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Original Article

Sustainable Paving Solutions: Laboratory Analysis of Geopolymer Paver Blocks with Reclaimed Asphalt Pavement Aggregates

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Abstract *- India's urban infrastructure faces a critical gap in pedestrian and non-motorized transport facilities. While Concrete Paver Blocks (CPBs) are commonly used for this purpose, their production has significant environmental impacts. This investigation examines geopolymer concrete as a viable, sustainable substitute for conventional paver blocks. Geopolymer Paver Blocks (GPBs) are synthesized utilizing fly ash, Ground Granulated Blast furnace Slag (GGBS), and an alkaline activating agent. Reclaimed Asphalt Pavement (RAP) aggregates were integrated to augment sustainability further as a substitute for traditional aggregates. The study evaluated the mechanical, durability, and abrasion properties of the developed GPBs, comparing them to traditional CPBs. Incorporating Reclaimed Asphalt Pavement (RAP) aggregates contributed to a decrease in the workability of freshly mixed concrete. Empirical investigations demonstrated that integrating RAP aggregates led to a deterioration in the mechanical strength characteristics of Geopolymer Binders (GPBs); however, they still adhered to the requirements as per IS 15658: 2021. Notably, GPBs exhibited enhanced durability attributes compared to traditional concrete. Moreover, the research found that the abrasion loss of GPBs was less than that of CPBs, although an increase in RAP content was associated with heightened abrasion loss. The insights gained from this study reinforce the potential of incorporating RAP into GPBs as a significant step toward sustainable infrastructure development, thereby reducing the carbon footprint associated with conventional cement-based materials.*

Keywords *- Geopolymer concrete, Geopolymer paver blocks, Reclaimed asphalt pavement, Sustainable concrete.*

1. Introduction

With an aggregate extent exceeding 5.8 billion kilometers, India's transportation infrastructure comprises one of the most extensive networks globally, attaining a prominent position on international rankings. [1]. While the government has made significant strides in enhancing road connectivity, pedestrian and non-motorized transport infrastructure remains largely inadequate. Paver Blocks (PBs) have emerged as a widely used solution for pedestrian and cycle tracks due to their ease of installation, durability, and aesthetic appeal [2, 3]. Among these, Concrete Paver Blocks (CPBs) are the most commonly used; however, their reliance on concrete poses significant environmental concerns. The production of concrete is resource-intensive and contributes heavily to carbon emissions, raising sustainability challenges across its entire life cycle—from the extraction of raw materials to the processes of production and application [4-7]. Additionally, CPB production demands large quantities of natural resources such as sand, gravel, and water, contributing to resource depletion and ecological degradation. The extraction of these materials disrupts natural ecosystems, while the energy-intensive manufacturing process further exacerbates greenhouse gas emissions. Moreover, the disposal of demolished concrete waste creates additional environmental burdens, with limited recycling and high landfill accumulation. There is a growing drive to examine substitute materials for construction that are economical as well as environmentally friendly due to the emerging global concern on sustainable infrastructure [8-10]. Despite ongoing efforts to develop sustainable construction materials, there is a notable gap in viable alternatives to conventional CPBs that balance durability, cost-effectiveness, and environmental responsibility. Addressing this gap, Geopolymer Paver Blocks (GPBs) have emerged as a promising alternative by integrating geopolymer technology, which replaces cement with an aluminosilicate-based binder activated by alkaline solutions [11-14]. Geopolymer technology is not just about producing an alternative to Portland cement; it is about rethinking construction materials to foster sustainability in the building sector and is produced when aluminosilicate material is chemically activated by alkaline solutions, creating an efficient binder than normal cement [15-19].

GPBs offer comparable or superior performance to conventional concrete and significantly reduce carbon footprints, making them a key innovation in sustainable infrastructure. The existing literature has comprehensively documented the utilization of waste materials as a partial alternative to conventional aggregates [20-24]. One of the materials that has the potential to function as a replacement for aggregates is Reclaimed Asphalt Pavement (RAP), which is defined as a recycled aggregate comprising asphalt and mineral aggregates produced during the activities involving the removal of asphalt pavements in the processes of reconstruction and resurfacing. The construction industry generates millions of tons of RAP annually due to ongoing roadway maintenance and construction endeavors [25-28].

This investigation intends to address this research void by methodically evaluating the feasibility of utilizing RAP as an aggregate in geopolymer paver blocks. Incorporating RAP into geopolymer concrete is a major advancement in the infrastructure sector's quest for circularity and regenerating waste into useful, sustainable paving materials. Through laboratory investigations, the research will evaluate the structural and environmental performance of GPBs with RAP, providing insights into their viability as a sustainable paving solution. By addressing the dual challenge of reducing dependence on traditional cement-based materials and promoting circular economy practices, this study contributes to the broader advancement of eco-friendly infrastructure.

2. Materials and Methodology

2.1. Materials

The principal components utilized in this investigation encompass 53-grade cement, Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), Natural Fine Aggregate (NFA), Natural Coarse Aggregate (NA), and Recycled Asphalt Pavement (RAP) aggregates. The RAP incorporated in the analysis is locally sourced from an RAP stockpile, which is manually crushed and lightly processed using water jets to remove dirt or other foreign objects on the surface. The processed RAP is sieved and used as RAP aggregates per the requirement. The aggregates of RAP utilized in the current investigation comprise two separate categories: coarse RAP (CRAP), which possesses a specific gravity of 2.62, and fine RAP (FRAP), which demonstrates a specific gravity of 2.55. The study incorporates analytical-grade sodium hydroxide (NaOH) pellets characterized by a purity of 99% alongside a sodium silicate (Na2SiO3) solution. An 8M NaOH solution, in conjunction with a Na2SiO3 solution distinguished by specific proportions of Na2O = 14.7%, SiO2 = 32.8%, and H2O = 52.5%, is employed as activators. Fly ash exhibiting a specific gravity of 2.38 has been procured from the NTPC Simhadri Power Plant. GGBS with a specific gravity of 2.85 was obtained from JSW Steel Ltd, Karnataka. The Super Plasticizer (SP) used was Complast 430, an SNF-based HRWRA.

2.2. Mix Proportions

Geopolymer Concrete (GPC) mix of M40 grade has been prepared based on the trial mixes based on mix proportions used in the literature. To understand the performance of GPC in comparison to normal concrete, an M40 grade Normal Concrete (NC) mix was also prepared as per IS 10262:2019 [29]. Geopolymer RAP concrete (GPRAPC) mixes with varying RAP dosages (0 to 100%) were also cast. The mix designation and corresponding quantities of each mix are presented in Table 1.

2.3. Testing Procedure

2.3.1. Fresh Properties

The examination of concrete consistency is carried out in alignment with the criteria specified in IS: 1199: Part 2-2018 [30] to assess the workability features of freshly prepared concrete.

2.3.2. Mechanical Properties

The examination of the mechanical attributes of the concrete compositions was carried out in compliance with the directives established in IS: 516: Part 1: Sec 1-2021 [31] and IS 15658: 2021 [32]. The compressive strength analysis was performed utilizing standardized cube specimens measuring 150 mm on each side. Paver blocks, with dimensions of 200x100x60 mm, underwent rigorous evaluations pertaining to block compressive strength, split tensile strength, and flexural strength.

2.3.3. Durability Properties

The characteristics of porosity, water absorption, and sorptivity were rigorously examined to achieve a comprehensive understanding of the durability characteristics inherent to concrete mixtures. ASTM C642–13 [33] was employed to evaluate both porosity and water absorption metrics. Utilizing Hall's methodology (Hall, 1989), the Sorptivity coefficient (S) was determined.

2.3.4. Abrasion Properties

The degradation of paver blocks is attributed to the abrasive forces exerted by vehicular movement, which adversely affects their functional efficacy, thereby necessitating their evaluation. Cantabro Abrasion Loss (CAL) was ascertained in accordance with the ASTM C1747 [34] standard. Specimens with 100mm cubic dimensions were fabricated. The Los Angeles abrasion apparatus was utilized to quantify the Coarse Aggregate Loss (CAL) of all mixtures following the fulfilment of 500 revolutions.

Table 1. Mix proportions in kg/m3

Mix ID	Cement	Fly ash	GGBS	NaOH	Na_2SiO_3	NCA	NFA	CRAP	FRAP	Water
NC	408	0	0	0	0	1234.0	648.0	0.0	0.0	144.4
GPC	0	286	122	41	103	1234.0	648.0	0.0	0.0	60.0
GPRAPC20	0	286	122	41	103	987.2	518.4	232.6	124.7	60.0
GPRAPC40	0	286	122	41	103	740.4	388.8	465.2	249.4	60.0
GPRAPC60	0	286	122	41	103	493.6	259.2	697.8	374.1	60.0
GPRAPC80	0	286	122	41	103	246.8	129.6	930.4	498.8	60.0
GPRAPC100	0	286	122	41	103	0.0	0.0	1163.0	623.5	60.0

3. Results and Discussion

3.1. Workability

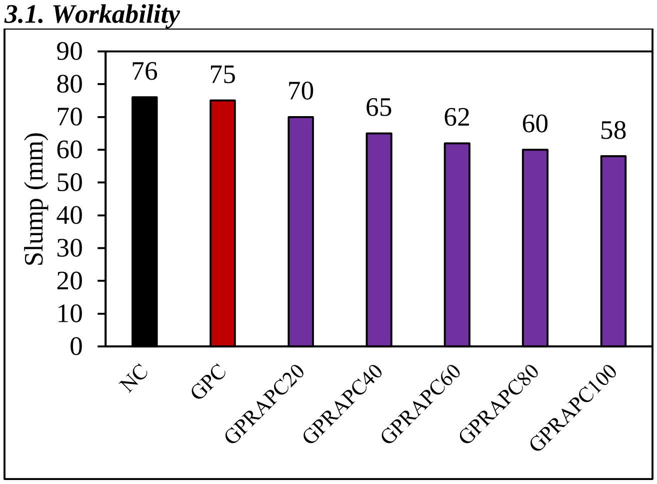


Fig. 1 Slump of the examined mixes

The slump values corresponding to all the mixtures have been quantitatively assessed and are represented in Figure 1. The integration of RAP seems to have resulted in a slump reduction, likely attributable to the increased viscosity linked to the asphalt coating on the RAP aggregates. The findings are consistent with the outcomes reported by earlier investigators [35-37].

3.2. Strength Properties

The data presented in Figures 2 and 3 demonstrate the changes in compressive strength observed during the curing durations of 7 and 28 days, respectively, for both cube specimens and paver block specimens. There was about 33% and 32% loss in the cube and block compressive strength of GPC when 100% RAP was used in place of NCA. It is noteworthy that all the concrete mixtures met the stipulated minimum compressive strength of 40 MPa, which is essential for light traffic, in accordance with IS 15658: 2021 [32].

The investigations carried out to measure the split tensile strength and flexural strength of the paver blocks indicated a correlation that closely aligned with the trend identified in the compressive strength data, a relationship that is illustrated in the graphical representations found in Figures 4 and 5. A notable decline of approximately 14.8% was identified in the split tensile strength, along with a 13.6% reduction in the flexural strength of Geopolymer Concrete (GPC) when employing 100% Recycled Asphalt Pavement (RAP) as a replacement for Natural Coarse Aggregate (NCA). The recorded decline in strength following the application of RAP as an alternative to NCA and Natural Fine Aggregate (NFA) corresponds with the conclusions reached by various academics [4, 12, 13].

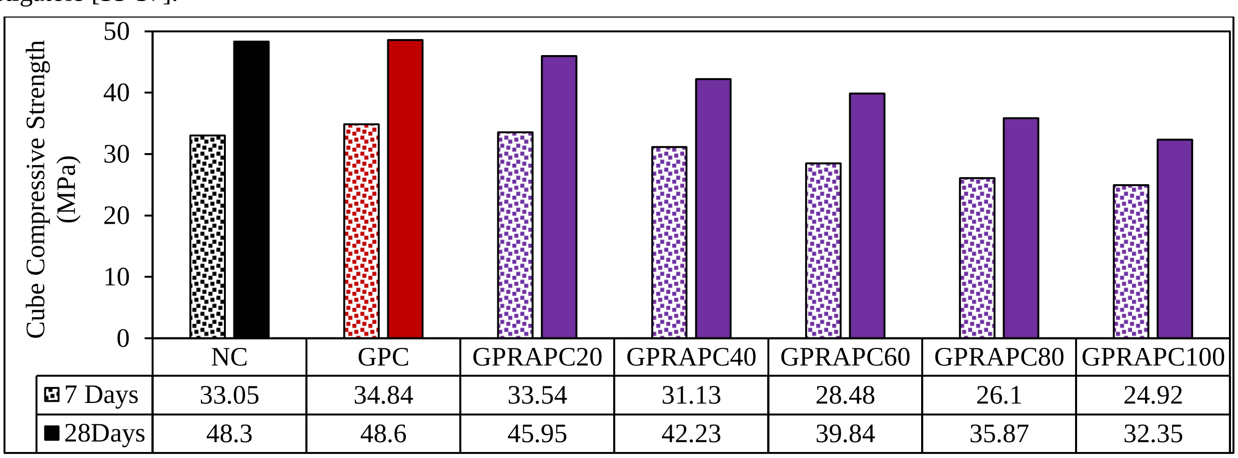
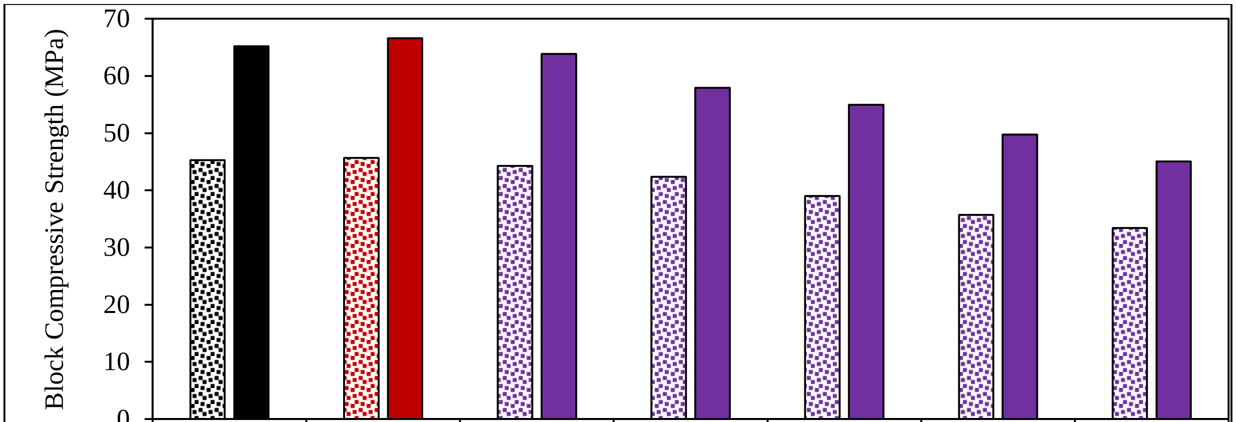
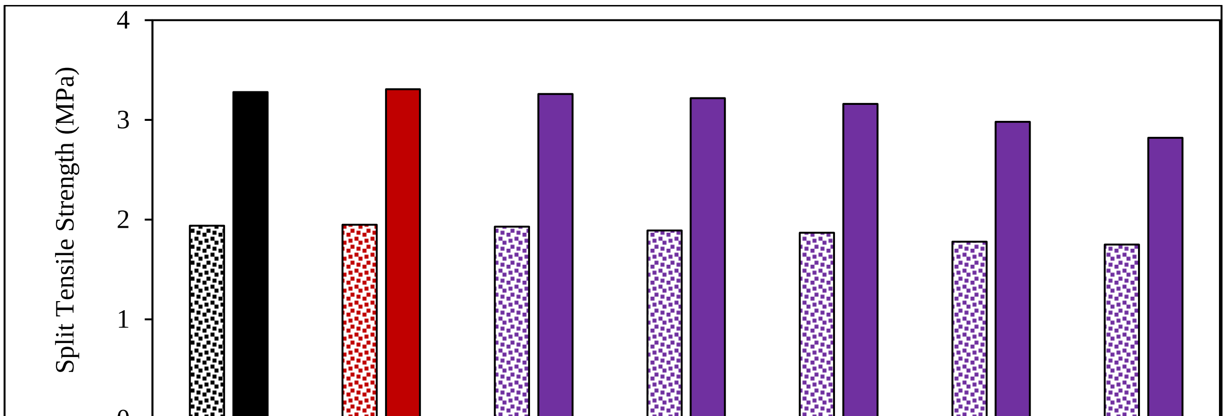


Fig. 2 Cube compressive strength of the examined mixes



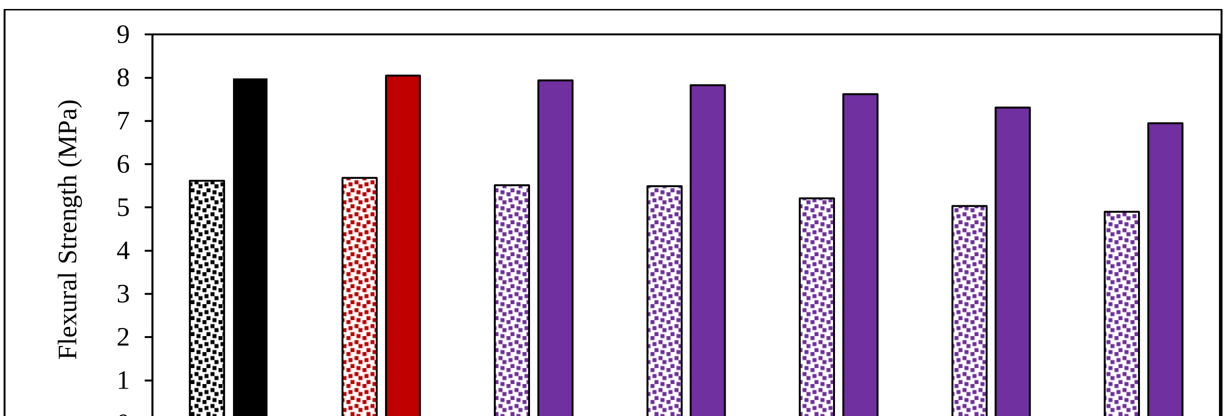
	NC	GPC	GPRAPC20	GPRAPC40	GPRAPC60	GPRAPC80	GPRAPC100
7 Days	45.27	45.64	44.28	42.34	39.02	35.71	33.39
28Days	65.21	66.58	63.87	57.9	54.98	49.78	45.06

Fig. 3 Paver block compressive strength of the examined mixes



	NC	GPC	GPRAPC20	GPRAPC40	GPRAPC60	GPRAPC80	GPRAPC100
7 Days	1.94	1.95	1.93	1.89	1.87	1.78	1.75
28Days	3.28	3.31	3.26	3.22	3.16	2.98	2.82

Fig. 4 Split tensile strength of the examined mixes



	NC	GPC	GPRAPC20	GPRAPC40	GPRAPC60	GPRAPC80	GPRAPC100
7 Days	5.62	5.68	5.51	5.49	5.21	5.03	4.9
28Days	7.98	8.05	7.94	7.83	7.62	7.31	6.95

Fig. 5 Flexural strength of the examined mixes

3.3. Durability Properties

The primary durability properties, such as water absorption and porosity, are influenced by the structural integrity of the material's void configuration. Figures 6 and 7 depict the porosity and water absorption properties associated with each specific mixture.

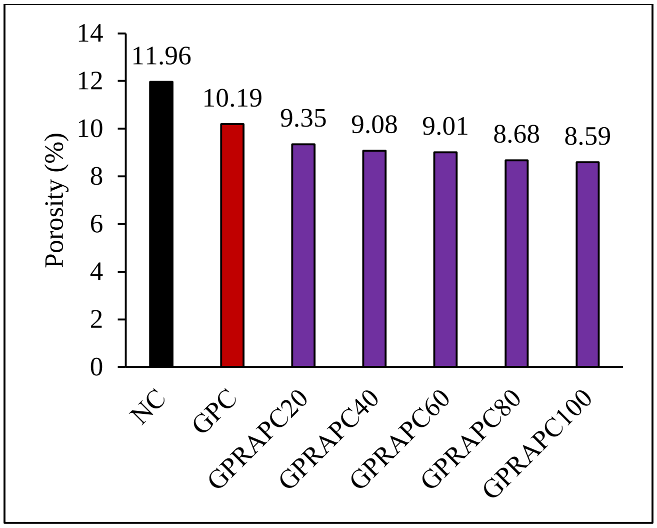


Fig. 6 Porosity of the examined mixes

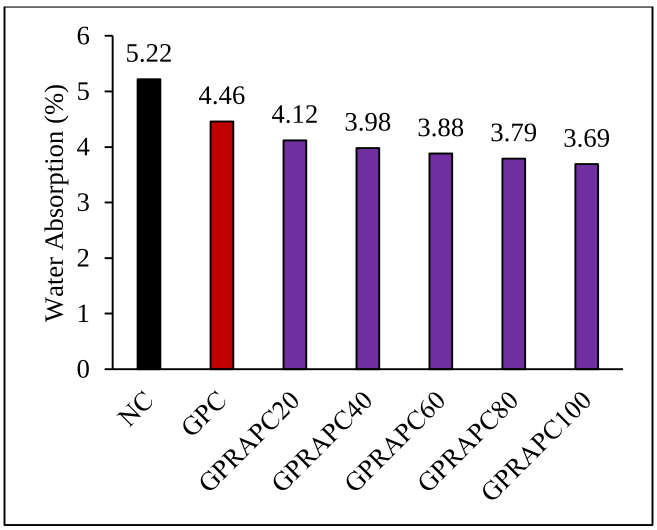


Fig. 7 Water absorption of the examined mixes

It is evident that, for comparable compressive strength, the GPC mixture exhibited superior durability relative to the NC mixture. GPC mix had 14.8% and 14.5% lower porosity and water absorption compared to the NC mix. The use of RAP aggregates further reduced these parameters. Higher RAP contents lead to notable reductions in porosity and water absorption. The more significant diminishment in porosity and moisture absorption observed in elevated RAP can be attributed to two fundamental factors. Firstly, the diminished water absorption exhibited by RAP aggregates results in a decreased water absorption rate. Secondly, the migration of asphalt contained within RAP into the voids during the oven drying process effectively seals the pores, thereby obstructing water ingress. The porosity and water absorption of GPRAPC100 is 28.18% and 29.31% less than the NC mix, implying that the GPRAPC100 performs better from a durability point of view; similar observations have been made by previous researchers as well [13].

Figure 8 illustrates the variation of the Sorptivity coefficient (S) for all the mixes. The sorptivity of GPC is about 12.93% less than that of the NC mix, and the GPRAPC100 mix had a sorptivity of 31.14% less than that of the NC mix. An underlying reason for the decreased sorptivity coefficient being RAP concretes possess fewer capillary gaps compared to NC.

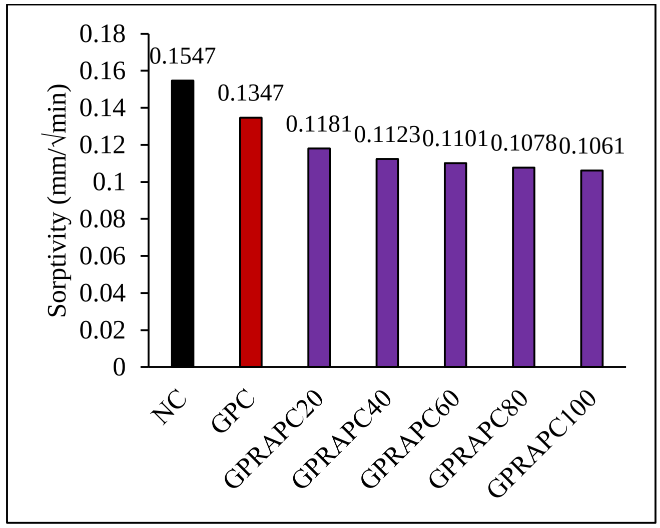


Fig. 8 Sorptivity of the examined mixes

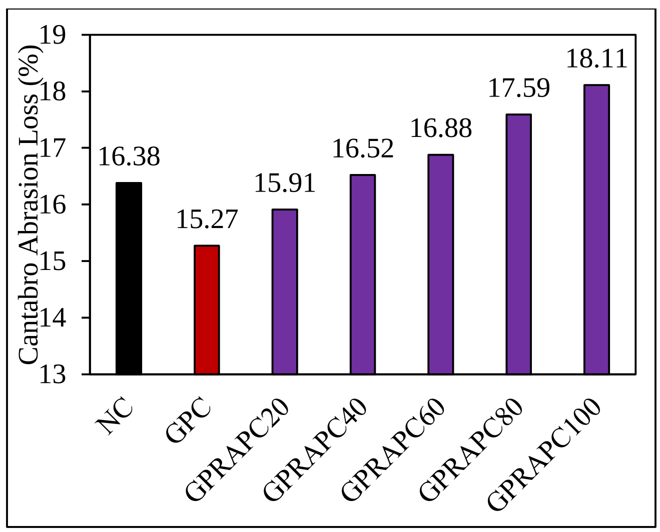


Fig. 9 Cantabro Abrasion Loss (%) of the examined mixes

3.4. Abrasion Properties

The computed metrics for Cantabro Abrasion Loss (CAL) are depicted in Figure 9. The CAL for Geopolymer Concrete (GPC) is approximately 6.77% lower than that of the Normal Concrete (NC) mix, suggesting that GPC exhibits superior performance in terms of abrasion resistance when compared to NC of equivalent compressive strength. It is noteworthy that the CAL exhibited an increase in response to a rise in the proportion of Recycled Asphalt Pavement (RAP). The GPRAPC100 mix demonstrated a CAL that was 10.56% greater than the NC mix. This phenomenon may be connected to the inadequate bonding between the cement mortar and the Recycled Asphalt Pavement (RAP), which consequently elevates its risk of structural failure.

3.5. Economic Analysis

The implementation and utilization of Geopolymer RAP Concrete (GPRAPC) presents a multitude of substantial economic benefits by significantly diminishing the dependence on traditional Portland cement and the extraction of quarried crushed aggregates. A detailed financial evaluation was systematically undertaken to analyze and quantify the economic gains that arise from replacing conventional natural aggregates with RAP aggregates, thus highlighting the possibility for greater economic efficiency in construction strategies. The overall production costs associated with GPRAPC are predominantly determined by the expenses incurred in acquiring aggregates along with the necessary binders and chemical activators required for the concrete formulation.

Table 2. Market value of materials used

Material	Cost (₹)
Cement	8/kg
Fly ash	1/kg
GGBS	2.5/kg
NaOH	25/kg
Na_2SiO_3	8/litre
NCA	0.7/kg
NFA	0.8/kg
CRAP	-
FRAP	-
Water	0.22/litre
SP	100/litre

Table 2 provides a comprehensive financial analysis of all materials utilized in the parameters of this research [12, 38]. Since RAP aggregates currently possess no commercially recognized value, as they are predominantly categorized as waste materials, thus rendering them a remarkably cost-effective substitute in the realm of construction materials. The projected production costs, expressed in terms of ₹ per cubic meter for all the mixes, including the Normal Concrete (NC), are visually represented in Figure 10. The findings from this analysis indicate that Geopolymer Concrete (GPC), when formulated with a complete 100% composition of natural aggregates, is estimated to be approximately 10% less expensive than its conventional counterpart, Normal Concrete. Moreover, substituting natural aggregates with RAP aggregates results in significant financial savings, with the GPRAPC100 mix demonstrating an impressive maximum cost reduction of 38% when juxtaposed against the baseline expenses associated with Normal Concrete.

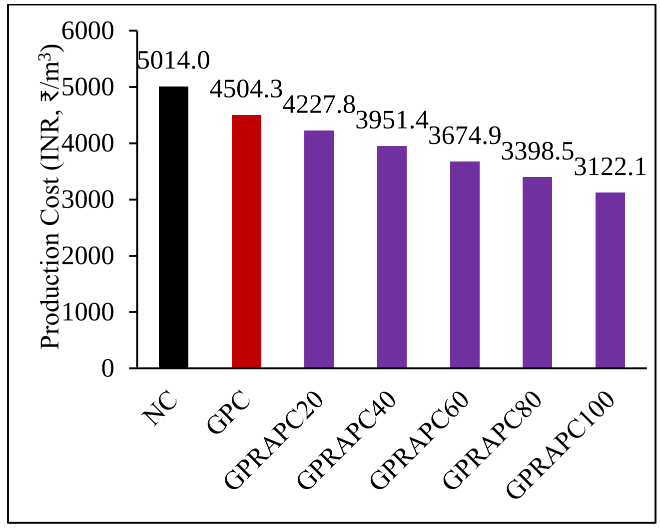


Fig. 10 Production cost of the examined mixes

4. Conclusion

Given the empirical investigation performed, the following conclusions may be articulated as follows:

- Incorporating Reclaimed Asphalt Pavement (RAP) aggregates has been associated with significantly reducing the workability of newly mixed concrete. In particular, applying 100% RAP has yielded an approximate 24% reduction in slump.
- The utilization of Recycled Asphalt Pavement (RAP) aggregates resulted in an adverse impact on the compressive, split tensile, and flexural strength attributes of the geopolymer paver blocks. Employing 100% RAP yielded an approximate 33% reduction in compressive strength for both cube and block specimens. Furthermore, there was a recorded 14.8% decline in split tensile strength and a 13.6% decrease in flexural strength when 100% RAP was utilized.
- GP mixes exhibited superior durability characteristics in comparison to conventional mixes. The augmentation of GP mixtures with RAP showcased enhanced durability, as indicated by a reduction in water absorption, porosity, and sorptivity when assessed against the NC mix. In comparison to the NC mix, the porosity, water absorption, and sorptivity of GPRAPC100 were reduced by 28.18%, 29.31%, and 31.14%, respectively, suggesting that GPRAPC100 is particularly advantageous in terms of durability.
- GPC demonstrated improved performance against abrasion when compared to NC with similar compressive strength. Significantly, the Cantabro Abrasion Loss (CAL) exhibited an upward trend alongside the RAP content. The GPRAPC100 mixture exhibited a CAL that was 10.56% greater than that observed in the standard concrete mix.

Regardless of the detected reduction in strength, all concrete formulations fulfilled the necessary minimum strength standards for light traffic applications in alignment with the IS 15658: 2021 specifications. Collectively, the incorporation of RAP in geopolymer paver blocks presents a promising environmentally sustainable and economically viable alternative to conventional concrete paver blocks, thereby contributing positively to sustainable infrastructure development.

From a policy and urban planning perspective, adopting GPBs with RAP can significantly contribute to sustainable infrastructure development by reducing construction waste and promoting circular economy practices. Governments and regulatory bodies should consider integrating GPBs into urban development guidelines and incentivizing their use in pedestrian pathways, cycle tracks, and low-traffic roadways. Municipal authorities could implement pilot projects to assess their real-world performance and encourage widespread adoption through public procurement policies. Additionally, establishing standards for RAP utilization in geopolymer concrete will enhance confidence in its application.

4.1. Scope for Future Work

Future research should focus on optimizing the mix design of GPBs with RAP to improve strength, workability, and durability while maintaining sustainability benefits. Long-term field studies are needed to assess their performance under real-world conditions, including varying traffic loads and weather effects. Strategies to enhance bonding between RAP and geopolymer binders, such as surface treatments or additives, should be explored.

A comprehensive Life Cycle Assessment (LCA) can also help quantify environmental benefits, while economic feasibility studies can support large-scale adoption. Expanding the application of GPBs with RAP to heavy-load pavements and roadways could further promote sustainable infrastructure development, reducing reliance on conventional cement-based materials and fostering circular economy practices.

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