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Effects of filler types on the microstructural and engineering properties of waste plastic binder composite for construction purposes

Yusuf Olawale Babatunde¹,²*, John Mwero¹, Raphael Mutuku¹, Yinus Jimoh² and Daniel Oguntayo¹,⁴

Abstract: Plastic is one of the prominent solid wastes and its ineffective disposal has caused environmental issues. Previous research focused on the replacement of aggregates with waste plastic in the concrete mix. This study focused on the utilization of waste polyethylene terephthalate (PET) plastic as a binder for construction application. The waste PET plastic was melted and mixed with different filler materials to give a homogenous and uniform mortar/concrete-like composite using different formulation ratio of 1:0, 1:1, 1:2, 1:3. The influence of the filler materials and the varying mix composition on the engineering and morphology properties of the resulting composite was investigated. The morphology of the waste plastic composite samples showed that the filler materials filled the pores present in the molten plastic, thereby reinforcing it. The results indicated that, the density, compressive strength, and water absorption increase as the content of the filler material increases. However, composites of plastic-sand, and plastic-quarry dust at ratio 1:3 gave higher compressive strength values of 20.30 and 20.10 N/mm² respectively, which meet up with the minimum requirement of 17 N/mm²-compressive strength for structural lightweight concrete as specified by ACI and BS standards. Thus, they can be adopted for structural purposes.

Subjects: Structural Engineering; Waste & Recycling; Environmental Health

Keywords: waste PET plastic; plastic binder composite; compressive strength; structural lightweight concrete

1. Introduction

The management of solid waste continues to be a major challenge, particularly in the urban agglomeration in developing and underdeveloped countries in the world. One type of solid waste that is of national and global concern is waste plastic, as it represents 10% of waste generated by human (Bahij et al., 2020). Globally, there is an increase in plastic demand and production, largely due to the growing population, which has directly increased the number of generated waste plastics, annually (Umasabor & Daniel, 2020). Plastic production rise from 1.5 million tonnes in 1950 to 365 million tonnes in 2019 (KARSLOĞLU, 2021; Li et al., 2020). Consequently, about 8 million tonnes of the generated plastic wastes ended up in oceans, which has led to the death of millions of wildlife and affected 700 species (Faraj et al., 2020; Getor et al., 2020; Mustafa Al Bakri et al., 2011). It is projected to triple by 2025 (Adeniran & Shakanatu, 2022). The growing trend would make the amount of waste plastic in the oceans to be more than fish by weight in the year 2050, if there is no intervention (Hahladakis et al., 2020). As a result, the United Nation (UN)
Sustainable Development Goals (SDG) adopted SGD 12 (sustainable consumption and production) and SDG 14 (conservation and sustainable use of the oceans, seas and marine resources) goals in 2015 (Hahladakis et al., 2020; Payne et al., 2019). Hence, utilization of these plastic wastes in construction will reduce the proliferation of waste plastics in oceans and contribute to green construction and sustainable infrastructural development.

Over the years, there has been a lot of research done on using plastic wastes in construction. Waste plastics have been transformed in different ways to be used as fibers, supplementary cementitious materials (SCMs), and aggregates in cement mortars and concrete. One of the most notable uses for plastic is the creation of composite materials of various types with outstanding technical behavior, particularly for increased water absorption (Babatunde et al., 2022; Aina et al., 2022; Aneke et al., 2021; Thiam et al., 2021; Agyeman et al., 2019; Ingabire et al., 2018, Ali Shar et al., 2019). Because of their enhanced strength/density ratio, among other factors, these polymer matrix composites are replacing metal parts more frequently (Nonato and Bonse, 2016). However, the filler spread in the matrix has a significant impact on how well a plastic composite performs. Therefore, in this study, Polyethylene terephthalate (PET) type of waste plastic was melted and mixed with different filler materials to produce a homogenous and uniform mortar/concrete-like composite. The influence of the varying composition of constituent materials on the micro-structural and engineering properties of the composite was investigated.

2. Materials and methods
Four different constituent materials were employed for this study, which are plastics, sand, quarry dust, and glass. The sand, quarry dust, and glass constitute the filler material while the PET bottles act as the only binder in the composite matrix.

2.1. Waste plastic
The Polyethylene terephthalate (PET) type of waste plastic was employed for this study. PET plastic is the most commonly generated waste plastic and it dominates waste plastic streams. The waste plastic was procured from a plastic recycling outlet in an industrial area, in Nairobi, Kenya. Collected waste plastic was sorted and pulverized into small sizes. The waste plastic was thoroughly washed and dried. The physical properties of the waste plastic such as specific gravity, water absorption, and density were determined and presented in Table 1.

| Property               | Plastic | Sand | Quarry Dust | Glass waste |
|------------------------|---------|------|-------------|-------------|
| Specific gravity (%)   | 1.12    | 2.61 | 2.48        | 2.52        |
| Water absorption (%)   | 0       | 0.6  | 2.96        | -           |
| Density (g/cm³)        | 1.02    | 1.45 | 1.60        | 2.43        |
| Composition (%)        | Sand    | Glass waste | Quarry dust | PET Plastic |
| SiO₂                   | 56.40   | 64.12 | 91.07       | 57.90       |
| Al₂O₃                  | 22.50   | 3.65 | 1.65        | 17.30       |
| Fe₂O₃                  | 6.50    | 0.40 | 0.65        | 6.10        |
| MnO                    | 0.02    | 0.25 | 0.01        | 0.02        |
| CaO                    | 1.60    | 10.08 | 2.80        | 10.13       |
| P₂O₅                   | -       | 0.99 | 0.08        | 0.10        |
| K₂O                    | 0.92    | 0.65 | 1.17        | 2.32        |
| TiO₂                   | 1.08    | 0.15 | 0.21        | -           |
| SO₃                    | 0.01    | 0.01 | 0.02        | 0.01        |
| Na₂O                   | 1.26    | 13.48 | 1.27        | 1.12        |
| LOI                    | 8.24    | 0.23 | 1.70        | 5.00        |
2.2. Filler materials

Three filler materials; sand, quarry dust, and glass waste were employed as shown in Figure 1. The sand was locally sourced, and from visual inspection, it can be regarded as sharp sand. Glass waste was sourced from the glass windows and doors retail workshop in Juja, Kiambu, while the quarry dust was procured locally from a construction materials supplier at Roysambu, Kenya. The glass was pulverized into fine particles. All the filler materials were sieved through a 2.36 mm sieve. Afterward, laboratory tests of particle size distribution, specific gravity, water absorption, and density were carried out in accordance with ASTM C128–01 and ASTM C136, and presented in Table 1. It can be observed that waste PET plastic gave zero water absorption property while the fillers materials showed significant water absorption values. This is because waste PET plastic is a hydrophobic material with a surface that repels water. Waste PET plastic is a lightweight material and which explained the lower density obtained compared to that of the fillers. Furthermore, from the XRF analysis conducted on the filler materials (Table 1), it can be observed that all the materials contain SiO₂, Al₂O₃, and Fe₂O₃. The tracer element CaO is higher in Glass waste and waste PET plastic, which makes them suitable for many industrial applications. The presence of CaO, SiO₂, Al₂O₃, and Fe₂O₃ could be attributed to its binding ability and which was exploited in this study. Figure 2 presents the particle size distribution of the filler materials.

2.3. Preparation of samples and laboratory tests

Three (3) different types of waste PET plastic and fillers combinations were investigated and which are; Plastic and Sand, Plastic and Quarry dust, and Plastic and Glass. Table 2 shows the mix design of the waste PET plastics and fillers studied. Batch by weight was adopted for all the mix ratios. The appropriate weight of the plastic was measured and poured into an aluminium container. The choice of aluminium container was because it has a melting point of 400°C, which is above the melting temperature of the plastic, 250°C (Dalhat and Wahab, 2015). The plastic inside the
aluminium container was placed into an electric furnace. The electric furnace was set to a temperature of 250°C. After about 40 minutes, the melted plastic was removed and the filler was added gradually and stirred continuously for uniformity and homogeneity. When it became sticky and difficult to stir further, whereby the plastic and filler composite had not mixed properly. Then, the composite was returned to the electric furnace and left to melt for additional 20 minutes. Afterward, it was removed and stirred properly. The period for plastic and filler to become homogenous composite depends on the quantity of the materials. However, the Waste Plastic Binder (WPB) composite was transferred into 100 × 100 mm cube moulds as shown in Figure 3 and allowed to cool at room temperature. Before the transfer of WPB composite into the moulds, the internal faces of the moulds were lubricated with oil for easy removal after cooling. After 1 hour, it was demoulded and labeled accordingly. The WPB composite matrix samples were left to cure under laboratory temperature of 20°C for 48 hours and afterward, density test (ASTM C138/C138M—17a), Compressive strength test (ASTM C39/C39M—18), Water absorption (ASTM C642), microstructural property and non destructive test (ASTM C597–16) were carried out on the WPB composites. An average of three sample measurements of different mix ratios for each mix was used.

3. Results and discussion

3.1. Influence of filler types and material composition on morphology properties of the Waste Plastic Binder Composite (WPB)

Figures 4–7 showed the Scanning Electron Microscopy (SEM) images of the WPB composites at different mix compositions, while Figures 8–11 showed the SEM/EDS of the WPB composite at different mix compositions. It can be observed that WPB composite containing P only has a large

| S/N | Plastic Type | Combination                  | Mix Ratio | Designation |
|-----|--------------|------------------------------|-----------|-------------|
| 1.  | PET          | Plastic alone                | 1:0       | P only      |
| 2.  | PET          | Plastic and Sand             | 1:1       | P&S:1:1     |
| 3.  | PET          | Plastic and Sand             | 1:2       | P&S:1:2     |
| 4.  | PET          | Plastic and Sand             | 1:3       | P&S:1:3     |
| 5.  | PET          | Plastic and Quarry Dust      | 1:1       | P&Q:1:1     |
| 6.  | PET          | Plastic and Quarry Dust      | 1:2       | P&Q:1:2     |
| 7.  | PET          | Plastic and Quarry Dust      | 1:3       | P&Q:1:3     |
| 8.  | PET          | Plastic and Glass waste      | 1:1       | P&S:1:1     |
| 9.  | PET          | Plastic and Glass waste      | 1:2       | P&S:1:2     |
| 10. | PET          | Plastic and Glass waste      | 1:3       | P&S:1:3     |
presence of voids as can be seen in Figure 8. This can be attributed to the escaped entrapped air. During production, the air ingress and got trapped in the molten plastic, which escaped at the cooling phase, thereby leaving voids. The presence of pores can endanger and depreciate the unit weight and compressive strength of composites (Belmokaddem et al., 2020). The addition of fillers tends to fill the voids, and the higher the dosage of the fillers, the lesser the voids as shown in Figures 5–7. The voids diminish as the content of fillers increases. Not only that it fills voids, it also prevents cracks widening and linkage. It can be observed that the fillers is dispersed in the plastic and the size distribution interlocks well, to provide reinforcement and consequently improve the strength of the composite. A similar observation was reported by Aneke et al. (2021), plastic waste bricks with a higher presence of foundry sand gave minimal pore space and consequently possessed greater strength. As can be seen in Figure 8, the major element of P only is Carbon C and Oxygen O. The dominant molecular element in a waste PET plastic is a long hydrocarbon chain of Carbon, Hydrogen and Oxygen (C₁₀H₁₄O₄). Based on the SEM/EDS results, the dominant tracer element of Si, Al, Fe, Ca, K, Na and Mg were observed to be present in P & S 1:1, 1:2, 1:3 WPB composites. The identified elements can be said to be rendered by the sand filler material as shown in Figure 9. Meanwhile, tracer elements of Si, Na, Ca and Mg were seen to be present in P & G 1:1, 1:2, 1:3 WPB composites. The elements can be attributed to the presence of waste glass as presented in Figure 10. Furthermore, tracer element of Si, Al, K, Na, Fe, Ca and Ti were present in the P & QD 1:1, 1:2, 1:3 Figure 12.

3.2. Influence of filler materials on the density of the WPB composite matrix
The density of material greatly influences the strength properties. High strength, low porosity, and a small number of voids are often attributed to denser cemented material (Thiam et al., 2021). Figure 13 showed the density results of plastic and filler materials composite. The unit weight of the hardened WPB composite samples increases as the proportion of filler materials increases. The result indicated that the density of the composite matrix is a function of the density of the filler material. However, the density of plastic and sand composite gave an increase of 56, 69, and 81 % for P&S 1:1, P&S 1:2, and P&S 1:3, in comparison with that of the control, P only. In the same vein, plastic and quarry dust composite matrix density rose by 55, 64, and 73 % for P&QD 1:1, P&QD 1:2, and P&QD 1:3, whereas a similar increase in density of 32, 55 and 65 % were noted for plastic and glass composite of P&G 1:1, P&G 1:2 and P&G 1:3 respectively. However, Plastic and sand composite gave the highest density results and lowest density results were derived from plastic and glass composite, irrespective of the mix ratio. In ACI 213 R-87, concretes were categorized on the premise of density. Based on this classification, all plastic and fillers combinations regardless of the ratio can be regarded as structural lightweight concrete. Hence, it can be used for some construction applications. The density of P only falls within the range of 800 and 1350 kg/m³, therefore, it can be said to be a moderate strength concrete (Neville,). According to Agyeman et al. (2019), the recommended density of lightweight concrete (LWC) is within the threshold of 500–
All the composites’ mixes are within the specified threshold except P&S and P&QD at mix ratio 1:3, which are slightly above the recommended values.

### 3.3. Influence of filler materials on compressive strength of WPB Composite

The compressive strength defines the resistance of WPB composite to failure under axial forces. It provides the property needed by Engineers to assess the behavior of materials throughout service conditions. Figure 14 presents the compressive strength of the composite matrix at different mix proportions. The results revealed that WPB composites containing P only, P & G1:2 and P&G1:3 gave compressive strength values of 2.3 N/mm², 3.71 N/mm², 5.59 N/mm² and 4.88 N/mm² respectively. Moreso, WPB composites comprising P&QD 1:1, P&QD 1:2, P&QD 1:3, P&S 1:1, P&S 1:2, and P&S 1:3 gave compressive strength values of 7.80 N/mm², 12.06 N/mm², 20.10 N/mm², 10.55 N/mm², 13.09 N/mm² and 20.3 N/mm² respectively. Generally, the addition of filler material improves the strength properties. The results indicated that the compressive strength increases as the plastic and filler materials ratio increases. A similar
increase in compressive strength of Plastic Waste Binder (PWB) as the percentage level of filler materials increases was also observed by (Agyeman et al., 2019; Akinwumi et al., 2019; Aneke et al., 2021; Thiam et al., 2021). Agyeman et al. (2019; Babatunde et al., 2022a; Babatunde et al., 2022b) attributed the improvement to the adhesive strength between the filler particles and waste plastic surface area. However, Thiam et al. (2021) opined that the strength is due to the high degree of crystallinity of polymers as a result of the different polymer branches, which increase as the polymer solidifies or cools. Generally, the addition of filler reinforced the plastic and improves its strength properties. It can be said that the strength of the WPB composite is a function of the proportion, intrinsic strength of the filler, and bond between plastic and filler material. Plastic and Sand composites gave higher strength results than plastic and quarry dust and plastic and glass composites. As observed, plastic and sand composite gave strength
differences in the range of 1–35% and 134–316% to plastic and quarry dust and plastic and glass composites respectively. At a mix ratio of 1:3, the plastic and quarry dust gave nearly the same result as plastic and sand. Meanwhile, the compressive strength of plastic and glass composite drops at this ratio. The lower compressive strength values of plastic and glass composite can be attributed to the lower strength characteristics of glass materials and weaker interfacial bond strength between plastic and glass. The poor molecular bond between the waste plastic and waste glass can be said to have influenced the decline in compressive strength for P&G 1:3 WPB composite, which contains a higher proportion of waste glass. The optimal combination with maximum compressive strength value was gotten when plastic and sand were combined at a ratio of 1:3. Furthermore, P&GQD and P&G at a ratio of 1:3 gave compressive strength values of 20.10 and 20.30 N/mm² respectively, which meet up with the minimum requirement of 17MPa compressive strength for structural lightweight concrete as specified by American Concrete Institute (ACI) and South African Standard (SANS 227:2007). Thus, they can be adopted for
Figure 8. SEM/EDS image of P only.

structural lightweight purposes. However, the morphology of the viscoelastic and ductile properties of plastic waste as its melts under temperature enabled it to form a stronger composite matrix, tension resistance, and developed high strength. The application of waste PET plastic in composite brick production improves the compressive and tensile strength of the composite, and as well contributes to a 40% reduction of CO₂ emissions (Aneke & Shabangu, 2021). Similar strength properties were reported for common lightweight concrete made with pumice, expanded slag, and rotary-kiln expanded clay. However, P&S and P&QD at ratios 1:1, 1:2 can be suitable for non-structural applications and thermal insulation as their compressive strength results fall within 7 and 17 N/mm². However, Figure 15 shows the relationship between density and compressive strength of the plastic waste binder composite. It can be observed that as the density increases, the compressive strength increases. The simultaneous increment can be said to be influenced by the proportion, strength, and density of filler materials. The findings showed a good correlation with an R² value of 0.98, 0.97, and 0.74 for P&S, P&QD, and P&G respectively.

3.4. Influence of filler materials on water absorption on WPB composite

Water absorption test was carried out to gain insight into the pore structure and durability of the plastic samples. It is an indirect method to assess the coarseness or fineness of the sample pore structure or porosity. The permeation ability of a porous material depends on the pore structure. In other words, the ease at which fluids flow into and through the porous medium (Thiam et al., 2021). Figure 16 presents the water absorption of waste plastic binder composite at different mix proportions. It can be observed that, the water absorption of hardened composite samples increases as the filler content increases. Also, the water absorption increases as the duration of the samples in water increases. Plastics are hydrophobic materials, which repel water on their surface. The nearly zero water absorption property of P only can be said to be due to ingress water that occupied the voids present in the material. All the filler materials are hydrophilic materials, which explained the higher water absorption results. Though, the level of absorption by the filler material depends on the number of pores available on its surface. Plastic and glass composite gave higher water absorption while plastic and quarry dust composite showed good water absorption properties. The obtained result is in agreement with that of Jacob-Vaillancourt and Sorelli (2018), who attributed the low water absorption to the hydrophobic nature of waste PET plastics. Water absorption capacity of concrete strongly correlates with carbonation depth, chloride ingress, corrosion initiation time, freeze and thaw resistance (Babak, 2013). Generally, the water absorption of all the plastic and filler composites is below 2%, and BS 6349 specifies a maximum water absorption of 3% for marine structures while BS 812 specifies a maximum of 2% for critical conditions such as freeze-thaw exposure and highly aggressive chloride.
3.5. Influence of material composition on ultrasonic pulse velocity

The Ultrasonic Pulse Velocity (UPV) reveals information on the rate of transfer of pulse in WPB composite specimens. Indirectly, it provides insight into the porosity of specimens. Figure 13 shows the results of the UPV of WPB composite samples for different mix ratios studied. The results showed an increase in UPV as the content of filler materials increased. In comparison with the UPV value of 609.48 m/s for P only, the presence of sand filler increased the UPV values to 1113.59, 1482.70, and 1739.23 m/s for mix ratios 1:1, 1:2, 1:3 respectively. Similarly, the addition of quarry dust led to a significant increment of UPV values to 1093.77, 1296.80, and 1710.23 m/s for P&QD 1:1, P&QD 1:2, and P&QD 1:3 respectively. Furthermore, the UPV values rose for P&G at a mix ratio...
of 1:1, 1:2 and drop slightly at a mix ratio of 1:3. Meanwhile, the lesser UPV value of P only is due to the large presence of voids created by the evaporation of air during cooling as seen in the SEM images. However, the filler materials tend to fill the voids, which explained the higher values of UPV as the addition of fillers increases. Belmokaddem et al. (2020) reported that the presence of voids decreases the velocity of the pulse due to the near effect of air. Some of the incident wave passing the samples gets partially reflected and the remainder is transmitted, which leads to
a reduction of velocity. The relationship between UPV and the compressive strength of WPB composites is shown in Figure 17. The finding showed a good correlation between the compressive strength and the UPV of the WPB composites. It can be observed that the compressive strength of the WPB composite increases as the UPV increases. Albano et al. (2009) reported that the elastic properties of medium and volumetric concentrations of components determine the wave velocity. Therefore, compressive strength can be estimated or predicted from the ultrasonic velocity, in a way that destructive tests can be exempted. According to Azhdarpour et al. (2016), PET plastic reduces the speed of sound wave propagation. It is therefore possible that the WPB composite would be suitable as a sound insulator to decrease the transmission of acoustic waves.
3.6. Influence of material composition on dynamic modulus of elasticity

Figure 18 shows the dynamic modulus of elasticity of the WPB composite against the mix compositions. It can be observed that the variation of the dynamic modulus of elasticity is a function of the content of quarry dust in the composite. This can be attributed to the lower young’s modulus of waste PET plastic compare to quarry dust which is a natural mineral. PET plastic has a modulus of elasticity between 2.1–3.1 GPa while Quarry dust has 70 GPa (Jacob-Vaillancourt & Sorelli, 2018). The lower value of the dynamic modulus of elasticity of only plastic sample is expected, while the presence of filler materials; sand, waste glass, and quarry dust significantly increase the dynamic modulus of elasticity. A similar trend was reported by Azhdarpour et al. (2016), Ferreira et al. (2012), Gesoglu et al. (2017), Hannawi
et al. (2010), and Yang et al. (2015). The modulus of elasticity of the individual materials has an appreciable effect on the modulus of elasticity of the composite (Mohammed et al., 2019) since the deformation of composite material is influenced by the elastic deformation of aggregates. Gesoglu et al. (2017) opined that lower density composite materials would have a lower modulus of elasticity. This may be potentially interesting for certain applications, where materials flexibility and low elastic modulus are perceived to be advantageous such as pavement (Belmokaddem et al., 2020). Figure 19 depicts the relationship between the compressive strength and dynamic modulus of elasticity. As shown, there are linear trends of compressive strength as the dynamic modulus of elasticity increases. The finding shows a good correlation with an $R^2$ value of 0.99, 0.96, and 0.95 for P&QD, P&S, and P&G respectively.
4. Conclusions
This study presents the experimental results of the influence of filler types on the engineering and micro-structural properties of plastic binder composite using waste PET plastic as the only binding material. The findings and conclusions are:

(1) The addition of fillers tends to fill the voids, and the higher the dosage of the fillers, the lesser the voids. Consequently, provide reinforcement and improved strength.

(2) WPB composites containing P only, P&G1:1, P & G1:2, and P&G1:3 gave compressive strength values of 2.3 N/mm², 3.71 N/mm², 5.59 N/mm², and 4.88 N/mm² respectively. Moreso, WPB composites comprising P&QD 1:1, P&QD 1:2, P&QD 1:3, P&S 1:1, P&S 1:2, and P&S 1:3 gave compressive strength values of 7.80 N/mm², 12.06 N/mm², 20.10 N/mm², 10.55 N/mm², 13.09 N/mm² and 20.3 N/mm² respectively.

(3) P&QD and P&S at a ratio of 1:3 gave compressive strength values of 20.10 and 20.30 N/mm² respectively, which meet up with the minimum requirement of 17MPa compressive strength for structural lightweight concrete as specified by American Concrete Institute (ACI) and South African Standard (SANS 227:2007).

(4) Generally, the water absorption of all the WBP composites is below 2%. BS 6349 specifies maximum water absorption of 3 % for marine structures while BS 812 specifies a maximum of 2 % for critical conditions such as freeze-thaw exposure and highly aggressive chloride.

(5) The UPV values of the WPB composite increase as the content of filler materials increases. This can be said to be due to less presence of void as the dosage of filler material increases.
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Author details
Yusuf Olawale Babatunde1,2
E-mail: babatundeysusu99@gmail.com
ORCID ID: http://orcid.org/0000-0002-5714-3673
John Mwero1
Raphael Mutuku3
Yinus Jimoh4
Daniel Oguntayo1,4
1 Pan African University, Institute for Basic Sciences, Technology and Innovation (PAUSTI), Juja, Kenya.
2 University of Ilorin, Ilorin, Nigeria.
3 Landmark University SDG 11 (Sustainable Cities and Communities Research Group).
4 Department of Civil Engineering, Landmark University, Omu-aran, Nigeria.

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