

Sustainable Geopolymer Concrete Using Recycled Brick Dust and Fly Ash: A Strength-Based Study

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Abstract - The rapid increasing demand for concrete driven by rapid urbanization has resulted in significant natural resource depletion and a rise in carbon dioxide emissions associated with ordinary Portland cement (OPC) production. This study investigates the development of geopolymer concrete (GPC) as a sustainable and environmentally friendly alternative, utilizing recycled brick dust (RBD) and fly ash (FA) as aluminosilicate-based binders. In this research focuses on the partial replacement of FA with RBD at varying ratios (0%, 20%, 40%, 50%, 60%, and 80%) to evaluate its impact on compressive strength. The geopolymer mixtures were activated used of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), with the NaOH concentration kept constant at 10M. A fixed $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 2.5 and an alkali activator-to-binder ratio of 0.4 were maintained across all mixes. Each Specimens were heat-cured at 90°C for 24 hours, followed by ambient curing for 3, 7, and 14 days. The Specimen compressive strength tests were conducted to determine the mechanical performance of the resulting GPC. The results shown that replacing fly ash with 40–60% brick dust produced the highest compressive strength, reaching approximately 48.03 MPa at 14 days, compared to 30 MPa for conventional cement concrete blocks. The study displayed that potential of RBD and FA-based GPC as a high-strength, eco-conscious construction material. By using this industrial waste, this application not only reduces dependency on OPC but also contributes to lower carbon emissions and enhanced sustainability in construction practices.

Keywords: Aluminosilicate, Binder, Recycled Brick dust, Compressive Strength, Geopolymer Concrete.

I. INTRODUCTION

Concrete is one of the most utilize construction materials globally, due to its durability, versatility and cost-effectiveness. However, the production of Ordinary Portland Cement (OPC) a primary binder in conventional concrete, accounts for approximately 8% of global CO_2 emissions and contributes significantly to natural resource depletion [1,2]. Owing to rapid urbanization increase demand for construction materials, there is an urgent need to progress sustainable

alternatives that not only mitigate environmental impacts but also maintaining structural performance.

Recent study, Geopolymer Concrete (GPC) has emerged as a promising solution, like Aluminosilicate materials such as Fly Ash (FA) and Recycled Brick Dust (RBD) activated by alkaline solutions to replace OPC entirely. Geopolymers not only reduce carbon footprints by up to 80% compared to OPC [3] but also valorize industrial byproducts (e.g. FA from coal combustion) and construction waste (e.g. RBD), aligning with circular economy principles [4]. Recent research determine that GPC can achieve compressive strengths exceeding 40 MPa, rivaling traditional concrete [5,6].

Research have demonstrated that Recycled Brick Dust (RBD) a finely ground byproduct of crushed bricks which displayed high concentrations of silica (SiO_2) and alumina (Al_2O_3). Whenever mixed with fly ash and activated using alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), RBD can form a robust geopolymer binder [7]. This sustainable alternative to traditional cement not only enhances the mechanical properties of concrete but also promotes the circular economy by repurposing industrial waste. Accordingly, geopolymer-based concrete blocks produced from RBD and fly ash present a viable eco-friendly solution for road construction and other construction, which reducing both environmental pollution and the reliance on virgin raw materials.

Recent research in geopolymer concrete (GPC) has explored using a range of industrial by-products to boost both mechanical performance and sustainability. For example, Ganesh and Mohana et al. (2023) produced GPC by replacing 0–40% of fly ash with ground granulated blast furnace slag (GGBS), activating the mix with 8–14 M sodium hydroxide and adding iron slag (10–45%) as fine aggregate along with banana fibers (0–1.5%) for reinforcement. They reported notable gains in compressive strength, workability, and durability, which they attributed to greater pozzolanic reactivity and the bridging effect of the fibers [8]. A study of Afonso et al. (2021) used glass polishing waste as a silicate-rich precursor, fine-tuning the $\text{SiO}_2/\text{Al}_2\text{O}_3$ molar ratio between 2.5 and 3.0. They found that a ratio of 2.5 delivered the best strength and microstructural stability under ambient curing,

showing how critical precursor chemistry is to performance [9]. Deb et al. (2014) found that mixing fly ash with GGBS could boost early-age strength thanks to its higher calcium content. However, it was shown that too much GGBS made the mix less workable, showing there's a balance to be struck between reactivity and ease of placement [10]. Zhang et al. (2021) They found that strength remain consistent up to a 40% replacement of fly ash with brick powder, but using more than that made the mix harder to work with because it required extra water and the binder became less effective [11]. Liu et al. (2019) pointed out the environmental benefits of using brick waste in geopolymer concrete, showing about a 70% reduction in CO₂ emissions along with lower production costs. It underscores how brick waste based geopolymer concrete could offer an affordable, low carbon option for construction [12]. Together, these studies show that incorporating alternative aluminosilicate sources like brick dust and industrial waste into geopolymer systems is not only practical but also supports circular economy principles and sustainable construction. Although these benefits, there are still challenges to overcome when it comes to optimizing geopolymer formulations. Some critical parameter such as the ratio of aluminosilicate precursors (FA/RBD), alkali activator concentration (NaOH/Na₂SiO₃) and curing regimes critically influence mechanical properties [13,14]. Some previous studies report conflicting results on partial RBD replacement while some indicate strength gains at 40–60% RBD [15] others note reduced workability at higher RBD content [16]. Furthermore, the relationship between RBD's particle size, chemical composition and reactivity remains underexplored [1]. Every year in Bangladesh, where brick kilns generate approximately 6 million tons of waste [17] and FA stockpiles from power plants pose disposal challenges, GPC presents a dual opportunity for waste repurposing and sustainable construction. This research investigates the compressive strength of FA–RBD-based GPC, with RBD replacing FA at 0%, 20%, 40%, 50%, 60%, and 80%. A fixed NaOH molarity (10M), Na₂SiO₃/NaOH ratio (2.5) and heat curing (90°C for 24 hours) are employed to isolate the impact of RBD content.

In this research, the present study aims to develop geopolymer concrete (GPC) blocks for construction applications by utilizing a mixture of Recycled Brick Dust (RBD) and fly ash (FA) as main aluminosilicate precursors. A multiple mix designs were formulated with varying proportions of RBD to evaluate their influence on the compressive strength of the geopolymer concrete. Through systematic testing, the objective was to identify the optimal FA–RBD blend that delivers superior mechanical performance. Additionally, a comparative cost analysis was showed between geopolymer concrete and conventional Ordinary Portland Cement (OPC) concrete to assess the economic feasibility and potential for large-scale application

of this sustainable construction material in the Bangladeshi context.

II. MATERIALS AND METHODS

This research focuses on producing geopolymer concrete (GPC) blocks suitable for road construction by using recycled brick dust (RBD) and fly ash (FA) as the main binder materials. This experimental approach involved selecting the suitable materials for preparing different mix designs, casting samples, and testing their mechanical properties, with a primary focus on compressive strength.

2.1 Materials

2.1.1 Fly Ash

The main focus of this study considered the application of Fly Ash (FA) as a supplementary cementitious material (SCM) in concrete. Fly ash is a fine material which generated from the combustion of pulverized coal in thermal power plants. It is primarily composed of silica (SiO₂), alumina (Al₂O₃) and iron oxide (Fe₂O₃), giving it pozzolanic properties which allow it to react with calcium hydroxide in the presence of water to form additional cementitious compounds. The fly ash used in this research collected from Confidence Cement Limited as well as conformed to ASTM C618 Class F specifications and had a specific gravity of approximately 2.20. It controlled less than 10% loss on ignition (LOI) and had a fineness such that at least 75% passed through a 45-micron sieve.

Table 1: Chemical composition of Fly Ash [18]

Chemical Composition	Fly Ash (%)
SiO ₂	55
Al ₂ O ₃	24.7
Fe ₂ O ₃	7.7
CaO	6.2
MgO	0.7
SO ₃	1.1
K ₂ O	1.1
Na ₂ O	N/A

2.1.2 Recycled Brick Dust (RBD)

This study incorporated Recycled Brick Dust (RBD) as a supplementary cementitious material (SCM) in the development of geopolymer concrete. RBD is a finely ground material obtained from discarded clay bricks which was collected from construction and demolition (C&D) sites. These bricks were crushed and pulverized to produce a consistent, fine powder suitable for use as a pozzolanic component in concrete. The brick powder primarily consists of silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and iron

oxide (Fe_2O_3) chemical constituents similar to those found in traditional pozzolans. These oxides enable to participate in geopolymerization reactions when activated with alkaline solutions, forming binding gels such as sodium aluminosilicate hydrate (N-A-S-H), which significantly increased the mechanical properties of the resulting concrete. In this research, the Brick was obtained from dismantled masonry structures which were approximately 30 years old. The demolished building consisted of traditional clay bricks which had lost their structural integrity. At first the collected bricks were manually cleaned to remove residual mortar, plaster and other surface contaminants. Subsequently, the bricks were broken into smaller fragments using a hammer and the coarse particles were manually ground to a fine powder using a mortar and pestle. To ensure that consistency in particle size, the powder was sieved through a 75 μm mesh. The resulting fine RBD was used as a partial replacement for fly ash in the geopolymer binder matrix. The RBD used in this research exhibited a specific gravity of approximately 2.15. Its fineness was suitable for blended binder systems, with at least 75% passing through a 45-micron sieve. Based on chemical analysis, the RBD contained approximately 63.21% SiO_2 , 16.41% Al_2O_3 , and 6.05% Fe_2O_3 , along with minor quantities of CaO , MgO , K_2O , and Na_2O . [19]

Table 2: Chemical composition of Recycled Brick Dust [19]

Chemical Composition	RBD (%)
SiO_2	63.21
Al_2O_3	16.41
Fe_2O_3	6.05
CaO	0.52
MgO	1.11
K_2O	2.83
Na_2O	1.19
SO_3	N/A

2.1.3 Alkali Activators

In this study, a blend of NaOH solution and Na_2SiO_3 solution is used as the alkaline solution. Sodium silicate (Na_2SiO_3) is a commonly used precursor in the synthesis of geopolymer materials. A 10M NaOH solution was prepared by dissolving locally sourced sodium hydroxide pellets, which had a purity of 97%, in tap water. The sodium silicate were collected from local market, featuring a molar ratio (MR) of 2.65 (calculated as SiO_2/Na_2O), with a composition of 34.4% SiO_2 , 13% Na_2O , and 52% H_2O . The alkaline activator solution was then prepared by combining sodium silicate and NaOH in a ratio of 2.5 ($Na_2SiO_3/NaOH$).

2.1.4 Fine Aggregate

The fine aggregate used in the study was locally available Sylhet sand with particle sizes below 4.75 mm, as confirmed by the sieve analysis. This type of sand was chosen due to its local availability and suitability for concrete production. Based on the gradation curve, Figure:1 the sand displays a well-distributed particle size range, and the calculated fineness modulus (FM) is 2.7, indicating it falls within the typical range for medium sand, making it appropriate for use as fine aggregate in geopolymer concrete.

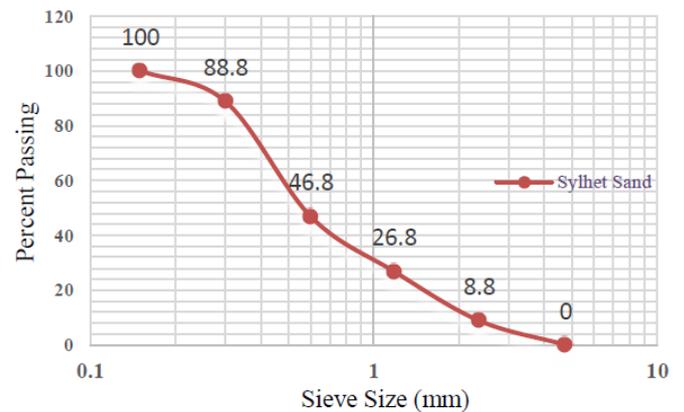


Figure 1: Grain size distribution curve of sand

2.1.5 Water

In this research, tap water supplied by the Water Supply and Sewerage Authority (WASA) was used all stage of the preparation of geopolymer concrete. This included the mixing of alkaline activator solutions (sodium hydroxide and sodium silicate), blending with dry materials such as fly ash and recycled brick dust, as well as for the casting and heat curing of cube samples. The water used at every stage had a pH between 6.5 and 9.5, to ensuring it was suitable for the chemical reactions in geopolymerization. Maintaining this range is important because water with the wrong pH or impurities can disrupt the dissolution of aluminosilicate precursors and slow down the formation of the geopolymer gel. Although no specialized water treatment was applied, the tap water used satisfied standard quality requirements for concrete production. It exhibited no detrimental effects on the compressive strength or setting characteristics of the geopolymer mix.



Demolished bricks collected from an old building site



Brick chips making from demolished brick



Recycled brick powder



Fly ash

Raw Materials



Sodium silicate



Sodium hydroxide pellets

Alkaline Activators



Sand: FM 2.7 (Size below 4.75 mm)



Water: pH 6.5- 9.5

Others

Figure 2: Materials used

2.2 Methods

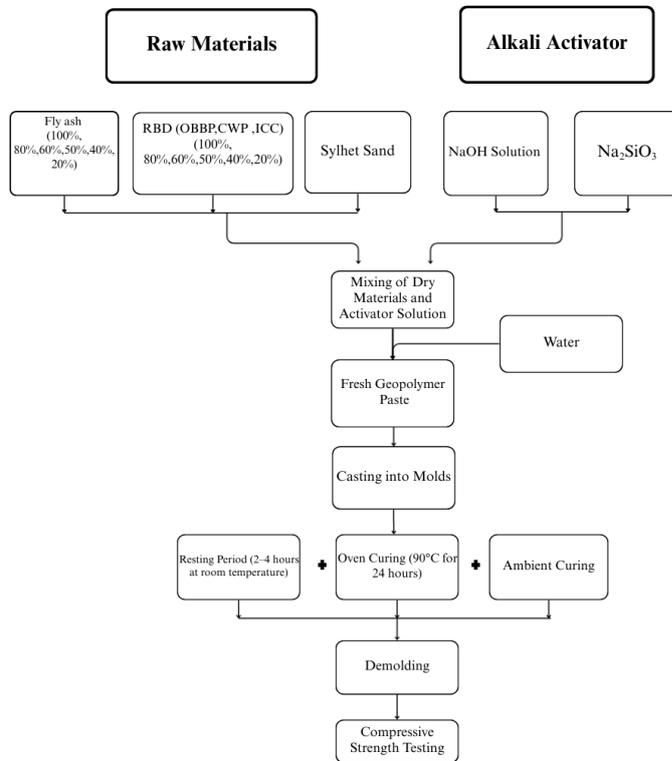


Figure 3: Methodology

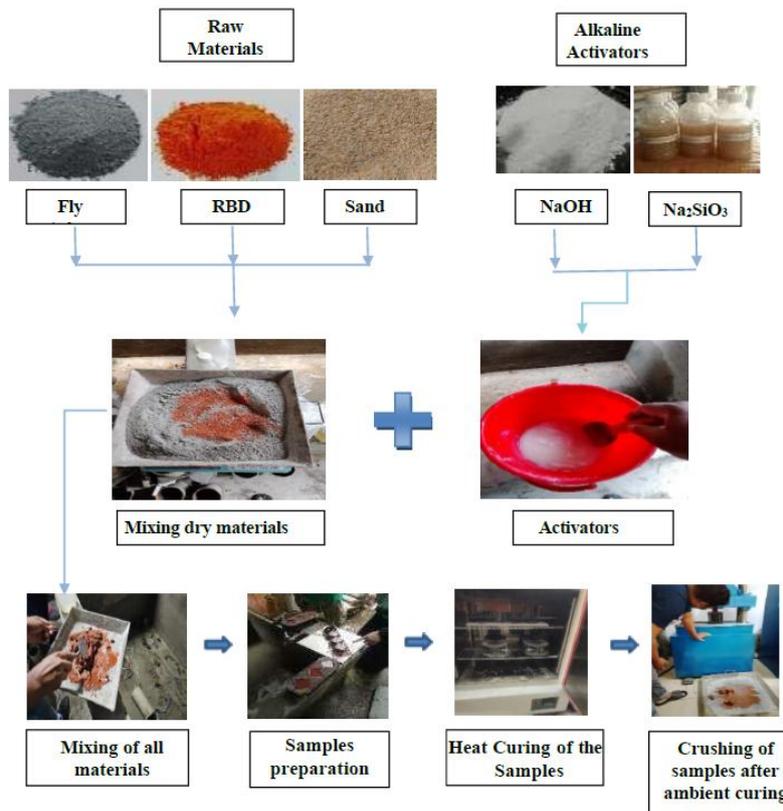


Figure 4: Flow chart of Mixing, Pouring, and Curing of GPC sample

2.2.1 Mixing of GPC Specimens

At first, the mixing process started with preparing the alkaline activator solution at least 24 hours in advance. A 10M sodium hydroxide (NaOH) solution was prepared by dissolving sodium hydroxide and pellets (97% purity) in tap water. This solution was then mixed with sodium silicate at a fixed mass ratio of 2.5:1. Before use, the mixture was allowed to cool to room temperature. The dry materials fly ash (FA) and recycled brick dust (RBD) were first blended in a mechanical mixer to achieve uniformity. We used fine and coarse aggregates, in a saturated surface-dry (SSD) condition, were then gradually added and thoroughly mixed. For all mixes containing RBD, the alkali activator solution was dosed at 70% of the RBD mass, with additional water added at 40% of the total binder mass. An alkali activator-to-binder ratio of 0.4 was remain fixed for all mixes. In this study, the alkaline solution and water were incorporated into the dry mix under continuous mixing to ensure uniform dispersion. After, the fresh geopolymer concrete was then placed into 100 mm cube molds in layers, each compacted manually with a tamping rod and lightly vibrated to expel air voids. Finally, we covered the mold by plastic sheets to maintain moisture during curing

Table 3: Materials proportion details

Proportion	Fly Ash (g)	Brick Dust (g)	10 Molarity of Alkaline Activator Solution (AAS)		Sand (g)	Water (g)
			Sodium Silicate (g)	Sodium Hydroxide (g)		
100% Fly ash (FA)	1200	-----	600	240	240	480
100% Brick Powder	-----	1200	600	240	240	480
80% FA+20% BP	960	240	120	48	240	480
60% FA+40% BP	720	480	240	96	240	480
40% FA+60% BP	480	720	360	144	240	480
50% FA+50% BP	600	600	300	120	240	480
20% FA+80% BP	240	960	480	192	240	480

2.2.2 Curing of Geopolymer Concrete (GPC) Blocks

After casting, the GPC specimens were left to rest for 2–4 hours before being placed in a laboratory oven for heat curing at 90 °C for 24 hours. This thermal treatment helped speed up the geopolymerization process and boost early-age strength development [20]. Once curing was complete, the specimens were removed from the molds, cooled to ambient temperature and kept under normal laboratory conditions for further curing. Finally, compressive strength tests were carried out at 3, 7 and 14 days to monitor the performance of the mixes and assess their strength development over time.

III. RESULTS AND DISCUSSION

3.1 Compressive Strength of GPC Specimens

The compressive strength results for the FA-RBD mixtures are shown in Table 4 and Figure 5, 6, 7 & 8 with each value representing the average of at least three tested specimens. The data expressed that the proportion of fly ash (FA) replaced by recycled brick dust (RBD) significantly influenced the strength development of the geopolymer mixtures. The compressive strength values ranged between 34.98 MPa and 48.03 MPa. The highest strengths were measured in the mixes F40+RBD60, F50+RBD50 and F20+RBD80, corresponding to 60%, 50% and 40% RRBD replacement levels, respectively. These mixes exhibited compressive strengths that were 37%, 35% and 34% higher than the control mix (F100+RBD0). As shown in Figure 9, increasing the RBD content from 0% to 60% led to a continuous improvement in compressive strength. Whenever, beyond 60% replacement, the strength began to decline slightly, reaching 35.75 MPa in the mix F0+RBD100, which remained comparable to the control mix. The optimum FA-RBD mixtures is F40+RBD60 which is 48.03 MPa, 45.87 MPa, 41.90 MPa respectively for 14 days, 7 days and 3 days compressive strength.

The rise in compressive strength is largely due to the combined contribution of soluble silica from the alkaline activator, fly ash (FA) and recycled brick dust (RBD). This well-balanced mix supports steady strength development throughout the curing process. A key factor is the gradual release of silica and alumina from the brick dust in the highly alkaline 10M NaOH solution, which accelerates the geopolymerization reaction [21]. However, when more than 40% of the FA is replaced, the total silica and alumina content drops—since FA is the main source of these compounds. With less silica and alumina available, fewer strong Si–O–Al bonds can form between the FA and RBD particles, which may explain the drop in compressive strength [22]. In addition,

mixes made entirely with FA tend to show lower strength because FA contains less calcium, meaning less material dissolves during activation. Table 5 compares the compressive strength of three mixtures—F40+RBD60, F100+RBD0, and Conventional Cement (CC) blocks—tested at 3, 7, and 14 days. By day 14, F40+RBD60 was about 37% stronger than F100+RBD0 and nearly 50% stronger than CC blocks. It also showed that more consistent strength gains from the early stages, suggesting faster and more efficient geopolymerization. Both geopolymer mixes outperformed cement concrete blocks, proving the superior mechanical performance of geopolymer concrete made with recycled brick dust. Among them, F40+RBD60 delivered the highest strength, making it a promising and sustainable alternative to both traditional cement concrete and fly ash-only geopolymers.

Table 4: Compressive strength test results

FA-RBD Mixtures	14 days, MPa	7 days, MPa	3 days, MPa
F100+RBD0	34.98	31.63	20.69
F80+RBD20	37.12	32.06	31.60
F60+RBD40	46.92	44.00	40.03
F40+RBD60	48.03	45.87	41.90
F50+RBD50	47.27	44.28	39.52
F20+RBD80	36.12	32.79	31.41
F0+RBD100	35.75	32.70	31.07

Table 5: Optimal Compressive strength compared to conventional cement concrete blocks

Mixtures Type	14 days, MPa	7 days, MPa	3 days, MPa
F100+RBD0	34.98	31.63	20.69
F40+RBD60	48.03	45.87	41.90
CC Blocks	32.07	28.86	19.50

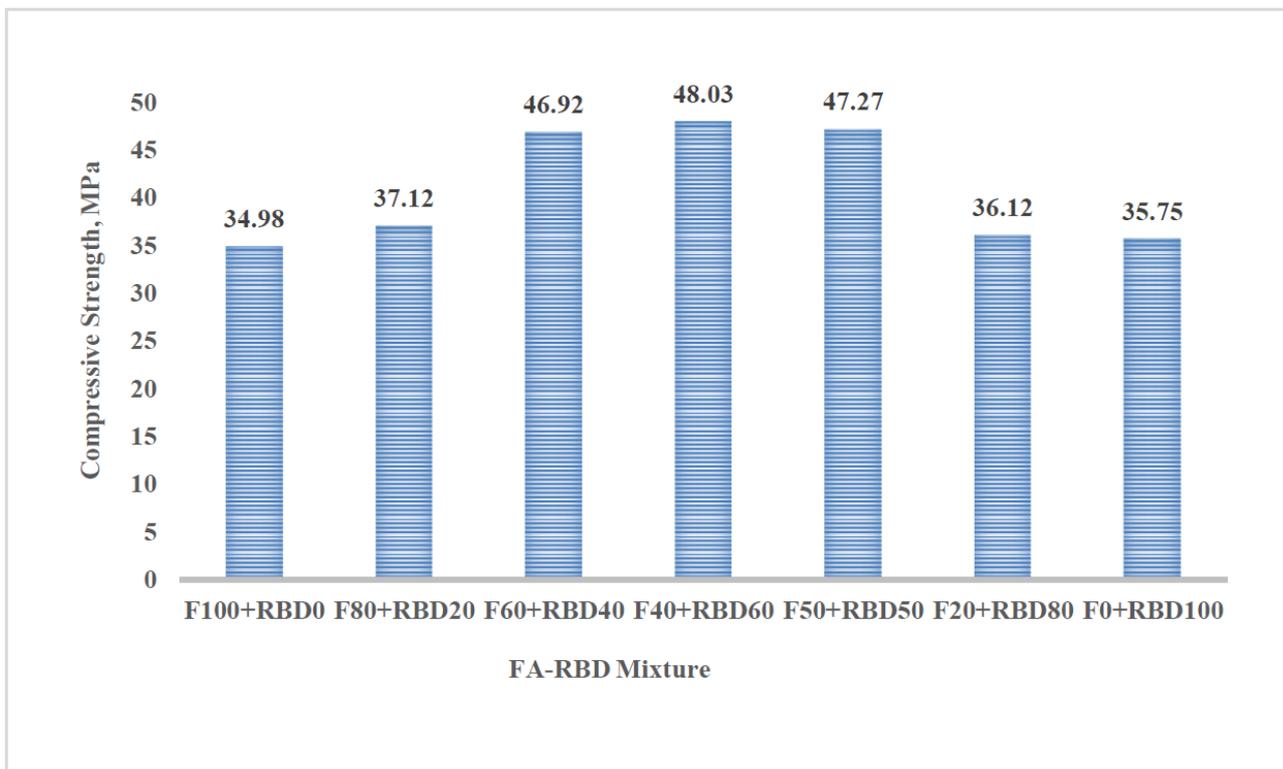


Figure 5: Compressive strength of FA-RBD after 3 days

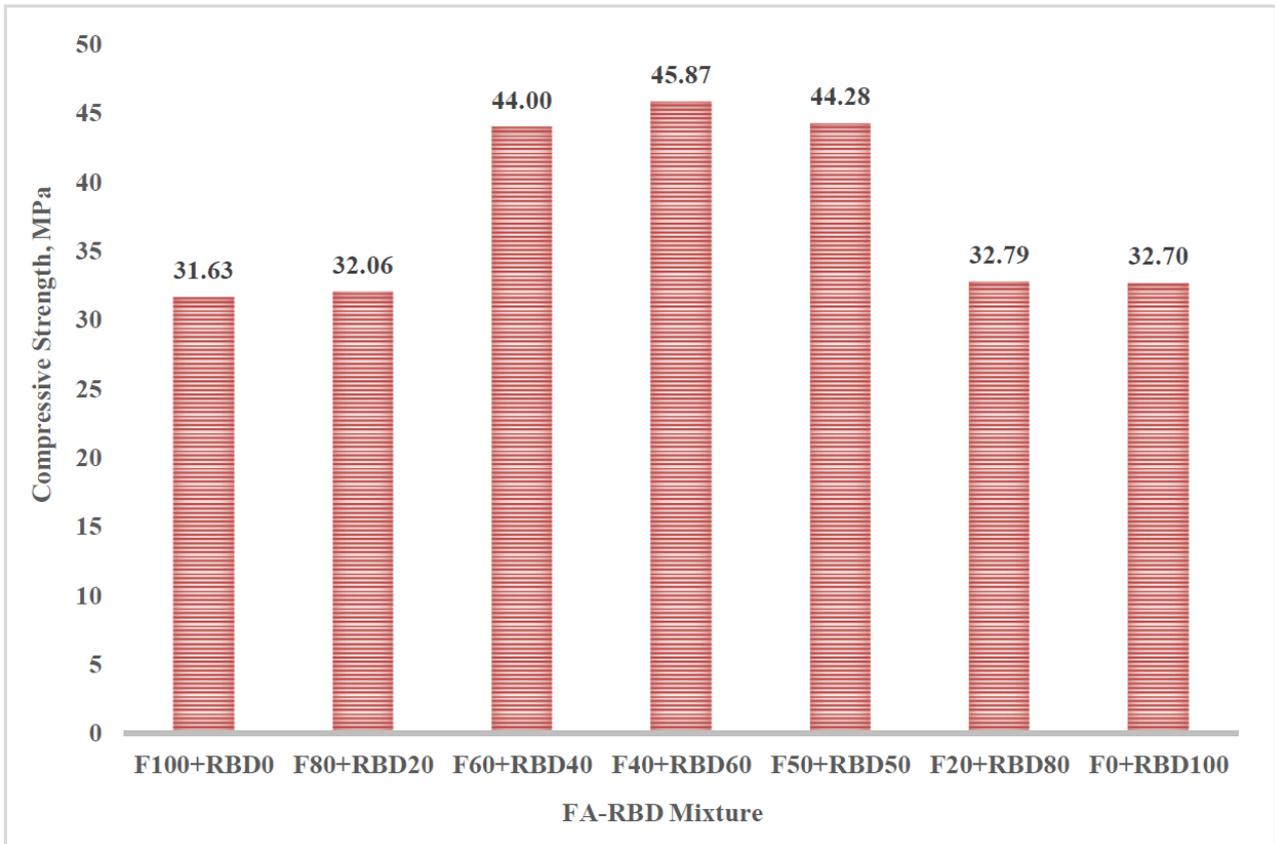


Figure 6: Compressive strength of FA-RBD after 7 days

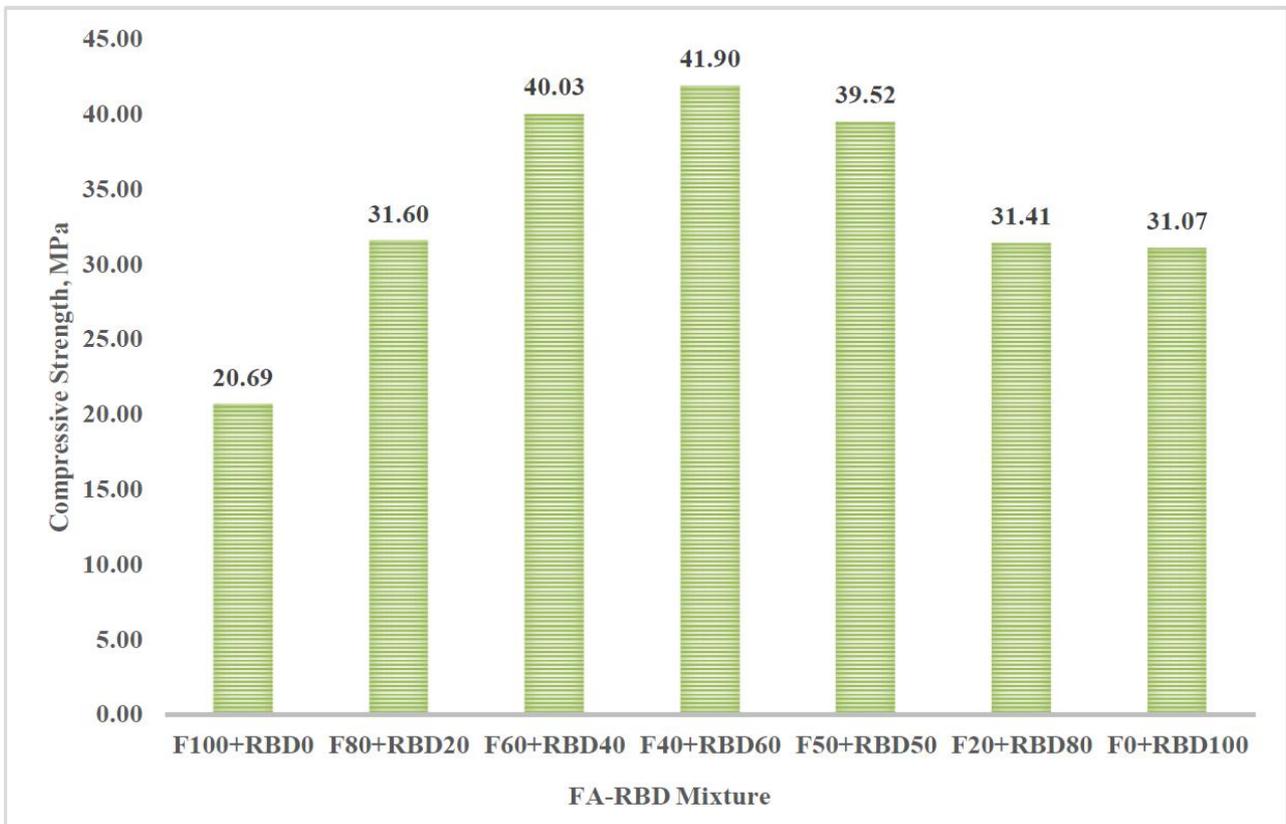


Figure 7: Compressive strength of FA-RBD after 14 days

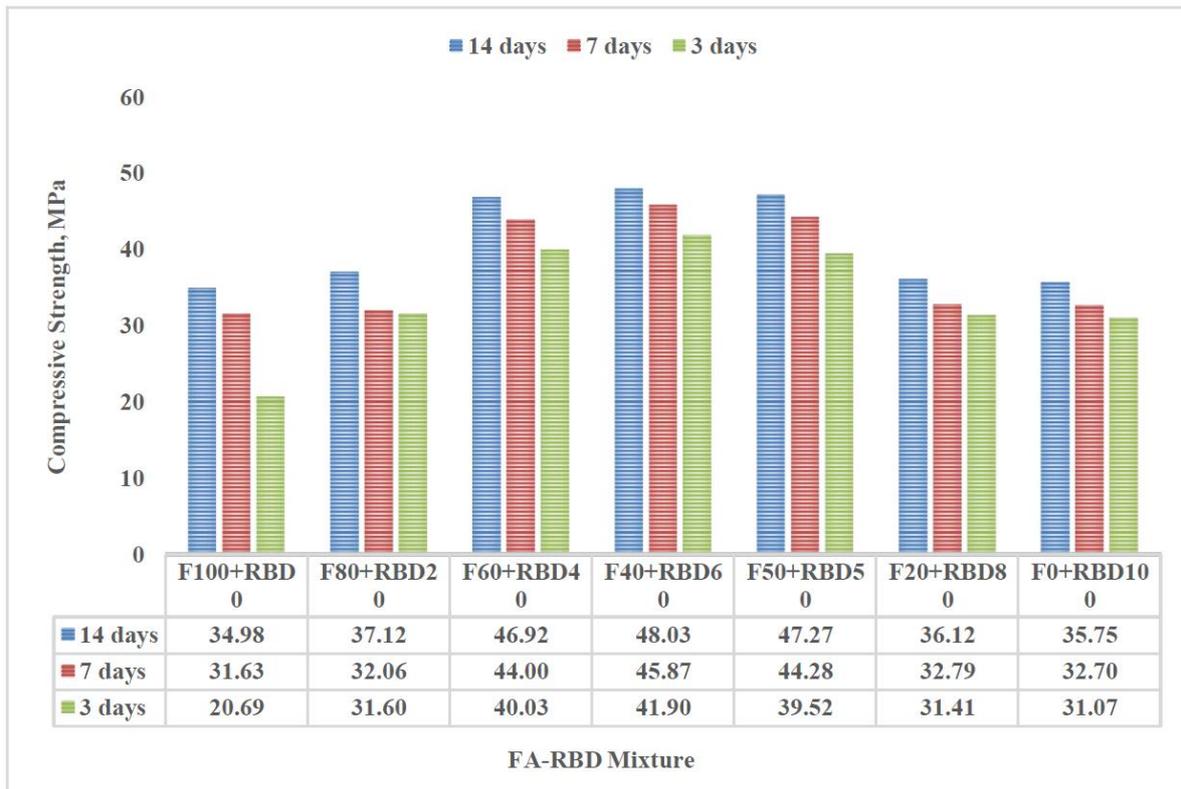


Figure 8: Compressive strength of FA-RBD after 3, 7 and 14 days

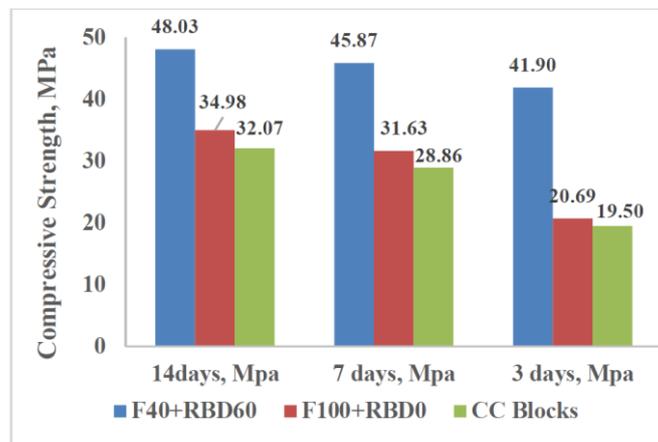


Figure 9: Optimal Compressive strength compared to conventional cement concrete blocks

IV. COST ANALYSIS

In this study, a cost analysis was conducted to assess the economic viability of geopolymer concrete (GPC) incorporating recycled brick dust (RBD) and fly ash (FA) as binders. According to local material prices, our total material cost of the optimal GPC mix (F40+RBD60) was approximately 601 BDT per 100 kg (Table 7), compared to 688 BDT per 100 kg (Table 6) for conventional OPC concrete (M20 grade)—a cost reduction of about 12.67%. This saving is largely due to replacing expensive cement with low-cost industrial by-products such as RBD and FA. This F40+RBD60 mix gained a compressive strength of 48.03 MPa at 14 days—over 2.4 times greater than the target strength for M20 grade concrete (20 MPa)—demonstrating its suitability for structural applications requiring high strength and early-age performance. While we use of alkali activators like, sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) added to the production cost, the overall mix remained economically competitive. However, these results show that GPC made from FA and RBD offers a cost-effective, high-performance alternative to OPC, while also reducing waste and lowering carbon emissions—making it a strong candidate for sustainable construction in Bangladesh.

Table 6: Cost of 100 Kg M20 concrete mixture

Material	Rate of TK per kg [23]	M20 Quantity in Kg	M20 Amount in Taka
Cement	11.00	18.18	200
Fine Aggregate	2.30	27.27	63
Coarse Aggregate	7.80	54.55	425
Water	0.017	9.09	0.155
Total Cost- Taka			688

Table 7: Cost of 100 kg mixture of Fly ash 40% Recycled Brick Dust 60%

Material	Rate of TK per kg [24]	Quantity in Kg	Amount in Taka
Fly Ash	0.8	19.8	16
Brick dust	1.3	29.7	39
Sand	2.3	9.9	23
NaOH (Solid)	60	1.79	107
Na ₂ SiO ₃	28	14.85	415.80
Water	0.017	24	0.41
Total Cost- Taka			601

V. CONCLUSION

In this study, we examined the potential of using recycled brick dust (RBD) as a replacement for industrial waste fly ash (FA) in concrete production. The findings show that increasing the proportion of RBD in FA-RBD blends noticeably improved compressive strength, with the highest value of 48.03 MPa achieved at 60% RBD replacement. Furthermore, this result suggests that RBD is not only a viable substitute for FA but also a promising material for producing strong and sustainable concrete.

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