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Cement concrete containing polyethylene terephthalate and steel slag powder for pavement application

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Abstract:
The solid waste produced by industrial and technological advancements in the environment and construction is increasing. A large amount of industrial waste is not properly disposed of in Nigeria, which causes inconvenience to the environment and society. Utilising such waste for sustainable construction is one of the easiest and least expensive methods of eliminating and protecting the environment. This study investigated the properties of concrete pavement incorporating steel slag powder (SSp) and PET powder (PETp). The cement was partially replaced with SSp and PETp at varying proportions, and the mechanical properties (compressive strength, flexural strength, and split tensile strength) and durability properties (resistance to acid attack and water absorption) were evaluated for the concrete pavement. The results obtained indicate that the addition of SSp improved the strength characteristics of the concrete pavement, whereas the incorporation of PETp enhanced the durability performance. The findings suggest that the use of SSp and PETp in concrete pavements is a promising approach to achieving both mechanical strength and durability requirements because PETp replaces the water lost and prevents cracks from forming in concrete samples. Furthermore, to achieve best performance of the concrete pavement, the study recommends 10 % SSp and 15 % PETp as the ideal combination.

Keywords:
plastic waste; steel slag; concrete; sustainability; PET

1 Introduction

Transport engineering includes the planning, construction, building, operating, and maintenance of roads, trains, tunnels, and bridges to ensure that people and goods are transported safely and conveniently [1]. Two types of pavements are primarily utilised to fulfil this purpose: rigid (concrete) and flexible pavements. However, concrete pavements are most commonly used on heavily trafficked roads because of their longevity, high stiffness, stress-carrying capacity, better deformation resistance, good light-reflection qualities, and low absorption of solar radiation [2-4]. Furthermore, if properly built, concrete pavements can withstand external loads and persist for long periods.

Cement is an essential ingredient in concrete and plays a crucial role as a binder, resulting in the development of a solid substance that can withstand loads [5]. However, cement production results in the release of CO_2, a greenhouse gas responsible for climate change, which affects the ability of the global population to live healthy lifestyles [6-8]. According to estimates, cement is the second-largest industrial generator of CO_2 on Earth [9] and is responsible for the annual emission of 4 billion metric tons of CO_2 into the environment [10]. Between 2015 and 2021, the direct CO_2 concentration in cement manufacturing increased by about 1,5 % per year [11-12]. Hence, for net zero discharge to be achieved by the year 2050, a yearly decrease of 3 % is required until 2030. Furthermore, water quality has been declining over time owing to the release of effluents into water bodies caused by cement production [13]. In addition to the adverse effects of cement on the environment, other limitations such as high energy consumption and excessive usage of naturally occurring, non-renewable raw resources have sparked severe doubts about the sustainability of cement [14-15]. Partial or complete cement replacement with eco-friendly materials is required to address this issue and promote sustainable development. Waste materials have been recognised as potential new resources in a circular economy, where they are integrated into the construction cycle rather than being discarded as byproducts.

The national waste creation rate in Nigeria is alarming and rising, with current statistics ranging from 0,4-0,8 t per capita per year and an expected yearly rate of approximately 0,5-0,7 % [16]; only 20-30 % of Nigeria's annual production of over 32 million tonnes of solid waste is collected and treated [17]. Waste generation is becoming increasingly complex, and over half of it is biodegradable. This means the nation has less than 10 % of its capacity to handle waste, resulting in an estimated average of nearly 50 million tonnes of non-recycled garbage [16]. Today, unlike in other industrialised nations, waste management is one of Nigeria's most significant challenges [18]. Studies have shown that poor waste management negatively impacts numerous ecosystems and species, contributing to environmental pollution and climate change [19]. Landfilling is the principal method of garbage disposal [20]. However, with the increased rate of waste generation in Nigeria and its effect on the environment, recycling has become the next option, resulting in the release of gases into the atmosphere [21]. Hence, it is of paramount importance that waste such as polyethylene terephthalate (PET) bottles and steel slag be recycled into supplementary cementitious materials (SCMs) for construction purposes. According to [22], the utilisation of these materials as SCMs offers two obvious benefits: the first is the utilisation of waste that must be managed in a landfill, and the second, even more significant, is the reduction in cement usage, necessitating a reduction in CO2 emissions required for its manufacturing.

The findings of this study will further broaden the applicability of these SCMs in construction to promote eco-friendly concrete. Furthermore, research on the use of PET powder as a SCM and the combined effects of PET and steel slag powders on the performance of concrete pavements is insufficient. Therefore, this study evaluated the effects of steel slag and PET powder on concrete pavement properties.

2 Methodology

2.1 Materials and methods

The following materials were used in this study:

- Aggregate: River sand obtained from Omu-aran was used as the fine aggregate. In addition, coarse aggregate with particle sizes larger than 4,75 and of granite origin was used.
- Cement: Grade 42,5 Portland cement (PLC) obtained from Omu-aran local market was used in this study.
- PET powder: Waste PET bottles were collected from the Landmark University Water Factory. The tags were detached. The bottles were washed and air-dried to allow easy melting during pyrolysis. The melted PET bottles were pulverised and sieved in the Geotechnics Laboratory at Landmark University. The particle size distribution according to ASTM, C 117 [23] and the chemical composition of PETp are shown in Figure 1 and Table 1, respectively.
- Steel Slag: The electric arc furnace (EAF)-type steel slag obtained from Prism Steel Mills Ltd., Ikirun, Nigeria was used in this study. The EAF slag was crushed into a fine powder and sieved.
- Water: Potable water from Landmark University was used in the cement concrete mixture and experimental procedures.

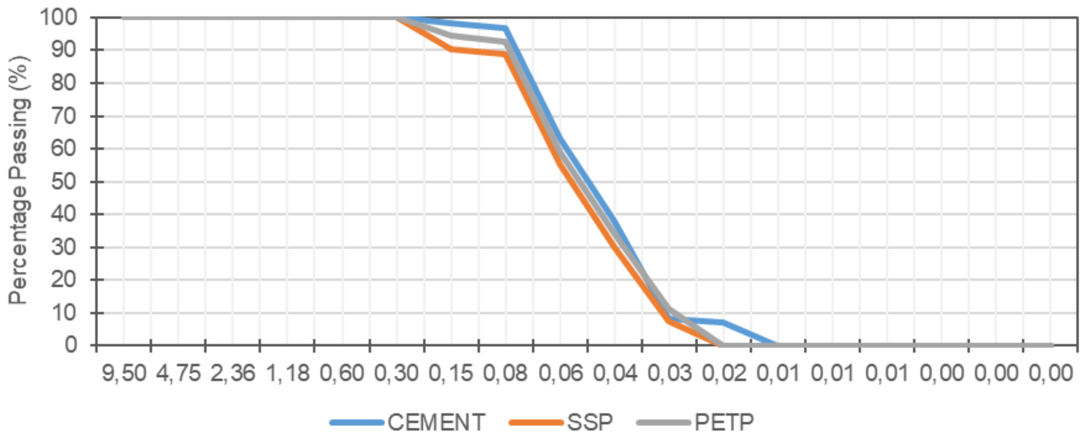


Figure 1. Sieve Analysis Graph of Cement, SSp, and PETp

Table 1. Chemical Composition of the Binders

Elements	PLC (%)	SSp (%)	PETp (%)
CaO	57,80	45,58	33,31
SiO_2	20,11	15,11	12,00
Al_2O_3	10,25	9,65	12,00
Fe_2O_3	2,53	7,27	6,12
MnO	0,00	14,14	0,80
MgO	4,50	3,28	0,00
TiO_2	0,00	2,07	8,61
K_2O	0,32	0,49	0,12
SO_3	2,57	0,21	8,31
SrO	0,00	0,22	0,00
Cl	0,00	0,99	5,33
Specific Gravity	3,09	0,87	1,70

2.2 Mix design and sample preparation

Suitable mixing sequence and duration are required to obtain high-quality samples. A typical rotating drum-type mixer with a volume of 8 m^3 was used to prepare the mixes. Initially, the mix percentages in Table 2 were used to combine fine aggregate, coarse aggregate (surface-dried), and cementitious materials for about 90 s to obtain a uniform mix under dry conditions. The mixture was manually blended by revolving it two or three times with a steel trowel to prevent the dry components from becoming stuck at the bottom of the mixer. The mixture was mechanically mixed for an additional 2 min to complete the mixing procedure. A suitable mould was filled with the freshly prepared mixtures. After casting, each specimen was covered with a slim plastic sheet, kept in the laboratory for 24 h, and cured in a water tank for 28 days before testing.

Table 2. Mix design

Mix	SSp (%)	PETp (%)	PLC (kg/m^3)	SSp (kg/m^3)	PETp (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)
1	0	0	750,0	0	0,0	990	660	225
2	10	0	675,0	75	0,0	990	660	225
3	10	5	637,5	75	37,5	990	660	225
4	10	10	600,0	75	75,0	990	660	225
5	10	15	562,5	75	112,5	990	660	225
6	10	20	525,0	75	150,0	990	660	225

Where PLC denotes Portland Cement; PETp PET powder; SSp Steel Slag powder; FA Fine Aggregate; CA Coarse Aggregate.

2.3 Laboratory investigation

Workability was assessed using a slump cone with a bottom diameter of 200 mm, top diameter of 100 mm, and height of 300 mm. The tests were conducted in according to [24]. Concrete was added in three layers, each receiving roughly 25 blows with a tampering rod, which was created from steel and measured 600 mm long and 16 mm in diameter. With a hand trowel, the additional concrete was removed after the third layer was filled. The mould was immediately and progressively lifted vertically. The mould height and the highest point of the test specimen were separated using the slump, which was expressed in cm.
The procedure in [25] was used to conduct the compressive strength tests. The strengths of the 100 mm cube specimens were evaluated using a control compression machine with a load capacity of 1500 kN. The test findings were presented as the average of three measurements.
At 28 days after curing, a three-point flexural strength test was conducted according to [26]. A black felt-tip marker was used. A centreline was drawn at the top of each of the 24 (400 × 100 × 100) beam specimens perpendicular to its length. The test subjects were supported over a 160 mm span as they were subjected to a central line load. A universal test device with a load capacity of 50 kN and displacement rate of 0,10 mm/min was employed for this test.
A split tensile strengths test was conducted according to [24]. The strengths of cylindrical specimens measuring 100 × 200 mm were assessed using a Denison compression machine with a load capacity of 3000 kN. The average of the three measurements was used to calculate the test results.
Water absorption tests were performed according to [27]. Each specimen sample was weighed after 28 days of curing to obtain its saturated weight (W_1), and then the samples were completely dried in an oven. Subsequently, they were removed and re-weighed to obtain their dry weights (W_2). This procedure was repeated for the other samples and the water absorption capacity was computed using the following formula:

$$Water\ Absorption\ (\%) = \frac{W_1 - W_2}{W_2} \cdot 100 \tag{1}$$

Chemical resistance was assessed by immersing the specimens in a solution of concentrated sulphuric acid according to [28]. Six 50 × 50 mm cubes were obtained from the water tank after 28 days of curing, and each specimen was labelled and wrapped with a nylon cord. After recording the initial weight, each specimen was immersed in a 3 % solution of sulphuric acid. The solution was supplemented every four weeks during the evaluation period to ensure a steady acid. Before weighing, the samples were removed from the solution and washed with a soft nylon brush. The samples were weighed in the fourth week, after which subsequent measurements were taken weekly. The cumulative mass loss of each specimen was calculated as a percentage using Eq. 2:

$$\text{cumulative mass loss} = \frac{M_t - M_{int}}{M_{int}} \cdot 100 \tag{2}$$

Where M_t denotes the mass at time t; M_{int} the initial mass before immersion in sulphuric acid.

3 Results and Discussion

3.1 Effect of PETp and SSp on concrete pavement workability

The workability of the concrete mixtures with various concentrations of PETp and SSp was evaluated using a slump test. The results are shown in Figure 2.

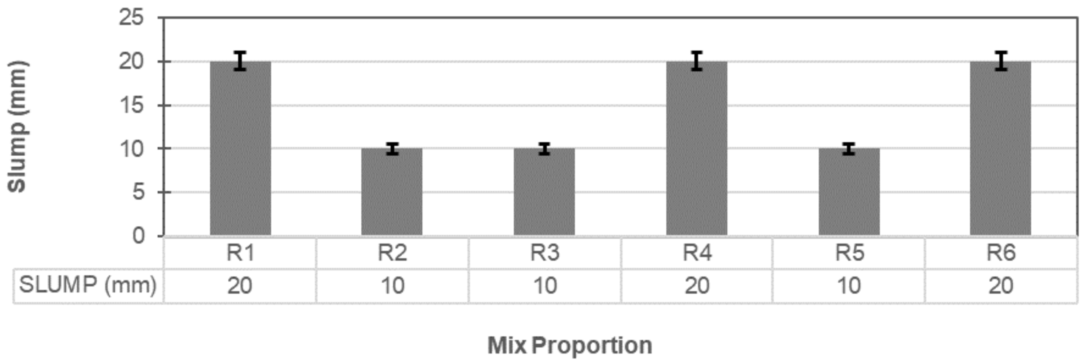


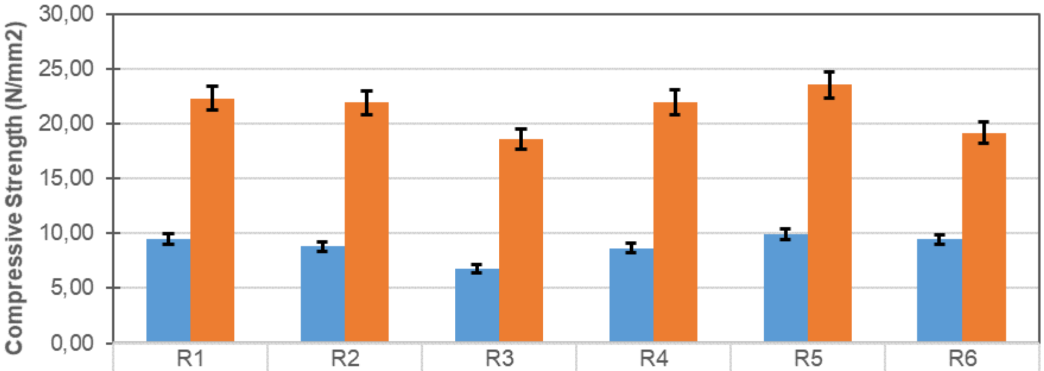
Figure 2. Slump properties of SSp and PETp-modified concrete

R1, which included neither PETp nor SSp, had a greater slump value of 20 mm as compared with R2, which had 10 % SSp and 0 % PETp at 10 mm. When SSp was added to the mixture, the slump decreased. This suggested that the workability of the concrete was diminished. The slump value indicated that the mix was stiffer or less fluid. According to [29], a decrease in the workability of concrete was caused by an increase in the amount of SSp. The hydrophobic properties of the SSp may have contributed to its decreased workability. The addition of 10 % PETp (run number 4) resulted in an increase in slump, which was 100 % greater than run number 2, as well as run number 3, which produced the same slump with 5 % PETp and 10 % SSp. SSp has a densifying action that reduces the quantity of water required to obtain the desired workability, thereby lowering the slump. In contrast, PETp functioned as a water-reducing agent, reducing the surface tension of the cement paste and increasing the fluidity of the mixture. This resulted in a more workable mix and an increased slump value. Although the addition of PETp can potentially counteract the densification effect of SSp, the addition of 15 % PETp and 10 % SSp, as observed in run number 5, can reduce the slump value. In run number 6, 10 % SSp and 20 % PETp resulted in an increase.

3.2 Effect of PETp and SSp on concrete pavement compressive strength

Investigating the compressive strength of the concrete samples provides insights into the resistance of concrete to external forces. Figure 3 shows the performance of the concrete

when subjected to a load until it failed. R5 with 10 % SSp and 15 % PETp exhibited the highest compressive strength after 7 days of curing, measuring 9,94 N/mm^2. Comparing this strength of the control, which had a strength of 9,47 N/mm^2, a 4,96 % increase was observed. Moreover, the strength of SSp reduced at a rate of 7,61 % lower than the control. It further decreased to 6,77 N/mm^2 with the addition of 5% PETp. An increase was observed when 10 % SSp and 10 % PETp were added to R4, yet a reduction occurred as the PETp reached 20 %. Similarly, compared with the control, R5 had the highest compressive strength at a rate of 5,37 % after 28 days of curing. Furthermore, there was a decrease in the strength with 20 % PETp addition. The results of Awolusi et al. [6] and Shi et al. [30] also revealed variations in the compressive strength with the addition of these materials.
Because PETp impedes the penetration of water into the concrete and prevents cracks from forming in concrete samples, SSp at 10 % and PETp at 15 % are the ideal combinations that should be used for achieving a high compressive strength. Previous studies have also revealed that binary binders always exhibit superior strength [31].

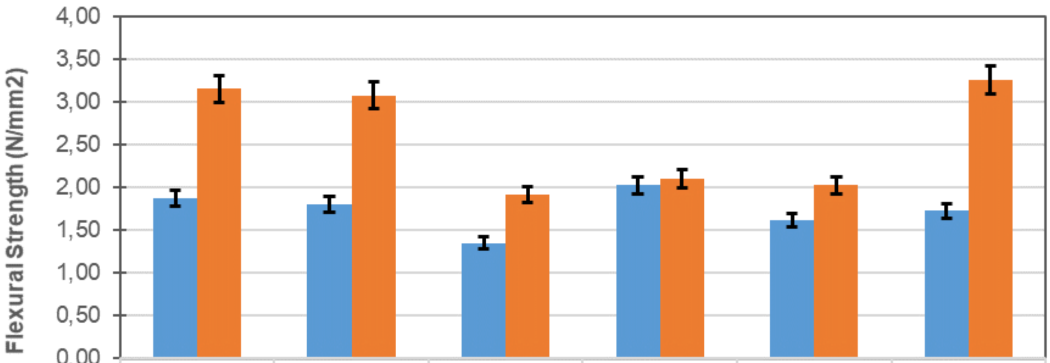


	R1	R2	R3	R4	R5	R6
7-Day	9,47	8,80	6,77	8,64	9,94	9,45
28-Day	22,34	21,93	18,58	21,97	23,54	19,17

Figure 3. Effects of PETp and SSp on the concrete compressive strength

3.3 Effect of PETp and SSp on concrete pavement flexural strength

The results of the flexural strength tests are shown in Figure 4. On day 7, R4 had the highest strength, followed by the control. The addition of 10 % SSp reduced the strength by 4,26 % to 1,80 N/mm^2, and it also reduced at 10 % SS and 5 % PETp by 25 % to 1,35 N/mm^2. An increase of 12,78 % was observed in R4, which was recorded the highest strength. A 20,69 % decrease was observed in R5, followed by a 7,4 5% increase in R6.



	R1	R2	R3	R4	R5	R6
7-day	1,88	1,80	1,35	2,03	1,61	1,73
28-day	3,15	3,08	1,91	2,10	2,03	3,26

Figure 4. Effects of PETp and SSp on the concrete flexural strength test

3.4 Effect of PETp and SSp on concrete pavement split tensile strength

Figure 5 shows the results of a split tensile strength test conducted on concrete specimens with varying percentages of SSp and PETp. The test was intended to assess the effects of these materials on the split tensile strength of concrete at 7 and 28 days.

In R1, where no SSp or PETp was added, the split tensile strength at 7 days was 1,38 N/mm^2, which slightly increased to 1,43 N/mm^2 at 28 days. In R2, with 10 % SSp and 0 % PETp, the split tensile strength significantly increased by 93,47 % to 2,67 N/mm2 at 7 days and increased slightly to 3,37 N/mm^2 at 28 days. In R3, with 10 % SSp and 5 % PETp, the split tensile strength decreased to 2,29 N/mm^2 at 7 days and slightly increased to 2,70 N/mm^2 at 28 days. Based on the provided data, the combination of SSp and PETp in the concrete mixture had varying effects on the split tensile strength. A recent study reported variations in the split tensile strength of concrete pavements containing pozzolans [31]. However, the inclusion of 10 % SSp without PETp (R2) resulted in a peak split tensile strength at both 7 days and R3 for 28 days.

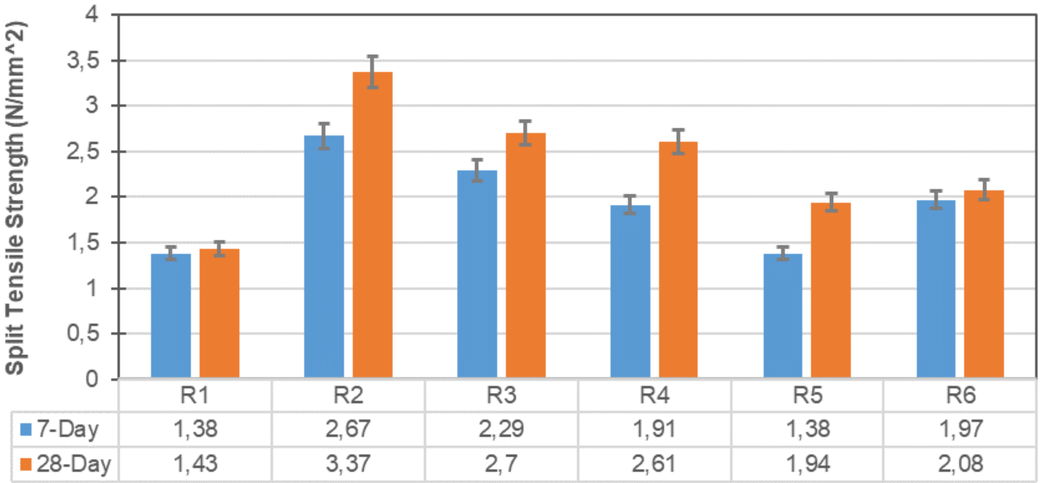


Figure 5. Effect of SSp and PETp on Concrete Split Tensile Test

3.5 Effect of PETp and SSp on concrete pavement water absorption capacity

Water absorption results were obtained after 28 days of curing, as shown in Figure 6. Lower water absorption values are generally desirable, indicating denser and more impervious concrete. R5 had the highest percentage of 7,63 %, whereas R2 had the lowest absorption rate of about 6,43 %. The overall range of water absorption values suggested that the concrete specimens can absorb moderate amounts of water according to IS 3495.

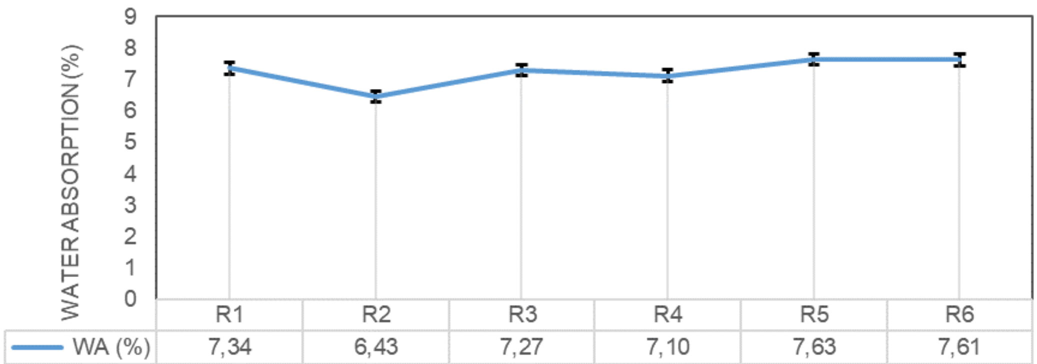
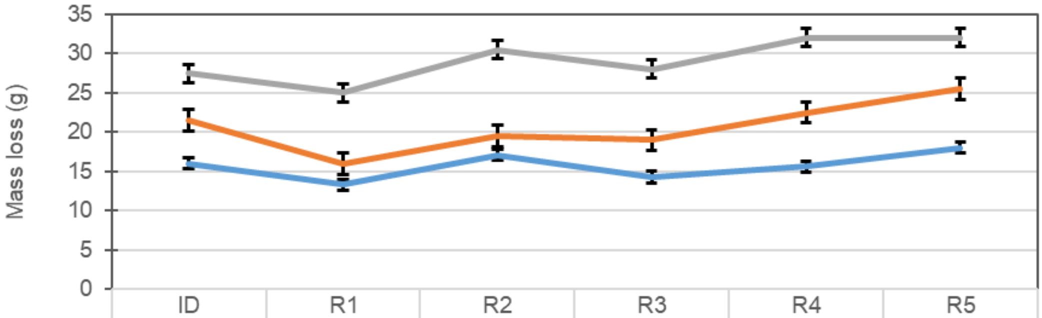


Figure 6. Water Absorption Test on Concrete Pavement

3.6 Effect of PETp and SSp on concrete pavement acid attack resistance

Figure 7 shows the chemical resistance values for various runs. Many samples experienced a gain, rather than a loss, in mass weekly. This was likely because the samples absorbed the liquid from the dilute acid rather than being dissolved. According to [32], when samples containing different percentages of PETp particles are exposed to a 5 % sulfuric acid solution, there are noticeable reductions in weight changes owing to the strongly acidic nature of sulfuric acid. Sulfuric acid is a highly corrosive substance that catalyses the hydrolysis of ester linkages in polyethene chains. This hydrolysis breaks down the polymer chains into smaller fragments. Higher percentages of PET particles in the samples resulted in smaller weight changes. Hence, it is safe to conclude that the increase observed in all weeks for R4–R6 was due to the presence of SSp.



	ID	R1	R2	R3	R4	R5
M4	16	13,3	17,1	14,3	15,6	18
M5	21,5	16	19,5	19	22,5	25,5
M6	27,5	25	30,5	28	32	32

Figure 7. Acid attack resistance test

4 Conclusions

Industrial and technological advancements in buildings and environment are producing increasing amounts of solid waste. Nigeria improperly disposes tonnes of industrial waste, which is inconvenient for the environment and society. One of the simplest and least expensive methods to remove this waste and protect the environment is to use it in sustainable construction. This study examined the characteristics of concrete pavements containing PETp and SSp. Based on these findings, the following conclusions were drawn:

- The densification effect of SSp results in less water being used to produce the necessary workability, which lowers the slump. In contrast, PETp functions as a water-reducing agent, reducing the surface tension of the cement paste and increasing the fluidity of the mixture.
- The maximum reduction in the compressive strength was observed when the cement was partially replaced with PETp. However, the concrete then experienced its maximum strength when the concrete mix is supplemented with 10 % SSp and 15 % PETp.
- Owing to the hydrophobic nature of SSp, 10 % SSp and 0 % PETp are recommended because they have the lowest water absorption.
- As the inclusion of SSp and PETp increases, and during the acid exposure period, the concrete experienced weight loss, which causes a decrease in its acid resistance.
- The use of SSp and PETp as partial substitutes for cement in concrete pavements offers a viable and environmentally friendly solution. The combination of their unique properties results in concrete pavements that are not only durable and strong but also contribute to reducing waste and carbon emissions.

Further tests should be conducted to assess the possibility of shrinkage and cracking in concrete pavements owing to the addition of PETp and SSp. In addition, the effects of other polymer types on the concrete pavement performance should be investigated.

Acknowledgments

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