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Comparative Study of Cement Replacement with Waste Plastic in Interlocking Paving Stone for Highway Construction in Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Portland cement remains the major binder used in the construction of concrete pavements, interlocking stones, and many other aspects of construction, and this implies a high dependence on the commodity thus making it scares and expensive and hence the need to explore other alternatives. This research compares the use of waste plastics and Portland cement for the production of paving stones. In this study, three cases were considered, each case having a study sample and a control sample. Case 1, case 2, and case 3 had mix ratios of (in order of, binder to sand to granite) 1:1:1, 1:1:1.5, and 1:1.5:2.5 respectively, of which the controls were made using Portland cement as the binder and the samples were made with waste plastic as the binder. The

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comparison was done using compressive strength and water absorption resistance values of the controls and the sample. The results showed that paving stones made from Portland cement have better compressive strength in all cases compared to the samples, the highest compressive strength obtained from the controls was 45N/mm^2 while that of the sample was 25N/mm^2, however, the study sample showed the highest water absorption resistance percentage of 5%, when compared to the control samples which had as low as 0.8%. This infers that paving stones made from melted waste plastics may not be as strong as those made from Portland cement can be used for roads expected to carry lighter traffic, and are also very suitable for areas of high water table or areas prone to flooding. The samples in this research were made locally and were limited to the three mix ratios mentioned. Further research can be done using a mechanized method to produce the samples, also partial replacement of cement with waste plastic may hence the strength of the paving stone.

Keywords: Paving stone; waste plastic; cement; compressive strength; percentage of water absorption resistance.

1. INTRODUCTION

Road project finance poses a herculean task in city development, mostly in developing countries and must be tackled if meaningful development must take place. The agitation for construction projects always exceeds the financial resources available [1]. Road construction generally, is expensive, from the machinery to labour requirements to the material requirements, an alternative to the regular construction materials that are relatively cheaper and readily available will have a positive impact on the construction financing.

Portland cement is the major concrete or mortar bonder used for road construction and is quite expensive. In Nigeria, only a few local manufacturers for construction materials exist, and hence experience little or no competition and consequently have the monopoly of the market [2]. It is therefore imperative to begin to source various alternatives to construction materials that are readily available at a reduced cost in the country, and will also give a good result. Researches revealed the possible use of Fly ash, Silica Fume, Metakaolin, and Ground granulated blast furnace slag as a replacement for Portland cement, since they possess good binding properties for the production of concrete elements used for construction [3].

Waste plastic which is in abundance in Nigeria, when melted can bind fine and coarse aggregates together and thereafter solidify. A Research discussed the use of plastic waste as a constituent of construction material; the use of plastic waste as a binder, aggregate, fine aggregate, modifier, or replacement for cement and sand in the production of bricks, tiles, concrete, and roadways was investigated in their work [4]. The amount of plastic in the environment has raised concerns on a global scale recently. More and more plastic and things made of plastic are being consumed and discarded as the world's population approaches eight billion [4]. Only in 2020 was it anticipated that 367 million tonnes (367 billion kg) of plastic were created, or roughly 12 tonnes (12,000 kg) of plastic waste every second [4]. Nigeria is the ninth-highest contributor to plastic pollution globally, producing around 2.5 million tonnes of plastic garbage each year. Sadly, less than 8% of the plastic garbage produced in Nigeria is recycled [4].

Instead, a large portion of it finds its way into lakes, rivers, drains, lagoons, and the ocean. Macro-plastic waste (items greater than 25 mm in diameter) and nano-plastic waste are both types of waste (less than 1,000 nm) [4]. It comes in a variety of shapes, including polystyrene, polyvinyl chloride, and polyethylene terephthalate, which are all used in the packaging of food, beverages, and personal care goods (used for food packaging, laboratory materials, toys, and computer housing) [4]. Studies conducted all across the world have shown the damaging effects plastic trash has on the ecosystem. Both the environment and the building sector would benefit from the reuse of waste plastic in construction [5].

This study compares the use of Portland cement to waste plastic as the binder for the production of road paving stones, in the bid to find a cheaper alternative to Portland cement used for the production of road paving stones. Interlocking paving stones are being more frequently used in Nigeria, especially in Lagos, as it is more durable in the face of flooding, this study will attempt to check the water absorption ability of the two interlocking paving stones being compared. Interlocking paving stones with interlocking configurations (particularly permeable interlocking paving stones) enable both surface and subsurface drainage of seepage of underground water without sacrificing strength or longevity, making them ideal for locations with a high-water table [6]. The comparison done in this study is done using two parameters; the compressive strength of the interlocking paving stone, which depicts the strength of the paving stone, and the water absorption resistance, which depicts its durability [7,8].

2. METHODOLOGY

For this research, three cases were considered, case 1, case 2, and case 3. For each case a control paving stone made of Portland cement and the study sample made from melted waste plastics were produced, using the same mix design.

2.1 Flow Chat

See Fig. 1 below.

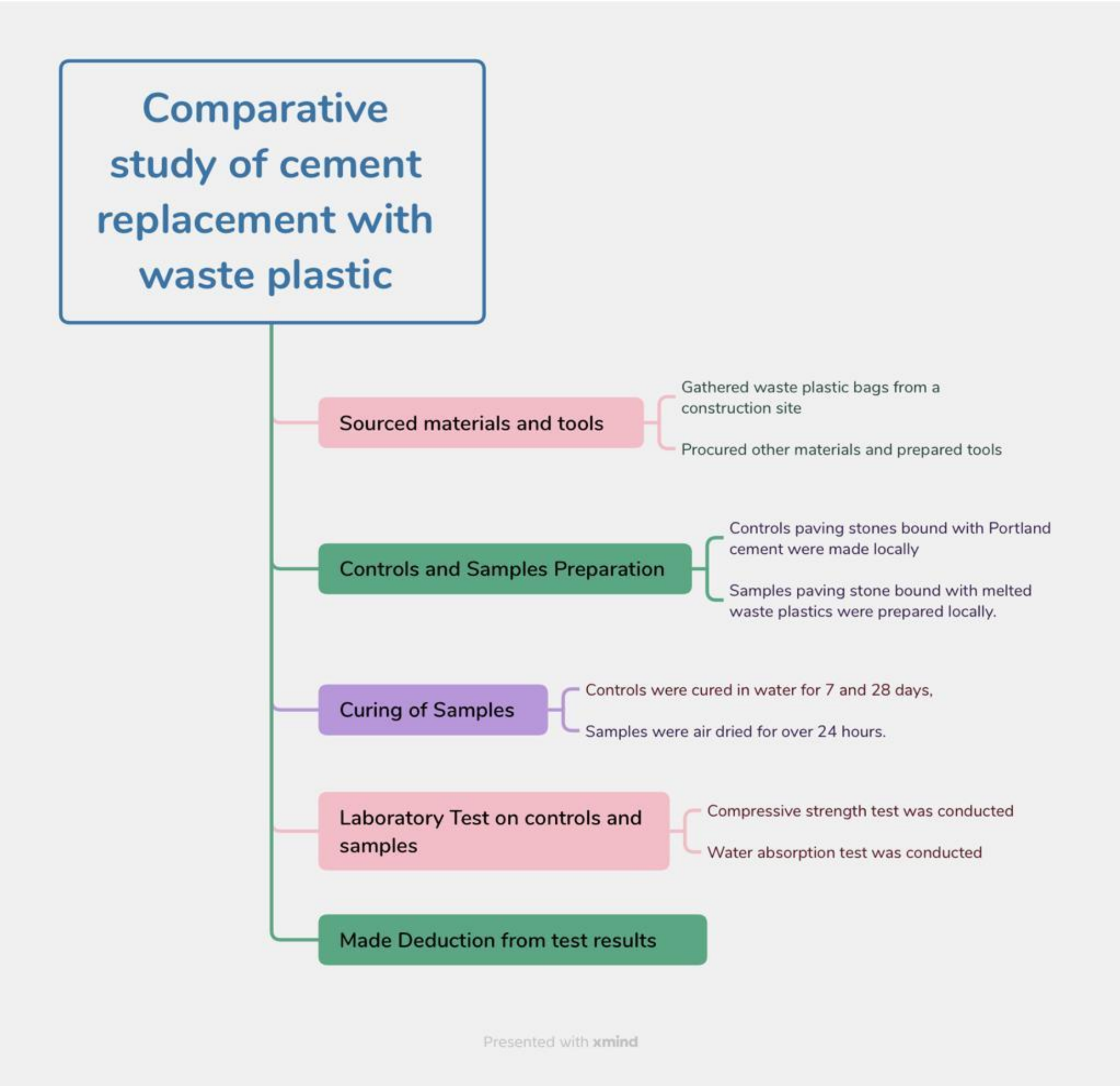

Fig. 1. Research methodological flow chat

2.2 Tools and Material Used

The tools used for making the paving stones include; Head pans, Shovel, Trowel, Plastic mould (200mm x 100mm x 80mm), Steel moulds (200mm x 100mm x 80mm), heating setup, Steel drum, Oil, Tamping rod, Digital weighing scale, Personal protective equipment.

The Materials include; Sand, Granite, Cement, Waste plastic (empty cement bags), and Potable water.

2.3 Major Physico-Chemical Properties of the Materials Used Mostly the Cement and Plastic Waste

Chart 1. PHYSICO-chemical properties of the materials

S.no	Cement	Low-density polyethylene (waste plastic)
1	Hydrates when water is added to it.	Very low water absorption
2	○ Soundness; retains its volume after setting without delayed expansion.	Excellent electrical insulating properties
3	Density of 1.44 g/cm3.	Density of LDPE: 0.910–0.940 g/cm3
4	Cement sets and hardens when water is added *Initial set:* When the paste begins to stiffen noticeably (typically occurs within 30-45 minutes).	It has significant chemical resistance.
5	*Final set:* When the cement hardens, being able to sustain some load (occurs below 10 hours).	LDPE is susceptible to stress-cracking beyond a point.
6	○ Portland cement has a specific gravity of 3.15.	LDPE Melting point: 105 to 115°C
7	Cement has high compressive strength. Thus, it provides stability and durability to the structure.	High impact strength at low temperature, good weather ability
8	It is a composistion of Lime, Alumina, Sulfur Trioxide, Iron oxide, Silica Alkaline, Magnesia.	It is made from the polymerization of ethylene (or ethene) monomer. Polyethylene chemical formula is $(C_2H_4)_n$

2.4 Mix Design

Nominal mix designs were adopted, for three cases that were considered for this research, case 1, case 2, and case 3, having mix ratios 1:1:1, 1:1:1.5, 1:1.5:2.5 respectively for the controls and the experimental sample, see Table 1. For the control, the water-cement ratio was about 35% to 40% [9].

Table 1. Controls and samples mix ratio

S/No.	Cases	Cement-bound paving stone	Waste plastic bound paving stone	Mix ratio
1	Case 1	Control 1	Sample 1	1:1:1
2	Case 2	Control 2	Sample 2	1:1:1.5
3	Case 3	Control 3	Sample 3	1:1.5:2.5

2.5 Batching

Batching by weight was adopted for the preparation of the paving stones in this study, using a digital scale, and each constituent material was measured, that is; the sand, granite, cement, and waste plastic to the required quantity.

2.6 Procedure

2.6.1 Preparation of the control mix

Firstly, the plastic moulds were oiled to allow for easy removal of the interlocking paving stones after it has been cast. Thereafter the constituent materials; cement, sand, and granite (see Plate 1.) were measured using a digital weighing scale, and then poured into a mixing drum and mixed thoroughly using a shovel. Then the mixture was introduced to the plastic moulds in two layers, compacting each layer with 25 blows using the tamping rod. The surface was then leveled and smoothened using a trowel. The interlocking paving stone was demoulded after 24 hours and cured. Controls: 1, 2, and 3 were prepared using this method. See Plate 2.

Plate 1. Constituent materials: from left to right: Portland cement, Sand, Granite

Plate 2. Control sample 2, (cement-bound paving stone)

2.6.2 Preparation of the sample mix

After the steel moulds were oiled, the constituent materials; waste plastics bags (the plastics used for this research are low-density polyethylene), sand, and granite (see Plate 3), were weighed using a digital scale. Thereafter a heating set-up was made, and a steel drum was placed on the setup to heat up. Then the waste plastic bags were placed into the drum to melt, after which the sand and granite were introduced and mixed thoroughly till a molten paste was formed. The molten paste was put into the steel moulds in two layers and compacted using a tamping rod with 25 blows for each layer, to remove the voids, then it was compacted using a hand rammer. The interlocking paving stone was demoulded after 24 hours [4]. See Plate 4.

2.7 Curing

The curing of the interlocking paving stone with cement concrete was done with potable water at room temperature, in a cool drum. Samples were cured for 7 days, and 28 days for the respective compressive strength tests, while the interlocking paving stones made from waste plastic were air-dried for about 24 hours.

3. RESULTS

The tests carried out for this experiment are, the compressive strength test and the water absorption resistance test.

3.1 Compressive Strength Test

This is the major defining characteristic of the cement replaced interlocking paving stones with waste plastic. It shows the maximum load the interlocking paving stone can withstand without failure. The test was carried out based on BS 6717. Crushing was done at 7 days (see Table 2) and 28 days (see Table 3). The tests were carried out in the Federal Ministry of Works & Housing, material, geotechnics & quality control pavement evaluation unit, Lagos, Nigeria. See Plate 5.

Plate 3. Constituent materials: from left to right: Waste plastic bags, Sand, Granite

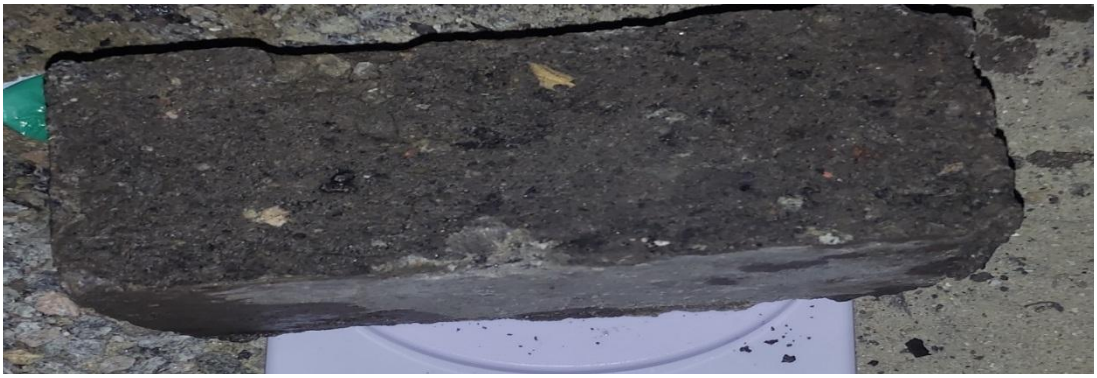

Plate 4. Sample 1, (waste plastic bound paving stone)

Plate 5. Crushing of control and sample paving stones

Table 2. Compressive strength results after 7 days

Item	Mix ratio	Weight (kg)	Load (kn)	Strength (n/mm^2)
Control 1	1:1:1	3.14	523	26.3
Control 2	1:1:1.5	3.35	558	34.9
Control 3	1:1.5:2.5	3.23	283	17.9
Sample 1	1:1:1	2.67	392	24.5
Sample 2	1:1:1.5	2.95	170	10.6
Sample 3	1:1.5:2.5	2.98	98.2	4.9

Table 3. Compressive strength results after 28 days

Item	Mix ratio	Weight (kg)	Load (kn)	Strength (n/mm2)
Control 1	1:1:1	3.22	611	38.2
Control 2	1:1:1.5	3.31	725	45.3
Control 3	1:1.5:2.5	3.40	456	28.5
Sample 1	1:1:1	2.71	412	25.75
Sample 2	1:1:1.5	2.90	168	10.5
Sample 3	1:1.5:2.5	3.01	106.2	6.6

Table 4. Water absorption resistance test results

Item	Dry weight (kg)	Wet weight (kg)	Weight of water absorbed (kg)	Percentage of absorption (%)	Percentage of water absorption resistance (%)
Control 1	3.142	3.192	0.05	1.6	0.8
Control 2	3.349	3.402	0.053	1.6	0.8
Control 3	3.230	3.288	0.058	1.8	0.9
Sample 1	2.67	2.675	0.005	0.2	5
Sample 2	2.95	2.959	0.009	0.3	3.3
Sample 3	3.95	4.03	0.08	2.0	0.5

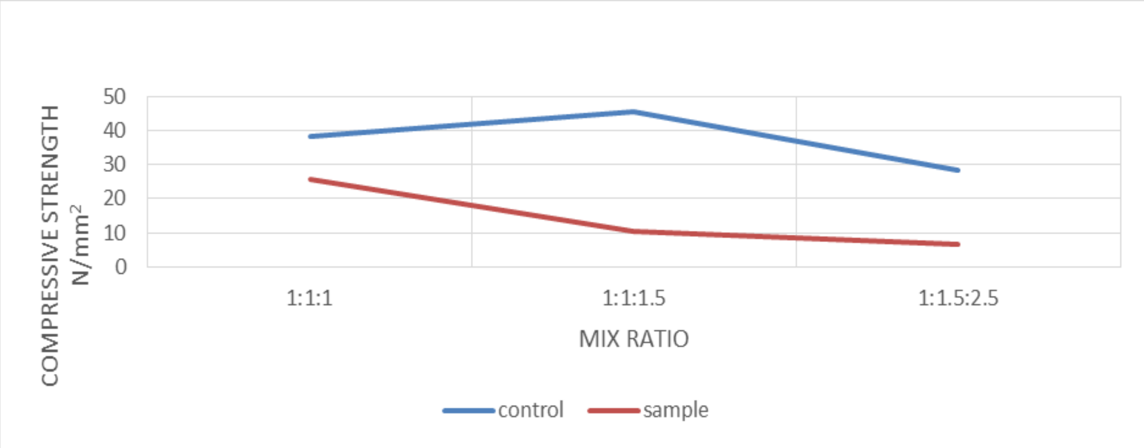

Fig. 2. Compressive strength against mix ratio

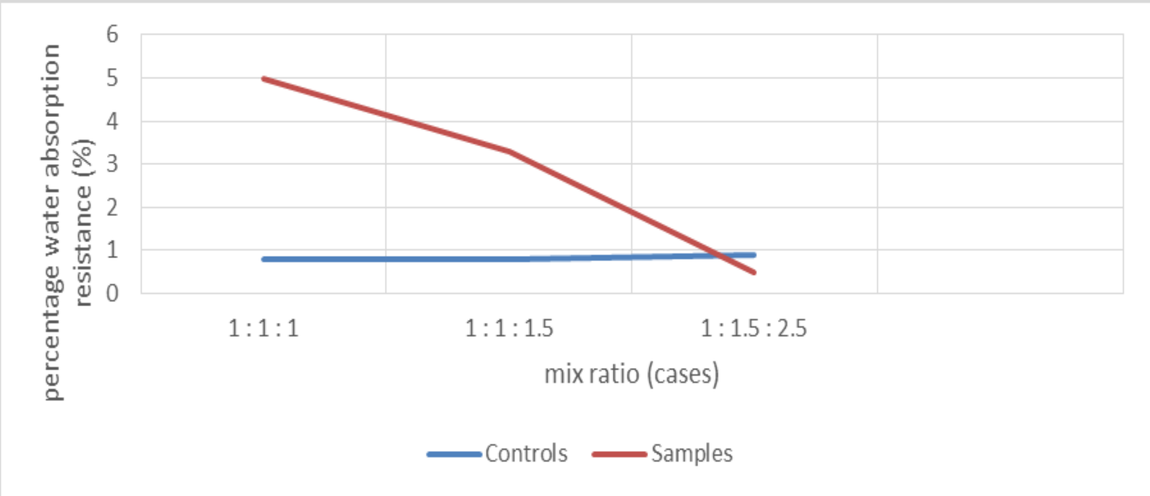

Fig. 3. Percentage of water absorption resistance against mix ratio

3.2 Water Absorption Resistance Test

This test indicates the ability of a paving stone to resist water penetration into it. The amount of water that penetrates the interlocking paving stone is a measure of the presence of air pores in the sample, which can influence the durability of the sample. The less water the interlocking paving stone absorbs, the fewer voids it contains, presence of fewer air pores or void depicts how well-bound the constituent materials are and this contributes positively to the durability of the interlocking paving stone. This was obtained by measuring the dry weight of the paving stones and thereafter measuring the wet weight of the paving stone (having soaked them for a period of 7 days) to ascertain the weight of water absorbed by the paving stones. The percentage of water absorption is inversely proportional to water absorption resistance, see Table 4.

4. DISCUSSION

4.1 Compressive Strength Results

The result of the samples was compared with that of the controls, for the following (mix ratios) being considered.

Following BS 6717, the compressive strength deductions are made from the 28-day crushing result, in case 1; the control had a compressive strength of 38.2N/mm^2 while the sample gave a compressive strength of 25.75 N/mm^2. For case 2; the control gave a strength of 45.3 N/mm^2 while the sample gave 10.5 N/mm^2, case 3; the control gave a compressive strength of 28.5 N/mm^2 while the sample gave 6.6 N/mm^2. In the three cases, the cement-bound paving stone revealed a much higher compressive strength than the plastic-bound paving stone [5, 10].

For the interlocking paving stones made from Portland cement, control 2, which is 28% cement and 71% aggregates, gave the highest and most suitable compressive strength for highway purposes, while for the interlocking paving stones made from waste plastics, sample 1, gave the best strength, which is about 33% waste plastic and 66% of aggregates. Generally, the compressive strength of the waste plastic-bound paving stone is seen to drop as the quantity of the aggregates increases from the graphical representation in Fig. 2 [11,12].

4.2 Water Absorption Resistance Test

The interlocking paving stone made from waste plastic shows far less water absorption levels compared to the interlocking paving stones made from cement as seen in Fig. 3, sample 1 had the best water resistance. From the graphical representation, the higher the waste plastic content the higher the water absorption resistance of the samples, however, the control seems to maintain its water absorption resistance in all cases and only slightly increased with an increase in the aggregates.

5. CONCLUSION

This study compared road paving stones, one made from waste plastic and the other made from Portland cement. The results reveal that cement-bound paving stones have a higher compressive strength compared to those made from waste plastics. The maximum compressive strength that could be obtained for the waste plastic-bound paving stones was 25N/mm^2, whereas the cement-bound paving stone gave a maximum compressive strength of 45N/mm^2.

On the other hand, the samples made from waste plastics possess a higher water percentage of absorption resistance of 5% than those made from cement whose highest percentage of water absorption resistance is 0.9%.

Consequently, while waste plastic-bound paving stones cannot completely replace the use of cement cement-bound stones, they can still be used for pavements expected to carry light traffic ways, rural roads, or unimportant roads, walkways, and due to their high percentage of water absorption resistance, it will be suitable for use flood-prone and high water table areas [13,14].

6. LIMITATIONS

The finding in this research need to be interpreted within a few limitations stated below:

- Just three design mixes were considered during this research.
- The controls and the samples were produced locally.
- Just two tests (a compressive strength test and the water absorption resistance) was conducted.

7. RECOMMENDATION

It is recommended that further research be done using mechanized methods for the production of these paving stones, also, partial replacement of cement with waste plastic bags be considered, and other kinds of waste plastics can be considered for further research.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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