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Evaluating the structural performance of waste PET-infused interlocking units versus traditional stone masonry

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HIGHLIGHTS

- Plastic pollution is gradually taking over the environment.
- There are many ways in which plastic waste is being recycled, and the construction industry must be involved.
- Effective usage of plastic in construction will reduce plastic pollution.

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ABSTRACT

This study focuses on PET waste reduction worldwide by looking at the application of these polymeric materials in the construction and building industries. An effective application of PET wastes will reduce PET pollution, especially in water bodies. Due to its rising cost, it can partially replace the conventional binder used (cement).Bricks were made in the conventional cement-sand and PET-sand, and a total of 72 cubes were produced for different mix ratios of 1:1, 1.5:1, and 2:1. Their properties like particle size analysis, water absorption, slump testing, and compressive strength were investigated and compared.The particle size analysis showed that the sand was well-graded with a Cu of 3.41 and a Cc of 1.07. The results of the water absorption test showed that, in both series and different mix ratios, the PET-sand interlocking blocks had a lower sorptivity (percentages of 2.02, 2.72, and 4.20) than the cement-sand interlocking blocks (percentages of 0.91, 2.40, and 3.31). The mixtures produced a 70 mm, 50 mm, and 80 mm slump for 1:1, 1.5:1, and 2:1, respectively.The maximum compressive strengths in cement-sand interlocking blocks were 13.89 N/mm^2, 17.34 N/mm^2, and 21.06 N/mm^2 in the 1:1, 1.5:1, and 2:1 respectively. Although the results showed that the compressive strength of PET-sand interlocking bricks was lower than that of cement-sand interlocking bricks, it can be useful in a low-density carriage road.

1. Introduction

Environmental challenges remain a global occurrence in all aspects of human activities. Most of the environmental hazards encountered in various aspects of life are artificial, and this is due to the quest for better and more comfort. The world is gradually drifting from heavy food and content packaging to lighter packaging materials such as PET. PET materials are gaining ground in the hearts of many manufacturers for the packaging of their products, and this is due to the weight they add to the total package. There is no denying that PETs have made significant contributions to the advancement of human civilization; nonetheless, the spread of PET waste (macro-, micro-, and nano-PETs) in the environment and its entrainment into biological systems has become a severe issue [1]. Consequently, PETs are becoming a menace to the environment after their useful lives have been completed, and this is due to improper disposal management practices.

In many developing countries like Argentina and Brazil, the recycling of Polyethylene Terephthalate (PET) material has not been given proper attention for years. In addition, the shipment of PET into the country has been a major issue because large quantity is transported to the country yearly [2]. In Nigeria, a country with a population of over 200 million, in the 2021 'PET Pollution by Country' report by the World Population Review, Nigeria was ranked seventh-largest country in the world, generating PET waste with about 5.96 million tons of PET waste every year [3]. In Nigeria, PET waste pollution is fast gaining momentum and becoming a menace to the environment and potential health risks to the populace [4,5]. PET pollution is a pressing global challenge due to its pervasive, near-unmanageable threat to living and nonliving systems and the environmental stress it causes [6,7]. PET pollution is a chronic global problem, with the first findings demonstrating its impact on the environment's living and nonliving components dating back more than a half-century [8]. Across the world, the issue of PET pollution has brought about a paradigm shift in discourses on climate change and ocean and environmental sustainability

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[9,10]. PET products come in different forms and shapes. Adepitan et al. [11] highlighted the need for recycling, reusing, and reducing (3R's) of some materials (though that's for e-waste), and this can be incorporated into PET waste. The conversion of discarded hydrocarbons is increasing daily [12]. It is now known that certain types of used vehicles can be converted into interlocks, which are used as walkways in homes and offices. However, little information is available about using PET bottles—a relatively soft PET—for interlock, even though these bottles are discarded daily in various forms, colors, and sizes [13]. This study focuses on the possibility of reusing PET wastes to produce interlocking bricks, different from the conventional cement used in their production.

The issue of discarded PET bottles, ubiquitous in society, results from using PET bottles as liquid product containers. This is an unforeseen result. Thus, the potential to turn these bottles into functional interlocks will aid in problem management. Nonetheless, research is required to evaluate the viability, sustainability, and strength of interlocking blocks composed of concrete and PET. This information is crucial for selecting the right paving materials for outdoor surfaces.

This creative strategy will decrease PET waste while creating job opportunities in the PET interlocking bricks sector. PET products are thrown in vast quantities daily after usage; therefore, materials will always be available for the firms that produce interlocking bricks using PET waste as their binders. There are several reasons to focus on PET bottles. First, PET bottles are widely available and easy to get into homes, workplaces, PET locations, and even cars. Second, since PET bottles are discarded freely in society, making interlocks out of them will be more affordable because getting the bottles will be free. Thirdly, there will be a significant decrease in the environmental harm caused by these discarded PET wastes. Figure 1 shows a section of discarded PET waste from one of the dump sites in Nigeria. The environmental hazards caused by this improper disposal of PET waste have greatly concerned the country's citizens and government agencies. The environmental damage caused by the improper disposal of these waste plastics includes drainage blockage, flooding during the rain, which consequently results in heavy traffic on motorways, and property damage, to mention a few.

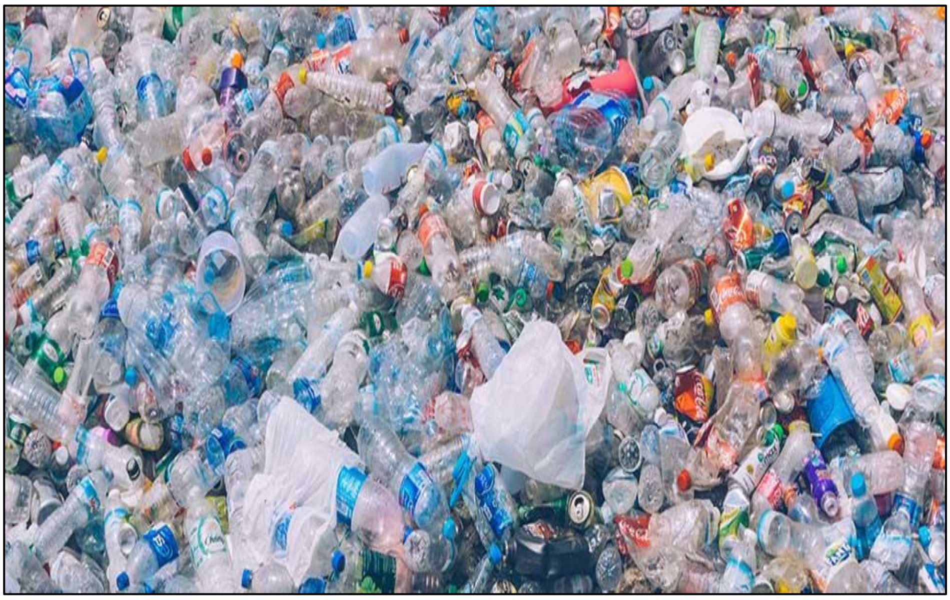

Figure 1: Improper disposal of PET wastes [14]

2. Materials and methods

This study was done on water absorption and fire resistance as a complete replacement for PET and cement in the case of compression resistance. Three parameters—case 1, case 2, and case 3—were taken into consideration for this study. Using the same mix design, a control paving stone made of cement and the research sample made of melted waste PETs were created for each case. The following materials were used in the study:

2.1 Wastes PET materials

The PET materials used in this study were PETs made from polyethylene terephthalate (PET). This is because the waste PETs are readily available and form over 60% of the PET waste in the country (Nigeria). The waste and discarded PET materials (PET) were collected at the dump site, and any impurities were washed off.

2.2 Sands

Sands form the basic constituents of both samples to be studied. One of the main ingredients in concrete mixes is sand. When making concrete, sand from broken rocks or natural gravel deposits works well as a fine aggregate. It can be used by itself with cement for mortars and plastering projects, or it can be combined with coarse aggregates to create structural concrete.

2.3 Granite

Rough-cut and polished granite is used to make these interlocking bricks.

2.4 Other equipment

A few more pieces of equipment were employed, including a digital weighing scale, a heating setup, a steel drum, a trowel, a shovel, and steel molds with a length of 200 mm, a width of 100 mm, and a height of 80 mm, as well as water and cement. The specification of the mold's dimensions was taken from the regular interlocking block dimensions used around the city.

3. Experimental setup

This study was done at different mixing ratios of the samples. There are two different samples with different mixing ratios.

3.1 Sand-cement

The sand-cement interlocking blocks are done with three different ratios, which are 1:1, 1:1.5, and 2:1, for the proper analysis and comparison of the effect of the characterization of PET and cement binders and using a constant water ratio of 0.4 as a control. The industrial standard for sand-cement ratio is 2:1 without the coarse aggregates. The mortar produced was placed into size 230 mm×140 mm×55 mm molds and allowed to set for about 24 hours. Twelve molds were prepared for each mix proportion. The sand-cement mix proportions used for producing the blocks are shown in Table 1.

Table 1: Sand-cement mix Proportion

1:1			1:1.5			1:2		
Mix No	**Sand (kg)**	**PET (kg)**	**Mix No**	**Sand (kg)**	**PET (kg)**	**Mix No**	**Sand (kg)**	**PET (kg)**
1	10	10	2	10	15	3	10	20

3.2 Sand-PET

The waste PETs were shredded, purified by washing, and dried in the open air until all the moisture was gone before being weighed and melted into liquid form for easy mixing. They were shredded into flakes and sent to the laboratory for experimentation. The sand-PET mix ratios considered were 1:1, 1:1.5, and 1:2, with a mixing time of 2 minutes. Table 2 gives the sand-pet ratio mix for producing the interlocking blocks. After each mix was done, the product of the mix was poured into a mold of 230 mm×140 mm×55 mm.

Table 2: Sand-PET mix Proportion

1:1			1:1.5			1:2		
Mix No	**Cement (kg)**	**Sand (kg)**	**Mix No**	**Cement (kg)**	**Sand (kg)**	**Mix No**	**Cement (kg)**	**Sand (kg)**
1	10	10	2	10	15	3	10	20

4. Results and discussion

The test examined the interlocking blocks' compressive strength in cement-sand and PET-sand combinations. The materials used in making the interlocking blocks were put through testing. Particle size analysis, bulk density, water absorption, and slump test are among the tests that are performed.

4.1 Particle size distribution analysis of sand

According to Table 3, the sieve analysis results show that D_{60}, D_{30}, and D_{10} have values of 1.05, 0.59, and 0.308, respectively. As per the Unified Soil Classification System (USCS), a soil particle is considered well-graded if its Coefficient of Uniformity (Cu) value falls between 4 and 10 and its Coefficient of Curvature (Cc) value falls between 1 and 3. Figure 2 also shows the percentage weight passing of the sand particles.

Table 3: Particle size analysis of sand

S/N	Sieve Size (mm)	Percentage Weight Passing (%)
1	10.0	100
2	5.0	95.3
3	2.36	81
4	1.18	59.6
5	0.60	32.8
6	0.30	8.4
7	0.190	2
8	Pan	0

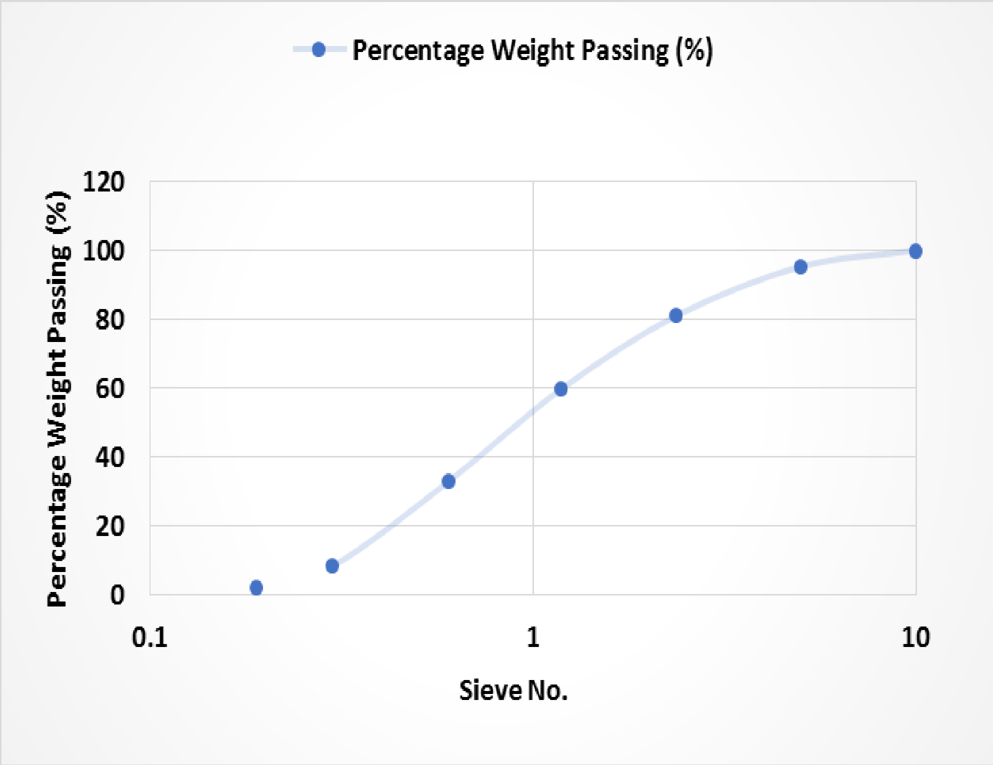

Figure 2: Chart of particle size analysis of sand

However, the soil particle is equally graded when the Cu value is less than four, and the Cc value is less than 1. Based on the computations from Table 3, the fine aggregates had Cu and Cc values of 3.41 and 1.07, respectively. The outcome shows that the sand has a good grade.

4.2 Water absorption test

The water absorption test was carried out by cleaning any oil and dirt on the interlocking and weighing it before being immersed in water for 24 hours and reweighed. This is a fundamental evaluation of a material's porousness and resistance to moisture ingress. In this study, we conducted water absorption tests in various mix ratios on two distinct concrete mixtures: concrete-sand and PET-sand. The results of these tests are presented in the tables below, offering valuable insights into the material's susceptibility to water infiltration.

The water absorption test of cement-sand and PET-sand interlocking blocks are presented in Table 4 and 5, respectively, and further depicted in Figure 3.

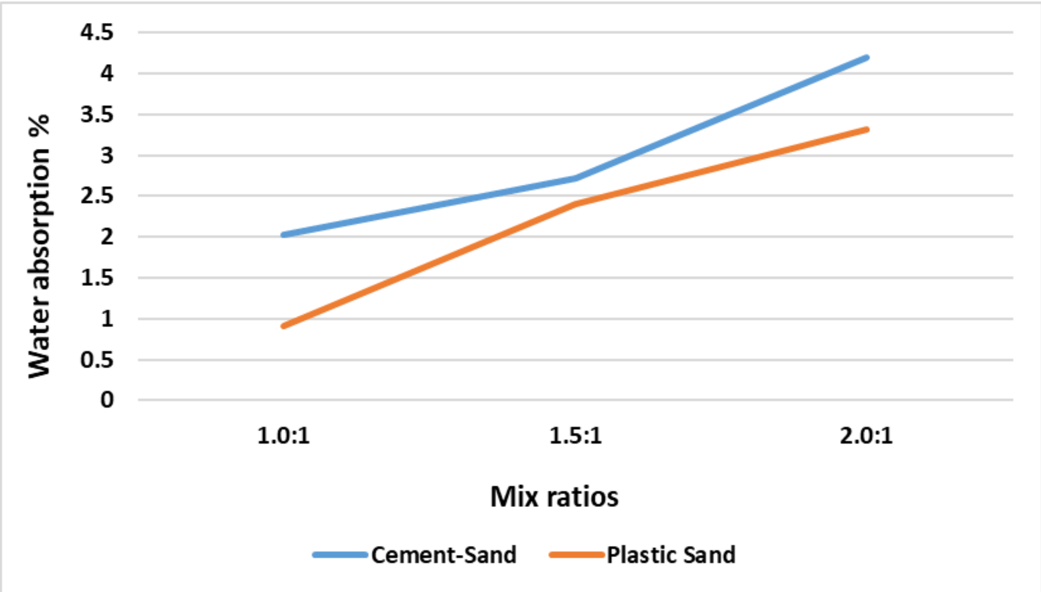

Figure 3: Water Absorption Test

Table 4: Water Absorption Test on Cement-Sand Concrete Material

Sample No	Dry weight of material (W_A)	Wet Weight of Material (W_B)	Change in mass (g)	Water absorption (%)
1:1	2.48	2.43	0.05	2.02
1.5:1	2.57	2.50	0.07	2.72
2:1	2.62	2.51	0.11	4.20

Table 5: Water Absorption Test on PET-Sand Concrete Material

Sample No	Dry weight of material (W_A)	Wet Weight of Material (W_B)	Change in mass (g)	Water absorption (%)
1:1	2.19	2.17	0.02	0.91
1.5:1	2.08	2.03	0.05	2.40
2:1	2.42	2.34	0.08	3.31

Table 4 displays the water absorption values for 1:1, 1.5:1, and 2:1, which are 2.02, 2.72, and 4.20, respectively. This suggests that the interlocking blocks' sorptivity rose as the cement percentage in the mix ratio increased. Similarly, Table 5's data on water absorption for the 1:1, 1.5:1, and 2:1 ratios demonstrates that the interlocking blocks' sorptivity rose as the amount of PET in the mix ratio increased, reaching 0.91, 2.40, and 3.31, respectively.

For both series, in the different mix ratios, the sorptivity of the interlocking blocks was lower in PET-sand interlocking blocks than in cement-sand interlocking blocks.

The water sorptivity value of the concrete was lowered by the addition of PET powder, as seen in Figure 2. It is not surprising that adding more ingredients makes concrete less soluble. Because PET powder contains smaller particles than cement, concrete has fewer pores than cement, resulting in lower sorptivity and water infiltration than plain concrete.

As can be seen, the partial replacement of cement with PET powder reduces concrete’s water absorption capacity. This is primarily because, in normal circumstances, supplementary materials register water absorption of less than 0.02%. As such, the low water absorption observed can only be attributed to the absence of pore formation. Consequently, the low sorptivity value strongly indicates that the PET mix's durability is higher than the conventional mix. This is because PET doesn’t allow water absorption through the mix, unlike the sand-cement mix, which has a high affinity for water.

4.3 Slump Test of Cement-Sand Interlock Mix Ratios

The slump test was carried out on the mix by filling a freshly prepared mixture in a conical-shaped mold with the mix. The cone-shaped object was turned upside-down and carefully removed gently with a slight vibration while removing it. The cone-shaped mold of the mix was allowed to slump off, and the height was measured. This is a widely used method for assessing the workability of concrete, which is a critical property that influences its ease of placement and subsequent performance. The slump test results on three different mix ratios of cement-sand concrete, 1:1, 1.5:1, and 2:1, are presented in Table 6 and Figure 4.

Table 6: Slump Test of Cement-Sand Interlock Mix Ratios

Slump Ratio	Slump Height
1:1	70 mm
1.5:1	50 mm
2:1	80 mm

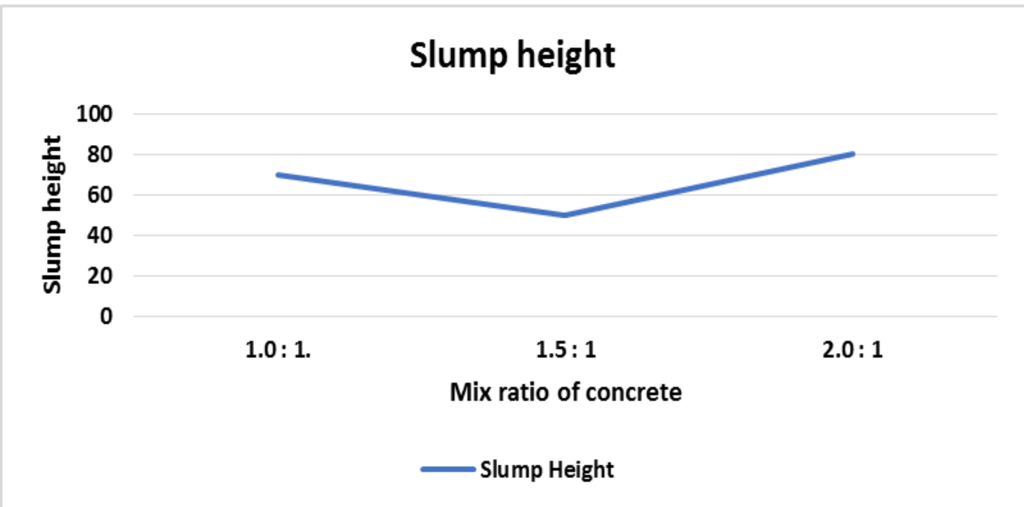

Figure 4: Slump Test of Cement-Sand interlock Mix Ratios

The slump test for the 1:1 cement-sand mixture yielded a slump height of 70 mm. This moderate slump indicates a balanced mix with good workability. This moderate slump indicates a well-balanced mix with good workability, making it suitable for creating interlocking patterns efficiently. This mix's ease of placement and compaction ensures a smooth and visually appealing surface for interlocking pavements.

The slump test for the 1.5:1 cement-sand mixture resulted in a slump height of 50 mm. A slump of 50 mm indicates a relatively lower workability compared to the 1:1 mix. With a slightly lower slump, this mix offers decreased workability compared to the 1:1 mix. While it may require a bit more effort during placement, it can be beneficial for creating interlocking pavements in areas where a sturdier surface is preferred, such as driveways or areas subject to heavier loads.

The slump test for the 2:1 cement-sand mixture produced a slump height of 80 mm. A slump of 80 mm suggests high workability and ease of placement. This mix is well-suited for creating intricate interlocking patterns with ease. The high workability ensures that the concrete can flow and fill the interlocking molds effectively, resulting in a visually appealing and precisely fitting pavement surface. The slump test findings for three different ratios of cement to sand in the concrete mix offer specific advantages when manufacturing interlocking pavement. The 1:1 mix is useful for quickly and effectively building aesthetically pleasing interlocking pavements since it balances workability and stability with a mild 70 mm droop. By comparison, the 1.5:1 mix has a lower 50 mm slump and is stiffer, which can be useful in locations where durability needs to be improved. The 2:1 mix, which has an 80 mm droop, is the last mix with outstanding workability and is perfect for creating complex interlocking designs.

4.4 Compressive strength test of cement sand interlock

The compressive strength test of cement sand is a critical evaluation of its structural integrity and load-bearing capacity. Tables 7, 8, and 9 represent the compressive strength test results for mix ratios 1:1, 1.5:1, and 2:1. From Table 7, the average compressive strength is 6.66 N/mm^2, 8.09 N/mm^2,10.01 N/mm^{2,} and 13.89 N/mm^2 for days 7, 14, 21, and 28 of curing, respectively. From Table 8, the average compressive strength at a mix ratio of 1.5:1, the compressive strength of cement-sand interlocking blocks was 7.40 N/mm^2, 10.07 N/mm^2, 14.3 N/mm^2 and 17.34 N/mm^2 at 7 day, 14 days, 21 days and 28 days of curing respectively. At a mix ratio of 2:1, the compressive strength of cement-sand interlocking blocks was 7.70 N/mm^2, 13.77 N/mm^2, 17.19 N/mm^2 and 21.06 N/mm^2 at 7 day, 14 days, 21 days and 28 days of curing respectively. The slump or stability of these interlocking blocks for mix 1:1, 1.5:1, and 2:1 are 70 mm, 50 mm, and 80 mm, respectively. Figure 5 gives the summary of the compressive strength of these mixes.

Table 7: Compressive strength Test for Cement-Sand interlocks at a ratio of 1:1

S/N	Days	Weight (kg)	Final load (kN)	Fcu (N/mm^2)	Average Fcu (N/mm^2)	Slump value
1	7	5.45	219.8	6.32		
2	7	5.61	228.6	6.57	6.66	70 mm
3	7	5.57	246.0	7.08		
4	14	5.72	278.0	7.80		
5	14	5.79	277.4	7.98	8.09	70 mm
6	14	5.75	287.1	8.27		
7	21	6.03	353.7	10.17		
8	21	6.02	342.6	9.86	10.01	70 mm
9	21	5.91	348.0	10.01		
10	28	6.62	4.68.8	13.49		
11	28	6.71	493.4	14.19	13.89	70 mm
12	28	6.68	486.2	13.98		

Table 8: Compressive strength Test for Cement-Sand interlocks at a ratio of 1.5:1

S/N	Days	Weight (kg)	Final load (kN)	Fcu (N/mm^2)	Average Fcu (N/mm^2)	Slump value
1	7	5.30	246.6	7.07		50 mm
2	7	5.51	258.2	7.43	7.40	
3	7	5.37	268.4	7.71		
4	14	6.18	347.1	9.98		
5	14	6.27	342.0	9.84	10.07	50 mm
6	14	5.96	360.8	10.38		
7	21	6.66	479.1	14.4		
8	21	6.47	521.0	15.0	14.3	50 mm
9	21	6.71	469.05	13.5		
10	28	6.80	596.4	17.15		
11	28	7.08	588.6	16.92	17.34	50 mm
12	28	6.81	625.65	17.99		

Table 9: Compressive strength Test for Cement-Sand interlocks at a ratio of 2:1

S/N	Days	Weight (kg)	Final load (kN)	Fcu (N/mm^2)	Average Fcu (N/mm^2)	Slump value
1	7	5.51	270.8	7.79		80 mm
2	7	5.57	273.6	7.88	7.70	
3	7	5.13	257.9	7.41		
4	14	5,52	486.0	13.98		
5	14	5.43	469.1	13.49	13.77	80 mm
6	14	5.71	481.6	13.86		
7	21	6.56	560.1	15.71		
8	21	6.63	597.5	17.18	17.19	80 mm
9	21	7.22	636.2	18.30		
10	28	6.62	728.8	20.96		
11	28	6.69	753.3	21.66	21.06	80 mm
12	28	7.98	714.5	20.55		

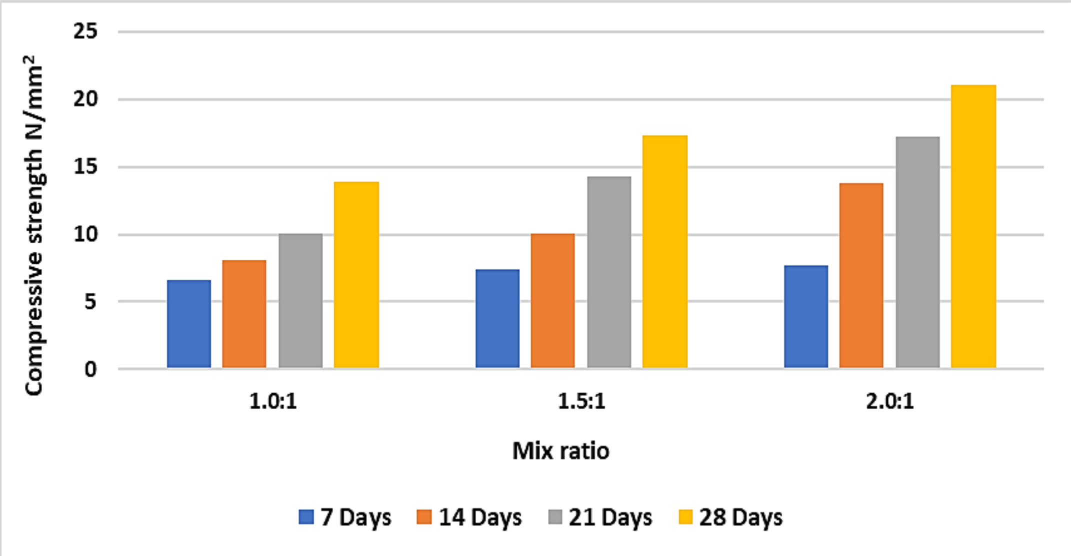

Figure 5: Compressive Strength Test for Cement-Sand interlock

4.5 Compressive strength test of PET-sand interlock

The compressive strength test of a PET-sand interlock is a critical evaluation of its structural integrity and load-bearing capacity. The compressive strength test results are shown in Tables 10, 11, and 12 for 1:1, 1.5:1, and 2:1, respectively. From the results in Table 10, the PET-sand interlock produced had a compressive strength of 6.38 N/mm^2 at 7 days, 14 days, 21 days, and 28 days of curing. At a mix ratio of 1.5:1 (Table 11), the compressive strength of PET-sand interlocking blocks was 9.18 N/mm^2 at 7 days, 14 days, 21 days, and 28 days of curing. At a mix ratio of 2:1, the compressive strength of PET-sand interlocking blocks was 9.58 N/mm^2 at 7 days, 14 days, 21 days, and 28 days, all through the curing period. This shows that the compressive strength of the PET-sand mix increases with and remains unchanged from days 7 to 28 of the curing period and cannot bear heavy loads. These results are better illustrated in charts, as shown in Figure 6, which shows the average compressive strength of the mix ratios.

Table 10: Compressive strength Test for PET-Sand interlock at ratio 1:1

S/N	Days	Weight (kg)	Final load (kN)	Fcu (N/mm^2)	Average Fcu (N/mm^2)
1	7	6.03	216.3	6.23	
2	7	5.68	231.0	6.65	6.38
3	7	5.40	217.75	6.28	
4	14	6.03	216.3	6.23	
5	14	5.68	231.0	6.65	6.38
6	14	5.40	217.75	6.28	
7	21	6.03	216.3	6.23	
8	21	5.68	231.0	6.65	6.38
9	21	5.40	217.75	6.28	
10	28	6.03	216.3	6.23	
11	28	5.68	231.0	6.65	6.38
12	28	5.40	217.75	6.28	

Table 11: Compressive strength Test for PET-Sand interlock at ratio 1.5:1

S/N	Days	Weight (kg)	Final load (kN)	Fcu (N/mm^2)	Average Fcu (N/mm^2)
1	7	5.78	319.3	9.18	
2	7	5.25	325.3	9.35	9.18
3	7	5.68	313.0	9.0	
4	14	5.78	319.3	9.18	
5	14	5.25	325.3	9.35	9.18
6	14	5.68	313.0	9.0	
7	21	5.78	319.3	9.18	
8	21	5.25	325.3	9.35	9.18
9	21	5.68	313.0	9.0	
10	28	5.78	319.3	9.18	
11	28	5.25	325.3	9.35	9.18
12	28	5.68	313.0	9.0	

Table 12: Compressive strength Test for Cement-Sand interlock at ratio 2:1

S/N	Days	Weight (kg)	Final load (kN)	Fcu (N/mm^2)	Average Fcu (N/mm^2)
1	7	5.95	335.5	9.65	9.58
2	7	6.03	324.0	9.34	
3	7	5.25	339.3	9.75	
4	14	5.95	335.5	9.65	9.58
5	14	6.03	324.0	9.34	
6	14	5.25	339.3	9.75	
7	21	5.95	335.5	9.65	9.58
8	21	6.03	324.0	9.34	
9	21	5.25	339.3	9.75	
10	28	5.95	335.5	9.65	9.58
11	28	6.03	324.0	9.34	
12	28	5.25	339.3	9.75	

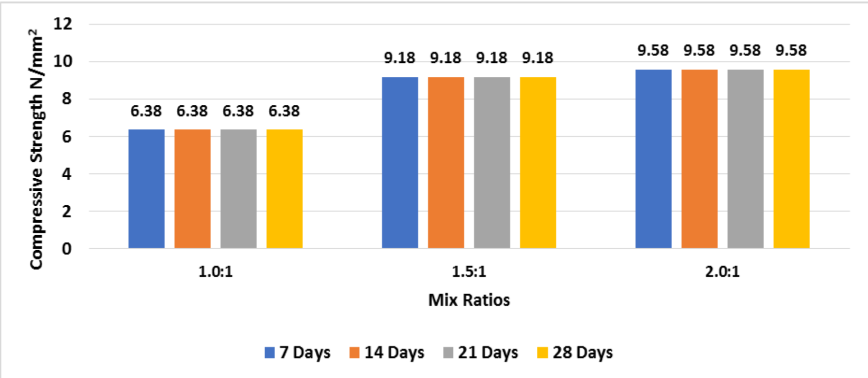

Figure 6: Compressive Strength Test for PET-Sand interlock

The findings demonstrated that PET-sand interlocking blocks' compressive strength was lower than that of cement-sand interlocking blocks. The PET-sand interlocking blocks' strength can be used for decorative and low-load-bearing applications, such as walkways.etc..

5. Conclusion

Regarding workability for interlocking pavement production, the slump test results underscore the suitability of different cement-sand mix ratios. The 1:1 mix ratio exhibited a moderate 70 mm slump, ideal for efficiently interlocking patterns. The 1.5:1 mix, with a 50 mm slump, offers enhanced durability and is suitable for areas subjected to heavier loads. Conversely, the 2:1 mix, with an 80 mm slump, provides exceptional workability, making it perfect for easily crafting intricate interlocking patterns. PET interlock has a lower water sorptivity value than cement interlock.

The water absorption test results indicate that as the mix ratio shifted towards a higher cement content, the sorptivity of the interlocking blocks increased. However, when PET was added to the mix, there was a noticeable reduction in water sorptivity, with PET-sand interlocking blocks consistently displaying lower sorptivity values than their cement-sand counterparts. This reduction in water sorptivity can be attributed to PET powder's smaller particle size than cement, resulting in fewer pores in the concrete.

The compressive strength test results revealed significant differences between the cement and PET-sand interlocking blocks. The cement-sand blocks exhibited notably higher compressive strengths across all mix ratios (1:1, 1.5:1, and 2:1) and curing durations (7 days, 14 days, 21 days, and 28 days). The highest compressive strength achieved by cement-sand blocks was 21.06 N/mm², whereas PET-sand blocks only reached a maximum of 9.58 N/mm². In the cement-sand mixture, the highest compressive strength was noticed after 28 days of curing in every mix ratio. PET-sand interlocking blocks gave a lower compressive strength than cement-sand interlocking blocks.

The result showed that PET-sand interlocking blocks' compressive strength was lower than cement-sand interlocking blocks' compressive strength. The strength achieved in the PET-sand interlocking blocks can be utilized for low load-bearing areas, like walkways and aesthetics. Further studies should be done on increasing the compressive strength of the PET mix to use it on heavy-traffic roads.

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Author contributions

Conceptualization, O. Adepitan.; formal analysis, O. Adepitan and A. Fasina. ; All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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