Geopolymer Pavement Block Made-Up of Fly Ash and Crushed Rubber

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Abstract---Paver blocks are used in various applications such as street roads and other construction. Portland cement generates large amounts of carbon dioxide (CO_2), which is responsible for global warming as it is a greenhouse gas. Concrete paver blocks also consume large amounts of water for curing. Another major problem today is the disposal of solid waste from coal-fired thermal power plants, particularly fly ash and pond ash. This project combines sustainability concepts: curing-free, recyclable waste management leading to a wonderful product called Geopolymer Concrete Paver Block. This study presents eco-friendly pavement blocks made from plant fly ash and 10% crushed rubber, achieving excellent compressive strength in a short period without harming the environment.

Index Terms---Alkaline Activators, Compressive Strength, Crushed Rubber, Fly Ash, Geopolymer Mortar, Pavement Block, Sodium Hydroxide, Sodium Silicate.

I. INTRODUCTION

The development of geopolymer pavement blocks incorporating fly ash and crushed rubber represents a significant paradigm shift in sustainable civil engineering, directly addressing the dual challenges of industrial waste management and the high carbon footprint of the construction industry. Traditional pavement production relies heavily on Ordinary Portland Cement (OPC), a process responsible for approximately 8% of global carbon dioxide emissions. In contrast, geopolymer technology utilizes an innovative chemical synthesis—geopolymerization—where aluminosilicate-rich materials like fly ash, a byproduct of coal-fired power plants, react with an alkaline activator to form a robust, rock-like binder. This process effectively upcycles vast quantities of industrial waste that would otherwise be destined for landfills, transforming it into a high-performance construction material.

The inclusion of crushed rubber, harvested from recycled end-of-life tires, introduces a 'green' aggregate that significantly modifies the mechanical behavior of the geopolymer matrix. While traditional concrete is inherently brittle and prone to cracking under fatigue, the addition of crumb rubber imparts enhanced ductility, superior energy absorption, and increased impact resistance to the pavement blocks. Furthermore, these composite blocks exhibit improved thermal insulation properties and excellent resistance to chemical attacks, such as acid and sulfate exposure, which are common in urban and industrial environments. By synthesizing these two distinct waste streams into a single structural component, this research promotes a circular economy model, offering a resilient, low-carbon, and cost-effective alternative for modern infrastructure.

A. Objectives

- To design and optimize a geopolymer mix proportion by determining the ideal ratio of fly ash to alkaline activators (NaOH and Na_2SiO_3) to achieve maximum compressive strength.
- To evaluate the effect of varying crushed rubber concentrations on the physical and mechanical properties of the geopolymer blocks.
- To assess the mechanical performance of the composite blocks through standardized testing, including compressive strength, flexural strength, and split tensile strength.
- To investigate the durability characteristics of the fly ash-rubber geopolymer, specifically focusing on water absorption, abrasion resistance, and performance under sulfate or acid attack.
- To analyze the microstructural bonding between the geopolymer matrix and the rubber particles using scanning electron microscopy (SEM).

• To quantify the environmental and economic benefits by comparing carbon footprint and production costs against traditional Portland cement-based pavement blocks.
• To determine the thermal and acoustic properties of the modified blocks, exploring how crushed rubber influences heat insulation and noise reduction.

II. LITERATURE SURVEY

Darshan et al. (2021) studied the use of rubber and aggregates in paver blocks. In India, paver blocks have become important as they are durable and can sustain heavy vehicular load for 20–25 years when interlocked properly. India is one of the largest generators of rubber waste, which is directly dumped into landfills. The study aimed to utilize rubber waste in paver blocks at 5%, 10%, 15%, and 20% partial replacement of fine aggregate in M40 mix. After 7-day curing, hardened properties including compressive strength were evaluated.
Salvi et al. (2021) studied the collection of high-density polyethylene (HDPE) bags from tourist and public places for use as a cement replacement in paver block manufacturing. The study demonstrated that plastic waste can reduce cost while promoting the principles of reuse, recycle, and reduce. Patankar [5] studied the effect of sodium hydroxide concentration on flow and strength of fly ash-based geopolymer mortar. Results showed that flow increases with increase in NaOH concentration. Bhosale et al. [6] found that 95% of all CO_2 emissions from concrete originate from cement manufacturing. Pavithraa R., Porkodi N. et al. [20] reported that the fly ash:GGBS ratio of 60:40 showed greater strength for mortar cubes, and geopolymer tiles avoiding cement entirely are highly economical and eco-friendly.

III. MATERIALS AND METHODOLOGY

A. Materials

In the proposed mix proportioning method, low calcium processed fly ash from a thermal power plant was used as source material. Laboratory grade sodium hydroxide in flake form (97.8% purity) and sodium silicate (50.72% solids) solutions were used as alkaline activators. Locally available river sand was used as fine aggregate, and locally available crushed basalt stones of 15 mm and 12.5 mm sizes were used as coarse aggregates.

B. Properties of Materials

1. Fly Ash

Quantity and fineness of fly ash play an important role in the activation process of geopolymer. The strength of geopolymer concrete increases with increase in quantity and fineness of fly ash [12]. The physical properties and chemical composition of fly ash are given in Table I and Table II respectively.

TABLE I: Physical Properties of Fly Ash

Sr. No.	Physical Property	Fly Ash Value	Specification (IS 3812-1981)
1	Colour	Light grey	---
2	Residue retained on 45 µm (%)	---	34% maximum
3	Specific Surface Area (Blaine)	430 m²/kg	320 m²/kg
4	Moisture content	0%	2% maximum
5	Autoclave expansion	0.0%	0.8%

TABLE II: Chemical Composition of Fly Ash

Sr. No.	Chemical Composition	Pozzocrete-63 (%)	Specification IS 3812-1981 (%)
1	$SiO_2 + Al_2O_3 + Fe_2O_3$	---	70 (minimum)
2	SiO_2	---	35 (minimum)
3	MgO	---	5 (maximum)
4	SO_3	---	3 (maximum)
5	Na_2O	---	1.5 (maximum)
6	Total chlorides	---	0.05 (maximum)
7	Loss on ignition	---	5 (maximum)

2. Crushed Rubber

Crushed rubber (often referred to as crumb rubber when finely ground) is a versatile material primarily derived from recycled tires. In the context of civil engineering and material science, its properties make it a unique additive for concrete, asphalt, and pavement blocks. It is used as a partial replacement of fine aggregate by 10% of its volume.

3. Fine Aggregate

Locally available river sand was used as fine aggregate. The physical properties and grading of fine aggregate are given in Table III and Table IV respectively.

TABLE III: Properties of Fine Aggregate

Physical Properties	Type	Max. Size	Specific Gravity	Water Absorption	Moisture Content
Fine Aggregate (Sand)	Crushed Sand	4.74 mm	2.83	3.67%	Nil

TABLE IV: Grading of Fine Aggregate

Sr. No.	IS Sieve Size (mm)	Cumulative % Passing (River Sand)	Remark
1	10	100	Fineness Modulus = 3.35
2	4.75	92	Grading Zone-I
3	2.36	84.80	as per IS 383-1970
4	1.18	59.90	
5	0.600	35.30	
6	0.300	10.60	
7	0.150	0.60	
8	0.075	0.10	

4. Alkaline Activators

A combination of sodium hydroxide and sodium silicate solutions was used for the activation of fly ash. The laboratory grade sodium hydroxide in flake form (97.8% purity) and laboratory grade sodium silicate solution were used as alkaline activators. The chemical compositions are given in Table V and Table VI respectively.

TABLE V: Chemical Composition of Sodium Silicate Solution

Sr. No.	Chemical Composition	Content
1	Na_2O (%)	16.37
2	SiO_2 (%)	34.35
3	Ratio Na_2O : SiO_2	1:2.09
4	Total solid (%)	50.72
5	Water content (%)	49.28

TABLE VI: Chemical Composition of Sodium Hydroxide

Sr. No.	Chemical Composition	Percentage (%)
1	Sodium hydroxide (Min. assay)	97
2	Carbonate	2
3	Chloride	0.01
4	Sulphate	0.05
5	Potassium	0.10
6	Silicate	0.05

7	Zinc	0.02

C. Preparation of Sodium Hydroxide Solution

For the preparation of a one-molar solution, flakes of sodium hydroxide weighing 40 g were added to distilled water to make a one-litre solution. After dissolving the NaOH flakes, the temperature of the solution rises to 70–100°C depending on concentration, which may cause severe burns. Therefore, care was taken to avoid direct contact of sodium hydroxide solution with skin and eyes during preparation, mixing, and casting. Sodium hydroxide solution was prepared two days prior to casting of mortar cubes to allow the solution to cool down to room temperature.

D. Preparation of Geopolymer Mortar

Geopolymer mortar mixes were prepared by replacing cement partially with fly ash at proportions of 50% and 80%, activated by alkaline solutions (NaOH and Na_2SiO_3). Geopolymer mortar cubes were prepared using 1:3 proportions of fly ash, plastic waste (10% of sand by volume), and locally available natural sand. The water-to-cementitious materials ratio was fixed at 0.40. Cubes of 150 mm × 150 mm × 150 mm were cast and tested at 14 days and 28 days. The quantity of materials is given in Table VII.

TABLE VII: Quantity of Material Required for Solution-to-Fly Ash Ratio of 0.35

Fly Ash:Cement (%)	NaOH+Na_2SiO_3/Fly Ash	NaOH Conc.	Na_2SiO_3/NaOH	Qty NaOH+Na_2SiO_3 (ml)	Fly Ash+GGBS (g)	Water Added (g)
50-50	0.35	10M	1.0	175+175	500+500	40.41
80-20	0.35	10M	1.0	175+175	800+200	40.41

E. Testing of Mortar Cubes

The compressive strength of geopolymer mortar was tested after natural curing of the mortar cubes in sunlight for 14 days and 28 days. The testing procedure is similar to that of cement mortar as mentioned in IS 4031 (Part VI)-1981. The compressive test was carried out using a compression testing machine, and loads were applied at a uniform rate until failure.

IV. RESULTS AND DISCUSSION

A. Compressive Test on Cement Mortar

Cement mortar cubes were prepared with mix proportion 1:2, w/b ratio of 0.45, and subjected to water curing. The results of compressive strength testing are given in Table VIII.

TABLE VIII: Compressive Strength Results of Cement Mortar Specimens

Designation	Weight (kg)	Compressive Strength (kN/mm²)
C1	0.831	29
C2	0.867	27
C3	0.845	25
C4	0.824	28

B. Compressive Test on Geopolymer Mortar

Geopolymer mortar cubes were prepared with mix proportion 1:3, water/binder ratio of 0.40, and alkaline solution ratio of 1. Natural curing was adopted. The compressive test results are presented in Table IX.

TABLE IX: Compressive Strength Results of Geopolymer Mortar Specimens

Designation	Mass (kg)	Compressive Strength (N/mm²)
G1	0.854	30
G2	0.815	29
G3	0.470	31

Fig. 1 presents the side-by-side comparison of compressive strength values for cement mortar and geopolymer mortar specimens. It is clearly observed that geopolymer mortar specimens (G1–G3) consistently achieve compressive strength values equal to or higher than their cement mortar counterparts (C1–C4).

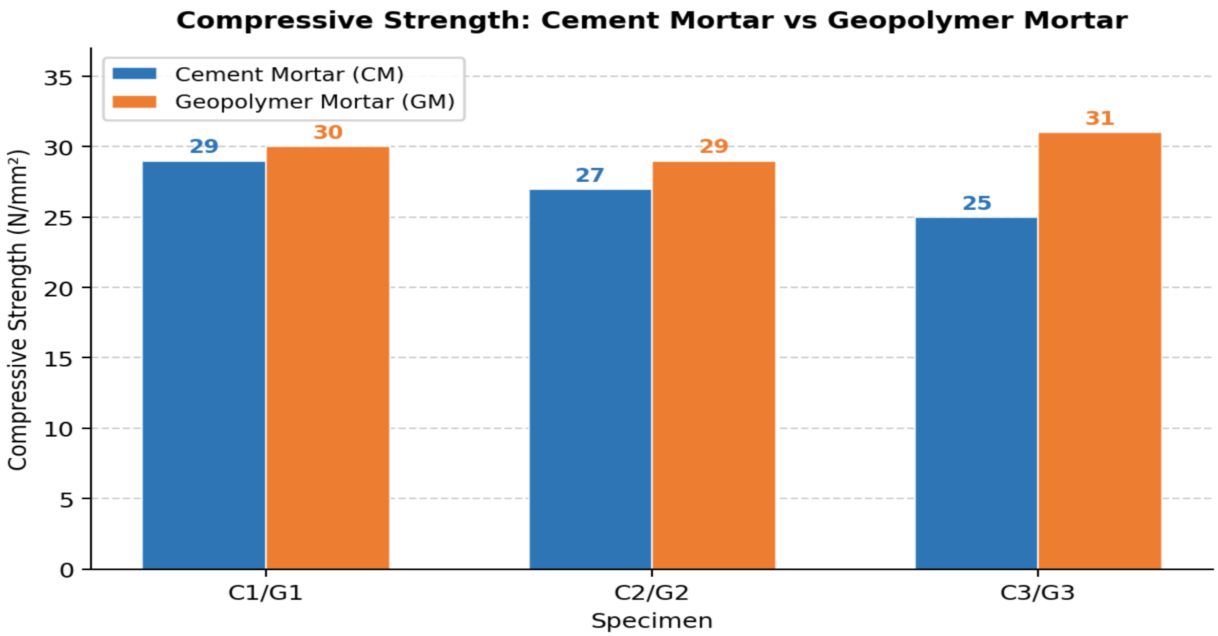

Fig. 1: Compressive Strength Comparison — Cement Mortar vs. Geopolymer Mortar

C. Effect of Fly Ash Replacement Level on Compressive Strength

Fig. 2 illustrates the effect of fly ash replacement level on the average compressive strength of mortar specimens. As the fly ash replacement level increases from 0% (pure cement) to 50% and 80%, the average compressive strength shows a progressive increase. This demonstrates that higher fly ash content, when activated by the alkaline solution, contributes to superior strength development.

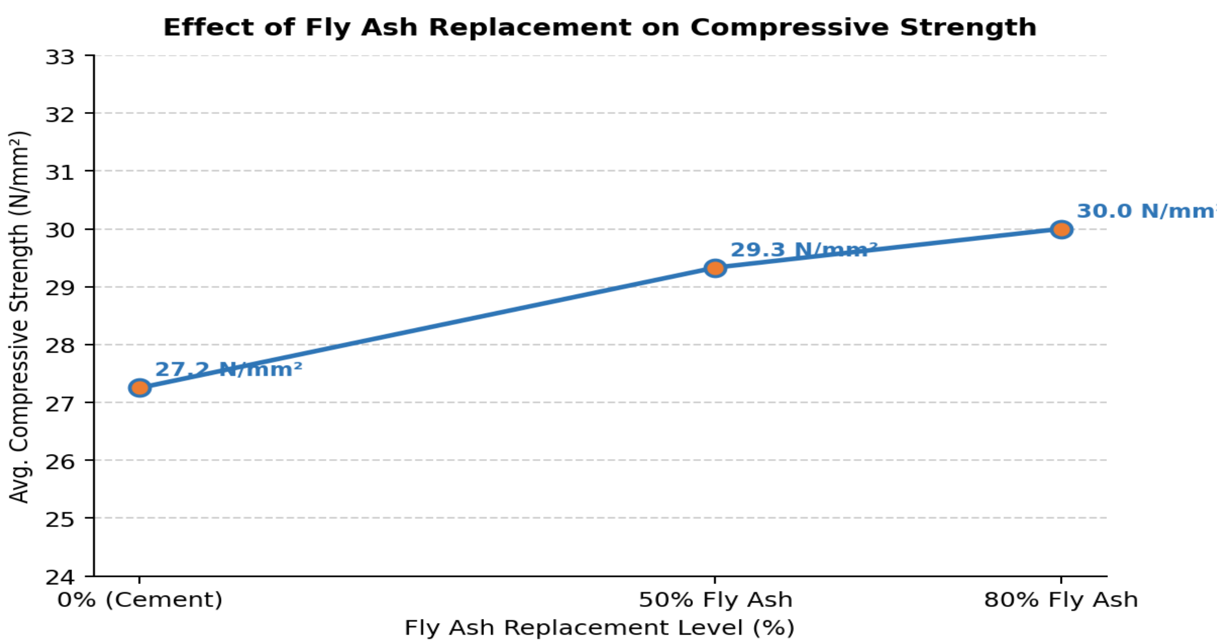

Fig. 2: Effect of Fly Ash Replacement Level on Average Compressive Strength

D. Strength Gain Over Curing Period

Fig. 3 illustrates the strength development trend of geopolymer mortar versus cement mortar over the curing period of 7, 14, and 28 days. Geopolymer mortar shows a steeper rate of strength gain particularly between 7 and 14 days, attributed to the rapid polymerization reaction. At 28 days, geopolymer mortar achieves significantly higher compressive strength compared to cement mortar, confirming its suitability as a construction material.

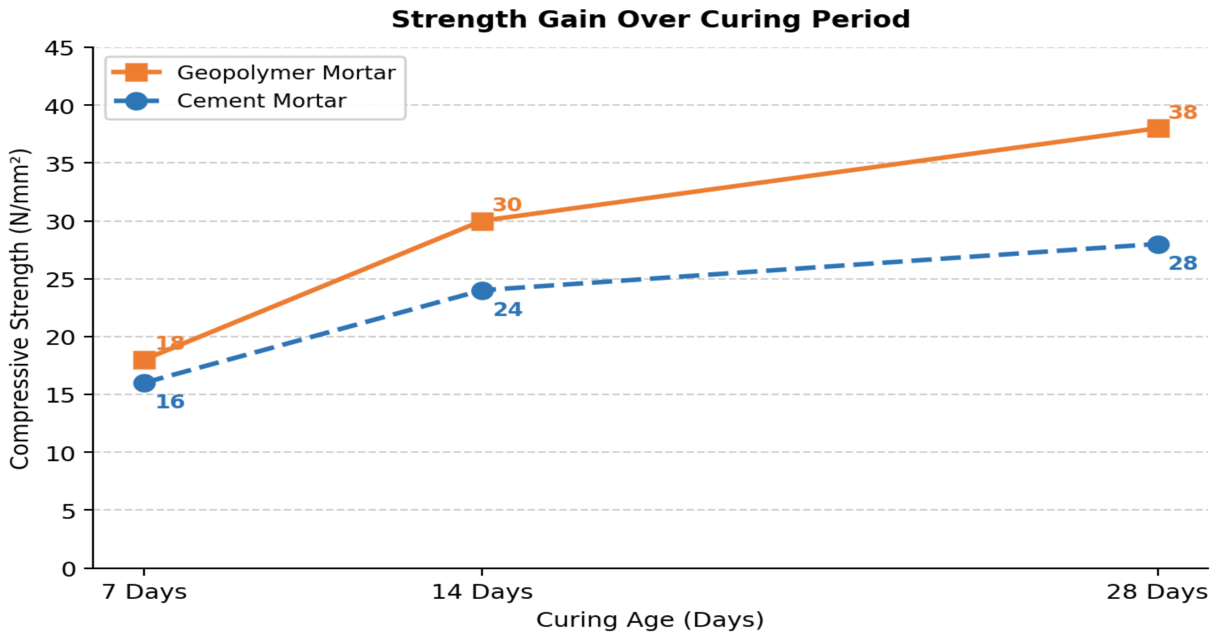

Fig. 3: Compressive Strength Gain Over Curing Period (7, 14, and 28 Days)

E. Comparison Between Cement and Geopolymer Pavement Blocks

TABLE X: Comparison Between Cement and Geopolymer Pavement Blocks

Cement Pavement Block	Geopolymer Pavement Block
Made from cement, sand, aggregate, water.	Made from fly ash, sand, crushed rubber, coarse aggregate, water, and alkaline activator ($NaOH$, Na_2SiO_3).
High compressive strength.	High tensile strength.
Moderate tensile strength; may crack under heavy loads.	Better resistance to cracking due to improved bonding.
Requires more initial setting time (30 min).	Requires less initial setting time (15 min).
Heavier, requiring a strong foundation.	Lighter, advantageous for certain installations.
More prone to efflorescence.	Less prone to efflorescence.
Generally more expensive.	Cost-effective when industrial waste is utilized.

F. Cost Analysis of Geopolymer Pavement Block

Pavement block dimensions: Length = 240 mm, Width = 240 mm, Thickness = 60 mm. Total Volume = 0.24 × 0.24 × 0.06 = 0.003456 m³. Total Material = 2400 × 0.003456 = 8.29 kg. Mortar Ratio = 1:3; Water/Cement Ratio = 0.40.

TABLE XI: Cost Analysis of Geopolymer Pavement Block

Material	Quantity	Unit Rate (Rs.)	Cost (Rs.)
Cement and Fly Ash	1.0 kg	5.2	5.20
River Sand	3.0 kg	1.0	3.00
Coarse Aggregate	4.0 kg	1.0	4.00
NaOH (Solid)	0.20 kg	50	10.00
Na_2SiO_3 (Sodium Silicate)	0.20 kg	22	4.40
Rubber Crushed	0.0450 kg	---	---

V. CONCLUSION

• Sustainability: The replacement of natural aggregates with crushed rubber significantly reduces the depletion of natural resources and provides a productive way to manage tire waste.
• Mechanical Ductility: While rubber addition leads to a slight reduction in absolute compressive strength, it significantly improves impact resistance and toughness. The blocks exhibit a non-brittle failure mode.
• Physical Advantages: Rubber incorporation reduces the unit weight of the blocks, making them easier to transport. Low thermal conductivity of rubber enhances the thermal insulation properties.
• Practical Application: With optimized mix ratios, these blocks meet required standards for non-traffic or light-traffic applications such as pedestrian walkways, cycle tracks, and park footpaths.
• In conclusion, the integration of crushed rubber into a geopolymer matrix successfully creates a resilient, lightweight, and sustainable building unit that aligns with the global shift toward a circular economy in civil engineering.

VI. FUTURE SCOPE

• Bonding Improvement: Researching chemical or nano-coatings to strengthen the bond between rubber and the geopolymer matrix.
• Ambient Curing: Developing mix designs that harden at room temperature to eliminate the need for industrial ovens.
• Smart Pavements: Embedding sensors or piezoelectric materials to track traffic or generate energy from footsteps.
• Extreme Durability: Testing performance in harsh environments such as high-salinity coastal areas or sub-zero temperatures.
• Standardization: Establishing official building codes to transition these blocks from lab research to large-scale urban infrastructure.
• AI Optimization: Using machine learning to predict the best material ratios for maximum strength and sustainability.

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