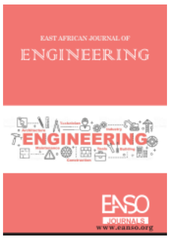

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Original Article

The Physical and Mechanical Properties of Recycled Plastic Waste Paving Blocks for Construction of Non-Motorized Transport (NMT)

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Pulverized Plastic Waste, Optimal mix design, Shredded Plastic Waste, Non-Motorized Transport (NMT), Recycled Plastic Waste Paving Blocks

ABSTRACT

The study focused on determining the appropriate partial mix of plastic waste as a replacement of aggregates in Recycled Plastic Waste Paving Blocks (RPWPB) production for the construction of Non-Motorized Transport (NMT) facilities. The plastic waste, quarry dust, and ballast were graded through a sieve analysis to help determine the particle distribution of their particles. The study began with an initial mix ratio of 1:1.7:3.75 as cement: fine aggregate: coarse aggregates. The paving block made from recycled plastic waste with quarry dust and ballast met the specifications required by KS 827:2003. The samples prepared based on the attained optimal mix design were cured for 7, 14, 21, and 28 days and tested in accordance with different BS standards to determine their physical and mechanical properties. A compressive strength of 33 Mpa and 50 Mpa was attained for fully cured samples made with shredded and pulverized plastic waste, respectively. The water absorption was attained at 6%; thus, the proposed paving blocks are suitable for NMT facilities. The study recommended future studies on using plastic as a binder to eradicate the use of cement and other natural products.

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INTRODUCTION

Background Information

Solid waste refers to all materials that arise from human and animal activities that are usually solid and are regarded as useless and thus discarded (Ayilara et al., 2020). The solid waste generated can be categorized into organic and inorganic wastes. Solid Waste Management (SWM) is a critical and obligatory function of any urban local authority (Amitha & Manoj, 2020). Management of solid waste uses approximately one per cent of the Gross Domestic Product and twenty to forty per cent of municipal revenues in developing countries (Sibanda et al., 2017).

Plastic waste constitutes two major categories of plastics; Thermoplastics and Thermosets. Thermoplastics constitute about 80% of the total post-consumer plastic waste generated in Municipal Waste (Rathi, 2017). Thermoplastics are recyclable plastics which include; Polyethylene Terephthalate (PET), Low-Density Poly Ethylene (LDPE), Poly Vinyl Chloride (PVC), High-Density Poly Ethylene (HDPE), Polypropylene (PP), Polystyrene (PS) (Brems et al., 2012). Thermoset plastics contain Alkyd, Epoxy, Ester, Melamine Formaldehyde, Phenolic Formaldehyde, Silicon, Urea Formaldehyde, Polyurethane, and Metalized and Multilayer Plastics (Singh, 2012).

Plastic waste presents several environmental challenges when disposed of without proper management, including blockage of stormwater drains and urban sewers leading to poor stormwater and sewer drainage. Plastic waste disposed into the sea does not support aquatic since they are indigestible, thus leading to death when ingested. This is true for livestock and other animals (Awuchi & Awuchi, 2019). In the road construction sector, littering on walkways, cycle tracks, drainage systems, and on the carriageway results in failure of the pavement layers and eventual development of potholes on the road due to leachate and poor drainage. Plastics also take 20 to 1000 years to break down (Chamas, et al., 2020). This means the waste remains in the ecosystem longer than biodegradable materials prolonging the highlighted negative impacts.

Non-Motorized Transport (NMT) is defined as any wheeled vehicle used for transporting people that does not have a motor or engine to propel it (Okoth, 2013). NMT entails walking, use of wheelbarrows and carts, animal transport (horses, camels, donkeys, mules, and oxen), animal-drawn carriages such as sledges, bicycles, and tri-cycles passengers transport have also been categorized as NMT. Other NMT modes captured under the Nairobi City County include the use of wheelchairs, skateboards, and strollers (NCCG 2015). Any city that aims to be sustainable in terms of transport provision should include Non-Motorized Transport Facilities in its development plan. Non-Motorized Transport facilities include footpaths and cycle tracks.

The state of NMT facilities in Kenya is poor (Orege, 2018). The report noted that the government needs to support healthier and cleaner NMT by increasing its investment in high-quality NMT facilities. It was noted that approximately 90% of the residents use public transport and once they alight, link to many places within city on foot (Orege, 2018). Therefore, improvement on the NMT facilities brings justice and equity in allocating resources to transportation demands since a large portion of resources is allocated to motorized transport.

Problem statement

The solid waste especially plastic waste production is at a high rate, and it is predicted to grow even higher in the future both in developed and developing countries. Kenya is a developing country, and an increase in the production of plastic waste is inevitable. By looking at the case of the Dandora dumpsite, solid waste, especially plastic waste, is not being reduced by either reusing or recycling. This is a clear indicator that the Nairobi City Council, like many other local governments, is grappling with the increase in solid waste, mainly plastic waste, due to a lack of proper disposal technologies and methodologies. Due to the challenges mentioned above, NCC and

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other local governments need a conventional method of plastic waste management. This can be achieved by reducing plastic waste dumped by recycling and reusing the waste. The application of recycled plastic waste in the production of paving blocks to construct non-motorized transport facilities can be an innovative way to achieve the much-needed plastic waste reduction. It primarily supports the effected ban on plastic bag usage by National Environment Management Authority (NEMA) that aimed to reduce the quantity of plastic waste in the environment by increasing the volume of plastic waste recycled hence facilitating a better solid waste management system.

LITERATURE REVIEW

Plastic is a synthetic material made from various organic polymers like polythene and PVC. They are moulded in shape while soft and set into a rigid elastic form (Brems et al., 2012). Plastics are produced from natural or synthetic materials. Natural materials include plants from which cellulose can be extracted to produce plastics; trees that produce latex, amber, and resin for plastics; horn and milk are products of animals used for making glues and shellac from insects that are used to produce polish. On the other hand, synthetic plastics are chemically produced from crude oil, coal, and natural gas.

Production of traditional plastics made from petroleum-based products increased from 1.5 million tonnes annually in 1950 to approximately 322 million tonnes annually in 2015 (Assad et al., 2020). Plastics have a wide range of applications and are preferred for packaging due to their durability and flexibility. However, the chemical composition that helps make plastics durable makes them equally resistant to the natural degradation process; hence, plastics degrade slowly when disposed.

Many scholars have proposed the use of plastic waste as alternative concrete materials in the manufacture of pavers. For instance, a study by Agyeman et al. (2019) proposed the use of recycled plastic waste as an alternative binder for paving block production. A mix design of 1:1:2 for cement, quarry dust and sand were used as a control for the experiment. A mixed design of 1:0.5:1 was adopted for the experiment, while the compressive strength was performed for 7, 14, 21 and 28 days. The curing process entailed sprinkling water, while the water absorption test was investigated after 72 hours. The maximum compressive strength (8.52 N/mm^2 and 7.31 N/mm^2) was obtained after 21 days for both HDPE and LDPE. The corresponding water absorption was 0.5 per cent and 2.7 per cent. The control had a maximum compressive strength of 6.0 7N/mm2 with a water absorption of 4.9%. The study also compared the findings with other existing research and noted that the proposed paving blocks are suitable for waterlog areas due to their low water absorption property and relatively low compressive strengths compared to global specs thresholds of 5–25% and low-density to moderate concrete strength of 0.69–17.24 N/mm2 respectively.

Shitote et al. (2019) studied the influence of coarse aggregate on the physical and mechanical performance of paving blocks made using waste plastic. The melted LDPE was used to make the paving blocks. This was achieved via a mixture of sand and 5 per cent coarse aggregate. The findings indicated better mechanical properties with ease of flexibility and resistance to water absorption. Binu et al. (2019) experimentally studied the replacement of coarse aggregates with recycled hospital plastic waste in pavers. The study aimed at reducing the unit cost of pavers by using various percentages of plastic replaced for coarse aggregates. The physical and mechanical tests revealed that the maximum compressive strength was achieved on the 14th day for 10% replacement Agyeman et al. (2019) and Shitote et al. (2019) studies used plastic as binder, while the current study proposed the continual use of cement as binder but partial replacement of quarry dust and shredded plastic waste instead of sand as in the traditional paving block production.

Walkways or NMTs facilitate the movement of pedestrians and other non-motorized transport

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systems. Studies have shown that the current state and performance of NMT facilities have neglected pedestrian's needs. Orege (2018) evaluated pedestrian walkways along urban roads using a case study of Komarock estate in Nairobi. The study noted that the poor quality of the pedestrian walkways has resulted in conflict between pedestrians and motorists as they compete for the use of the main carriageway. Kituku (2020), while evaluating the pedestrian facilities at the Donholm interchange along Outering road in Nairobi, also noted that the sidewalks' dilapidated state has led to numerous road accidents involving pedestrians. This is because pedestrians leave the sidewalks and compete with motorists on the motorized carriageway. Klopp (2017) noted that between 2016 and 2017 alone, out of the 3 million pedestrians involved in traffic-related accidents in Nairobi, 447 died. The cause of the accidents is related to pedestrians being forced onto the carriageway when the end of the sidewalk is missing or damaged. Thus, an improvement in the NMT facilities is inevitable.

PROPOSED WORK

Materials

The materials used for the production of the proposed pavers were pigments, cement, fine aggregates (quarry dust), coarse aggregates (ballast), water, and plastics. The cement used was Bamburi cement of grade 52.5 according to KS EAS 18-1: Kenya Standard Cement. Fine aggregates were composed of quarry dust whose size is less than 4.75mm with the properties determined in the field during the pilot study. Coarse aggregates were standard ballast of average $\simeq 6mm$ for paver designs according to BS EN 12620:2013.

Plastic

Plastic waste was obtained from suppliers (plastic waste handlers located around Balozi Estate). The suppliers had graded the plastics based on HDPE, polypropylene, polyethylene, and LDPE. Only HDPE waste was sourced from the suppliers. The plastic waste was sieved between 5 mm to 10 mm sieves in the laboratory according to BS EN 933-2 2020.

Mix Design of Materials for RPWPB

The mix design was based on the ISO 15658:2006. The standard specifies constituent materials, products requirements and test methods for solid, unreinforced pre-cast cement concrete paver blocks and complimentary products used for light, medium, heavy, and very heavy traffic paving applications. The materials were mixed based on established weights from Binu et al. (2019) of the ratio of 1:1.7:3.75 for cement: fine aggregate (quarry dust): coarse aggregate (ballast). The design mix was attained by partial replacement of quarry dust and ballast with plastics. These were performed based on the weights of the mix. The initial partial replacement by percentages were: (i) 20:80, (ii) 40:60, (iii) 60:40, and (iv) 80:20 for fine aggregates and coarse aggregates respectively. These initial replacements were selected to give the datum for the commencement of the research. The replacement was in the ratio of quarry dust:plastic waste. Thus, for every 20% of the quarry dust, there was 80% of plastic waste. These partial replacements were based on the weight of the fine and coarse aggregates used per batch. This is for the commencement of the study in order to have a general outlook of the pavers, then narrowed down to the best ratio that gave better results in terms of physical and mechanical properties. Upon attaining the most suitable mix design, a pilot study was done where around 5000 pavers were produced for construction of pilot footpath of around $200m^2$. The pilot footpath enabled the researcher to assess the users' adaptability and the impact of the produced pavers.

The procedure for the determination of various properties was as outlined in the BS EN 1338:2003 (specifies materials properties and reinforcement for paving blocks for pedestrian, and vehicular use) and KEBS standards (KS 827:2003) outlining the thickness and strengths of the pre-cast paving blocks. The physical properties investigated were particle size or grading (sieve analysis) and water absorption.

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Water Absorption

The specimen was dried until a constant weight was attained after some time. The increase in weight as a percentage of the original weight was expressed as its absorption as shown in the equation below (BS EN 196-1: 2005).

$$\frac{\{(W_s - W_d) \times 100\}}{W_s}$$

Where W_s is the saturated weight, W_d is the dry weight.

Compressive Strength (Cube Crushing)

Compressive strength is maximum compressive stress that when applied to the load at a solid state can sustain without fracture. The test is the most common test conducted on hardened concrete due to ease of performance. Many properties of characteristic strength are related to this test. The test was carried out on the cube sample made at the concrete laboratory according to BS 1881: Part 116: 1983. The test was done on the compressive test machine as indicated in *Plate 1*.

Plate 1: The compressive strength machine used in the laboratory (showing compressive strength of $\left(\frac{1233.7\times10^3}{28059.2231} = \frac{43.9681N}{mm^2}\right)$

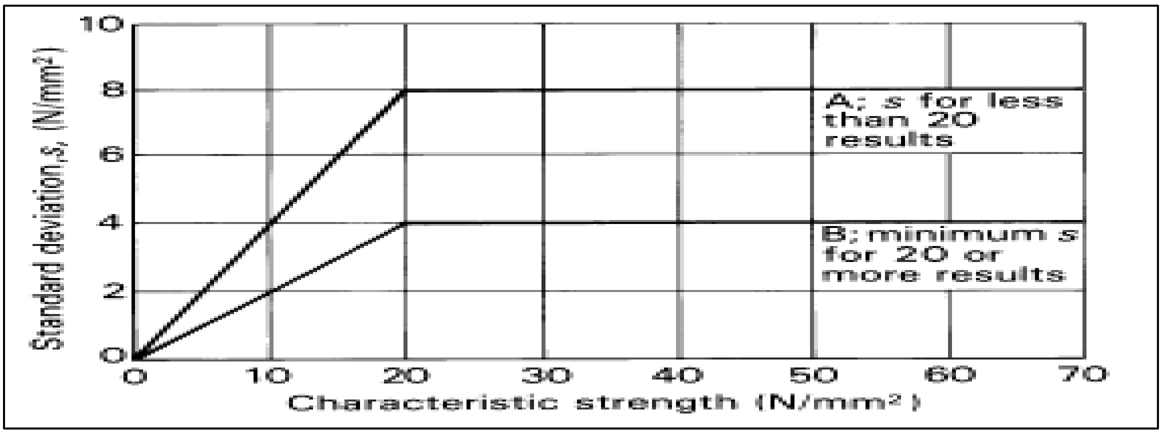
Optimal Mix

The procedure for optimal mix design was done in accordance with British Research Establishment (BRE). The paver was Type S blocks and of grade M. This has a nominal thickness of 60 mm and compressive strength of 35 N/mm^2. Other procedures that are associated with the optimal mix are listed in the following sections.

Target Mean Strength

The desired characteristic strength of paver is $35N/mm^2$. Target mean strength = target average paver strength of sample tested. The test required was below 40, and the design standard deviation was based on **Figure** 1.

Figure 1: Relationship between standard deviation and compressive strength



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The target mean strength, f_m shall be given by $f_m = f_{cu} + 1.64s$, where $f_m = target\ mean\ strength$, $f_{cu} = characteristic\ strength$, $s\ is\ the\ standard\ deviation, s = 4$

Using the above formula, $f_m = 41.56Mp$.

Determining the Fine and Coarse Aggregate Contents

This was to be done in accordance with BS EN 206-11. A summary of the contents is provided as follows:

- The paver type is hexagonal (see Figure 3) whose design specifications are $a = thickness = 60mm$
- The volume of the design paver is $Area \times t = \frac{3\sqrt{3}}{2}a^2 \times 60 = 1683.5526 \times 10^6\ mm^3 \times \sigma|_{\sigma=0.05}$
- Thus, in terms of the volume of content based on $cement: crushed\ stone\ dust: balast = 1: 1.7: 3.75$.

EXPERIMENTAL RESULTS AND ANALYSIS

Mechanical and Physical properties

Plate 1 is a sample of the final proposed recycled plastic waste paving blocks.

Plate 2: Sample of the proposed recycled plastic waste paving blocks

Sieve Analysis of Shredded Plastic Waste, Quarry Dust and Optimal Mix of Shredded Plastic Waste and Quarry Dust

Sieve analysis provides the raw data, and the gradation curve visually represents the particle size distribution within a material (Stark & Wilk, 2018). The sieve analysis test was performed from all the aggregates namely, shredded plastic waste, quarry dust and ballast (chips). The results together with their fineness modulus (FM) are presented in *Table 1* and *Figure 2*.

Table 1 indicates that the shredded plastic waste has a fineness modulus (FM) of 4.44, above the recommended range of 2.3–3.1. This FM value shows a need for a blend with materials with lower FM to reduce the amount of water required to achieve proper workability, but the strength of the concrete product was lower. The gradation curve for shredded plastic waste in Figure 2 indicates an almost smooth curve. However, most materials are in a limited range of sizes, which can lead to voids and increased instability in the paving blocks. Quarry dust has an FM of 2.03, below the recommended range of 2.3–3.1. This FM value shows a need for a blend with materials with a higher FM to achieve proper workability and desired concrete strength. The gradation curve in Figure 4 indicates an almost smooth curve. However, FM is too low, indicating aggregate requiring additional cement and increasing water demand. Since both shredded plastic waste and quarry dust have weaknesses that complement each other, there is a need for optimal mix design,

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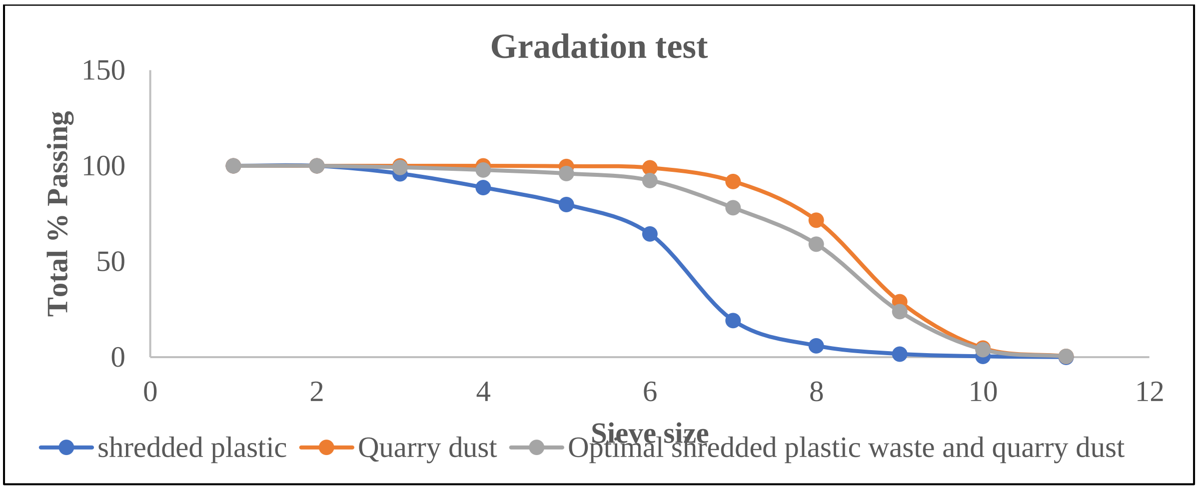
which will address both problems. An optimal mix design achieved an FM value of 2.49 (see *Table 1*), within the recommended range of 2-3.1. The gradation curve also indicates a smooth curve compared to shredded plastic waste and quarry dust, indicating that the paver made from such a mix would be stable and would not demand too much cement and water.

Table 1: Sieve analysis for shredded plastic waste, quarry dust and optimal mix of shredded plastic and quarry dust

Sieve size	Total % Passing		
	Shredded plastic	Quarry dust	Optimal mix of shredded plastic waste and quarry dust
20	100	100	100
14	100	100	100
10	95.95	100	99.23
5	88.7	100	97.85
2.36	79.85	99.79	96
1.18	64.45	99	92.43
0.6	19.25	91.94	78.12
0.3	6.02	71.59	59.13
0.15	1.72	29.07	23.87
0.075	0.43	4.78	3.96
Pan	0.05	0.49	0.41
FM	4.4	2.03	2.49

Figure 2: Gradation curves for shredded plastic waste, quarry dust, and optimal mix of shredded plastic and quarry dust.



Sieve Analysis of Pulverized Plastic Waste, Quarry Dust, and Optimal Mix of Shredded Plastic Waste and Quarry Dust

Plate 3 indicates an evaluation of the pilot study after 90 days, showing one major disadvantage of the proposed paving blocks; that is the visibility of the plastic shreds. This shortcoming of the paving blocks made from shredded plastic waste such as physical appearance of the plastic shreds after 3 months during the pilot study as indicated in arguably prompted research into better forms of plastic waste. Thus, the use of pulverized plastic waste in the production of paving blocks as opposed to use of pellets and shredded plastic waste was proposed. Besides, the initial compressive strength of the paving blocks made from shredded plastic waste as tested by Kenya Bureau of Statistics (KERBS) was Mapa, which was less than the minimum threshold of 35 Mpa.

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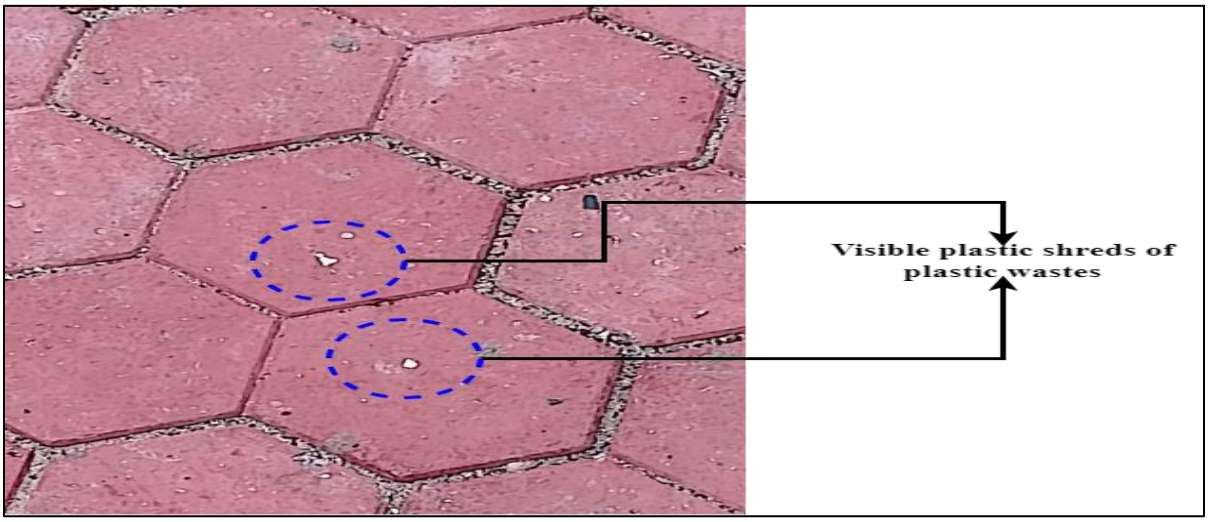
Plate 3: Analysis of Installed Paving Blocks



A sieve analysis test for the pulverized plastic waste in order to understand why it has a huge impact on the strength of the paving block is presented in *Table 2* and its corresponding gradation curve in *Figure 3*.

Table 2: Sieve analysis for pulverized plastic waste, quarry dust and optimal mix of shredded plastic and quarry dust

Sieve size	Total % Passing		
	Pulverized plastic waste	Quarry dust	Optimal mix of pulverized plastic waste and quarry dust
20	100	100	100
14	100	100	100
10	100	100	100
5	100	100	100
2.36	93.6	99.79	98.61
1.18	88.9	99	97.08
0.6	9.9	91.94	76.34
0.3	4.46	71.59	58.83
0.15	3.38	29.07	24.18
0.075	3.36	4.78	4.51
Pan	0.46	0.49	0.49
FM	3	2.03	2.4

Figure 3: Gradation curves for pulverized plastic waste, quarry dust and optimal mix of shredded plastic and quarry dust.

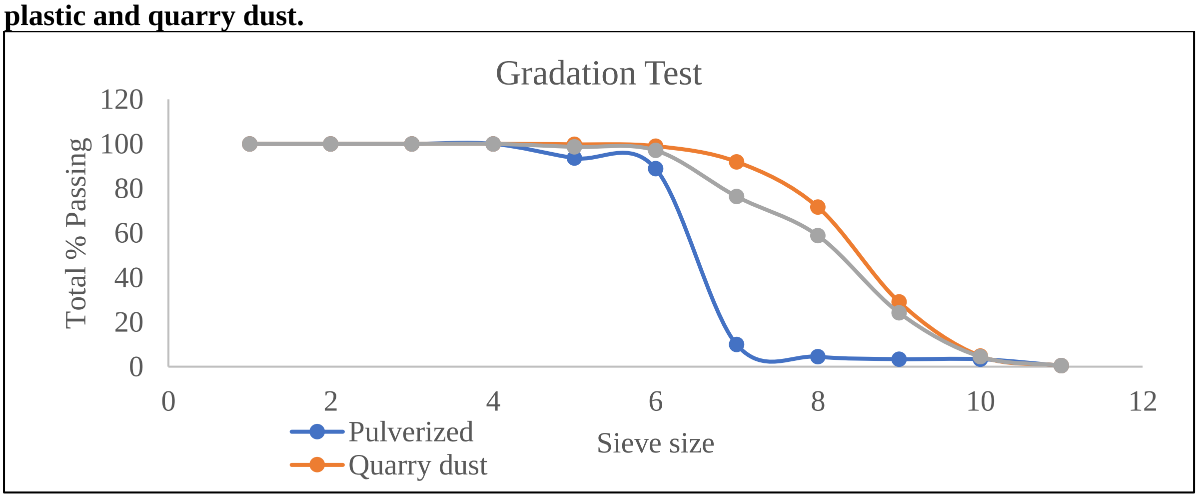


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Table 2 indicates the FM value is 3, within the recommended range of 2-3.1. This explains why the pulverized plastic waste impacted the strength of the proposed paving block. This value of FM suggests the paving block produced is less likely to crack, which translates to its better strength than that of shredded plastic waste. Figure 6 shows a gradation curve for the sieve analysis of pulverized plastic waste. The curve shows that pulverized plastic waste presents a well-represented particle distribution throughout the graph. In order to ascertain the impact of pulverized plastic on the ultimate optimal blend with quarry dust, a sieve analysis test was performed and presented in *Table 2* and *Figure 5*.

Table 2 also shows a sieve analysis test for the optimal mix design of pulverized plastics waste and quarry dust. The FM value was 2.4, which is lower than that of pulverized plastic waste in Table 2. Its corresponding gradation curve in *Figure 3* is smooth representing a well distributed particle size. The sieve analysis for the different materials also compared with the BS 812-103.1:1985 for the standard aggregate is presented in *Table 3* as the amount of materials that should pass through 75μm sieve.

Table 3: An extract of the amount of material passing the 75 µm sieve shall not exceed the quantities given (BS 812-103.1:1985)

Aggregate type	Percentage by mass passing 75 µm sieve (max.)
Uncrushed, partially crushed, or crushed gravel coarse aggregate	2
Crushed rock aggregate	4
Uncrushed, partially crushed or crushed gravel sand	4
Crushed rock sand	16 (9 for use in heavy duty floor finishes)
Gravel all-in aggregate	3
Crushed rock all-in aggregate	11
NOTE The nature of the fines can vary between different aggregates. The limits given above are appropriate for most aggregates found in the UK. Evidence of performance in use or the result of trial mixes may be used to justify the adoption of higher or lower limits.	

Table 3 indicates that the % passing 75μm for uncrushed coarse aggregate (such as shredded plastic waste) should be 2%, while that of crushed rock aggregate (such as quarry dust) should be 4%, while that of gravel in all aggregate should be 3%. These values suggests that in all instances, for example in *Table 1*, the % passing 75μm was 0.43, which is lower than 2% stipulated value. Sieve analysis of quarry dust in Table 1 and Table 2 indicate % passing 75 μm is 4.78, which is close to the recommended value of 4%. A summary of the % passing 75 μm is presented in *Table 4.*

Table 4: Ablation summary of the aggregates based on the % passing of 75 μm.

Aggregate	Recommended (%)	Attained (%)	Satisfactory (✓ or ×)
Shredded plastic waste	2	0.43	×
Quarry dust	4	4.78	✓
Ballast (chips)	2	2.47	✓
Optimal shredded plastic plus quarry dust	3	3.96	✓
Pulverized plastic waste	3	3.36	✓
Optimal pulverized plastic waste plus quarry dust	4	4.51	✓

Batching

In order to attain the optimal mix design, a total of 26 batches were created based on different percentages of aggregates. The preliminary results approximated that a mix design of (1:0.967:1.05:0.24:0.045 for C: CSD: B: PCSD: PB) where CSD is crushed stone dust and B is ballast, gave the best mix design. This was used further to estimate the accurate mix design via

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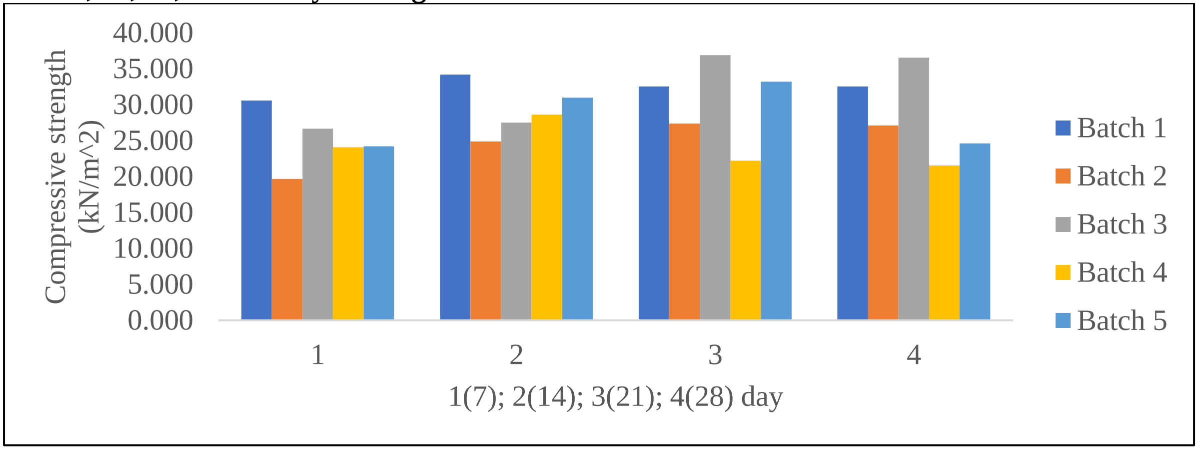
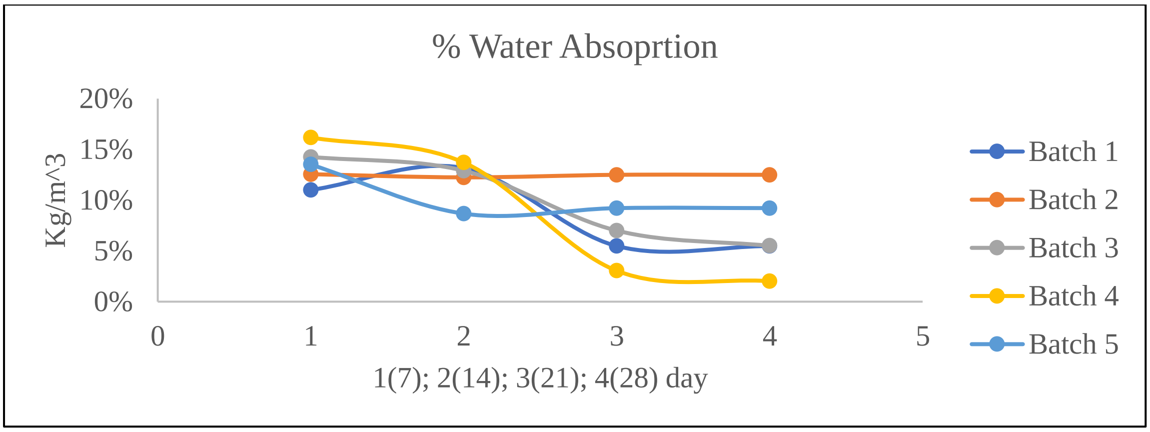
testing of samples on the 7th, 14th, 21st and 28th days. The compressive strength was obtained by the formula; $CS = \frac{kN}{A}$, where A is the area of the paving block, which is given by $A = \frac{3\sqrt{3}}{2}a^2$, where $a = 60$, thus $A = \frac{3\sqrt{3}}{2} \times 60^2 = 9353.07\ mm^2$.

Figure 4: Comparison of compressive strength test for different batches modified from Batch 3 after 7, 14, 21, and 28 days curing.



Summary of the % of water absportion is presented in is presented in Figure 5.

Figure 5: Percentage of water absorption



The graphs suggest that Batch 4 had the largest differential losses between day 7th and 28th. Batch 2 was fairly uniform, an implication of a lack of voids in the samples. Batch 3 had a smooth curve, an indication that the 28th day blocks had less voids compared to the 7th day blocks. Batch 3 was more suitable since according to BS EN-1338:2003, a 28th day cured paving block should have a % water absorption value of$\leq$ 6.

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Figure 6: Comparison of slump test for different batches modified from Batch 3 after 7-, 14-, 21-, and 28-days curing

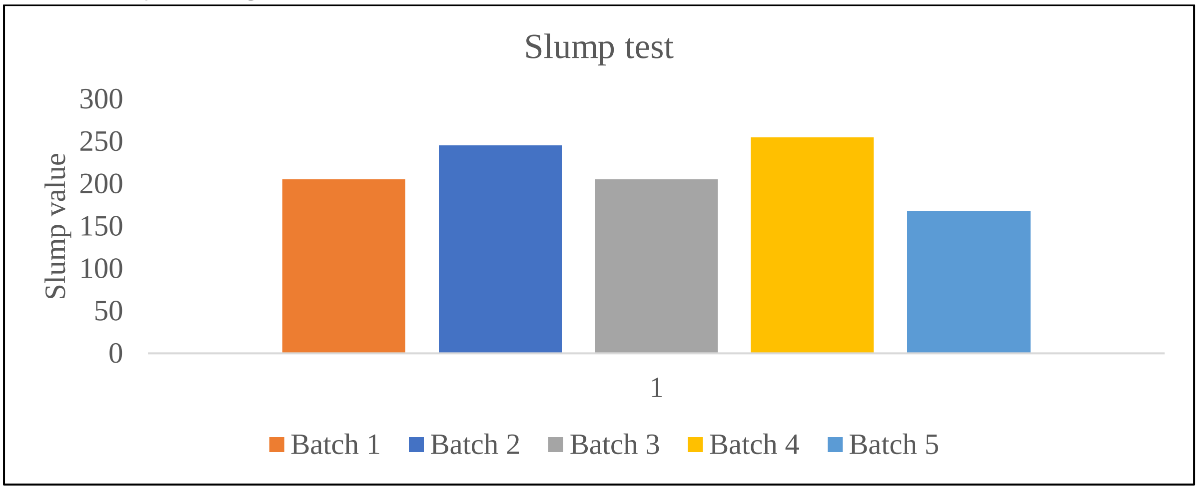

Figure 3 to *Figure 6* suggest that Batch 3 gives the best optimal mix design.

$[C: CSD: B: P] = [1: 0.971: 1.051: 0.228]$

However, the slump value for Batch 3 is 205, which near the 210 mm, a best value as indicated in BS EN 12350-2:2019. 12 samples were prepared from the identified optimal mix design (Batch 3) and taken to KEBS for testing. Batch 3 was extended to attain a further result using pulverized plastic waste. The pulverization of plastic waste reduced the microstructure within the paving blocks, thus, sufficing to increase the strength and physical appearance of the paving blocks as indicated from the 12 samples taken to KEBS for compressive test analysis.

CONCLUSION

The paving block made from recycled plastic waste with quarry dust and ballast met the specifications required by KEBS standards (KS 827:2003). The paving blocks were developed in two folds; the first fold used shredded plastic waste, the second used pulverized plastic waste. The second was an improvement of the first. The improvement of the second was based on the rigorous sieve analysis, which entailed checking of the FM value in order to meet the recommended range for fine aggregates. The physical and mechanical properties that were investigated were water absorption rate and compressive strength. Besides the laboratory test, the 12 samples of each fold were taken for assessment to KEBS yielded: (a) The paving blocks made from shredded plastic waste yielded an average compressive strength of 33Mpa. (b) The paving blocks made from pulverized plastic waste yielded an average compressive strength of 50 MPa. These values were compared with paving blocks from five companies and the ablation study shows that the performance of the proposed paving block ticks all the metrics. Thus, the optimal mix design $[C:CSD:B:P]$=[1:0.971:1.051:0.228] is suitable for recommended commercial production. The water absorption for the proposed paving block was also attained to be 6%, which is within the recommendation by BS EN-1338:2003. The study recommended that the proposed paving blocks is suitable for walkways and cycle paths for Non-Motorized Transport facilities. Future studies need to consider using plastic as a binder to eradicate the use of cement and other natural products.

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