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The Characteristics of Resin Waste (RW)/Recycled High-Density Polyethylene (R-HDPE) Blends to Enhanced Pavement

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ABSTRACT

Permeable pavement is characterized by open cell structures that enable the drainage of rainfall and snowmelt, as opposed to the runoff observed on impervious pavements. The structural strength of commercial permeable pavement materials is lower than that of conventional pavements due to inherent permeability and structural distinctions. This research focuses on the fabrication of samples using a combination of Resin Waste (RW) and reinforced Recycled High-Density Polyethylene (R-HDPE) in varying ratios of RW (30%, 40%, 50%, 60% and 70% wt/wt). The fabrication process involves a 3-hour heating process at 200°C in a furnace, followed by a 24-hour cure at room temperature. Physical and mechanical properties of the RW/R-HDPE Blends were examined, revealing that the 60% R-HDPE ratio resulted in the lowest density (4.523 g/cm3) and porosity (0.246%). SEM images displayed fewer voids, indicating effective filler dispersion and resin matrix interaction at the 60% resin waste ratio. Tensile strength and stiffness elasticity were maximized at 60% wt/wt of R-HDPE, reaching 3.36 MPa, while the bending strength peaked at 1.1 MPa at the same ratio. The 60% RW/R-HDPE ratio recorded the highest impact strength (26.25 kJ/m2) and energy absorption (1.69 J), showcasing the sample's ability to absorb impact energy through controlled failure mechanisms. In conclusion, the 60% wt/wt RW/R-HDPE Blends exhibit promising potential for enhancing the properties of permeable pavement, particularly in road applications, due to its superior bending and tensile strength.

1. Introduction

Permeable pavement is now widely acknowledged as a sustainable paving solution, with a history dating back to the 18th century when it was initially employed for urban purposes. Over the years, its applications have expanded and it has emerged as an effective method for managing runoff water

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[1]. The construction of permeable pavements involves a diverse range of surface materials designed to specific applications, including permeable pavers, pervious concrete and porous drainage asphalt.

These materials are strategically chosen to achieve the overarching objective of facilitating the infiltration of surface water, particularly during heavy rainfall events and substantial precipitation. This infiltration is facilitated through the entire pavement structure, with a crucial role played by permeable subbase materials, also referred to as coarse-grained aggregates [2]. The ongoing evolution and recognition of permeable pavement underscore its significance as a sustainable and versatile solution for contemporary urban infrastructure challenges.

Moreover, the innovation in permeable pavement extends to the popular use of composite materials, exemplified by HDPE and LDPE [3]. Serving as environmentally friendly alternatives to traditional impermeable asphalt and concrete pavements, permeable pavements feature interconnected empty gaps that enable water penetration into a subterranean storage zone [4]. This permeable subbase layer can serve a dual purpose, functioning either as a reservoir or temporary storage [5]. The utilization of High-Density Polyethylene (HDPE), a widely employed material globally, underscores the technical advancements, lightweight nature and cost-effectiveness of plastics. Despite these advantages, the management of end-of-life plastic items poses challenges due to high degradation. The combination of permeable pavement has demonstrated its capacity to enhance road strength and flexibility. HDPE tests, indicating a positive correlation between increased HDPE content and heightened strength and durability [6]. This multifaceted approach not only underscores the versatility of permeable pavement but also addresses the crucial aspect of sustainable material choices in the realm of urban infrastructure development.

Typically, high-density polyethylene (HDPE) finds more widespread application in slope land engineering rather than road engineering, where its primary purpose is to mitigate water intrusion [7]. HDPE boasts durable, opaque and temperature-resistant material properties. This lightweight and non-toxic substance is not only easily recyclable but is also increasingly being adopted as an environmentally preferable alternative to less sustainable components [8]. The enhancement of road paving quality through polymer addition to bituminous mixtures has been recognized as a pivotal approach, as revealed in a comprehensive review of the literature. The incorporation of polymers into bituminous mixtures is typically achieved through either the wet or dry method, although the compound layer approach has been employed in this study by *Rabbi et al.,* [9]. Within the research, a thorough exploration of the benefits of polymer incorporation for road paving has been conducted, with the author delineating various polymer addition processing methods [10].

2. Literature Review

The impact of HDPE on the tensile strength within a polymer matrix composite material, employing a combination of nylon, epoxy resin and fiberglass for pavement. The tensile strength of samples with a high percentage of fiberglass exhibited a reduction, while the material reinforced solely with HDPE demonstrated heightened tensile strength. This increase was attributed to the superior boundary interaction between nylon and epoxy resin compared to the combination of fiberglass and epoxy resin [11]. In a complementary vein, the optimal aggregate size and PEFB-to-box waste materials (PEFB/BW) polymer blend ratio was identified based on tensile strength test results. The initial series of test batches highlighted the superiority of the 13-16 mm gradation with a PEFB/BW ratio of 4. Polymer blends on these findings in stage 2, both 13-16 mm and 10-13 mm aggregates were investigated with the same PEFB/RB ratio. Subsequent stages introduced the 10-13 mm aggregate size of PEFB based on the belief that its performance could be significantly enhanced by the addition of fibres to the mixes [12]. This strategic approach not only emphasizes the optimization of blend materials for improved tensile strength but considerations involved in selecting aggregate sizes and ratios for composite formulations.

The tensile strength of metal-resin bonds, specifically investigating the impact of an epoxy monolith layer between SUS and resin plates. To establish a baseline, a flat epoxy surface was prepared as a reference under identical curing conditions, excluding pyrogen. The lap shear strength values for three bonding scenarios were compared: metal-resin bonding via an epoxy monolith layer, metal-resin bonding via a flat epoxy layer and direct metal-resin bonding. The representative curves from tensile tests utilizing various resins (PE, PP, POM and ABS) with or without the epoxy monolith mediator. The comprehensive findings revealed the adhesion strength values, specifically, the bonding with PE and PP exhibited adhesion strength values of 2.00 ± 0.22 and 1.36 ± 0.20 MPa, respectively, when utilizing the epoxy monolith mediator. These values demonstrated a substantial enhancement, being two or three times larger compared to the strength values observed in direct metal-resin bonding scenarios. The efficacy of the epoxy monolith mediator extended beyond PE and PP to encompass other high-performance resins, including POM and ABS. For these resins, bonding strength values were measured at 1.22 ± 0.57 and 2.66 ± 0.74 MPa, respectively [13]. It highlights the versatility and consistent improvement in bonding strength achieved through the application of the epoxy monolith mediator. The results signify a significant advancement in the field of metal-resin bonding, showcasing the potential of the epoxy monolith layer as a mediator to enhance adhesion strength across various resin materials. This strategic use of epoxy monolith layers not only demonstrated substantial increases in bonding strength but also emphasized their effectiveness as a universal mediator for diverse high-performance resins. This research contributes valuable into the optimization of metal-resin bonds, paving the way for improved materials and methodologies in various industrial applications. The findings have implications for engineering and manufacturing processes, offering a promising avenue for enhanced performance and reliability in metal-resin composite structures.

The mechanical and physical testing of permeable pavement, specifically examining the impact of incorporating hemp fibre into the composite matrix. The research revealed that the addition of hemp fibre significantly enhances the impact resistance of the composite material. Intriguingly, this improvement is nearly proportional to the increase in the quantity of hemp fibres, indicating a direct correlation between fibre content and impact resistance. The research presented in the study visually demonstrates this relationship, highlighting the positive influence of hemp fibre on the composite's ability to withstand impacts [14]. A feature associated with lignocellulosic fibres, specifically hemp fibres was discovered. The standard deviation, indicative of the variability or spread of data points, was relatively significant at higher fibre percentage levels. This dispersion of values is a well-recognized heterogeneous characteristic of lignocellulosic fibres and underscores the complex nature of their distribution within the composite matrix. Understanding this variability is crucial for optimizing the performance and consistency of composite materials in practical applications [15]. The variation of Charpy impact energy with the quantity of hemp fibre in the epoxy composite was a key focus of the research. Charpy impact testing is a widely employed method to assess the resistance of materials to sudden impact or shock loading. According to Buritatum *et al.,* [16] who sought to comprehensively understand how the energy absorption capacity of the composite responds to varying levels of hemp fibre incorporation. The findings elucidated that as the amount of hemp fibre increased in the epoxy composite, there was a corresponding change in the Charpy impact energy.

This research contributes valuable insights into the optimization of permeable pavement, particularly concerning the use of hemp fibres in enhancing impact resistance. The proportional relationship between hemp fibre content and impact resistance suggests that careful control of fibre quantity can be a pivotal factor in modifying the performance of these composite materials.

Additionally, the acknowledgment of variability in lignocellulosic fibre distribution emphasizes the need for meticulous engineering considerations to ensure consistent and reliable outcomes in real-world applications [17]. This study provides an understanding of the impact of hemp fibre incorporation. The literature review emphasizes the potential of composite materials in sustainable infrastructure, with implications for the design and construction of permeable pavements that can withstand varying degrees of impact. Consequently, this study aims to leverage resin waste in the fabrication of permeable pavement as a blend polymer, thereby aligning with the broader context of utilizing advanced materials and methodologies for sustainable and resilient urban infrastructure development.

3. Methodology

3.1 Preparation of RW/R-HDPE Blend Samples

The fabrication of mixed resin waste (RW) reinforced recycled high-density polyethylene (R-HDPE) for the development of RW/R-HDPE Blends to enhance pavement created with the preparation of raw materials and samples. The raw material, illustrated in Figure 1 as resin waste (RW) reinforced R-HDPE, served as the substance for RW/R-HDPE Blends designed to enhance pavement applications. Sample preparation encompassed various compositions of resin waste-reinforced R-HDPE plastic, involving several stages of the process such as weighing, mixing, heating and cooling processes. STMicroelectronics Sdn. Bhd. provided the resin waste abundant in the industry, while Angkasa Kawaris Plastic Sdn. Bhd. provided R-HDPE plastic waste.

(a) (b)

Fig. 1. Raw material: (a) R-HDPE (b) Resin waste (RW)

A total of five samples of RW/R-HDPE Blends were accurately produced, at different ratios of resin waste mixed with R-HDPE, as tabulated in Table 1. This comprehensive process of the RW/R-HDPE Blends for evaluating the characteristics and potential applications of RW/R-HDPE Blends in the context of sustainable permeable pavement solutions. Figure 2 shows the process fabrication of permeable pavement composite

Table 1
The composition ratios of raw materials in preparing permeable pavement composite

Sample	Resin Waste (RW) (wt/wt)	Recycled HDPE (R-HDPE) (wt/wt)	Binder (Epoxy Adhesive Binder) (wt/wt)
A	30%	50%	5%
B	40%	50%	5%
C	50%	50%	5%
D	60%	50%	5%
E	70%	50%	5%

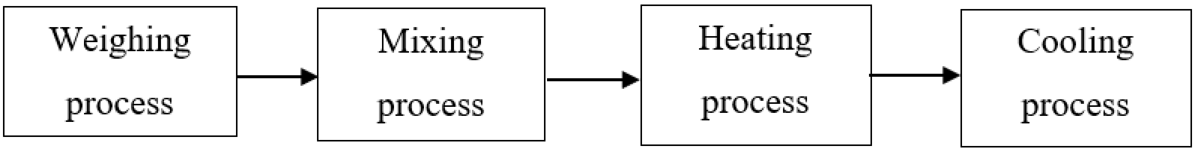


Fig. 2. Process fabrication of permeable pavement composite

A series of five RW/R-HDPE Blend samples were meticulously prepared, each featuring distinct ratios of resin waste (RW) reinforced by a composite of recycled high-density polyethylene (R-HDPE) as depicted in Figure 3.

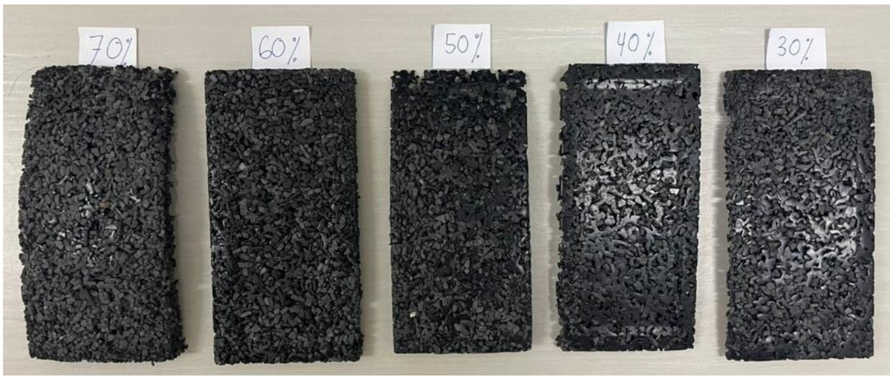


Fig. 3. RW/R-HDPE Blends sample at different weight ratios of RW

The elaborate process unfolded in several key stages to ensure precision and consistency. The first step involved the weighing process, where the samples of RW/R-HDPE Blend were meticulously weighed according to the specified composition ratios. This procedure was executed using the Mettler Toledo electronic precision balance, renowned for its accuracy with a readability of 0.1 mg. This meticulous weighing process took place at the Laboratory of Packaging, Faculty of Engineering Technology, UTHM, ensuring the precise measurement of each component in the composite. Subsequently, the mixing process ensued, where the resin waste was blended according to the predetermined composition ratios. This step was critical in achieving a homogenous distribution of the components within the composite, ensuring uniformity and optimal performance. The final mixture was transferred by casting method over the prepared mould with a dimension of 200mm x 200mm with uniform thickness and width.

Following the mixing phase, the composite underwent a heating process. The RW/R-HDPE samples were subjected to a controlled temperature of 300°C within a furnace for a duration of 1 hour. This carefully regulated heating process aimed to facilitate the fusion and bonding of the composite components, enhancing the overall structural integrity. Finally, the composite samples underwent a cooling process, left undisturbed for 24 hours at room temperature. This period allowed the material to gradually reach ambient conditions, promoting stability and preventing thermal stresses that could affect the structural properties of the RW/R-HDPE Blends. The preparation of these RW/R-HDPE Blends samples involved weighing, thorough mixing, controlled heating and gradual cooling processes. Each step played a crucial role in ensuring the precision, homogeneity and structural integrity of the resulting RW/R-HDPE Blends to be applied on sustainable permeable pavement applications.

4. Results and Discussion
4.1 SEM Microstructure Analysis

The fractured surface of RW/R-HDPE, captured in SEM images and illustrated in Figure 4, underwent detailed analysis to discern the factors influencing rupture during mechanical tests. The cross-section morphology and microstructure of the composites were meticulously examined using SEM images, particularly at a 500x image magnification of matrix-reinforcement bonding before subjecting the samples to tensile strength testing [18]. In Figure 4(d), the SEM analysis of the 60% RW/R-HDPE revealed a commendable matrix-reinforcement bonding, showcasing a cohesive structure. However, at a 30% ratio, as depicted in Figure 4(a), observations indicated that resin waste was extracted from the sample, leaving a flat surface—a clear indication of poor adhesion between the reinforcement and the matrix [19]. Figure 4(b) and 4(c), depicts the SEM analysis of the 60% RW/R-HDPE ratio, where matrix debris formed around the composite breaking point and resin waste exhibited splitting rather than being pushed out of the matrix. Meanwhile, Figure 4(e) represents the SEM analysis of the 70% ratio RW/R-HDPE, showcasing a significant amount of resin being pulled out from the matrix, leaving a wide and deep hole.

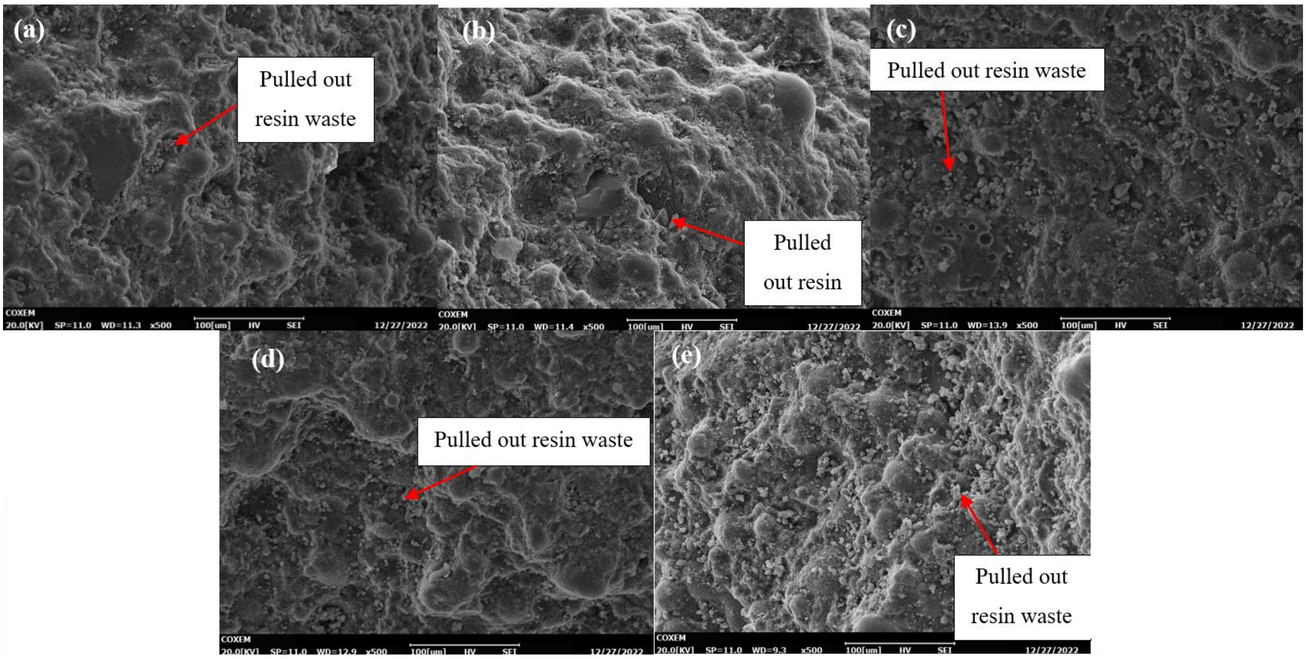


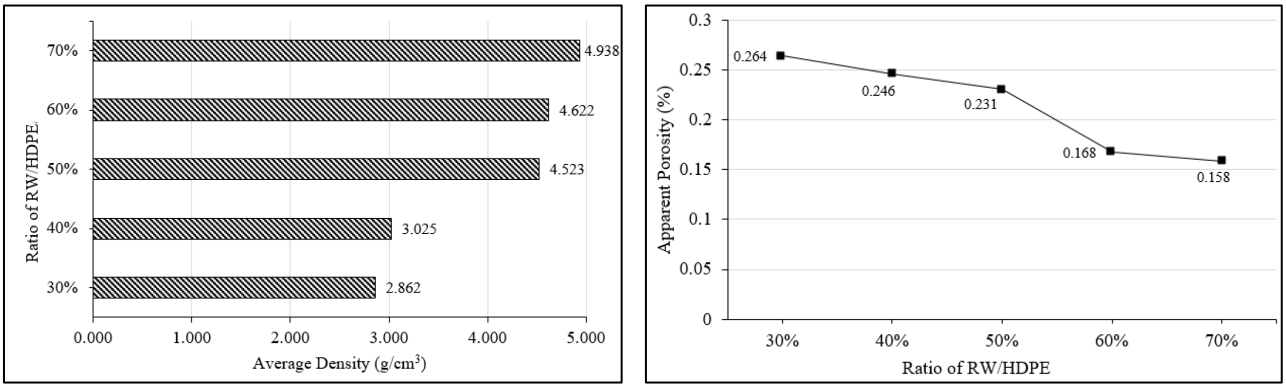
Fig. 4. SEM image of fractured surface sample: Ratio (a) 30% (b) 40% (c) 50% (d) 60% R (e) 70% wt/wt RW-R-HDPE Blends

It is a similar finding by Xiaoguang, that small and sharp marks appeared in the direction of crack propagation. An intriguing observation was made regarding the resin-matrix interface, as the percentage ratio increased, the particle surface became more visible in the SEM images [20]. This phenomenon was attributed to inadequate adhesion in matrix-reinforcement bonding, exacerbated the use of less epoxy to establish bonding with higher resin waste (RW) and R-HDPE composite. The SEM images also revealed instances of resin waste-matrix R-HDPE interface failure, leading to adhesive fractures, a consequence of tensile stress accumulation in the resin waste-matrix interface for 60% wt/wt RW/R-HDPE Blends. The SEM analysis provided valuable insights into the matrix-reinforcement bonding characteristics at different RW/R-HDPE ratios. While a 30% wt/wt ratio demonstrated optimal bonding, lower ratios exhibited poor adhesion and higher ratios showcased pronounced resin extraction, indicative of challenges in achieving effective matrix-reinforcement bonding [21]. These findings highlight the critical part of reinforcement in ensuring strong and resilient bonds between resin waste (RW) and the matrix R-HDPE in RW/R-HDPE Blends in permeable pavement applications [22].

4.2 Density and Porosity Analysis

The density and porosity tests on RW/R-HDPE Blends constitute a critical aspect of this study. Figure 5 provides a comprehensive overview of the density results at different weight ratios of RW/R-HDPE, revealing a consistent upward trend as the ratio increases. At the 30% RW/R-HDPE ratio, the average density is 2.86 g/cm^3, rising to 3.03 g/cm^3 at the 40% wt/wt RW/R-HDPE. Subsequent increments result in average densities of 4.52 g/cm^3 at 50% wt/wt RW/R-HDPE and 4.62 g/cm^3 at 60% wt/wt RW/R-HDPE. The density at the 70% wt/wt RW/R-HDPE ratio peaks at 4.938 g/cm^3. This observed increase in density underscores a direct correlation between resin waste (RW) content and the overall density of the RW/R-HDPE Blends. In line with a study by Khotbehsara *et al.,* [23] there is a parallel increase in density observed in the previous pavement when epoxy replaces polymeric materials across all ages and mixtures. This phenomenon can be attributed to an enhanced adhesive force between the mortar and the gravel studied by Fodzi *et al.,* [24] coupled with a reduction in the number of voids in the polymeric materials or mortar. These findings align with the current study, affirming that the escalating density with an increase in the RW/R-HDPE ratio results from a decrease in the number of voids within the composite mixture.

The graph representation of apparent porosity in Figure 5, derived from the porosity test for RW/R-HDPE ratios of 30%, 40%, 50%, 60% and 70%, unveils a discernible trend. The apparent porosity at the 30% wt/wt RW/R-HDPE ratio stands at 0.26%, showing minimal deviation from the 0.25% apparent porosity at the 40% wt/wt RW/R-HDPE. Subsequent ratios demonstrate a declining trend, with the 50% RW/R-HDPE ratio displaying 0.23%, followed by the 60% wt/wt RW/R-HDPE with a value of 0.17%. Finally, the apparent porosity at the 70% RW/R-HDPE ratio reaches its lowest point at 0.16%. Throughout this process, there is a consistent reduction in the porosity of the RW/R-HDPE Blends. The study by Abdel-Reheem *et al.,* [25] further enriches the understanding of porosity dynamics. The gradual coating or partial filling of aggregate particles with epoxy resin, observed as the resin content increases, results in a decrease in porosity. This highlights the material of the resin waste (RW), particularly within HDPE mixtures, in influencing the porosity of permeable pavement composites. From mechanical properties, the increase in epoxy resin content leads to thorough wetting of aggregate surfaces, a thickening of the resin layer between aggregates and the filling of certain pores. As the porosity of the resin-based permeable brick decreases, the originally connected pores gradually diminish and become disconnected [26]. The thorough density and porosity tests in RW/R-HDPE Blends elucidate a compelling relationship between resin waste (RW) content and structural characteristics. The inclusion of epoxy resin emerges as a critical factor, impacting bonding, void reduction and overall composite properties. These findings involved the effect between resin waste ratios and material attributes, guiding the optimization of RW/R-HDPE Blends for enhanced performance and durability in permeable pavement applications.



(a) (b)

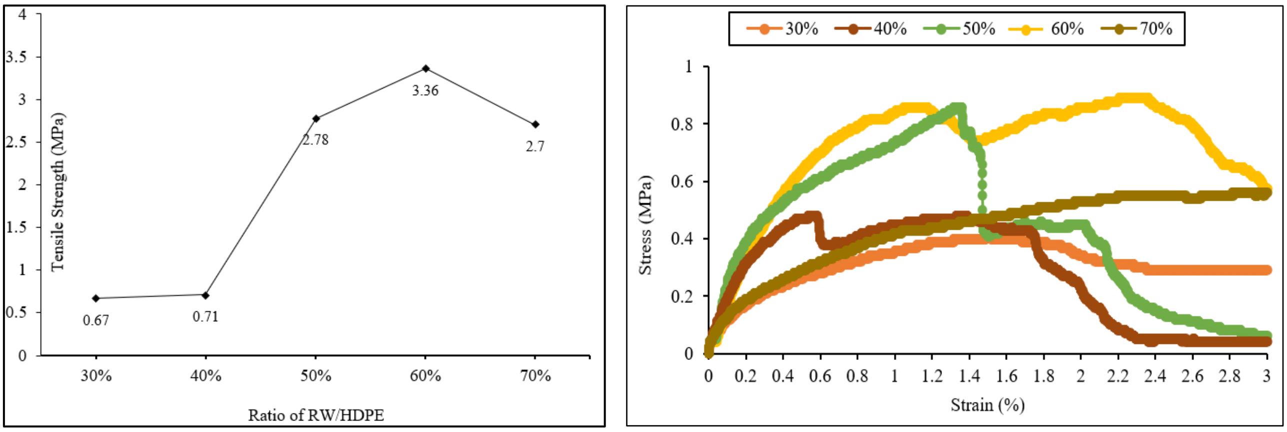
Fig. 5. (a) The density results (b) Apparent porosity at different ratios of RW/R-HDPE blends

4.3 Tensile Strength Analysis

Figure 6(a) shows the correlation between the tensile strength and the RW/R-HDPE ratio. The tensile strength of the composite, consisting of HDPE and resin waste (RW) exhibited an increasing trend, reaching its peak value at 60% wt/wt RW/R-HDPE. Subsequently, a slight decrease was observed. At the 60% wt/wt RW content, the composite achieved the maximum tensile strength of 3.36 MPa, followed by the 50% wt/wt ratio at 2.78 MPa, the 70% wt/wt at 2.70 MPa, the 40% ratio of RW/R-HDPE at 0.71 MPa and the 30% ratio at 0.67 MPa. The ascending trend in tensile strength was evident up to the 60% wt/wt RW/R-HDPE ratio, beyond which a decline occurred at the 70% wt/wt RW/R-HDPE ratio. This phenomenon may be attributed to the compromised interfacial bonding within the recycled HDPE and resin waste composite, emphasizing the importance of meticulous fabrication processes similar with employing bisphenol-A epoxy resin in Resin-Based Permeable Brick [27].

Figure 6(a) highlights the optimum resin waste-reinforced recycled HDPE is 60% wt/wt before observing a decline in tensile strength results. At a 70% RW ratio, a poorly bonded R-HDPE led to a decreasing trend, indicating an inability to sustain 70% resin waste composites. Inefficient stress transfer at the permeable pavement interface was evident in poorly bonded samples [28]. However, RW/R-HDPE Blends at 40% to 60% wt/wt RW exhibited a more favourable interface between resin waste and recycled HDPE. Figure 6(b) shows the stress-strain behaviour for each permeable pavement sample with varying resin waste ratios. The 50% RW/R-HDPE ratio displayed the maximum stress-strain at 3.10%, attributed to the polymer matrix composite's robust interfacial cohesion bonding. Subsequent ratios included 60% with 3.07%, 40% with 3.07%, 70% with 3.05% and 30% with 3.02%. With increasing applied stress, the resin waste underwent stretching, causing the mixture to tear apart, leaving the permeable pavement apertures exposed until failure. The stress-strain behaviour of permeable pavements incorporating RW/R-HDPE showed no significant difference, with the most favourable resin waste ratio identified as 60% for stress-strain analysis.

Resin characteristics reveal that the resin binder is rigid and brittle, capable of withstanding static pressure and meets the performance criteria for permeable bricks [29]. The tensile properties of reinforced polymers are primarily influenced by the interfacial adhesion between the epoxy matrix and fibres [30]. Each curve exhibits a maximum stress, assumed to be the material's tensile strength due to robust adhesion between the composite and polymer matrix. The even dispersion of resin waste filler facilitates a mechanical interlocking process between HDPE and the matrix, enhancing the load-bearing strength of the blend during tensile loading. As the matrix undergoes cracking under load, it becomes the weakest element in the tertiary composite system. The stress is subsequently transferred from the matrix to the resin waste filler, reaching maximum elasticity through the bridging effect of the mechanical interlocking system. Tensile strength is influenced by the interfacial adhesion between the epoxy matrix and fibres. The even dispersion of resin waste enhances the composite's load-bearing strength during tensile loading [31]. In contrast, the potential of combining resins to create polymer concrete with a low modulus of elasticity, making it suitable for overlay and repair applications on Portland cement concrete, especially in situations involving significant heat and mechanical movements [32]. Resin combinations for polymer concrete with a low modulus of elasticity, are suitable for enhancing the mechanical properties of pavement applications.



(a) (b)

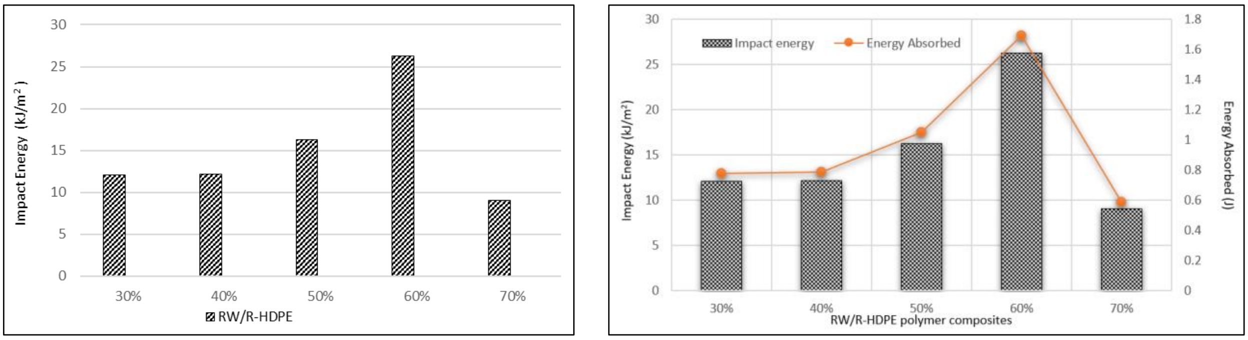
Fig. 6. (a) Tensile strength (b) Stress-strain for the different ratios of RW/R-HDPE Blends

4.4 Impact Strength Analysis

Figure 7(a) displays the variations in impact energy concerning different RW/R-HDPE ratios in permeable pavement-reinforced resin blends. As the RW/R-HDPE ratio increased, a consistent rise in impact energy was observed. The ratio of 60% RW/R-HDPE exhibited the highest impact energy at 2.77 J/m, followed by 50% at 2.44 J/m, 40% at 0.60 J/m, 30% at 0.59 J/m and the lowest energy of 0.39 J/m was noted at 70% RW/R-HDPE. Increasing the RW/R-HDPE ratio saw a rise in impact energy, peaking at 2.77 J/m for 60% RW/R-HDPE and declining to 0.39 J/m at 70% RW/R-HDPE. Polymer incorporation remarkably enhanced impact toughness, with low filler loading causing micro voids, affecting material hardening [33]. Higher resin waste ratios (40%, 50%, 60%) absorbed more energy before rupture, attributed to epoxy resin's viscosity and low surface tension enabling better penetration.

The incorporation of polymers into the matrix significantly enhances composite impact toughness [34]. Low filler loading may create micro-voids around the filler, affecting material hardening [35]. Higher resin waste content at ratios of 40%, 50% and 60% wt/wt in RW/R-HDPE showed increased energy absorption before specimen rupture compared to lower resin waste ratios (30%). Epoxy resins, due to their low viscosity and surface tension, facilitate easy composite penetration. However, pure epoxy resins exhibit poor resistance to crack growth, leading to lower absorbed energy in control samples [36].

In Figure 7(b), the relationship between absorbed energy and impact strength for various RW/R-HDPE ratios are depicted. The highest impact strength was achieved at a 60% RW/R-HDPE ratio (26.25 kJ/m^2), followed by 50% (16.27 kJ/m^2). Other ratios exhibited impact strengths of 12.19 kJ/m^2 (40%), 12.07 kJ/m^2 (30%) and 9.05 kJ/m^2 (70%). This trend correlates with fracture toughness variations due to filler loading. These findings show a proportional relationship between absorbed energy and impact strength. The sample with a 60% RW/R-HDPE ratio displayed the highest energy absorption and impact strength, showcasing its ability to manage failure mechanisms and modes effectively after impact loading. The resin waste inclusion significantly boosts impact resistance in composites, aligning with these findings [37].



(a) (b)

Fig. 7. (a) Impact energy (b) Relationship between energy absorbed and impact test at different ratio of RW for RW/R-HDPE blends

4.5 Bending Strength Analysis

Figure 8 presents the bending strength, at different ratios of resin waste (RW) for RW/R-HDPE Blends. These blends displayed a ductile mode when subjected to bending loads, demonstrating deformation upon force application. The RW/R-HDPE reinforced resin waste blends exhibited slight deformation, indicating a tendency toward rupture just beyond the elastic limit upon force application. The bending strength trend showcased an increase up to the 60% RW/R-HDPE ratio, followed by a slight decrease from the 70% ratio onward. The 60% RW/R-HDPE ratio exhibited the highest bending strength at 1.1 MPa, succeeded by ratios of 70% (0.78 MPa), 50% (0.63 MPa), 40% (0.54 MPa) and 30% (0.41 MPa). These findings underscore the influence of resin waste content on composite strength, where an optimal ratio led to maximum bending strength before declining at higher ratios.

The observed poor bending properties in RW/R-HDPE blends were linked to weak interfacial bonding between HDPE and resin waste. The non-uniform distribution of resin waste within the composites resulted in weak adhesion regions, impairing stress transfer efficiency between HDPE and resin waste, ultimately contributing to reduced strength properties [38]. Contrary to these observations, various factors affecting interfacial bonding quality was emphasized, including fibre nature, binder characteristics, manufacturing processes, mixing procedures and fibre treatment. Their study highlighted the multifaceted nature of interfacial bonding, suggesting that other factors beyond resin content might contribute to the observed composite behaviour [39]. Additionally, one of the researchers delved into fracture toughness assessment, providing insights into a mixture's resistance to crack propagation and its overall fracture performance [40]. This aspect of the study involved evaluating a composite's fracture behaviour beyond interfacial bonding, offering an interpretation of factors influencing composite strength and performance.

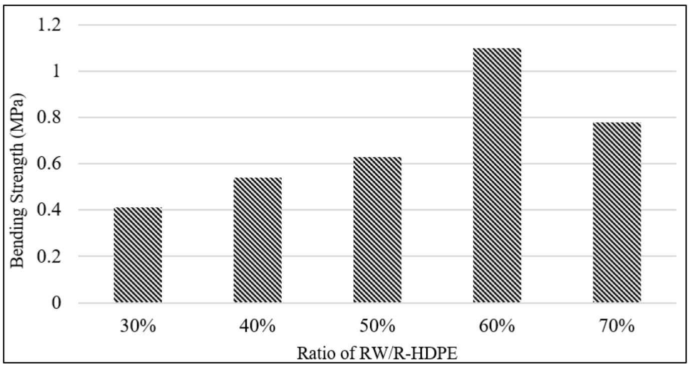


Fig. 8. Bending strength test at different ratios of RW for RW/R-HDPE blends

5. Conclusions

In conclusion, this study demonstrates the RW/R-HDPE Blends exhibit commendable physical and mechanical attributes suitable for permeable pavement applications. In terms of physical characteristics, SEM analysis of the fractured surface morphology at a 60% RW/R-HDPE ratio displayed fewer instances of composite pull-out, broken resin waste and void content compared to other ratios. This improvement in composite performance and properties was evident. Density and porosity tests indicated an increase in density across different RW/R-HDPE ratios, with the 60% ratio achieving a commendable density of 4.62 g/cm^3 and an apparent porosity of 0.231%, classifying it as a lightweight composite.

Mechanical properties revealed the superior performance of the 60% RW/R-HDPE Blends ratio over others. This ratio exhibited the highest tensile strength at 3.36 MPa, the top bending strength at 1.1 MPa and the maximum impact strength at 26.25 kJ/m^2. These results underscore the 60% RW/R-HDPE ratio as the optimal configuration for fabricating resin waste-based composite permeable pavements. This suggests the potential of polymer composite materials in transportation applications. Additionally, utilizing resin waste as recyclable material promotes eco-friendly practices, reducing landfill usage and air pollution. The RW/R-HDPE Blends' viability extends beyond permeable pavement applications for road-related manufacturing contributing to sustainable technology materials.

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