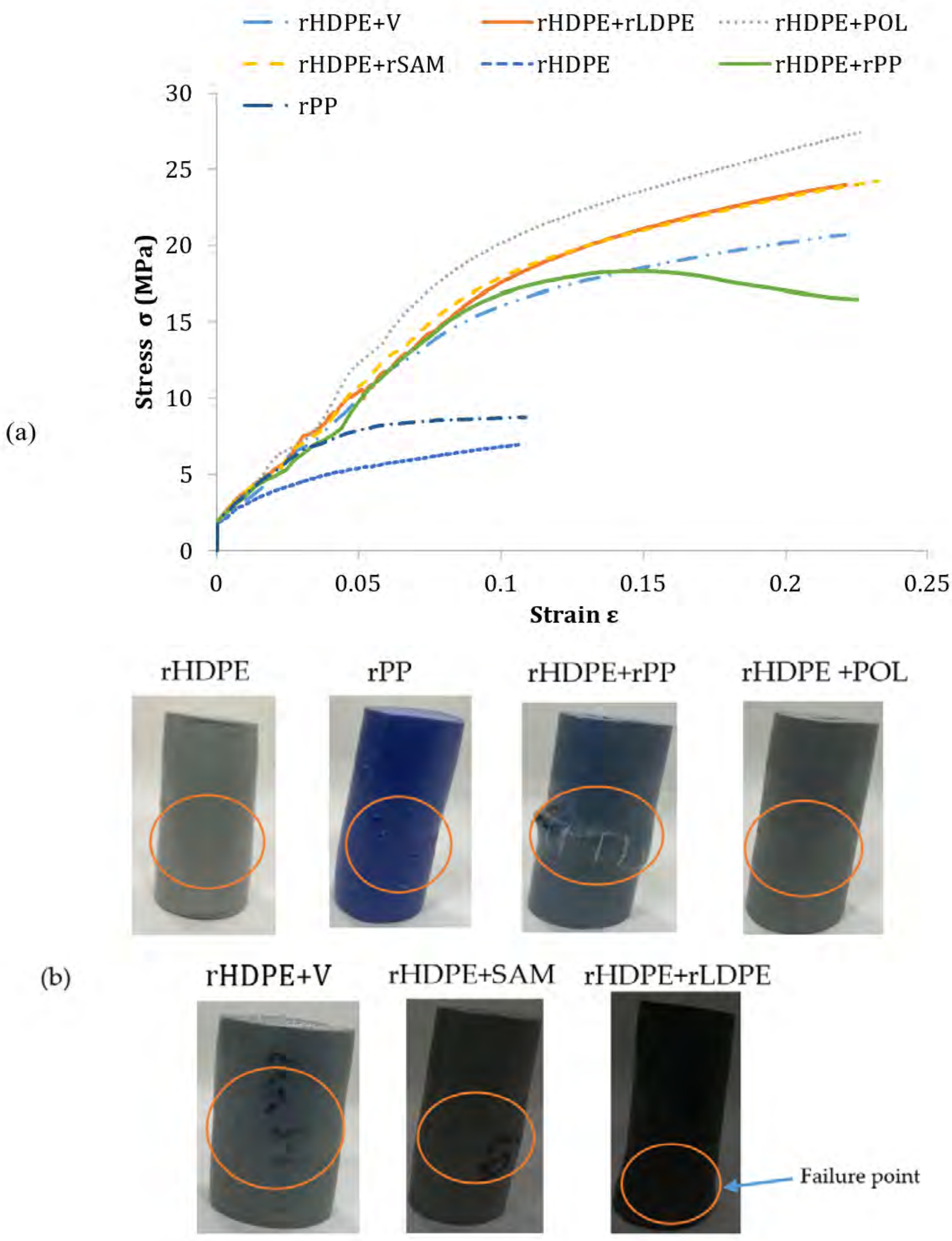


FIGURE 3.14: Compression behavior of recycled plastic. (a) Stress–strain curves; (b) compression failure.

strain curve of rHDPE + rPP has moderate stress and a reasonable strain capacity. Since the stress response is not as high as that of rHDPE + SAM or rHDPE + POL, the increased ductility makes rHDPE + rPP an appropriate material for use in automotive parts, consumer products, and semi-flexible packaging. From the stress–strain graph, it is also evident how polymer blending and the inclusion of fillers can be used to control the mechanical properties of recycled materials. Thus, compo-sites such as rHDPE + SAM and rHDPE + POL are characterized by high strength and stiffness, while blends including rHDPE + LDPE and rHDPE + rPP are characterized by a balanced combination of toughness and flexibility. These findings highlight the potential of recycled polymers and their composites in promoting sustainable material solutions for industrial applications for the construction industry; Table 3.8 and Figure 3.15. The present work focuses on a comparative study of the compression properties of material mixes, including high-density polyethylene, PP (polypropylene), and HDPE-based blends with additives or other polymers. The parameters assessed were compression total energy absorption (C-TEA), the compression toughness index (C-TI), and compression maximum stress (C-MS). These properties are vital in the assessment of materials for their ability to withstand compressive forces, especially in the context of objects that are expected to be strong, elastic, and resistant to failure under mechanical stress. The C-TEA values, which represent the energy absorption capacity of the materials under compression, have a wide range of values among the samples. The highest C-TEA value was obtained from rHDPE+POL with the mean value of 4.23 kJ/m^3 and a relatively small standard deviation, which implies that it has both a high and consistent energy absorption capacity. This implies that HDPE+POL is very efficient in compressive energy absorption and, therefore, is suitable for applications that require good energy-handling properties. At the opposite end of the spectrum, pure HDPE has the lowest C-TEA value of 0.55 kJ/m^3, which shows its poor energy absorption capacity. This trend clearly shows that material blending is beneficial as the addi-tion of POL, or any other polymer, improves the energy absorption properties of rHDPE significantly. The C-TI (toughness) of the materials also follows a similar trend. The highest C-TI value of 3.17 J is exhibited by HDPE + PP, which means that this material is the toughest and can operate under compressive loads with a possibility of absorbing much energy before failing.

This reveals that the preparation of HDPE/PP blend is a better alternative for

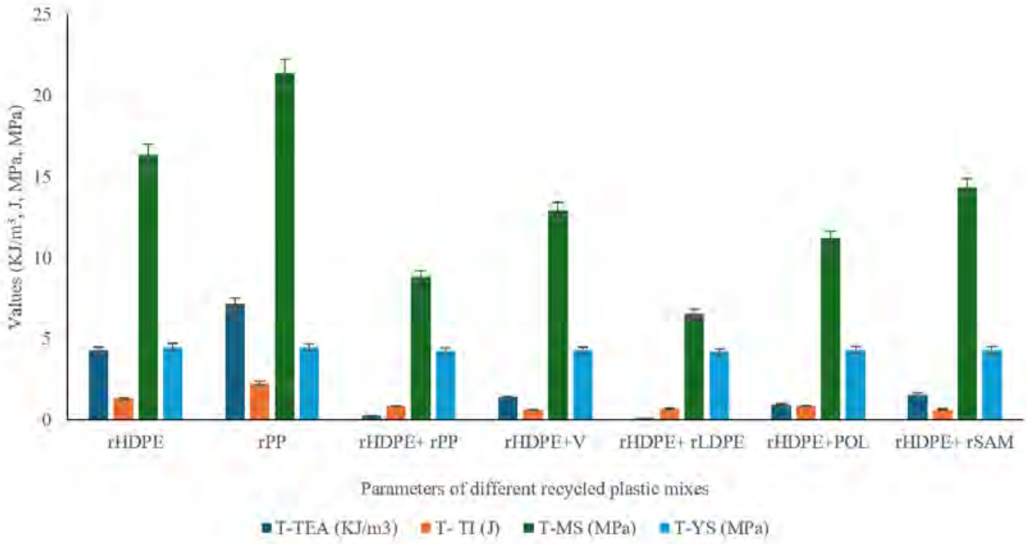


FIGURE 3.15: Graphical representation of C-TEA, C-TI, and C-MS of recycled plastic.

TABLE 3.5: The C-TEA, C-TI, and C-MS of recycled plastic and mixed samples.

Parameter	**Recycled Plastic and Mixes**						
	rHDPE	**rPP**	**rHDPE + V**	**rHDPE + rLDPE**	**rHDPE + POL**	**rHDPE + rSAM**	**rHDPE + rPP**
C-TEA (kJ/m^3)	0.55 ± 0.06 (11)	0.77 ± 0.02 (3)	3.22 ± 0.41 (13)	3.60 ± 0.32 (9)	4.23 ± 0.41 (10)	3.90 ± 0.27 (7)	3.17 ± 0.18 (6)
C-TI (J)	0.37 ± 0.04 (11)	0.27 ± 0.02 (7)	1.88 ± 0.11 (6)	2.21 ± 0.21 (9)	2.78 ± 0.09 (3)	2.38 ± 0.07 (3)	3.17 ± 0.09 (3)
C-MS (MPa)	6.97 ± 0.12 (2)	8.77 ± 1.12 (13)	20.68 ± 3.4 (16)	23.98 ± 2.4 (10)	27.47 ± 4.8 (17)	24.21 ± 1.22 (5)	18.33 ± 0.76 (4)

Note: the values in parentheses are CoV (%).

producing a material with improved strength. At the opposite end of the spectrum is pure PP, which has the lowest toughness of 0.27 J for C-TI, which in turn means that it has a poor ability to resist fracture under compressive loads. The data show that the blending of rHDPE with other polymers enhances the energy absorption capacity, as well as the toughness of the material. For C-MS, which is the maximum stress that the material can oppose in compression, once again rHDPE+POL has the highest value of 27.47 MPa.

This means that rHDPE + POL is the strongest material of the series because it can sustain high compressive forces without failing. On the other end of the spectrum, pure HDPE has the lowest C-MS value of 6.97 MPa, which implies that it has poor compressive strength. The consistency in the performance of HDPE + POL across the three characteristics indicates that it is suitable for use in situations that require the material to have high mechanical properties and strength. The Coefficient of Variation (CoV) in the compressive properties of recycled plastic mixes varies based on material compatibility and processing conditions. rHDPE + rSAM and rHDPE + rPP exhibit the lowest CoV across all the parameters, indicating highly uniform properties due to effective blending. rHDPE, rPP, and rHDPE + rLDPE show moderate CoV values, suggesting controlled variability influenced by polymer crystallinity and melt flow properties. rHDPE + V and rHDPE + POL have the highest CoVs, particularly in compressive strength (C-MS), indicating inconsistencies likely due to phase separation or poor interfacial bonding. rHDPE + POL shows stable toughness but fluctuating compressive strength, while rHDPE + V exhibits significant variability in both energy absorption and strength. Overall, lower CoV values suggest consistent mechanical behavior, while higher values indicate material heterogeneity due to differences in polymer compatibility, degradation effects, and processing conditions.

3.3.1.4 Tensile Behavior

Tensile tests were carried out according to ASTM D790 standards. The tests were performed at a loading rate of 1.6 mm/min to find the peak load (P_{max}), maximum strength (σ_{max}), maximum strain (ϵ_{max}), and energy absorption of the 35 samples. The tensile analysis graph in Figure 3.16 presents the stress–strain behavior of nine different recycled plastic blends, and their unique mechanical properties based on their composition are presented in the graph.

The rHDPE is taken as a reference point and it exhibits average tensile strength and ductility. This is because research has shown that recycled HDPE has mechanical properties that are quite similar to those of virgin HDPE when proper recycling conditions are met. Adding 15% rLDPE to rHDPE enhances the flexibility of the material and increases the elongation at break; however, the tensile strength is slightly decreased. This is consistent with studies that have investigated the effect of rLDPE on the ductility of polymer blends [15]. The blend of rHDPE and polyolefins (POL) is seen to be tougher than the others because polyolefins are known to enhance the strength and flexibility of polymers. The mechanical performance of the sample is also dependent on the type and ratio of polyolefins used. Adding rPP to rHDPE increases the stiffness and tensile strength of the material because polypropylene is a relatively stiff polymer. However, the compatibility of rHDPE and rPP is an important factor as phase separation can lead to poor mechanical properties [5].

Blending rHDPE with samicanite (SAM) enhances tensile strength and thermal stability, attributed to the rigid structure and reinforcing effect of samicanite particles. However, the blend shows reduced ductility due to the brittle nature of samicanite, consistent with findings on filler-reinforced polymer composites. The rHDPE+rLDPE blend with a higher proportion of LDPE demonstrates increased ductility, highlighting LDPE's significant contribution to flexibility in polymer matrices [27]. Adding vinyl polymers (V) to rHDPE improves tensile strength and stiffness, though processing challenges and compatibility issues must be addressed to optimize performance [5]. The rPP sample exhibits high stiffness and tensile strength, typical of polypropylene. However, recycled polypropylene may exhibit slightly reduced mechanical properties compared to virgin PP due to thermal and oxidative degradation during recycling processes. Table 3.9 and Figure 3.17 show the analysis that examines the tensile properties of various recycled plastic composites, including rHDPE, rPP (recycled polypropylene), rHDPE + rPP, rHDPE + V (virgin material), rHDPE + rLDPE (Low-Density Polyeth-ylene), rHDPE + PL (polyolefin), and rHDPE + rSAM (recycled samicanite pellets). The mechanical properties assessed include tensile total energy absorption (T-TEA), the tensile toughness index (T-TI), tensile maximum stress (T-MS), and tensile yield stress (T-YS). These properties are critical for evaluating the material's performance under tensile (stretching) loads, particularly in structural applications where strength and ductility are important. The T-TEA for rHDPE is 4.27 kJ/m^3, showing that rHDPE has moderate energy absorption during tensile deformation. This suggests that the rHDPE can absorb some energy before failure but is not as resilient as composites like rPP. The T-TI for rHDPE is 1.30 J, indicating that rHDPE has moderate toughness under tensile stress. It shows a fair level of resistance to crack

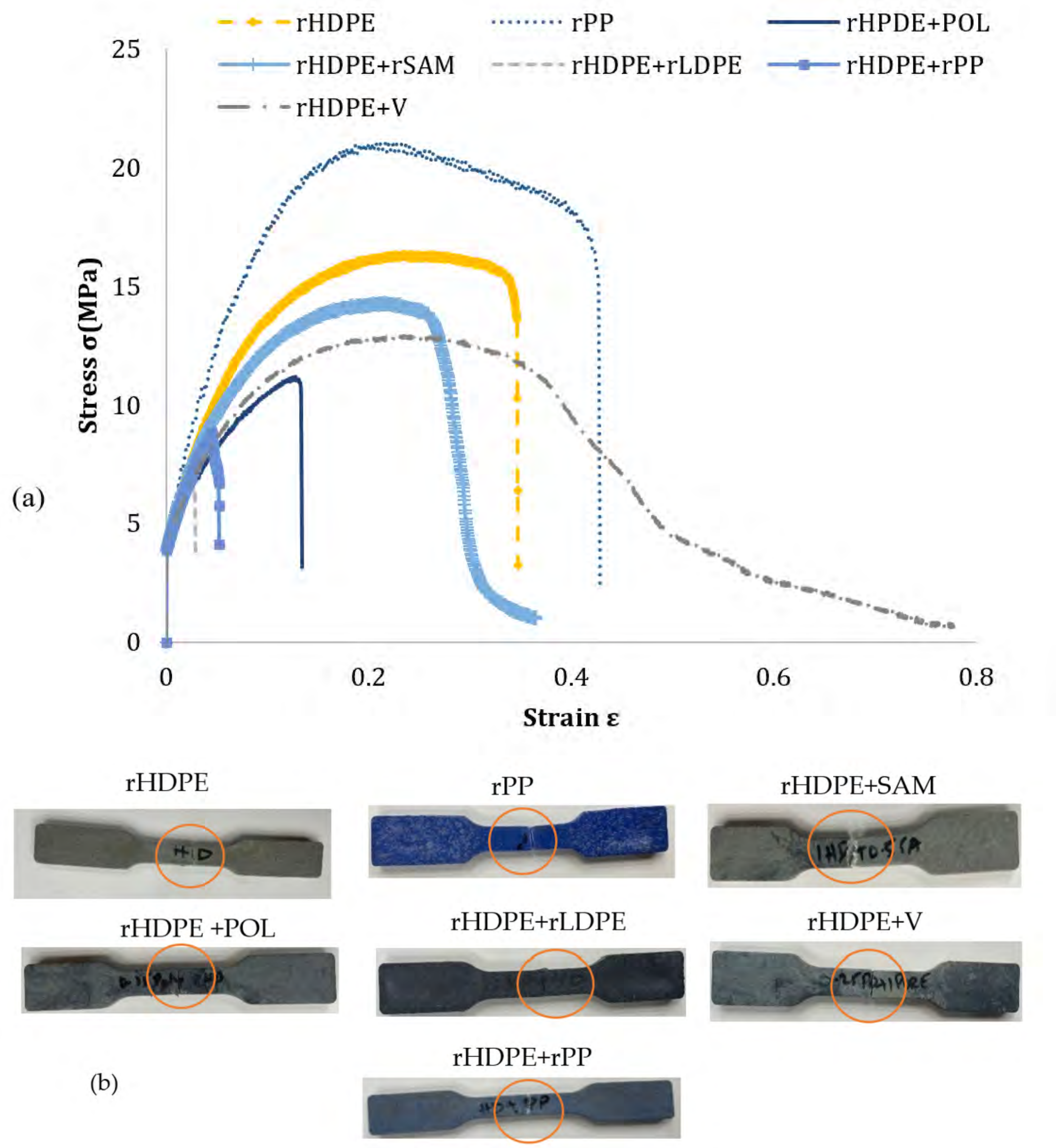


FIGURE 3.16: Tensile behavior of recycled plastic. (a) Stress–strain curves; (b) tensile failure.

propagation during stretching. The T-MS for rHDPE is 16.32 MPa, demonstrating that HDPE can withstand moderate ten-sile stress before failure.

For tensile deformation, rPP has a T-TEA of 7.13 kJ/m^3, which is higher than that of rHDPE, indicating that rPP has a better energy absorption capability and is thus more suitable for applications where energy dissipation is of concern. For tensile stress, the T-TI of rPP is 2.25 J, meaning that rPP has a higher toughness than rHDPE and is thus more likely to resist cracking. The T-MS of rPP is 21.4 MPa, which is higher than that of rHDPE, which means that rPP has better tensile

TABLE 3.6: T-TEA, T-TI, T-MS, and T-YS values of all specimens of recycled plastic.

Parameter	**Recycled Plastic and Mixes**						
	rHDPE	**rPP**	**rHDPE + rPP**	**rHDPE + V**	**rHDPE + rLDPE**	**rHDPE + POL**	**rHDPE + rSAM**
T-TEA (kJ/m^3)	4.27 ± 0.65 (16)	7.13 ± 2.00 (17)	0.25 ± 0.03 (8)	1.40 ± 0.60 (17)	0.10 ± 0.00 (0)	0.94 ± 0.10 (9)	1.56 ± 0.50 (14)
T-TI (J)	1.30 ± 0.65 (14.91)	2.25 ± 1.30 (10.98)	0.84 ± 0.08 (8.17)	0.62 ± 0.40 (10.87)	0.68 ± 0.00 (0.48)	0.87 ± 0.10 (6.00)	0.63 ± 0.60 (16.34)
T-MS (MPa)	16.32 ± 0.83 (5)	21.4 ± 0.51 (2)	8.84 ± 0.23 (6)	12.89 ± 0.25 (2)	6.55 ± 0.29 (4)	11.19 ± 0.58 (5)	13.41 ± 0.66 (5)
T-YS (MPa)	4.48 ± 0.12 (2.80)	4.46 ± 0.09 (2.14)	4.24 ± 0.06 (1.43)	4.27 ± 0.05 (1.11)	4.20 ± 0.00 (0.00)	4.31 ± 0.02 (0.49)	4.31 ± 0.05 (1.12)

Note: the values in parentheses are CoV (%).

strength before failure. The T-TEA of rHDPE + rPP is 0.25 kJ/m^3, which is quite low compared to rHDPE and rPP. This implies that rHDPE + rPP has a limited energy absorption capacity and is hence not very useful for high impact resistance applications. The T-TI of rHDPE + rPP is 0.84 J; hence, rHDPE + rPP is much softer than other composites, like rHDPE or rPP. The T-MS of rHDPE + rPP is 8.84 MPa, which means that it has the poorest tensile strength among the three materials.

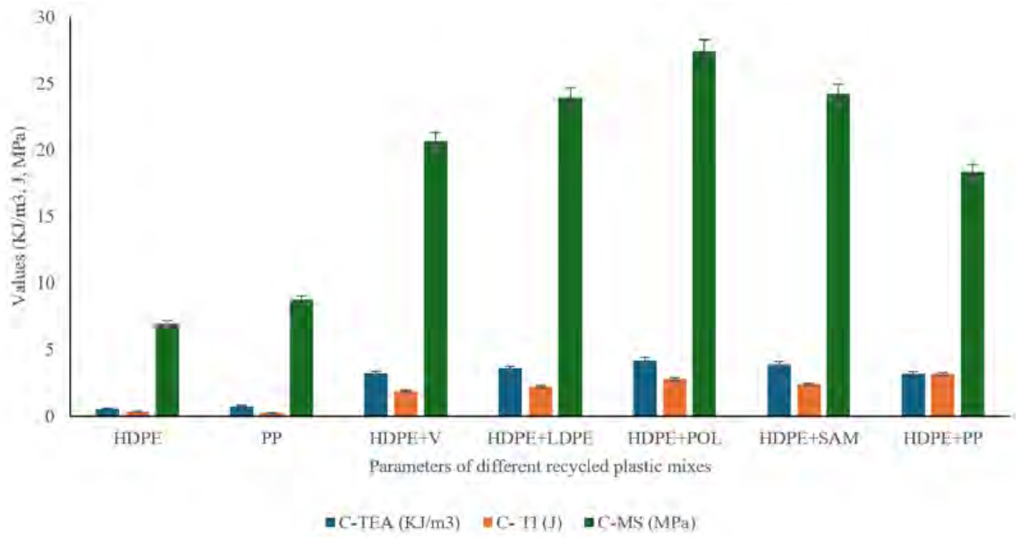


FIGURE 3.17: Graphical representation of T-TEA, T-TI, T-MS, and T-YS of recycled plastic.

For tensile deformation, rPP has a T-TEA of 7.13 kJ/m^3, which is higher than that of rHDPE, indicating that rPP has a better energy absorption capability and is thus more suitable for applications where energy dissipation is of concern [54]. For tensile stress, the T-TI of rPP is 2.25 J, meaning that rPP has a higher toughness than rHDPE and is thus more likely to resist cracking. The T-MS of rPP is 21.4 MPa, which is higher than that of rHDPE, which means that rPP has better tensile strength before failure. The T-TEA of rHDPE + rPP is 0.25 kJ/m^3, which is quite low compared to rHDPE and rPP. This implies that rHDPE + rPP has a limited energy absorption capacity and is hence not very useful for high impact resistance applications [54].

The T-TI of rHDPE + rPP is 0.84 J; hence, rHDPE + rPP is much softer than other composites, like rHDPE or rPP. The T-MS of rHDPE + rPP is 8.84 MPa, which means that it has the poorest tensile strength among the three materials. The T-TEA for rHDPE + V is 1.40 kJ/m^3 greater than rHDPE + rPP, which means that it has better energy absorption under tensile stress. The T-TI for HDPE + V is 0.62 J, which means that it has lower toughness than rHDPE and rPP. The T-MS for rHDPE + V is 12.89 MPa, which means that it can sustain moderate tensile stress before failure [22]. The T-YS for rHDPE + V is 4.27 MPa, and this is like rHDPE and rPP, which means that it has good initial deformation resistance.

The T-TEA for rHDPE + rLDPE is 0.10 kJ/m^3; this is the lowest of all the composites. This implies that rHDPE + rLDPE has very low energy absorption under tensile stress and hence is not recommended for use in applications which require a material to deform significantly [54]. The T-TI for rHDPE + rLDPE is 0.68 J, and this shows that it has a moderate toughness but is not as tough as HDPE + V and PP. The T-MS for HDPE + LDPE is 6.55 MPa, which is an indication of the material's tensile stress resistance. The T-TEA for rHDPE + PL is 0.94 kJ/m^3, indicating that the material has a moderate energy absorption capacity, which can be suitable for certain applications. The T-TI for rHDPE + PL is 0.87 J, which shows that it has a moderate toughness under tensile stress. The T-MS for rHDPE + PL is 11.19 MPa, which means that it can bear a moderate level of tensile stress. The T-YS for rHDPE + PL is 4.24MPa, indicating that it has a good resistance to deformation under tensile loading. The T-TEA for rHDPE + rSAM (samicanite pellets) is 1.56 kJ/m^3, which is better than that of some other composites in energy absorption. The T-TI for rHDPE + SAM is 0.63 J, which shows that it has a good resistance to crack propagation under tensile loading. The T-MS for rHDPE + rSAM is 14.31MPa and is the highest among the tested composites, which indicates strong resistance to tensile stress. The T-YS for rHDPE + rSAM is 4.31 MPa, which indicates a good resistance to deformation under tensile loading. The Coefficient of Variation (CoV) in the tensile properties of recycled plastic mixes varies based on polymer compatibility, blending efficiency, and processing conditions. rHDPE + rLDPE and rHDPE + POL exhibit the lowest CoV, indicating highly uniform properties due to good poly-mer compatibility. rHDPE + rPP and rPP show moderate CoV, suggesting controlled variability in energy absorption and toughness. rHDPE and rHDPE + V have higher CoVs in T-TEA, indicating variability in energy absorption, likely due to differences in their molecular structure and processing history. rHDPE + rSAM show the highest CoV, particularly in toughness and tensile strength, suggesting phase separation or the inconsistent dispersion of additives. Overall, lower CoV values indicate stable mechanical behavior, while higher values suggest material inconsistencies due to phase incompatibility, degradation effects, and processing variations.

3.3.1.5 Cross Property Correlations Between Mechanical Strengths of Recycled Plastics

The experimental data facilitate a systematic comparison of tensile strength with compressive, shear, and flexural strengths across the tested recycled plastics. The observed patterns and empirical correlations reveal how tensile strength governs the relative performance of these materials under different modes of loading. For recycled HDPE (rHDPE), the ultimate tensile strength (T-MS) was approximately 16.3 MPa, whereas the compressive maximum stress (C-MS) was only 6.97 MPa, corresponding to about 40–45% of its tensile strength. This indicates that rHDPE is inherently more efficient in resisting tensile forces than compressive ones, most likely due to yielding or buckling under compressive stresses. This behavior contrasts sharply with conventional structural materials such as concrete, which typically exhibit superior compressive strength. In terms of shear resistance, rHDPE demonstrated a maximum shear stress (S-MS) of 10.4 MPa, which corresponds to nearly 64% of its tensile strength. The shear stress–strain response displayed a distinct yield point followed by limited plastic deformation, signifying moderate toughness. Despite its relatively brittle behavior in bending, the flexural strength of rHDPE (34–35 MPa) was still more than double its tensile strength, with an F-MS/T-MS ratio of 2.1. The flexural response was characterized by a sharp post-peak drop, reflecting brittle failure once the outer fibers fractured.

For recycled polypropylene (rPP), a similar trend was evident. Its tensile strength was 21.4 MPa compared to a compressive strength of 8.8 MPa (41% of T-MS). In shear, rPP attained 13.1 MPa, about 61% of its tensile strength, representing the highest shear resistance among all samples tested. The shear curve revealed large deformation at failure, demonstrating high ductility albeit at a lower peak stress compared with some of the stiffer HDPE-based blends. Notably, rPP displayed outstanding flexural performance, with an F-MS of 72.23 MPa—approximately 3.4 times its tensile strength owing to its stiffness and ability to sustain significant bending stresses prior to fracture of the outer fibers. Blending strategies substantially altered these relationships.

The rHDPE+LDPE blend exhibited a complete reversal of the tensile–compressive balance. Its tensile strength dropped to 6.6 MPa, while compressive strength increased markedly to 23.98 MPa, making C-MS about 3.6 times higher than T-MS. This enhanced compressive capacity is attributable to LDPE's ductility, which permits plastic deformation without premature brittle fracture, though at the expense of tensile performance. Interestingly, its shear strength (7.3 MPa) slightly exceeded its tensile strength, yielding an S-MS/T-MS ratio of 1.12. This anomalous case indicates that under punching shear, the flexible LDPE-rich material redistributes stresses more effectively than under direct tension.

The rHDPE+Polyolefin (POL) blend recorded the highest compressive strength among all compositions, reaching 27.47 MPa. Its tensile strength was moderate

(11.2 MPa), resulting in a C-MS/T-MS ratio of 2.5. The polyolefin additive likely enhanced crystallinity and improved stress transfer under compression, producing a stiff composite with superior load-bearing capacity. Shear strength was 7.5 MPa (67% of T-MS), showing balanced performance and stable post-yield response. In flexure, the same blend attained 72.23 MPa, representing an F-MS/T-MS ratio of 6.5—the most pronounced disparity observed in this study. This indicates highly efficient stress transfer in bending and suggests the development of a strong compression zone that delays tension-side cracking.

The rHDPE+rPP blend also demonstrated significant improvements in compressive performance, with C-MS 18.3 MPa (2.1× T-MS), though tensile strength fell to 8.8 MPa due to weak interfacial adhesion between the two polymers. Its shear strength (7.4 MPa) was nearly 84% of tensile strength, unusually high compared with other materials, indicating that despite low tensile resistance, the blend could still sustain appreciable shear loads. For the rHDPE+Samicanite composite, the rigid filler improved flexural behavior considerably. The blend displayed higher peak stress and greater deflection capacity than neat rHDPE, with estimated flexural strength in the range of 50–60 MPa compared to a tensile strength of 14.3 MPa, yielding an F-MS/T-MS ratio of 3–4. This enhancement is attributed to reinforcement effects of the filler, which increase stiffness and delay crack propagation, thereby making the blend suitable for applications requiring both strength and toughness in bending.

In contrast, the rHDPE+Virgin HDPE blend did not show improvements in flexural capacity. Its flexural strength (13.6 MPa) was nearly equal to its tensile strength (12.9 MPa), giving an F-MS/T-MS ratio of 1.05, the lowest among all blends. Poor interfacial bonding and high variability (as indicated by a large coefficient of variation in flexural tests) likely undermined any potential reinforcement, underscoring the importance of compatibility between recycled and virgin polymers. Overall, the results confirm an inverse relationship between tensile and compressive strengths across the investigated blends. Pure rHDPE and rPP exhibited $T-MS > C-MS$, whereas the addition of LDPE, POL, or similar modifiers significantly boosted compressive capacity while reducing tensile strength. Quantitatively, the ratio C-MS/T-MS ranged between 0.4–0.5 for the neat polymers and increased to 1.6–2.5 for optimized blends, reaching as high as 3.6 in the rHDPE+LDPE case.

Shear strength consistently scaled with tensile strength, generally falling between 60–70% of T-MS, with variations from 0.5 to 0.85 depending on blend composition. This indicates that improvements in tensile performance are usually accompanied by proportional gains in shear resistance. Flexural strength, on the other hand, was consistently much higher than tensile strength, typically two to six times greater. For stiff and crystalline systems such as rPP and rHDPE+POL, flexural strength reached the upper limit (3–6× T-MS), while more ductile or poorly bonded compositions approached the lower bound (1–2× T-MS).These findings emphasize that recycled plastic composites can be engineered to meet specific structural requirements by tailoring blends to enhance desired properties.

Empirically, the data can be summarized as:

$$C_{MS} \approx 0.4\,T_{MS} \qquad \text{(pure HDPE/PP)} \tag{3.1}$$

$$C_{MS} \approx 2-3\,T_{MS} \qquad \text{(optimized blends)} \tag{3.2}$$

$$S_{MS} \approx 0.6\,T_{MS} \tag{3.3}$$

$$F_{MS} \approx (3-5)\,T_{MS} \tag{3.4}$$

These relationships provide a quantitative basis for predicting compressive, shear, and flexural performance from tensile strength, thereby supporting material selection and design optimization in structural applications of recycled plastics.

3.3.2 Microstructure Analysis

3.3.2.1 SEM Analysis of Damaged Surfaces of Specimens

The analysis of the microstructure of recycled plastic composites showed that there are voids of about 20 µm in size. Such voids, which are often attributed to the incomplete fusion of the polymer, entrapment of air in the process, and poor interfacial contact between the phases, have a considerable effect on the mechanical and structural properties of the composites. It has been shown that voids in polymer composites serve as stress concentrators that decrease tensile strength and toughness and increase the probability of crack onset and growth. The SEM images in Figure 3.18 provide the microstructural details of various recycled polymer materials. There are large voids and crack surfaces in the rHDPE (recycled high-density polyethylene) sample, which means that the material has poor interfacial bonding. These defects mean that the material may well be of reduced mechanical strength because, as everyone knows, voids and cracks are stress concentrators. By and large, the rPP (recycled polypropylene) sample has a more homogeneous matrix with fewer voids than the rHDPE sample, and this may be due to better processing conditions or a denser structure. This improved microstructure is associated with improved material properties, that is, strength and toughness, because of the minimal defects present. The addition of SAM (samicanite pellets) to rHDPE shows a cracked surface with more defined patterns, which may be related to the fracture mechanisms of the additive. However, the fact that there is crack propagation indicates that there is still a need for further optimization to improve compatibility and reduce crack formation.

The influence of voids on the properties of recycled composites is further emphasized in [31], and it is shown that even minimal void content can reduce the inter laminar shear strength and the compressive strength, especially in blends with high phase incompatibility. In the blends like rHDPE + rPOL, the poor interfacial adhesion worsens the formation of voids and leads to phase separation and formation of local stress concentrations. In contrast, the blends containing rLDPE had few voids and improved mechanical properties, which can be due to better polymer compatibility and chain entanglement. The rHDPE + POL (recycled high-density polyethylene with poly-olefin) blend the material is clustered together but the surfaces are relatively planar which means that the two components are compatible and mixed well, although some defects may still exist and affect the structure. The rHDPE + PP (recycled HDPE with polypropylene) blend shows visible material clustering along with cracks. These cracks indicate that the two polymer phases have poor interfacial bonding, which may re-strict the blend's

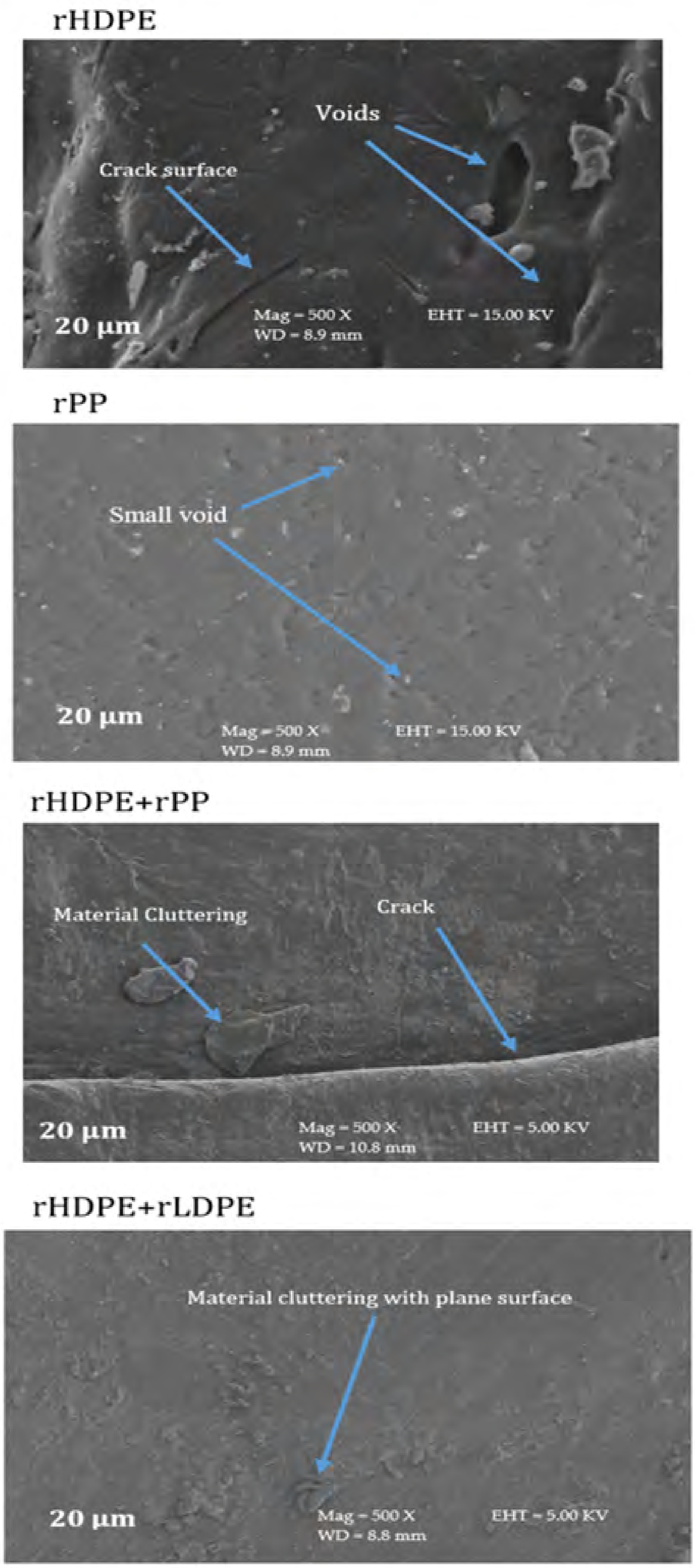


Figure 3.18: SEM images of samples after failure continued ...

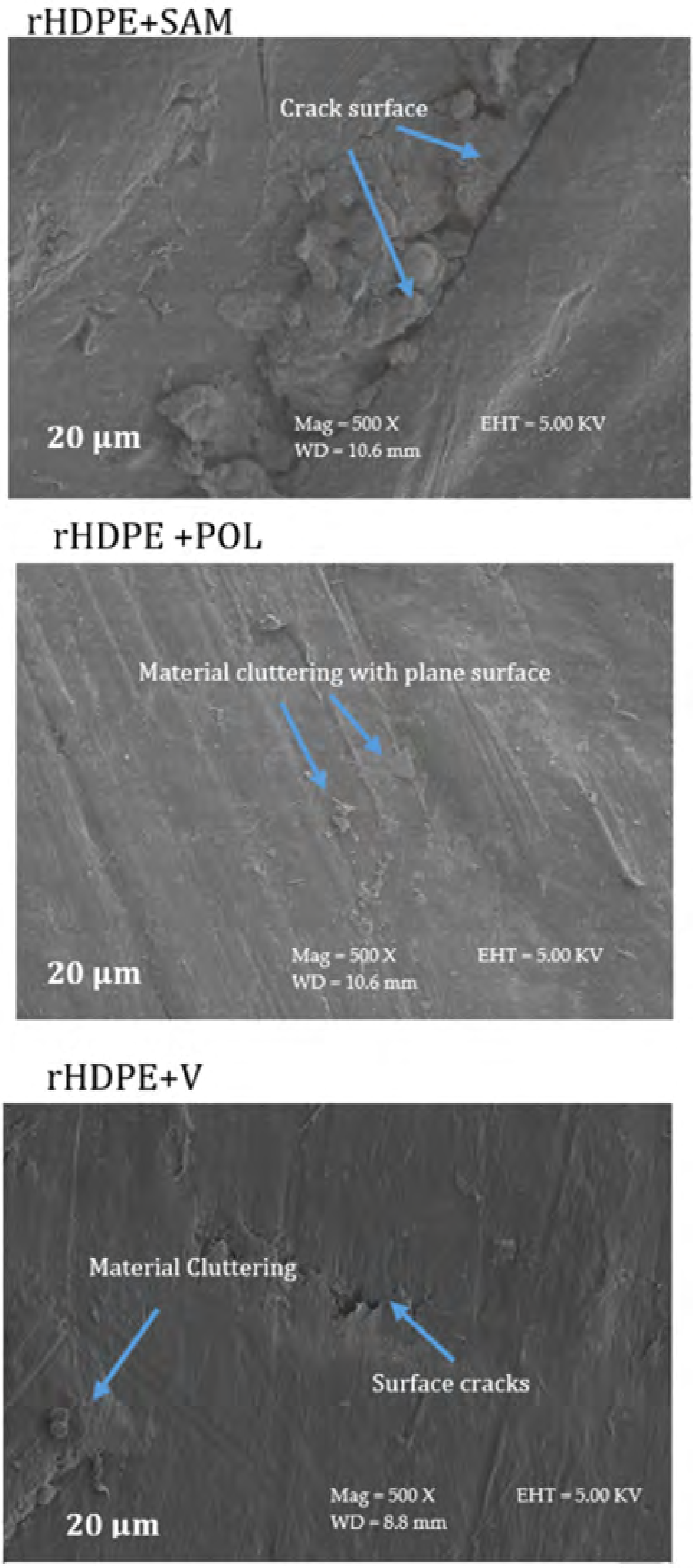
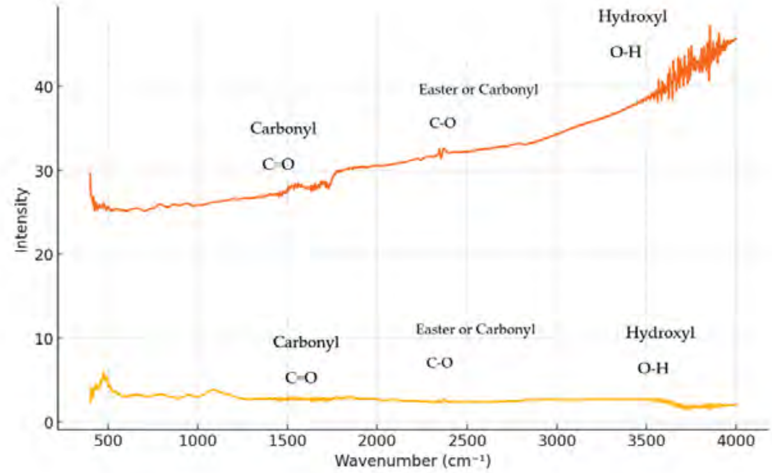


FIGURE 3.18: SEM images of samples after failure.

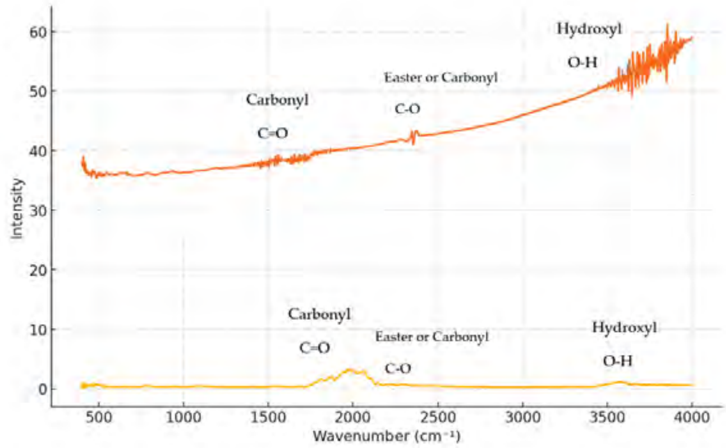
strength and toughness. The rHDPE + V (recycled HDPE with vinyl) sample has surface cracks and material clustering, showing that the blend was not properly mixed or that there was phase separation. These surface defects could be potential failure points when the material is under stress. In the rHDPE + LDPE (recycled HDPE with Low-Density Polyethylene) blend, material clustering is seen, but the surface is relatively even and planar, indicating stronger compatibility than the other blends. Although the clustering is not fully prevented, the general appearance of the structure is more uniform, with fewer potential stress concentrators. These findings highlight the need for proper void control and structural optimization to create high-performance recycled plastic composites and highlight their potential use in the demanding construction industry. The SEM analysis conducted in this study was primarily qualitative, focusing on the identification of fracture morphology, polymer matrix continuity, and filler dispersion. While quantitative interpretation of micrographs (such as porosity estimation and void fraction analysis) would indeed provide valuable insights, this was not incorporated due to the absence of advanced image-analysis facilities within the scope. Nevertheless, the influence of microvoids and porosity is indirectly reflected in the variability of mechanical test results. For future work, integrating quantitative SEM image analysis or complementary techniques such as X-ray micro-computed tomography and mercury intrusion porosimetry is recommended to establish a direct correlation between microstructural porosity and macroscopic mechanical behavior.

3.3.2.2 FTIR

Polymer extrusion processes often cause significant chemical changes within the material due to heat, shear, and pressure. This can lead to polymer chain scission, resulting in the formation of new functional groups, such as carbonyls (C=O), hydroxyls (O-H), and esters or carboxyl groups (C-O), which appear as distinct peaks in the FTIR spectrum of Figure 3.19. Alongside these oxidative changes, the intense mechanical stress during extrusion can break polymer chains into smaller fragments. These fragments may be recombined in novel ways, forming previously unseen molecular structures that also manifest as new FTIR peaks.



(a) wHDPE vs. rHDPE



(b) wPP and rPP

FIGURE 3.19: Comparison of FTIR of raw palette and recycled plastic.

High temperatures can further induce chemical crosslinking, creating stronger bonds like C-C or C-O-C and generating additional peaks in the 1000–1200 cm^{-1} range. When additives or stabilizers are present, they too may react under extrusion conditions, contributing to the formation of new compounds. Moisture absorption or oxygen exposure during the process can lead to additional hydroxyl and carbonyl groups, seen as increased intensity at around 3500 cm^{-1} and 1700 cm^{-1}. Both materials show differences in their infrared absorption properties in Figure 3.19, reflected in the varying intensity values across different wavenumbers. One material generally exhibits lower intensity values compared to the other, suggesting potential differences in composition or structural properties. Distinct peaks and valleys in the spectra correspond to the vibrational modes of molecular bonds, with some peaks overlapping and others unique to a particular material. This indicates variations in chemical composition. The infrared absorption characteristics can be used to identify functional groups and assess potential modifications between the materials. Differences in intensity imply variations in transmittance and reflectance, providing clues to compositional changes. Comparing these materials with others that were previously analyzed highlights how each responds differently to infrared spectroscopy.

3.3.3 Optimization

The findings of this research underscore the significant potential of specific recycled plastic materials and blends in construction applications, with HDPE and PP as contending materials in a complementary manner. rPP has overall shown good performance in shear, flexure, and tensile tests, and rHDPE has also shown encouraging results. However, these materials were not able to perform well under compression, primarily due to differences in the manufacturing mechanisms than other samples. The blends with LDPE had better flowability, but strength wise this blend performed the poorest. The gas emission analysis during the extrusion process also supported the environmental sustainability of the proposed materials since they emitted minimal gas. Hence, based on mechanical behavior, thermal stability, and environmental compliance, rHDPE and its blends are the most suitable materials for practical construction applications. Furthermore, the rPP had flowability problems during extrusion but is still the highest performer in mechanical properties. These findings highlight the versatility and transformative potential of recycled plastics in advancing sustainable construction practices. Table 3.10 presents the highest performing recommended recycled plastics and the poorest performers. Although rPP has shown the highest values and is recommended based on strength parameters, the polymer, having different rheological properties, was comparatively difficult to handle during the material meltdown in extrusion [193]. Further to this, the amount of PP in municipal waste is also low com-pared to HDPE. The HDPE maintained a reasonable performance in all the tests and during extrusion and was better during extrusion, making it plausible for molding different products for construction.

TABLE 3.7: Mechanical properties of high performing recommended recycled plastic mixes.

Parameter															
	Tensile Behavior				**Compression Behavior**				**Flexural Behavior**					**Shear Behavior**	
T-TEA (KJ/m^3)	**T-TI (J)**	**T-MS (MPa)**	**T-YS (MPa)**	**C-TEA (KJ/m^3)**	**C-TI (J)**	**C-MS (MPa)**	**F-TEA (KJ/m^3)**	**F-PEA (J/m^3)**	**F-TI (J)**	**F-MS (MPa)**	**F-YS (MPa)**	**S-TEA (KJ/m^3)**	**S-TI (J)**	**S-MS (MPa)**	**S-YS (MPa)**
Materials with highest performance															
	rPP		rHDPE	rHDPE + POL	rHDPE + rPP	rHDPE + POL			rPP				rPP		
7.13 ± 2.00 (17)	2.25 ± 1.30 (10.98)	21.4 ± 0.51 (2)	4.48 ± 0.12 (2.80)	4.23 ± 0.41 (10)	3.17 ± 0.09 (3)	27.47 ± 4.8 (17)	45.74 ± 7.64 (17)	208.81 ± 7.00 (28)	9.42 ± 0.32 (3)	72.23 ± 12.07 (17)	14.14 ± 0.14 (1)	8.69 ± 0.09 (5.06)	13.12 ± 0.04 (4.61)	13.12 ± 0.34 (3.39)	2.65 ± 0.02 (0.89)
Materials with second highest performance															
	rHDPE		rPP	rHDPE + SAM	rHDPE + POL	rHDPE + SAM	rHDPE + SAM	rHDPE		rHDPE + SAM	rHDPE	rHDPE + V		rHDPE	
4.27 ± 0.65 (16)	1.30 ± 0.65 (14.91)	16.32 ± 0.83 (5)	4.46 ± 0.09 (2.14)	3.90 ± 0.27 (7)	2.78 ± 0.09 (3)	24.21 ± 1.22 (5)	13.66 ± 1.83 (13)	50.79 ± 6.40 (13)	7.37 ± 0.93 (13)	34.61 ± 4.63 (13)	14.05 ± 0.16 (1)	6.74 ± 0.10 (8.15)	10.39 ± 0.03 (4.90)	10.39 ± 0.47 (6.14)	2.08 ± 0.06 (3.18)
Materials with poorest performance															
	rHDPE + rLDPE			rHDPE	rPP	rHDPE			rHDPE + rLDPE				rHDPE + rLDPE		
0.10 ± 0.00 (0)	0.68 ± 0.00 (0.48)	6.55 ± 0.29 (5)	4.20 ± 0.00 (0.00)	0.55 ± 0.06 (11)	0.27 ± 0.02 (7)	6.97 ± 0.12 (2)	1.11 ± 0.50 (5)	5.56 ± 0.06 (1)	1.15 ± 0.01 (1)	13.60 ± 0.06 (1)	12.98 ± 0.17 (1)	4.48 ± 0.03 (4.84)	7.35 ± 0.01 (9.29)	7.35 ± 0.65 (12.4)	1.87 ± 0.25 (15.32)
Recommended material for construction products															
First priority: rPP (from strength and toughness point of view)															
7.13 ± 2.00 (17)	2.25 ± 1.30 (10.98)	21.4 ± 0.51 (2)	4.46 ± 0.09 (2.14)	0.77 ± 0.02 (3)	0.27 ± 0.02 (7)	8.77 ± 1.12 (13)	45.74 ± 7.64 (17)	208.8 ± 7.00 (3)	9.42 ± 0.32 (3)	72.23 ± 12.07 (17)	14.14 ± 0.14 (1)	8.69 ± 0.09 (5.06)	13.12 ± 0.04 (4.61)	13.12 ± 0.34 (3.39)	2.65 ± 0.02 (0.89)
Second priority: rHDPE (from yield strength, performance, and recyclability point of view)															
4.27 ± 0.65 (16)	1.30 ± 0.65 (14.91)	16.32 ± 0.83 (5)	4.48 ± 0.12 (2.80	0.55 ± 0.06 (11)	0.37 ± 0.04 (11)	6.97 ± 0.12 (2)	12.80 ± 1.97 (15)	50.79 ± 6.40 (13)	7.37 ± 0.93 (13)	25.83 ± 3.97 (15)	14.05 ± 0.16 (1)	5.43 ± 0.13 (9.96)	10.39 ± 0.03 (4.90)	10.39 ± 0.47 (6.14)	2.08 ±0.06 (3.18)

3.4 Perspective Use of Recycled Plastic Waste in Construction Industry

The construction industry faces mounting pressure to adopt sustainable practices and materials in response to environmental and economic challenges. This research highlights the potential of recycled plastics as a valuable resource for construction applications, transforming environmental liability into a useful asset. Through a detailed analysis of seven types of plastics, including high-density polyethylene (HDPE), Low-Density Polyethylene (LDPE), polypropylene (PP), polyolefin, samicanite, and virgin polyethylene (PE), this study demonstrates their viability as materials for various construction purposes. The findings emphasize HDPE as the best-performing material due to its superior tensile strength, shear resistance, and ductility. Its dense crystalline structure ensures exceptional toughness, making it suitable for structural components, such as load-bearing elements and reinforcements. The SEM analysis of damaged HDPE specimens revealed ductile tearing and energy-dissipative failure patterns, affirming its ability to perform under stress. Blends of HDPE with LDPE and PP also showed excellent mechanical properties, with HDPE-LDPE offering enhanced ductility and impact resistance, while HDPE-PP exhibited significant energy absorption, making both blends ideal for lightweight panels, protective barriers, and applications requiring flexibility and shock resistance. Polyolefin and samicanite demonstrated remarkable thermal stability for use with HPDE, expanding the potential applications of recycled plastics to insulation panels, weather-resistant membranes, and fire-resistant barriers. The uniform carbon structure of samicanite ensures consistent thermal behavior, making it particularly effective in environments requiring heat resistance. This has a great contribution to environ-mental benefits when recycled plastics are incorporated in construction. Plastic recycling also helps in reducing the amount of waste that is sent to landfills and helps in the conservation of raw materials since it does not need virgin materials. The current study shows that the extrusion process is environmentally friendly because gas emissions are within safety limits. It thus complies with the circular economy guidelines and suggests the ability to develop construction materials with a lower carbon foot-print than conventional materials like concrete and steel. The emission of gases was very small compared to other processes, like calcination. Recycled plastics are, therefore, a good example of materials that can be used in various ways in construction. They can be used in load-bearing and structural applications, like beams and reinforcement, or in non-structural applications, such as lightweight partitions, blocks, corrugated sheets, and protective barriers, and in the thermal insulation of buildings for energy efficiency. Additionally, further developments in recycling technologies, including chemical and enzymatic methods, may improve the quality and performance of the recycled materials. The mechanical and thermal properties of the material could be enhanced by the incorporation of nanomaterials or advanced additives and thus expand the range of their application. To quantify the environmental and economic benefits of using recycled plastics in construction projects, lifecycle assessments will be necessary. Products formed from recycled plastic will have lower maintenance costs in the overall building products. These findings reveal how recycled plastics can be used to address both waste management and sustainable construction concerns. This approach provides a novel approach to managing environmental pollution, conserving natural resources, and achieving the Millennium Development Goals by transforming waste plastics into eco friendly, cost-effective, and versatile construction materials. Thus, this study suggests a way to make the construction industry more resource efficient and to support the growth of innovative solutions for sustainable building demands.

3.5 Summary

This research is an exhaustive investigation of recycled plastics as viable and environmentally friendly alternatives for the construction industry. This study presents innovative strategies for managing waste plastics, focusing on enhancing recycling efficiency and addressing the technological gaps in plastic recycling sector. By exploring the potential of municipal plastic waste in construction, this research demonstrates its feasibility for developing structural elements with essential mechanical properties. A detailed analysis of seven types of recycled plastics—HDPE, LDPE, PP, polyolefin, samicanite, and virgin polyethylene (PE) was conducted using SEM, FTIR, and TGA to assess their composition, thermal stability, and impurity levels. Mechanical testing on 140 samples revealed that HDPE and PP exhibited superior tensile strength and shear resistance, making them strong candidates for structural applications. Unlike previous research that primarily investigated recycled plastics as additives in concrete compo-sites, soil stabilization, and road construction, this study explored their potential as standalone structural materials. Mechanical extrusion is environmentally suitable as gas emissions are minimal, reinforcing the sustainability of the proposed recycling approach. The following are the detailed conclusions that can be drawn;

- The SEM and TGA results of the HDPE indicate that there are impurities. The raw materials are thermally stable, and their low weight confirms that the decomposition does not release hazardous gases. The materials are easily molda-ble in the temperature ranges defined in this study.

- The materials' behaviors for use in construction were tested by subjecting the ma-terials to different loading conditions, and the performance of the polymers was reasonable.

  - Shear behavior testing revealed that rHDPE had almost the same ranging shear energy as rPP. Based on optimization, blends are also recommended for energy absorbing capabilities in shear intensive applications.
  - The flexural behavior test revealed that rHDPE + rSAM performed well for bearing loads. However, rPP exhibited the highest F-PEA of 208.81 J/m^3. This behavior was unmatched by the rHDPE blends.
  - The compressive parameters of rHDPE+POL and rHDPE+rSAM indicate that these two would be useful for structural applications, although rHDPE and rPP showed the lowest energy absorption during compression compared to the blends.
  - The tensile behavior of rPP had the highest energy absorption (T-TEA: 7.13 kJ/m^3) and thus proved to be the toughest under tensile loads, while rHDPE had a balanced performance between strength and ductility. Mixed composi-tions like rHDPE + rLDPE exhibited poor results, which is probably due to the incompatibility of the polymers.

- The SEM and FTIR of the polymer confirm improvement in chemical cross linking.
  - Through the SEM analysis of the materials after failures appeared, voids, material cluttering, the cleavage of the failure surface, and the ductile tearing and energy dissipative behavior of rHDPE under stress was confirmed, with its toughness and reliability for load-bearing applications being affirmed.
  - Polymer extrusion induces significant chemical changes due to heat, shear-ing, and pressure, leading to chain scission, oxidative modifications, and new functional groups becoming detectable in FTIR spectra. High temperatures and mechanical stress can also cause crosslinking, the recombination of fragments, and reactions with additives, further altering the material's com-position.
- It has been found that rHDPE and rPP behave significantly well in tensile and ductility tests. Such properties make them suitable for application in load-bearing components, reinforcements, and protective barriers in construction.
- Recycled HDPE and PP are recommended for the construction industry, and the recycling process is feasible and is compatible with the concepts of the circular economy, which promotes the use of recycled materials instead of raw ones and drastically decreases the carbon footprint of construction materials like concrete and steel.

Although the above experiments demonstrate the feasibility of using recycled plastics in construction, there are several challenges that need to be overcome for their widespread adoption. Since raw waste plastics are often contaminated, maintaining a consistent material quality is vital. This will be necessary to overcome this limitation. Advanced sorting and purification technologies will be essential. Future work shall ex-plore different prospects of recycled plastic in construction products like rebars, blocks, and their use in mortar-free construction. The relationship of impurities to strength needs exploration in future studies Exploring other elements like corrugated sheets and beams and their connections to the static, dynamic, and thermal properties for use in building construction.

SDG 12 – Responsible Consumption and Production The reuse of plastic waste in construction addresses the critical need for sustainable material consumption. This work exemplifies responsible production by diverting waste from landfills and repurposing it into functional building components. It fosters circular economy principles by ensuring that resources are utilized efficiently, reducing the environmental footprint associated with conventional plastic disposal and construction practices.

Chapter 4

Assessment of Recycled Plastic Rebars for Light Loads

Related Article

1. **Das, A. J.** and Ali, M. (2025). "Sustainable Development and Assessment of Low-Strength/High-Toughness Recycled Plastic Rebars for Structural Elements Under Light Loads". Sustainability, 17(11), 4997.

   https://doi.org/10.3390/su17114997

2. **Das, A. J.** and Ali, M. (2021). "Energy Absorption capabilities of recycled-plastic reinforcing bars for earthquake resistant housing construction." *In proceedings of Australian Earthquake Engineering Society Conference. (25th – 26th November, 2021)*

3. **Das, A. J.** and Ali, M. (2021). "An overview on different reinforcing bars from manufacturing to strengthening element" *In proceedings of International Conference on Civil Engineering for Sustainable Development, Bangladesh. (10th – 12 February 2022)*

4.1 Background

This study presents an innovative approach to plastic-waste management by enhancing recycling efficiency through the development of construction-grade products.

To address this gap, the present research explores the use of municipal plastic-waste, specifically high-density polyethylene (HDPE) and polypropylene (PP) for the fabrication of novel reinforcement bars (rebars) suitable for mortar-free construction systems. Recycled plastic rebars developed in this study are suited for non-load bearing or lightly loaded structural applications. Examples include partition walls, boundary fences, footpaths, and mortar-free interlocking units. These elements experience minimal stress, making them compatible with the mechanical limits of recycled HDPE and PP.

Unlike previous studies that primarily evaluated recycled plastics as additives in concrete, roads, or soil stabilization, this research investigates their potential as independent structural elements. A total of 48 rebar samples were manufactured using mechanical extrusion, covering three different diameters (12 mm, 19 mm, and 25 mm) with both plain and ribbed surface textures. The use of mechanical extrusion not only reduces environmental hazards but also supports circular economic practices by converting plastic-waste into durable, resource-efficient construction materials. Given the absence of specific ASTM standards for tensile testing of recycled plastic rebars, mechanical behavior was evaluated following the guidelines of ASTM A615, traditionally used for steel reinforcement. The assessment also included identification of material impurities and comprehensive analysis of mechanical and microstructural properties. XRD patterns revealed crystalline peaks corresponding to HDPE and PP, confirming the retention of polymeric identity post-recycling. SEM images of fractured surfaces demonstrated ductile failure in HDPE and brittle fracture in PP, aligning with their known mechanical profiles. The results showed that both polymers possessed significant tensile strength, with HDPE displaying superior extrusion compatibility and recyclability. This study is among the first to validate the use of 100% recycled plastic for full-section rebars, offering a viable, corrosion-resistant, and cost-effective alternative to traditional steel reinforcement, particularly for non-critical and light-load applications. This research addresses critical gaps in Pakistan's recycling infrastructure by demonstrating a scalable method to transform plastic-waste into full-section recycled rebars, thereby expanding the structural use of polymers beyond conventional filler based applications.The specific arrangement of recycled plastic rebars was beyond the experimental scope of the present study. However, previous research indicates that a bidirectional or orthogonal placement of reinforcement tends to improve load distribution and crack control. This aspect will be examined in greater detail in future investigations to establish optimized configurations for light-load applications. Light-load applications are defined as structures subjected to ≤ 1 kN/m^2 loads, such as boundary walls, lightweight roofs, partitions, and wall panels. These findings pave the way for further research on optimized polymer blends and large-scale implementation in sustainable infrastructure development.

4.2 Experimental Program

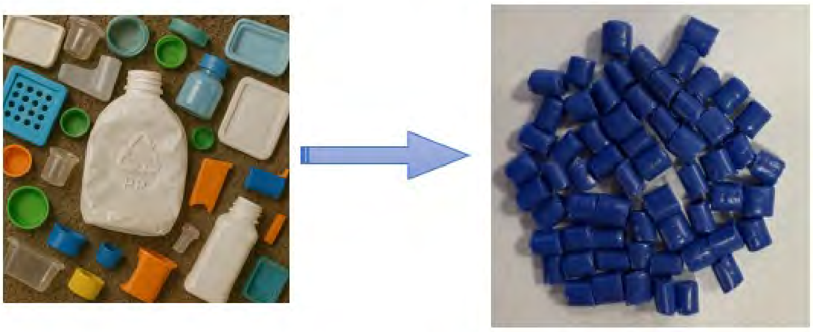
4.2.1 Collection and Synthesis of Recycled Plastic

The collection and sorting of waste plastic materials constituted a vital preliminary step to ensure the quality, consistency, and reliability of the samples used for mechanical recycling and testing in this study. Municipal solid waste (MSW) streams served as the primary source, with a targeted focus on isolating recyclable thermoplastics applicable for construction-related applications. Collected plastics underwent manual sorting to remove contaminants such as organic residues, paper, metals, and multilayer composites that could compromise material homogeneity. Municipal plastic waste was sourced from local waste collection centers and informal recyclers operating in the Islamabad and Rawalpindi regions. The collected waste primarily included post-consumer HDPE and PP products such as detergent bottles, food containers, and packaging materials. To ensure material purity, a multistage cleaning protocol was implemented, plastics were manually sorted to remove multilayer, PVC, PET, and heavily contaminated items, followed by soaking in a mild detergent solution and thorough rinsing with clean water. The washed materials were sun dried and visually inspected to ensure no residual organic matter or foreign particles remained. No chemical pretreatment was used. The sorting strategy prioritized the separation of high-density polyethylene (HDPE) and polypropylene (PP), with comparative material characterization guiding the selection. The sample preparation procedure in this research was followed as per the methodology outlined in study [119], ensuring standardized practices for cleaning, drying, and mechanical shredding.. Palletization was performed, and the resulting granules. For this research rHDPE and rPP samples were prepared with grey and blue pallets respectively. The recycled pallets of HDPE and PP are shown in Figure 4.1. Although handling PP is difficult in extrusion as compared to HDPE, on the other side engineering properties of PP are considerable for the construction industry. Research has also emphasized the importance of controlling processing parameters such as temperature and mixing ratio during multi-material blending to ensure consistency in product performance [119]. The experimental setup employed conventional extrusion-based recycling techniques to reprocess the sorted waste plastics into rebar forms, suitable for mechanical testing. Recent advancements in extrusion technology have significantly improved the sustainability and efficiency of recycling post-consumer and post-industrial plastics, particularly by enabling the processing of diverse polymers such as HDPE and LDPE with better output quality and reduced environmental impact. Furthermore, emerging catalytic extrusion processes offer new pathways to selectively upcycle polyolefin-based waste into high-value structural materials, aligning with the broader objectives of waste reduction and promoting circular economy principles [119].

4.2.2 Sustainable Development of Recycled Plastic Waste Rebars

Palletization confirmed the production of recycled plastic to be used for a second round of extrusion. The extrusion temperature was maintained in the range of 150–170 °C to accommodate the melting characteristics of HDPE and PP, which have typical melting ranges of 130–171 °C depending on polymer grade and crystallinity [119, 187]. Since the recycled plastic feedstock was unsorted and potentially contained minor impurities, including residual additives or other polyolefins, a slightly extended temperature range was necessary to ensure complete melt flow and avoid partial fusion. This approach enabled uniform extrusion without excessive thermal degradation, even in the presence of contaminants that could

(a) HDPE plastic waste to recycled pallets



(b) PP plastic waste to recycled pallets

Figure 4.1: Plastic waste recycled to pallets (a) HDPE (b) PP

alter melting behavior. To form rebars of specific diameters and lengths, custom-designed sizing molds were employed, integrated with a water-cooling setup to ensure dimensional stability. In the initial phase, plain rebars without ribbed surfaces were produced. Figure 4.2 (a–d) illustrates the typical layout of the extrusion and molding system, including the sizing molds used to fabricate the novel recycled plastic rebars (RPRs), while Figure 4.3 displays the finished rebar specimens. During operation, plastic material was fed through a hopper and conveyed by a motor-driven screw mechanism.

Table 4.1: Average weight of recycled plastic rebars.

	Weight (gms/m)		
Sample Type	**Dia (25 mm)**	**Dia (19 mm)**	**Dia (12 mm)**
Plain rPP	417.5 ± 2.1	225.0 ± 0.9	116.3 ± 0.7
Ribbed rPP	442.9 ± 1.7	250.0 ± 1.2	100.0 ± 0.8
Plain rHDPE	353.2 ± 1.5	214.7 ± 1.3	110.4 ± 1.4
Ribbed rHDPE	450.4 ± 1.1	236.0 ± 1.8	105.8 ± 1.8

Heating elements, controlled via an electronic module and monitored by thermocouples, softened the plastic, which exited the die in a semi-solid state. The

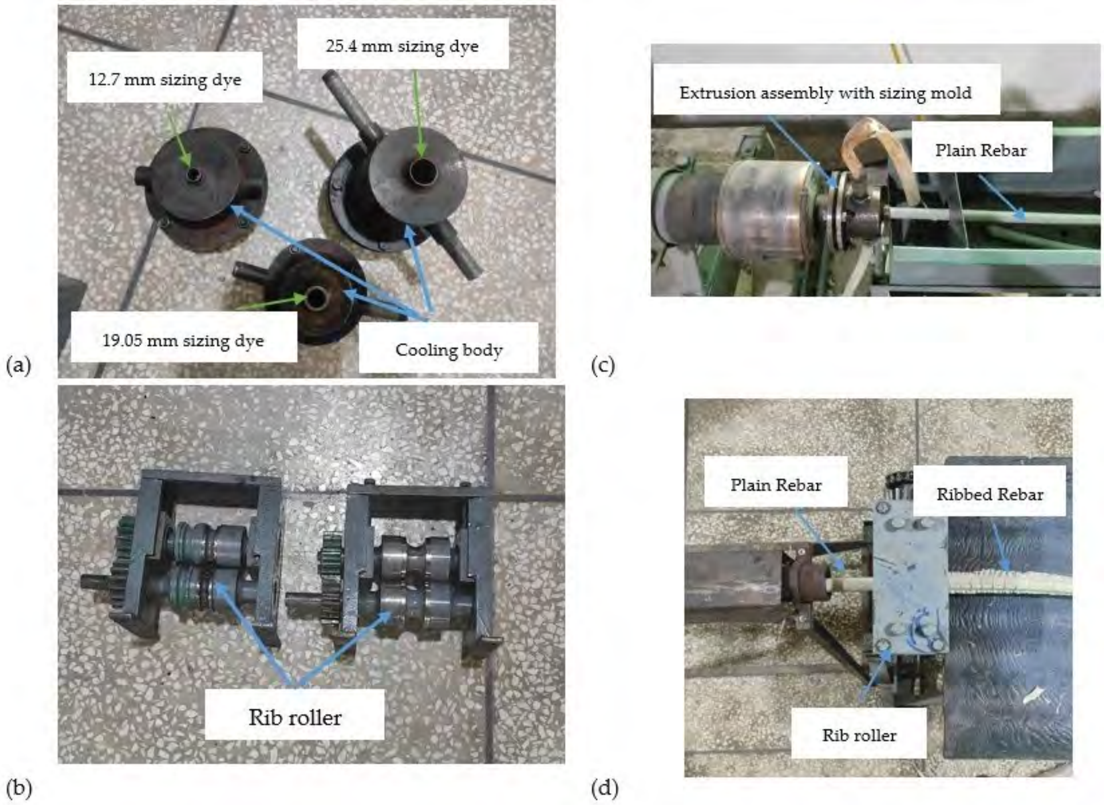


FIGURE 4.2: (a) Sizing molds for 12 mm, 19 mm and 24 mm (b) Rib rollers (c) Extrusion of plain rebars (d) Rib formulation on plain rebars

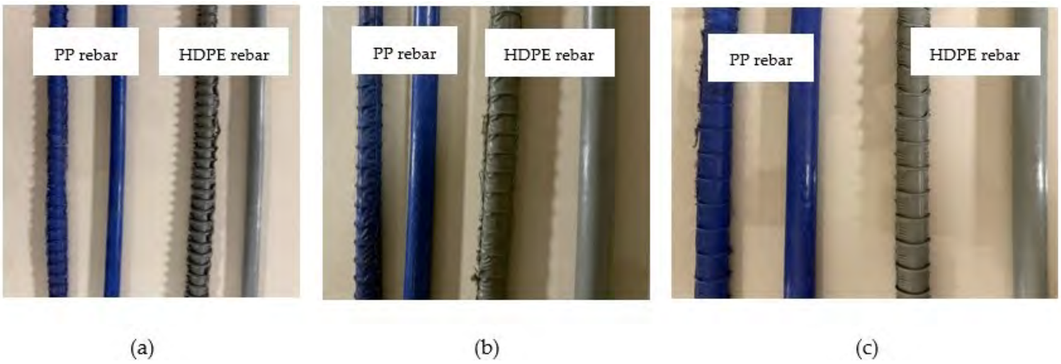


FIGURE 4.3: Recycled Plastic Rebars PP and HDPE, Plain and Ribbed, (a) 12 mm (b) 19 mm (c) 25 mm

extrudate solidified within 10–15 minutes upon cooling, depending on machine temperature. Each rebar was labelled prior to testing. The resulting products were lightweight and displayed visibly ductile characteristics. The samples were developed after the second round of extrusion. The first round was of palletization. The second round was for making plain bars from pallets. The ribbed bars were obtained after heating the plain bars and feeding them to the specialized rollers to create ribs on the surface of the rebars. The extrusion system featured an electronic control panel that allowed precise adjustment of both temperature and screw speed settings. To maintain optimal operational conditions, the machine was housed in a closed, moisture-free environment. The motor operated at a maximum speed of 900 RPM, which was reduced through a gear mechanism to approximately 45–46 RPM. To produce all samples, the final extrusion speed was further controlled electronically and maintained within a range of 20–25 RPM to ensure consistent material flow and quality. The extruded plain bars which came out from the sizing molds were cooled down first from the custom fixed water body, in which the water was continuously flowing at room temperature. The second cool down was done by directly flowing water onto the extruded bars. The continuous flow of the extruded plastic was monitored and after the desired lengths were obtained the plain bars were cut. At this speed, the recycled plastic extrude was workable and easily flowing through the extrusion machine. This arrangement was manually handled. The average time for making 10 feet was 15- 20 minutes for rHDPE and rPP rebars. For rHPDE and rPP, the average weights of the samples are shown in Table 4.1.

The extrusion process was carried out through a screw system divided into four operational zones: the feed section, compression area, melting zone, and discharge outlet. Each stage maintained a specific temperature range, regulated by thermocouples, with values set between 50–55 °C, 100–110 °C, 120–130 °C, and 120–135 °C from the first to the fourth zone, respectively. To ensure consistent material flow and effective melting of recycled plastic, the screw speed was maintained between 40 and 50 RPM, depending on processing stability. The machine utilized six heating coils, each linked to a thermocouple, all managed through an automated control panel for accurate thermal adjustment. After shaping, the extruded plastic rebars were cooled in a water bath to retain their dimensional accuracy. A total of 48 specimens were produced for tensile testing, comprising both plain and ribbed bars in three different diameters: 12 mm, 19 mm, and 25 mm. Figure 4.2 illustrates the layout of the extrusion equipment and highlights the main sections used in the moulding process. Figure 4.3 represents recycled plastic rebars developed from PP and HDPE, plain and ribbed: (a) 12 mm, (b) 19 mm, (c) 25 mm. The extrusion method applied in this study supports environmental sustainability by minimizing emissions and material waste compared to conventional construction material production techniques.

4.2.3 Test Setup

4.2.3.1 Tensile Tests

It is important to note that ASTM A615 is a tensile test standard developed for steel reinforcement bars and does not account for the viscoelastic and ductile nature of thermoplastics. However, due to the absence of established testing standards for full-scale recycled plastic rebars, ASTM A615 was used to facilitate structural-level comparisons with conventional reinforcement. The use of this standard may influence the observed stress-strain response, particularly regarding yield definition and post-yield behavior. The usual method for testing plastics for

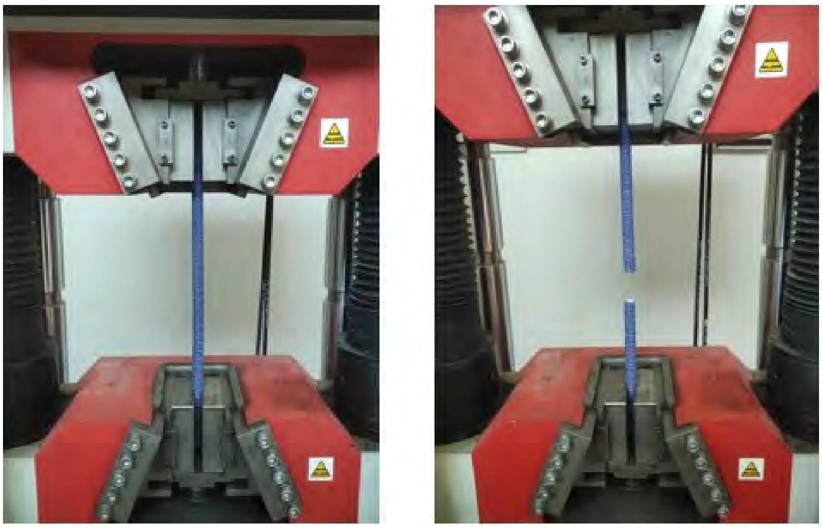


FIGURE 4.4: (a) Tensile test setup of recycled rebars (b) PP Rebar at failure

tensile properties is as per ASTM D638 [187]. The test setup available contains a servo-hydraulic universal testing machine as shown in Figure 4.4. The ASTM A615 procedure was used to test the tensile strength of recycled plastics [194]. The weights of the samples are given in Table 4.1. Earlier, a sample of bamboo was also tested to check tensile strength absorption [149]. The Recycled Plastic Rebars (RPR) were easy to bend and, therefore, a bend test was not required. Testing was conducted under controlled laboratory conditions, maintaining a room temperature of approximately 23 ± 2 °C and a relative humidity of 50 ± 5%. The recorded properties were analyzed for behavior under tensile loads. Future work may explore the adaptation or development of polymer-specific tensile testing protocols for large-diameter structural rebars.

4.2.3.2 Characterization and Microstructural Analysis Procedure

a. SEM analysis procedure

The Scanning Electron Microscopy (SEM) analysis was performed using a ZEISS NCP instrument equipped with a secondary electron (SE2) detector. The micrographs were acquired under a high-vacuum environment, with the gun vacuum maintained between 5.74×10^{-10} and 5.82×10^{-10} mbar, and the system vacuum ranging from 2.89×10^{-6} to 6.39×10^{-6} m bar. An accelerating voltage (EHT) of 15.00 kV was applied during imaging, which provided sufficient electron beam energy to resolve surface topography and morphological features of the polymeric samples. The working distance was set between 9.0 mm and 9.3 mm across the samples to optimize resolution and depth of field. Two magnification levels were used: 1.00 KX for broader surface observations (scale bar = 10 µm), and 5.00 KX for detailed morphological examination (scale bar = 2 µm) [195].

b. X-Ray Diffraction procedure

The X-ray Diffraction (XRD) analysis was conducted utilizing a θ–2θ locked-coupled scan geometry to examine the crystallographic structure of polymer samples. A copper (Cu) anode was employed as the X-ray source, producing characteristic Cu Kα radiation with wavelengths of 1.5406 Å (Kα1) and 1.54439 Å (Kα2), and an average wavelength of 1.5418 Å, which is suitable for analyzing semicrystalline polymer matrices such as high-density polyethylene (HDPE) and polypropylene (PP). The operating conditions of the X-ray tube were set at a voltage of 40 kV and a current of 30 mA, providing adequate beam intensity for polymeric materials. The scan was performed using a goniometer (Model 512) with a 560 mm diameter. The primary and secondary Soller slits were fixed at 2.5°, ensuring minimized axial divergence and improved peak resolution. No monochromator or beam analyzer was applied, allowing for rapid data collection. The 2θ scan range initiated at 10° and continued up to approximately 32.2°, capturing the principal diffraction peaks relevant for HDPE and PP. Fine step resolution was used, which enabled accurate peak identification and reliable estimation of crystallinity. The test setup reflects standard XRD measurement protocols for polymeric materials, providing sufficient resolution and data quality for distinguishing crystalline peaks associated with polymer phase identification and structural analysis [196].

4.2.4 Empirical modelling for Max Load and Max Stress

The mechanical behavior of recycled plastic rebars was analyzed through an empirical modelling approach by fitting second-degree polynomial equations to the experimental data. This method allowed the derivation of mathematical relationships between critical performance parameters (such as maximum load and maximum stress) and bar diameter. By determining the quadratic, linear, and constant coefficients for each material configuration, the modelling captures the non-linear trends inherent to polymeric materials under tensile loading. The use of polynomial fitting provides a robust framework to predict mechanical responses at intermediate diameters and facilitates comparative evaluation across different material types and surface structures [154].

4.3 Results

4.3.1 Tensile Performance of Recycled Plastic Rebars

4.3.1.1 Tensile Behavior

The load–elongation behavior of 12 mm diameter recycled plastic rebars, comprising both plain and ribbed configurations of HDPE and PP composites, is illustrated in Figure 4.5a. All specimens exhibited a non-linear increase in load with elongation, characteristic of polymeric materials transitioning from elastic to plastic deformation. Plain-HDPE rebars showed the lowest load-carrying capacity and a gradual, ductile failure mode, whereas Plain-PP rebars displayed higher initial stiffness, a greater peak load, and earlier onset of softening. The ribbed-HDPE rebars demonstrated a slight improvement in load-bearing capacity compared to their plain counterparts, primarily due to enhanced surface interlocking, while retaining similar ductility profiles. Conversely, ribbed-PP rebars achieved the highest maximum load and elongation, demonstrating superior toughness and delayed necking attributed to the inherent strength of polypropylene combined with the mechanical benefits of ribbed surface geometry. Yield points, identified using the 0.2% offset method and marked with red crosses, highlighted that PP-based rebars yielded at higher loads and lower elongations than HDPE rebars [197]. Overall, the ribbed configurations outperformed the plain ones, with ribbed PP rebars emerging as the most promising candidate for structural reinforcement applications requiring a balance of high strength and ductility, consistent with findings reported for surface structured polymer reinforcements [198]. The load–elongation

Table 4.2: Elastic modulus and ultimate strain of recycled plastic rebar.

Material	**Dia (12 mm)**		**Dia (19 mm)**		**Dia (25 mm)**	
	E (MPa)	**Ultimate strain**	**E (MPa)**	**Ultimate strain**	**E (MPa)**	**Ultimate strain**
Plain rHDPE	∼200	−0.17	∼320–360	−0.045	∼200–240	−0.035
Ribbed rHDPE	∼330–360	−0.24	∼400–500	−0.06	∼380–450	−0.06
Plain rPP	∼430–660	−0.16	∼580–620	−0.07	∼400–500	−0.065
Ribbed rPP	∼300–430	−0.23	∼780–830	−0.10	∼550–650	−0.18

behavior of 19 mm diameter recycled plastic rebars, encompassing both plain and ribbed forms fabricated from HDPE and PP composites, is depicted in Figure 4.5b. All specimens exhibited typical non-linear load elongation curves associated with thermoplastic-based materials undergoing elastic deformation followed by plastic flow. Among the specimens, plain HDPE rebars recorded the lowest load-bearing capacity, characterized by a gradual and ductile failure behavior due to the material's relatively low modulus of elasticity and high strain tolerance. In contrast, plain PP rebars demonstrated enhanced stiffness and achieved greater peak loads and elongations before failure, highlighting polypropylene's superior mechanical properties [199]. Surface ribbing further improved the mechanical performance of both materials, with ribbed HDPE rebars showing increased early-stage stiffness relative to the plain HDPE, though overall ductility remained unchanged. Ribbed

PP rebars achieved the highest load bearing and elongation capacities, indicating significant toughness improvements and extended plastic deformation phases. Yield points determined by the 0.2% offset method occurred at higher loads for PP-based rebars, underscoring the material's higher stiffness and yield strength [200]. The curves further illustrate that despite a slightly lower maximum stress, plain PP rebars absorbed considerable energy through ductile deformation, consistent with prior studies on semi-crystalline polymer matrices [201]. The load–elongation responses of 25 mm diameter recycled plastic rebars, including both plain and ribbed configurations of HDPE and PP composites, are presented in Figure 4.5c. All specimens demonstrated the characteristic non-linear behavior of thermoplastics, involving an initial elastic region followed by yielding and plastic deformation. Plain HDPE rebars showed the lowest peak loads and exhibited steep post-yield softening, reflecting the brittle behavior of HDPE at larger cross-sectional dimensions. Plain PP rebars outperformed HDPE with higher peak loads, improved stiffness, and better ductility prior to failure. Ribbed HDPE rebars exhibited enhanced early-stage load capacities, suggesting that ribbed geometries effectively delayed failure initiation by promoting mechanical interlocking, although ultimate ductility gains remained modest. Ribbed PP rebars achieved the highest overall load-bearing capacity and elongation, sustaining extended plastic deformation and demonstrating excellent toughness and energy absorption properties. The consistent shift of yield points to higher loads in PP-based rebars confirmed the mechanical superiority of polypropylene composites, while the ribbed geometry promoted better stress distribution and delayed crack propagation. These results align with previous findings emphasizing the benefits of surface structuring in enhancing polymer composite performance [202].The combination of larger cross-sectional area, extended elongation before failure, and superior energy absorption capacities makes ribbed PP rebars a highly promising sustainable alternative for reinforcing applications in structures demanding high impact resistance and durability.

Table 4.2 and 4.3 and Figure 4.6 summarize the tensile behavior of recycled plastic rebars (RPR). In all diameter groups, polypropylene (PP)-based rebars exhibited superior mechanical performance compared to their high-density polyethylene

TABLE 4.3: Mechanical properties of recycled plastic rebars.

Sample	Max Load (kN)	Max Elongation (mm)	Energy Absorption (N-m x 10)	Max Stress (MPa)	Yield Load (kN)	Elongation at Yield (mm)	Energy Absorption up to Yield (N-m)	Toughness Index
Rebar Diameter (12 mm)								
Plain HDPE	1.2 ± 0.1 (6.2)	123.9 ± 6.2 (6.8)	8.4 ± 0.4 (11.9)	10.3 ± 0.5 (5.3)	0.7 ± 0.01 (2.1)	15.7 ± 0.8 (4.2)	6.9 ± 0.3 (8.1)	12.3 ± 0.6 (3.7)
Plain PP	2.0 ± 0.1 (7.2)	39.7 ± 2.0 (7.9)	5.6 ± 0.2 (10.5)	17.6 ± 0.9 (3.8)	1.0 ± 0.1 (7.8)	7.1 ± 0.4 (3.5)	4.0 ± 0.2 (8.0)	14.2 ± 0.7 (2.4)
Rib PP	1.7 ± 0.1 (7.2)	140.8 ± 7.0 (7.3)	19.6 ± 0.1 (13.5)	15.1 ± 0.8 (3.1)	1.1 ± 0.1 (8.6)	18.1 ± 0.9 (3.5)	13.0 ± 0.7 (7.7)	15.1 ± 0.8 (2.2)
Rib HDPE	1.7 ± 0.1 (4.2)	129.8 ± 6.5 (4.3)	19.7 ± 0.9 (11.2)	15.3 ± 0.8 (4.2)	1.3 ± 0.1 (17.1)	16.8 ± 0.8 (1.5)	14.0 ± 0.7 (5.9)	14.1 ± 0.7 (2.9)
Rebar Diameter (19 mm)								
Plain HDPE	3.4 ± 0.2 (5.2)	28.8 ± 1.4 (5.6)	5.9 ± 0.3 (10.2)	12.1 ± 0.6 (4.5)	1.7 ± 0.1 (27.1)	6.7 ± 0.3 (7.5)	6.6 ± 0.3 (9.5)	9.0 ± 0.5 (2.1)
Plain PP	4.9 ± 0.2 (3.2)	45.5 ± 2.3 (9.1)	16.5 ± 0.8 (11.4)	17.2 ± 0.9 (2.2)	2.3 ± 0.1 (3.1)	7.6 ± 0.4 (8.8)	10.2 ± 0.5 (9.5)	16.2 ± 0.8 (2.9)
Rib HDPE	4.2 ± 0.2 (7.2)	31.9 ± 1.6 (5.3)	8.9 ± 0.4 (9.9)	14.9 ± 0.7 (11.2)	2.1 ± 0.1 (3.1)	7.2 ± 0.4 (4.2)	8.7 ± 0.4 (8.7)	10.2 ± 0.5 (2.4)
Rib PP	6.6 ± 0.3 (4.2)	63.4 ± 3.2 (4.6)	32.6 ± 1.6 (5.9)	23.3 ± 1.2 (14.3)	3.4 ± 0.2 (7.1)	9.1 ± 0.5 (4.3)	18.1 ± 0.9 (3.9)	18.0 ± 0.9 (2.1)
Rebar Diameter (25 mm)								
Plain HDPE	3.0 ± 0.1 (6.2)	18.9 ± 0.9 (5.1)	4.0 ± 0.2 (3.9)	6.1 ± 0.3 (11.2)	2.3 ± 0.1 (8.2)	4.6 ± 0.2 (4.9)	6.3 ± 0.3 (3.9)	6.4 ± 0.3 (3.7)
Plain PP	8.0 ± 0.4 (3.2)	47.0 ± 2.3 (6.6)	25.6 ± 1.2 (17.9)	16.3 ± 0.8 (13.2)	4.1 ± 0.2 (4.6)	8.1 ± 0.4 (4.8)	18.7 ± 0.9 (2.8)	13.7 ± 0.7 (8.7)
Rib HDPE	9.3 ± 0.5 (2.2)	32.8 ± 1.6 (3.6)	20.5 ± 1.0 (11.9)	19.0 ± 1.0 (17.2)	4.3 ± 0.2 (4.1)	6.8 ± 0.3 (7.5)	16.0 ± 0.8 (3.4)	12.8 ± 0.6 (8.7)
Rib PP	12.2 ± 0.6 (9.2)	100.6 ± 5.0 (6.1)	101.6 ± 5.0 (13.9)	24.9 ± 1.2 (6.2)	7.1 ± 0.4 (6.1)	12.8 ± 0.6 (6.5)	52.6 ± 2.6 (5.6)	19.3 ± 1.0 (9.7)

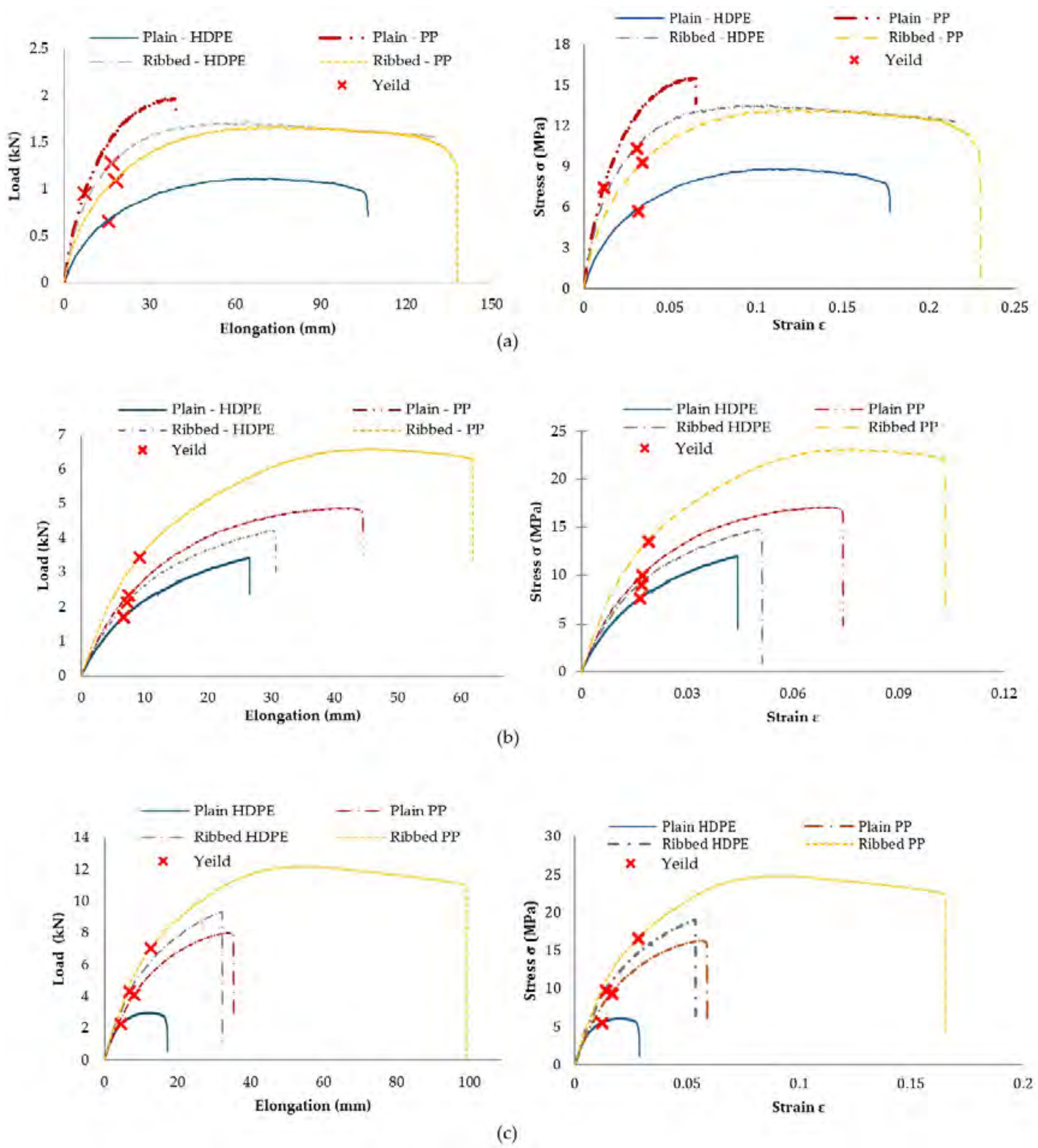


FIGURE 4.5: Load-elongation and Stress – Strain Behavior of (a) 12 mm (b) 19 mm (c) 25 mm Recycled Plastic Rebars.

(HDPE) counterparts, with ribbed PP rebars consistently achieving the highest values of maximum load, elongation, energy absorption, and toughness index. For the 12 mm diameter group, plain HDPE rebars displayed the lowest maximum load 1.2 kN and energy absorption 84.9 N-m, alongside a lower yield load 0.7 kN and energy absorption up to yield 6.9kN-mm.Conversely, ribbed PP rebars attained the highest elongation 140.8 mm and a substantially improved toughness index 15.1, underscoring the positive influence of ribbing and material choice. At 19 mm diameter, similar trends were observed. Ribbed PP rebars exhibited a maximum

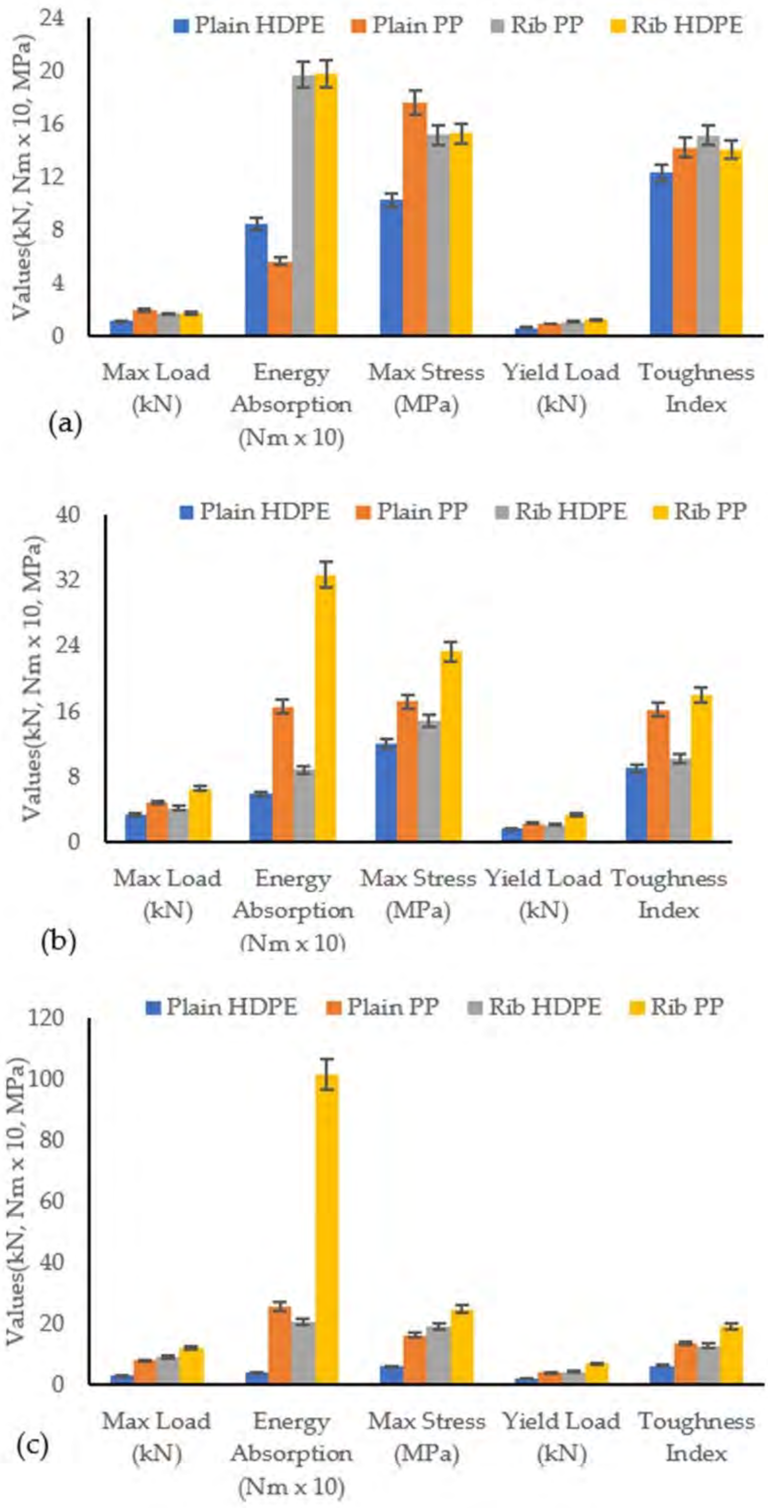


FIGURE 4.6: Maximum Tensile Stress, Tensile Energy Absorption and Tensile Toughness index of (a) 12 mm (b) 19 mm (c) 25 m Recycled Plastic Rebars.

load of 6.6 kN, a toughness index of 18.0, and the highest energy absorption up to yield 18.1 N-m, demonstrating a pronounced enhancement compared to plain rebars. The ductility, as measured by elongation at yield, remained relatively stable across configurations but was highest for ribbed PP rebars 9.1 mm. In the 25 mm diameter group, the mechanical advantage of ribbed PP rebars became even more pronounced. They achieved a maximum load of 12.2 kN, an elongation at failure of 100.6 mm, and a remarkable toughness index of 19.3. In contrast, plain HDPE rebars at the same diameter exhibited significantly lower values across all categories, including maximum load 3.0 kN and toughness index 6.4. Overall, the data indicate that increasing diameter generally enhanced the load-carrying capacity and energy absorption for all specimens; however, the degree of improvement was notably higher in PP-based rebars, particularly those with ribbed surfaces. Ribbing consistently contributed to improvements in both strength and toughness across all material types and diameters, validating the design strategy of incorporating surface structuring to enhance the mechanical performance of recycled plastic composites used for structural reinforcement [119].

4.3.1.2 Empirical Modelling for Max Load and Max Stress

The given set of behavior can be trended into empirical modelling by second degree polynomial equations for the given data for the values of each diameter of the rebar shown in Figure 4.7. The relationship between maximum load (P) and bar diameter (d) for recycled plastic rebars, including Plain-HDPE, Plain-PP, Ribbed-HDPE, and Ribbed-PP, is illustrated through second-degree polynomial fitting, following the general equation

$$P = ad^2 + bd + c \tag{4.1}$$

where P is the maximum load in kN, d is the diameter of the bar in mm, and a, b, and c are the quadratic, linear, and constant coefficients, respectively. For the materials studied, the quadratic coefficients (a) were determined as 0.0181 for Ribbed-PP, 0.0084 for Plain-PP, 0.0384 for Ribbed-HDPE, and -0.0303 for Plain-HDPE rebars. The corresponding linear coefficients (b) were 0.1370, 0.1505, -0.8339, and 1.2621, respectively, while the constant terms (c) were found to be -2.5392, -1.0306, 6.2057, and -9.6179, respectively. The positive values of the quadratic coefficients for Ribbed-PP, Plain-PP, and Ribbed-HDPE indicate that the maximum load capacity increases with diameter, whereas the negative quadratic coefficient for Plain-HDPE suggests a peak load at an intermediate diameter (around 19 mm),

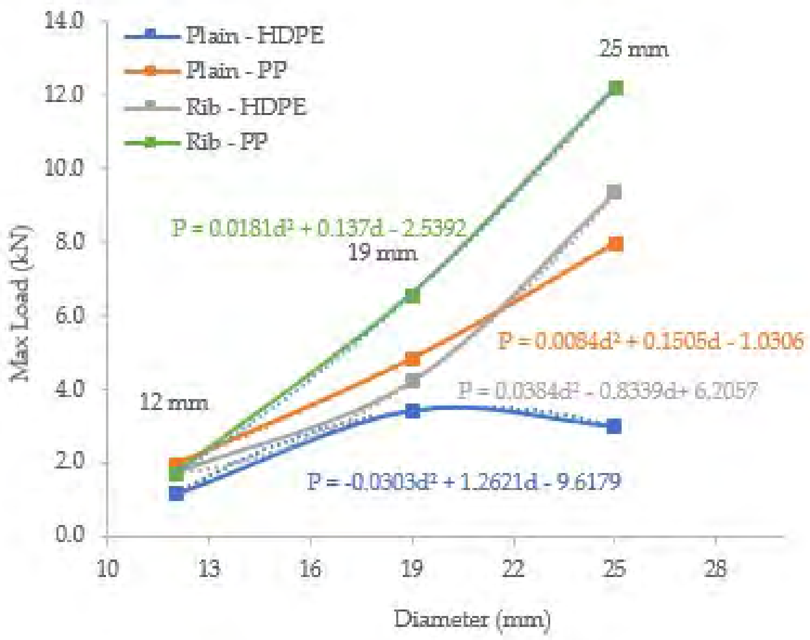


FIGURE 4.7: Empirical modelling for (a) Maximum Load (kN) for 12 mm, 19 mm, 25 m Recycled Plastic Rebars

followed by a decline at 25 mm[203]. Figure 4.8 shows the empirical relation of the maximum stress and diameter of the bar.

The relationship between maximum stress (σ) and bar diameter (d) for recycled plastic rebars, including Plain-HDPE, Plain-PP, Ribbed-HDPE, and Ribbed-PP configurations, is represented by second-degree polynomial fitting, following the general equation:

$$\sigma = ad^2 + bd + c \tag{4.2}$$

Where σ is the maximum stress in MPa, d is the bar diameter in mm, and a, b, and c are the quadratic, linear, and constant coefficients, respectively. The values obtained for the quadratic coefficient (a) are -0.0962, -0.0068, 0.0384, and -0.0692 for Plain-HDPE, Plain-PP, Ribbed-HDPE, and Ribbed-PP rebars, respectively. The corresponding linear coefficients (b) are 3.2382, 0.1515, -0.8339, and 3.3079, while the constant terms (c) are -14.714, 16.758, 6.2057, and -14.591 for the respective materials. The negative quadratic coefficients for Plain-HDPE, Plain-PP, and Ribbed-PP indicate a slight decrease or saturation in maximum stress at larger diameters, while the positive coefficient for Ribbed-HDPE suggests a consistent increase with diameter.

The fitted polynomial curves closely align with the experimental data points at 12 mm, 19 mm, and 25 mm diameters, illustrating the combined influence of material type and surface structuring on the stress-bearing capacity of recycled plastic rebars. The polynomial regression model was used to capture the relationship between rebar diameter and mechanical properties such as maximum load and tensile strength.

While the fitting offers a statistically valid representation, its practical utility lies in providing an early-stage estimation tool for designers and engineers. This model enables performance prediction for intermediate diameters not explicitly tested, supports trend visualization for future material scaling, and offers insight into how dimensional variations affect load-bearing capacity. Such modelling is especially valuable during the material optimization phase or for rapid assessment in pilot construction scenarios using recycled plastic reinforcement.

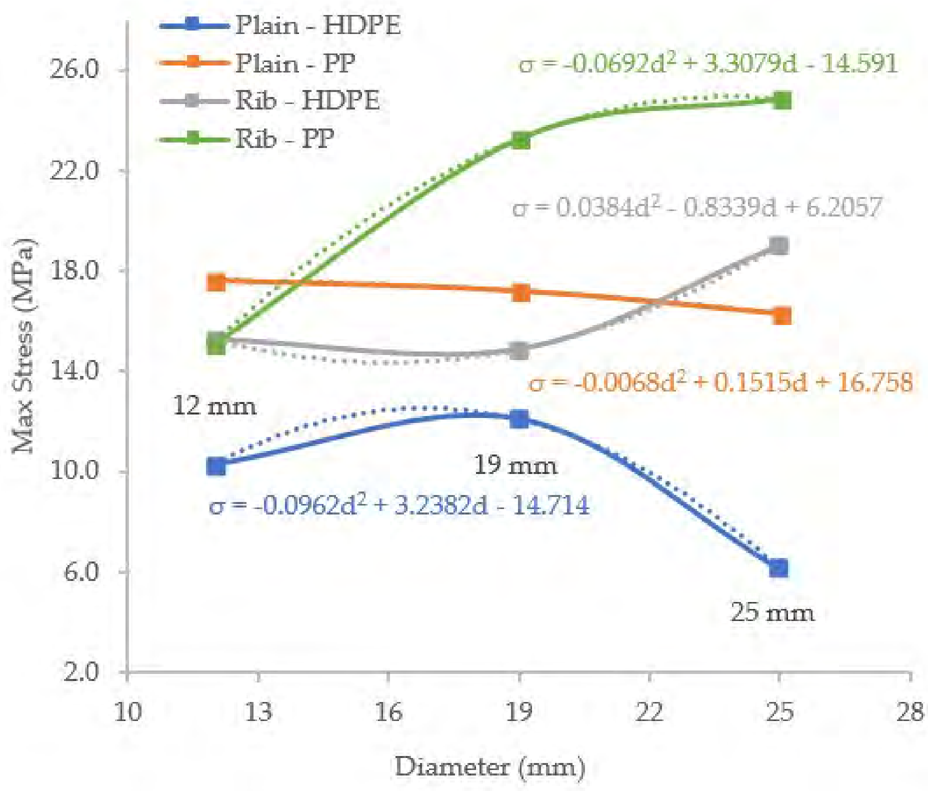


FIGURE 4.8: Empirical modelling for Maximum Stress (MPa) for 12 mm, 19 mm, 25 m Recycled Plastic Rebars

4.3.2 Microstructural Behviour

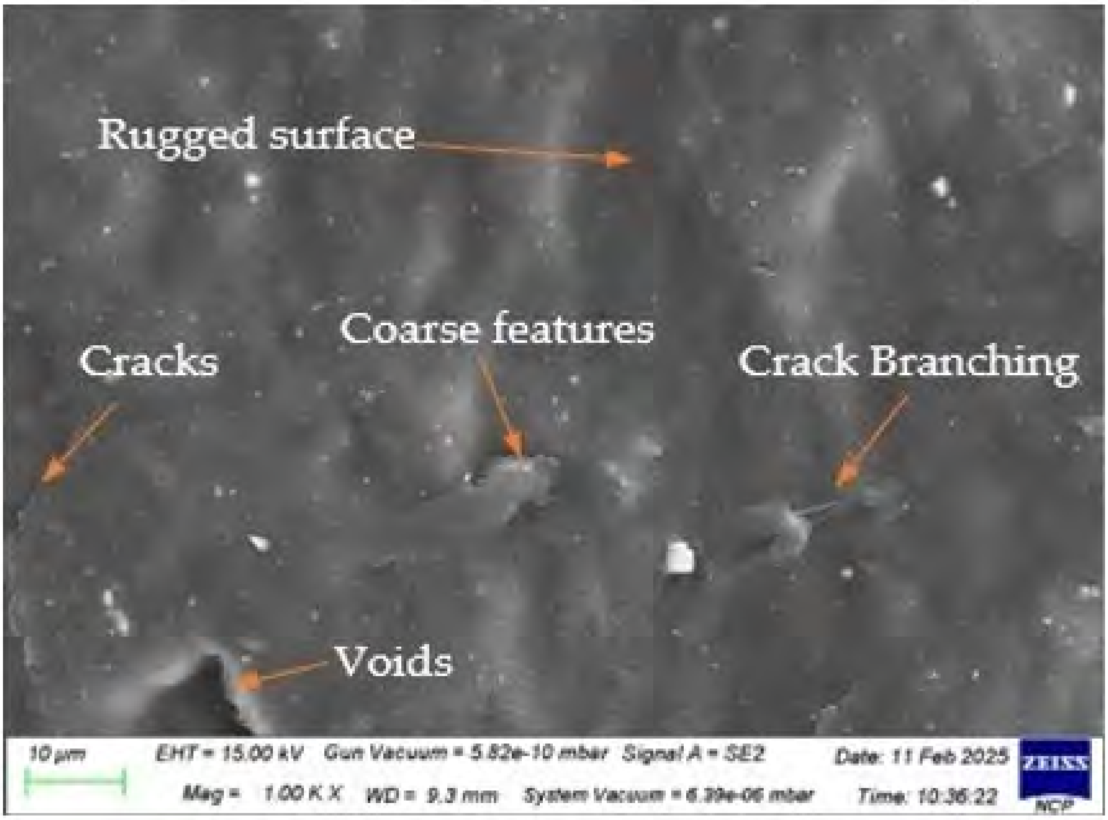
4.3.2.1 SEM Analysis

The SEM image of HDPE in Figure 4.10 reveals a highly irregular and rugged surface morphology, indicating that the material has undergone substantial mechanical stress or fracture. The surface appears fragmented with signs of delamination and flaking, suggesting localized failure zones. The texture is notably rough, featuring a mixture of sharp ridges and more rounded depressions, which points to a combination of abrasive and erosive degradation mechanisms. A prominent crack runs centrally across the image, branching into several fine, interconnected sub-cracks. The tortuous path of these cracks implies they propagated through a heterogeneous matrix, possibly containing multiple phases or inclusions. The sharp crack tips are indicative of brittle fracture behavior, which may have been initiated or accelerated by the material's internal structure. Scattered pores are visible, some of which are clustered near the crack regions. These voids likely acted as stress concentrators and played a role in the initiation and growth of cracks. Additionally, areas of particle pull-out and surface detachment are apparent, along with hints of embedded second-phase particles or inclusions that could have influenced crack path deflection and surface irregularity. Overall, this image suggests that the material experienced significant structural degradation due to combined mechanical and microstructural factors.

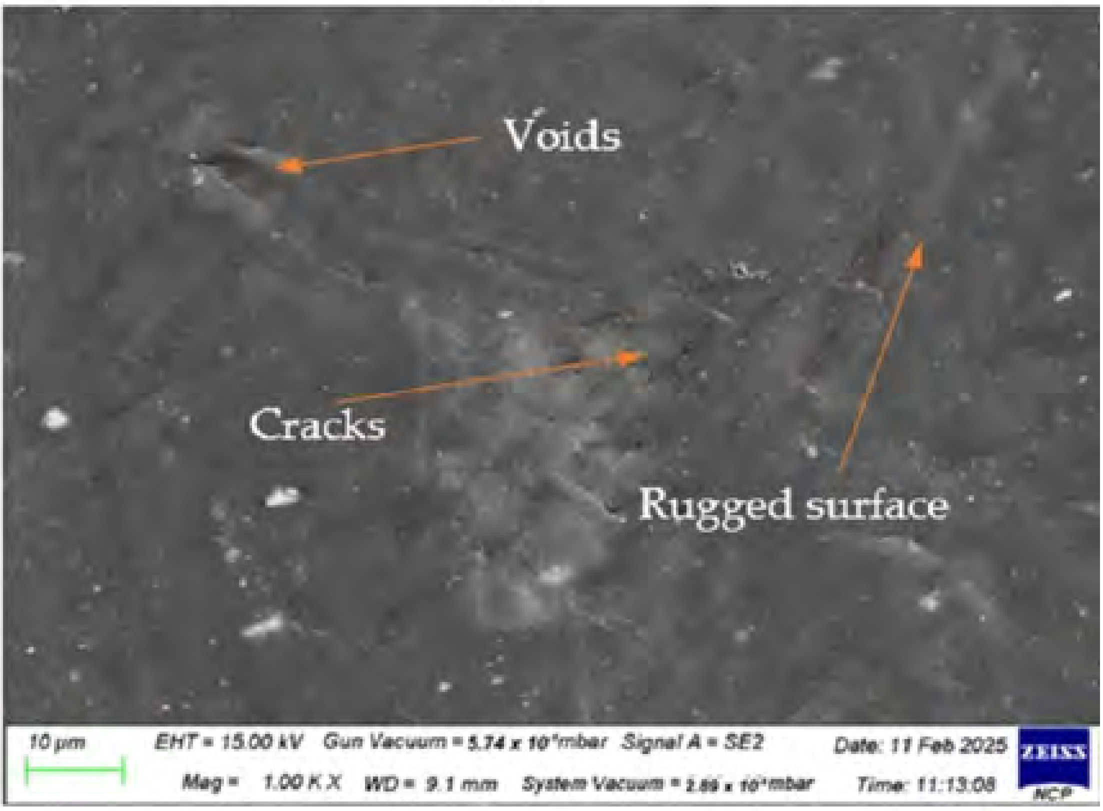
The SEM image displays a complex and uneven surface, characterized by substantial topographical variation. The morphology indicates a combination of coarse and fine features, with regions that appear compact and others that are more fractured and open. The texture is highly rugged, showing signs of intense surface disruption likely caused by mechanical loading or environmental exposure. Several long and interconnected cracks are observed traversing the surface. These cracks exhibit branching behavior and irregular paths, hinting at propagation through a structurally non-uniform or multiphase material. The edges of the cracks are sharp and clean, consistent with brittle fracture characteristics, although minor plastic deformation may be present at localized points where the material seems slightly smeared. Pores are visible across the image, particularly concentrated around crack intersections and defect-rich zones. These pores vary in size and appear to be both isolated and clustered, suggesting possible gas entrapment during processing or post-fabrication degradation. Additionally, surface spalling and material pull-out are noticeable, particularly in the upper and mid-regions of the image, rein-forcing the presence of mechanical damage.

The SEM image of PP exhibits a distinctly brittle fracture surface with radial crack propagation patterns, indicative of a stress concentration origin [203]. A circular fracture zone in the center of the image features multiple radiating cracks, suggesting a failure initiated by a point load or localized impact [204]. The overall morphology is smooth in the undamaged regions, contrasting sharply with the rough, fragmented zones around the crack front. The fracture pattern is dominated by trans granular cracking, evidenced by the uninterrupted cracks traversing through the material without significant deflection [205]. This crack morphology is characteristic of brittle failure, where the material lacks sufficient plasticity to arrest crack growth.

The well-defined crack tips and branching behavior further indicate that the crack growth was rapid and unstable. Such features are typically observed in polymer-based or composite materials under tensile stress conditions [203, 205]. Several pores and voids are distributed near the crack origin and along the radial fracture lines. These features likely served as crack initiation sites or weakened the local structure, facilitating crack propagation [205]. The relatively clean background and absence of significant particle pull-out suggest a uniform matrix composition in this region, with minimal filler reinforcement or secondary phase presence. Overall, the image illustrates a classic case of brittle failure influenced by stress concentration and intrinsic material weakness. The presence of radially expanding cracks and micro-voids reflects a sudden fracture event likely exacerbated by pre-existing flaws or environmental embrittlement [204]. The fracture behavior is predominantly transgranular, as the cracks pass directly through the bulk of the material without significant deviation or deflection. This is characteristic of brittle materials, particularly those with low fracture toughness and high stiffness [205].

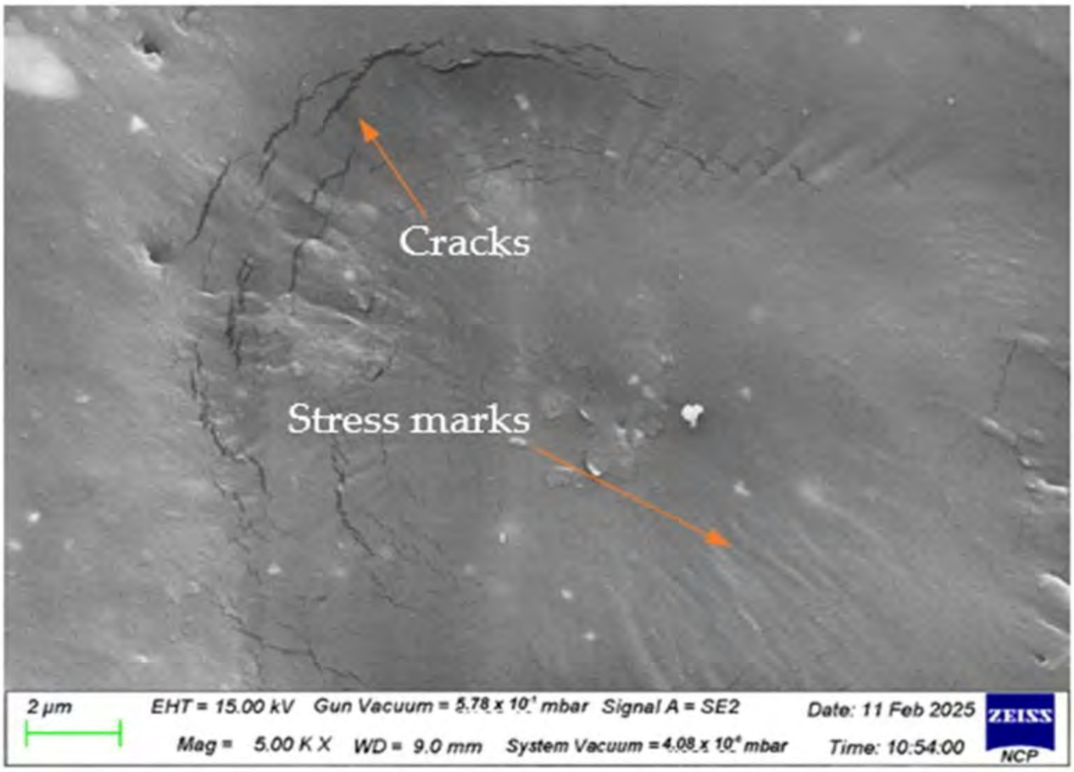


(a)

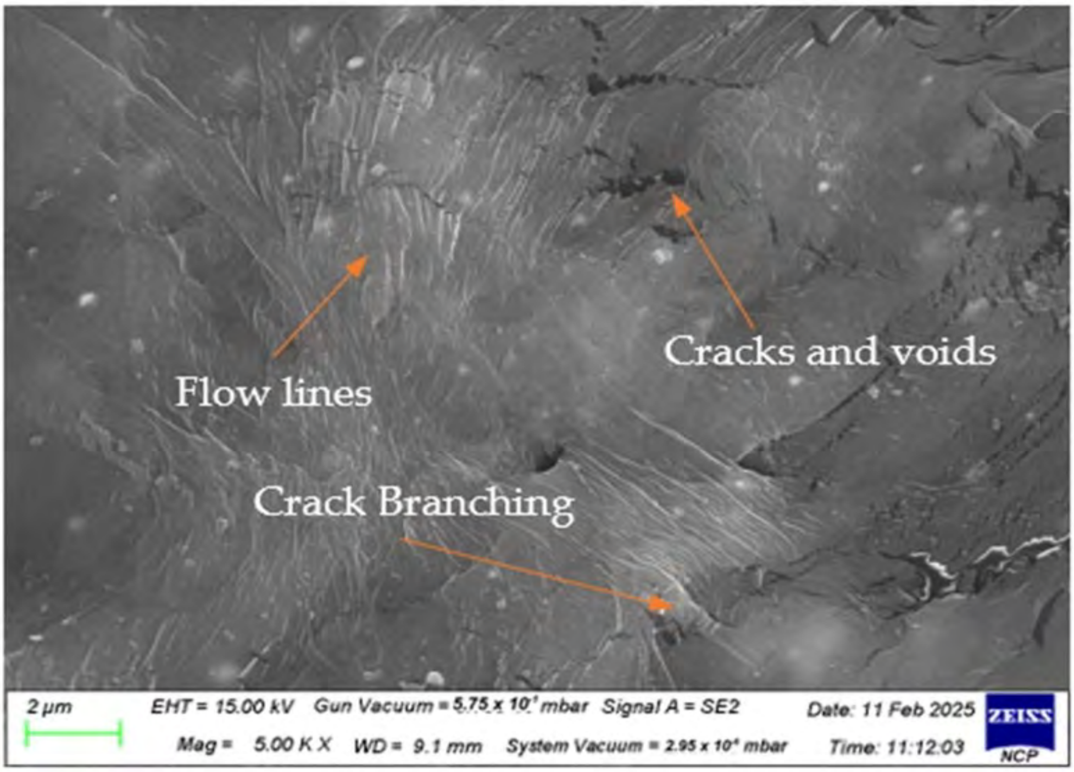


(b)

FIGURE 4.9: SEM images of failure surface (a) HDPE (25mm Plain Rebar) (b) HDPE (25 mm Ribbed Rebar) (c) PP (25 mm Plain Rebar) (d) PP (25 mm Ribbed Rebar) continued ...



(c)



(d)

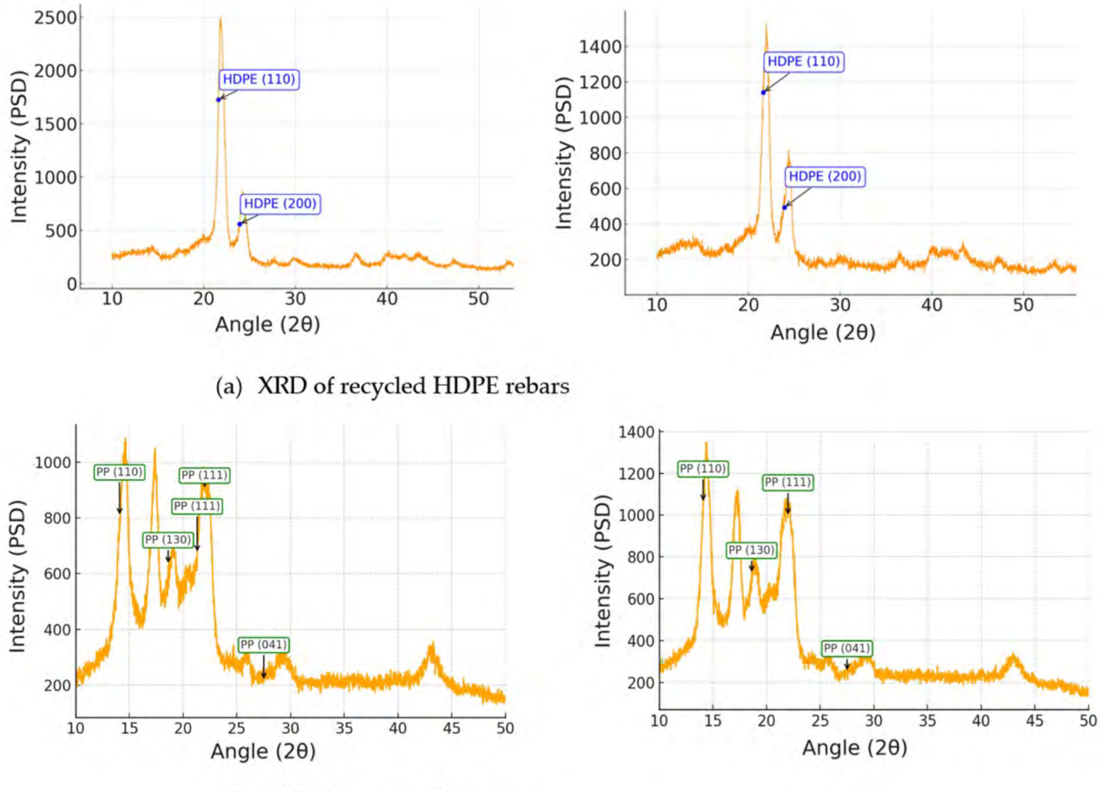
FIGURE 4.9: SEM images of failure surface (a) HDPE (25mm Plain Rebar) (b) HDPE (25 mm Ribbed Rebar) (c) PP (25 mm Plain Rebar) (d) PP (25 mm Ribbed Rebar)

The sharp and clean crack edges, coupled with the absence of plastic flow lines or necking, reinforce this interpretation. Additionally, the crack network displays tortuosity and branching, suggesting a heterogeneous internal structure or the presence of micro-defects that influenced crack trajectory [206]. Pores and voids are visible throughout the image, particularly along the crack path. These features act as stress risers and contribute to premature crack initiation and propagation [205]. In some zones, fragmented material and evidence of particle pull-out can be observed, which further signifies localized failure due to inter facial weaknesses or the breakdown of bonding between matrix and filler phases [204]. Overall, the image portrays a material that failed under brittle fracture conditions, influenced by microstructural heterogeneity and stress concentration points. The features suggest that the material lacks sufficient ductility to absorb applied energy, leading to catastrophic failure upon crack initiation [203].

4.3.2.2 XRD Analysis

The XRD spectra in Figure 4.11 (a) depict polymeric samples with distinct crystallinity features of High-Density Polyethylene (HDPE). Both spectra exhibit the characteristic HDPE diffraction peaks at approximately 21.6° and 23.9° 2θ, corresponding to the (110) and (200) crystallographic planes, respectively. In the top spectrum, these peaks are sharp and intense, indicating a high degree of crystallinity and structural order, suggesting the sample HDPE was minimally processed. In contrast, the bottom spectrum shows broader and less intense peaks, implying reduced crystallinity due to thermal degradation and mechanical processing.

The XRD spectra shown in Figure 4.11 (b) illustrate the crystallographic behavior of polypropylene (PP) in two different samples. Both charts reveal prominent diffraction peaks at approximately 14.1°, 16.8°, 18.6°, 21.3°–21.9°, and 25.5° 2θ, corresponding to the PP crystallographic planes (110), (040), (130), and (111)/(041), respectively. The upper spectrum features relatively sharp and distinct peaks, indicating a well-ordered crystalline structure typical of isotactic polypropylene.



(b) XRD of recycled PP rebars

FIGURE 4.10: XRD images of (a) Waste HDPE rebars and (b) PP rebars.

The presence of multiple well-defined peaks suggests high purity and minimal structural disruption. In comparison, the lower spectrum also displays the same PP peaks, but with slightly sharper intensities and a marginally broader baseline, which may suggest subtle differences in molecular orientation, degree of crystallinity, or presence of minor additives or processing effects. Overall, both samples confirm the presence of crystalline PP, with the second spectrum potentially representing a purer or less processed form [119]. The overlapping nature of the peaks may also indicate minor polymorphic transitions or a heterogeneous polymer blend, as similarly reported in studies investigating nucleating agents and crystallization kinetics in polypropylene systems [119, 120].

These findings are critical when evaluating the structural integrity of recycled polypropylene used in composite or construction applications, where crystallinity significantly influences material strength and durability. Overall, the XRD analysis provides robust evidence of the semicrystalline nature of both HDPE and PP within the respective samples. It also highlights the subtle structural variations that can arise due to differences in processing, recycling stages, or additives. XRD patterns of recycled (a) HDPE and (b) PP showing characteristic Bragg reflections corresponding to the α-orthorhombic and α-monoclinic crystalline phases, respectively. The main peaks—HDPE (110), (200) and PP (110), (130), (111), (041)—confirm the retention of semi-crystalline order after mechanical recycling, as governed by Bragg's law $n\lambda = 2d \sin\theta$ [207].

Such crystallographic evaluations are vital for assessing the suitability of these materials in advanced applications such as polymeric reinforcement in construction or infrastructure development, particularly when derived from post-consumer waste streams [121].The mechanical property comparison in Figure 4.6 strongly aligns with the structural observations from SEM and XRD analyses. Ribbed PP rebars consistently exhibit the highest values in maximum load, stress, and energy absorption, especially evident in the 25 mm samples, correlating with their higher crystallinity observed in XRD and brittle fracture morphology in SEM. Conversely, HDPE samples, particularly the plain ones, show moderate strength but superior elongation and toughness indices, which is supported by ductile fracture patterns and moderate crystallinity, confirming their suitability for ductility driven, light load applications.

The distinct mechanical responses of recycled HDPE and PP rebars are strongly governed by their microstructural characteristics, as evidenced by SEM and XRD analyses. XRD results confirmed that both polymers are semi-crystalline, with PP showing sharper and more intense diffraction peaks indicative of higher crystallinity, which explains its superior stiffness and initial strength but also its tendency toward brittle fracture. In contrast, HDPE exhibited lower crystallinity and a higher amorphous fraction, enabling greater chain mobility and plastic deformation, reflected in its higher strain-to-failure and toughness.

SEM fracture surfaces further reinforced this structure–property relationship: PP displayed granular, cleavage-like features with limited evidence of plastic flow, characteristic of rapid brittle failure, while HDPE revealed fibrillated surfaces with drawn polymer strands, indicative of significant ductile yielding before rupture.

The presence of voids and inclusions acted as stress concentrators in PP, accelerating crack initiation, whereas the relatively uniform morphology of HDPE facilitated more homogeneous deformation. Collectively, these observations demonstrate that the balance between crystallinity, morphology, and defect distribution directly dictates the macroscopic behavior of recycled polymer rebars, providing a clear framework to interpret their performance and to guide future modifications aimed at improving toughness and durability.

4.4 Proposed Practical Utilization of Developed Rebars for Elements Under Light Loads

This study presents a novel approach to advancing sustainable development in construction by repurposing post-consumer plastic-waste, specifically high-density polyethylene (HDPE) and polypropylene (PP), into low strength recycled plastic rebars (RPRs) intended for elements subjected to light loads. Utilizing mechanical extrusion, plain and ribbed rebars were fabricated in diameters of 12 mm, 19 mm, and 25 mm, specifically designed for mortar-free construction systems that eliminate the need for cementitious bonding agents. Material characterization through XRD, and SEM confirmed the structural integrity of the recycled polymers, revealing ductile fracture modes in HDPE and comparatively brittle behavior in PP.

Addressing critical gaps in Pakistan's recycling infrastructure, this research offers a scalable, high-value application for plastic waste by converting it into durable, load-bearing structural elements. Practical application areas for these mortar-free systems include non-load bearing partition walls, boundary walls, pedestrian pathways, lightweight modular shelters, and prefabricated furniture where moderate strength and high ductility are essential [142].

While PE and PP are prone to degradation through UV exposure and environmental aging, our previous study [119] demonstrated that such degraded plastics can still be mechanically recycled for structural use. Building on that work, the current study focuses on transforming unsorted HDPE and PP waste into full-section rebars, showing that even moderately degraded plastics can be repurposed for light-load construction, supporting circular economy goals.

The introduction of ribbed profiles significantly enhanced stress distribution and mechanical interlocking, critical for ensuring stability in mortar-free construction. Ribbed PP rebars demonstrated superior mechanical properties, achieving higher tensile strengths, energy absorption, and toughness indices across all tested diameters. Empirical modeling using second-degree polynomial fitting successfully captured the relationship between bar diameter and mechanical behavior, confirming their suitability for scalable applications. These mechanical advantages make recycled plastic rebars particularly attractive for dry-joint modular systems, seismic-resilient structures, pre-fabricated wall panels, modular floor systems, and roof trusses, especially in construction methodologies that avoid the use of wet concrete or mortar. Their inherent ductility and capacity for energy dissipation also make them ideal for rapidly deployable infrastructure in disaster-prone or resource-constrained regions where quick, mortar free assembly is necessary. While the developed recycled plastic rebars exhibit promising mechanical and structural properties, their application is presently limited to light-load scenarios.

These include non-critical infrastructure such as footpaths, modular shelters, fencing, and boundary walls. The rebars are not yet suitable for load-bearing structural applications where high compressive and flexural demands exist. Moreover, several challenges must be addressed for large-scale adoption. These include thermal deformation under elevated temperatures, long-term creep behavior, bonding performance with concrete in hybrid applications, and the lack of recognized design codes for plastic-based reinforcement. Commercialization also requires scalable production processes, material consistency across waste streams, and alignment with national construction standards. Addressing these factors will be essential to transition from pilot-scale research to practical implementation. From a sustainability perspective, the mechanical extrusion of municipal plastic-waste into functional rebars represents a significant advancement toward low-carbon, mortar-free construction practices.

Unlike previous studies that confined recycled plastics to secondary roles, this work establishes recycled HDPE and PP as primary structural reinforcements capable of supporting modular, dry-assembly construction techniques. The energy-efficient and scalable extrusion process minimizes environmental impacts associated with both plastic disposal and cement production, addressing two major sources of carbon emissions simultaneously. The successful development and validation of RPRs across multiple diameters and surface configurations not only promote material-efficient strategies but also set a new benchmark for integrating recycled materials into structural applications. By enabling durable, ductile, and eco friendly mortar-free construction systems, this research supports the broader vision of sustainable urbanization, circular economy adoption, and resilient infrastructure development[119].

4.5 Summary

This study introduces a novel about the use of municipal plastic waste HDPE and waste PP as stand alone structural rebars for mortar-free construction. Unlike previous works limited to fillers, this research develops and tests full-scale recycled plastic rebars. A total of 48 plain and ribbed samples in three diameters were evaluated using ASTM A615 guidelines. FTIR, XRD, and SEM analyses confirmed the polymers' chemical integrity, crystallinity, and fracture modes. Recycled plastic rebars transfer stress through mechanical interlock the rebars can be rolled up to desired length. Although laps can be provisioned and studied in future research.The bend test as per ASTM was irrelevant. However, in recent studies, bond tests have been performed. The rebars are being proposed for mortarless construction [118]. The products cannot replace steel with reinforced concrete but provide sustainable alternatives for secondary and light-duty elements.The mechanical performance of the recycled-plastic rebars was benchmarked against conventional and natural reinforcements. While steel and GFRP exhibit higher tensile strength (400–1000 MPa) and stiffness (40–200 GPa), the recycled rPP and rHDPE rebars developed in this study achieved 16–21 MPa strength and 1.8–2.0

GPa modulus, comparable to wood–plastic composites and approximately 15–25 percent of bamboo performance. Their high ductility, corrosion resistance, and recyclability make them suitable for light-load, non-primary applications such as modular panels and boundary walls. Further improvement in material by using admixtures will enhance the performance for use in other structural elements. To achieve desired reinforcement ratio against strength. The number of rebars will be more as compared to steel rebars. The same has to be quantitatively evaluated in future studies.The development of empirical relationships between rebar diameter, tensile capacity, and material behaviour has been contextualized with studies on recycled polymer composites and predictive modelling approaches. The revised discussion now links observed mechanical responses to microstructural characteristics, such as crystallinity and fracture morphology, explaining variations in strength and toughness with geometry and material type. Supporting literature has been integrated to validate the adopted polynomial fitting approach and the observed trends, thereby enhancing the scholarly depth and aligning the interpretations with current research on recycled polymer materials. [208, 209]The findings establish a sustainable, low-impact alternative to other rebars in the industry, advancing circular economy goals in the construction sector. The following conclusions are drawn from the study.

- Ribbed polypropylene (PP) rebars displayed the highest mechanical performance among all samples, achieving a maximum load of 12.2 ± 0.6 kN and a toughness index of 19.3 ± 1.0. The inclusion of ribs enhanced stress distribution, delaying failure and improving ductility, making ribbed PP the most effective option for light-load reinforcement Products are recommended for non-primary components under service loads ≤ 1 kN/m^2 such as panels, fences, and roofing sheets.
- SEM analysis revealed brittle fracture patterns in both polymers. HDPE exhibited irregular fracture surfaces with signs of crack branching and delamination, while PP showed smoother, trans granular fractures, indicating rapid failure under localized stress.
- XRD analysis verified the semi crystalline structure of both materials. HDPE showed clear peaks at $2\theta \approx 21.6°$ and $23.9°$, and PP exhibited distinct peaks

near 14.1°, 16.9°, and 18.6°, reflecting structural differences influenced by polymer type and processing conditions.

- Regression modelling showed positive load trends for ribbed PP and HDPE rebars across increasing diameters, while plain HDPE showed reduced performance at larger sizes. These trends highlight the effect of geometry and material on tensile behavior.
- The study successfully demonstrated that recycled HDPE and PP can be processed into structural rebars suitable for non-critical, mortar-free construction systems. Their application in boundary walls, partition panels, and modular systems offers a sustainable alternative to conventional materials, promoting waste valorization and circular economy practices. Future research should focus on strain-based testing, polymer-specific standards, and durability studies to enhance applicability.

Although the above experiments confirm the feasibility of using recycled plastics in construction, challenges such as material contamination and quality inconsistency must be addressed. Advanced sorting and purification techniques are essential to ensure uniformity in recycled inputs. Future research should explore a broader range of modifications like polymer mixes, rib arrangements and construction applications items, including interlocking blocks, corrugated sheets, and beams for mortar-free systems. Evaluating their static, dynamic, and thermal performance will be key to validating their structural reliability. This innovative method contributes to circular economic objectives by reducing plastic-waste and offering an alternative to traditional materials like steel. The research also opens prospects for future work, including the optimization of composite formulations, durability testing under environmental exposures, and scaling up production for full scale structural trials.

SDG 9 – Industry, Innovation, and Infrastructure – The research strongly aligns with SDG 9 by introducing an innovative pathway for transforming municipal plastic waste into structural rebars suitable for light-load applications in the construction industry. Through the use of mechanical extrusion and empirical modeling, the study develops full-scale recycled plastic rebars from HDPE and polypropylene, diverging from traditional reliance on steel and fiber-reinforced composites. This not only showcases material innovation but also enhances the infrastructure sector by offering lightweight, corrosion-resistant, and low-cost alternatives for boundary walls, partition panels, and mortar-free construction. By addressing the challenges of standardization and material consistency, the study advances sustainable industrial practices and promotes scalable, eco-efficient infrastructure solutions that support circular economy objectives.

Chapter 5

Multiscale Evaluation of Recycled Plastic Corrugated Panels for Sustainable Construction

Related Article

1. **Das, A. J.** and Ali, M. (2025). "Multiscale Evaluation of Recycled Plastic Corrugated Panels for Sustainable Construction". Buildings 15(14), 2423. https://doi.org/10.3390/buildings15142423
2. **Das, A. J.** and Ali, M. (2021).“An overview on different corrugated sheets from manufacturing to housing element” *In proceedings of International Conference on Advances in Engineering, Architecture Science and Technology, Turkey (15th – 17th December 2021)*
3. **Das, A. J.** and Ali, M. (2022). “Flexural Capacity of Recycled Plastic Corrugated Sheet” *In proceedings of 1st International Conference on Advances in Civil and Environmental Engineering, University of Engineering and Technology Taxila, Pakistan. (22nd and 23rd February 2022)*

5.1 Background

This research offers a significant contribution to the sustainable transformation of plastic waste by demonstrating the structural and functional viability of recycled rHDPE and rPP corrugated panels in construction applications [210]. Unlike conventional approaches that often restrict recycled plastics to non-structural uses, this study provides empirical validation for their performance under flexural, impact, dynamic, and prototype loading conditions. The comprehensive methodology spanning ASTM-standard mechanical testing [211], resonance based dynamic analysis, and microstructural assessments via XRD and SEM-EDS, confirms that recycled polymers retain sufficient mechanical integrity and crystallinity for use in modular building elements. This work provides a combined quantitative and qualitative evaluation of recycled HDPE and PP under flexural and impact loading conditions. Recycled PP retained over 50% of its flexural strength after impact, compared to approximately 28% for HDPE, corresponding to the relationship described by the derived empirical equation. Qualitative observations further confirmed rPP's greater toughness and deformation capacity, supporting its use in impact-sensitive structural applications. In the prototype slab, the ability of these recycled panels to resist water ingress, withstand service loads up to 1.86 kN, and exhibit material-specific damping and energy absorption profiles positions them as practical, eco efficient alternatives for roofing and walling systems. At 1.86 kN and 27 mm deflection (L/60), the prototype complies with L/150–L/240 service limits for lightweight roofing; additional stiffness may be achieved with deeper. This work not only advances engineering applications of recycled plastics but also directly supports global sustainability goals by enabling circular economic solutions in the built environment.

5.2 Experimental Program

5.2.1 Raw Materials

The plastic waste utilized in this study was systematically sourced from post-consumer municipal solid waste (MSW), with a targeted emphasis on end-of-life automotive components such as bumper covers and underbody shields, recognized as rich sources of thermoplastics. These waste streams were previously validated for structural material recovery in earlier studies, including the methodology outlined in previous research [210], which demonstrated an efficient material recovery pathway for construction applications. A detailed manual sorting protocol was followed to isolate recyclable thermoplastics, specifically high-density polyethylene

(HDPE) and polypropylene (PP), commonly used in automotive and packaging sectors due to their favorable mechanical and environmental profiles [158, 176].

The process involved removal of heterogeneous contaminants, such as metals, multilayer laminates, paper, and organic residues, to enhance the feedstock purity. The cleaned plastics were washed thoroughly using a mild alkaline solution and dried at ambient conditions to prevent thermal degradation during reprocessing. Subsequently, the materials were mechanically shredded and pelletized. Distinct coloration was used to identify the polymer types, dark grey pellets for HDPE and blue pellets for PP, as established in earlier lab scale documentation [210].

FIGURE 5.1: Recycling of Waste plastic to form pallets of HDPE and PP

These pellets were employed as input for extrusion-based manufacturing of composite sheets and rebars. Special attention was given to the extrusion of PP, which demanded tighter process control due to its sensitivity to shear and thermal fluctuations [212]. The extrusion parameters, including temperature (optimized between 150–170), screw speed, and material feed ratios, were finely tuned to achieve homogeneous melt flow and ensure consistent mechanical performance of the recycled products. This collection and synthesis protocol demonstrates the scalability of a sustainable recycling framework for structural applications, aligning with global circular economy goals [176].

The process of converting post-consumer plastic waste into pallets is systematically represented in Figure 5.1. These pellets were utilized as feedstock in an extrusion system, where they were melted and directly injected into a custom-fabricated steel mold designed with a corrugated profile. Upon cooling and demolding, the process yielded durable corrugated plastic sheets in respective polymer colors. This method not only enables efficient material recovery but also demonstrates a sustainable approach to transforming municipal plastic waste into practical construction components.

5.2.2 Preparation of Samples

5.2.2.1 Preparation of Corrugated Panel

The development of Recycled Plastic Corrugated Panels (RPCP) was achieved using a controlled thermomechanical extrusion and molding process. Recycled HDPE and PP pellets, prepared from sorted municipal plastic waste, were first introduced into a single screw extrusion unit equipped with a temperature controlled barrel. The processing temperature was maintained between 150 °C and 170 °C, depending on the polymer type, to achieve a consistent molten flow without initiating thermal degradation [210].

At the extrusion outlet, a custom-engineered steel nozzle was affixed, which directed the hot, viscous polymer melt into a precision-fabricated steel mold featuring a cycloidal wave profile (Figure 5.2). This mold was designed to replicate the geometrical features of standard corrugated roofing sheets. As shown in Figure 5.2(a), the mold was securely clamped to a robust steel platform and filled directly from the nozzle under manual or semi-automatic control.

To ensure proper compaction and profile conformance, the mold cavity was preheated to approximately 80–100 °C, minimizing thermal shock and promoting uniform filling. Once the mold was filled with molten polymer, it was sealed and allowed to cool under ambient or assisted air-cooling conditions.

The dwell time for cooling was maintained at 15–25 minutes, depending on panel thickness and environmental factors.

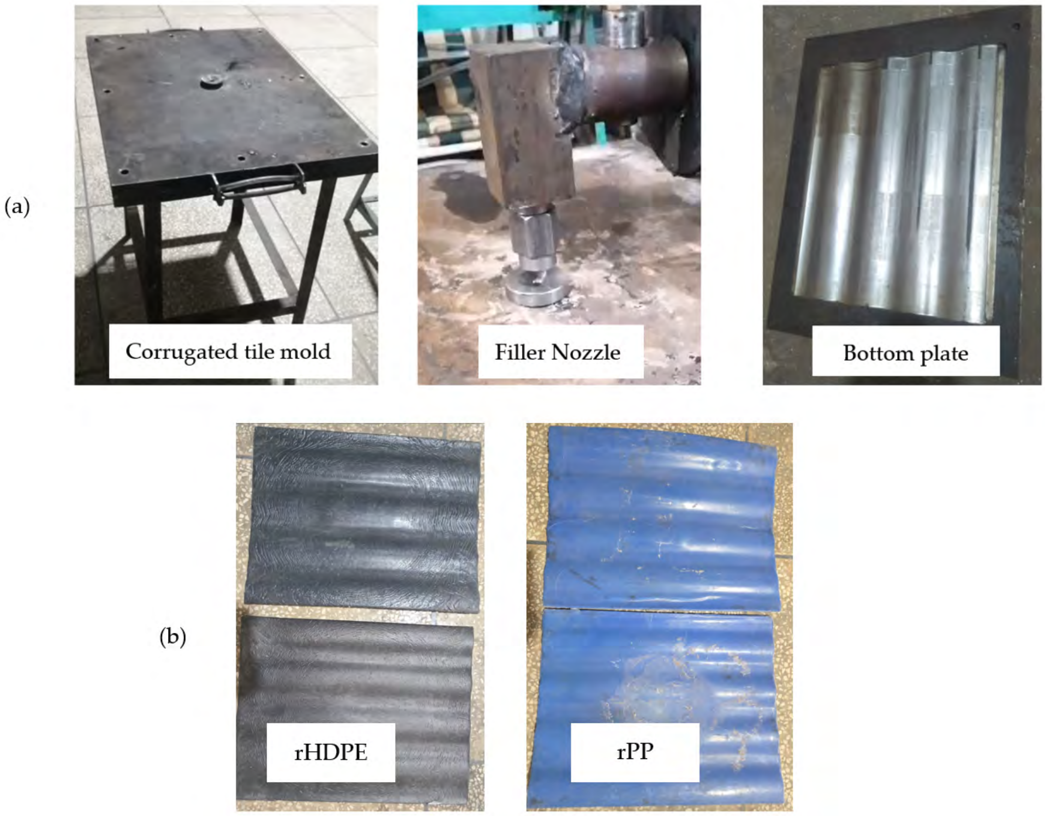


FIGURE 5.2: (a) Components of the Molding Assembly for Fabrication of Recycled Plastic Corrugated Sheets (b) molded recycled plastic corrugated panels produced from rHDPE and rPP materials.

Upon cooling, the mold was carefully opened, and the formed corrugated panel was demolded, exhibiting a stable profile with minimal warping or shrinkage. This direct mold-filling extrusion method allowed for the efficient and repeatable production of RPCPs with consistent dimensional accuracy, surface finish, and mechanical integrity, demonstrating the feasibility of manufacturing lightweight roofing solutions from post-consumer recycled plastics. The fabricated corrugated panel had standardized final dimensions of $600 \times 450 \times 12$ mm as shown in Figure 5.2(b). These panels were produced solely from post-consumer recycled HDPE or PP, with no incorporation of virgin polymers or reinforcing fibers, thereby reinforcing the principles of a closed-loop recycling approach [176]. The extrusion and molding setup employed in this process aligns with previously established methodologies for recycled plastic production [156] and was operated manually with strict quality control measures to ensure material consistency and to minimize environmental emissions during fabrication.

5.2.2.2 Preparation of Prototype Slab

To assess real-world applicability, a prototype slab platform measuring 1.63 m × 1.6 m was constructed using corrugated panels fabricated from recycled high-density polyethylene (rHDPE). These Recycled Plastic Corrugated Panel (RPCP) were specifically prepared to interlock through an overlapping joint system. Each panel was machined to include edge cuts designed to provide a consistent 50 mm overlap, ensuring both dimensional continuity and load transfer integrity across panel seams [158, 162].

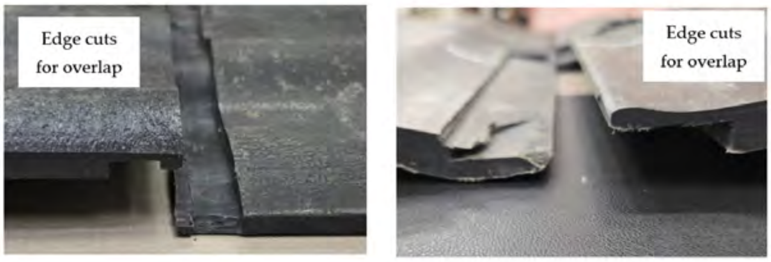


FIGURE 5.3: Edge modifications in recycled plastic corrugated sheets overlapping joints for full-scale slab assembly.

As depicted in Figure 5.3, special attention was given to the shaping of the panel edges, enabling a snug and flush fit. This overlapping configuration not only minimized potential gaps that could weaken the system under load but also contributed to enhanced water resistance and structural coherence [177]. The precision in edge preparation played a crucial role in emulating real-life slab assemblies, thus allowing for accurate mechanical and impact performance testing of the composite assembly.

5.2.3 Corrugated Panels Test Procedure

Table 1 presents a summarized outline of the experimental methods used to evaluate recycled plastic roofing panels, along with relevant standards and applications. Each test, mechanical, structural, or durability-focused, assesses key performance attributes such as strength, stiffness, impact resistance, and waterproofing.

TABLE 5.1: Experimental Methods, Standards, and applicability

Specimen	Test Type	Applicability	Reference
Corrugated Panel	Flexural Test	Evaluate load-carrying capacity and comparative stiffness of rHDPE and rPP corrugated panels	[205]
	Dynamic Resonance	Assess out-of-plane stiffness and damping behavior of rHDPE and rPP roofing sheets	[213]
	Vertical Impact Test	Investigate dynamic impact resistance and crack development for vertical use such as claddings etc.	[214]
	Horizontal Impact	Investigate dynamic impact resistance and crack development for horizontal use such as roof etc.	[215]
	XRD Analysis	Verified post-load crystallinity retention in rHDPE and rPP corrugated samples	[216]
	SEM–EDS Analysis	Characterized homogeneity, dispersion, and micro-defects in recycled plastic-based panels	[217]
Prototype Slab	Flexural Test	Full-scale slab (1.63 $\times$ 1.6 m, 12 mm) test for load-bearing capacity, deflection profile, and failure mode	[218]
	Water Leakage Test	Waterproof performance using 6-hour custom ponding test, aligned with metal roof static water penetration methods	[219]

To maintain consistency in comparing rHDPE and rPP panels, all samples were manufactured with uniform cross-sectional profiles, controlled extrusion temperatures, and standardized cooling parameters. Mechanical testing adhered strictly to ASTM procedures with consistent span lengths, support setups, and loading rates. This controlled approach prioritized material-driven assessment; however, future research could incorporate solid block testing to enhance cross-validation of component-level performance.

5.2.3.1 Dynamic Elastic Property Evaluation Procedure for Corrugated Panels

The dynamic mechanical characterization of the recycled plastic corrugated panel (RPCP) was carried out in accordance with ASTM E1876-15, which outlines the impulse excitation technique (IET) for determining the dynamic elastic properties of materials, as shown in Figure 5.4 [220]. Rectangular specimens of rHDPE and rPP-based corrugated panels were prepared with uniform dimensions and supported in a free-free condition to minimize boundary constraints during vibration. A calibrated impact hammer was used to excite the specimens with a light mechanical tap, and the resulting vibrational response was captured using a precision microphone or piezoelectric accelerometer placed at an optimized distance [178].

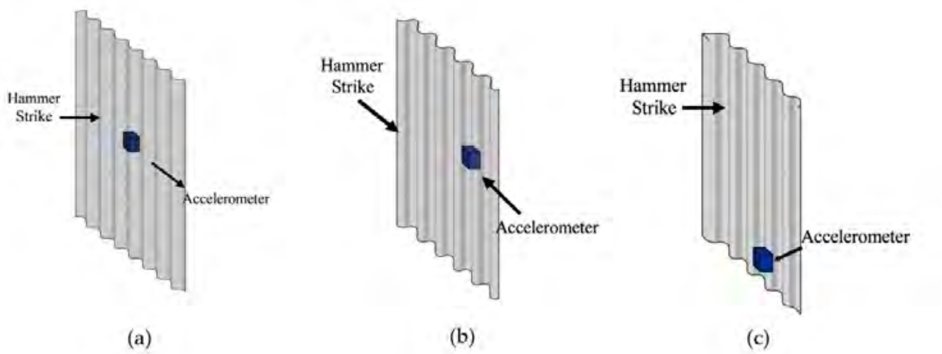


FIGURE 5.4: Schematic representation of impact response and damping behavior through (a) longitudinal, (b) In Plane, and (c) Out of Plane resonance frequencies on corrugated sheets.

The acquired time-domain signals were processed through a data acquisition system and transformed into frequency-domain data using Fast Fourier Transform

(FFT) to identify the natural resonance frequencies of the samples [212]. Specifically, three fundamental resonance modes were identified for each panel type: longitudinal mode (RFL), in-plane flexural mode (RFF(IP)), and out-of-plane flexural mode (RFF(OOP)). From these resonance frequencies, the Dynamic Elastic Moduli (DEM) were calculated using the mass, dimensions, and resonance equations defined in ASTM E1876 [221]. In addition, the damping ratio (ξ) was estimated by analyzing the decay of the resonant vibration peaks, providing insight into the energy dissipation characteristics of the materials [220, 222].

5.2.3.2 Flexural Test Procedure

Flexural performance of the Recycled Plastic Corrugated panels (RPCP) was assessed using a three-point bending test setup, in accordance with the modified ASTM D790 [223] standard for determining the flexural properties of unreinforced and reinforced plastics. The tests were conducted using a calibrated Universal Testing Machine (UTM) equipped with precision load cells and deflection measurement capabilities. As shown in Figure 5.5, each RPCP specimen was placed horizontally on two roller supports, with a span length of 500 mm, while a centrally applied vertical load was introduced through a compression fixture mounted on the crosshead. Prior to testing, the panels were visually inspected for any surface inconsistencies or defects. The loading rate was controlled to ensure quasistatic conditions, and testing was carried out at room temperature.

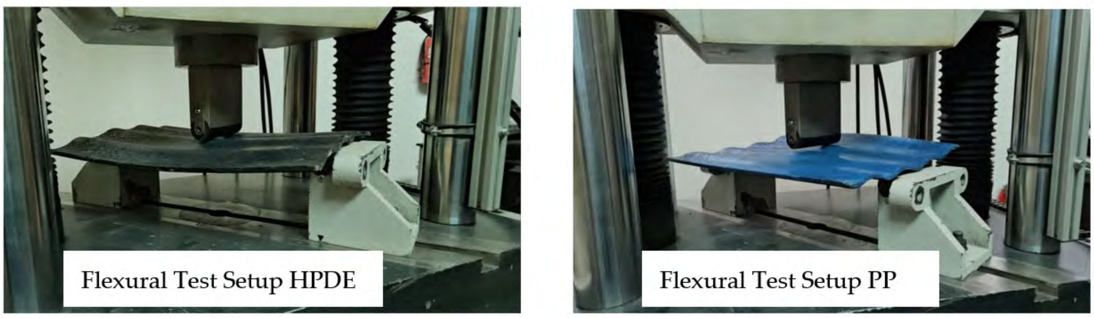


Figure 5.5: Flexural Testing of Recycled Plastic Corrugated Sheets (RPCS) under Three-Point Bending Configuration

Real-time load–deflection data were recorded to evaluate the flexural behavior of both HDPE and PP-based panels. Key parameters such as maximum load, stiffness (slope of the initial linear region), and deflection at failure were extracted from the resulting curves. The RPCP specimens demonstrated notable ductility and load absorption capacity, with gradual deformation observed prior to failure, indicative of a tough and energy-absorbing response. The panels fabricated from PP exhibited slightly higher stiffness, while HDPE based panels showed more pronounced ductility. These characteristics suggest that RPCP possess the mechanical resilience required for non-load bearing structural applications, including cladding, enclosures, and other secondary construction uses where moderate flexural resistance is essential.

5.2.3.3 Vertical Panel Test Procedure - Modified Pendulum Impact Test

The pendulum impact apparatus consisted of a steel hammer arm with a hemispherical striking head mounted on a pivot frame, allowing it to swing freely from a fixed height as shown in Figure 5.6. The corrugated panel specimen was clamped horizontally on a rigid steel base with minimal constraint at the edges to replicate real-life support conditions.

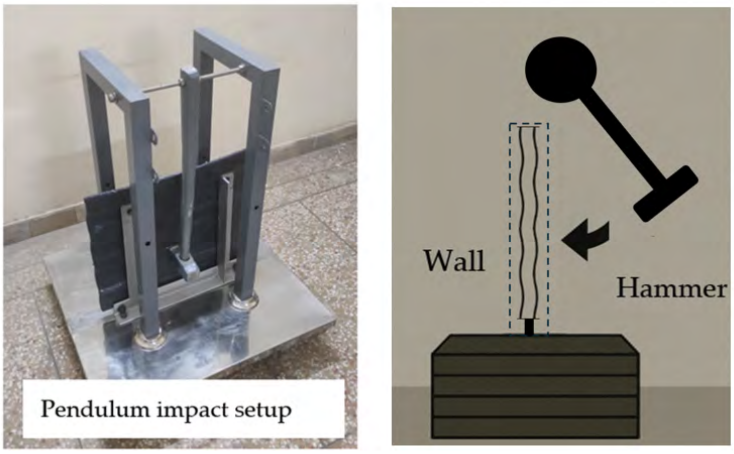


FIGURE 5.6: Experimental and Schematic Setup for modified pendulum impact testing

The impact load and rebound height were recorded using a high-speed camera and deflection sensors, allowing evaluation of absorbed energy, failure modes, and damage propagation. Observations were made for crack initiation, deformation behavior, and delamination, particularly in peak regions of the corrugated profile [220, 221].

5.2.3.4 Horizontal Panel Test Procedure - Modified Drop Impact Test

In the drop weight test, a cylindrical steel mass was allowed to fall vertically from set heights onto the center of the corrugated panels placed over a support shown in Figure 5.7. Impact energy levels were constant for drop height and mass. The failure patterns were analyzed to determine the energy absorption capacity and dynamic toughness of the materials in number of blows. Both rHDPE and rPP samples were tested under identical conditions for comparative analysis.

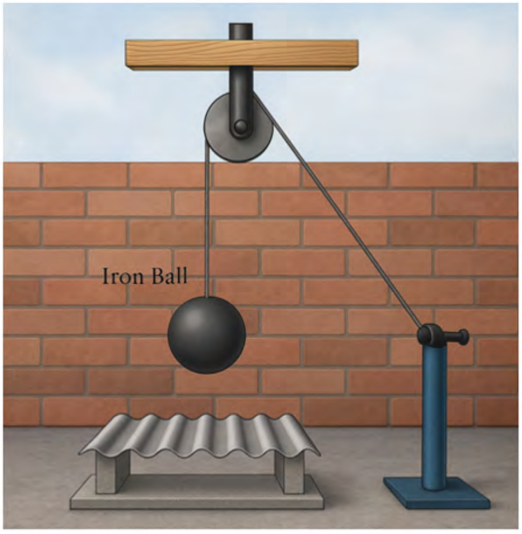


FIGURE 5.7: Schematic Setup for modified drop Impact Testing

The rPP corrugated panels generally exhibited higher peak force resistance but lower ductile deformation, whereas rHDPE panels showed greater deflection and energy absorption prior to failure, indicating their ability to withstand impact loads. This dual-impact testing framework provided a comprehensive assessment of the mechanical resilience and suitability of recycled plastic corrugated panels for applications involving dynamic loads, roofing, flooring in traffic areas, and protective barriers in construction zones in cases of hailstorms [224] and other impact loads[220, 222].

5.2.3.5 Characterization and Microstructural Assessment

a. XRD Analysis Procedure

X-ray Diffraction (XRD) analysis was employed to investigate the crystallographic characteristics of the recycled HDPE and PP used in the fabrication of corrugated panels. The measurements were conducted using a θ–2θ locked-coupled scan configuration, which is widely adopted for examining semi-crystalline polymer systems [225]. A copper (Cu) anode X-ray source was utilized, generating characteristic Cu Kα radiation with an average wavelength of 1.5418 Å, suitable for resolving polymeric crystalline structures. The diffractometer was operated at an accelerating voltage of 40 kV and a current of 30 mA, providing sufficient beam intensity for the analysis of plastic-based composites [225].

Data acquisition was carried out using a goniometer with a 560 mm radius (Model 512), offering high angular precision. To optimize peak resolution and reduce axial divergence, both primary and secondary Soller slits were fixed at 2.5°. The scan range spanned from 10° to 32.2° in 2θ, effectively capturing the dominant diffraction peaks associated with the orthorhombic and monoclinic crystalline phases typical of HDPE and PP. A fine step size was applied to enhance peak definition and support reliable identification of crystallographic features. Although no monochromator or beam analyzer was used, allowing for rapid throughput, the data quality remained robust for structural analysis. X-ray diffraction (XRD) analysis confirmed the semi-crystalline nature of the recycled polymers.

The HDPE sample exhibited two distinct Bragg reflections at approximately 21.6° and 23.9° (2θ), corresponding to the (110) and (200) planes of the α-orthorhombic phase, while PP showed multiple reflections at 14.1°, 18.6°, 21.2°, and 25.5° (2θ), indexed to the (110), (130), (111), and (041) planes of the α-monoclinic phase. These Bragg reflections arise from constructive interference of X-rays scattered by periodically spaced atomic planes according to Bragg's law ($n\lambda = 2d \sin\theta$), revealing interplanar spacings of 4.1 Å for (110) and 3.7 Å for (200) in HDPE. The persistence of these characteristic peaks indicates retention of crystalline order after mechanical recycling, suggesting that extrusion did not disrupt the polymer lattice but slightly reduced crystallite size, as reflected by minor peak broadening [207, 226].

This procedure adheres to standard XRD protocols for semi-crystalline polymers and enabled clear differentiation of the crystalline domains within the corrugated panels, thereby supporting the evaluation of phase composition, material structure, and degree of crystallinity in recycled polymer matrices [227].

b. SEM and EDS Analysis Procedure

Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDS) was employed to investigate the surface morphology and elemental composition of the recycled plastic corrugated panels (RPCP) fabricated from HDPE and PP [228]. The analysis was carried out using a field-emission SEM (FE-SEM) under high vacuum conditions to obtain high-resolution surface micrographs. Prior to imaging, the specimens were cleaned with compressed air to remove loose particles and sputter-coated with a thin layer of gold (Au) using a DC magnetron sputter coater, to enhance surface conductivity and reduce charging effects during electron bombardment. The SEM images were captured at a magnification range suitable for microstructural evaluation, with an accelerating voltage set to 15 kV [229]. The working distance was optimized between 8–12 mm, and the detector mode was switched between secondary electron (SE) and backscattered electron (BSE) to resolve both topographical and compositional contrasts. Multiple regions of interest were selected for EDS analysis, identified as spectrums and others, to ensure a representative assessment of the elemental distribution across the polymer matrix. EDS spectra confirmed that carbon (C) and oxygen (O) were the dominant elements, consistent with the hydrocarbon-based composition of the polymers. Trace elements such as Ca, Si, Mg, Cl, Ti, and sputtered Au were also detected, which may arise from fillers, surface residues, or processing additives. The EDS maps provided quantitative weight percentages (Wt%) for each detected element, assisting in the evaluation of purity, homogeneity, and the presence of inorganic constituents within the recycled material. This characterization protocol enabled a comprehensive understanding of the microstructural integrity and elemental uniformity of the RPCS, contributing to the assessment of their suitability for structural and environmental applications [210, 229].

5.2.4 Prototype Slab Test Procedure

5.2.4.1 Water Leakage Test Procedure

A prototype slab measuring 1.63 m × 1.6 m was fabricated using RPCS HDPE panels for practical performance evaluation as per ASTM E2140 [55]. The joints of the panels were made in such a way that a 50 mm overlap is achieved. These joints were properly shaped to achieve good overlap finish. Epoxy sealant was applied along the roof joints to create a durable, watertight barrier that prevents water infiltration. Its strong adhesion and airtight joints ensured long-term protection against leakage [163].

5.2.4.2 Flexural Capacity Test Procedure for Prototype Slab

The prototype slab was subjected to centrally applied through incremental 10 Kg bags placed at center of the arrangement till failure [230]. Deflection at central point was recorded by a customized arrangement with a free hanging bar fixed with center point as per ASTM E661 [54]. The recycled plastic panels demonstrated stable performance under loads, showing controlled deflection without structural rupture during load increments [231]. This experiment validated the load-bearing capability under flexural loads of recycled plastic prototype slab RPPS and underscored their feasibility for applications in pedestrian walkways, temporary stages, lightweight decks, and low-load roofing systems [230, 232].

Figure 5.8 illustrates a schematic setup for evaluating the structural deflection of a prototype slab (PS) under applied loading. A vertical load is applied at the center of the PS with an increment of 98.1 N to simulate service conditions, while the downward curvature indicates deflection due to bending [177]. A custom deflection gauge setup was positioned at the center to monitor deformation and measure the structural response of the prototype slab to the applied load.

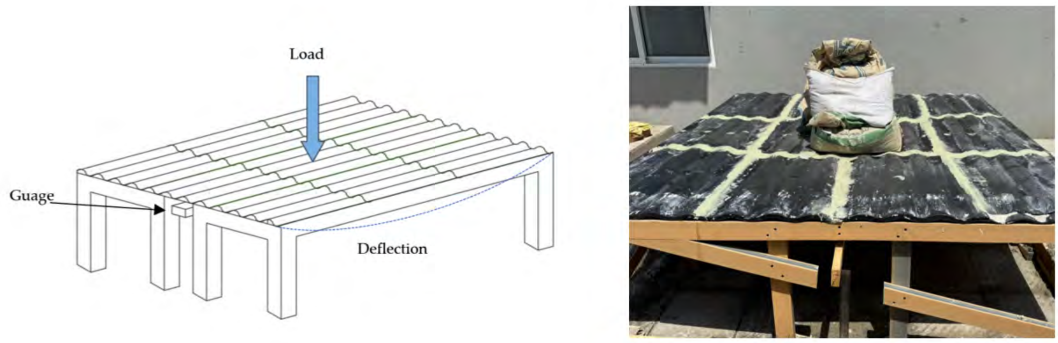


FIGURE 5.8: Schematic Representation and flexural capacity test setup of Corrugated Panel

5.2.5 Empirical Relationship Procedure Between Impact and Flexural Strength of Panel

Impact strength was determined by dividing the total absorbed energy by the area of impact. The energy absorbed during failure was measured in Joules, while the impact area was calculated based on the hammer face dimensions (50.8 mm × 12.7 mm, yielding 645.16 mm^2). The resulting value, expressed in J/mm^2, was directly equivalent to megapascals (MPa), reflecting the material's ability to resist sudden applied loads. To establish a correlation between flexural and impact strength of recycled plastic materials, a systematic formulation procedure was adopted. Flexural strength was determined using standard three-point bending tests, where the maximum stress sustained by each specimen was recorded. Impact strength was assessed separately through drop-weight and pendulum impact tests, with energy absorbed during fracture measured and normalized over the impact area to express results in megapascals (MPa). The ratio of impact strength to flexural strength was then calculated for each material type, providing a dimensionless value that represents the proportion of static bending strength retained under dynamic loading. To enhance interpretability, these ratios were also expressed as percentages. This approach allowed for a direct comparison of the material's toughness relative to its bending capacity, offering both numerical and qualitative insights into its suitability for structural applications involving sudden or cyclic loads. The method provides a practical framework for evaluating recycled polymers when selecting materials for impact-prone environments. This approach provides a reliable assessment of the toughness and durability of recycled plastic panels under dynamic loading conditions.

5.3 Results

5.3.1 Behavior of Corrugated Panel

5.3.1.1 Fundamental Frequency and Damping Behavior

The dynamic mechanical properties of recycled HDPE (rHDPE) and recycled PP (rPP) corrugated panels were assessed according to ASTM E1876-15 [221] using resonance frequency analysis to determine stiffness and damping characteristics under flexural and longitudinal modes. Figure 5.4 presents the schematic arrangement. The evaluation included measurements of longitudinal resonance frequency (RFL), flexural resonance frequencies in in-plane (RFF(IP)) and out-of-plane (RFF(OOP)) directions, dynamic elastic modulus (DEM) across all corresponding modes, and material damping quantified through the logarithmic decrement (ξ). The longitudinal resonance frequency (RFL) of rHDPE was measured at 1043.1 ± 110.9 Hz, closely matched by rPP at 1042.5 ± 22.5 Hz. This parity indicates similar mass-to-stiffness ratios in longitudinal vibration for both polymers. However, a distinct difference was observed in flexural resonance behaviour. While the in-plane flexural frequencies (RFF(IP)) were similar for both rHDPE and rPP (1065.3 ± 88.7 Hz vs. 1065.0 ± 0.0 Hz), the out-of-plane frequency (RFF(OOP)) revealed a substantial increase in rPP (998.6 ± 66.4 Hz) compared to rHDPE (976.1 ± 43.9 Hz), suggesting a stiffer out-of-plane response for rPP under flexural loading. The dynamic elastic modulus (DEM) data further substantiates this observation. rHDPE demonstrated a longitudinal modulus (DEML) of 1.53 ± 0.33 GPa and in-plane flexural modulus (DEMF(IP)) of 2.43 ± 0.40 GPa. Comparatively, rPP exhibited slightly lower longitudinal stiffness (1.37 ± 0.14 GPa) but demonstrated superior out-of-plane stiffness (DEMF(OOP) = 2.17 ± 0.33 GPa) versus rHDPE (2.04 ± 1.07 GPa). This indicates that rPP, though less stiff in axial loading, may offer better flexural resistance, particularly in out-of-plane structural configurations. Damping properties, represented by the

TABLE 5.2: Dynamic properties of rHDPE and rPP corrugated panels (ASTM E1876-15).

Sample	**RF_L (Hz) (1)**	**RF_{IP} (Hz) (2)**	**RF_{OOP} (Hz) (3)**	**DEM_L (GPa) (4)**	**DEM_{IP} (GPa) (5)**	**DEM_{OOP} (GPa) (6)**	**ξ_L (%) (7)**	**ξ_{IP} (%) (8)**	**ξ_{OOP} (%) (9)**
rHDPE	1043.1 ± 110.9	1065.3 ± 88.7	976.1 ± 43.9	1.53 ± 0.33	2.43 ± 0.40	2.04 ± 1.07	3.4 ± 0.4	6.9 ± 2.8	8.2 ± 0.1
rPP	1042.5 ± 22.5	1065.0 ± 0.00	998.6 ± 66.4	1.37 ± 0.14	1.91 ± 0.26	2.17 ± 0.33	8.6 ± 0.7	5.8 ± 0.5	4.2 ± 0.2

logarithmic decrement (ξ), revealed contrasting behaviours between the materials. rHDPE showed a moderate longitudinal damping ratio of 3.4 ± 0.4%, higher in-plane damping ($\xi_{F(IP)}$) of 6.9 ± 2.8%, and substantial out-of-plane damping ($\xi_{F(OOP)}$) at 8.2 ± 0.1%. This trend implies that rHDPE may be more effective in attenuating vibrational energy, especially in complex structural motions. Conversely, rPP exhibited a high longitudinal damping ($\xi_L = 8.6 \pm 0.7$), but lower values for in-plane (5.8 ± 0.5%) and out-of-plane (4.2 ± 0.2%) damping, summarized in Table 5.1. This dichotomy suggests that while rPP may absorb energy efficiently in axial resonance, it exhibits lower energy dissipation in bending modes compared to rHDPE. Overall, the results highlight nuanced differences in the dynamic behaviour of rHDPE and rPP corrugated panels. rPP offers improved stiffness in flexural out-of-plane response and greater consistency in resonance behaviour, while rHDPE provides superior damping in flexural configurations. These findings indicate that rPP may be more suitable for applications requiring higher flexural rigidity, whereas rHDPE could be advantageous in scenarios where vibration attenuation is critical.

The experimental findings show that rHDPE panels possess higher damping in the out-of-plane direction, making them suitable for roofing elements subjected to dynamic loads. rPP panels, on the other hand, exhibit greater longitudinal damping and out-of-plane stiffness, supporting their use in façade or cladding systems. These material-specific properties allow engineers to assign recycled panels based on directional loading demands. The comparative evaluation of dynamic elastic modulus in the out-of-plane direction (DEM_x) revealed that rPP panels exhibited superior stiffness (2.17 ± 0.33 GPa) compared to rHDPE (2.04 ± 1.07 GPa), indicating a more rigid structural response under transverse dynamic excitation. This distinction is critical when optimizing building envelopes and lightweight roofing systems where flexural resistance and dynamic load attenuation are essential. The relatively lower DEM_x of rHDPE, coupled with its higher damping ratio ($\xi_x = 8.2 \pm 0.1\%$), suggests its effectiveness in energy dissipation rather than load bearing, making it more suitable for acoustic insulation and vibration mitigation applications. In contrast, rPP's combination of higher DEM_x and lower damping ($\xi_x = 4.2 \pm 0.2\%$) positions it as a viable material for structural skins subjected to repetitive wind or seismic excitation where stiffness and dimensional stability are prioritized. The reduced flexural damping observed in rPP is linked to its higher crystallinity and lower chain entanglement, which constrain viscoelastic energy dissipation under bending loads. Conversely, rHDPE's greater amorphous content facilitates internal friction, resulting in enhanced flexural damping. The superior longitudinal damping of rPP is attributed to its molecular alignment, which supports more efficient axial vibration attenuation. The superior mechanical performance of rHDPE arises from its semicrystalline structure with well-distributed amorphous regions that enhance toughness and energy dissipation. Its higher molecular branching also contributes to better ductility compared to rPP. Optimizing extrusion temperature, cooling rate, and incorporating compatibilizers can further refine its microstructure and mechanical response. Both materials, however, demonstrate adequate mechanical performance for potential use in sustainable roofing and cladding applications where dynamic loading and acoustic insulation are performance criteria [220, 222].

5.3.1.2 Flexural Performance of Recycled Corrugated Panels

The flexural performance of recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP) corrugated panels was assessed through three-point bending tests, conducted in accordance with ASTM D790. The recycled HDPE corrugated sheet (rHDPE CS) demonstrated an ultimate strain of approximately 0.0125 (1.25%) with a modulus of 1.17 GPa, whereas the recycled PP corrugated sheet (rPP CS) exhibited a slightly higher ultimate strain of 0.014 (1.4%) but a lower modulus of 0.83 GPa, indicating that rHDPE offers greater stiffness while rPP provides enhanced ductility.

The stress-strain responses, depicted in Figure 5.9, reveal notable distinctions in mechanical behaviour between the two materials. rHDPE demonstrates a steeper stress rise and higher ultimate stress, indicating superior load resistance and structural stiffness. In contrast, rPP exhibits a more gradual increase in

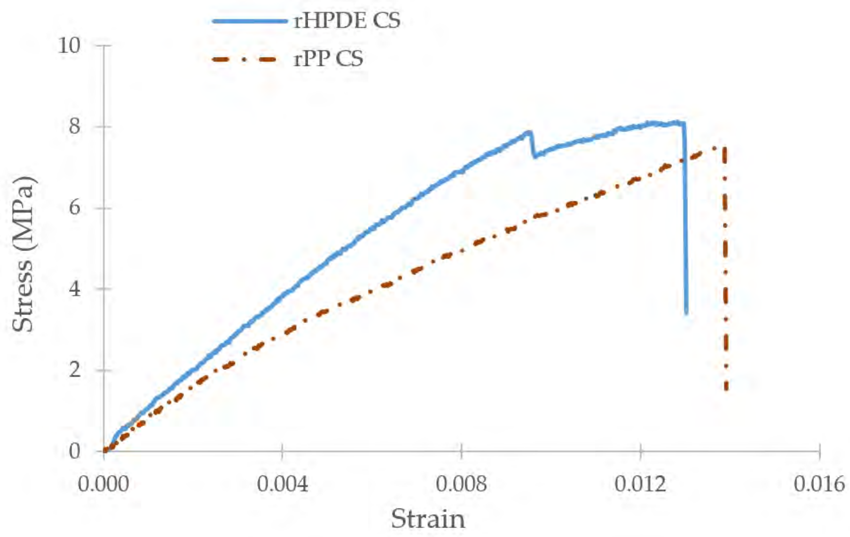


FIGURE 5.9: Stress – Strain Behavior of rHDPE and rPP Corrugated panels.

TABLE 5.3: Flexural performance metrics of rHDPE and rPP corrugated panels.

Material	**Weight (kg)**	**Max Load (kN)**	**Max Deflection (mm × 10)**	**Max Stress ($\times 10^{-2}$)**	**Max Strain**	**Total Energy Absorption (MJ/m^3 $\times 10^{-2}$)**	**Toughness Index**
rHDPE	3.100 ± 0.155	1.958 ± 0.098	2.860 ± 0.143	8.136 ± 0.407	1.302 ± 0.065	6.826 ± 0.341	1.017 ± 0.051
rPP	3.200 ± 0.160	1.816 ± 0.091	3.051 ± 0.153	7.546 ± 0.377	1.391 ± 0.070	5.918 ± 0.296	1.000 ± 0.050

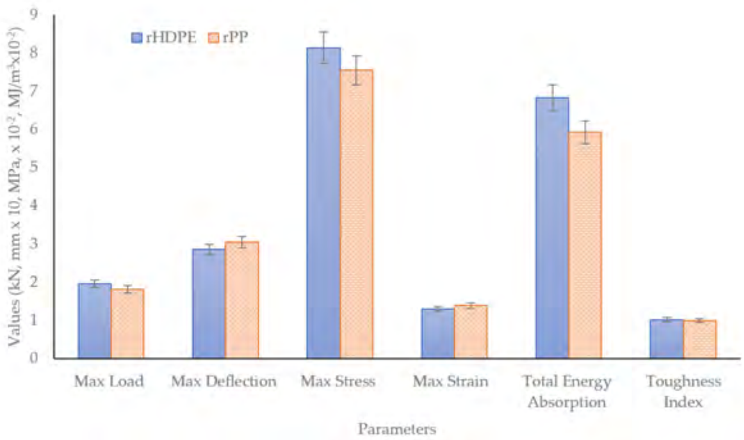


FIGURE 5.10: Summary of behavior of rHDPE and rPP Corrugated panels

stress and sustains a slightly larger strain at failure, highlighting its higher ductility. Quantitative results are summarized in Table 5.2.From the tabulated results, rHDPE panels demonstrate superior mechanical performance relative to rPP across most critical indicators. Specifically, rHDPE panels supported a maximum load of 1.958 ± 0.098 kN, indicating higher structural capacity compared to rPP, which sustained a slightly lower peak load of 1.816 ± 0.091 kN. This enhanced load-bearing capacity in rHDPE is further supported by its maximum stress value of 8.136 ± 0.407 MPa, which surpasses that of rPP at 7.546 ± 0.377 MPa. The higher stress resistance is indicative of better stiffness and internal bonding in rHDPE-based composites. In terms of deformation behavior, rPP panels experienced greater deflection (30.51 ± 1.53 mm) compared to rHDPE panels (28.60 ± 1.43 mm), suggesting relatively lower rigidity in rPP composites. Corresponding strain values further confirm this trend, with rPP reaching a strain of $(1.391 \pm 0.070) \times 10^{-2}$, slightly exceeding rHDPE's $(1.302 \pm 0.065) \times 10^{-2}$. Despite the higher strain, rPP's capacity to absorb energy under load remains lower, with total energy absorption recorded at $(5.918 \pm 0.296) \times 10^{-2}$ MJ/m^3 for rPP, compared to $(6.826 \pm 0.341) \times 10^{-2}$ MJ/m^3 for rHDPE. Furthermore, the toughness index, an indicator of post-yield energy absorption relative to yield strength, was marginally higher for rHDPE (1.017 ± 0.051) than rPP (1.000 ± 0.050), reinforcing the former's better energy dissipation and crack-resistance properties. Overall, these findings highlight rHDPE's mechanical superiority for structural applications requiring higher flexural resistance, energy absorption, and toughness [233]. These comparative results are visually consolidated in Figure 5.10, where the bar chart illustrates the relative performance of both materials across all key parameters, including load, deflection, stress, strain, energy absorption, and toughness index. Collectively, the data suggest that while both rHDPE and rPP corrugated panels exhibit promising flexural characteristics, rHDPE offers enhanced strength and energy absorption, making it more suitable for structural applications demanding higher resistance to flexural stress. rPP, on the other hand, may be preferred in scenarios requiring greater flexibility and ductility.

5.3.1.3 Behavior of Vertical Panel Under Pendulum Impact

The impact energy and toughness properties of recycled HDPE and PP panels were evaluated through both drop-weight and pendulum impact tests. The energy per impact was calculated using the potential energy equation $E = mgh$, assuming no energy loss (ideal conditions), with the mass of the falling body being 2.94 kg, gravitational acceleration $g = 9.81$ m/s^2, and drop heights of 1.8 meters for the drop test and 0.6 meters for the pendulum test. These values yielded individual blow energies of 52.06 J (0.052 kJ) and 17.35 J (0.017 kJ), respectively. By multiplying these by the number of impacts sustained before failure, the total energy absorption for each sample was calculated. The total energy was then normalized by the specimen volume (0.00354 m^3) to derive the material toughness in kJ/m^3.

Figure 5.11 illustrates the failure patterns of rPP and rHDPE corrugated panels subjected to a modified pendulum impact test. The rPP sample (top row) exhibits a characteristic radial cracking pattern extending across a 75 mm radius from the impact center, indicative of localized tensile failure and material ductility under dynamic load. In contrast, the rHDPE sample (bottom row) displays a projectile-like disintegration at the impact zone, suggesting a brittle fracture mode with minimal crack propagation and energy absorption.

These visual differences confirm the superior impact toughness of rPP over rHDPE in resisting high-strain-rate deformation.Under high strain rate impact, rPP exhibits radial cracking due to its higher crystallinity and localized stress concentration, leading to brittle fracture paths. In contrast, rHDPE undergoes a more distributed failure characterized by projectile-like fragmentation, attributed to its ductile matrix and energy dissipation through fibrillation and cavitation. These contrasting behaviors reflect fundamental differences in their molecular architecture and deformation mechanisms.

5.3.1.4 Behavior of Horizontal Panel Under Drop Impact

In the drop-weight tests, rHDPE withstood 28 ± 3 blows, resulting in a total energy absorption of 1.458 ± 0.156 kJ and a material toughness of 411.85 ± 44.13 kJ/m^3. In contrast, rPP absorbed significantly more energy, withstanding 51 ± 4 blows and absorbing 2.655 ± 0.208 kJ, corresponding to a toughness of 750.15 ± 58.84 kJ/m^3. Under pendulum impact conditions, rHDPE absorbed 0.816 ± 0.069 kJ from 47 ± 4 blows, with a toughness of 230.44 ± 19.61 kJ/m^3, whereas rPP exhibited enhanced performance again, absorbing 1.770 ± 0.156 kJ over 102

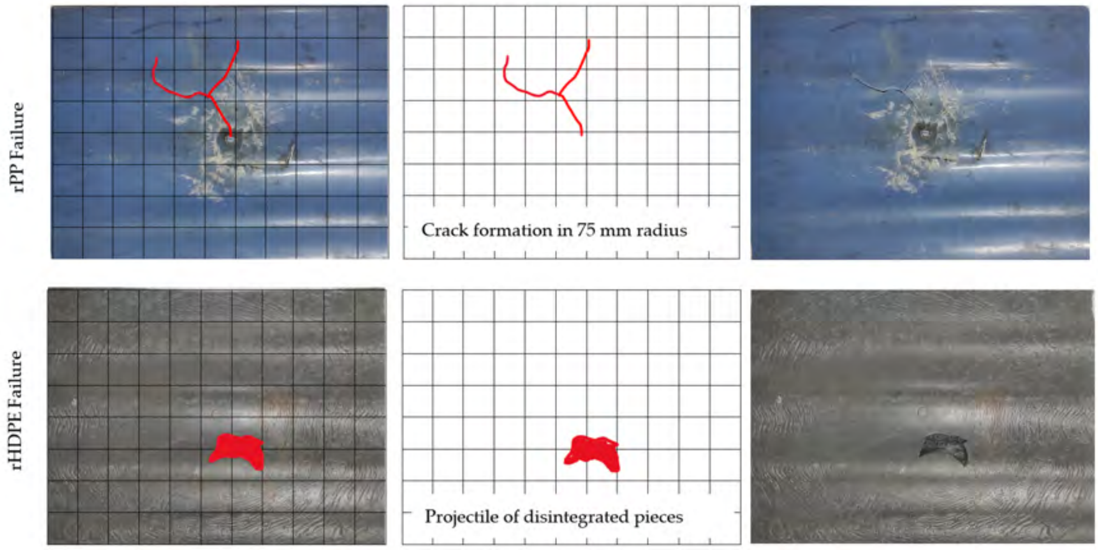


FIGURE 5.11: Failure of Corrugated panels in modified pendulum impact test

± 9 blows, yielding a toughness of 500.10 ± 44.13 kJ/m^3. Figure 5.12 depicts the failure morphology of rPP and rHDPE corrugated panels subjected to a modified drop impact test. The rPP sample (top row) demonstrates a clean longitudinal split along the length of the panel, signifying a ductile tearing behavior that maintains structural continuity at the edges. This indicates a gradual energy dissipation mechanism characteristic of more flexible thermoplastics. Conversely, the rHDPE sample (bottom row) exhibits a brittle failure pattern with fragmentation into three distinct sections, denoting a sudden loss of load-bearing capacity upon impact. The fracture propagation across multiple directions highlights the material's limited toughness and resistance under high-energy impact loading.

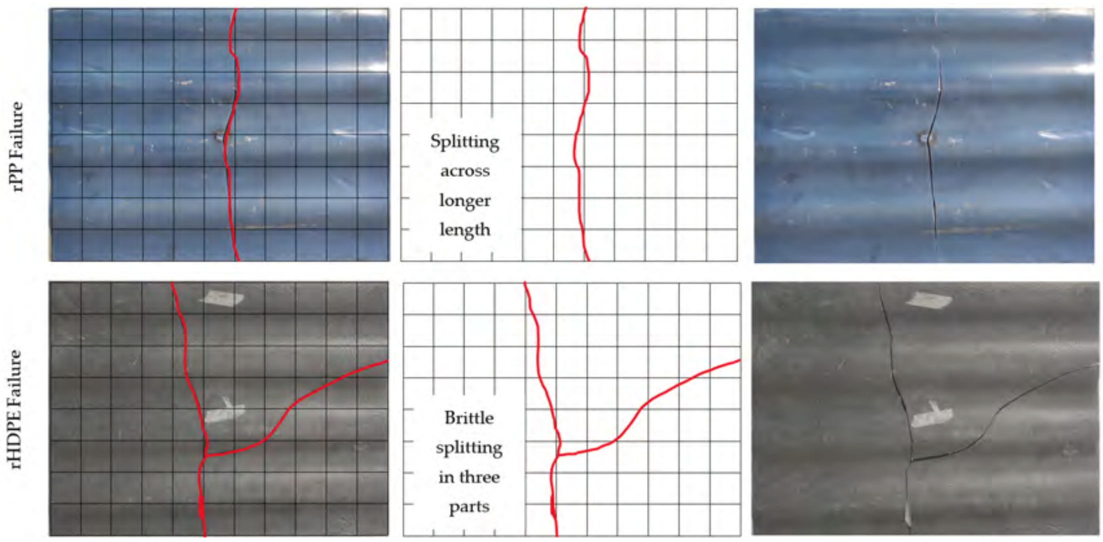


FIGURE 5.12: Failure of Corrugated panels in modified drop impact test

TABLE 5.4: Summary of impact strength results of rHDPE and rPP corrugated panels.

Test Type	**Sample**	**Impact Height (m)**	**Angular Distance (m)**	**Impact Energy (J/blow)**	**Impact Strength (blows)**	**Total Energy (kJ)**	**Impact Strength (MPa)**	**Material Toughness (kJ/m³)**
Drop	rHDPE	1.8	–	52.06	28 ± 3	1.45 ± 0.15	2.25 ± 0.23	411.84 ± 44.12
Weight	rPP	1.8	–	52.06	51 ± 4	2.65 ± 0.20	4.11 ± 0.31	750.15 ± 58.83
Pendulum	rHDPE	–	0.6	17.35	47 ± 4	0.81 ± 0.06	1.26 ± 0.09	230.43 ± 19.61
Pendulum	rPP	–	0.6	17.35	102 ± 9	1.77 ± 0.15	2.74 ± 0.23	500.10 ± 44.12

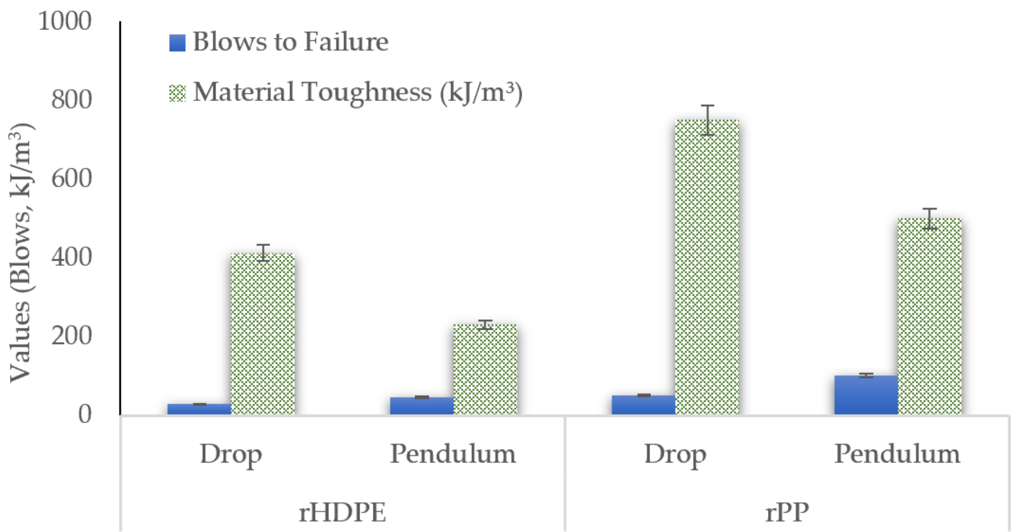


FIGURE 5.13: Comparison of results of blow to failure and Material toughness of rHDPE and rPP for modified pendulum and modified drop test

In recent research [222, 223], the same mechanism was adopted to evaluate impact resistance, observing significant gains in energy absorption and dynamic resilience [222, 223]. Their empirical modelling underlined the relevance of repeated blow analysis in quantifying dynamic load behavior. These findings clearly indicate that recycled polypropylene exhibits better impact resistance and toughness compared to recycled HDPE under both dynamic testing regimes. The results are summarized in Table 5.3 and Figure 5.13 for both the tests. The higher energy absorption and toughness values of the rPP highlight its potential as a sustainable and resilient material for construction applications, particularly in environments subject to repeated or high-intensity impacts. Its durability makes it a promising candidate for recycled corrugated roofing and cladding elements, supporting the transition toward circular and high-performance construction materials.Table 5 summarizes the failure morphology of the corrugated panels. Under pendulum impact testing, recycled polypropylene (rPP) panels exhibited radial crack propagation extending approximately 75 mm from the center of impact, forming a star-like fracture pattern with angular spacing of around 60° between primary cracks. In contrast, recycled high-density polyethylene (rHDPE) panels displayed a highly localized failure, limited to a central impact zone with negligible crack extension confined within a crater roughly 100 mm in diameter—indicating a brittle fragmentation mode. During drop-weight impact testing, rPP panels developed a single dominant longitudinal crack spanning nearly the entire panel length (450 mm), while the remainder of the panel remained intact, suggesting a ductile tearing mechanism with minimal material loss. Conversely, rHDPE panels fractured into three sizable sections due to two prominent cracks (450 mm and 250 mm), diverging at approximate angles of 0° and 60°, characteristic of brittle fracture propagation. Despite the severe cracking, rHDPE showed minimal fine debris, and the fragmented zones were composed of cleanly separated sections rather than pulverized material, indicating that the disintegration area was limited to macroscopic divisions.

Table 5.5: Failure morphology of impact strengths of rHDPE and rPP corrugated panels.

Material	**Test**	**Approx. Crack Lengths**	**Disintegration Area**	**Crack Orientation**
rPP	Pendulum	∼75 mm radial cracks (2–3 emanating)	Negligible (no pieces detached)	Radial from impact (∼60° apart)
rPP	Drop Weight	One crack ∼450 mm (along panel length)	None (intact except for split)	∼0° (along corrugation/length)
rHDPE	Pendulum	Minimal crack propagation (<20 mm)	∼100 mm diameter impact crater	Localized shatter at center
rHDPE	Drop Weight	Two cracks ∼450 mm and ∼250 mm	No small debris (broke into 3 large sections)	∼0° and ∼60° (diverging paths)

5.3.1.5 Microstructural Behavior

a. XRD Analysis

The presented XRD patterns were obtained from recycled HDPE and PP samples post-failure under flexural loading, as part of a structural assessment study. Despite undergoing mechanical deformation and fracture during flexural testing, both polymers retained distinct crystalline peaks, suggesting that their core crystalline regions remained largely unaffected. However, minor peak broadening and reduced intensity, particularly in the rHDPE pattern, may indicate localized structural disorder or microcrack formation induced by mechanical loading. Figure 5.8 presents X-ray diffraction (XRD) patterns of recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP), highlighting their respective crystalline structures. The graph in Figure 5.14(a) corresponds to rHDPE, showing two prominent diffraction peaks located at approximately 21.6° and 23.9° 2θ, which are indexed to the (110) and (200) crystallographic planes. These peaks are characteristic of the orthorhombic crystal structure typical of semi-crystalline HDPE, indicating a moderate degree of crystallinity retained in the recycled polymer. Figure 5.14(b) displays the XRD pattern of rPP, which exhibits multiple well-defined peaks, including reflections at around 13.9°, 16.7°, 18.6°, 21.2°, and 25.7° 2θ. These peaks correspond to the (110), (111), (040), and (041) planes of the monoclinic α-phase of polypropylene. The intensity and multiplicity of peaks in rPP suggest a relatively higher crystalline order compared to rHDPE. The pronounced peak intensities reflect the semi-crystalline nature of the polymer and indicate that the recycling process preserved significant structural integrity [210].

The influence of recycling processes, such as melting, extrusion, and remolding, can also impact the degree of crystallinity by altering molecular alignment. Nonetheless, the preservation of prominent diffraction peaks in both rHDPE and rPP implies that the recycling process did not significantly compromise their crystalline structure.

This structural resilience, even after flexural failure, highlights the potential of mechanically recycled polymers to maintain functional integrity in load-bearing applications. Overall, the XRD analysis confirms the presence of distinct crystalline domains in both recycled polymers, validating their suitability for structural applications. The identifiable peaks further reinforce the retention of polymer-specific lattice arrangements, crucial for ensuring mechanical performance in recycled plastic products [234]

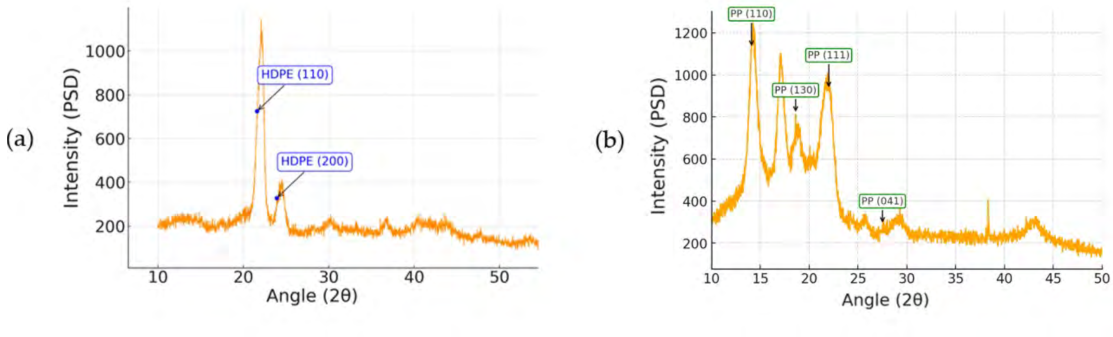


FIGURE 5.14: X-ray Diffraction (XRD) Patterns of Recycled (a) HDPE and (b) PP Corrugated Sheets after Flexural Failure

Crystallinity indices derived from XRD analysis, based on Gaussian fitting and baseline-corrected integration, indicated values of 22.12% for rPP and 17.20% for rHDPE. The XRD patterns exhibited by rHDPE and rPP indicate notable microstructural differences. rHDPE showed broader and less intense peaks, suggesting lower crystallinity and a higher amorphous fraction, which may enhance its ductility and energy absorption under impact. Conversely, rPP displayed sharper and more defined peaks, pointing to a more ordered structure that contributes to higher stiffness but reduced impact tolerance. These differences support the contrasting mechanical behaviors observed during high strain rate testing. b. SEM and EDS Analysis

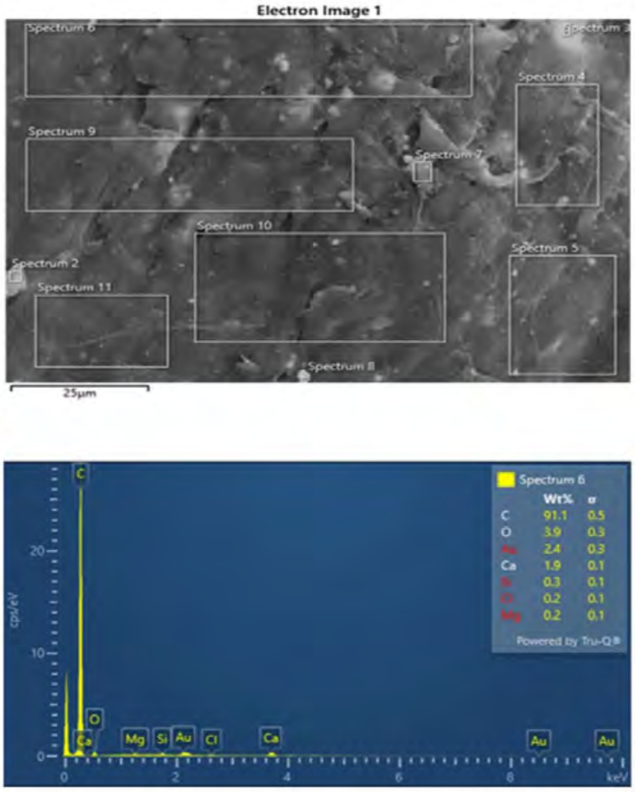
The scanning electron microscopy (SEM) images and energy-dispersive X-ray spectroscopy (EDS) analysis of recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP) following mechanical testing are shown in Figure 5.15. The SEM micrographs offer insight into the surface morphology of both materials, while the EDS spectra provide detailed elemental composition from selected regions. The SEM image of rHDPE (Figure 5.15a) reveals a rough and uneven surface with visible micro-voids and surface irregularities, which likely developed during flexural loading or because of inhomogeneities introduced during recycling. The distribution of rectangular boxes labeled *Spectrum* indicates multiple areas analyzed for chemical composition. These morphological features suggest the presence of embedded fillers or incomplete fusion of polymer chains, characteristic of recycled thermoplastics [233].

In contrast, the SEM image of rPP (Figure 5.15b) displays a relatively smoother and denser surface morphology, though minor rough patches and particulate residues are also visible. This may indicate better flow and dispersion during reprocessing, though the presence of surface inclusions still reflects its recycled nature [235]. The EDS spectrum for rHDPE, *Spectrum 6*, shows that the dominant element is carbon (91.1 wt%), followed by oxygen (3.9 wt%), gold (2.4 wt%), calcium (1.9 wt%), and trace amounts of silicon (0.3 wt%), chlorine (0.2 wt%), and magnesium (0.2 wt%). For rPP (*Spectrum 9*), carbon content is higher at 95.2 wt%, with oxygen at 2.2 wt%, and trace levels of gold (0.6 wt%), titanium (0.6 wt%), chlorine (0.2 wt%), and iron (0.1 wt%) summarized in Table 5.4. The peaks in

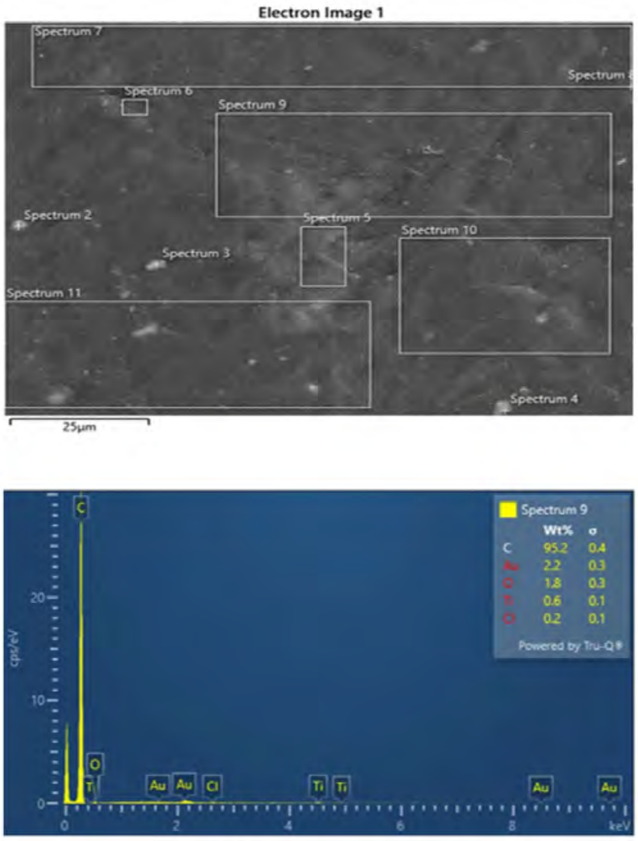
Table 5.6: Elemental composition (wt%) of recycled HDPE and PP from EDS analysis.

Sample	**C (wt%)**	**O (wt%)**	**Au (wt%)**	**Ca (wt%)**	**Si (wt%)**	**Cl (wt%)**	**Mg (wt%)**	**Ti (wt%)**	**Fe (wt%)**
rHDPE	91.1 ± 0.5	3.9 ± 0.3	2.4 ± 0.3	1.9 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	–	–
rPP	95.2 ± 0.4	2.2 ± 0.3	0.6 ± 0.3	–	–	0.2 ± 0.1	0.6 ± 0.1	–	0.1 ± 0.1

both samples arise from the conductive sputter coating used during SEM imaging. The presence of calcium, silicon, and magnesium in rHDPE and titanium and iron in rPP suggests residual inorganic fillers, pigments, or impurities retained from the recycling stream or previous use. The SEM-EDS analysis confirms that both rHDPE and rPP retain significant carbon-based polymer structure after flexural failure, while also containing minor elemental residues indicative of additives, contamination, or process-related modifications. This highlights the complexity of recycled plastic compositions and the importance of microstructural and compositional evaluation in assessing their mechanical reliability and consistency for



(a) SEM and spectrum analysis of r HDPE



(b) SEM and spectrum analysis of rPP

FIGURE 5.15: SEM and composition analysis of (a) rHDPE and (b) rPP

reuse in structural applications [210].The SEM analysis in this study was limited to qualitative observations of fracture morphology, matrix continuity, and filler dispersion. Quantitative assessments such as porosity or void fraction were not undertaken due to the lack of advanced image-analysis facilities; however, their effects are indirectly evident in the variability of mechanical results. Future studies should employ quantitative SEM analysis or complementary methods such as X-ray micro-CT and mercury intrusion porosimetry to directly link microstructural porosity with mechanical performance.

5.3.2 Behaviour of Prototype Slab

5.3.2.1 Water Leakage Behaviour of Prototype Slab

The structural performance and water resistance of recycled corrugated plastic prototype slab was evaluated through experimental procedures, as depicted in the figures 5.16. Initially, edge modifications were made to facilitate overlapping joints between adjacent panels. These modifications, visible in Figure 5.16, involved precise edge-cutting techniques designed to enhance interlocking capability and prevent water ingress at junctions. The overlapping design mimics conventional roofing practices, offering both mechanical interlock and coverage continuity. This

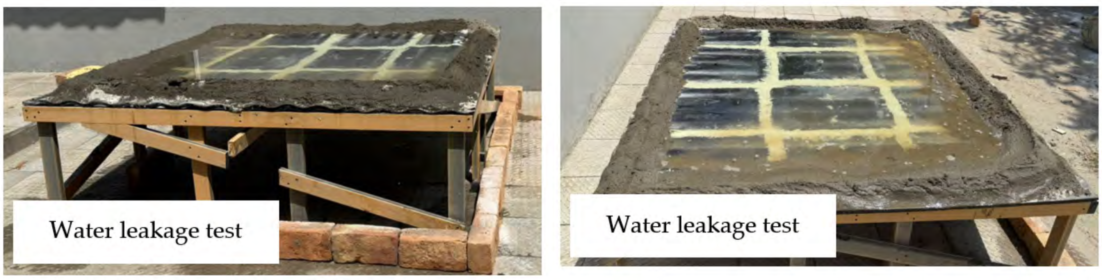


FIGURE 5.16: Water leakage testing of recycled plastic corrugated prototype slabs test

detailing is critical for achieving long-term waterproofing and structural integrity in roofing applications using recycled plastic components. Subsequently, to assess the water resistance performance of the assembled system, a water leakage test was conducted on a mock-up frame covered with the joined corrugated panels, as shown in Figure 5.15 (b). The test setup included a soil-bound reservoir filled with water over the surface of the assembled prototype slab. The setup was kept for 6 hours, and no water leakage was observed. Observations revealed that the modified edges effectively minimized water leakage, validating the proposed joint design for practical use in roofing or cladding systems subjected to rainfall or wet environmental conditions.

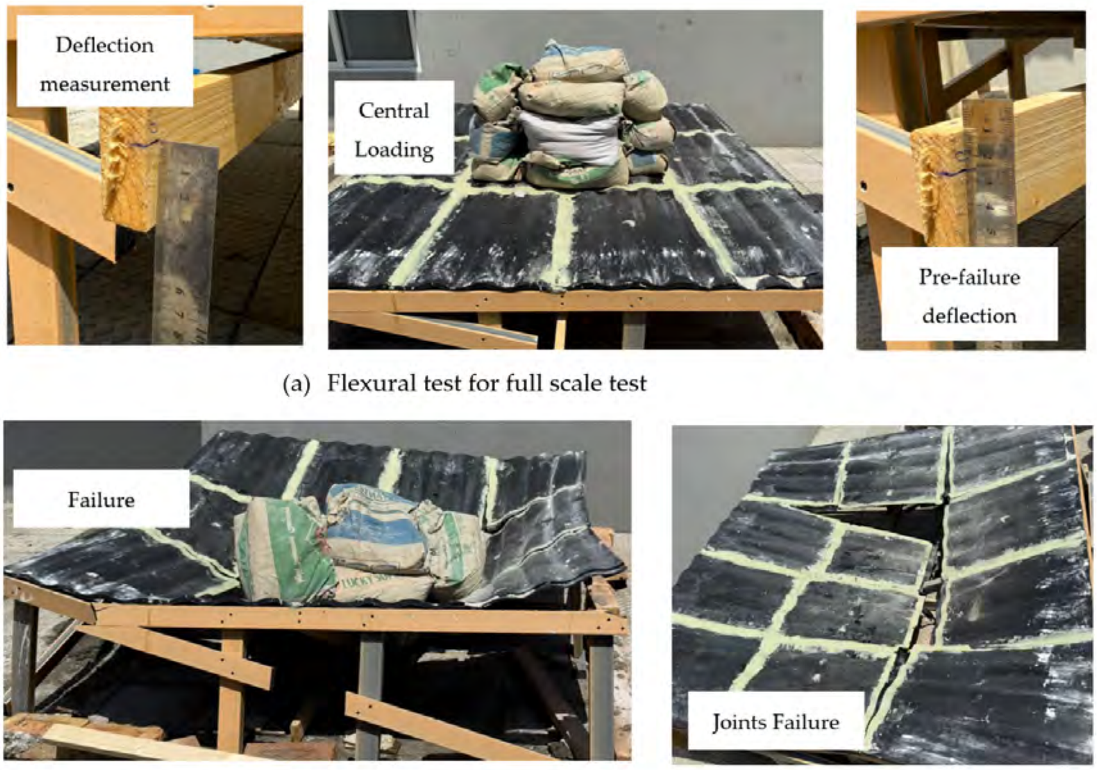
Table 5.7: Water leakage test results for rHDPE prototype slab.

Time Interval (hrs)	**Water Head* (cm)**	**Water Leakage Observed**	**Water Collected Below (litres)**	**Remarks**
0	7.67	0%	0	No leakage
2	7.67	0%	0	No leakage
4	7.67	0%	0	No leakage
6	7.67	0%	0	No leakage

*Note: 200 litres of water placed on slab top.

5.3.2.2 Recycled Plastic Prototype Slab Flexural Capacity

In the next phase of evaluation, load testing was performed to investigate the structural response of the recycled prototype slab assemblies (1.68 m × 1.60 m × 12.7 mm) under applied loads. Figure 5.17(a) from the second image set presents the experimental configuration used to simulate service loading by applying stacked sandbags centrally on the surface. Deflection was recorded using a calibrated measuring scale, both at mid-span and at the supports, to monitor the elastic and plastic deformation response of the prototype slab assembly. Pre-failure conditions exhibited a gradual increase in deflection without visible cracking, indicating satisfactory energy dissipation and flexibility within the safe load-bearing range. However, upon exceeding the material's ultimate strength, the prototype slab exhibited visible failure modes, as captured in Figure 5.17 (b). Cracking sound was heard before failure and the failure was not sudden. The failure patterns were predominantly characterized by significant mid-span sagging and the opening of joints, particularly at the interfaces between overlapping panels. These failures point to the necessity for additional reinforcement or improved joint treatment in future designs to enhance structural continuity and overall durability.



(a) Flexural test for full scale test

(b) Failure of slab panel

FIGURE 5.17: Testing of recycled plastic prototype slabs. (a) Test setup and (b) failure of prototype slab.

The observations gathered from this testing provide critical insights into the mechanical behaviour, joint reliability, and application feasibility of recycled plastic corrugated panels for structural use in sustainable construction solutions [236, 237].

The structural performance of recycled corrugated plastic prototype slab was quantitatively assessed through a load–deflection test, as illustrated in Figure 5.18. The graph demonstrates the non-linear relationship between applied load and vertical deflection, with the prototype slab exhibiting progressive deformation under incremental loading until failure. The curve shows a gradual increase in deflection

corresponding to the applied load, reaching a maximum value near 190 kg (1.86 kN) at approximately 27 mm of deflection, indicating ductile behaviour and considerable energy absorption capacity prior to failure. Table 5.5 presents a summarized evaluation of the panel's geometric and mechanical performance parameters.

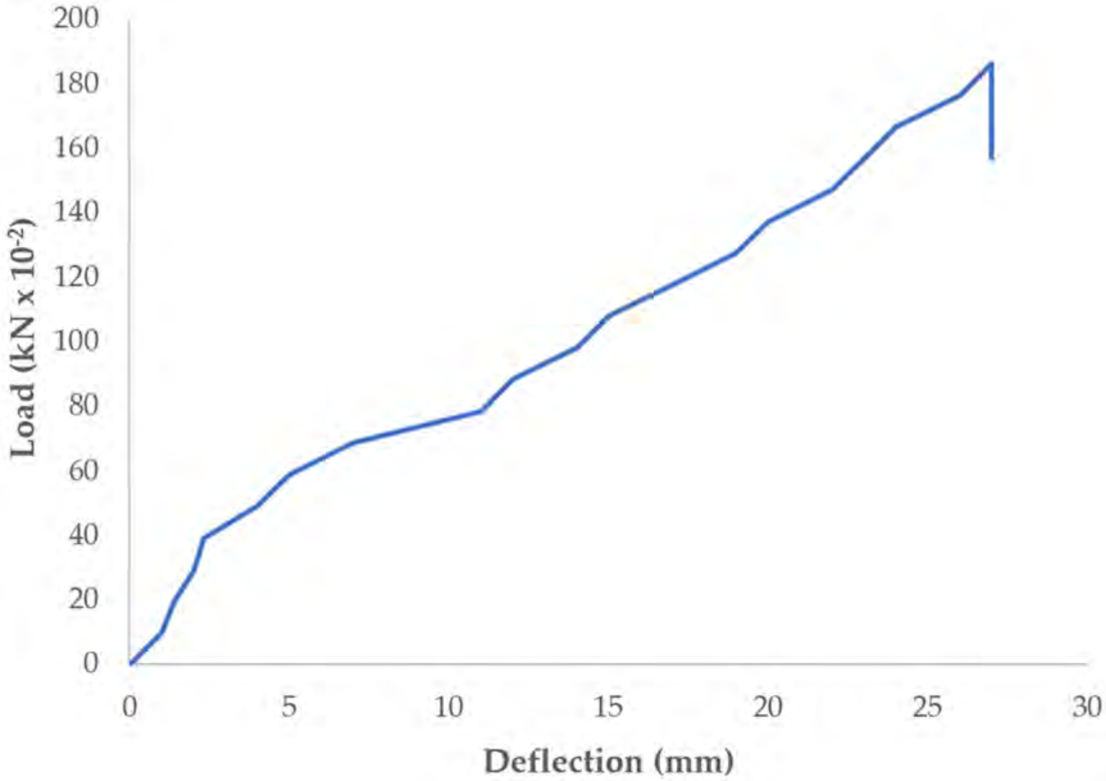


FIGURE 5.18: Load Deflection behavior of Full-scale setup

The tested prototype slab had a width of 1.6 meters, a length of 1.68 meters, and a thickness of approximately 12.7 mm. The Prototype slab withstood a peak load of 1.86 kN, corresponding to substantial flexural resistance in the context of lightweight roofing applications. The recorded maximum deflection was 27 mm, reflecting its ability to undergo elastic deformation without immediate fracture.

TABLE 5.8: Load–deflection behavior of the recycled rHDPE prototype slab.

Max Load (kN $\times$ 10^{-2})	**Slab Width** (m)	**Slab Length** (m)	**Slab Thickness** (mm)	**Max Deflection** (mm $\times$ 10)	**Energy Absorption** (N·m)
186.33	1.6	1.68	12.7	2.7	26.8

Furthermore, the calculated energy absorption was 26.8 N-m emphasizing its capacity to absorb energy underload without catastrophic failure. These findings affirm the feasibility of using mechanically recycled plastic panels in structural applications where moderate loading and impact resistance are required, such as affordable housing and temporary shelter systems.

5.3.3 Empirical Relationship of Flexural Strength to Impact Strength of Recycled Panels

To evaluate the relationship between flexural and impact performance of recycled polymer panels, a comparative analysis was conducted using normalized ratios. Flexural strength was determined through three-point bending tests, while impact strength was assessed via drop-weight and pendulum impact methods. For each material type—recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP)—the ratio of impact strength to flexural strength was calculated, offering insight into the material's dynamic response relative to its static bending capacity. The ratios were expressed both in decimal and percentage form, facilitating a clearer interpretation of impact performance as a proportion of flexural capacity.

Table 9 provides a summary to establish a quantitative relationship between static and dynamic mechanical performance; the impact strength of recycled plastic panels was normalized with respect to their flexural strength. This approach enables a direct comparison of the material's ability to resist sudden impact relative to its bending resistance. The formulation was based on the ratio

$$R = \frac{\sigma_{\text{impact}}}{\sigma_{\text{flexural}}}$$

where both strengths are expressed in megapascals (MPa). The resulting dimensionless ratios were further converted to percentage form to enhance interpretability.

For recycled polypropylene (rPP), the impact-to-flexural strength ratio under drop-weight impact testing was 0.5449 (54.49%), while for pendulum impact testing, it was 0.3632 (36.32%). These values indicate that rPP retains a substantial portion of its flexural strength under dynamic loading, suggesting tough and energy-absorbing behavior. In contrast, recycled high-density polyethylene (rHDPE) exhibited lower ratios of 0.2765 (27.65%) and 0.1549 (15.49%) under drop and pendulum tests, respectively. These results point toward a more brittle or stiff response under impact despite relatively strong flexural resistance. Overall, the significantly higher ratios observed for rPP demonstrate its superior adaptability to impact stresses, making it more suitable for applications requiring combined structural rigidity and impact tolerance. The following empirical equation was developed to understand the correlation between impact and flexural strengths:

$$\sigma_{\text{impact}} = 0.155 \times A \times B \times \sigma_{\text{flexural}} \tag{1}$$

In the above equation, σ_{impact} is the impact strength, σ_{flexural} is the flexural strength, A is 1 for rHDPE and 2 for rPP, and B is 1 for vertical panels and 2 for horizontal panels. The corresponding values are presented in Table 9. The predictive equation using the constant 0.155 was evaluated against experimental data for both recycled HDPE and PP in vertical and horizontal panel configurations. The coefficient value of 0.155 was selected after iterative evaluation to ensure that the percentage error across all test configurations remained within $\pm 15\%$. This optimized value enhances the reliability and generalizability of the empirical model, as shown in Figure 19. The coefficient 0.155 corresponds to a corrugated panel with similar geometric parameters and configuration, including pitch count, crest height, span length, and impact location. The results showed minimal error for the rHDPE vertical panel (+0.08%) and a reasonably good approximation for the rHDPE horizontal panel (+12.09%). For rPP, the horizontal panel condition slightly over predicted (+13.83%), while the vertical panel configuration showed a larger under prediction (−14.62%). Overall, the formulation offers reliable accuracy, particularly for rHDPE, with potential refinement needed for rPP vertical panel scenarios.

Table 5.9: Summary of relationship of impact load and flexural load.

Material	**Panel**	**Test Type**	**Impact Strength Original (MPa)**	**Impact Strength Empirical (MPa)**	**Percentage Error**
rHDPE	Horizontal	Drop Test	2.25 ± 0.23	2.52 ± 0.13	+12.09%
	Vertical	Pendulum Test	1.26 ± 0.09	1.26 ± 0.06	+0.08%
rPP	Horizontal	Drop Test	4.11 ± 0.31	4.68 ± 0.23	+13.83%
	Vertical	Pendulum Test	2.74 ± 0.23	2.34 ± 0.12	-14.62%

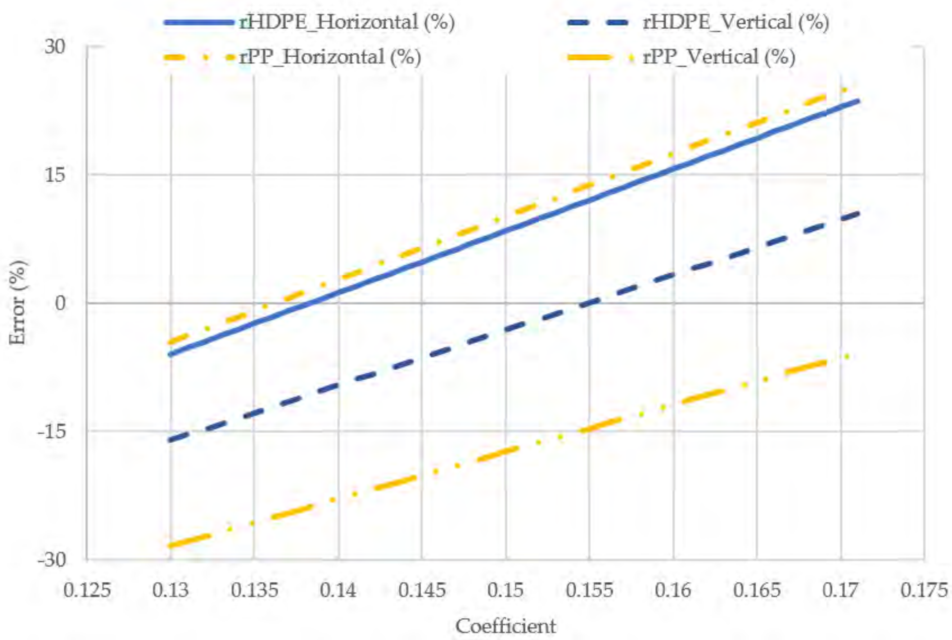


FIGURE 5.19: Variation of percentage error in empirical impact strength with respect to coefficient values for rHDPE and rPP corrugated panels under different configurations.

5.4 Challenges in Practical Applications and Their Solutions

This study demonstrates that recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP) corrugated panels possess considerable potential as sustainable materials for structural applications, especially in roofing and cladding systems. Through a comprehensive experimental program encompassing flexural, impact, dynamic, microstructural, and prototype slab evaluations, both materials have shown promising mechanical integrity, durability, and performance consistency under various load conditions. Flexural testing revealed that rHDPE offered higher maximum stress (8.136 ± 0.407 MPa) and energy absorption capacity (6.826 ± 0.341 MJ/m$^3 \times 10^{-2}$), underscoring its stiffness and load-bearing capability. In contrast, rPP exhibited enhanced ductility, with greater deflection (3.051 ± 0.153 mm $\times$ 10) and strain ($1.391 \pm 0.070 \times 10^{-2}$), indicating its suitability for applications where flexibility and post-yield resilience are critical. These material distinctions provide opportunities for designers to tailor solutions based on specific structural performance requirements, be it rigidity for static loading or ductility for dynamic environments. Dynamic mechanical analysis further enriched this perspective. rPP displayed higher longitudinal damping ($\xi_L = 8.6 \pm 0.7\%$), suggesting superior energy dissipation during vibrational excitation, while rHDPE performed better in out-of-plane damping ($\xi_F^{(\mathrm{OOP})} = 8.2 \pm 0.1\%$), which is advantageous in minimizing vertical resonance. These complementary traits underscore the feasibility of using either material in contexts where acoustic insulation, shock absorption, or vibration control is desired. Impact resistance was a defining metric where rPP outperformed rHDPE across both pendulum and drop-weight tests. It exhibited significantly higher blows-to-failure (102 ± 9) and material toughness ($750.15 \pm 58.84\,\mathrm{kJ/m^3}$), along with ductile fracture patterns characterized by distributed crack formation. Conversely, rHDPE experienced brittle failure with disintegration into fragments, a behavior less ideal for high-strain-rate conditions. These findings reflect rPP's ability to dissipate energy more effectively and maintain structural continuity, key for components subject to repeated or sudden impacts in hailstorms and abnormal weather conditions for use in the construction industry. Recycled polypropylene (rPP) showed a greater ability to retain its flexural strength under impact, with ratios of 54.49% in drop tests and 36.32% in pendulum tests. In contrast, recycled HDPE demonstrated lower retention, with corresponding values of 27.65% and 15.49%. These results quantitatively highlight rPP's superior toughness and its potential for use in applications involving dynamic or sudden loading. Microstructural investigations via SEM and EDS revealed differences in morphological texture and elemental distribution. rPP exhibited a smoother and more homogenous surface with minimal voids, while rHDPE showed roughness and embedded particulate clusters, likely due to incomplete polymer fusion during recycling. Nonetheless, XRD analysis confirmed the retention of crystalline peaks in both polymers post-failure, validating that their semi-crystalline structure was largely preserved despite mechanical deformation. The robust crystallinity underscores the mechanical reliability of the recycled material and suggests long-term dimensional and structural stability under service conditions. The prototype slab fabricated from recycled panels endured peak loads of up to 1.86 kN with a deflection of 27 mm, validating their ability to sustain service loads without abrupt failure. The failure observed near mid-span and joints indicates the importance of improving inter-panel connections, yet the ductile failure mode observed implies predictable and non-catastrophic performance. The water leakage test further affirmed the practicality of the proposed edge-modified panels, where six-hour submersion of overlapped panels showed no leakage. This indicates that simple, yet precise edge detailing can effectively maintain watertight integrity, mimicking traditional roofing practices and enhancing real-world application viability. Despite these promising outcomes, several challenges must be addressed to ensure successful real-world deployment. Variability in feedstock quality, contamination during recycling, inconsistencies in extrusion, and interfacial weaknesses at joints remain notable concerns. Environmental factors, such as prolonged UV exposure, moisture cycling, and temperature fluctuations, could degrade material performance over time. Incorporating UV stabilizers, fiber reinforcement, or advanced compatibilizers may be necessary to overcome these limitations. Nonetheless, the collective findings from this study affirm that recycled polymer corrugated panels are not merely alternatives but serious contenders for sustainable construction materials. Their favorable balance of strength, ductility, energy absorption, and manufacturability, combined with validation and predictive modeling, illustrates their readiness for application in sustainable housing, temporary shelters, and resilient infrastructure. These insights support broader adoption in line with circular economic principles, where waste is valorized into high-performance building components. With continued refinement in processing and joint design, recycled plastics can transition from environmental liabilities into engineered solutions that meet both structural and sustainability goals [210].

5.5 Summary

This study comprehensively assessed the structural, mechanical, and dynamic performance of recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP) corrugated panel made from rHDPE to determine their feasibility for use in construction applications. Corrugation enhances stiffness while reducing mass and embodied energy, promoting eco efficient design. It is further highlighted that corrugated panel arrangement is easy to assemble for housing. The results underscore that both materials retain promising mechanical properties after recycling, though their performance characteristics differ significantly based on loading conditions and failure mechanisms. The following conclusions are drawn for evaluation of corrugated panel:

- rPP demonstrated superior out-of-plane flexural stiffness (2.17 ± 0.33 GPa) with lower damping ($\xi_{F(OOP)} = 4.2 \pm 0.2\%$), indicating enhanced rigidity under dynamic loading. In contrast, rHDPE exhibited higher damping capacity ($\xi_{F(OOP)} = 8.2 \pm 0.1\%$) but lower stiffness ($2.04 \pm 1.07$ GPa), making it more effective for vibration mitigation. These distinctions suggest rPP is preferable for structural applications requiring flexural strength, whereas rHDPE is better suited for acoustic or energy-dissipative roles. Both materials satisfy the functional demands of sustainable roofing and cladding solutions.

- rHDPE demonstrated higher flexural strength ($8.136 \pm 0.407\,\mathrm{MPa}$) and energy absorption $\left(6.826 \pm 0.341\,\mathrm{MJ\,m^{-3}}\right)$ than rPP, indicating superior load-bearing capacity. In contrast, rPP showed greater strain $(1.391 \pm 0.070) \times 10^{-2}$ and larger deflection, highlighting better ductility. These results suggest rHDPE is optimal for rigid structural use, whereas rPP suits flexible applications. Both materials meet performance criteria for sustainable corrugated panels.

- rPP exhibited radial cracking and higher energy absorption, indicating superior ductility and impact toughness. In contrast, rHDPE showed brittle fragmentation with minimal crack propagation. The calculated toughness confirmed rPP's enhanced resistance to dynamic loads. Thus, rPP is more suitable for impact-prone applications.

- rPP outperformed rHDPE in both drop-weight and pendulum impact tests, exhibiting higher total energy absorption ($2.65 \pm 0.20\,\mathrm{kJ}$) and material toughness $\left(750.15 \pm 58.84\,\mathrm{kJ\,m^{-3}}\right)$. The ductile failure pattern in rPP confirms its superior impact resistance. rHDPE, though structurally sound, showed brittle fracture and lower toughness. These findings position rPP as a more resilient material for impact-prone construction applications.

- XRD analysis confirmed that both rHDPE and rPP retained their semi-crystalline structures post-flexural failure. rHDPE showed two prominent peaks at 21.6° and 23.9°, while rPP displayed multiple sharp reflections, indicating higher crystallinity. These results demonstrate that the recycling process preserved the polymers' lattice integrity. Such structural resilience supports their use in mechanically demanding applications. SEM-EDS analysis confirmed that both rHDPE and rPP retained carbon-rich polymer matrices post-failure, with minor inorganic residues. rHDPE showed rougher morphology and higher elemental diversity, suggesting filler remnants or inhomogeneities. In contrast, rPP exhibited a denser surface and cleaner composition, indicating better dispersion. These findings highlight rPP's superior structural uniformity and recycling consistency. The following conclusions are drawn for evaluation of recycled plastic corrugated prototype slab(1.68 m $\times$ 1.60 m $\times$ 12.7 mm).

- The water leakage test demonstrated the effectiveness of edge-modified recycled plastic Prototype slabs in preventing water ingress. The overlapping joint configuration ensured tight interlocking and continuous coverage. No leakage was observed over a 6 hour test duration, confirming the system's waterproofing capability. These results validate the joint design for reliable use in roofing and cladding under wet conditions.

- The flexural evaluation of the recycled plastic prototype slab demonstrated progressive load-deflection behavior, indicating adequate energy dissipation without catastrophic failure. The prototype slab withstood a peak load of 1.86 kN with a maximum deflection of 27 mm, showcasing ductile deformation characteristics. The calculated energy absorbed was 26.8 N·m, confirming structural viability for lightweight applications. These results support their use in affordable housing and sustainable infrastructure requiring moderate load-bearing capacity.

- The empirical relationship between impact and flexural strength showed that, the recycled polypropylene (rPP) exhibited superior impact-to-flexural strength ratios, indicating enhanced toughness. It retained over 50% of its flexural strength under drop impact, compared to 27.65% for rHDPE. This confirms rPP's suitability for applications requiring both strength and impact resistance. The equation using 0.15 constant offers consistent and reliable impact strength predictions, especially for rHDPE, with slight deviations observed in rPP vertical panel applications.

- Long-term performance assessments, including accelerated aging, creep, and UV resistance studies, are recommended to establish comprehensive lifecycle performance. Incorporating durability assessments, such as accelerated UV exposure and creep testing, alongside the use of functional additives, can further improve environmental resilience and extend lifecycle performance of recycled plastic composite

- Future research should prioritize strain-based testing in accordance with polymer-specific standards and employ advanced measurement techniques such as digital image correlation (DIC) to generate precise data for predictive modeling and durability assessment.

Overall, rPP emerges as a more flexible and impact-resilient material, ideal for use in structures exposed to dynamic or repetitive loading. rHDPE, with its superior stiffness and damping capacity, is more suitable for static load bearing or vibration-sensitive applications. Both materials, when properly processed and assembled, show strong potential for integration into sustainable construction solutions, especially in sustainable housing, temporary shelters, and cladding systems where mechanical efficiency, durability, and environmental resilience are critical. Further studies shall facilitate the production of sustainable products and full-scale behaviour in housing. SDG 11- Sustainable Cities and Communities – This study contributes to SDG 11 by promoting the use of recycled plastic waste, specifically rHDPE and rPP, for manufacturing durable corrugated roofing panels. These panels provide a sustainable alternative to conventional materials while reducing landfill accumulation and supporting circular construction practices. By validating the structural and environmental viability of recycled plastics in building applications, the research supports the creation of more resilient and eco-friendly urban infrastructure.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

The study established that, while plastic waste has received increasing attention for partial applications such as fillers in concrete, road pavements, and temporary structures the concept of using recycled plastics as primary construction materials remains underutilized. It became evident that most previous studies lacked an integrated approach to mechanical, thermal, and structural evaluation, and that the absence of regulatory frameworks and technical guidelines poses a significant barrier to adoption.

Furthermore, the review underscored the urgency of transitioning toward circular economic practices in the construction sector, especially in regions where plastic waste mismanagement is prevalent. This study by identifies research gaps and justifies the need for a performance-driven, sustainability-oriented exploration of recycled plastic for use in structural products. The study focuses on the development of products from recycled plastic. Competitive market analysis for mortarless construction is recommended in future research.

This doctoral study culminates in the following major conclusion:

- The feasibility of transforming municipal plastic waste into structural construction components through mechanical extrusion. The 166 specimens that were tested across shear, flexural, tensile, and compression categories, showed high tensile and shear strength of rHDPE, while LDPE and PP blends improved ductility and energy absorption. Polyolefin and samicanite exhibited good thermal stability, and gas emission analysis confirmed environmental sustainability.
    - The SEM and TGA evaluations of raw recycled polymers indicated the existence of minor contaminants, yet confirmed their overall thermal stability. The negligible weight reduction during thermal degradation suggests that these materials do not emit harmful gases, underscoring their environmental safety. Additionally, the polymers exhibited good processability within the thermal parameters outlined in this study.
    - Mechanical testing under various loading conditions validated the suitability of these materials for construction-related applications. Shear tests demonstrated that rHDPE and rPP have comparable energy absorption capacities, making them effective for scenarios where shear resistance is critical. Optimizing blended formulations is encouraged to improve their energy absorption in such conditions. Flexural assessments showed that the rHDPE + rSAM combination performed well under load, while rPP recorded the highest flexural peak energy absorption (F-PEA) of 208.81 J/m^3, surpassing all other blends tested. In compression testing, rHDPE+POL and rHDPE+rSAM showed superior performance, indicating their structural application potential, whereas the base polymers rHDPE and rPP exhibited relatively lower energy absorption levels.
    - Tensile analysis revealed that rPP had the highest energy absorption capacity (T-TEA: 7.13 kJ/m^3), highlighting its robustness under tensile forces. rHDPE offered a moderate balance between strength and ductility. In contrast, mixtures such as rHDPE + rLDPE performed

poorly, likely due to incompatibility between the polymer constituents, emphasizing the critical role of blend compatibility in recycled plastic applications.

  - Supporting these mechanical findings, morphological and chemical characterizations provided further insight. SEM images of fractured surfaces revealed voids, clustered regions, and ductile tearing patterns in rHDPE, reinforcing its effectiveness for load-bearing functions. FTIR spectroscopy detected changes in chemical structure and enhanced cross-linking after the extrusion process. This process likely caused molecular changes such as chain scission, oxidation, and the formation of new functional groups, which collectively contributed to the enhanced mechanical behavior of the recycled materials.
  - Both rHDPE and rPP demonstrated desirable tensile strength and ductility, making them viable candidates for structural reinforcements, protective barriers, and other load-bearing elements in the construction sector. Their compatibility with extrusion-based recycling methods, alongside their strong mechanical performance, supports their role as sustainable substitutes for traditional building materials. Their reuse aligns with circular economy strategies by reducing the reliance on virgin materials and significantly lowering the environmental impact of construction.

- The development of recycled plastic rebars for mortar-free and lightly loaded structural applications. A total of 48 rebars of varying diameters and profiles were tested, with 25 mm ribbed PP rebars showing the highest strength and energy absorption. SEM and XRD analyses confirmed material integrity, with HDPE exhibiting ductile failure and PP showing brittle fractures. An empirical model was developed to predict tensile behavior, supporting future design use. The study validated mechanical extrusion as a scalable, low-emission method for producing structural-grade recycled plastic reinforcements.

  - Recycled plastic rebars were fabricated in plain and ribbed configurations across three diameters, with the 25 mm ribbed rPP rebars showing optimal mechanical performance.
  - Recycled plastic rebars were fabricated in both plain and ribbed configurations, across three diameters. Among them, the 25 mm ribbed rPP rebar exhibited the most favorable mechanical performance.The ribbed rPP rebars (21 MPa) and rHDPE (16 MPa) exhibit 5–10% of the tensile strength of steel (400 MPa) and 15–25% of bamboo (100–200 MPa) while maintaining superior ductility and corrosion resistance.
  - SEM confirmed ductile fracture in HDPE and brittle behavior in PP; XRD analysis revealed that crystallinity was retained post-processing.
  - The empirical model for tensile behavior prediction of recycled rebars proved reliable, supporting design integration.
  - The study marks a significant shift from using recycled plastics as fillers to their use as full-section, load-bearing reinforcements.

- The corrugated panels underwent flexural, dynamic, and impact evaluations, with rHDPE showing higher stiffness and load capacity, while rPP exhibited superior ductility and impact resistance. Dynamic tests highlighted distinct damping behaviors in each material. Prototype slab testing confirmed structural viability and resistance to water ingress. The findings affirm the potential of recycled panels as sustainable and durable alternatives to traditional sheet materials.

  - rHDPE exhibited higher flexural strength and stiffness (8.136 ± 0.407 MPa and 6.826 ± 0.341 MJ/m^3), while rPP demonstrated greater ductility and impact absorption.
  - o rPP panels showed better adaptability under dynamic loads, retaining over 50% of their original flexural strength post-impact.
  - rHDPE was more suitable for static load-bearing due to higher damping and stiffness, whereas rPP was ideal for dynamic and impact-resilient applications.

- XRD confirmed preserved crystalline structure in both materials; SEM-EDS showed better homogeneity in rPP compared to rHDPE.
- Water leakage tests confirmed the watertight performance of edge-modified panels, proving their real-world applicability for roofing.
- Full-scale slab tests showed that recycled panels could withstand 1.86 kN with 27 mm deflection, confirming ductility and structural reliability.
- An empirical equation linking impact and flexural strength ($\sigma_{\text{impact}} = 0.15AB\sigma_{\text{flexural}}$) was validated, particularly accurate for rHDPE.
- o These panels demonstrated potential for use in roofing, wall claddings, shelters, and affordable housing systems, aligning with circular construction goals.

The cumulative findings of this thesis demonstrate that mechanically recycled plastics, when properly processed and characterized, possess the structural, thermal, and environmental qualities necessary for widespread adoption in construction applications. This research not only extends the utility of plastic waste beyond its conventional disposal or filler roles but also pioneers the development of standardized structural elements such as rebars and corrugated panels from 100% recycled polymers. The approach contributes meaningfully to circular economy practices, reduces dependency on virgin resources, and offers scalable, cost-effective alternatives for infrastructure in both rural and urban settings. These results signify a transformative shift toward eco-efficient construction systems that harmonize material innovation with sustainability goals.

6.2 Addressing the Research Questions

1. How can the direct application of post-consumer HDPE and PP in structural elements help mitigate the environmental impacts of plastic waste accumulation?

- By directly integrating post-consumer HDPE and PP into structural construction products, the research diverts plastic waste from landfills and incineration, addressing critical environmental challenges. This promotes circular resource utilization and significantly reduces the ecological footprint of both waste management and building material production.

2. What is the feasibility of transforming recycled thermoplastics into structurally competent construction materials using mechanical extrusion techniques?

- The study demonstrates that recycled thermoplastics can be mechanically extruded into construction-grade materials with consistent quality and minimal emissions. A total of 140 specimens were successfully processed and tested, confirming that the technique is both technically viable and environmentally sustainable for structural applications.

3. To what extent do recycled HDPE, PP, and polyolefin blends retain their chemical integrity and generate low emissions during processing for sustainable construction applications?

- FTIR and TGA analyses revealed that the recycled materials maintained stable chemical bonds post-extrusion. Additionally, emissions recorded during the process were minimal, supporting the eco-efficiency of mechanical recycling as a clean and repeatable method for producing construction elements.

4. How can recycled plastic rebars be engineered to withstand structural loads in light-duty construction applications?

- Rebars fabricated from rHDPE and rPP were designed in plain and ribbed configurations and tested under tensile loading. Ribbed rPP rebars with 25 mm diameter achieved peak tensile loads of 12.2 kN and showed strong energy absorption, validating their use in light-load structural systems like walls and modular units.

5. What influence do surface texture and cross-sectional dimensions have on the mechanical performance of extruded recycled plastic rebars?

- Surface ribbing enhanced bonding and tensile strength, while larger diameters provided improved structural integrity. The 25 mm ribbed rPP rebars outperformed other configurations in terms of mechanical strength and toughness, demonstrating the critical role of geometry in performance optimization.

6. How do the failure modes and microstructural characteristics of rHDPE and rPP rebars affect their suitability for use as primary reinforcement materials?

- SEM imaging revealed ductile failure in rHDPE and brittle cracking in rPP. XRD results showed high crystallinity in well-extruded rebars, correlating with better load distribution and mechanical stability. These insights help identify material-specific design strategies for structural reinforcement use.

7. How do recycled HDPE and PP corrugated panels perform under flexural, impact, and dynamic loading typical of roofing and cladding applications?

- rHDPE panels exhibited high flexural strength (>1.9 kN), while rPP panels showed superior impact resistance and retained more than 50% of original strength after repeated impacts. These results confirm their capacity to endure service conditions typical of roofing and wall systems.

8. What are the dynamic mechanical properties of recycled plastic panels under in-plane and out-of-plane resonance conditions?

- Dynamic testing (ASTM E1876) revealed that rPP had higher damping in longitudinal modes, whereas rHDPE provided better attenuation in out-of-plane vibration. These material-specific properties enable tailored application in environments exposed to dynamic loads or mechanical vibrations.

9. How effective are recycled plastic corrugated panels in providing water-tightness and mechanical stability when used in overlapping structural assemblies?

- Prototype slab testing demonstrated that the panels remained watertight and structurally sound under overlapping conditions, making them viable for cladding and roofing. Their resistance to leakage and mechanical deformation supports practical adoption in sustainable construction systems.

6.3 Recommendations

To facilitate the adoption of recycled plastics in construction, it is crucial to develop formalized testing protocols and performance benchmarks. National and international standards organizations should collaborate to establish specifications for recycled plastic rebars, sheets, and blocks. These should include design guidelines tailored for light structural loads and quality control systems to ensure consistent material properties.Standardization of testing protocols in line with international polymer standards, coupled with benchmarking against conventional materials, will enhance comparability and model robustness. Furthermore, while laboratory-based evaluations indicate mechanical viability, real-world environmental testing must be undertaken. Exposure to UV radiation, humidity, temperature fluctuations, and fire conditions will reveal the long-term durability and limitations of these materials under operational stresses. Future research should pilot field-scale or prototype applications to assess real-world performance, scalability, and economic viability.

Further research should focus on improving the material characteristics of recycled polymer blends. The incorporation of compatibilizers, nano-fillers, or natural fiber reinforcements can significantly boost mechanical strength, impact resistance, and thermal performance. Investigations into additives that improve UV resistance, color stability, and weather durability will enhance the suitability of these materials for outdoor construction. These innovations will help elevate recycled plastics from low-grade fillers to high-performance alternatives that can compete with traditional construction materials such as steel and concrete.

Pilot construction projects using recycled plastics in modular buildings, walls, and roofing can help validate lab findings at scale. Monitoring these implementations will provide insights into labor requirements, structural performance, and community acceptance. Additionally, life cycle assessments (LCA) and techno-economic analyses (TEA) are recommended to quantify energy savings, cost benefits, and carbon reduction. Policy support, including incentives for recycled material usage, streamlined waste collection systems, and training for construction professionals, will be instrumental in aligning this practice with the goals of sustainable urban development and the circular economy. Future research should expand on this work by incorporating durability testing protocols that capture creep behavior, fatigue resistance, and environmental degradation to better reflect in-service performance of recycled polymer rebars. Establishing quantitative benchmarks such as minimum tensile strength thresholds for structural acceptance and optimal rebar cross-sections for specific applications—would provide clearer guidance for practical adoption. Additionally, integrating sustainability evaluations, including life cycle assessment (LCA), embodied carbon calculations, and recyclability analyses, is recommended to align material development with broader environmental objectives. Such efforts will strengthen the scientific foundation of recycled polymer rebars while supporting their use in sustainable construction practices. Although rebar arrangement was not directly investigated, literature suggests bidirectional placement enhances stress distribution; this will form part of future work. Future benchmarking with GFRP, bamboo, and GI alternatives is planned to evaluate durability, stiffness-to-weight ratio, and economic feasibility.

This study primarily focused on the mechanical and microstructural characterization of recycled polymer rebars under short-term laboratory conditions. Long-term performance aspects such as creep, fatigue, and deformation under sustained loading were not experimentally investigated. Similarly, the influence of environmental factors, including ultraviolet (UV) degradation, thermal aging, and weathering, was acknowledged but not assessed, as such evaluations require extended exposure periods and specialized facilities beyond the scope of the present work. Although these recycled-plastic components are unsuitable as direct replacements for steel in reinforced concrete, they present sustainable solutions for secondary, and light-duty uses. Benchmarking with conventional materials indicates that recycled-plastic rebars offer lower stiffness but superior ductility and corrosion resistance. Their sustainable composition and adequate strength confirm their feasibility for light-load structural use, supporting circular construction objectives. Further material enhancement through admixtures can improve performance and facilitate their adoption in other structural elements. These limitations, while valid within the research design, highlight areas that need to be explored before large-scale structural implementation.

Bibliography

[1] M. A. R. Bhuiyan, M. A. Darda, A. Ali, A. R. Talha, M. F. Hossain, M. Mohebbullah, and M. A. Islam, "Heat insulating jute-reinforced recycled polyethylene and polypropylene bio-composites for energy conservation in buildings," *Materials Today Communications*, vol. 37, p. 106948, 2023.

[2] M. M. Ajmal, A. U. Qazi, A. Ahmed, U. A. Mughal, S. Abbas, S. M. S. Kazmi, and M. J. Munir, "Structural performance of energy-efficient geopolymer concrete confined masonry: An approach towards decarbonization," *Energies*, vol. 16, no. 8, p. 3579, 2023.

[3] B. Haba, S. Djellali, Y. Abdelouahed, S. Boudjelida, F. Faleschini, and M. Carraro, "Transforming plastic waste into value: A review of management strategies and innovative applications in sustainable construction," *Polymers*, vol. 17, no. 7, p. 881, 2025.

[4] R. Geyer, J. R. Jambeck, and K. L. Law, "Production, use, and fate of all plastics ever made," *Science Advances*, vol. 9, p. 1005, 2023.

[5] Y. Chen and M. Zhang, "Nanomaterial-based modifications for improving the thermal stability of recycled plastics," *Journal of Polymer Science*, vol. 62, pp. 301–319, 2024.

[6] H. Khan and M. Raza, "Enhancing the mechanical properties of waste plastics through advanced recycling techniques," *Materials Science Advances*, vol. 45, pp. 192–211, 2024.

[7] F. Vilaplana and S. Karlsson, “Quality concepts for the improved use of recycled polymeric materials: A review,” *Macromol. Mater. Eng.*, vol. 293, pp. 274–297, 2008.

[8] Y. Liang, Q. Tan, Q. Song, and J. Li, “An analysis of the plastic waste trade and management in asia,” *Waste Manag.*, vol. 119, pp. 242–253, 2021.

[9] Y. Liang, “An analysis of the plastic waste trade and management in asia,” *Waste Management*, vol. 119, pp. 242–253, 2021.

[10] M. Al-Maadeed, “An overview of solid waste management and plastic recycling in qatar,” *Journal of Polymers and the Environment*, vol. 20, pp. 186–194, 2012.

[11] U.S. Environmental Protection Agency, “National overview: Facts and figures on materials, wastes and recycling.” https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials, 2021. Accessed: 2025-04-30.

[12] L. Shen, “Open-loop recycling: A lca case study of pet bottle-to-fibre recycling,” *Resources, Conservation and Recycling*, vol. 55, pp. 34–52, 2010.

[13] K. P. Gopinath, “A critical review on the influence of energy, environmental, and economic factors on plastic waste recycling,” *Journal of Cleaner Production*, vol. 274, p. 123031, 2020.

[14] R. C. Thompson, S. H. Swan, C. J. Moore, and F. S. vom Saal, “Our plastic age,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, no. 1526, pp. 1973–1976, 2009.

[15] A. A. Yussuf, M. A. Al-Saleh, S. T. Al-Enezi, and G. Abraham, “Synthesis and characterization of conductive polypyrrole: The influence of the oxidants and monomer on the electrical, thermal, and morphological properties,” *International Journal of Polymer Science*, vol. 2018, p. 4191747, 2018.

[16] A. Das, C. Chatham, J. Fallon, C. Zawaski, E. Gilmer, C. Williams, and M. Bortner, "Current understanding and challenges in high temperature additive manufacturing of engineering thermoplastic polymers," *Addit. Manuf.*, vol. 34, p. 101218, 2020.

[17] L. Lai, B. Chivers, D. Burke, A. H. Dinh, L. Ye, Y. Wang, Y. Wang, L. Wei, and Y. Chen, "Solid carbon co-products from hydrogen production by methane pyrolysis: Current understandings and recent progress," *Carbon*, vol. 216, p. 118507, 2024.

[18] N. Ahmed and T. Khan, "Structural analysis of sustainable polymer composites for circular construction," *Construction and Building Materials*, vol. 383, p. 131311, 2023.

[19] J. Tanner, K. Wilson, and Y. Huang, "Circular economy strategies for enhancing waste plastic recycling," *Journal of Environmental Policy*, vol. 51, pp. 22–44, 2024.

[20] N. C. Onyenokporo, A. Beizaee, O. F. Adekeye, and M. A. Oyinlola, "The bottle house: Upcycling plastic bottles to improve the thermal performance of low-cost homes," *Sustainability*, vol. 16, p. 1360, 2024.

[21] M. Xanthos, "Pet recycling: Processes and applications," *Journal of Polymers and the Environment*, vol. 31, pp. 11–29, 2023.

[22] J. Hopewell, R. Dvorak, and E. Kosior, "Plastics recycling: Challenges and opportunities," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, pp. 2115–2126, 2009.

[23] A. R. Rahimi and J. M. Garciá, "Chemical recycling of waste plastics for new materials production," *Nature Reviews Chemistry*, vol. 1, p. 0046, 2017.

[24] K. Ragaert, L. Delva, and K. Van Geem, "Mechanical and chemical recycling of solid plastic waste," *Waste Management*, vol. 69, pp. 24–58, 2017.

[25] R. Volk, "Techno-economic assessment and comparison of different plastic recycling pathways," *Journal of Industrial Ecology*, vol. 25, no. 5, pp. 1207–1222, 2021.

[26] K. Sharma and N. Patel, "Surface modification techniques for improving the performance of recycled plastics," *Advanced Materials Research*, vol. 58, pp. 87–106, 2024.

[27] W. Ferdous, A. Manalo, R. Siddique, P. Mendis, Y. Zhuge, H. S. Wong, W. Lokuge, T. Aravinthan, and P. Schubel, "Recycling of landfill wastes (tyres, plastics and glass) in construction—a review on global waste generation, performance, application and future opportunities," *Resources, Conservation and Recycling*, vol. 173, p. 105745, 2021.

[28] J. Maris, S. Bourdon, J. M. Brossard, L. Cauret, L. Fontaine, and V. Montembault, "Mechanical recycling: Compatibilization of mixed thermoplastic wastes," *Polymer Degradation and Stability*, vol. 147, pp. 245–266, 2018.

[29] H. Ahmad and D. Rodrigue, "Crosslinked polyethylene: A review on the crosslinking techniques, manufacturing methods, applications, and recycling," *Polymer Engineering and Science*, vol. 62, pp. 2376–2401, 2022.

[30] A. Schade, M. Melzer, S. Zimmermann, T. Schwarz, K. Stoewe, and H. Kuhn, "Plastic waste recycling—a chemical recycling perspective," *ACS Sustainable Chemistry Engineering*, vol. 12, no. 33, pp. 12270–12288, 2024.

[31] K. Kabirifar, "Waste management factors contributing to reuse and recycle strategies," *Journal of Cleaner Production*, vol. 263, p. 121265, 2020.

[32] M. Phanisankar, R. Das, and S. Rao, "Pyrolysis and gasification of plastic waste: A sustainable approach to waste management," *Energy and Environmental Research*, vol. 41, pp. 145–162, 2023.

[33] L. Shi and L. Zhu, "Recent advances and challenges in enzymatic depolymerization and recycling of pet wastes," *ChemBioChem*, vol. 25, p. 202300578, 2024.

[34] J. van Engeland, "Strategic network optimization models in waste supply chains," *Omega*, vol. 91, p. 102012, 2020.

[35] K. F. Drain, W. R. Murphy, and M. S. Otterburn, "Polymer waste-resource recovery," *Conservation and Recycling*, vol. 4, pp. 201–218, 1981.

[36] S. A. Mansour, A. Mohammed, and R. Khalid, “Pet plastic aggregates in sustainable concrete production: A critical review,” *Journal of Cleaner Production*, vol. 362, p. 132112, 2022.

[37] M. Abu-Saleem, Y. Zhuge, R. Hassanli, M. Ellis, M. Rahman, and P. Levett, “Evaluation of concrete performance with different types of recycled plastic waste for kerb application,” *Construction and Building Materials*, vol. 293, p. 123477, 2021.

[38] X.-F. Chen and C.-J. Jiao, “Effect of physical properties of construction wastes based composite photocatalysts on the sulfur dioxide degradation: Experimental investigation and mechanism analysis,” *Case Studies in Construction Materials*, vol. 17, p. e01237, 2022.

[39] N. I. Ibrahim, “Overview of bioplastic introduction and its applications in construction,” *Coatings*, vol. 11, no. 11, p. 1423, 2021.

[40] M. Oliveira, K. L. Pickering, and C. Gauss, “Hybrid polyethylene composites with recycled carbon fibres and hemp fibres produced by rotational moulding,” *Journal of Composites Science*, vol. 6, no. 11, p. 352, 2022. Reports increased Young’s modulus in hybrid PE composites reinforced with recycled carbon fibre and hemp.

[41] M. M. Ajmal, A. U. Qazi, A. Ahmed, U. A. Mughal, S. Abbas, S. M. S. Kazmi, and M. J. Munir, “Structural performance of energy-efficient geopolymer concrete confined masonry: An approach towards decarbonization,” *Energies*, vol. 16, no. 8, p. 3579, 2023.

[42] S. Ahmed and M. Ali, “Development and engineering evaluation of interlocking hollow blocks made of recycled plastic for mortar-free housing,” *Buildings*, vol. 15, no. 17, p. 2996, 2025.

[43] A. J. Babafemi, “Engineering properties of concrete with waste recycled plastic: A review,” *Sustainability*, vol. 10, no. 11, p. 3875, 2018. Documents reductions in density and compressive strength with increasing plastic aggregate substitution (up to 50

[44] Y. Aocharoen and [and others], “Compressive mechanical and durability properties of concrete with recycled hdpe and pet aggregates,” *Construction and Building Materials*, vol. ?”volume?”, 2023.

[45] S. C. Kou and C. S. Poon, “Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates,” *Construction and Building Materials*, vol. 325, p. 126856, 2022.

[46] R. Saxena, S. Siddique, T. Gupta, R. Sharma, and S. Chaudhary, “Impact resistance and energy absorption capacity of concrete containing plastic waste,” *Construction and Building Materials*, vol. 176, pp. 415–421, 2018.

[47] R. Siddique, J. Khatib, and I. Kaur, “Use of recycled plastic in concrete: A review,” *Waste Management*, vol. 28, no. 10, pp. 1835–1852, 2008.

[48] Tamrin and J. Nurdiana, “The effect of recycled hdpe plastic additions on concrete performance,” *Recycling*, vol. 6, p. 18, 2021.

[49] T. Naik, S. Singh, C. Huber, and B. Brodersen, “Use of post-consumer waste plastics in cement-based composites,” *Cement and Concrete Research*, vol. 26, pp. 1489–1492, 1996.

[50] A. Jassim, “Recycling of polyethylene waste to produce plastic cement,” *Procedia Manufacturing*, vol. 8, pp. 635–642, 2016.

[51] J. Sule, “Use of waste plastics in cement-based composite for lightweight concrete production,” *International Journal of Research in Engineering and Technology*, vol. 2, pp. 44–54, 2017.

[52] A. Choudhary, J. Jha, K. Gill, and S. Shukla, “Utilization of fly ash and waste recycled product reinforced with plastic wastes as construction materials in flexible pavement,” in *Proceedings of Geo-Congress 2014: Geo-Characterization and Modeling for Sustainability*, pp. 3890–3902, 2014.

[53] N. Mashaan and C. Ouano, “An investigation of the mechanical properties of concrete with different types of waste plastics for rigid pavements,” *Applied Mechanics*, vol. 6, no. 1, p. 9, 2025.

[54] N. Simon, K. Raubenheimer, N. Urho, S. Unger, D. Azoulay, T. Farrelly, J. Sousa, H. van Asselt, G. Carlini, C. Sekomo, and M. Schulte, "A binding global agreement to address the life cycle of plastics," *Science*, vol. 373, no. 6550, pp. 43–47, 2021.

[55] O. Marzouk, R. Dheilly, and M. Queneudec, "Valorization of post-consumer waste plastic in cementitious concrete composites," *Waste Management*, vol. 27, pp. 310–318, 2007.

[56] Y. Choi, D. Moon, J. Chung, and S. Cho, "Effects of waste pet bottles aggregate on the properties of concrete," *Cement and Concrete Research*, vol. 39, pp. 33–38, 2009.

[57] C. Albano, N. Camacho, M. Hernández, A. Matheus, and A. Gutiérrez, "Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios," *Waste Management*, vol. 29, pp. 2707–2716, 2009.

[58] M. Frigione, "Recycling of pet bottles as fine aggregate in concrete," *Waste Management*, vol. 30, pp. 1101–1106, 2010.

[59] K. Ramadevi and R. Manju, "Experimental investigation on the properties of concrete with plastic pet (bottle) fibres as fine aggregates," *Journal of Emerging Technologies and Advanced Engineering*, vol. 2, pp. 42–46, 2012.

[60] R. Silva, J. Brito, and N. Saikia, "Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates," *Cement and Concrete Composites*, vol. 35, pp. 23–31, 2013.

[61] K. Hannawi, S. Kamali-Bernard, and W. Prince, "Physical and mechanical properties of mortars containing pet and pc waste aggregates," *Waste Management*, vol. 30, pp. 2312–2320, 2010.

[62] M. Juki, "Relationship between compressive, splitting tensile and flexural strength of concrete containing granulated waste polyethylene terephthalate (pet) bottles as fine aggregate," *Advanced Materials Research*, vol. 795, pp. 356–359, 2013.

[63] N. Saikia and J. Brito, "Waste polyethylene terephthalate as an aggregate in concrete," *Materials Research*, vol. 16, pp. 341–350, 2013.

[64] J. Correia, J. Lima, and J. Brito, "Post-fire mechanical performance of concrete made with selected plastic waste aggregates," *Cement and Concrete Composites*, vol. 53, pp. 187–199, 2014.

[65] A. Mohammed, "Flexural behavior and analysis of reinforced concrete beams made of recycled pet waste concrete," *Construction and Building Materials*, vol. 155, pp. 593–604, 2017.

[66] N. Saikia and J. Brito, "Waste polyethylene terephthalate as an aggregate in concrete," *Materials Research*, vol. 16, pp. 341–350, 2013.

[67] J. Correia, J. Lima, and J. Brito, "Post-fire mechanical performance of concrete made with selected plastic waste aggregates," *Cement and Concrete Composites*, vol. 53, pp. 187–199, 2014.

[68] A. Mohammed, "Flexural behavior and analysis of reinforced concrete beams made of recycled pet waste concrete," *Construction and Building Materials*, vol. 155, pp. 593–604, 2017.

[69] S. Shubbar and A. Al-Shadeedi, "Utilization of waste plastic bottles as fine aggregate in concrete," *Kufa Journal of Engineering*, vol. 8, pp. 132–146, 2017.

[70] Y. Bandodkar, A. Gaonkar, and N. Gaonkar, "Pulverised pet bottles as partial replacement for sand," *International Journal of Earth Sciences and Engineering*, vol. 4, pp. 1009–1012, 2011.

[71] B. Safi, M. Saidi, D. Aboutaleb, and M. Maallem, "The use of plastic waste as fine aggregate in the self-compacting mortars: Effect on physical and mechanical properties," *Construction and Building Materials*, vol. 43, pp. 436–442, 2013.

[72] M. Batayneh, I. Marie, and I. Asi, "Use of selected waste materials in concrete mixes," *Waste Management*, vol. 27, pp. 1870–1876, 2007.

[73] B. Rai, S. Rushad, B. Kr, and S. Duggal, "Study of waste plastic mix concrete with plasticizer," *ISRN Civil Engineering*, vol. 2012, p. 469272, 2012.

[74] Y. Ghernouti, B. Rabehi, B. Safi, and R. Chaid, "Use of recycled plastic bag waste in the concrete," *Materials Processing and Environment*, vol. 8, pp. 480–487, 2009.

[75] B. Jaivignesh and A. Sofi, "Study on mechanical properties of concrete using plastic waste as an aggregate," in *IOP Conference Series: Earth and Environmental Science*, vol. 80, IOP Publishing, 2017.

[76] M. Aldahdooh, A. Jamrah, A. Alnuaimi, M. Martini, M. Ahmed, and A. Ahmed, "Influence of various plastics-waste aggregates on properties of normal concrete," *Journal of Building Engineering*, vol. 17, pp. 13–22, 2018.

[77] J. Akinyele and A. Ajede, "The use of granulated plastic waste in structural concrete," *African Journal of Science, Technology, Innovation and Development*, vol. 10, pp. 169–175, 2018.

[78] H. Dweik, M. Ziara, and M. Hadidoun, "Enhancing concrete strength and thermal insulation using thermoset plastic waste," *International Journal of Polymer Materials and Polymer Biomaterials*, vol. 57, pp. 635–656, 2008.

[79] S. Kou, G. Lee, C. Poon, and W. Lai, "Properties of lightweight aggregate concrete prepared with pvc granules derived from scraped pvc pipes," *Waste Management*, vol. 29, pp. 621–628, 2009.

[80] N. Haghighatnejad, S. Mousavi, S. Khaleghi, A. Tabarsa, and S. Yousefi, "Properties of recycled pvc aggregate concrete under different curing conditions," *Construction and Building Materials*, vol. 126, pp. 943–950, 2016.

[81] C. Aciu, D. Ilutiu-Varvara, D. Manea, Y. Orban, and F. Babota, "Recycling of plastic waste materials in the composition of ecological mortars," in *Procedia Manufacturing*, vol. 22, pp. 274–279, 2018.

[82] P. Asokan, M. Osmani, and A. Price, "Improvement of the mechanical properties of glass fibre reinforced plastic waste powder filled concrete," *Construction and Building Materials*, vol. 24, pp. 448–460, 2010.

[83] S. Ahmed and M. Ali, "Use of agriculture waste as short discrete fibers and glass-fiber-reinforced-polymer rebars in concrete walls for enhancing impact resistance," *Journal of Cleaner Production*, vol. 268, p. 122211, 2020.

[84] J. Galvão, K. Portella, A. Joukoski, R. Mendes, and E. Ferreira, "Use of waste polymers in concrete for repair of dam hydraulic surfaces," *Construction and Building Materials*, vol. 25, pp. 1049–1055, 2011.

[85] F. Liu, Y. Yan, L. Li, C. Lan, and G. Chen, "Performance of recycled plastic-based concrete," *Journal of Materials in Civil Engineering*, vol. 27, p. A4014004, 2015.

[86] T. Chandni and K. Anand, "Utilization of recycled waste as filler in foam concrete," *Journal of Building Engineering*, vol. 19, pp. 154–160, 2018.

[87] M. Záleská, M. Pavlíková, J. Pokorný, O. Jankovský, Z. Pavlík, and R. Černý, "Structural, mechanical and hygrothermal properties of lightweight concrete based on the application of waste plastics," *Construction and Building Materials*, vol. 180, pp. 1–11, 2018.

[88] J. Thorneycroft, J. Orr, P. Savoikar, and R. Ball, "Performance of structural concrete with recycled plastic waste as a partial replacement for sand," *Construction and Building Materials*, vol. 161, pp. 63–69, 2018.

[89] J. Appiah, V. Berko-Boateng, and T. Tagbor, "Use of waste plastic materials for road construction in ghana," *Case Studies in Construction Materials*, vol. 6, pp. 1–7, 2017.

[90] R. Vasudevan, S. Saravanavel, S. Rajasekaran, and D. Thirunakkarasu, "Utilisation of waste plastics in construction of flexible pavement," *Indian Highways*, vol. 34, pp. 5–20, 2006.

[91] K. Zhang, J. Xiong, C. Ruiz, and J. Zhang, "Design and performance assessment of sustainable road pothole patching materials using waste cooking oil, plastic, and reclaimed asphalt pavement," *Construction and Building Materials*, vol. 429, p. 136426, 2024.

[92] M. Pallavi, S. Dey, G. Veerendra, S. Padavala, and A. Manoj, "Optimizing the bituminous pavement constructions with waste plastic materials improved the road constructions performance and their future applications," *AI in Civil Engineering*, vol. 3, p. 16, 2024.

[93] R. Vasudevan, A. Sekar, B. Sundarakannan, and R. Velkennedy, "A technique to dispose waste plastics in an ecofriendly way—application in construction of flexible pavements," *Construction and Building Materials*, vol. 28, pp. 311–320, 2012.

[94] A. Priyanka, K. NarasimhaReddy, and N. Balaji, "Analysis in the application of plastic waste as a constructive material in flexible pavement," *Mathematics Education*, vol. 12, pp. 166–170, 2021.

[95] E. Ahmadinia, M. Zargar, M. Karim, M. Abdelaziz, and P. Shafigh, "Using waste plastic bottles as additive for stone mastic asphalt," *Materials and Design*, vol. 32, pp. 4844–4849, 2011.

[96] F. Giustozzi, "Polymer-modified pervious concrete for durable and sustainable transportation infrastructures," *Construction and Building Materials*, vol. 111, pp. 502–512, 2016.

[97] A. Al-Hadidy and Y. Tan, "Mechanistic approach for polypropylene-modified flexible pavements," *Materials and Design*, vol. 30, pp. 1133–1140, 2009.

[98] A. Dandge, "Utilization of waste plastic materials in road construction," *Journal of Advanced Research in Mechanical and Civil Engineering*, vol. 3, pp. 1–9, 2016.

[99] A. Gawande, G. Zamare, V. Renge, S. Tayde, and G. Bharsakale, "An overview on waste plastic utilization in asphalting of roads," *Journal of Engineering Research and Studies*, vol. 3, pp. 1–5, 2012.

[100] M. Chavan, "Use of plastic waste in flexible pavements," *International Journal of Application or Innovation in Engineering and Management*, vol. 2, pp. 540–552, 2013.

[101] B. Mishra and R. Mishra, "A study on use of industrial wastes in rural road construction," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 4, pp. 10387–10398, 2015.

[102] J. Oliveira, "Developing enhanced modified bitumens with waste engine oil products combined with polymers," *Construction and Building Materials*, vol. 160, pp. 714–724, 2018.

[103] D. Casey, C. McNally, A. Gibney, and M. Gilchrist, "Development of a recycled polymer modified binder for use in stone mastic asphalt," *Resources, Conservation and Recycling*, vol. 52, pp. 1167–1174, 2008.

[104] V. Punith and A. Veeraragavan, "Behavior of asphalt concrete mixtures with reclaimed polyethylene as additive," *Journal of Materials in Civil Engineering*, vol. 19, pp. 500–507, 2007.

[105] P. Suriya, S. Sangeetha, R. Abirami, and P. Subathra, "Stabilization of red soil using polypropylene," *Materials Today: Proceedings*, vol. 46, pp. 5881–5884, 2021.

[106] A. Hasanzadeh, M. Ayatollahi, and M. Hashemi, "Influences of silica fume particles and polyethylene terephthalate fibers on the mechanical characteristics of cement-treated sandy soil using ultrasonic pulse," *Construction and Building Materials*, vol. 81, p. 14, 2022.

[107] S. Kumar and M. Mishra, "Effect of naoh treated polyethylene terephthalate (pet) plastic bottle strips on stabilization of soil," in *IOP Conference Series: Materials Science and Engineering*, vol. 1273, (Bristol, UK), p. 012013, IOP Publishing, 2023.

[108] S. Tesfaw, T. Bogale, and O. Fatoba, "Evaluation of tensile and flexural strength properties of virgin and recycled high-density polyethylene (hdpe) for pipe fitting application," *Materials Today: Proceedings*, vol. 62, pp. 3103–3113, 2022.

[109] H. Jones, J. McClements, D. Ray, C. Hindle, M. Kalloudis, and V. Koutsos, "Thermomechanical properties of virgin and recycled polypropylene—high-density polyethylene blends," *Polymers*, vol. 15, p. 4200, 2023.

[110] A. Drozdov, R. Jermiin, and J. Christiansen, "Lifetime predictions for virgin and recycled high-density polyethylene under creep conditions." https://arxiv.org/abs/2404.10336, 2024. arXiv:2404.10336.

[111] P. Kamalian, S. Khorasani, A. Abdolmaleki, M. Karevan, S. Khalili, M. Shirani, and R. Neisiany, "Toward the development of polyethylene photocatalytic degradation," *Journal of Polymer Engineering*, vol. 40, pp. 181–191, 2020.

[112] K. Cho, B. Lee, K. Hwang, H. Lee, and S. Choe, "Rheological and mechanical properties in polyethylene blends," *Polymer Engineering Science*, vol. 38, pp. 1969–1975, 1998.

[113] H. Jones, J. McClements, D. Ray, M. Kalloudis, and V. Koutsos, "High-density polyethylene–polypropylene blends: Examining the relationship between nano/microscale phase separation and thermomechanical properties," *Polymers*, vol. 17, p. 166, 2025.

[114] J.-O. Jeong, Y.-H. Oh, S.-I. Jeong, and J.-S. Park, "Optimization of the physical properties of hdpe/pu blends through improved compatibility and electron beam crosslinking," *Polymers*, vol. 14, p. 3607, 2022.

[115] S. Cestari, P. Martin, P. Hanna, M. Kearns, L. Mendes, and B. Millar, "Use of virgin/recycled polyethylene blends in rotational moulding," *Journal of Polymer Engineering*, vol. 41, pp. 509–516, 2021.

[116] M. Ali, "Role of post-tensioned coconut-fibre ropes in mortar-free interlocking concrete construction during seismic loadings," *KSCE J. Civ. Eng.*, vol. 22, pp. 1336–1343, 2018.

[117] J. Amirtharaj and A. L. Rose, "Comparative performance of alternative rebars for reinforced concrete applications," *Journal of Building Engineering*, vol. 111, p. 113387, 2025.

[118] S. Ahmed and M. Ali, "Investigation on pullout and shear behavior of recycled plastic rebar-concrete connection for mortar-free housing," *Journal of Building Engineering*, p. 114266, 2025.

[119] A. Das and M. Ali, "Prospective use and assessment of recycled plastic in construction industry," *Recycling*, vol. 10, p. 41, 2025.

[120] M. Adam, M. Curbach, and M. Shams, "Behaviour of concrete beams reinforced with gfrp bars," *Construction and Building Materials*, vol. 78, pp. 409–419, 2015.

[121] M. Ali, "Coir fibre rope as confinement in rc columns," *Construction and Building Materials*, vol. 61, pp. 320–327, 2014.

[122] S. Mousavi and M. Esfahani, "Dowel action of gfrp bars in reinforced concrete connections," *Composite Structures*, vol. 94, pp. 2130–2137, 2012.

[123] H. Archila, S. Kaminski, D. Trujillo, K. Harries, and A. Salenikovich, "Bamboo reinforced concrete: A critical review," *Construction and Building Materials*, vol. 174, pp. 713–726, 2018.

[124] M. Ali, "Natural fiber rope confinement in reinforced concrete columns," *Materials and Structures*, vol. 47, pp. 135–148, 2014.

[125] F. Jawad, C. Adarsha, T. Raghavendra, B. Udayashankar, and K. Natarajan, "Structural behavior of concrete beams and columns reinforced with waste plastic incorporated gfrp (wpgfrp) rebars," *Journal of Building Engineering*, vol. 23, pp. 172–184, 2019.

[126] S. Ahmed and M. Ali, "Potential applications of different forms of recycled plastics as construction materials—a review," *Engineering Proceedings*, vol. 53, no. 1, p. 5, 2023.

[127] K. Cox, G. Covernton, H. Davies, J. Dower, F. Juanes, and S. Dudas, "Human consumption of micro-plastics," *Environmental Science & Technology*, vol. 53, pp. 7068–7074, 2019.

[128] J. Hopewell, R. Dvorak, and E. Kosior, "Plastics recycling: Challenges and opportunities," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, pp. 2115–2126, 2009.

[129] V. Intrakamhaeng, K. Clavier, Y. Liu, and T. Townsend, "Antimony mobility from e-waste plastic in simulated municipal solid waste landfills," *Chemosphere*, vol. 241, p. 125042, 2020.

[130] M. Lacerda, M. Fiatkoski, M. Maceno, F. Agostinho, M. Spier, M. Kleina, and M. Marques, "Lca and emergy approach to evaluate the environmental performance of plastic bags from fossil and renewable sources with the function of conditioning msw," *Sustainability*, vol. 16, no. 11, p. 11293, 2024.

[131] J. Low, S. Berry, G. Hernandez, P. Thomson, G. Steinhorn, H. Waghela, C. Briggs, C. Berry, and T.-A. Berry, "Comprehensive plastic waste characterisation to enhance landfill diversion in new zealand's construction industry," *Sustainability*, vol. 17, 2025.

[132] N. Singh, D. Hui, R. Singh, I. Ahuja, L. Feo, and F. Fraternali, "Recycling of plastic solid waste: A review," *Composites Part B: Engineering*, vol. 115, pp. 419–432, 2020.

[133] K. Ragaert, L. Delva, and K. Van Geem, "Mechanical and chemical recycling of solid plastic waste," *Waste Management*, vol. 69, pp. 24–58, 2017.

[134] J. Laria, R. Gaggino, J. Kreiker, L. Peisino, M. Positieri, and A. Cappelletti, "Mechanical and processing properties of recycled pet and ldpe-hdpe composite materials for building components," *Journal of Thermoplastic Composite Materials*, vol. 36, pp. 418–431, 2023.

[135] P. Stepaniak, S. Softić, S. Woźniak, M. Fabijański, and K. Nowakowski, "Właściwości regranulatów polietylenowych wyprodukowanych z wyrobów wycofanych z użytkowania," *Przemysł Chemiczny*, vol. 1, pp. 75–79, 2023.

[136] J. Hidalgo-Crespo, A. Velastegui-Montoya, M. Soto, J. Amaya Rivas, P. Zwolinski, A. Riel, and P. Rivas-García, "Improving urban waste management: A comprehensive study on household waste generation and spatial

patterns in the grand guayaquil metropolitan area," *Waste Management and Research: Journal for a Sustainable Circular Economy*, vol. 42, pp. 918–931, 2024.

[137] J. Hidalgo-Crespo, J. Amaya, M. Soto, and L. Caamaño-Gordillo, "Domestic plastic waste in the city of guayaquil: Generation rate and classification," in *Proceedings of the 19th LACCEI International Multi-Conference for Engineering, Education, and Technology*, (Buenos Aires, Argentina), pp. 1–8, 2021.

[138] Y. Blikharskyy, J. Selejdak, and N. Kopiika, "Corrosion fatigue damages of rebars under loading in time," *Materials*, vol. 14, p. 3416, 2021.

[139] S. Patil and K. Manjunatha, "Impact behavior of gfrp rebars in jute fibre concrete," *Materials Today: Proceedings*, vol. 45, pp. 3540–3545, 2020.

[140] M. Qaiser, M. Yousaf, and S. Ali, "Feasibility of bamboo as rebar in concrete members," *Case Studies in Construction Materials*, vol. 13, p. e00482, 2020.

[141] M. Al-Fasih, A. Khadim, and S. Hasan, "Bamboo as alternative to steel in underdeveloped regions," *Journal of Green Building*, vol. 16, pp. 87–102, 2021.

[142] H. Ibrahim, M. El-Hawary, M. Nabil, and A. Ibrahim, "Seismic retrofitting of urm walls using natural fiber ropes," *Buildings*, vol. 14, p. 1082, 2024.

[143] J. Wang, D. Zhang, Z. He, and L. Li, "Review of ferrocement strengthening methods for rc structures," *Materials*, vol. 17, p. 1990, 2024.

[144] Y. Shaheen, H. Al-Gahtani, and Rasheeduzzafar, "Strengthening of rc beams with nsm steel wire strips," *Structures*, vol. 52, pp. 481–495, 2023.

[145] M. Sk, S. Singh, and N. Mahure, "Performance of tmt bars under cyclic loads," *International Journal of Structural Integrity*, vol. 7, pp. 365–374, 2016.

[146] Z. Alam, S. Ahmed, M. Fiaz, and E. Noroozinejad Farsangi, "An insight into the characteristics of the september 24, 2019, mw 5.8 mirpur, pakistan,

earthquake and reconnaissance of the induced-failure modes in buildings and civil infrastructure facilities," *Practice Periodical on Structural Design and Construction*, vol. 28, no. 4, p. 05023005, 2023.

[147] M. Hadi, H. Mahmoud, and A. Al-Azzawi, "Behavior of reinforced concrete members with basalt frp bars," *Construction and Building Materials*, vol. 268, p. 121084, 2021.

[148] J. Pluskal, R. Šomplák, V. Nevrlý, V. Smejkalová, and M. Pavlas, "Strategic decisions leading to sustainable waste management: Separation, sorting and recycling possibilities," *Journal of Cleaner Production*, vol. 278, p. 123359, 2021.

[149] A. Das and M. Ali, "Energy absorption capabilities of recycled-plastic reinforcing bars for earthquake resistant housing construction," in *Australian Earthquake Engineering Society Virtual Conference*, pp. 197–205, 2021.

[150] C. Lee and D. Kim, "Seismic performance of interlocking block structures," *Journal of Structural Engineering*, vol. 148, p. 04022045, 2022.

[151] T. Nguyen and Q. Tran, "Innovations in interlocking block manufacturing," *Construction Innovation*, vol. 19, pp. 567–579, 2019.

[152] L. Garcia and P. Martinez, "Load-bearing capacity of mortarless walls," *Engineering Structures*, vol. 256, p. 113989, 2023.

[153] X. Chen and Z. Huang, "Moisture resistance in dry-stack systems," *Building and Environment*, vol. 200, p. 107975, 2022.

[154] A. Thompson and R. Green, "Modular designs in mortar-free construction," *Automation in Construction*, vol. 123, p. 103534, 2021.

[155] M. Silva and L. Torres, "Environmental impact of mortarless building methods," *Journal of Cleaner Production*, vol. 275, p. 123456, 2020.

[156] N. Thomson and P. Banfill, "Corrugated-iron buildings: An endangered resource within the built heritage," *J. Archit. Conserv.*, vol. 11, pp. 71–87, 2005.

[157] S. Delvasto, E. Toro, F. Perdomo, and R. De Gutiérrez, "An appropriate vacuum technology for manufacture of corrugated fique fiber reinforced cementitious sheets," *Constr. Build. Mater.*, vol. 24, pp. 187–192, 2010.

[158] B. Haba, S. Djellali, Y. Abdelouahed, S. Boudjelida, F. Faleschini, and M. Carraro, "Transforming plastic waste into value: A review of management strategies and innovative applications in sustainable construction," *Polymers*, vol. 17, p. 881, 2025.

[159] O. Jara-Vinueza, W. Pavon, A. Remache, F. Arroyo, M. Gutiérrez, and E. Mora Figueroa, "Hybrid panels from recycled ldpe–aluminum–totora fibers for lightweight roofing," *Buildings*, vol. 15, no. 5, p. 2212, 2025.

[160] A. Besir and E. Cuce, "Green roofs and facades: A comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 915–939, 2018.

[161] J.-O. Jeong, Y.-H. Oh, S.-I. Jeong, and J.-S. Park, "Optimization of the physical properties of hdpe/pu blends through improved compatibility and electron beam crosslinking," *Polymers*, vol. 14, no. 18, p. 3607, 2022.

[162] J. Kumaraswamy, P. Vijay Praveen, H. Alzahrani, S. Sharma, V. Shetty, and B. Shabari Shedthi, "Experimental investigation of heat transfer rate for building roof with corrugated sheets using phase change material (pcm)," *Case Stud. Therm. Eng.*, vol. 59, p. 104508, 2024.

[163] J.-M. Almodóvar-Melendo and P. La Roche, "Thermal evaluation of a water-to-air heat exchanger combined with different roof configurations for passive cooling," *Buildings*, vol. 15, p. 1098, 2025.

[164] H. Mohammed and J. Kennedy, "Fatigue resistance of corrugated steel sheets bolted lap joints under flexure," *Pract. Period. Struct. Des. Constr.*, vol. 14, pp. 242–245, 2009.

[165] H. Jones, J. McClements, D. Ray, M. Kalloudis, and V. Koutsos, "High-density polyethylene–polypropylene blends: Relationship between microscale phase separation and thermomechanical properties," *Polymers*, vol. 17, no. 1, p. 166, 2025.

[166] S. Malek and C. Williams, “The equilibrium of corrugated plates and shells,” *Nexus Netw. J.*, vol. 19, pp. 619–627, 2017.

[167] B. Kittisak and S. Prayoon, “Properties of corrugated roofing sheet material from sugarcane bagasse fibers,” *Journal of Physics: Conference Series*, vol. 1860, no. 1, p. 012007, 2021.

[168] M. Yang, C. Gao, J. Pang, S. Li, D. Hu, X. Li, and Z. Zhang, “High-cycle fatigue behavior and fatigue strength prediction of differently heat-treated 35crmo steels,” *Metals*, vol. 12, p. 688, 2022.

[169] J. Kumaraswamy, M. V. Praveen, H. A. H. Alzahrani, S. Sharma, V. Shetty, and S. Shabari, “Experimental investigation of heat transfer in building roofs with corrugated sheets using pcm,” *Case Studies in Thermal Engineering*, vol. 59, p. 104508, 2024.

[170] D. Henderson and J. Ginger, “Response of pierced fixed corrugated steel roofing systems subjected to wind loads,” *Eng. Struct.*, vol. 33, pp. 3290–3298, 2011.

[171] M. Brochu, Y. Verreman, F. Ajersch, and D. Bouchard, “High cycle fatigue strength of permanent mold and rheocast aluminum 357 alloy,” *Int. J. Fatigue*, vol. 32, pp. 1233–1242, 2010.

[172] M. A. R. Bhuiyan, M. A. Darda, A. Ali, A. R. Talha, M. F. Hossain, M. Mohebbullah, and M. A. Islam, “Heat insulating jute-reinforced recycled polyethylene and polypropylene bio-composites for energy conservation in buildings,” *Materials Today Communications*, vol. 37, p. 106948, 2023.

[173] D. Vijayalakshmi and N. Rajeshkumar, “Comparative study on corrugated roofing materials and their performance in tropical climates,” *Construction and Building Materials*, vol. 380, p. 131423, 2023.

[174] D. Setyanto, “Design and fe modeling of upvc corrugated hollow roofing sheet,” in *Proceedings of the MATEC Web of Conferences*, vol. 258, p. 01017, 2019.

[175] G. Thakre, V. Kaushal, and M. Najafi, "A comparative impact assessment of hail damage to tile and built-up roofing systems: Technical review and field study," 2024.

[176] T. Da Silva, A. De Azevedo, D. Cecchin, M. Marvila, M. Amran, R. Fediuk, N. Vatin, M. Karelina, S. Klyuev, and M. Szelag, "Application of plastic wastes in construction materials: A review using the concept of life-cycle assessment in the context of recent research for future perspectives," *Materials*, vol. 14, p. 3549, 2021.

[177] D. Setyanto, "Design and fe modeling of upvc corrugated hollow roofing sheet," *MATEC Web Conf.*, vol. 258, p. 01017, 2019.

[178] G. Thakre, V. Kaushal, and M. Najafi, "A comparative impact assessment of hail damage to tile and built-up roofing systems: Technical review and field study," *Preprints*, vol. 202407.2020.v1, 2024.

[179] M. De Mello Innocentini, M. Vieira De Faria, M. Rosseto Crespi, and V. Batista Andrade, "Air permeability assessment of corrugated fiber-cement roofing sheets," *Cem. Concr. Compos.*, vol. 97, pp. 259–267, 2019.

[180] F. Soto, J. Bueno, M. Mendoza López, M. Chavela, M. Ramos, and A. Manzano-Ramírez, "Hydrothermal evaluation of vernacular housing: Comparing case studies of waste pet bottles, stone, and adobe houses," *Buildings*, vol. 12, p. 1162, 2022.

[181] J. G. Rosenboom, L. P. Sherwood, J. Clark, *et al.*, "Bioplastics for a circular economy," *Nature Reviews Materials*, vol. 7, pp. 117–134, 2022.

[182] P. Klingenberg, R. Brüll, T. Fell, B. Barton, M. Soll, T. Emans, F. Bakker, and G. Geertz, "Quality comparison of plastic packaging waste from different separation systems: Result enhancement with non-negative matrix factorization of ftir spectra," *Waste Management*, vol. 178, pp. 135–143, 2024.

[183] F. Gu, "From waste plastics to industrial raw materials," *Science of The Total Environment*, vol. 601–602, pp. 1192–1207, 2017.

[184] ASTM International, "Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials." https://www.astm.org/d790-17.html, 2017. ASTM-D790-17.

[185] ASTM International, "Standard test method for compressive properties of rigid plastics." https://www.astm.org/d695-23.html, 2023. ASTM-D695-23.

[186] ASTM International, "Standard test method for shear strength of plastics by punch tool." https://www.astm.org/d732-24.html, 2024. ASTM D732-24.

[187] ASTM International, "Standard test method for tensile properties of plastics." https://www.astm.org/d638-22.html, 2022. ASTM D638-22.

[188] P. Jiang, "Social media and household waste management," *Resources, Conservation and Recycling*, vol. 164, p. 105146, 2021.

[189] A. Graziano, S. Jaffer, and M. Sain, "Review on modification strategies of polyethylene/polypropylene immiscible thermoplastic polymer blends for enhancing their mechanical behavior," *Journal of Elastomers and Plastics*, vol. 51, no. 4, pp. 291–336, 2019.

[190] J. Zhang, V. Hirschberg, and D. Rodrigue, "Blending recycled high-density polyethylene hdpe (rhdpe) with virgin (vhdpe) as an effective approach to improve the mechanical properties," *Recycling*, vol. 8, no. 1, p. 2, 2023.

[191] E. Hanna, "Recycling of waste mixed plastics blends (pe/pp)," *Journal of Engineering Science and Technology Review*, vol. 12, pp. 87–92, 2019.

[192] S. Liu, W. Gong, and B. Zheng, "The effect of peroxide cross-linking on the properties of low-density polyethylene," *Journal of Macromolecular Science, Part B*, vol. 53, pp. 67–77, 2014.

[193] V. Gavande, M. Jeong, and W.-K. Lee, "On the mechanical, thermal, and rheological properties of polyethylene/ultra-high molecular weight polypropylene blends," *Polymers*, vol. 15, p. 4236, 2023.

[194] ASTM International, "ASTM A615/A615M-22: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement," 2022. Available from ASTM International.

[195] A. Pang, M. Husin, A. Arsad, and M. Ahmadipour, "Effect of graphene nanoplatelets on structural, morphological, thermal, and electrical properties of recycled polypropylene/polyaniline nanocomposites," *Journal of Materials Science: Materials in Electronics*, vol. 32, pp. 9574–9583, 2021.

[196] P. Svoboda, K. Trivedi, K. Stoklasa, D. Svobodova, and T. Ougizawa, "Study of crystallization behaviour of electron beam irradiated polypropylene and high-density polyethylene," *Royal Society Open Science*, vol. 8, p. 202250, 2021.

[197] F. Zhang, P. Sun, X. Li, and G. Zhang, "An experimental study on deformation behavior below 0.2% offset yield stress in some sicp/al composites and their unreinforced matrix alloys," *Materials Science and Engineering: A*, vol. 300, pp. 12–21, 2001.

[198] R. Faidallah, M. Hanon, Z. Szakál, and I. Oldal, "Mechanical characterization of 3d-printed carbon fiber-reinforced polymer composites and pure polymers: Tensile and compressive behavior analysis," *International Review of Applied Sciences and Engineering*, vol. 16, pp. 22–31, 2025.

[199] H. Liu, T. Ka, N. Su, Y. Zhu, S. Guan, J. Long, and T. Tafsirojjaman, "Experimental study of dimensional effects on tensile strength of gfrp bars," *Buildings*, vol. 14, p. 1205, 2024.

[200] D. Kramer, H. Huang, M. Kriese, J. Robach, J. Nelson, A. Wright, D. Bahr, and W. Gerberich, "Yield strength predictions from the plastic zone around nanocontacts," *Acta Materialia*, vol. 47, pp. 333–343, 1998.

[201] S. Satya and P. Sreekanth, "An experimental study on recycled polypropylene and high-density polyethylene and evaluation of their mechanical properties," *Materials Today: Proceedings*, vol. 27, pp. 920–924, 2020.

[202] A. Wiater and T. Siwowski, "Comparison of tensile properties of glass fibre reinforced polymer rebars by testing according to various standards," *Materials*, vol. 13, p. 4110, 2020.

[203] D. Malyuta, K. Matteson, M. Berry, D. Bajwa, and C. Ryan, "Experimental statistical modeling of tensile properties and flexural stiffness of recycled high-density polyethylene (rhdpe) thermoplastic using response surface methodology (rsm)," *Results in Materials*, vol. 20, p. 100472, 2023.

[204] J. Karger-Kocsis, "Fracture and failure of polymers," in *Encyclopedia of Polymer Science and Technology*, Hoboken, NJ, USA: John Wiley & Sons, 2016.

[205] M. Thouless, "Fracture of polymer–matrix composites," *Composites Science and Technology*, vol. 72, pp. 1456–1460, 2012.

[206] H. Zhang, J. Wang, and Y. Huang, "Analysis of fracture behavior in polymer blends using sem and image-based modeling," *Polymer Testing*, vol. 81, p. 106195, 2019.

[207] A. P. Shembekar, J. Yu, M. Zhang, C. Griffin, and D. Ray, "Recycling continuous glass fibre-reinforced polyamide 6 laminates via compression moulding," *Polymers*, vol. 17, no. 15, p. 2160, 2025.

[208] A. Hussain, Y. Dong, and I. J. Davies, "Mechanical characterization and predictive modelling of recycled polymer composites: Empirical correlations between tensile, flexural, and impact behaviour," *Composites Part B: Engineering*, vol. 224, p. 109180, 2021.

[209] Y. Zhou, H. Zhang, and J. Chen, "Correlation between crystallinity and mechanical performance in recycled polyolefins," *Polymer Testing*, vol. 106, p. 107470, 2022.

[210] A. Das and M. Ali, "Prospective use and assessment of recycled plastic in construction industry," *Recycling*, vol. 10, p. 41, 2025.

[211] ASTM International, "Astm d790-17: Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," tech. rep., 2017.

[212] M.-C. Lin, J.-H. Lin, J.-Y. Lin, T. Lin, and C.-W. Lou, "Fabrication, properties, and failure of composite sandwiches made with sheet extrusion method," *J. Sandw. Struct. Mater.*, vol. 22, pp. 689–701, 2020.

[213] *ASTM E1876-15: Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration.* West Conshohocken, PA, USA: ASTM International, 2015.

[214] S. Ahmed and M. Ali, "Use of agriculture waste as short discrete fibers and glass-fiber-reinforced-polymer rebars in concrete walls for enhancing impact resistance," *Journal of Cleaner Production*, vol. 268, p. 122211, 2020.

[215] T. Hussain and M. Ali, "Improving the impact resistance and dynamic properties of jute fiber reinforced concrete for rebars design by considering tension zone of frc," *Construction and Building Materials*, vol. 213, pp. 592–607, 2019.

[216] D. Li, L. Zhou, X. Wang, L. He, and X. Yang, "Effect of crystallinity of polyethylene with different densities on breakdown strength and conductance property," *Materials*, vol. 12, p. 1746, 2019.

[217] H. Sutar, P. C. Sahoo, P. S. Sahu, S. Sahoo, R. Murmu, S. Swain, and S. C. Mishra, "Mechanical, thermal and crystallization properties of polypropylene (pp) reinforced composites with high density polyethylene (hdpe) as matrix," *Materials Science and Applications*, vol. 09, pp. 502–515, 2018.

[218] *ASTM E661-15: Standard Test Method for Performance of Panel-Type Wall Constructions.* West Conshohocken, PA: ASTM International, 2015.

[219] *ASTM E2140-22: Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors and Curtain Walls by Uniform Static Air Pressure Difference.* West Conshohocken, PA: ASTM International, 2022.

[220] S. Ahmed and M. Ali, "Use of agriculture waste as short discrete fibers and glass-fiber-reinforced-polymer rebars in concrete walls for enhancing impact resistance," *J. Clean. Prod.*, vol. 268, p. 122211, 2020.

[221] ASTM International, "Astm e1876-15: Standard test method for dynamic young's modulus, shear modulus, and poisson's ratio by impulse excitation of vibration," tech. rep., 2015.

[222] T. Hussain and M. Ali, "Improving the impact resistance and dynamic properties of jute fiber reinforced concrete for rebars design by considering tension zone of frc," *Constr. Build. Mater.*, vol. 213, pp. 592–607, 2019.

[223] ASTM, "Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," tech. rep., 2017.

[224] G. Thakre, V. Kaushal, and M. Najafi, "A comparative impact assessment of hail damage to tile and built-up roofing systems: Technical review and field study," 2024.

[225] S. Abubaker, F. Chaqmaqchee, and A. Taha, "X-ray fluorescence techniques," *ARO*, vol. 9, pp. 22–25, 2021.

[226] V. Moravskyi, A. Kucherenko, M. Kuznetsova, L. Dulebova, and E. Spišák, "X-ray diffraction study of metallized polyethylene for creating heat storage systems," *Applied Sciences*, vol. 14, no. 10, p. 4183, 2024.

[227] A. Pang, M. Husin, A. Arsad, and M. Ahmadipour, "Effect of graphene nanoplatelets on structural, morphological, thermal, and electrical properties of recycled polypropylene/polyaniline nanocomposites," *J. Mater. Sci. Mater. Electron.*, vol. 32, pp. 9574–9583, 2021.

[228] E. Liço, V. Rapa, S. Drushku, and E. Chatzitheodoridis, "Morphological and chemical study of recycled plastic materials by using scanning electron microscopy and energy dispersive analysis," *Zašt. Mater.*, vol. 52, pp. 231–236, 2011.

[229] H. Jones, J. McClements, D. Ray, M. Kalloudis, and V. Koutsos, "High-density polyethylene–polypropylene blends: Examining the relationship between nano/microscale phase separation and thermomechanical properties," *Polymers*, vol. 17, p. 166, 2025.

[230] R. Kassab and P. Sadeghian, "Effects of material non-linearity on the structural performance of sandwich beams made of recycled pet foam core and pet fiber composite facings: Experimental and analytical studies," *Structures*, vol. 54, pp. 1259–1277, 2023.

[231] M. Wang, J. Zhang, H. Yuan, H. Guo, and W. Zhuang, "The plastic behavior in the large deflection response of fiber metal laminate sandwich beams under transverse loading," *Materials*, vol. 15, p. 439, 2022.

[232] A. Smith and B. Johnson, "Experimental investigation of flexural capacity and deflection of low strength rcc beam strengthened with flexural steels and steel shear key," *Asian J. Civ. Eng.*, vol. 23, pp. 987–1001, 2022.

[233] S. Tesfaw, T. Bogale, and O. Fatoba, "Evaluation of tensile and flexural strength properties of virgin and recycled high-density polyethylene (hdpe) for pipe fitting application," *Mater. Today Proc.*, vol. 62, pp. 3103–3113, 2022.

[234] D. Li, L. Zhou, X. Wang, L. He, and X. Yang, "Effect of crystallinity of polyethylene with different densities on breakdown strength and conductance property," *Materials*, vol. 12, p. 1746, 2019.

[235] H. Sutar, P. Sahoo, P. Sahu, S. Sahoo, R. Murmu, S. Swain, and S. Mishra, "Mechanical, thermal and crystallization properties of polypropylene (pp) reinforced composites with high density polyethylene (hdpe) as matrix," *Mater. Sci. Appl.*, vol. 9, pp. 502–515, 2018.

[236] Q. Cheng, Z. Li, S. Deng, H. Jiang, Y. Tian, and J. Geng, "Full-scale experimental study on flexural performance of the new precast uhpc diaphragm slab in utility tunnels," *Buildings*, vol. 13, p. 1349, 2023.

[237] M. Acharya, K. Gurung, and M. Mashal, “Full-scale flexural testing of slabs made of modular structural concrete insulated panels,” *PCI J.*, vol. 67, 2022.

Annexure A

Supplementary Data SEM Analysis conducted for different recycled plastic

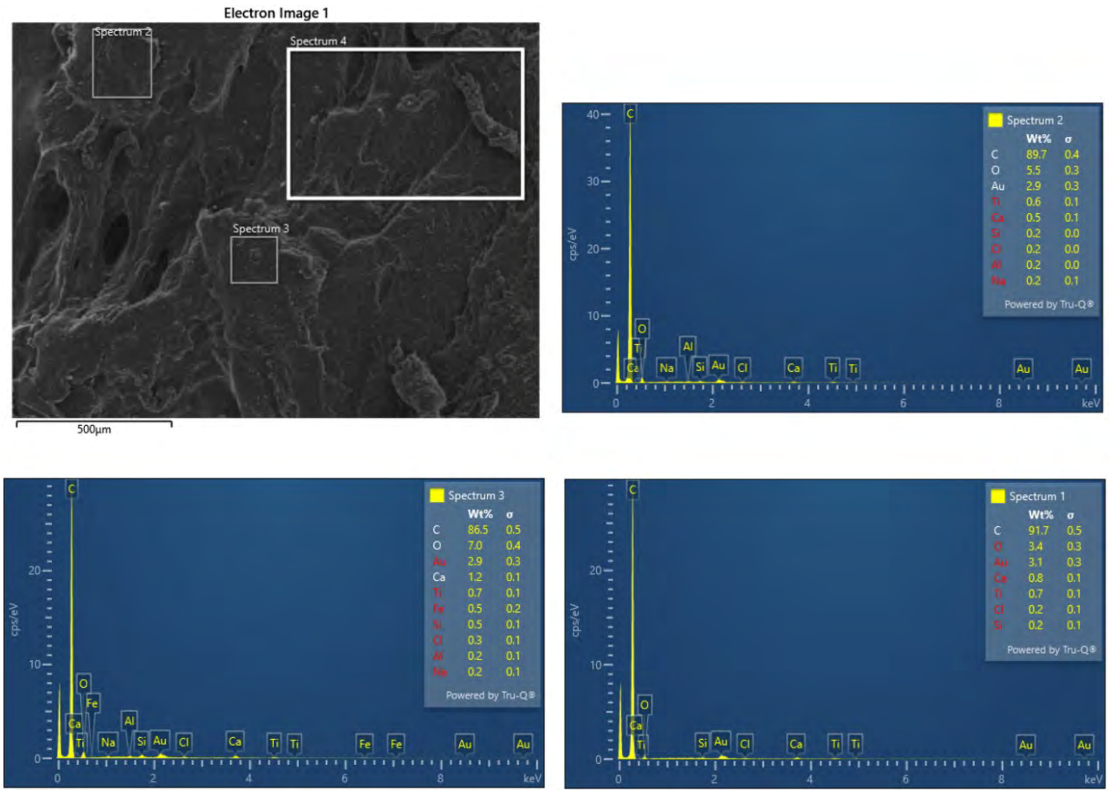


FIGURE A.1: FESEM images and spectrums for composition of rHDPE

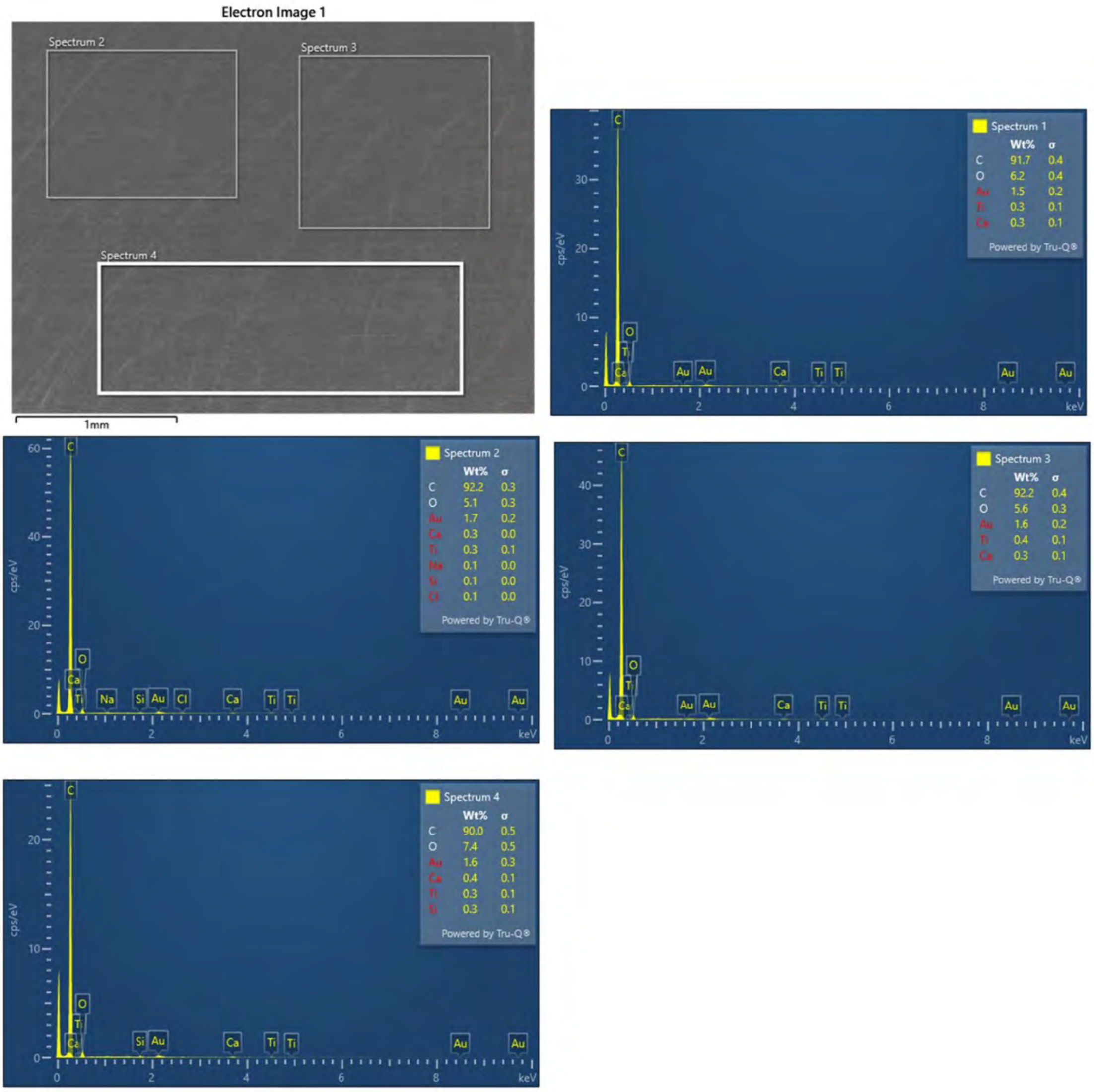


FIGURE A.2: FESEM images and spectrums for composition of rHDPE + POL

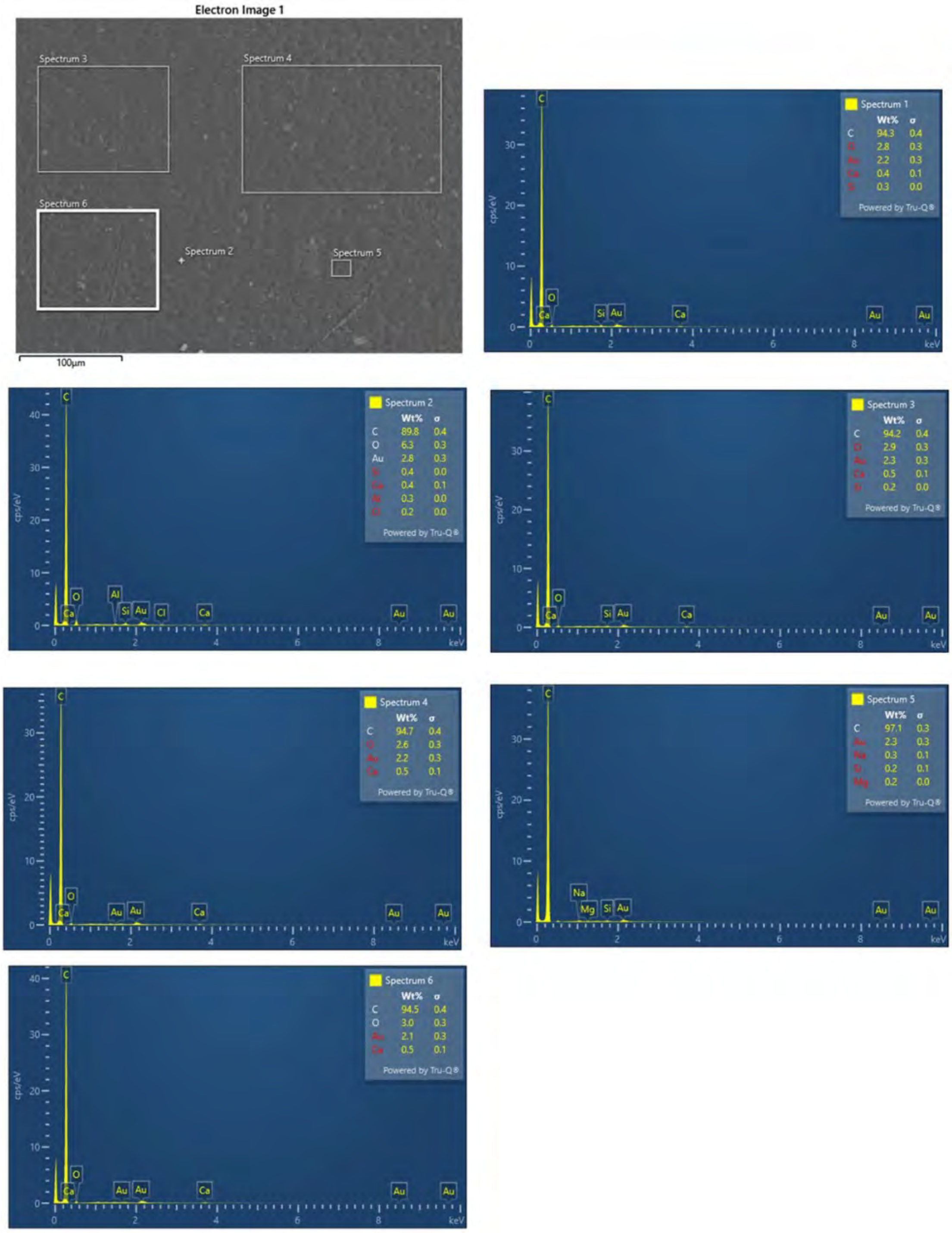


FIGURE A.3: FESEM images and spectrums for composition of rPP

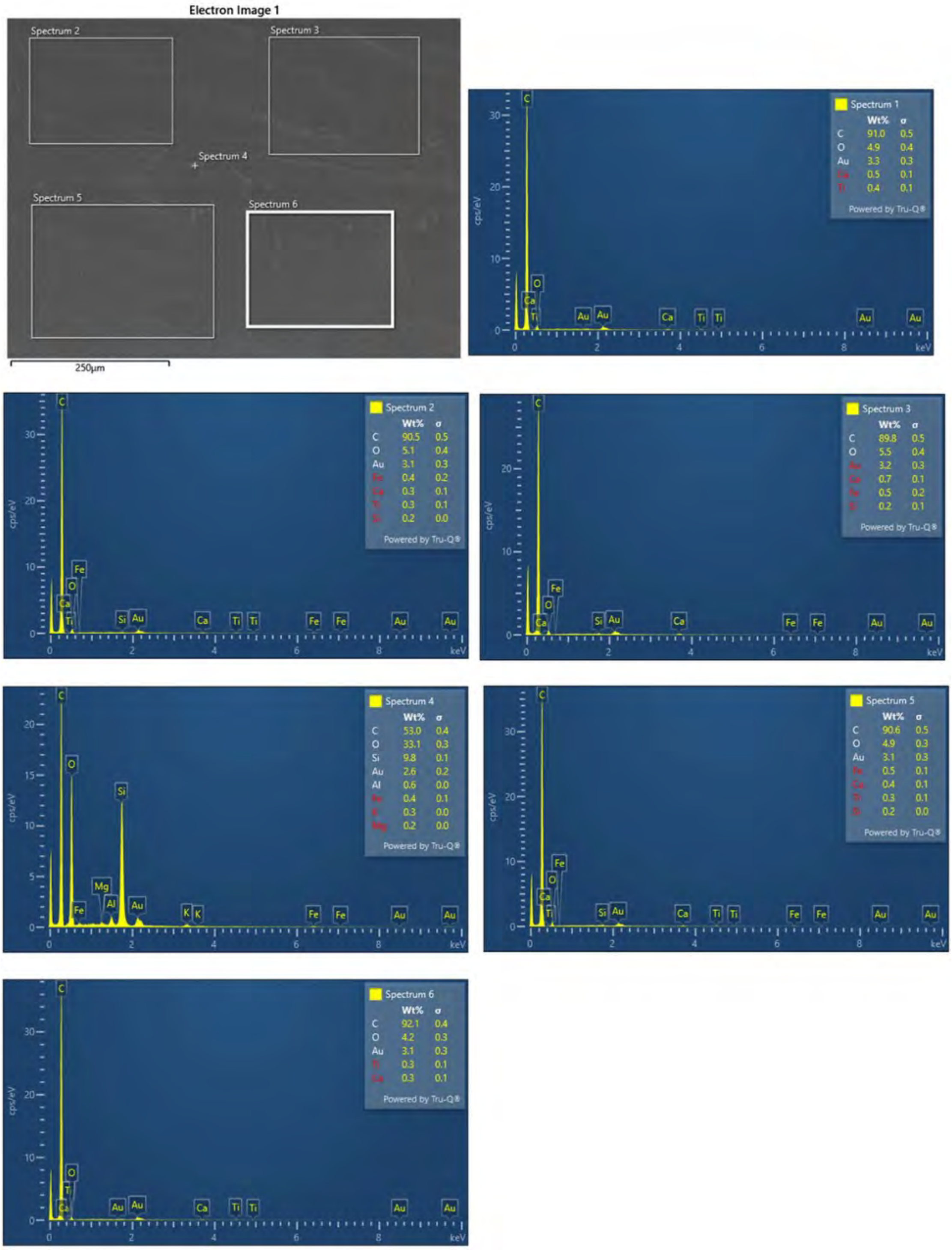


FIGURE A.4: FESEM images and spectrums for composition of rHDPE + rLDPE

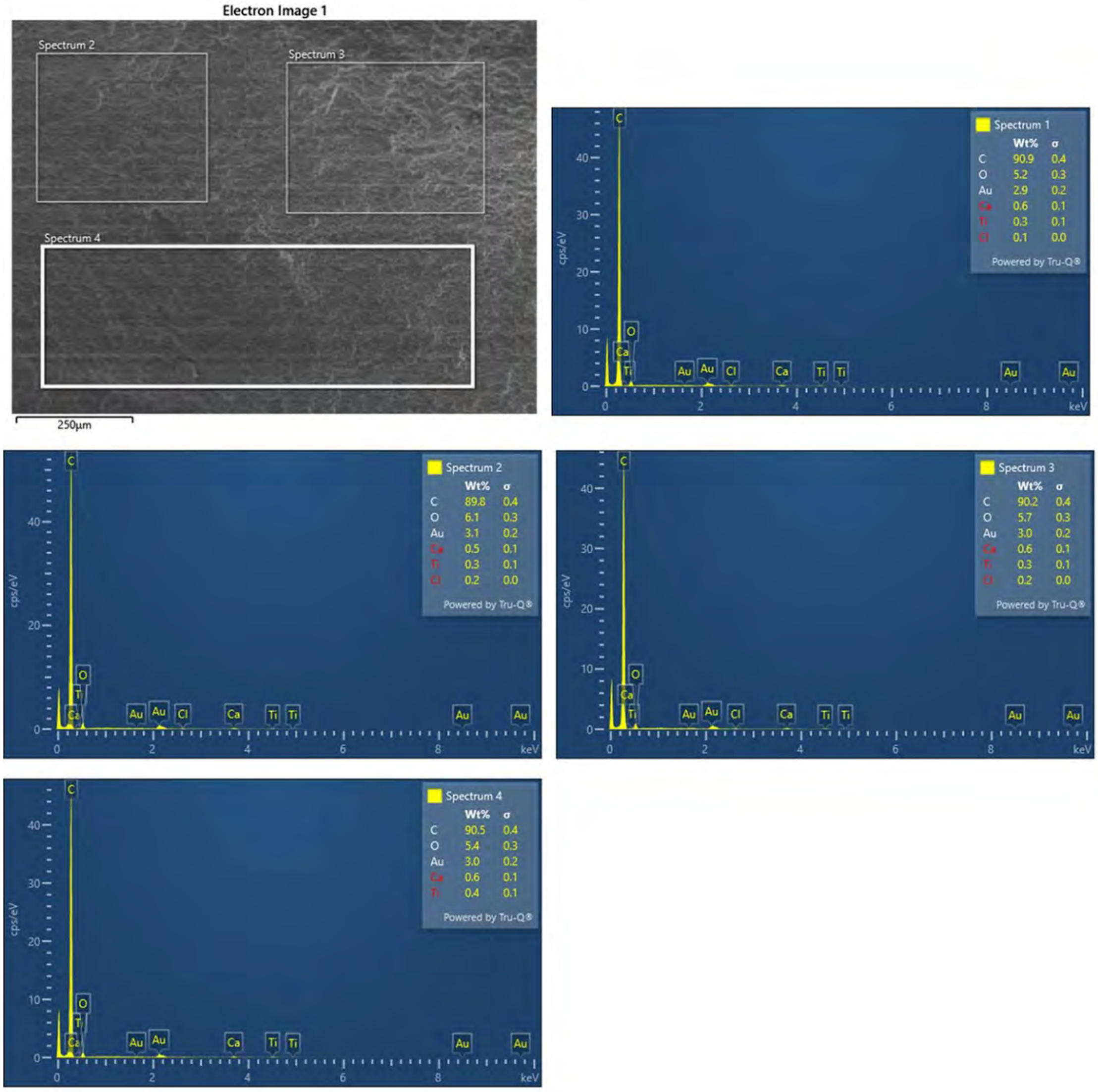


FIGURE A.5: FESEM images and spectrums for composition of rHIPS

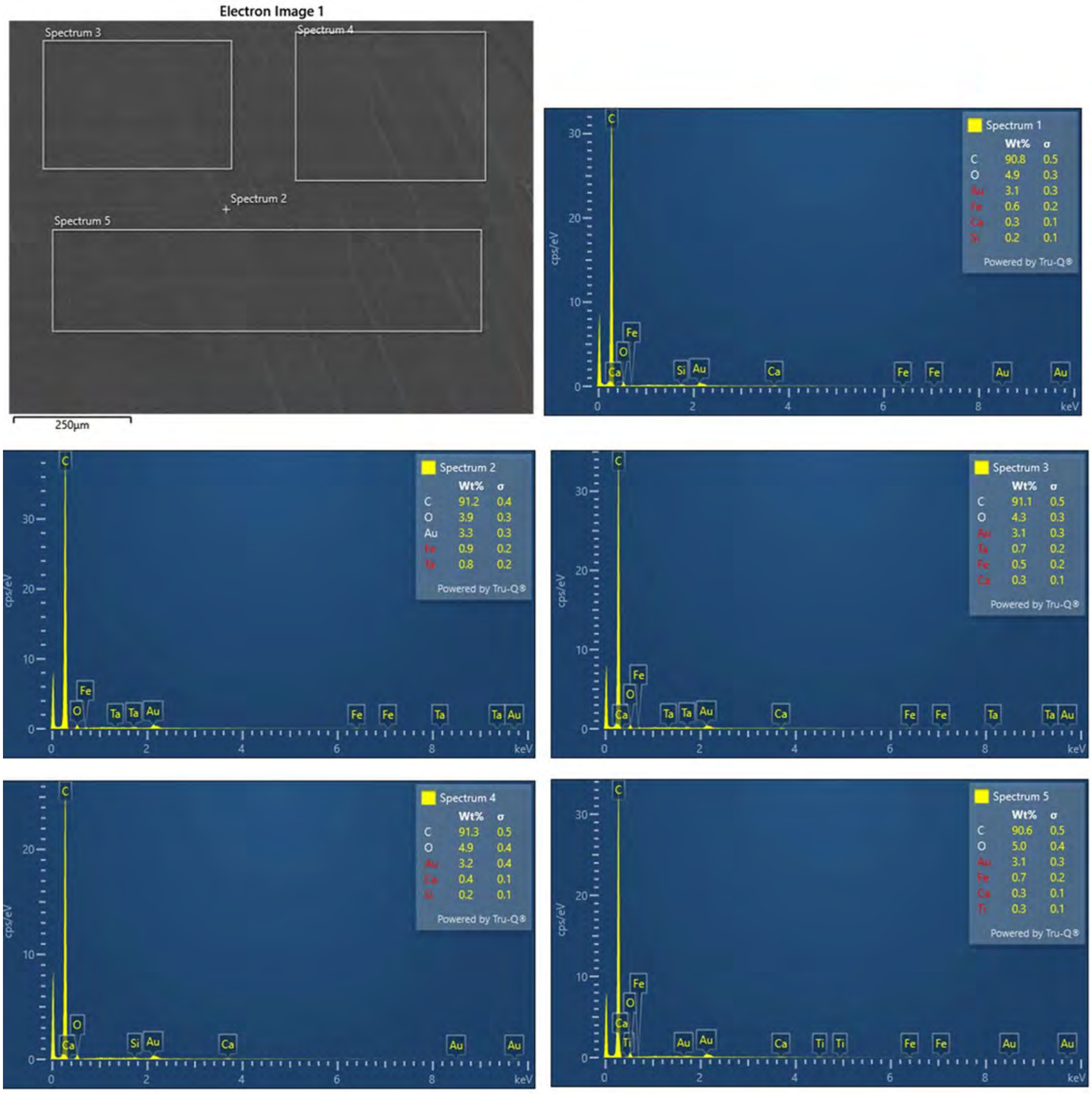


FIGURE A.6: FESEM images and spectrums for composition of rHDPE

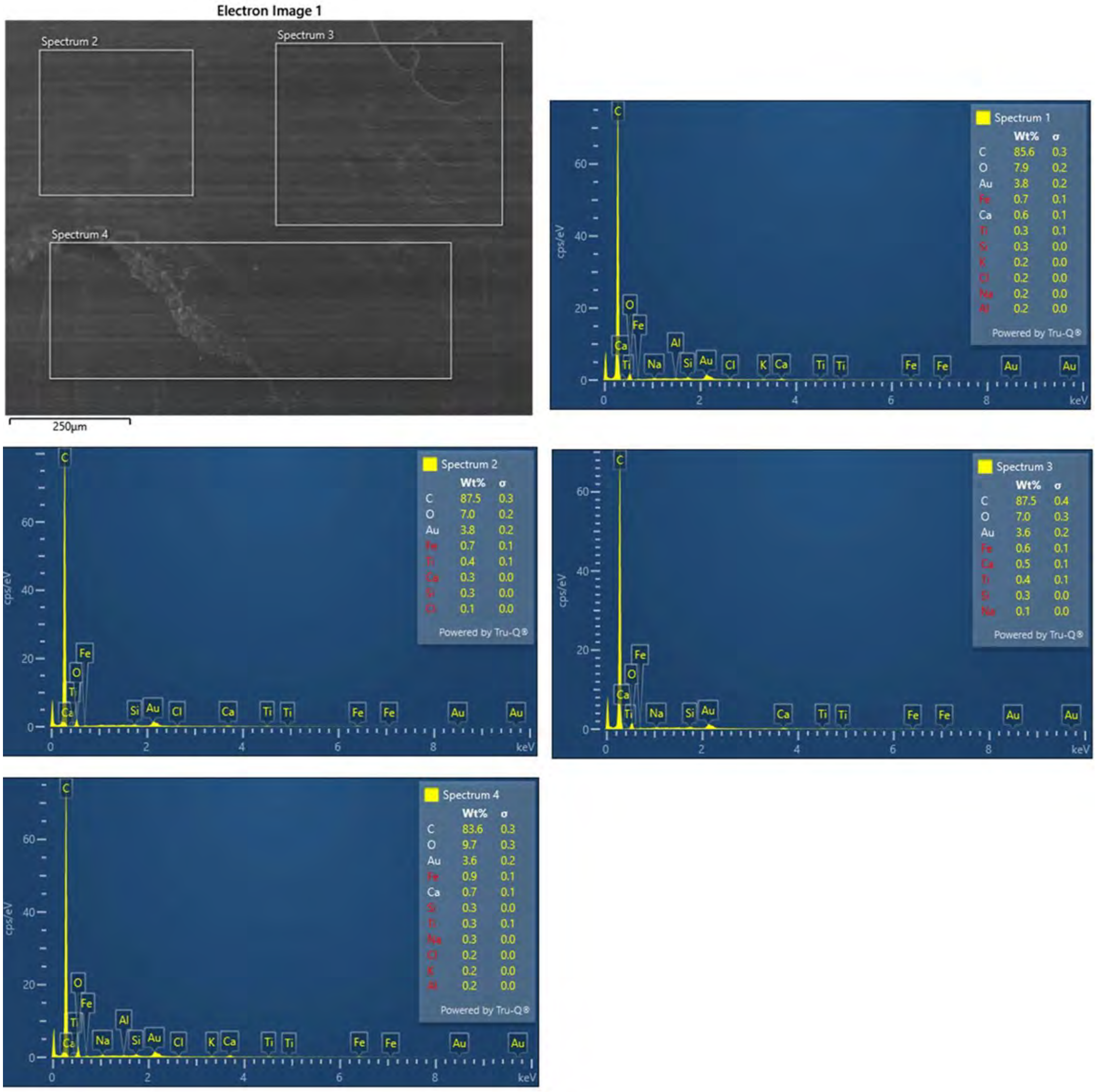


FIGURE A.7: FESEM images and spectrums for composition of rHDPE + rPP

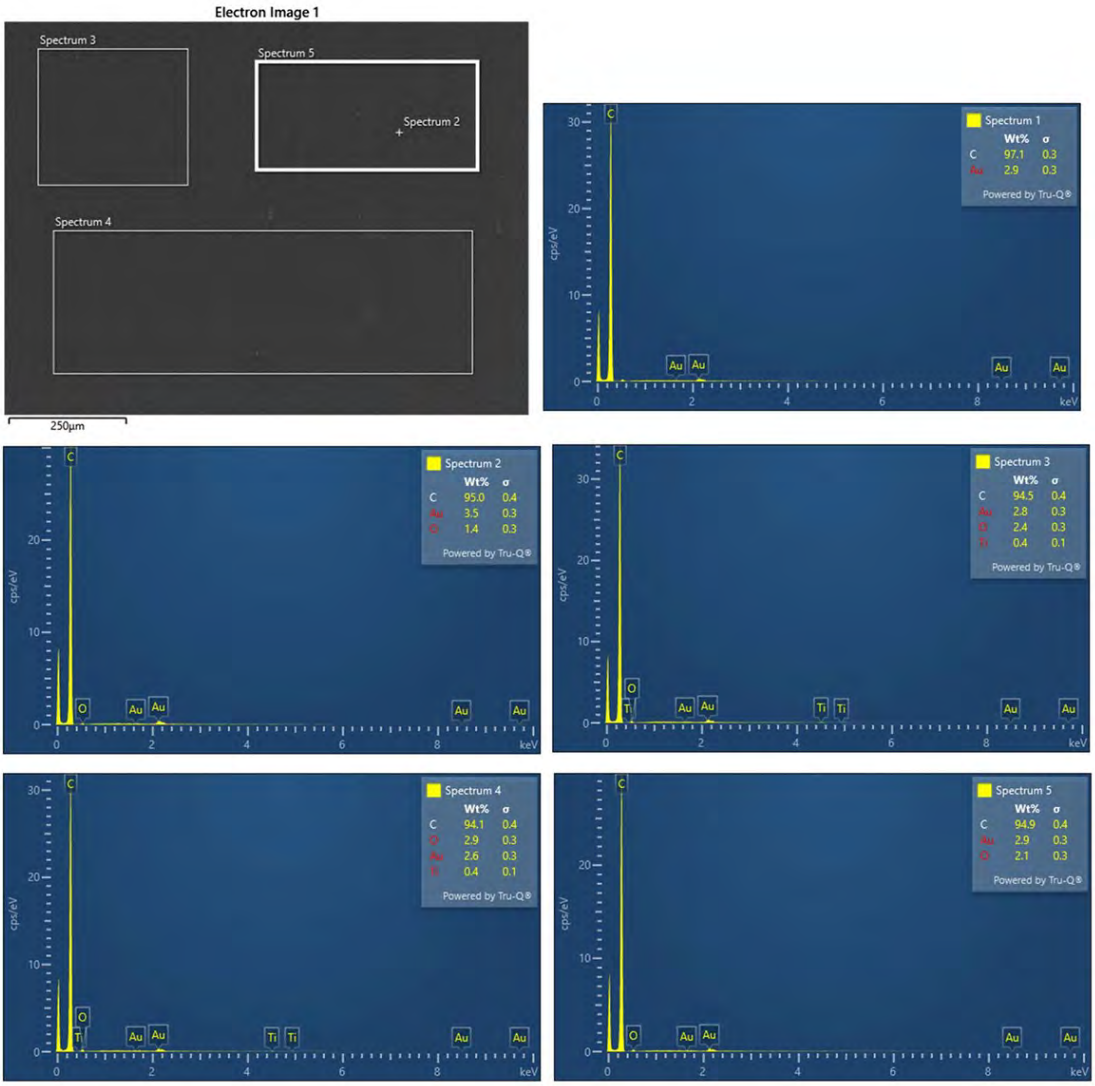


FIGURE A.8: Composition obtained from different spectrum of rHDPE + V

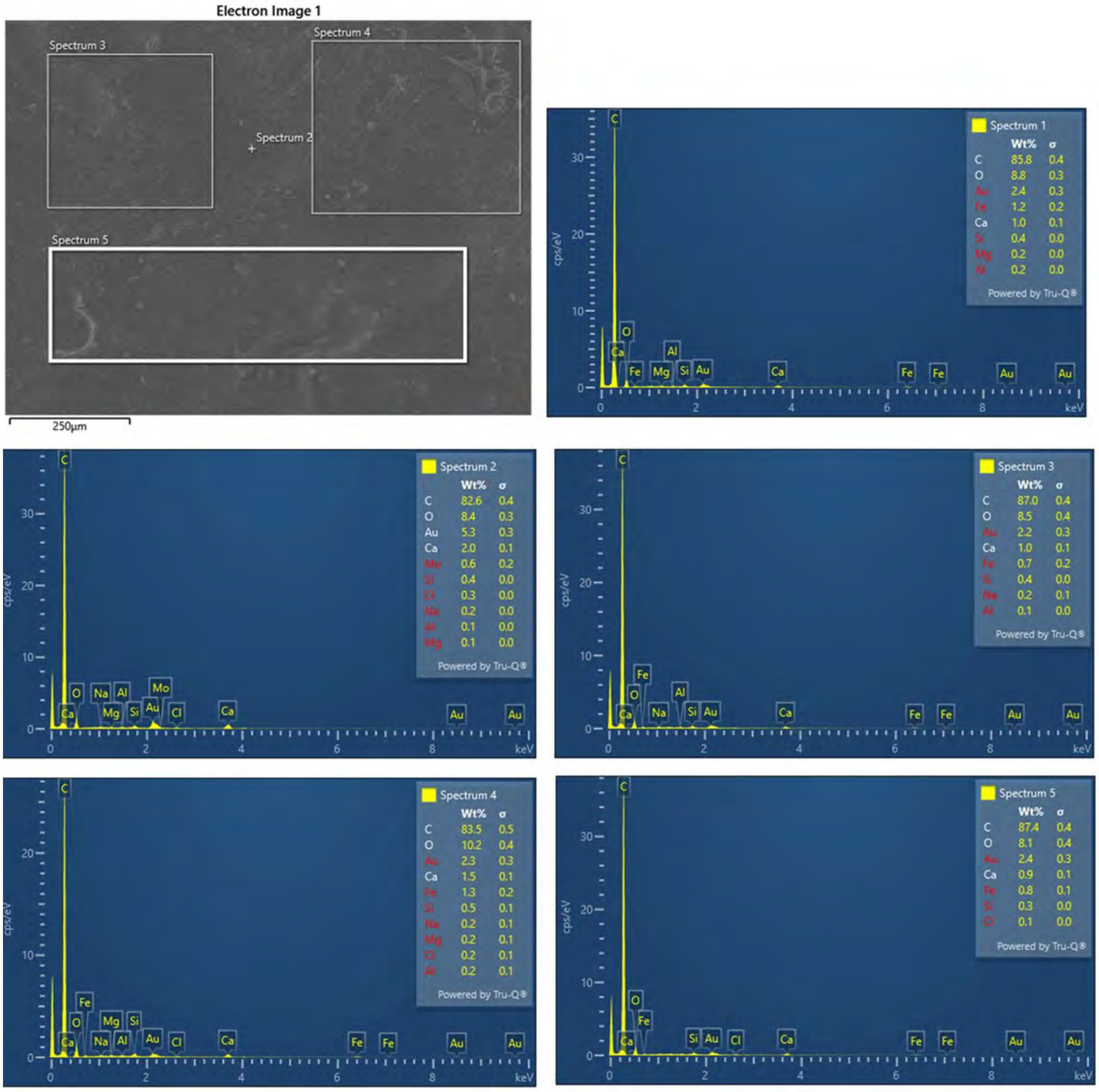


FIGURE A.9: Composition obtained from different spectrum of rLDPE

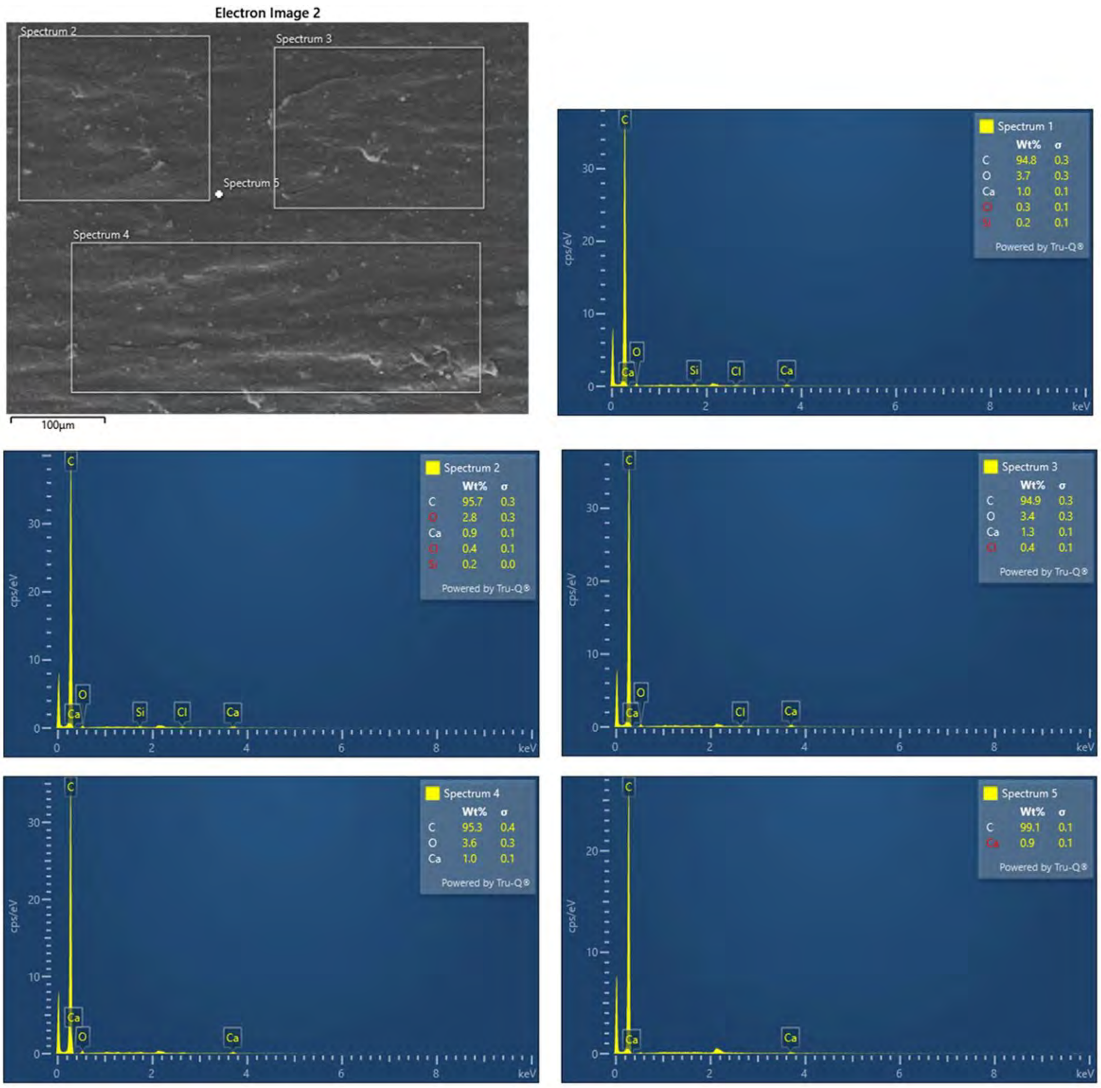


FIGURE A.10: Composition obtained from different spectrum of rHDPE pallet

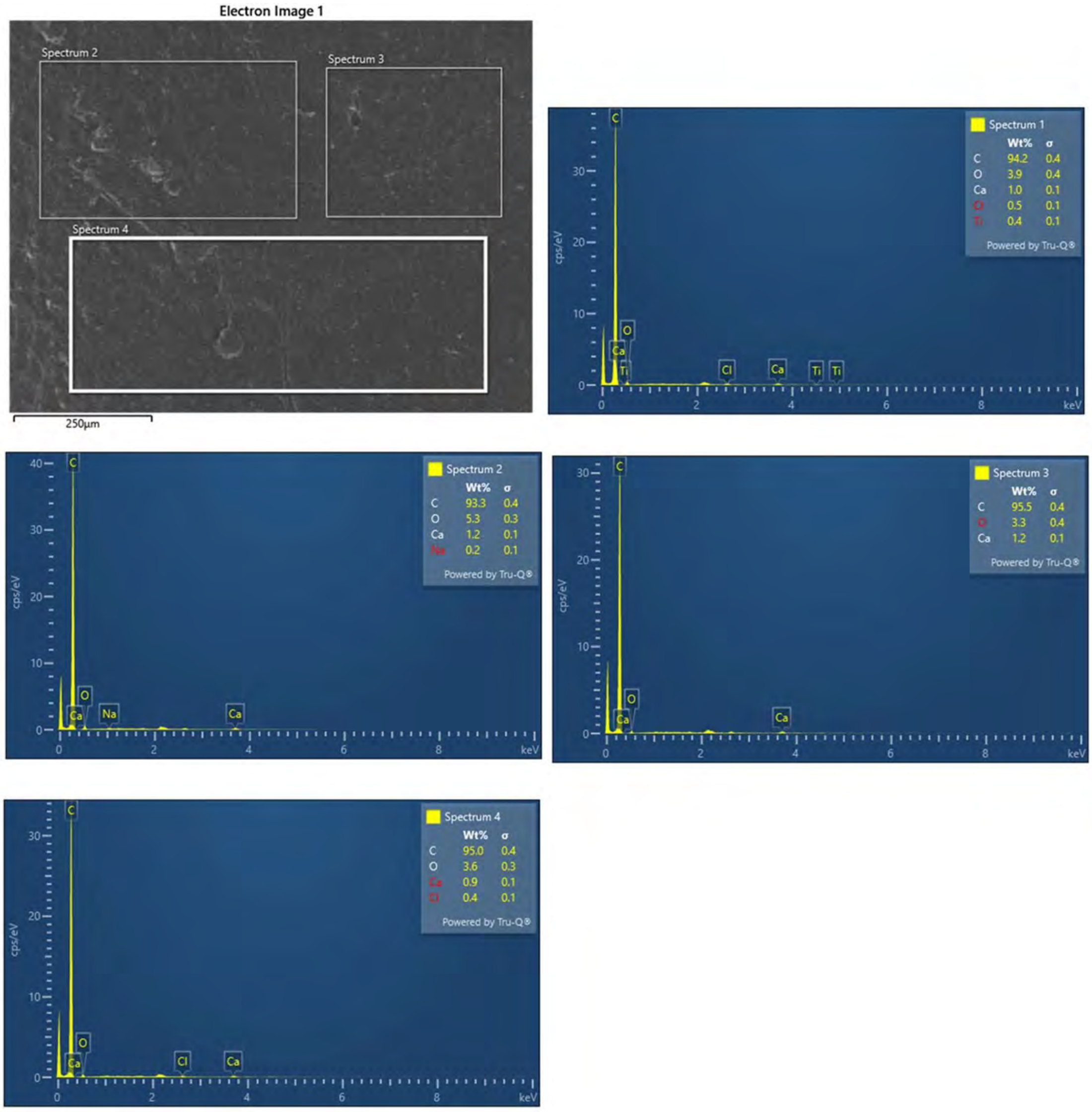


FIGURE A.11: FESEM images and spectrums for composition of SAMICAN-ITE pallet

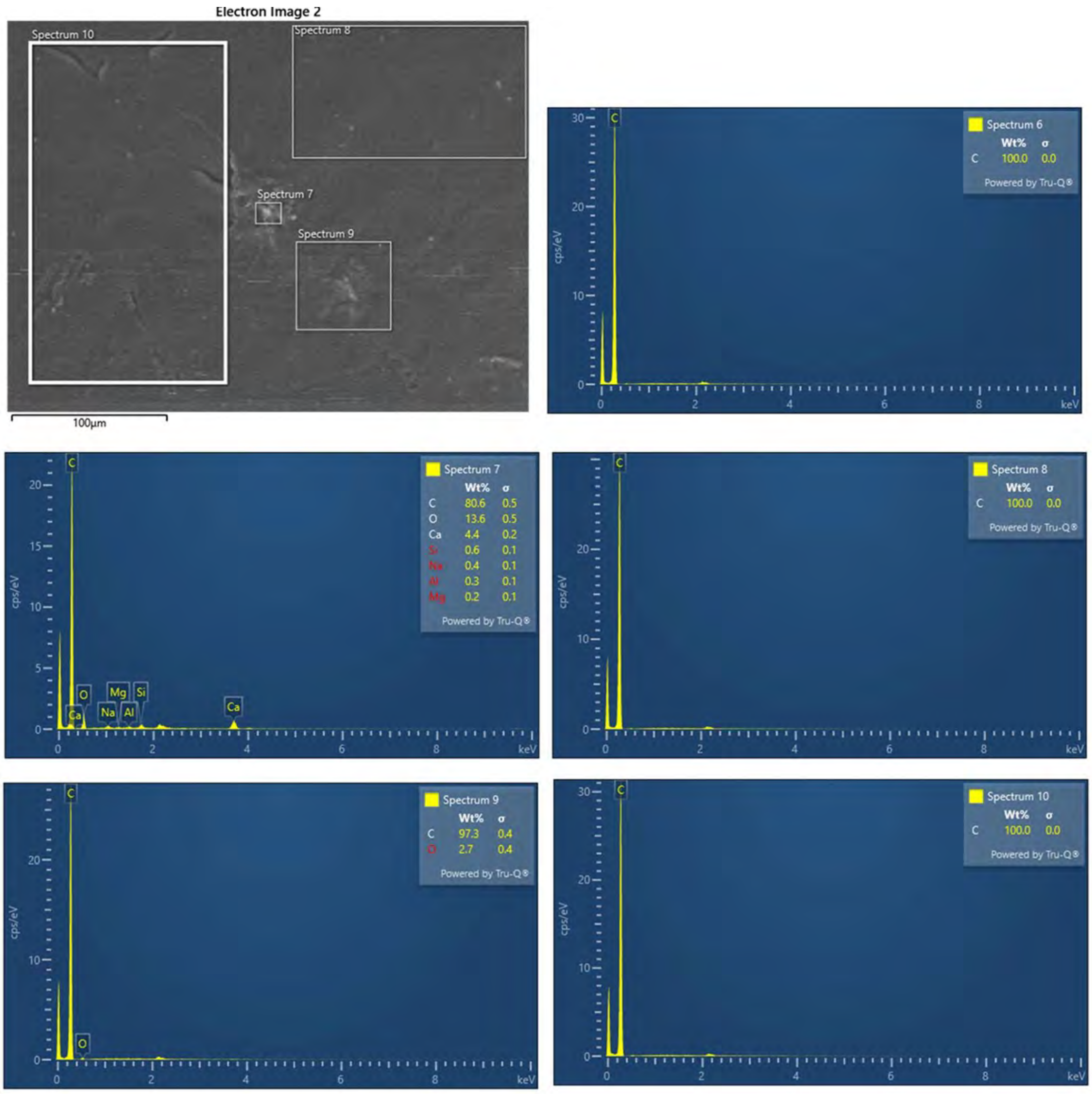


FIGURE A.12: FESEM images and spectrums for composition of polyolefin pallet

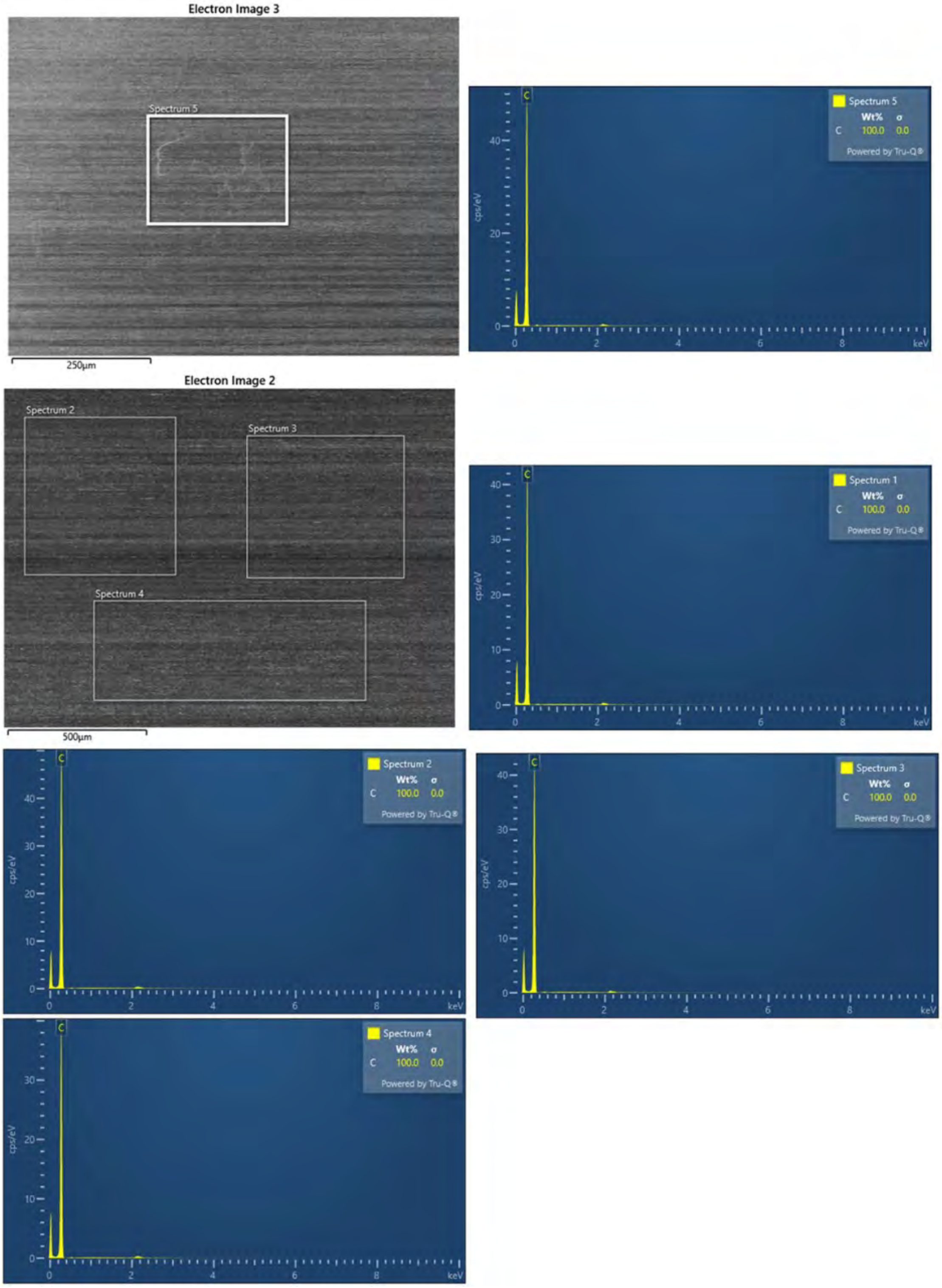


Figure A.13: FESEM images and spectrums for composition of Virgin PE pallet

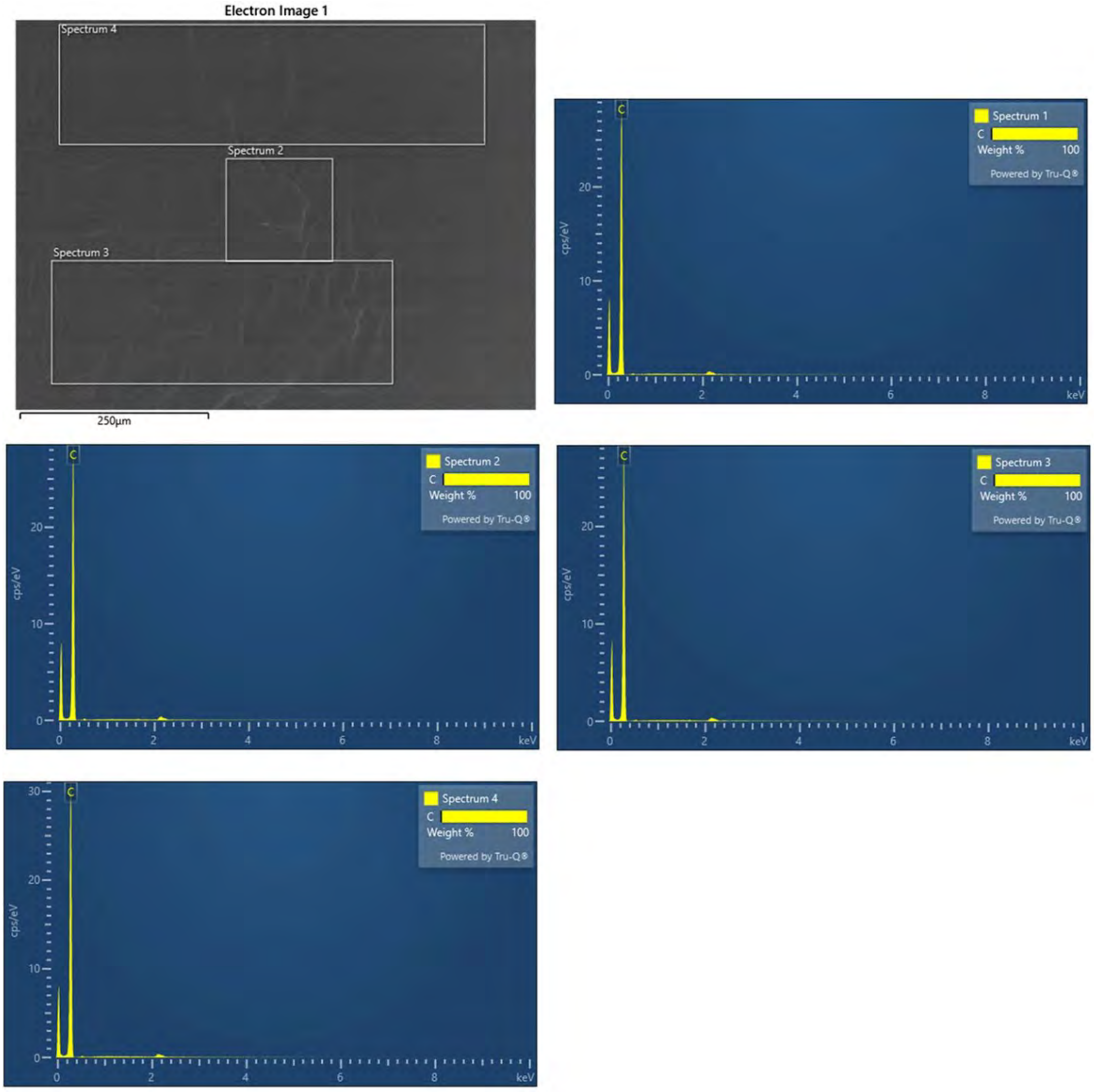


FIGURE A.14: FESEM images and spectrums for composition of polyolefin pallet

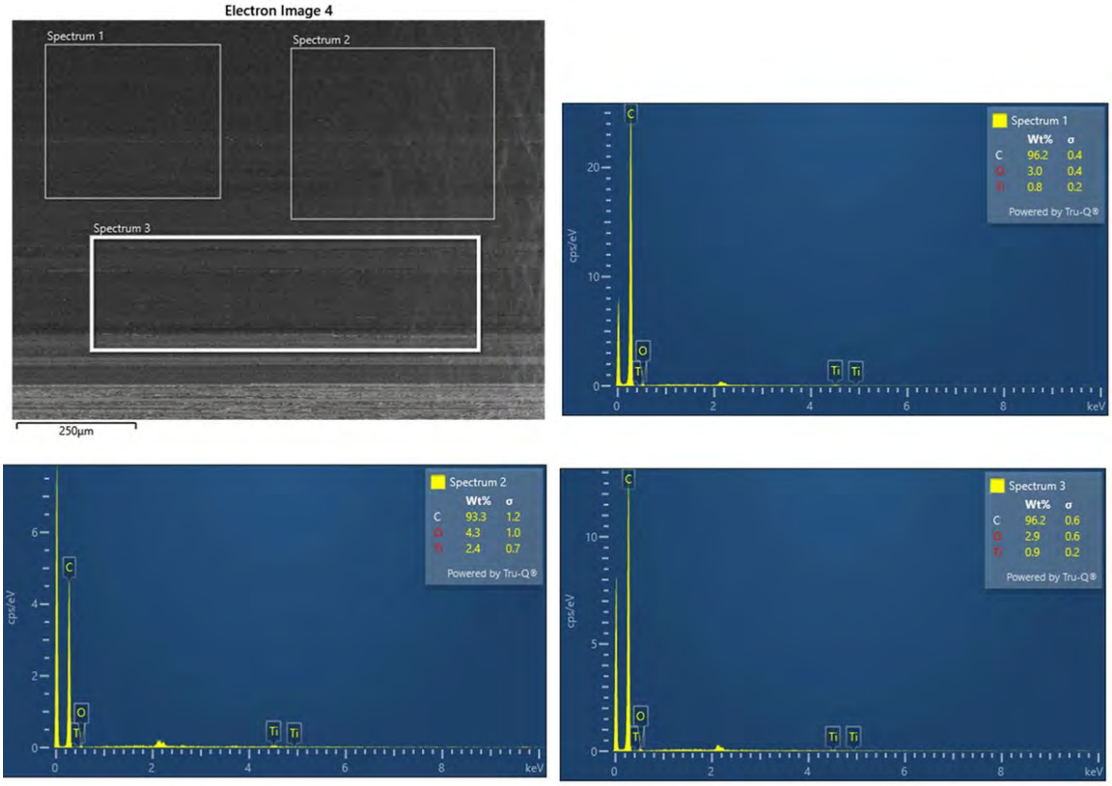


Figure A.15: FESEM images and spectrums for composition of rHDPE pallet

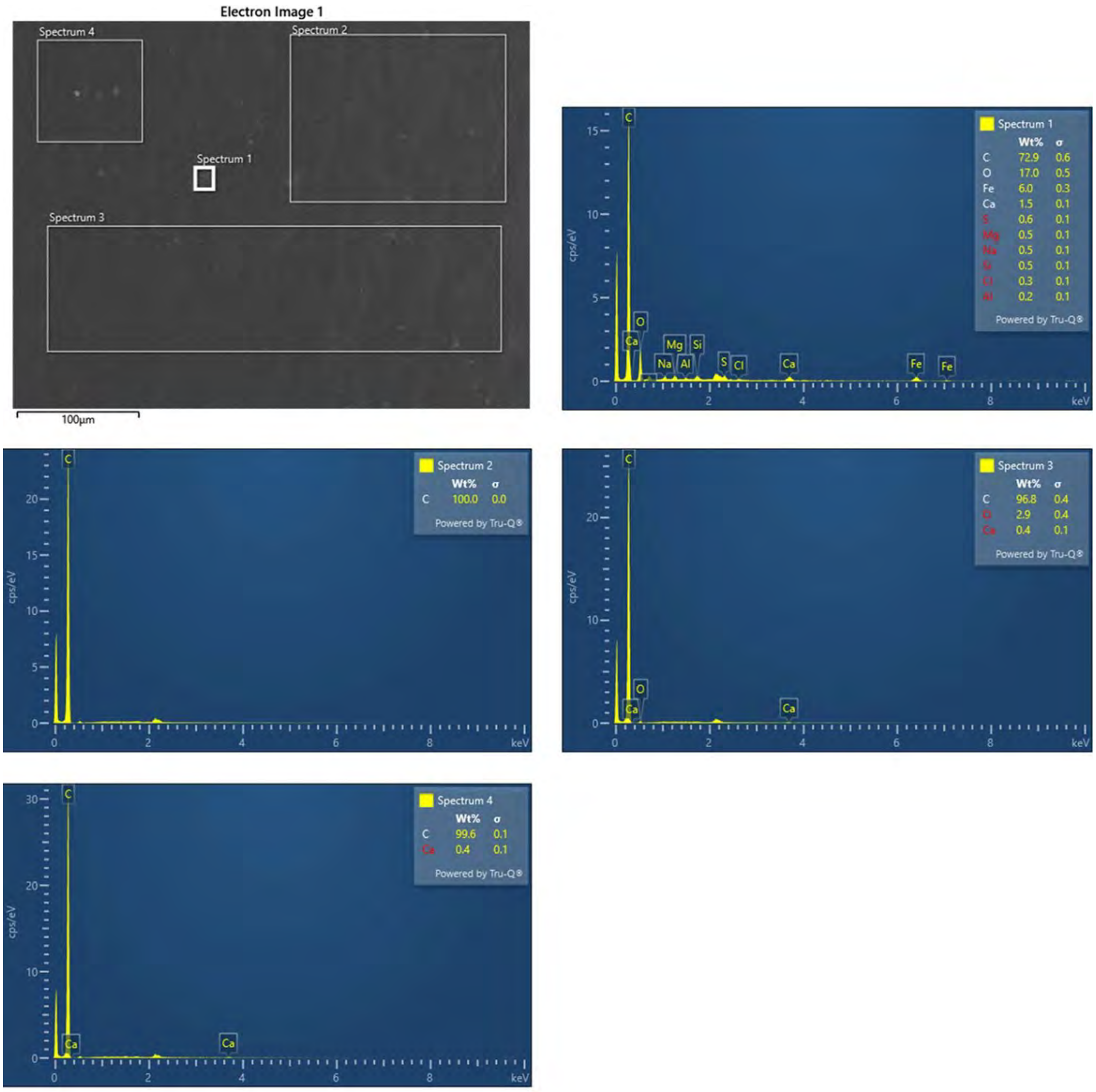


FIGURE A.16: FESEM images and spectrums for composition of rLDPE pallet

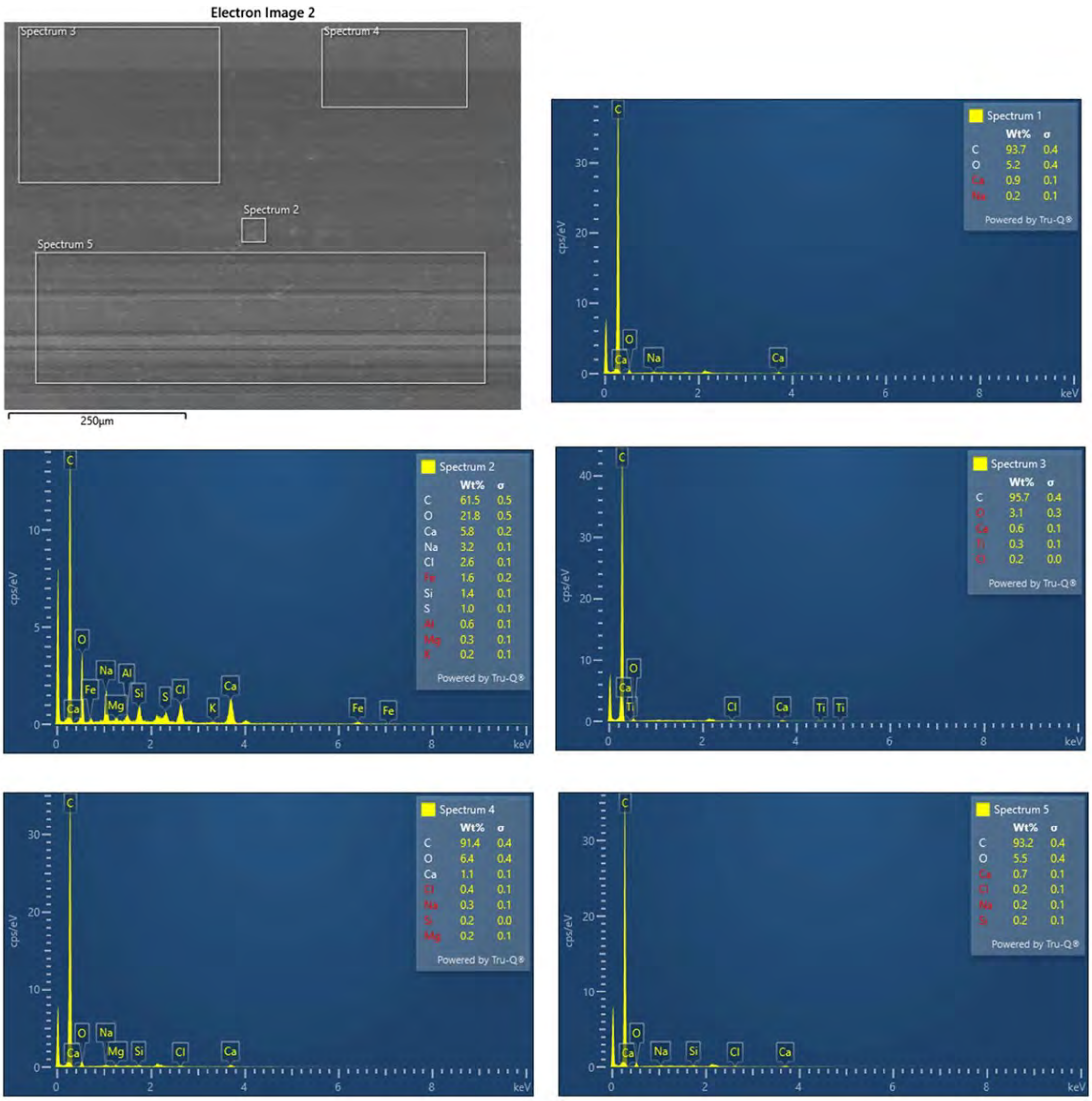


FIGURE A.17: FESEM images and spectrums for composition of rHDPE pallet

Table A.1: Composition obtained from different spectrum of rHDPE

Spectrum	C	O	Au	Ca	Ti	Cl	Si	Al	Na	Fe
Spectrum 1 (Wt%)	91.7	3.4	3.1	0.8	0.7	0.2	0.2			
Spectrum 2 (Wt%)	89.7	5.5	2.9	0.5	0.6	0.2	0.2	0.2	0.2	
Spectrum 3 (Wt%)	86.5	7	2.9	1.2	0.7	0.3	0.5	0.2	0.2	0.5

Table A.2: Composition obtained from different spectrum of rHDPE + POL

Spectrum	C	O	Au	Ti	Ca	Na	Si	Cl
Spectrum 1 (Wt%)	91.7	6.2	1.5	0.3	0.3			
Spectrum 2 (Wt%)	92.2	5.1	1.7	0.3	0.3	0.1	0.1	0.1
Spectrum 3 (Wt%)	92.2	5.6	1.6	0.4	0.3			
Spectrum 4 (Wt%)	90	7.4	1.6	0.3	0.4		0.3	

Table A.3: Composition obtained from different spectrum of rPP

Spectrum	C	O	Au	Ca	Si	Cl	Na	Al	Mg
Spectrum 1 (Wt%)	94.3	2.8	2.4	0.4					
Spectrum 2 (Wt%)	89.6	6.3	2.6	0.4	0.4	0.3		0.3	
Spectrum 3 (Wt%)	94.2	2.6	2.5	0.3	0.2	0.2			
Spectrum 4 (Wt%)	94.7	2.6	2.2	0.5					
Spectrum 5 (Wt%)	97.1	0.3	2.3		0.2		0.3		0.1
Spectrum 6 (Wt%)	94.5	3	2.1	0.5					

Table A.4: Composition obtained from different spectrum of rHDPE +rLDPE

Spectrum	C	O	Au	Ti	Ca	Fe	Cr	Si	Al	K	Mg	S
Spectrum 1 (Wt%)	91	3.3	3.3	0.4	0.3							
Spectrum 2 (Wt%)	90.5	3.1	3.1	0.2	0.3	0.4	0.3					
Spectrum 3 (Wt%)	89.6	5.6	3	0.2	0.3	0.5	0.2					
Spectrum 4 (Wt%)	53		3.3					33.1	6.6	0.3	0.2	
Spectrum 5 (Wt%)	90.6	3.9	4.2	0.3	0.3	0.3	0.3	0.2				0.2
Spectrum 6 (Wt%)	92.1	3.1	3.1	0.3	0.3							

Table A.5: Composition obtained from different spectrum of rHIPS

Spectrum	C	O	Au	Ca	Ti	Cl
Spectrum 1 (Wt%)	90.9	5.2	2.5	0.6	0.3	0.1
Spectrum 2 (Wt%)	89.8	6.1	3.1	0.5	0.3	0.2
Spectrum 3 (Wt%)	90.6	5.7	3	0.3	0.3	0.1
Spectrum 4 (Wt%)	90.5	5.4	3	0.4	0.4	0.3

Table A.6: Composition obtained from different spectrum of rHDPE + SAM

Spectrum	C	O	Au	Fe	Ca	Si	Ta	Ti	S
Spectrum 1 (Wt%)	90.8	3.1	3.1	0.6	0.3	0.2	0.2		0.1
Spectrum 2 (Wt%)	91.2	3.9	3.3	0.9			0.8		
Spectrum 3 (Wt%)	91.3	3.1	3.1	0.6	0.2		0.3		
Spectrum 4 (Wt%)	91.3	3.9	3.2		0.4	0.2			
Spectrum 5 (Wt%)	90.6	3.1	3.1		0.3		0.3	0.1	

Table A.7: Composition obtained from different spectrum of rHDPE + rPP

Spectrum	C	O	Au	Fe	Ca	Ti	Si	Cl	Na	Al	S	K
Spectrum 1 (Wt%)	85.6	7.9	3.6	0.7	0.3	0.3	0.3	0.2	0.2	0.2		
Spectrum 2 (Wt%)	87.5	7	3.8	0.7	0.3	0.4	0.3	0.1				
Spectrum 3 (Wt%)	87.5	7	3.6	0.6	0.1	0.4			0.1		0.2	
Spectrum 4 (Wt%)	83.6	9.7	3.6	0.7	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.2

Table A.8: Composition obtained from different spectrum of rHDPE + V

Spectrum	C	Au	O	Ti
Spectrum 1 (Wt%)	97.1	2.9		
Spectrum 2 (Wt%)	95	3.5	1.4	
Spectrum 3 (Wt%)	95	2.8	2.4	0.1
Spectrum 4 (Wt%)	94.1	2.9	2.6	0.4
Spectrum 5 (Wt%)	94	2.9	2.1	0.3

Table A.9: Composition obtained from different spectrum of rLDPE

Spectrum	C	O	Au	Fe	Ca	Si	Na	Al	Mg	Mo	Cl	Sr
Spectrum 1 (Wt%)	85.8	8.4	2.4	1.2	0.3	0.2	0.2	0.2	0.2			
Spectrum 2 (Wt%)	82.6	8.4	5.3		2	0.4	0.3	0.2	0.2	0.4	0.1	
Spectrum 3 (Wt%)	87.6	6.7	2.2	0.6	0.3	0.2	0.2	0.1				
Spectrum 4 (Wt%)	83.5	10.2	2.3	0.3	1.5	0.2	0.2	0.1	0.2		0.1	0.2
Spectrum 5 (Wt%)	87.4	6.7	2.2	0.4	0.3	0.2	0.2	0.1				

Table A.10: Composition obtained from different spectrum of rHDPE pallet

Spectrum	C	O	Ca	Cl	Si	S
Spectrum 1 (Wt%)	94.8	3.7	0.3	0.2	0.2	0.2
Spectrum 2 (Wt%)	95.7	2.8	0.9	0.4	0.2	0.2
Spectrum 3 (Wt%)	94	3	1.3	0.4		
Spectrum 4 (Wt%)	95.3	3.6	1			
Spectrum 5 (Wt%)	99.1	0.9				

Table A.11: Composition obtained from different spectrum of SAMICANITE pallet

Spectrum	C	O	Ca	Cl	Ti	Na	Ne
Spectrum 1 (Wt%)	94.2	3	1	0.5	0.4		
Spectrum 2 (Wt%)	93.3	5.3	1.2			0.2	0.2
Spectrum 3 (Wt%)	93.5	3.3	1.2				
Spectrum 4 (Wt%)	95	3.6	0.6	0.4			

Table A.12: Composition obtained from different spectrum of polyolefin pallet

Spectrum	C	O	Ca	Si	Na	Al	Mg
Spectrum 6 (Wt%)	100						
Spectrum 7 (Wt%)	80.6	13.6	4.4	0.6	0.4	0.3	0.2
Spectrum 8 (Wt%)	100						
Spectrum 9 (Wt%)	97.3	2.7					
Spectrum 10 (Wt%)	100						

Table A.13: Composition obtained from different spectrum of Virgin PE pallet

Spectrum	C
Spectrum 1 (Wt%)	100
Spectrum 2 (Wt%)	100
Spectrum 3 (Wt%)	100
Spectrum 4 (Wt%)	100
Spectrum 5 (Wt%)	100

Table A.14: Composition obtained from different spectrum of polyolefin pallet

Spectrum	C
Spectrum 1 (Wt%)	100
Spectrum 2 (Wt%)	100
Spectrum 3 (Wt%)	100
Spectrum 4 (Wt%)	100

Table A.15: Composition obtained from different spectrum of rHDPE pallet

Spectrum	C	O	Ti
Spectrum 1 (Wt%)	96.2	3	0.8
Spectrum 2 (Wt%)	93.3	4.3	2.4
Spectrum 3 (Wt%)	96.2	2.9	0.9

Table A.16: Composition obtained from different spectrum of rLDPE pallet

Spectrum	C	O	Fe	Ca	Mg	Si	Na	Al	S	Cl
Spectrum 1 (Wt%)	72.9	6	6	1.5	0.5	0.5	0.3	0.3	0.3	0.3
Spectrum 2 (Wt%)	100									
Spectrum 3 (Wt%)	96.8	2.9		0.4						
Spectrum 4 (Wt%)	99.6			0.4						

TABLE A.17: Composition obtained from different spectrum of rHDPE pallet

Spectrum	C	O	Ca	Na	Cl	Fe	Mg	Si	Al	Ti	K	Sr
Spectrum 1 (Wt%)	93.7	5.2	0.9	0.2								
Spectrum 2 (Wt%)	61.5	21.8	5.8	3.2	2.6	1.6	1.6	1.4	1		0.2	
Spectrum 3 (Wt%)	95.7	3.6	0.3	0.2	0.3					0.2		0.2
Spectrum 4 (Wt%)	91.4	6.4	1.1	1	0.3		0.2	0.2				
Spectrum 5 (Wt%)	93.2	5.5	0.4	0.2	0.2							

TABLE A.18: Advantages and disadvantages of different corrugated and there fixing method [173]

Material used in construction	Advantages	Disadvantages	Fixing method
Corrugated Galvanized steel with coating of zinc	▪ These are light weight ▪ Comes in differnet thickness and largely available and used ▪ Commercially available easily and at a very low cost	▪ The durability is limited to climatic conditions and expects corrosion depends upon the coating ▪ Gets heated in thermal conditions ▪ Noisy during rain and have low acoustics	▪ Rubber washers with screws bolts and with sealing materials
Corrugated aluminium with coating of zinc	▪ These are lightweight ▪ Comes in differnet thickness and largely available and used ▪ Commercially available easily and at a very low cost ▪ Have resistance to corrosion ▪ Recommended for industrial use	▪ Are expensive than CGI ▪ Better than CGI in thermal conductivity ▪ Gets reacted with copper sulphate lead bronze etc ▪ Noisy during rain and have low acoustics	▪ Same as CGI Rubber washers with screws bolts and with sealing materials
Corrugated aluminium sheets	▪ These are lightweight ▪ Comes in differnet thickness and largely available and used ▪ Commercially available easily and at a very low cost ▪ Have resistance to corrosion ▪ Recommended for industrial use	▪ Expensive than CGI ▪ Better than CGI in thermal conductivity ▪ Gets reacted with copper sulphate lead bronze etc ▪ Noisy during rain and have low acoustics	▪ Same as CGI Rubber washers with screws bolts and with sealing materials
Bitumen sheets having corrugations	▪ High resistant and do not rust ▪ Thermally insulated ▪ Less noisy in weather like rain etc ▪ Lesser in cost ▪ Recommended for marine urban environments	▪ Only one size as that of the manufacturing limitations ▪ Are not easily comercially available ▪ Are heavy and can catch fire	▪ Rubber washers with galvanized screws bolts and with sealing materials
Fibre glass sheets with corrugations	▪ Comes in transparent colours ▪ Comes in light weight and good aesthetical colours	▪ Only one size as that of the manufacturing limitations ▪ Brittle and break due to fatigue or shocks ▪ Expensive than other sheets	▪ Rubber washers with galvanized screws bolts and with sealing materials
Fibro cement sheets with corrugations	▪ Good resistance against rust ▪ Bear heavy load and donot deform	▪ Only one size as that of the manufacturing limitations ▪ Brittle and break due to fatigue or shocks ▪ Expensive to make and tranport ▪ Acoustically low	▪ Proper washers of galvanized steel with bolts and sealing materials
Plastic sheets with corrugation	▪ High resistant and do not rust ▪ Comes in light weight and good aesthetical colours	▪ Brittle and break due to fatigue or shocks ▪ Expensive than other sheets	▪ Rubber washers with galvanized screws bolts and with sealing materials
Corrugated asbestos sheets	▪ Do not rust and is in lighter weight	▪ Have health hazards and is prohibited in some countries. ▪ Not recommended for commercial or domestic uses	▪ Rubber washers with galvanized screws bolts and with sealing materials

Turnitin Originality Report

Characterization of Waste Plastic as Construction Material for Selected Building Products in Housing by Aaroon Joshua Das

From Quick Submit (Quick Submit)

- Processed on 28-Oct-2025 13:52 PKT
- ID: 2795445952
- Word Count: 52262

Graduate Studies Office

06%

Within Limits after Excluding Student's Own Work

Similarity Index
6%
Similarity by Source

Internet Sources:
4%
Publications:
4%
Student Papers:
3%

sources:

1 2% match (Internet from 22-Sep-2025)
https://www.mdpi.com/2075-5309/15/17/2996

2 < 1% match (Internet from 15-Oct-2025)
https://www.mdpi.com/2227-9717/12/12/2851

3 < 1% match (Internet from 20-Oct-2025)
https://www.mdpi.com/2673-7167/5/3/33

4 < 1% match (Internet from 03-Jan-2020)
https://www.mdpi.com/2073-4360/10/3/312/htm

5 < 1% match (Internet from 28-Jan-2025)
https://www.mdpi.com/2073-4360/17/3/263

6 < 1% match (Internet from 16-Oct-2023)
https://WWW.MDPI.COM/1996-1073/15/3/859

7 < 1% match (Shehryar Ahmed, Majid Ali. "Development and Engineering Evaluation of Interlocking Hollow Blocks Made of Recycled Plastic for Mortar-Free Housing", Buildings, 2025)
Shehryar Ahmed, Majid Ali. "Development and Engineering Evaluation of Interlocking Hollow Blocks Made of Recycled Plastic for Mortar-Free Housing", Buildings, 2025

8 < 1% match (Internet from 05-Aug-2025)
https://ideas.repec.org/a/gam/jsusta/v17y2025i11p4997-d1667460.html

9 < 1% match (Safeer Ullah, Majid Ali. "Development and Properties Investigation of Recycled Plastic Solid Interlocking Blocks", Case Studies in Construction Materials, 2025)
Safeer Ullah, Majid Ali. "Development and Properties Investigation of Recycled Plastic Solid Interlocking Blocks", Case Studies in Construction Materials, 2025

10 < 1% match (Internet from 28-Oct-2025)
https://cust.edu.pk/our_team/dr-majid-ali/

11 < 1% match (Internet from 27-Jan-2024)