Pertanika J. Sci. & Technol. 32 (2): 819 - 838 (2024)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Mechanical Properties of Virgin and Recycled Polymer for Construction Pile Application

Hoo Tien Nicholas Kuan[1], Yee Yong Lee[2]*, Sim Nee Ting[2], Chee Khoon Ng[2] and Mohd Khairul Afiq[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia
[2]Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

ABSTRACT

Annual polymer waste generated in Malaysia has increased significantly to more than 1 million tonnes. The prolonged degradation periods required by diverse industrial polymer waste streams are a matter of significant concern, with some taking up to 1000 years to fully degrade. Pursuing a similar environmental concern, the use of bakau piles as supports for lightweight structures in Sarawak, including drainage systems, roads, sewerage, and other water-related structures, has become a matter of concern due to the deforestation of mangrove forests. Both bakau deforestation and polymer waste issues are significant environmental and global concerns. The idea of mitigating mangrove degradation and the non-biodegradable nature of polymer waste has led to the conceptualization of an alternative solution whereby recyclable thermoplastic polymer piles are utilized to supplant bakau piles in providing support for lightweight structures during civil engineering construction projects. Therefore, the study of polymer piles is conducted to examine their mechanical properties in the form of virgin (V) and recycled (R) thermoplastic polymers. In this study, high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC) are considered, and the possibility of being utilized in pile application has been discussed. Based on the results, all virgin types of thermoplastic polymers (HDPE, PP, and PVC), 50%V:50%R for PP, PP(R), and PVC(R), respectively, exceed the bakau ultimate tensile strength. Thermoplastic polymer piles showed great potential to be

ARTICLE INFO

Article history:
Received: 16 May 2023
Accepted: 12 September 2023
Published: 26 March 2024

DOI: https://doi.org/10.47836/pjst.32.2.18

E-mail addresses:
khtnicholas@unimas.my (Hoo Tien Nicholas Kuan)
yylee@unimas.my (Yee Yong Lee)
snting@unimas.my (Sim Nee Ting)
ckng@unimas.my (Chee Khoon Ng)
22020081@siswa.unimas.my (Mohd Khairul Afiq)
* Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

the substitution for bakau piles to serve in the construction industry, with the recorded experimental tensile and compressive strength tests.

Keywords: Compression, mechanical properties, polymer, construction pile, tensile

INTRODUCTION

The increasing volume of polymer waste produced by industries has been alarming, especially in polymer pollution. The available types of synthetic polymers in the market include polyvinyl chloride (PVC), polyethylene (PE), polycarbonate (PC), polyethylene terephthalate (PET), and polypropylene (PP). PVC is a polymer that consists of half chlorine by weight. PC and PET are the most commonly used thermoplastic polymers in the market and are known as polyester in the textile industry. PE and PP are part of the polyolefin family, but PE is slightly more rigid and heat-resistant. Their qualities and various characteristics make them appropriate for a wide range of uses in industries, including packaging, construction, home and sporting goods, cars, electronics, and agriculture. As a result of polymer materials' applications, 13.2% of polymer waste is generated per year, amounting to 53 kg of polymer waste per person per year or 1.59 million tons per year (Akenji et al., 2020). Municipal solid trash accounts for roughly two-thirds of total polymer trash, while the supply and industrial sectors account for the remaining third (Perugini et al., 2005).

Polymer pollution is becoming a huge environmental issue due to the large amounts generated, which endangers the environment and its population (Awoyera & Adesina, 2020). In addition, polymers need a long period to degrade, approximately 1000 years (Gerrard, 2020). The non-biodegradable nature of polymer waste generated over the years, compounded with the escalating amount of waste deposited in landfills worldwide, has become a pressing environmental issue. Polymer waste poses a significant threat to various facets of the environment, including oceanic health, human health, coastal regions, food safety and quality, as well as climate change. It brings a challenge to the polymer in construction to segregate, reuse and recycle polymer waste at the end of its life or alternatively combine it with natural fiber into a green polymer composite (Tan et al., 2017; Kuan et al., 2021). In line with this, biodegradable polymer is also introducing since the early 1980s due to the increasing volume of polymer waste, which is hard to recycle and has had a long life on the earth since its birth (Wang, 2022). However, due to their cost, biodegradable polymers are still unfavorable in the market. The recycling of polymer waste presents a viable solution to curb the mounting issue of polymer waste accumulation in landfills. In light of this, greater emphasis should be placed on recycling industrial polymer waste to mitigate the adverse environmental impact of polymer pollution caused by the accumulation of polymeric waste.

Polymer recycling is becoming a way to reduce environmental problems caused by the polymeric waste accumulation generated from day-to-day applications. Polymer recycling is one approach to decreasing pollution and resource depletion issues generated by polymeric waste aggregation from utilization in various sectors of the economy. Recycling is the final result of the intermediate stages of collection, sorted by polymer type and processing (Hawkins, 2018). Because only clean, homogenous polymers can produce the highest quality recycled polymer products in the existing secondary process, material recycling, and high-value chemical products in the current tertiary process, feedstock recycling (Curlee & Das, 1991; Hawkins, 1987). As a result, recycling polymer has the possibilities; meanwhile, the recovery and simple treatment of polymers from mixed, contaminated wastes into at least down-cycling products seems to be possible (Möllnitz et al., 2021).

Various approaches exist for the recycling of polymers, including mechanical recycling, chemical recycling, and reuse. The reuse of post-consumer packaging, such as glass bottles and jars, was a common practice in which items like milk and drink bottles were returned to be cleaned and used again. However, in the context of plastic packaging, reuse is not extensively adopted, primarily due to the single-use nature of plastic products. As a result, plastic items are typically discarded after their initial use. Meanwhile, the transformation/downgrading of waste plastic into a less demanding product via mechanical means such as screw extrusion, injection molding, blow molding, and compression molding, also known as mechanical recycling (Lamberti et al., 2020; Cui & Forssberg, 2003). As for chemical recycling, polymer waste is turned back into its oil/hydrocarbon component in the cases of polyolefin and monomers in the case of polyesters and polyamides, which can be used as raw materials for new polymer production and petrochemical industry, or directly into other useful materials (Lamberti et al., 2020; Sasse & Emig, 1998).

Bakau pile usage is one of the high-demand materials produced from the mangrove forest, pursuing a similar line of environmental concerns. According to JKR (2017), the bakau pile is generally designed as a friction pile in a light civil works structure where the load-bearing resistance is derived mainly from skin friction. In Sarawak, mangroves are harvested as bakau piles in light civil works, especially drainage, road, light water-related structures, and sewerage works. The construction industry's high demand for materials for construction activities has resulted in the overharvesting of mangroves. Consequently, the overuse of mangrove trees resulted in the indiscriminate destruction of mangroves along the coastline, leading to coastal erosion and other environmental issues. In addition, the escalation or destruction of mangroves impacts food security, biodiversity, and the lives of some of the most marginalized coastal populations in developing countries, with over 90% of the world's mangrove species (UNEP, 2014). Therefore, further study on using thermoplastic polymers to produce engineered construction piles is needed as an alternative to bakau piles or maybe to replace them.

Until about 15–20 years ago, the conventional materials for piling were timber, steel, and reinforced concrete. With the introduction of polymer materials and then composite polymeric material, the traditional materials for piling have changed dramatically (Dutta & Vaidya, 2003). The deterioration of materials, concrete oxidation, steel corrosion, degradation, and marine borer attacks on bakau or timber products are significant obstacles in pile construction and can be neglected by replacing polymer materials, raising pile durability, and lowering environmental effects. Dutta and Vaidya (2003) mentioned that PVC is the most popular and first commercially produced polymer, and it has been used as a sheet pile in pile construction. Even the 10-year-old PVC sheet piles in Louisiana showed no signs of cracks, blemishes, or deterioration (Dutta & Vaidya, 2003). Besides, current products include fiber-reinforced polymers (FRP) piles (Sakr et al., 2005), FRP sheet piles (Boscato et al., 2011), concrete-filled polymer shells, recycled polymers reinforced with stiffer bar elements, and piles made entirely of recycled polymers (Robinson & Iskander, 2008). Many tests in regard to polymers in soil stated that utilization of polymers brings benefits to construction piles, such as an increase of interface friction between soil and polymer surface (Vineetha & Ganesan, 2014) and reduced soil erosion (Yakupoglu et al., 2019). The existing polymer pile application creates the possibility of replacing bakau pile materials with polymer, especially in light structures. Moreover, it prevents the overharvesting of mangroves due to the usage of traditional pile materials. The recyclable behaviour of polymers can also reduce the polymer waste embedded in landfills.

Increasing volumes of synthetic polymers are manufactured for various applications such as HDPE, PP, and PVC. In this study, mechanical recycling is adopted together with the usage of raw materials for comparison. Hence, three types of virgins, recycled polymers, which are HDPE, PP, and PVC, are used in the study. Despite being categorized as thermoplastics, each type possesses unique characteristics and applications, particularly their melting points and densities. The recycling of plastics refers to the processing of plastic waste into secondary raw material without significantly changing the chemical structure of the material. In order to obtain the most stable and sustainable combination while fulfilling its application in pile construction, the material characterization of the polymers and recycled polymers, which best emulate bakau piles, is carefully formulated in terms of the optimized mix proposed for this study.

MATERIAL AND METHODS

Material

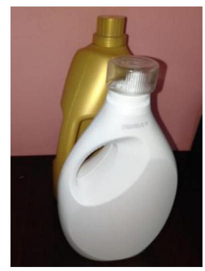
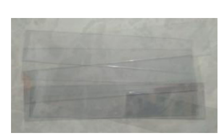
This study used three types of virgin and recycled polymers, HDPE, PP, and PVC, for testing. These are all thermoplastics; however, they have varying characteristics and uses, especially their melting temperatures and densities. The hot compression method was used to fabricate samples for all the polymers.

The hot press machine was used for laminating the virgin and recycled polymers at their respective melting temperatures and pressure to maintain the shape of the laminate and remove excess air bubbles due to the boiling of the polymer. It is to ensure a neat sample while avoiding the failure of fabrication of samples. The samples were fabricated according to ASTM D3039 for tensile testing and ASTM D695 for compression testing. The results were averaged over five sample measurements for each type of laminate.

There are three types of polymers, including recycled (R), virgin (V), and mixed 50%R:50%V in combination for polymer fabrication. All the respective raw materials for recycled polymers were collected for cleaning purposes, while virgin polymers were purchased from local suppliers. Other than that, recycled polymers were cut and ground into smaller sizes to feed into the mold. Prior to the hot press process, the prepared polymers would be weighed beforehand to ensure the laminate was in the desired size according to ASTM testing standards. Finally, suppose the laminate is without visible physical defects such as air bubbles, cracking, or warping. In that case, the laminate is considered successfully fabricated, and continuation with ASTM tensile and compression testing would be performed, respectively.

For the gathering of recycled polymers such as HDPE, PVC, and PP, recycled HDPE (RHDPE) was gathered from used detergent bottles, recycled PVC (RPVC) from used pipes, while recycled PP (RPP) was collected from used containers. All the polymers went through the hot-pressed method to form compression and tensile samples. Table 1 summarizes the materials used for sample fabrication.

Table 1
Materials used for sample fabrication

Class	Polymer	Description	Image
Recycled	HDPE	Used Detergent Bottles	
	PP	Used Food Containers	
	PVC	Used PVC Pipes	
Virgin	HDPE	HDPE Sheets	
	PP	PP Sheets	
	PVC	PVC Sheets	

Testing Procedure

Tensile testing and compression testing were conducted according to ASTM D3039 and ASTM D695 standards, respectively.

Tensile Testing. Tensile testing was conducted with a crosshead displacement rate of 3 mm/min. Based on the ASTM standards, the dimension of tensile samples is 3 mm in thickness, 25 mm in width, and 250 mm in length (Figure 1). This testing produced a stress-strain diagram, which is then used to determine tensile modulus. Ambient temperature and humidity were maintained as constant as possible throughout this test.

Compression Test. A compression test was conducted following the ASTM D695 standards to determine the strength and modulus of the polymer material. Compressive properties describe the behaviour of a material subjected to a compressive load. The specimen was positioned parallel to the surface between the compressive plates. The specimen was then compressed with a uniform load. The maximum load was recorded using the computer system and the collected data. The sizing of the block specimen was 12.7 mm × 12.7 mm × 25.4 mm (Figure 2).

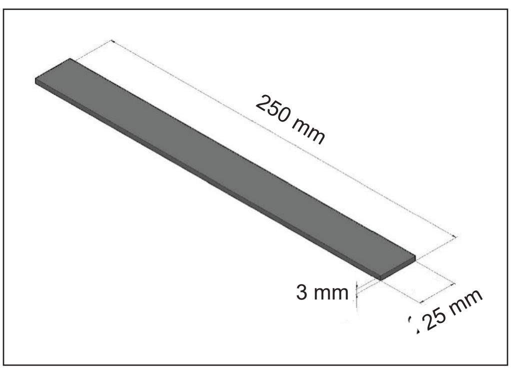


Figure 1. Tensile test sample 3D model

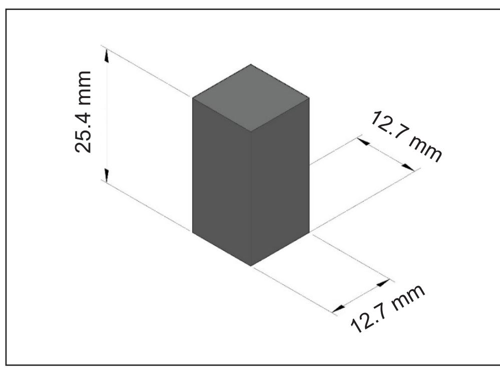


Figure 2. Compression test sample 3D model

RESULTS AND DISCUSSION

Tensile Testing

A material subjected to stretching or tension requires significant tensile strength. Tensile properties, such as the tensile strength and tensile modulus of the thermoplastic polymers, were determined. Figure 3 illustrates the comparison of the tensile strength among polymers.

Figure 3 compares the tensile strength of virgin polymers and their recycled counterparts, where results show that all virgin-class polymers demonstrate greater tensile strength values. For the 50%R:50%V samples, it varies among the polymer types. However, it is evident that the values are not on par with the virgin samples. For HDPE, the 50%R:50%V samples have a slightly higher tensile strength at 21.05 MPa than the recycled samples at 18.31 MPa. For PP, the results indicate that the recycled samples possess higher tensile strength at 19.31 MPa, while the 50%R:50%V samples are only at 14.92 MPa. The weaker strength of recycled polypropylene could be attributed to the adverse impact of impurities or contaminants on its binding with the virgin counterpart. However, in comparison among polymers, PVC exhibits the highest tensile strength for its virgin and recycled samples. Generally, it is observed that virgin polymers display superior tensile strength properties in comparison to their recycled counterparts. This observation may be attributed to the fact that recycled polymers have undergone prior processing and have been subjected to post-consumer utilization. It can cause the recycled polymer to deteriorate in its mechanical characteristics, leading to diminished performance as it may have gone through various resultant effects, such as long exposure to heat, sunlight, chemical exposure, or overextended consumer usage.

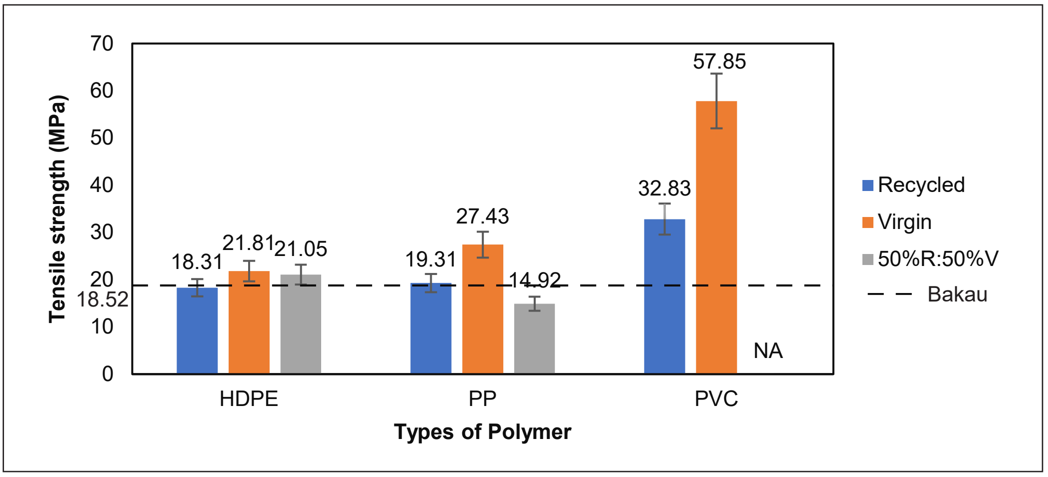


Figure 3. Comparison of the tensile strength among polymers

Tensile Modulus

Due to the differences in strains among the samples and classes, it is only possible to compare the average values when comparing the tensile modulus. It differs among samples due to several factors, including but not limited to surrounding temperature, minute human errors, and sample defects. Hence, from Figure 4, the highest tensile modulus, which is 1336.88 MPa, is exhibited by the virgin PVC. In comparison among the polymers, the tensile modulus of HDPE is significantly lower among PP and PVC, regardless of class, where its virgin sample only achieved 208.66 MPa. Virgin PP can be seen to have a lower tensile modulus in comparison with its recycled and 50%R:50%V counterparts, which indicates virgin PP is less stiff. The increased stiffness of recycled PP that makes it more suitable for consumer usage may be attributed to small amounts of additives or stabilizers.

At the same time, 50%R:50%V PP exhibits higher tensile modulus in comparison to its virgin and recycled counterparts. It might be due to the possibility of either the virgin or recycled PP acting as filler material instead, similar to reinforced materials, increasing the tensile modulus. On the other hand, virgin PVC that does not have additives tends to perform better than recycled PVC in tensile modulus. This discrepancy can be attributed to the additives present in recycled PVC, which are often intended to improve its elastic properties and water absorption. Such modifications are particularly relevant in applications such as piping within housing projects.

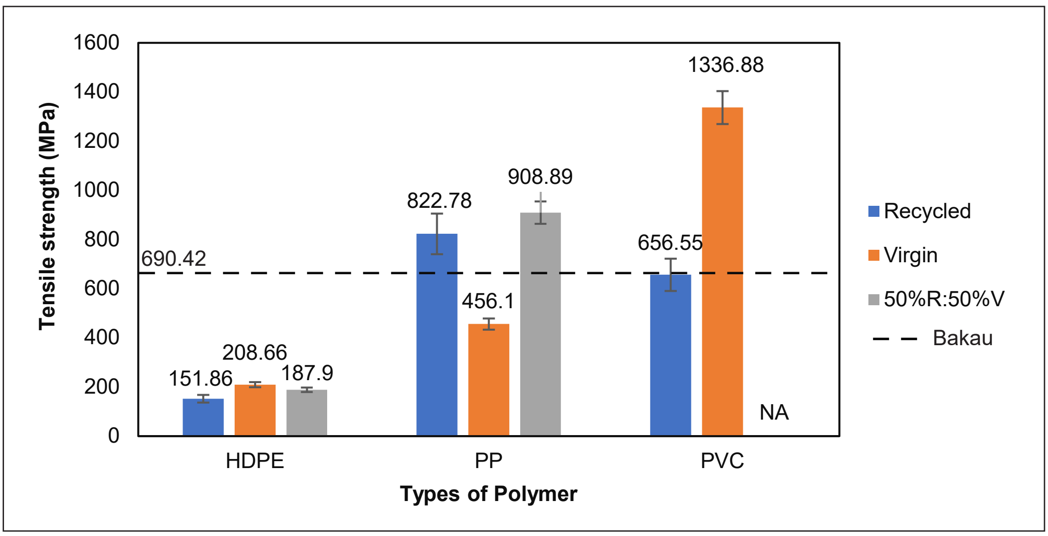


Figure 4. Comparison of the tensile modulus among polymers

Compression Testing

Compression properties such as the compression strength and compression modulus of the thermoplastic polymers were determined. Table 3 presents the compression strength of different classifications of thermoplastic polymer. Meanwhile, Figure 5 illustrates the comparison of the compression strength among polymers.

In Figure 5, the recycled samples for HDPE and PP show slightly higher compressive strengths in comparison to the virgin samples. The underlying cause of enhanced compressive characteristics in recycled PP and HDPE can be additives or stabilizers. It stands in contrast to virgin PVC, where superior performance is observed. However, regardless of the class of polymers, PVC samples demonstrated overall better compressive strength performance. It is solely due to the chemical bonding of PVC, which involves the repeating monomer Vinyl Chloride (C_2H_3Cl), which makes the density of PVC greater than both PP and HDPE. HDPE has a repeating monomer of Ethylene (C_2H_4), while PP has a repeating monomer of Propene (C_3H_6).

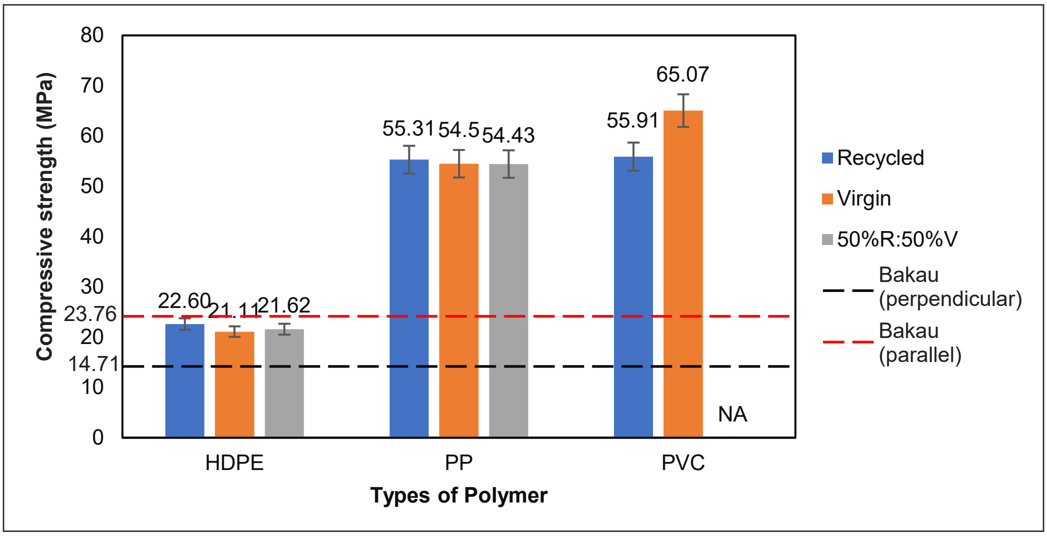


Figure 5. Comparison of the compressive strength among polymers

Due to the variability of strains among the samples and classes, the only way to compare compressive modulus is to compare average values. Figure 6 shows that virgin polymers excel in compressive modulus, which indicates that virgin polymers are much stiffer in compression compared to their counterparts. In addition, virgin PP has a greater compressive modulus of 728.16 MPa than virgin PVC, which is 637.82 MPa. Regardless of class, HDPE still performs lower in comparison to other tested polymers. The reason is that virgin polymers were not exposed to consumer-used environments, which is likely to maintain their polymer characteristics.

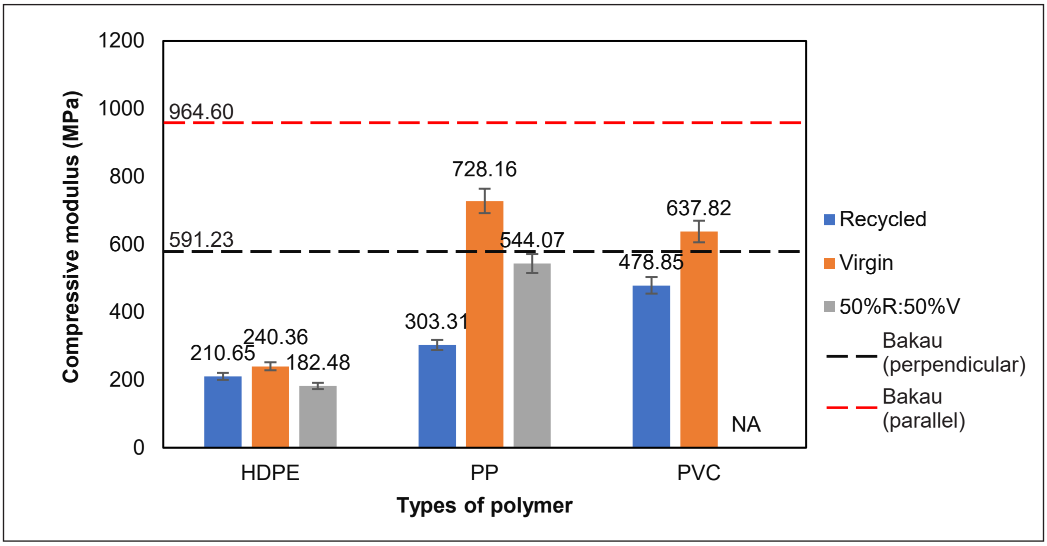


Figure 6. Comparison of the compressive modulus among polymers

Tensile Stress-strain Analysis

Figure 7 demonstrates that virgin HDPE can withstand higher stress at a given strain compared to its counterparts. The curve displays a distinct sudden dip at 0.25 strain for the 50%R:50%V HDPE due to internal cracking, nucleating, or premature delamination during testing. It may be found that the incomplete ability of recycled and virgin HDPE is probably due to the effects of colorants, residual chemicals, and abs and orbed fluids. However, for all classes of HDPE, even after 0.4 strain, the sample does not fail completely, which then proves the durability of HDPE.

From Figure 8, the low strain exhibited by virgin PP suggests its brittleness relative to other thermoplastic polymers. Tensile failure can be clearly seen in Figure 8 across the different classes of PP. The steepness of the curve for virgin PP suggests its stiffness compared to other classes of PP, particularly when compared to virgin PVC. The early failure of the 50%R:50%V PP sample suggests a possible incompatibility issue between the recycled and virgin PP materials. The incompatibility may be due to causes, and not limited to, prior manufacturing processes, water absorbed, minor defects and minute additives.

In Figure 9, virgin PVC is stiffer and can withstand greater strains than recycled PVC. A dip can also be observed in the

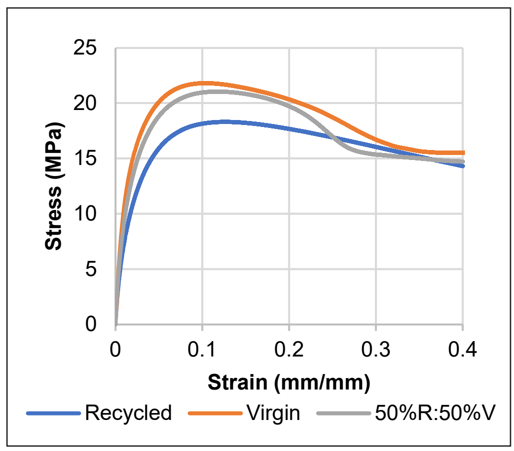


Figure 7. Tensile stress-strain curves for classes of HDPE

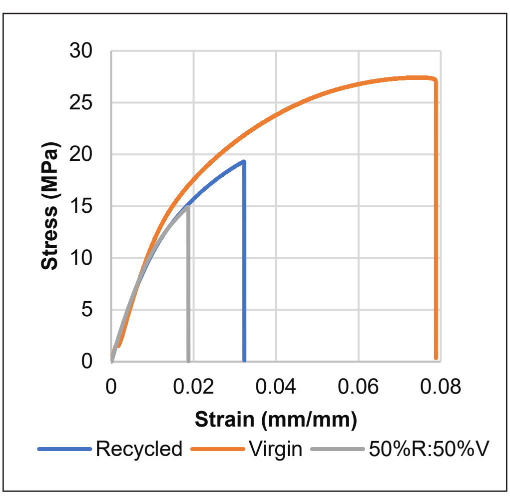


Figure 8. Tensile stress-strain curves for classes of PP

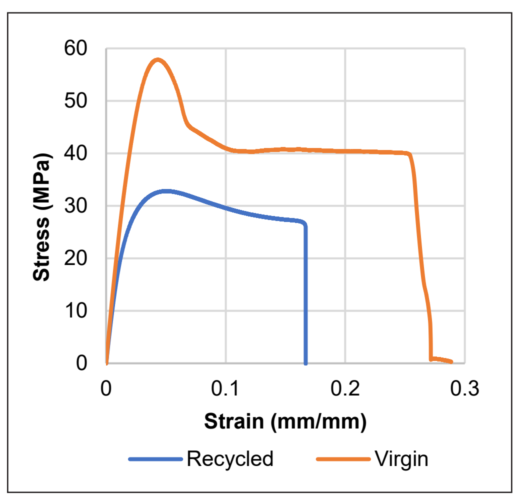


Figure 9. Tensile stress-strain curves for classes of PVC

curve of virgin PVC, indicating potential internal delamination, nucleation, or premature internal failure during testing. For 50%R:50%V PVC, the fabrication of samples could not be completed.

Meanwhile, as illustrated in Figure 10, the virgin PVC and recycled PVC did not seem to merge well. Several factors could possibly cause it, primarily the difference in melting temperatures of the two mentioned PVCs. Recycled PVC required a higher melting temperature with plasticizers and additives, resulting in an elevated melting point compared to virgin PVC. This incompatibility can be overcome only with heavy-duty chemical and mechanical manufacturing (You et al., 2022), which is highly strenuous. Instead, propositions of the addition of synthetic or natural reinforcing materials would increase the mechanical properties of polymers. Luck et al. (2022) stated that the use of seawater sea sand concrete (SWSSC) filled fiber reinforced polymer (FRP) tubes offers several benefits, including the prevention of resource shortages and corrosion resistance. Compressive strength and ductility improvements were also evident (Bazli et al., 2021). Furthermore, the utilization of fibers plays an important role in enhancing the mechanical properties of polymers. Jahan et al. (2012) experimented on glass and jute FRP and found that LDPE reinforced with either jute or glass fibers possess greater mechanical properties in comparison to standalone LDPE. Synthetic fibers offer high strength in a composite material, but their recyclability is challenging (Kamarudin et al., 2022). Hence, the utilization of SWSSC, natural and synthetic fibers, or hybrid fibers in reinforcing polymers can benefit future construction works.

From Figure 11, the stress-strain curves of the tested recycled, virgin, and 50%R:50%V samples for HDPE, PP, and PVC are compared. The 50%R:50%V PVC samples are not included because the fabrication of the samples was not successful, as seen in Figure 10.

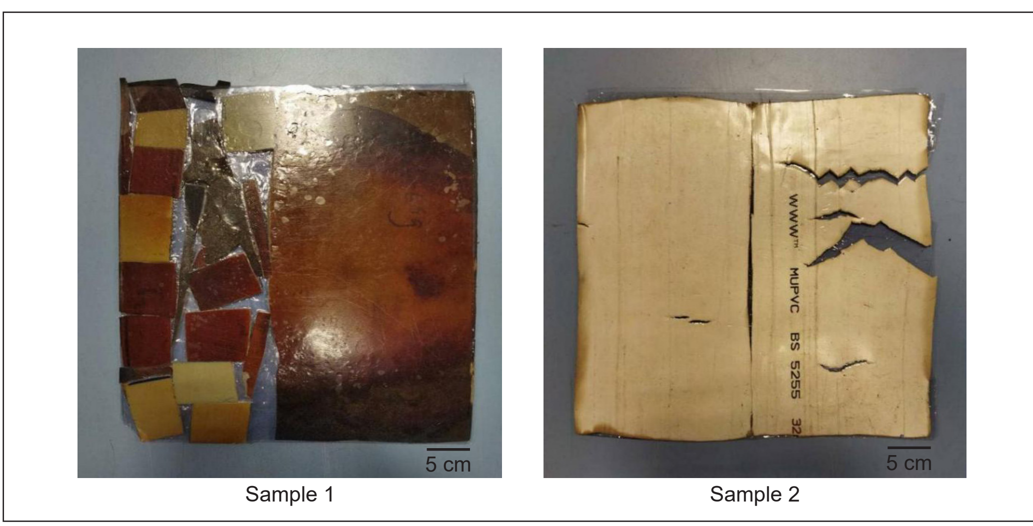


Figure 10. Failed 50%R:50%V PVC samples

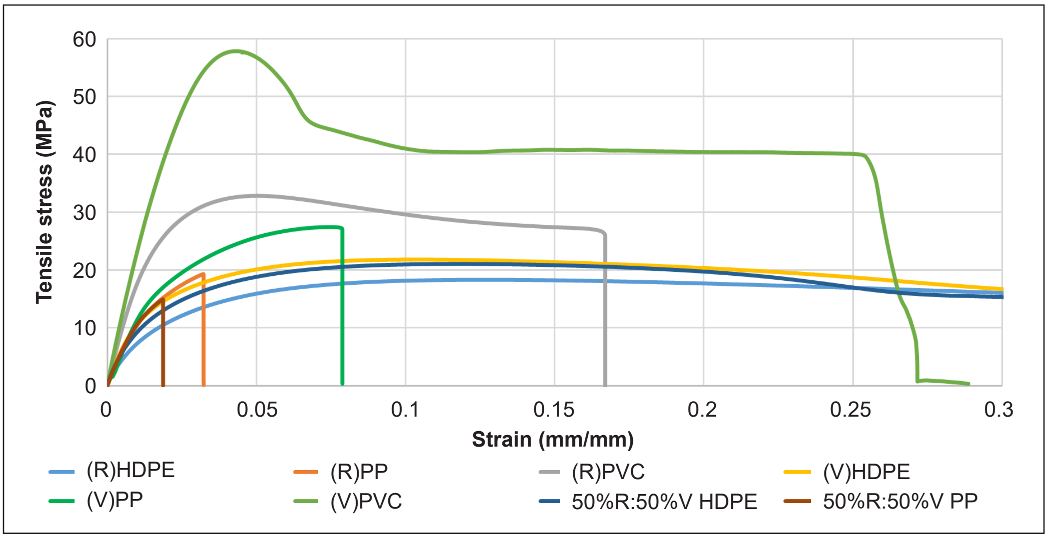


Figure 11. Comparison of tensile stress-strain curves

Compressive Stress-strain Analysis

In Figure 12, HDPE experiences close values of compressive yield stress across the classes, as seen above. The dip observed in the curve for 50%R:50%V HDPE is likely due to the incompatibility between the recycled and virgin HDPE, potentially caused by the presence of colorants, residual chemicals, absorbed fluids, or similar factors. The failure of virgin HDPE samples is attributed to premature cracking or slipping caused by compressive stresses. The imperfect samples may also contribute to the slipping before densification, likely caused by the compression of the samples in a tilted manner. Rough observation can hypothesize that the stiffness of HDPE across classes is rather similar under compressive stresses.

From Figure 13, it can be observed that the maximum compressive stress for PP is similar among the different classes. A dip in the curve is observed for virgin PP, which may be attributed to its brittleness compared to other polymers, resulting in cracking. It is probably due to minor defects or small bubbles appearing in the samples. Another possibility is that the virgin PP does not have additives or stabilizers to aid its mechanical properties. It is also observed that all samples undergo densification. The curve for 50%R:50%V PP shows good performance, suggesting that the recycled and virgin PP blend well and have good lamination.

50%R:50%V PVC could not be fabricated due to the inability to achieve lamination without chemical treatment or mechanical manufacturing, as seen in Figure 10. Nonetheless, a comparison between recycled and virgin PVC was carried out. As shown in Figure 14, virgin PVC has a steeper curve, indicating greater stiffness compared to recycled PVC. The straight decrease of compressive stress observed in recycled PVC suggests failure

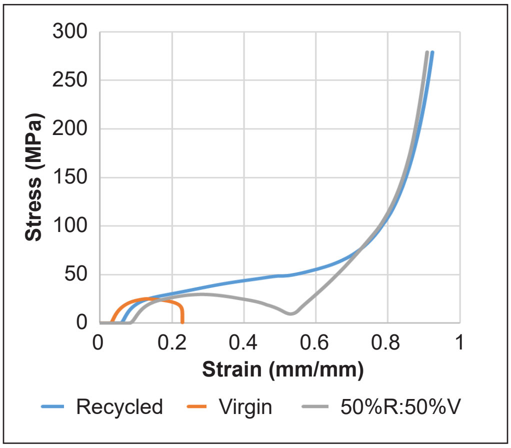


Figure 12. Compressive stress-strain curves for classes of HDPE

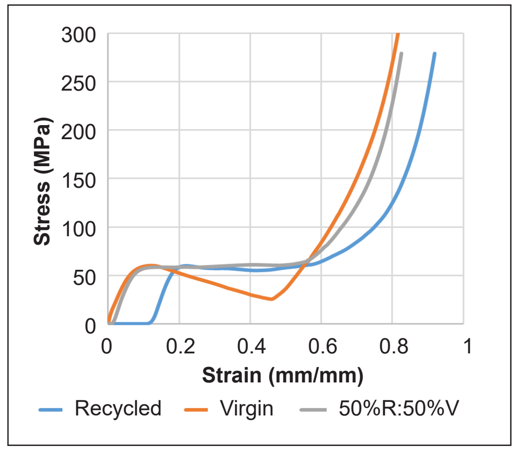


Figure 13. Compressive stress-strain curves for classes of PP

during testing, likely due to the brittleness of PVC under compressive stress, resulting in the delamination of samples.

Figure 15 compares the stress-strain curves of the tested recycled, virgin, and 50%R:50%V samples for HDPE, PP, and PVC. The 50%R:50%V PVC samples are not included because the fabrication of the samples was not successful, as seen in Figure 10. The exponential behaviour in the fracture region may be due to the large deformation by buckling.

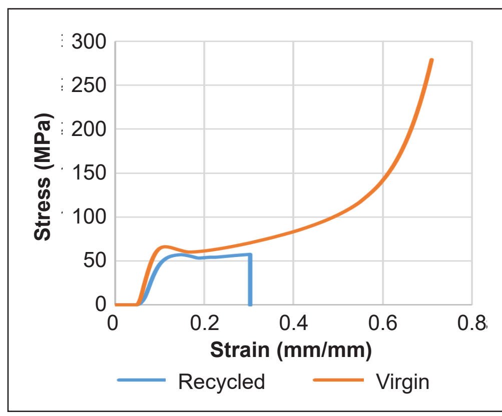


Figure 14. Compressive stress-strain curves for classes of PVC

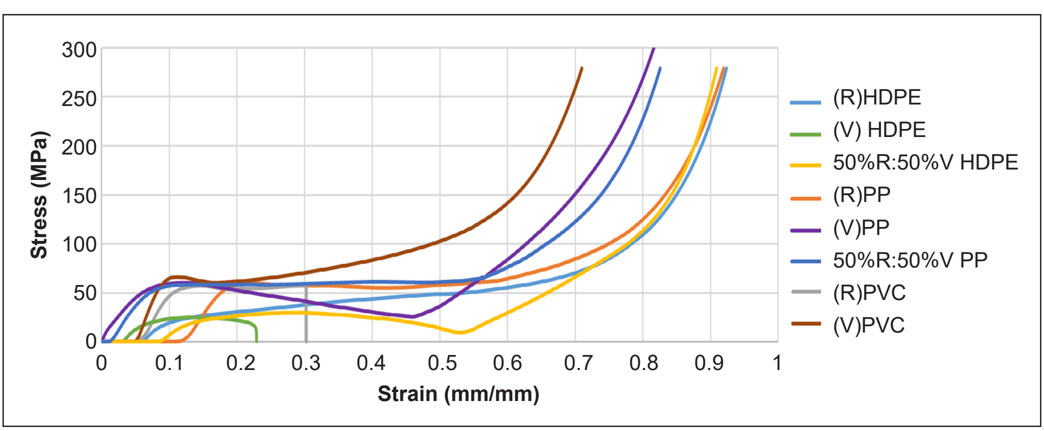


Figure 15. Comparison of compressive stress-strain curves

Application of Plastic Pile

Elastic Behaviour Under Serviceability Limits State Design. When designing for a serviceability limit state, it is important to consider that permanent deformation should be avoided as it can cause occupants to feel insecure in the building. The different plastic materials investigated in this study had tensile elastic modulus values ranging from 151.86 to 1336.88 MPa and compressive elastic modulus values ranging from 182.48 to 728.16 MPa. Since the focus of the application is on the pile, a higher compressive elastic modulus is preferred. All the materials mostly exhibited tensile elastic strain ranging from 0.02 to 0.05, with a compressive elastic strain of 0.1.

The initial intention was to utilize plastic materials to create piles as a substitute for bakau piles in the construction industry. Table 2 summarizes the properties obtained from tensile stress-strain curves. From Table 2, the polymer with an elastic modulus that approaches bakau wood is PP (R), PVC (R), PVC (V), and 50% R:50%R PP, which exceeded the elastic modulus of bakau in the elastic region. Table 3 summarizes the properties obtained from compressive stress-strain curves. Table 3 shows that none of the

Table 2
Properties obtained from tensile stress-strain curves

Materials	Young's Modulus, E (MPa)	Ultimate stress, MPa	Ultimate strain, ϵ
HDPE (R)	151.86	18.31	> 0.3
HDPE (V)	208.66	21.81	> 0.3
PP (R)	822.78	19.31	0.02
PP (V)	456.10	27.43	0.08
PVC (R)	656.55	32.83	0.16
PVC (V)	1336.88	57.85	0.25
50%R:50%V HDPE	187.90	21.05	> 0.3
50%R:50%V PP	980.89	14.92	0.02
Bakau wood (Yunus, 2018)	690.42	18.52	-

Table 3
Properties obtained from compressive stress-strain curves

Materials	Young's Modulus, E (MPa)	Ultimate stress (MPa)	Ultimate strain
HDPE (R)	210.65	22.60	> 0.80
HDPE (V)	240.36	21.11	0.21
PP (R)	303.31	55.31	> 0.80
PP (V)	728.16	54.50	> 0.80
PVC (R)	478.85	55.91	0.30
PVC (V)	637.82	65.07	> 0.70
50%R:50%V HDPE	182.48	21.62	> 0.80
50%R:50%V PP	544.07	54.43	> 0.80
Bakau wood (Yunus, 2018)	964.60 (parallel) 591.23 (perpendicular)	23.76 (parallel) 14.71 (perpendicular)	-

specimens exceeded the bakau's compressive elastic modulus parallel to the wood grain. However, PP (V) and PVC (V) exceeded their compressive elastic modulus perpendicular to the direction of the wood grain.

Plastic Behaviour During Ultimate Limit State Design

The investigation of tensile and compression modulus at ultimate stress is crucial in pile design to avoid premature failure, such as the development of eccentric moments, which could reduce the pile capacity. Thus, it is important to examine these properties. All samples met the tensile ductility requirement except for PP, which set the benchmark at 0.10 strain.

All virgin types of polymer (HDPE, PP and PVC), 50%V:50%R PP, PP(R), and PVC (R) exceed the bakau's ultimate tensile strength. In terms of compression stress-strain behaviour in the ultimate limit state, all specimens exceeded ultimate strength (perpendicular to wood grain), and PP(V), PP(R), PVC(V), PVC (R) and 50% R: 50% V PP were higher than bakau's ultimate stress with parallel wood grain. Regardless of the wood grain arrangement, plastic piles could be substituted for bakau piles in the construction industry, with the recorded experimental tensile and compression strength tests. As mangrove ecosystems are declining at an alarming rate (Goldberg et al., 2020), the urge to recycle polymers into construction piles is needed to promote the sustainability of bakau. This further coincides with the Sustainable Development Goals (SDG) 12, responsible consumption and production (United Nations, 2022).

The Load Capacity of the Plastic Pile

The compressive strength data was used to compute the total cross-section area based on the load capacity of the pile. Thus, the optimum cross-section area can be identified. The pile is assumed to be a polymer pile that replaces the timber pile, which has an average diameter of 75 mm due to the range of available timber. The unsupported length (L) is assumed to be 3 m below the ground surface in soft soils. Utilizing Euler's equation, the critical axial loads and critical stress for respective polymers can be obtained, as shown in Table 4.

In Figure 16, it can be observed that all of the virgin polymer classes exhibit a high critical axial load, with PP having the highest at 673.38 kN. It suggests that PP is well-suited for use under axial loads. In general, the performance of the virgin samples is superior to that of the recycled and 50%R:50%V classes.

Figure 17 compares the critical stress for all polymers. Regardless of class, it is clear that PP will outperform HDPE and PVC. In the case of a polymer pile, virgin PP has a critical stress of 2976.66 MPa, virgin HDPE has 982.56 MPa, and virgin PVC has 2607.38 MPa.

Furthermore, the study also investigated the pile dimension and cross-sectional area across different types of polymer with respect to the buckling load capacity of a 3-meter length, where the effective length is taken as 3.3 m. The rule of thumb we use here is a

Table 4
Critical axial load and critical stress of polymers

Polymer		Compressive Modulus (MPa)	Critical Axial Load (kN)	Critical Stress (MPa)
Recycled (R)	HDPE	210.65	861.12	194.80
	PP	303.31	1239.91	280.49
	PVC	478.85	1957.51	442.82
Virgin (V)	HDPE	240.36	982.56	222.27
	PP	728.16	2976.66	673.38
	PVC	637.82	2607.38	589.84
50%R:50%V	HDPE	182.48	745.98	168.75
	PP	544.07	2224.11	503.13
	PVC	NA	NA	NA

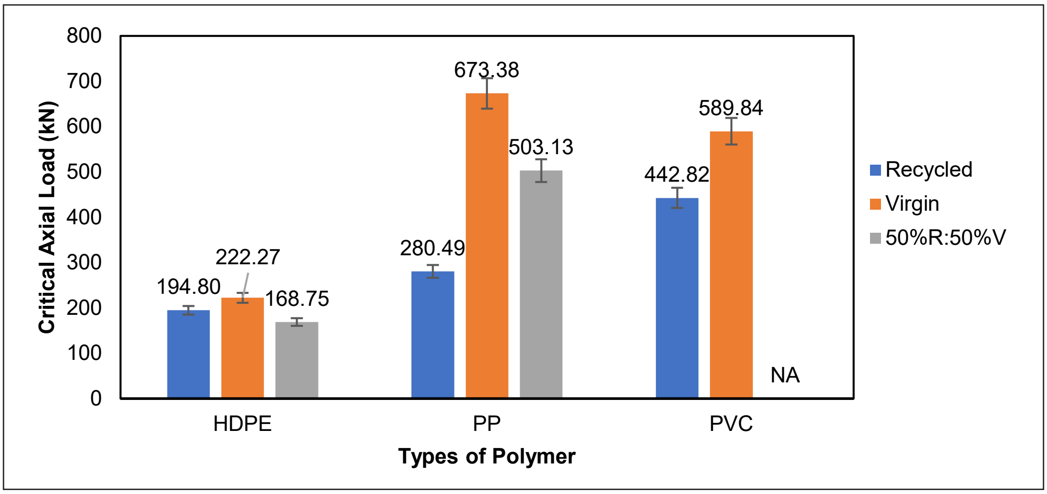


Figure 16. Critical axial load comparisons among classes of polymers

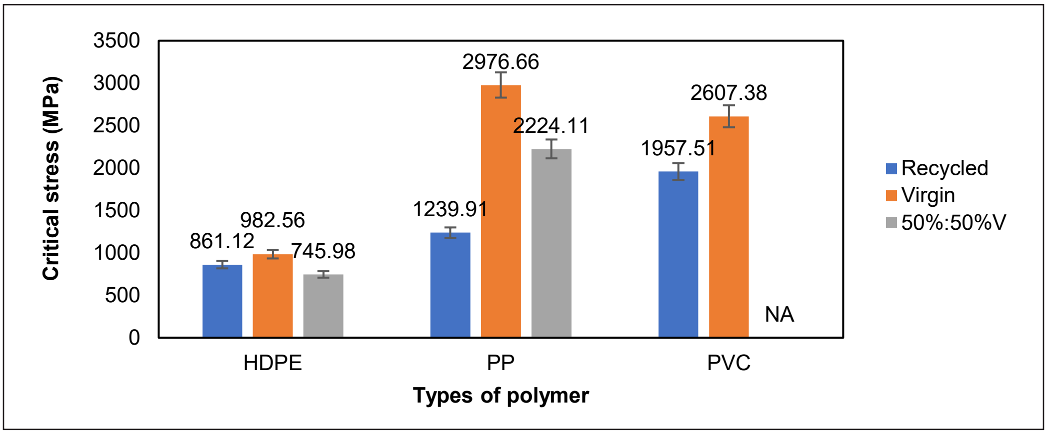
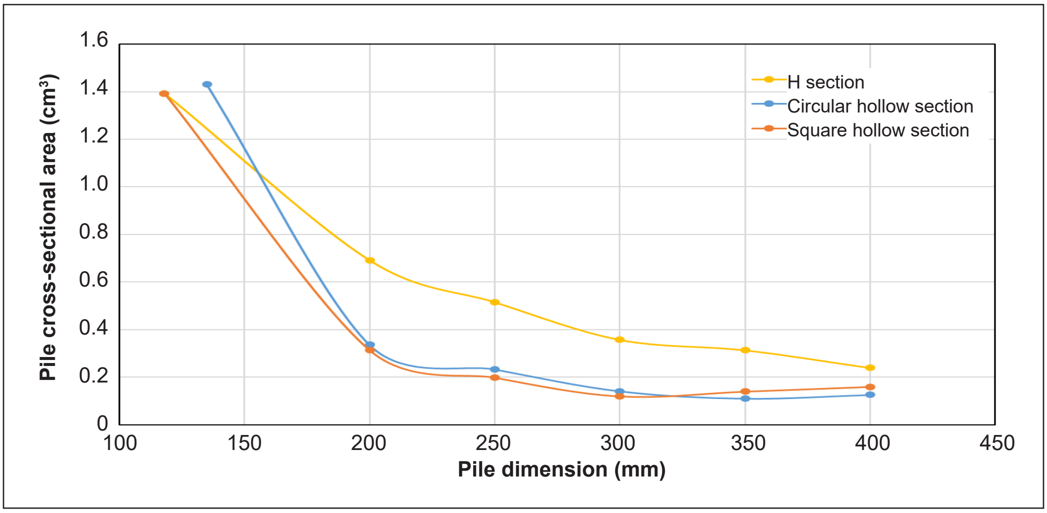
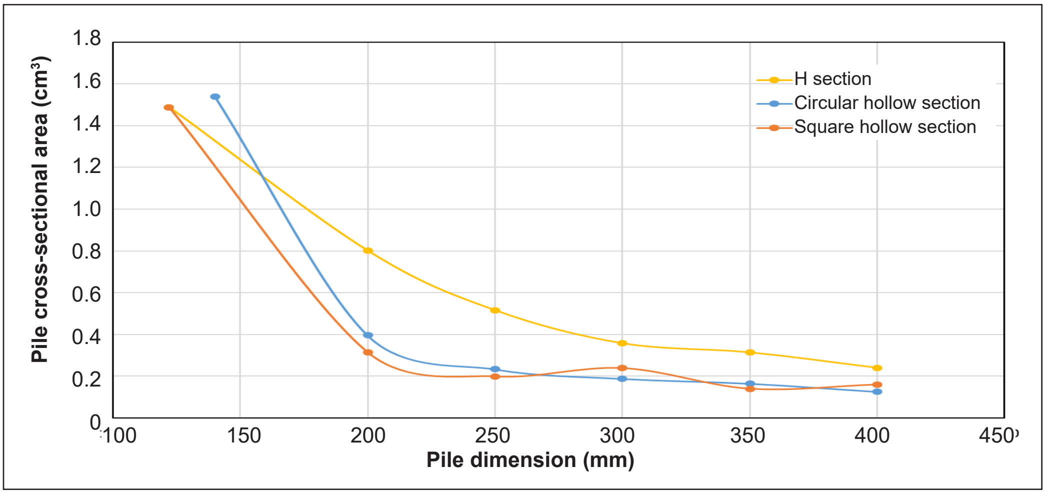


Figure 17. Critical stress comparisons among classes of polymers



(a)



(b)

Figure 18. Cross-sectional area vs pile dimension: (a) PP(V); and (b) PVC (V)

capacity of 1 metric ton per pile, simulating bakau pile capacity, with a typical safety factor of 1.3. Two polymers are being considered here: PP (V) and PVC (V), which have the highest compressive elastic modulus. Figure 18 shows that the section efficiency is the same across different types of polymers regardless of polymer type. The pile's cross-sectional area decreases as the pile dimension increases. The feasible dimension for both circular and square hollow sections is 250 mm, as the larger dimension does not indicate a significant reduction in cross-sectional area. The H-section's feasible dimension is 200 mm to ensure sufficient thickness to avoid local buckling, although a larger dimension can yield a smaller cross-sectional area.

CONCLUSION

The mechanical properties of virgin and recycled polymers, namely HDPE, PVC, and PP, were investigated, and the possibility of being applied in pile application was discussed and summarized as follows. The elastic moduli that approach bakau wood are PP (R), PVC(R), PVC (V), and 50% R:50%R PP, which exceeded the elastic modulus of bakau in the elastic region. None of the specimens exceeded the compressive elastic modulus of bakau parallel to the wood grain, while PP (V) and PVC (V) exceeded their compressive elastic modulus perpendicular to the wood grain direction. Besides that, all virgin types of plastic (HDPE, PP and PVC), 50%V:50%R PP, PP(R), and PVC (R) exceeded the bakau's ultimate tensile strength. In terms of compression stress-strain behaviour in the ultimate limit state, all specimens exceeded ultimate strength (perpendicular to wood grain), and PP(V), PP(R), PVC(V), PVC (R) and 50% R: 50% V PP were higher than bakau's ultimate stress with parallel wood grain. Calculated critical stress subjected to polymer pile also showed that virgin PP exhibited a critical stress of 2976.66 MPa, while virgin HDPE had 982.56 MPa, and virgin PVC had 2607.38 MPa. The results of experimental tensile and compression strength tests indicate that polymer material has the potential to serve as a viable alternative to bakau piles in the construction industry, particularly in light structures. The buckling load analysis also shows that polymer piles can be shaped in circular hollow, square hollow, and H sections of 200 to 250 mm to carry a similar load in bakau piles. Polymer piles could replace traditional bakau piles, thereby addressing issues related to polymer wastes and mangrove deforestation while maintaining, if not enhancing, the structural integrity of lightweight structures in construction.

ACKNOWLEDGEMENT

The authors acknowledge the Sarawak Research and Development Council (Sarawak RDC) through the Research Initiation Fund (RDCRG/RIF/2019/11) and Universiti Malaysia Sarawak for their financial support and research facilities.

REFERENCES

Akenji, L., Bengtsson, M., Hotta, Y., Kato, M., & Hengesbaugh, M. (2020). Chapter 21 - Policy responses to plastic pollution in Asia: Summary of a regional gap analysis. In T. M. Letcher (ed.), *Plastic Waste and Recycling* (pp. 531-567). Academic Press. https://doi.org/10.1016/b978-0-12-817880-5.00021-9

American Society for Testing and Materials. (2014). *Standard test method for tensile properties of polymer matrix composite materials (ASTM D3039).* https://www.astm.org/d3039_d3039m-08.html

American Society for Testing and Materials. (2023). *Standard test method for compressive properties of rigid plastics (ASTM D695).* https://www.astm.org/d0695-23.html

Awoyera, P. O., & Adesina, A. (2020). Plastic wastes to construction products: Status, limitations and future perspective. *Case Studies in Construction Materials, 12*, Article e00330. https://doi.org/10.1016/j.cscm.2020.e00330

Bazli, M., Heitzmann, M., & Hernandez, B. V. (2021). Hybrid fibre reinforced polymer and seawater sea sand concrete structures: A systematic review on short-term and long-term structural performance. *Construction and Building Materials,* 301, Article 124335. https://doi.org/10.1016/j.conbuildmat.2021.124335

Boscato, G., Mottram, J. T., & Russo, S. (2011). Dynamic response of a sheet pile of fiber-reinforced polymer for waterfront barriers. *Journal of Composites for Construction, 15*(6), 974-984. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000231

Cui, J., & Forssberg, E. (2003). Mechanical recycling of waste electric and electronic equipment: A review. *Journal of Hazardous Materials, 99*, 243-263. https://doi.org/10.1016/S0304-3894(03)00061-X

Curless, T. R., & Das, S. (1991). *Plastic Wastes: Management, Control, Recycling, and Disposal*. Noyes Data Corp.

Dutta, P. K., & Vaidya, U. (2003). *A Study of the Long-Term Applications of Vinyl Sheet Piles*. US Army Corps of Engineers, Engineer Research and Development Center.

Gerrard, N. (2020). *The Construction Industry Rises to the Plastics Challenge*. https://www.marsh.com/ph/industries/construction/insights/construction-industry-rise-to-the-plastic-challenge.html

Goldberg, L., Lagomasino, D., Thomas, N., & Fatoyinbo, T. (2020). Global declines in human-driven mangrove loss. *Global Change Biology,* 26(10), 5844-5855. https://doi.org/10.1111/gcb.15275

Hawkins, W. L. (1987). Recycling of polymers. *Conservation and Recycling* 10(1), 15–19. https://doi.org/10.1016/0361-3658(87)90003-8

Jahan, A., Rahman, M. M., Kabir, H., Kabir, M. A., Ahmed, F., Hossain, M. A., & Gafur, M. A. (2012). Comparative study of physical and elastic properties of jute and glass fiber reinforced LDPE composites. *International Journal of Scientific and Technology Research, 1*(10), 68-72.

JKR. (2017). *Guideline for Piling Works*. Jabatan Kerja Raya. https://vdokumen.net/guideline-for-piling-works-epsmgjkrgov-cpka-jkr-malaysia-1172017-2-1-0.html

Kamarudin, S. H., Basri, M. S. M., Rayung, M., Abu, F., Ahmad, S., Norizan, M. N., Osman, S., Sarifuddin, N., Desa, M. S., Abdullah, U. H., Tawakkal, I. S. M. A., & Abdullah, L. C. (2022). A review on natural fiber reinforced polymer composites (NFRPC) for sustainable industrial applications. *Polymers, 14*(17), Article 3698. https://doi.org/10.3390/polym14173698

Kuan, H. T. N., Tan, M. Y., Shen, Y., & Yahya, M. Y. (2021). Mechanical properties of particulate organic natural filler-reinforced polymer composite: A review. *Composites and Advanced Materials, 30*, 1-17. https://doi.org/10.1177/26349833211007502

Lamberti, F. M., Román-Ramírez, L. A., & Wood, J. (2020). Recycling of bioplastics: Routes and benefits. *Journal of Polymers and the Environment, 28*, 2551-2571. https://doi.org/10.1007/s10924-020-01795-8

Luck, J. D., Bazli, M., & Rajabipour, A. (2022). Bond between fibre-reinforced polymer tubes and sea water sea sand concrete: Mechanisms and effective parameters: Critical overview and discussion. *Fibers,* 10(1), Article 8. https://doi.org/10.3390/fib10010008

Möllnitz, S., Feuchter, M., Duretek, I., Schmidt, G., Pomberger, R., & Sarc, R. (2021). Processability of different polymer fractions recovered from mixed wastes and determination of material properties for recycling. *Polymers, 13*(3), Article 457. https://doi.org/10.3390/polym13030457

Perugini, F., Mastellone, M. L., & Arena, U. (2005). A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. *Environmental Progress, 24*(2), 137-154. https://doi.org/10.1002/ep.10078

Robinson, B., & Iskander, M. (2008). Static and dynamic load tests on driven polymeric piles. In *GeoCongress 2008: Geosustainability and Geohazard Mitigation* (pp. 939-946). ASCE Publishing. https://doi.org/10.1061/40971(310)117

Sakr, M., El Naggar, M. H., & Nehdi, M. (2005). Interface characteristics and laboratory constructability tests of novel fiber-reinforced polymer/concrete piles. *Journal of Composites for Construction, 9*(3), 274-283. https://doi.org/10.1061/(asce)1090-0268(2005)9:3(274)

Sasse, F., & Emig, G. (1998). Chemical recycling of polymer materials. *Chemical Recycling of Polymer Materials, 21*, 777-789. https://doi.org/10.1002/(SICI)1521-4125(199810)21:10%3C777::AID-CEAT777%3E3.0.CO;2-L

Tan, M. Y., Kuan, H. T. N., & Khan, A. A. (2017). Tensile properties of ground coffee waste reinforced polyethylene composite. In *Materials Science Forum* (Vol. 880, pp. 73-76). Trans Tech Publications Ltd.

United Nations. (2022). *The Sustainable Development Goals Report 2022*. United Nations. https://unstats.un.org/sdgs/report/2022/

UNEP. (2014). *Destruction of Carbon-Rich Mangroves Costs up to US$42 billion in Economic Damages Annually*. UNEP Report. https://www.unep.org/news-and-stories/press-release/destruction-carbon-rich-mangroves-costs-us42-billion-economic

Vineetha, V. J., & Ganesan, K. (2014). Interface friction between glass fibre reinforced polymer and gravel soil. *Advanced Materials Research, 984-985*, 707-710. https://doi.org/10.4028/www.scientific.net/amr.984-985.707

Wang, X. H. (2022). Biodegradable polymers, history tells polymer science's fortune. *Chinese Journal of Polymer Science, 40*, 431-432. https://doi.org/10.1007/s10118-022-2737-x

Yakupoglu, T., Rodrigo-Comino, J., & Cerdà, A. (2019). Potential benefits of polymers in soil erosion control for agronomical plans: A laboratory experiment. *Agronomy, 9*(6), Article 276. https://doi.org/10.3390/agronomy9060276

You, J., Jiang, Z., Jiang, H., Qiu, J., Li, M., Xing, H., Xue, J., & Tang, T. (2022). A "plasticizing-foaming-reinforcing" approach for creating thermally insulating PVC/polyurea blend foams with shape memory function. *Chemical Engineering Journal,* 450, Article 138071. https://doi.org/10.1016/j.cej.2022.138071

Yunus, M. (2018). Model test ultimate bearing capacity of bakau piles foundation on soft soil deposit. *EPI International Journal of Engineering, 1*(2), 94-99. https://doi.org/10.25042/epi-ije.082018.15