Performance of Modified Polymer as a Binder with Qarry Dust and Ballast in the Production of Paving Blocks

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ABSTRACT

The city of Nairobi is in need of pedestrian and cyclist infrastructure as an answer to an increasing reliance on automobiles. Collaborative efforts are underway to reduce congestion, although challenges such as sand mining persist. The utilization of plastic waste and Quarry Dust (QD) may provide a sustainable solution. The proposed study aims to assess the mechanical properties and optimal blend design for the production of paving blocks using a modified polymer and a combination of ballast (B) and QD. The gradation curve constituted a pivotal stage in the research process, as it provided vital information regarding the ratio of B and QD required for the optimal mix design. The study methodically explored the optimal ratio of materials for the production of paving blocks incorporating a modified polymer, QD, and B. It was observed that there were minor reductions in strength under acidic conditions, which suggests that the proposed paving blocks may be suitable for use in a variety of outdoor applications. Additionally, it would be advantageous to investigate innovative solutions for Non-Motorized Transport (NMT) infrastructure.

Keywords-recycling; sustainability; NMT; polymers

I. INTRODUCTION

The composition of waste varies according to the specific management programs and consumption trends in question, but it is notable that plastic constitutes a considerable proportion of the total waste stream [1]. The two main components of plastic waste are HDPE and LDPE. Due to the longevity of plastic, the recycling process can be highly effective when the material is allocated to its intended purpose [2]. One of the most significant challenges associated with plastic bags is their inability to degrade effectively within the environment. The estimated time required for degradation is between 20 and 1,000 years, depending on their composition [3]. Nairobi generates a daily solid waste output of 2,400 tons, approximately 20% of which is composed of plastic [4]. The combination of inadequate waste management and an expanding population has heightened the risk of environmental degradation in the 4.4-million-person city. Only 45% of municipal waste is recycled, repurposed, or converted into a form that can offer economic or ecological value, falling significantly below the 80% objective established by the National Environment Management Authority.

In Kenya, NMT is highly popular, with 45% of Nairobi's population walking to work and many others using public transportation [5]. Despite its widespread use, NMT often needs more consideration in urban planning. The 2012 Integrated National Transport Policy acknowledged NMT's importance regarding the health of the underprivileged and the population in general, with some counties making strides in providing facilities [6]. However, challenges still need to be addressed, including increased car ownership leading to more traffic, reduced road safety, and poorer air quality in Nairobi. NMT infrastructure is frequently inadequate, posing risks, especially to women and children. Pedestrian fatalities rose by 20% in April 2020 compared to the previous year, highlighting the necessity for enhanced NMT support and infrastructure.

The Institute of Transportation and Development Authority (ITDP) is engaged in collaboration with Kisumu County on the development of a Sustainable Mobility Plan, with a particular focus on walking, cycling, public transportation, and parking. Since 2015, the UN Environment Share the Road Program has been working with Nairobi City County, with the support of the Fédération Internationale de l'Automobile (FIA) Foundation, to implement a NMT policy. This commits 20% of the road construction budgets to NMT. Nairobi has made considerable progress, with all new and upgraded roads now required to include NMT components. In addition, the city has launched initiatives such as the Clean Air 4 Schools program, which aims to educate children on air pollution. Furthermore, the Nairobi Metropolitan Services (NMS) are leading the 'Kazi Mtaani' project, which aims to reduce traffic congestion through NMT infrastructure. This project is supported by the EU and the Kenyan government-funded by Nairobi Missing Link Roads and NMT Facilities Project.

The use of river sand as a fine aggregate has resulted in a number of significant challenges in mining regions [7]. The extraction of sand, which serves as a protective layer for water that flows beneath and within it, has the consequence of depleting underground water reservoirs, compromising the availability of clean water. Furthermore, this process has a harmful impact on the quality and quantity of surface water, as well as on the aquatic ecosystem. The transportation of sand by large trucks, substantially deteriorates the environment, accelerating soil erosion and destabilizing the soil structure within mining zones. In addition, this process contributes to environmental pollution. Cement production has an essential adverse impact on the environment, due to the emission of CO_2 and other greenhouse gases, the combustion of fossil fuels, and the release of particulate matter containing heavy metals [8]. Mitigation efforts include eco-friendly cement, cleaner technologies, and renewable energy adoption to reduce the industry's carbon footprint.

The benefits of improving NMT in urban areas have been exceeded by the rising costs of construction, due to the scarcity of essential materials. This has prompted research into alternative materials, such as plastic waste and QD, which are both plentiful but under-recycled and often considered garbage. Using these materials in construction could result in a notable reduction in environmental pollution caused by plastic and cement, with the latter being a significant air pollutant. The replacement of sand with QD in construction can also assist in the preservation of rivers by reducing the necessity for sand mining, which affects river flow. The study proposes the combination of modified plastics (HDPE, PVC, and LDPE) with QD and aggregates to create eco-friendly paving blocks, aiming to minimize environmental impact.

Integrating plastic waste into the production of paving blocks significantly advances waste management and sustainable construction [9, 10]. A number of studies have demonstrated that the incorporation of diverse plastics can enhance the mechanical properties of paving materials, reduce the environmental impact, and contribute to the circular economy [11-18]. For example, authors in [13] demonstrated that paver blocks manufactured with a minimum of 60% plastic waste exhibited a compressive strength of 14.7 MPa. Other studies such as [12, 13], have concentrated on the utilization of plastic bags and coarse aggregate in block production. Additionally, in [14] it was identified that LDPE-bonded sand blocks exhibited superior properties. A report in [15] showed an average compressive strength of 16.05 MPa while adding plastic waste and QD. In [16], an economical method was introduced using recycled concrete and Polyethylene Terephthalate (PET) bottle fibers. In [17], blocks made from municipal plastic waste, particularly those with HDPE, were found to exhibit higher strength and suitability for lightly trafficked areas. Furthermore, in [18], the potential of modified plastic waste in mortar was examined, concluding the fact that it is suitable for use in non-traffic zones. Authors in [19, 20] have highlighted the benefits of higher plastic content in paving blocks, suggesting their use in pedestrian areas due to improved durability and performance.

The objective of this study is to evaluate the efficacy of modified polymers (HDPE, LDPE and PVC) as binders with QD and B in the production of paving blocks. Different plastics have different properties; hence their optimum design mix would give superior properties (compressive and flexural strength). The novelty of the study lies in the approach of deciding upon the optimum design mix in two stages. The first stage is to determine the optimum design mix of B and QD, followed by finding the optimum design mix of HDPE, LDPE and PVC. The study notes that the use of plastic waste in construction materials represents a significant step towards the development of more sustainable and environmentally friendly construction methods.

II. MATERIALS AND METHODS

A. Source

The aggregate particles are inert and are typically bound by a cementing agent. In the proposed study, however, the aggregate is composed of QD and B and is bound by a polymer. QD is a by-product of extracting B from rock and was used as a fine aggregate in place of river sand. The material was sourced from Mihango, Utawala, Kenya. In many concrete productions, B is the coarse aggregate, that was assumed free of impurities. Polymer is a combination of HDPE, PVC and LDPE. A combination of these materials served as a binder in cement. The initial composition was calculated to be 33.33% for HDPE, PVC and LDPE. It was assumed that the initial percentage in the paving block would be similar to that of cement in conventional manufacture. The plastic was sourced from plastic waste handlers in Nairobi, specifically Mukuru Kwa Reuben. The pre-treatment process involved washing the plastic with soapy water to remove impurities and drying it under the sun. Subsequently, the plastic was placed in waterproof bags for further contamination to be prevented.

B. Batching

The materials deployed for paving blocks were combined in a batching process based on their respective densities. The initial composition involved replacing cement with a polymer, with the corresponding composition being 33.33% for HDPE, PVC and LDPE. The QD and B were combined in a ratio consistent with that of a conventional concrete mix, with QD replacing sand. The subsequent polymer addition was increased by 5% of polymer substituting QD and B. Upon completion of the optimum mix design, the polymer's composition ratio was either reduced or increased. The mixing process commenced with the heating of the B and QD to a temperature of 1500 °C. Subsequently, the plastic polymers were added and mixed while still heating until all the contents of the mix were completely melted. The resulting mixture was then poured into molds of 250 mm × 250 mm × 50 mm. It should be noted that for the purposes of this experiment, heating and mixing were carried out in the open air.

C. Physical Properties of Materials

1) Sieve Analysis

A sieve analysis of the aggregates was conducted according to the specifications set forth in BS 812-1:1975. The percentage of particles passing a 75 µm sieve for uncrushed coarse aggregates should be 2%, while for crushed rock aggregates (such as QD), should be 4%. For gravel in all aggregates, the percentage should be 3%. These values indicate that in all instances, for example in Table II, the percentage passing 75 µm was 3.8%, which is below the stipulated value of 4%. The sieve analysis of the B in Table II indicates that the percentage passing a 75 µm sieve is 1.15%, which is below the recommended value of 2%. A summary of the gradation curves is presented in Figure 1.

Table I portrays an optimal mix designed for B and QD, which met the specific requirements of the control experiment. Figure 1 shows that the gradation curve for sand is relatively smooth in comparison to that of B and QD. The gradation curve for B is the most uneven, exhibiting the inconsistencies associated with the product made from it if no other materials were to be used to smoothen the curve. In order to make a combination of B and QD useful for the next objective, it was necessary to determine an optimal blend of the two materials in comparison with sand. The optimal value was determined based on the required percentage passing a 75-micrometre sieve, which is approximately 2.74%. A series of sieve analyses were conducted until a percentage passing the 75 µm threshold was achieved. This resulted in a transformation of the optimal design mix of QD and B from a ratio of 2:3 to a ratio of 0.085: 0.128 ≡ 1:1.51.

2) Moisture Content

The moisture content of construction materials is of critical importance, as it can influence the workability, strength, and durability of the final product. A summary of the average moisture content of the QD and B is depictede in Table II. It contains three columns. One for the average moisture content for QD, the second for B and the third is for the proposed optimal control mix.

It is crucial to maintain optimal moisture content in construction materials. A moisture level of 4.4% in QD is indicative of handling issues, while a moisture content of 1.7% in B is indicative of a low water content. The optimal blend, with a moisture content of 2.8%, ensures optimal workability, strength, and compaction, which is essential for achieving consistent quality in uniform paving block production. Regular monitoring is essential for maintaining consistent quality.

TABLE I. SUMMARY OF SIEVE ANALYSIS TO ATTAIN OPTIMAL MIX RATION OF QD TO B OF 1:1.8.

Sieve Size	% Passing			
	B	QD	Sand (control)	Optimal (1:1.81)
20.00	100.00	100.00	100.00	100
14.00	99.25	100.00	100.00	99.70
10.00	87.75	100.00	100.00	95.08
6.30	52.90	96.80	99.80	79.16
5.00	36.95	92.50	99.50	70.18
2.36	9.55	79.95	97.74	51.66
1.18	5.15	62.40	92.44	39.39
0.60	3.75	32.25	77.38	20.80
0.30	2.05	18.15	36.08	11.68
0.15	1.40	8.55	14.13	5.68
0.0755	1.15	3.80	2.74	2.74
Pan	1.00	1.50	1.74	1.30

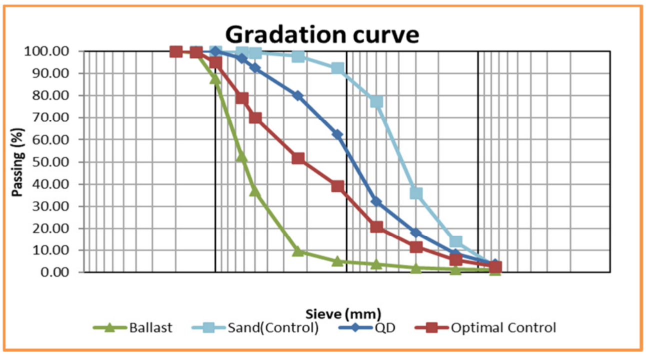

Fig. 1. A comparison of gradation curves for B, QD, Sand (control) and an attained optimal mix.

TABLE II. AVERAGE MOISTURE CONTENT FOR OPTIMUM DESIGN MIX OF QD AND B

	QD	B	Optimal control
Moisture content (%)	4.4	1.7	2.8

3) Specific Gravity

The specific gravity of fine aggregate is an important property that provides information about the density of the material. It is defined as the ratio of the mass of a given volume of aggregate to the mass of an equal volume of water at a specified temperature. The specific gravity of the fine aggregate was determined to be 2.9. This value indicates the density of the material, which affects the compactness and strength of the concrete. Denser aggregates generally enhance quality. However, considering particle shape, gradation, and cleanliness is vital for a comprehensive suitability assessment. Low specific gravity may be indicative of high porosity, which could affect the water absorption and workability of concrete. Conversely, a specific gravity of 2.9 indicates lower porosity, which is desirable to increase the strength of the concrete and has a beneficial effect on the properties of the pavers.

III. EXPERIMENTAL RESULTS

A. Optimal Mix Design Ratio of Modified Polymer with QD and B

The initial study involved determining the properties of paving blocks made from each plastic waste. The initial mix design ratio was based on IS 15658:2006 for M-30 as 1:2:3 for polymer QD. B did not yield a compact paving block. The ratio was adjusted to 2:2:3, but the results were similar. The final ratio was 4:2:3 and it yielded the results in Figure 2. The compressive and flexural strength tests were based on BS881: Part III 1983 and BS EN 12390-5:2009, respectively.

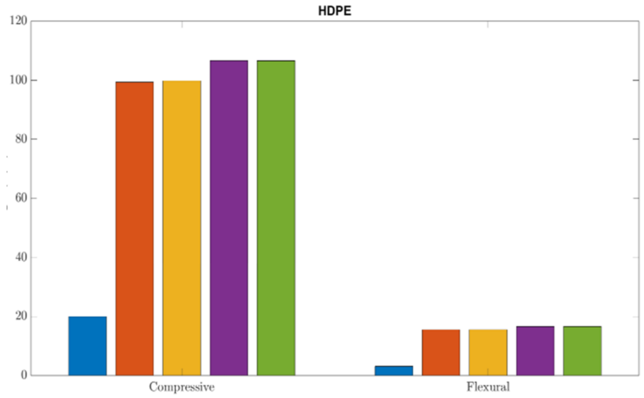

Fig. 2. Compressive strength test for different 5 major batches during experiment where HDPE is highest as indicated in Table III.

Table III demonstrates that paving blocks manufactured from the highest quantity of HDPE with QD and B, exhibited the highest compressive strength. Furthermore, the weight of these blocks was also the highest compared to that of LDPE and PVC. The results also indicated that the tensile strength from paving block made from LDPE was the highest. The results of the compressive and flexural strength tests on paving blocks with a higher ratio of LDPE and PVC are presented in Figure 3 and Figure 4, respectively.

TABLE III. PRELIMINARY MIX DESIGN WITH HIGHEST RATIO OF HDPE

	HDPE	LDPE	PVC	Q	B	Weight	Compressive	Flexural
	kg						MPa	
LDPE	0.194	0.194	0.194	0.085	0.128	0.176	19.982	3.109
	0.194	0.33	0.194	0.085	0.128	0.343	38.992	6.068
	0.194	0.446	0.194	0.085	0.128	1.034	59.217	9.103
	0.194	0.602	0.194	0.085	0.128	0.472	53.735	8.362
	0.194	0.738	0.194	0.085	0.128	0.522	39.396	6.243
PVC	0.194	0.194	0.194	0.085	0.128	0.176	19.982	3.109
	0.194	0.194	0.33	0.085	0.128	0.600	95.332	14.872
	0.194	0.194	0.446	0.085	0.128	0.677	68.352	12.872
	0.194	0.194	0.602	0.085	0.128	0.840	77.012	11.984
	0.194	0.194	0.738	0.085	0.128	0.811	95.571	14.368
HDPE	0.194	0.194	0.194	0.085	0.128	0.176	19.982	3.109
	0.194	0.194	0.194	0.085	0.128	0.873	99.415	15.470
	0.194	0.194	0.194	0.085	0.128	0.878	99.894	15.545
	0.194	0.194	0.194	0.085	0.128	0.919	106.696	16.603
	0.194	0.194	0.194	0.085	0.128	0.937	106.640	16.593

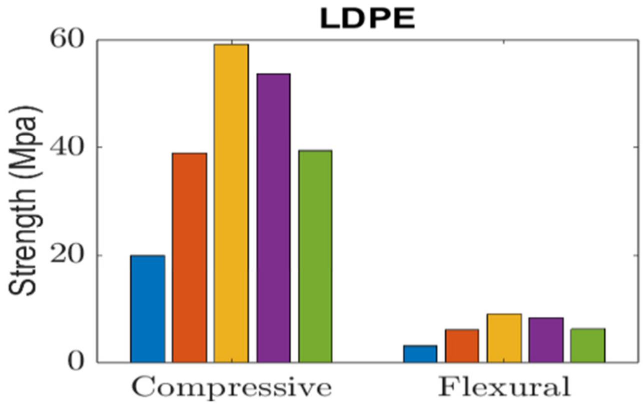

Fig. 3. Compressive strength test for different 5 major batches during experiment where LDPE is highest as indicated in Table III.

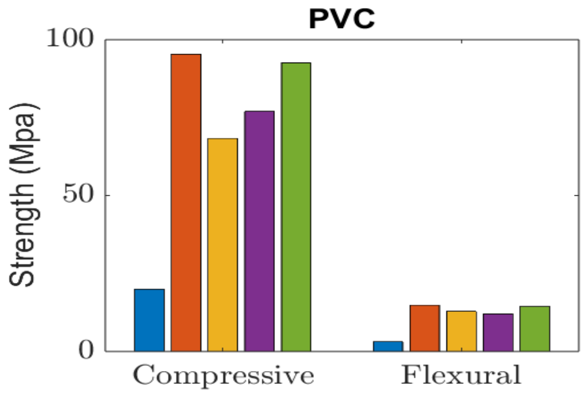

Fig. 4. Compressive strength test for different 5 major batches during experiment where LDPE is highest as indicated in Table III.

Determining the optimal mix design ratio for paving blocks incorporating modified polymer, QD, and B involved a systematic approach that considered the properties of each component and their interactions. The process started by testing the materials, then the best ratio was chosen and used to make the best mix. The highest ratio was selected and utilized to estimate the optimum design mix, while keeping QD and B constant as evidenced on Table III. Thus, the optimum mix design begun with HDPE: LDPE: PVC: QD: B = 0.602: 0.446: 0.33: 0.085: 0.12, as pointed out in Table IV, but the optimal design mix concluded at HDPE: LDPE: PVC: QD: B = 0.7: 0.5: 0.3: 0.085: 0.1. and the results are manifested in Figure 5.

B. Durability Test

The durability test was based on two key criteria: water absorption and acidity.

1) Water Absorption

A series of tests were conducted over a six-day period to assess the water absorption properties of a number of samples. As observed in Table V, the paving blocks regained original weight after four days of immersion, indicating that the water had been completely lost. The data are illustrated in Figure 7.

TABLE IV. PRELIMINARY MIX DESIGN WITH HIGHEST RATIO OF HDPE

HDPE	LDPE	PVC	QD	B	Weight	Compressive	Flexural
kg						MPa	
0.602	0.446	0.330	0.085	0.128	0.980	111.554	17.359
0.616	0.461	0.240	0.085	0.128	0.990	112.694	17.537
0.630	0.431	0.247	0.085	0.128	1.019	115.961	18.045
0.644	0.478	0.255	0.085	0.128	1.050	119.566	18.606
0.658	0.493	0.275	0.085	0.128	1.133	128.944	20.065
0.672	0.486	0.280	0.085	0.128	1.155	131.521	20.466
0.686	0.475	0.285	0.085	0.128	1.175	133.802	20.821
0.693	0.463	0.287	0.085	0.128	1.184	134.830	20.981
0.695	0.482	0.289	0.085	0.128	1.194	135.872	21.143
0.700	0.500	0.300	0.085	0.128	1.237	140.815	21.913
0.742	0.509	0.311	0.085	0.128	1.242	96.740	10.080

TABLE V. WATER ABSORPTION IN 6 DAYS

Day	W1	W2	Water absorption
1	1237	1325.040	7.1200%
2	1237	1310.690	5.9600%
3	1237	1279.400	3.4300%
4	1237	1250.834	1.1200%
5	1237	1239.820	0.2280%
6	1237	1237.559	0.0452%

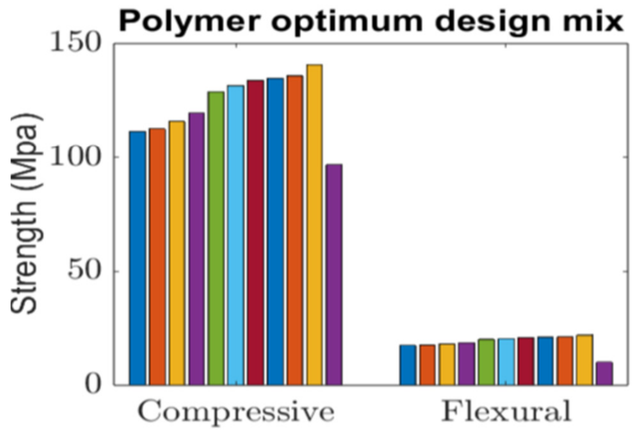

Fig. 5. Compressive and flexural strength test for different batches during determination of optimum design mix ratio extracted from Table IV.

Fig. 6. Setup for specimen production, final product, and testing.

The setup for the experiment is presented in Figure 6. A series of tests were conducted over a six-day period to assess the water absorption properties of a number of samples. As shown in Table V, the paving blocks regained original weight after four days of immersion, indicating that the water had been completely lost. The data are presented in Figure 7.

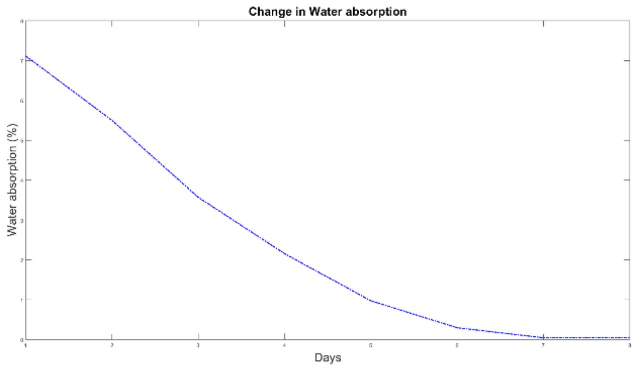

Fig. 7. Tracking of water absorption by the proposed paving blocks

A comparison with the specifications set out in BS EN 13755:2008 reveals that the water absorption of the paving blocks is below the recommended 8%, indicating that there is a reduced risk of damage from moisture exposure. A reduction in absorption levels enhances durability and resistance to weathering, maintains surface quality, and suggests higher compressive strength, thereby ensuring reliability for outdoor paving.

2) *Acid Resistance*

The acidity test was conducted on a paving block made by using an optimal mix design. A solution of Hydrochloric Acid (HCl) at a concentration of 2% was prepared and the blocks were completely immersed in it for a period of 56 days. The blocks were removed, washed with tap water, and left outdoors until they reached a stable weight after six days. The compressive and flexural strength of the paving blocks was obtained as noticed in Table VI, and a comparison can be seen in Figure 8. The results suggest a slight reduction in compressive and flexural strength, with a decrease of 2.533% and 7.800%, respectively.

TABLE VI. RESULTANT COMPRESSIVE AND FLEXURAL TEST AFTER ACIDITY IMMERSION

Sample	Compressive	Flexural
Initial	140.815	21.913
1	136.591	20.160
2	138.984	20.335
3	136.168	20.116
Average	137.248	20.203
% Reduction	2.533%	7.800%

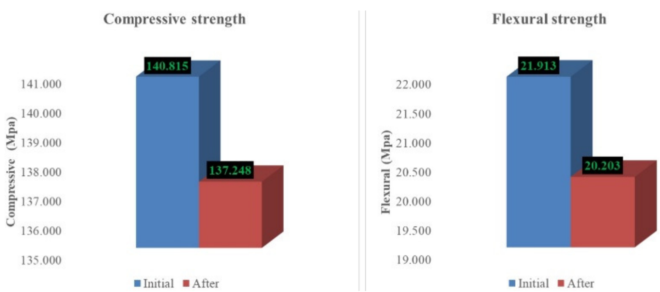

Fig. 8. Comparison of compressive strength test (left) and flexural strength (right) of proposed paving blocks after and before acidity test.

IV. CONCLUSION

Effective recycling strategies are crucial to manage waste, mainly plastic, in Nairobi. Despite widespread Non-Motorized Transport (NMT), urban planning must prioritize pedestrian and cyclist infrastructure amid rising automobile usage. Collaborative efforts aim to improve transportation and reduce congestion, yet challenges like sand mining and cement production persist. Utilizing alternative construction materials like plastic waste and Quarry Dust (QD) can mitigate pollution and environmental degradation, offering promising solutions for sustainable development. The objective of the proposed study is to assess the mechanical properties and optimal mix design for the production of paving blocks from a modified polymer in combination with QD and Ballast (B).

Sieve analysis demonstrated the significance of an optimal design mix for QD and B in order to achieve enhanced strength in paving blocks. The gradation curves demonstrated the necessity for a harmonious combination of materials, such as B and QD, to ensure uniformity. This resulted to transforming an optimum design mix of QD and B from 2: 3 to 0.085: 0.128 ≅ 1: 1.51. It is essential to maintain a moisture content of 2.8% in order to achieve the optimal balance between workability and strength, which is crucial for the successful compaction and durability of the material. A specific gravity of 2.9 indicated a dense, desirable material for concrete mixes, enhancing workability and strength. The study methodically explored the optimal ratio for the paving blocks incorporating modified polymer, QD, and B. The initial pre-final ratio of 4: 2: 3 was modified, resulting in the production of compact paving blocks. This ratio was used to attain final optimum mix design based on sieve analysis and mechanical properties of paving blocks to final optimum mix design of HDPE: LDPE: PVC: QD: B = 0.7: 0.5: 0.3: 0.085: 0.1.

The systematic approach in determining the optimum design mix emphasizes the importance of considering material properties and interactions. Compressive and flexural strength indicated the yielded paving blocks with 140 MPa and 21 MPa for compressive and flexural strength, respectively. Durability tests of the proposed paving blocks demonstrated a water absorption rate of 7.12%, below the recommended value, demonstrating improved resistance to weathering. Additionally, minor reductions in strength under acidic conditions suggested enhanced durability, highlighting the potential of the proposed paving blocks for various outdoor applications, offering superior performance and longevity. Future research should focus on optimizing mix design ratios for paving blocks using modified polymer, QD and B for strength, durability, and environmental sustainability, while also exploring innovative solutions for NMT infrastructure.

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