The Effect of Sand on Pavement Blocks: Mechanical and Microstructural Analysis*

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Abstract

In Ghana, the volume of plastic waste generated each year as part of the Municipal Solid Waste (MSW) stream has risen. As a result of the challenges associated with its management and disposal, plastic recycling has emerged as one of the most pressing issues in recent years. Waste Polyethylene Terephthalate (PET) is plastic waste that is produced in huge quantities and, therefore, a substantial component of the Municipal Solid Waste (MSW) stream, which poses a significant danger to the sustainability of the environment. However, studies show the potential usage of PET plastics in producing pavement blocks as a recycling method. Therefore, this research produced pavement blocks by melting PET and mixing it with sand to create a homogenous mixture using different proportions of PET to sand of 30-70% to 70-30% of PET and sand, respectively. The pavement blocks were tested for compressive strength, water absorption and the influence of filler on the micro-structural characteristics of the pavement blocks. The outcome demonstrates that while water absorption reduced with increasing filler content, compressive strength rose as a result. The pavement blocks with the optimal mix are PET30; however, there were higher compressive strengths of 22.843 N/mm², 20.725 N/mm² and 18.462 N/mm² for PET30, PET40 and PET50 that meet the minimum requirement of 17 N/mm² for lightweight structural concrete. Thus, it can be used for the appropriate application. The micro-structural properties of the pavement block showed that the filler materials filled the voids there to enhance the interfacial adhesion and reinforcement effect, thereby increasing the compressive strength and water absorption.

Keywords: Waste PET plastic; plastic-sand pavement blocks; compressive strength; water absorption; microstructural analysis

1 Introduction

Like many Developing Countries, the authorities in charge of waste management, like the Metropolitan, Municipal and District Assemblies of Ghana, struggle with solid waste collection and management (Seshie *et al*., 2020). Plastic waste, which constitutes approximately 10% to 15% of the total garbage generated by humans and ranks as the second-largest component of the waste stream, holds significant significance both at national and international levels (Seshie *et al.*, 2022; Bahij *et al.*, 2020; Seshie *et al.*, 2020). The global demand and production of plastics have been on the rise, primarily attributed to the wide range of applications that plastics offer. This includes their extensive use in packaging as well as their ability to replace traditional materials like wood and metal with plastic alternatives. This report by UNEP (2023) states that over 400 million tonnes of plastic are produced globally each year, approximately 50% of that being single-use plastic. The report also highlights that less than 10% of plastic is recycled, leading to significant environmental challenges and pollution. It has also been estimated that 12% of the plastics have been burnt, and the remainder end up in soils, oceans, and landfill explained by (Babatunde *et al*., 2022).

Notwithstanding, several types of research have shown that the properties of plastics, including but not limited to their high durability, higher ratio of strength to weight, low density, and long lifespan, are suitable for developing construction materials such as concrete. Several kinds of research have revealed the usage of recycled plastic waste materials within conventional concrete (Siddique *et al*., 2008; Dharan and Anand, 2012; Pacheco-Torgal *et al*., 2012; Usman *et al*., 2018), with the establishment of the potential use of PET plastic waste in replacing fine or coarse aggregates in concrete or replacement of cement in concrete production. This is noted as a better disposal strategy for landfilling and thus promoting proper plastic waste management. In addition, Eweed *et al*. (2018) revealed that the benefit of using plastic waste in construction materials spans as far as increasing the properties of concrete. High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-density polyvinyl chloride (LDPE), Polypropylene (PP) and Polystyrene (PS) are other types of thermoplastics which can be recycled and used for plastic pavement blocks production but Polyethylene Terephthalate (PET) would be used for the production of pavement block. PET is used because the PET, which is also among the highest in the waste stream is also the most recycled with about 29% recycled globally in 2018 (Plastic Europe, 2019). Also, apart from the morphology of the pavement blocks determined using SEM, by most researchers (Tulashie *et al.*, 2020; Kumi-Larbi *et al*., 2018; Gashahun, 2020), the link between the mechanical property and the microstructural property by understanding the

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interaction of the PET and sand were not established. The characteristics of the sand for construction purposes is very important. According to Kandasamy and Murugesan (2011), for adequate packing density, structural stability and compaction to reduce the porosity, the sand should contain a well-graded combination of coarse, medium, and fine particles. The specific gravity and the fineness modulus are factors that influence the porosity and the strength of the composite material when they do not meet the limits.

This work, therefore, seeks to examine and determine properties such as the strength and resistance to abrasion of pavement blocks made from the optimal mix of plastics with fine aggregates. As part of enhancing and promoting proper plastics management, key information on these properties will be documented for the institution of standards for the production of pavement blocks which involves a more significant percentage of the mix being plastics.

2 Resources and Methods Used

For this study, two distinct materials were used: plastics and sand. The sand serves as the filler material, while the PET bottles exclusively function as the binder within the composite matrix.

2.1 PET Waste Plastic

This study used Polyethylene Terephthalate (PET) type waste plastic, the second largest in the waste plastic stream and the most often produced waste plastic. PET contributes about 12% of global solid waste (Benyathiar *et al*., 2022). The PET waste plastic was obtained from Tarkwa, Ghana-based eateries, water-producing packaging businesses, and the University of Mines and Technology campus. The PET plastic materials were manually sorted and categorised according to the Plastic Identification Code (PIC). The previously separated plastic materials were washed with detergent and water to remove labels from bottles and other impurities like glue and grime, and the materials were then dried in the sun. The polymers were broken down into tiny fragments ranging in size from 2.36 mm to 4.75 mm. After being broken down into smaller pieces, the plastics were weighed and divided into various ratios (masses of 3,000, 4,000, 5,000, 6,000, and 7,000 grams).

2.2 Filler material

In Fig. 1, it can be observed that the study utilised one type of filler material, which is sand, along with waste. The sand used in the study was sourced locally and appeared to be a combination of sharp sand and builder's sand based on visual inspection. To ensure uniformity and remove any debris larger than 5 mm, all the filler materials underwent sieving using a 5.00 mm sieve. Afterwards, laboratory tests of the particle size distribution (gradation curve), Fineness modulus, specific gravity, silt content and water absorption were carried out in accordance with BS 1377: Part 2:1990 and BS 812: Part 103 and presented in Table 1 and Fig. 1.

Table 1 Properties of Sand (Filler)

Parameter	Result	Limits
Silt/Clay Content	3%	3% (Cho, 2013)
Specific Gravity	2.68	2.6-3.0 (Abas and Pandey, 2015)
Fineness Modulus	2.58	2.0-3.5 (BS 812: Part 103)
Water Absorption	0.008%	5% maximum limit

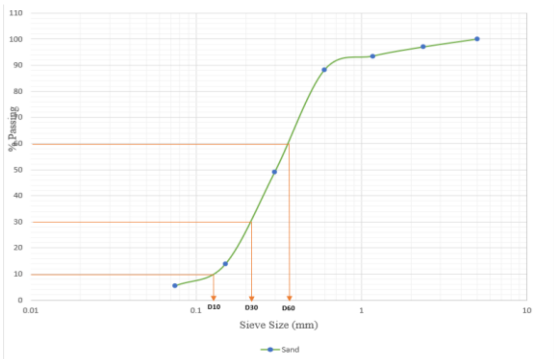


Fig. 1 Gradation Curve

2.3 Preparation of samples and laboratory tests

For this experiment, a mixed design combination was appropriately constructed for proportioning the feeder components (PET waste plastic and filler). The mix design of the investigated waste PET plastics and filler is shown in Table 2.

Table 2. Mix Design Proportions and Designation

SN	Plastic Type	Ratio of plastic to sand	Designation
1	PET	3:7	PET30
2	PET	4:6	PET40
3	PET	5:5	PET50
4	PET	6:7	PET60
5	PET	7:3	PET70

For all mix ratios, the feeders were adopted and weight-batched. The plastic was weighed appropriately, poured into a stainless-steel container, and set atop a reactor ignited with a charred palm kennel. The container was chosen because its melting point is higher than that of the plastic, 220 °C, and the sand, 1700 °C. In order to ensure uniformity and homogeneity, the filler was added gradually and mixed constantly for 5 minutes after the melted plastic had been heated for approximately 20 minutes. The molten liquid was poured into greased, 50 x 50 x 50 mm³ brass moulds that had been pre-heated to 100 °C.

Along with a flat, rectangular board to eliminate extra air bubbles, the pre-heated moulds aid in releasing bubbles.

After the moulds and their contents were left to cool and harden at room temperature for a duration of 40 minutes, they were demoulded and labeled accordingly. The compressive strength and water absorption tests of the pavement blocks were conducted at curing ages of 7, 14, and 28 days. Additionally, a microscopic analysis was performed specifically at the 28-day mark. There were 45 cubes created in all. The flowchart of the method for producing the pavement block is shown in Fig. 2.

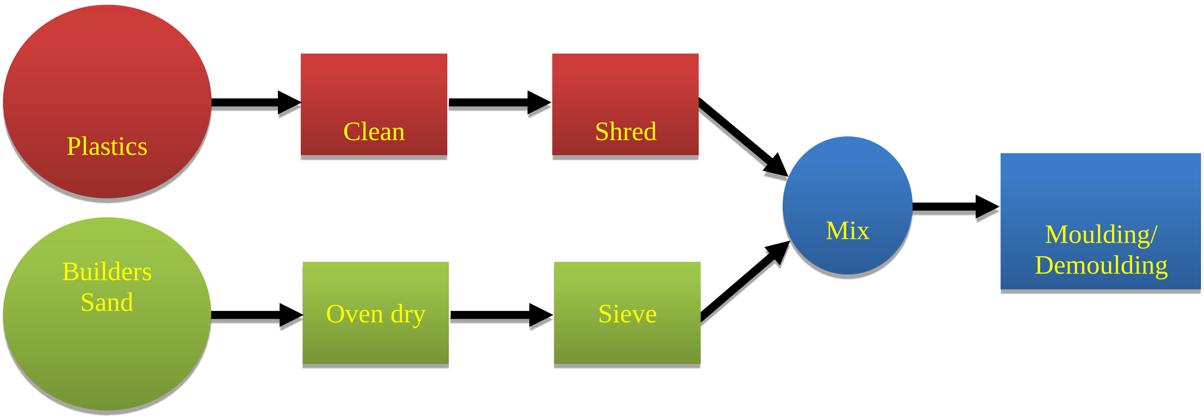


Fig. 2 The Process Flowchart Used to Produce the PET Bonded Sand Pavement Blocks

3 Results and Discussion

3.1 Uniaxial Compressive Strength

The resistance of a pavement block to failure under uniaxial stresses is determined by its compressive strength. This characteristic is necessary for engineers to evaluate the behaviour of materials. The compressive strength of the blocks at different levels of the mix design is shown in Fig. 3.

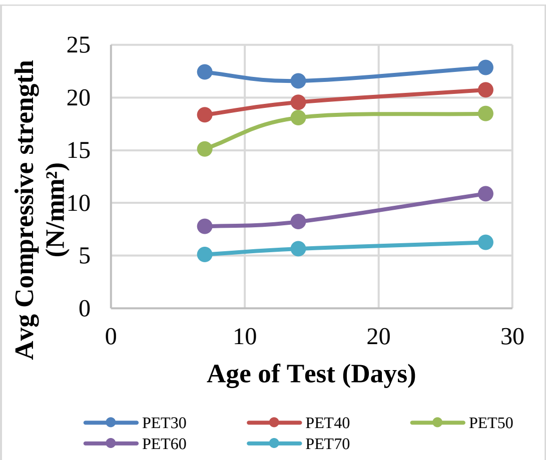


Fig. 3 Variation of compressive strength with curing age

The trend seen in this research did indicate a similar pattern where the compressive strength of the pavement blocks increased with increasing curing age; as per Jain *et al*. (2019), the compressive strength (CS) of concrete specimens normally increases with an increase in curing age. The compressive strength of the pavement blocks generally increased with age at the different mixed percentages, as shown in Figure 3. The PET plastic-sand pavement blocks' compressive strength generally increased for each curing age as the plastic component rose from day 7 to 28. However, when the percentage of PET content increased from 30% to 70%, the compressive strength declined. According to the results, the pavement block with a 30% PET component has the highest compressive strength, that is, the optimal strength. The compressive strength decreased with increasing percentage plastic content which conform to the result obtained by Ababio Ohemeng *et al*. (2014) and Jain *et al*. (2019). The decrease according to these authors can be attributed to a weak interfacial bonding which leads to pores and cavities forming. The pavement blocks that were produced in this study exhibited compressive strengths ranging from 5.1 N/mm² to 22.84 N/mm². These values fall within the globally recognized standard threshold of 0.69 N/mm² to 17.24 N/mm² for pavement production (Agyemang *et al*., 2019). Thus, the pavement blocks can be deemed suitable for various applications in non-traffic areas. These include walkways, footpaths, pedestrian areas, landscapes, and waterlogged areas, where heavy vehicular traffic is not expected.

3.2 Influence of PET on water absorption on PET-sand bonded pavement block

An experiment assessing water absorption was carried out to understand more about the pore structure and durability of the pavement blocks. It is an indirect approach for determining whether a material has a coarse or fine pore structure or porosity. The results for water absorption of the pavement blocks produced from the different mix proportion of PET plastics when immersed in water for 24 hours is illustrated in Fig. 4.

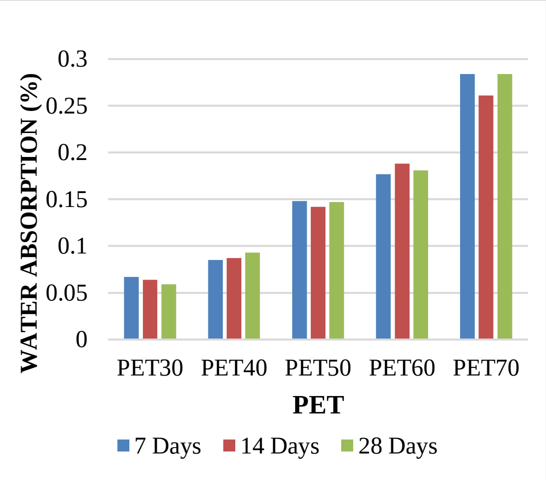


Fig. 4 A graph of Water Absorption of pavement blocks with increasing PET content

During the study, a consistent pattern was observed regarding the water absorption of pavement blocks made with PET plastics. Generally, as the filler content increased, there was a decrease in water absorption at different curing ages. However, when the plastic content increased, there was an observed increase in water absorption for the pavement blocks. This suggests that the amount of filler material has an influence on reducing water absorption, while an increased proportion of plastic content may lead to higher water absorption in the pavement blocks. The pavement blocks recorded water absorption between 0.06-0.29%, nearly zero which did not exceed the standard limit of 5% per BS 13338:2003. The findings align with results obtained by Temitope *et al.* (2015) and Jacob-Vaillancourt and Sorelli (2018), where zero water absorption was recorded. The low water absorption is attributed to PET's hydrophobic nature, which expels water and fills voids in the pavement blocks. Based on the results which indicate low water absorption of the pavement blocks, it can be concluded that they have the ability to resist absorbing water. This makes them suitable for applications where water exposure is common, such as floor and wall tiles for bathroom and kitchen areas. Additionally, their resistance to water absorption makes them suitable for use in waterlogged areas, where the pavement blocks can withstand the effects of moisture over time.

3.3 Influence of filler on the micro-structural properties of molten PET-sand bonded pavement blocks

Scanning Electron Microscopy (SEM) microstructure study, as shown in Fig.s 5-9, revealed that the pavement blocks manufactured with different mix amounts of PET and sand exhibited voids and cracks. The voids and cracks in these pavement blocks result from the disconnect at the boundary between the PET and sand, which results in weak interfacial bonding. The uniform transfer of stress between the sand and PET is ineffective because of the stress concentrator due to the voids. The pores or voids that can act as stress concentrators lead to the initiation and propagation of cracks, further reducing the composite's strength (Chen *et al*., 2018). Kumar *et al*. (2015) and Mukherjee *et al*. (2017) also observed voids and the composite material studied and concluded it is due to the porosity of the filler used. Again, the manual mixing process used may introduce some voids into the pavement blocks because the process, which requires careful attention to ensure uniform distribution of the molten plastic within the sand matrix techniques, tends to be more prone to variations in mixing consistency, which can lead to inconsistencies in material distribution, compaction, and packing density. These inconsistencies result in insufficient wetting and adhesion between the filler and matrix that produces voids. These voids and cracks may impact the mechanical and durability features of the pavement blocks, such as compressive strength and water absorption. These qualities deteriorate because the voids formed by the porosity of the fillers might impair the reinforcing action in various ways. A filler with a high porosity may reduce the effect of reinforcement due to decreased interfacial adhesion between the filler particles and the plastic matrix. This is because the voids inside the filler can trap air, resulting in insufficient wetting and adhesion between the filler and matrix (Aneke *et al*., 2021). The compressive strength of pavement blocks constructed with a filler content ratio of 30% to 70% (see Fig.) shows that the compressive strength increases with filler content and decreases with PET content. Voids in the SEM/EDS images can be attributed to the escape of restricted air during the curing process, which leaves voids that can limit the pavement blocks' compressive strength and water absorption (Belmokaddem *et al*., 2020). The filler occupies the voids as the filler content increases from 30% to 70%, and the higher the filler content, the smaller the voids, as evidenced by the compressive strength data (see Fig. 3). Mukherjee *et al*. (2017) discovered that composites with the highest porosity fillers had the lowest compressive strength, whereas composites with the lowest porosity fillers had the highest compressive strength. The compressive strength increases as the filler content increases, whereas the water absorption decreases (see Fig. 4). The voids are reduced when the filler increases, preventing the cracks from expanding.

The presence of voids reduces the contact area between the filler and the polymer matrix, reducing interfacial bonding strength and load transfer efficiency (Chen *et al*., 2018; Kumar *et al*., 2015), which affects compressive strength and water absorption capacity. Furthermore, filler with a high specific gravity can lower pavement blocks' porosity and water absorption. A filler with a high specific gravity can minimise block porosity by filling the voids. This can help reduce water absorption and increase the pavement blocks' durability (Mannan and Kader, 2017). The filler employed in this study has a specific gravity of 2.68, which is comparable to the specific gravity range of 2.20 to 2.65 g/cm^3 that Zhang *et al*. (2017) believe is the specific gravity range that has been demonstrated to enhance the compressive strength of pavement blocks. This specific gravity range improves the characteristics of the pavement blocks by increasing the mixture's packing density. In other words, when the filler has a high specific gravity, it takes up less volume in the mixture, allowing the plastic matrix to fill the voids more effectively. As a result, the mixture becomes more compact and uniform, which can improve mechanical qualities such as compressive strength (Jia *et al*., 2019). Li *et al*. (2020) discovered that as the block's filler content increased, so did its compressive strength. Because silica filler is hydrophobic, the water absorption of the blocks reduced as the filler quantity rose.

According to the SEM/EDS images (Fig.s 5 to 9), the most abundant elements are C and O, the most abundant molecular elements in waste PET plastic, i.e., Carbon, Hydrogen, and Oxygen ($C_{10}H_8O_4$). Other trace elements present included Fe, K, Na, Al, Si, Ti, Cr, and Zn, all associated with the filler. A filler's chemical composition can influence its usefulness in plastic composites. The presence of impurities or other components in the fillers might impact the mechanical and physical properties of the composite material. Fe impurities in the filler can alter the pavement blocks' compressive strength and water absorption, according to this study. For example, fillers with a high iron oxide content can lower the composite's (pavement block's) reinforcing effect and compressive strength. Zhao *et al*. (2020) investigated the influence of silica filler chemical composition on the mechanical properties of plastic composites. They discovered that fillers with a high iron oxide concentration reduced the reinforcing effect and compressive strength. Another study found that including impurities in silica fillers, notably iron oxide, can impair the compressive strength of composite materials (Kumar *et al*., 2015). According to the researchers, this was owing to the creation of weak interfacial adhesion between the filler and the polymer matrix, which reduced the filler's overall efficacy in reinforcing the material. Wu *et al*. (2015) investigated how iron oxide content affected the mechanical characteristics of a silica-filled epoxy composite. The interfacial bonding strength between the filler and matrix dropped as the iron oxide content increased, resulting in a decrease in the compressive strength of the composite. The interfacial bonding and reinforcing effect are reduced due to the disconnection between the filler and the PET matrix. Fig.s 5–9 showed the Scanning Electron Microscopy (SEM) and SEM/EDS images of the pavement blocks at different mix design compositions.

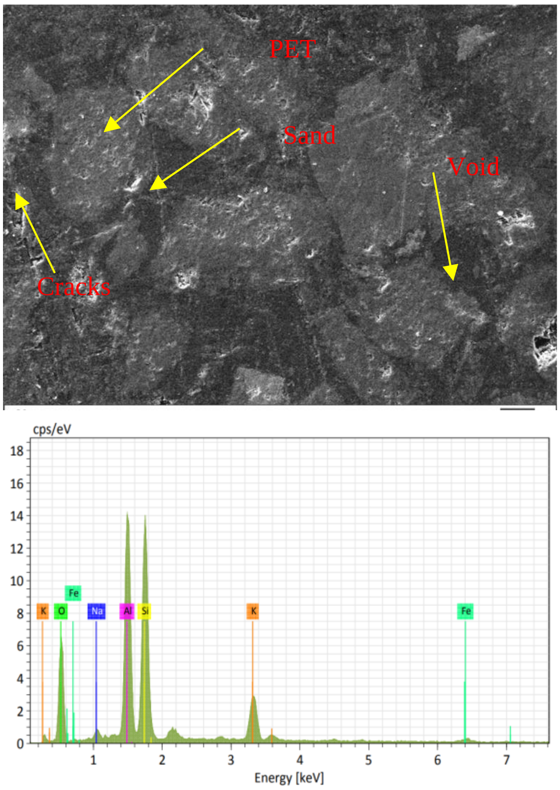
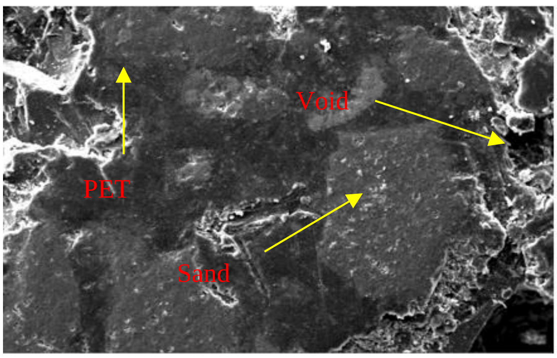


Fig. 5 shows SEM/EDS images of pavement blocks with 30% PET.



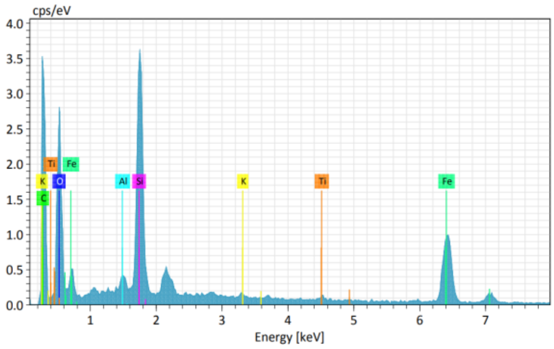


Fig. 6 shows SEM/EDS images of pavement blocks with 40% PET.

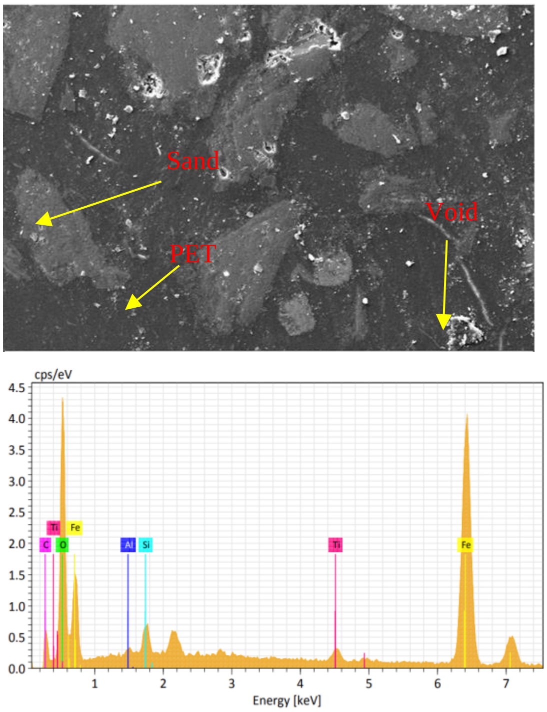
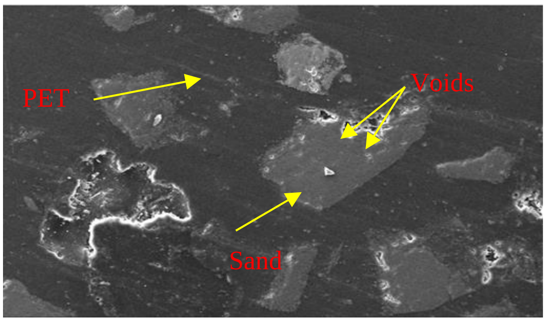


Fig. 7 shows SEM/EDS images of pavement blocks with 50% PET



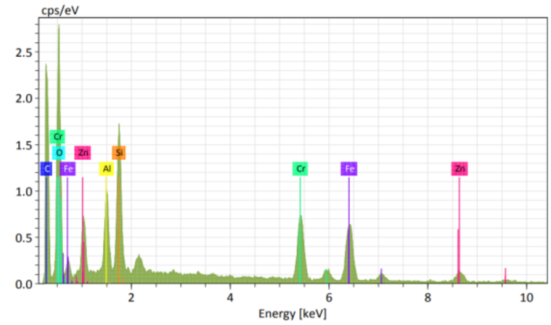


Fig. 8 shows SEM/EDS images of pavement blocks with 60% PET.

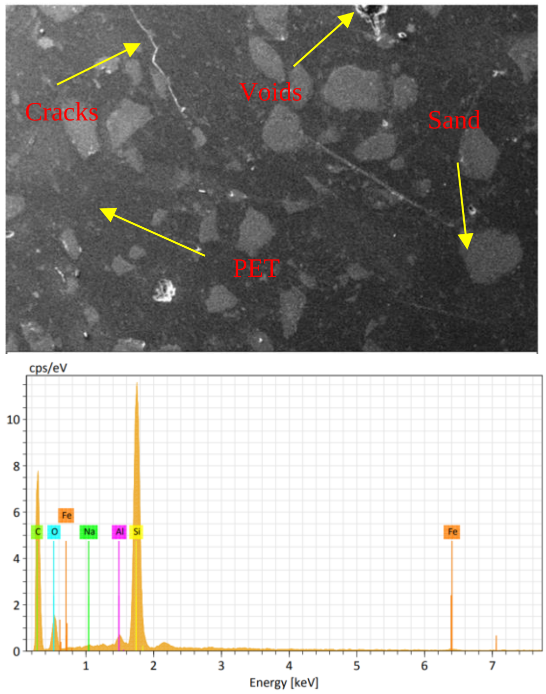


Fig. 9 shows SEM/EDS images of pavement blocks made with 70% PET

4 Conclusions

This study focuses on the compressive strength, water absorption, and the impact of filler on the microstructural properties of pavement blocks made from molten PET-sand with waste PET plastic serving as a complete replacement for cement.

The study concludes that the compressive strength of the pavement blocks improves as the filler content increases, particularly between 30% and 70% filler content. The optimal mix, PET30, achieves a compressive strength of 22.843 N/mm².

The water absorption shows a decreasing trend with increasing filler content. The water absorption recorded for all the pavement blocks with the various mix ratio was below the maximum water absorption of 5%.

The result shows that for a pavement block that exhibit even distribution of stress, adequate packing density and compaction as well as filled voids, ratio of PET to sand should be 30:70.

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