Mechanical, Durability, and Microstructural Performance of Mud-Based Geopolymer Blocks Incorporating Industrial and Agricultural Wastes Comparative Analysis with Conventional Blocks

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Mechanical, durability and microstructural studies were conducted to evaluate the mud-based geopolymer blocks using red soil, ground granulated blast furnace slag (GGBFS), and some agricultural wastes such as bagasse ash (BA) and rice husk ash (RHA). These geopolymer blocks were compared under atmospheric curing with those prepared using cement-stabilized blocks (90% red soil, 10% cement). The best mix found using 6% GGBFS with 4% BA and 6% GGBFS with 4%RHA yielded the maximum dry densities of 1.88 g/cm³ and 1.86 g/cm³ and the highest compressive strengths of 11.00 MPa and 10.5 MPa respectively at the age of 28days. Compared to the conventional mix, these geopolymeric mixes showed better performances due to the density of matrices and improved bonding between matrices via geopolymerization. The geopolymer blocks showed excellent durability, as they had reduced water absorption rates and superior spray erosion resistance. Ultrasonic pulse velocity (UPV) values confirmed structural integrity improvement.
In contrast, prism efficiency tests reported near-optimal strength-to-weight ratios for the geopolymer blocks exemplary performance, especially 6% GGBFS with 4% BA and 6% GGBFS with 4%RHA geopolymeric mixes. Strength, durability,

and sustainability were higher for geopolymer mixes than conventional blocks, making them viable alternatives to environmentally friendly construction. This study highlights the possible use of GGBFS and agro-waste in producing high-performance building materials with lowered environmental impacts.
Keywords: Mud-based Geopolymeric block, red soil, GGBFS, Bagasse Ash, Rice Husk Ash, mechanical, durability, and microstructural performance.

1. Introduction

Motivated by the increasing pressure to reduce the ecological footprint of conventional cement-based materials, the global construction industry is now integrating sustainable practices. Such practices usually tackle the direct contribution of cement production toward CO_2 emissions, which is almost 8% of the global emissions [1]. This has resulted in researchers looking for alternative binders such as geopolymers, materials made of by-products from industry and agriculture, to reduce the carbon footprints of the final eco-friendly construction materials[2]. Red soil is abundant in tropical and subtropical regions, and it is found to be an excellent potential base material in the production of geopolymer due to its alumino-silicate composition and availability[3]. Mixed with ground granulated blast furnace slag (GGBFS), a supplementary material for cement, this red soil transforms itself into geopolymeric blocks with better strength, durability, and environmental sustainability[4].

Additionally, it has also been found that some agro-industrial wastes, such as bagasse ash (BA) and rice husk ash (RHA), function as effective pozzolanic materials that improve the properties of geopolymers [5,6]. Good. Plenty of literature on GGBFS use in geopolymer systems has been documented to increase reactivity and densify the matrix. The study showed that GGBFS-based geopolymers outperformed their cement-based counterparts for compressive strength and durability [7]. Similarly, the study demonstrated that the RHA improved geopolymer composites' long-term strength and void resistance [6]. Bagasse ash is a sugarcane residue containing a silica-rich and calcium-rich pozzolanic material that is good for geopolymerization. The research shows that BA improves the geopolymer's mechanics and decreases the porosity [8, 9]. Another agricultural by-product known for its high silica is rice husk ash, which promotes geopolymer materials' bonding and dense manifestation [4, 10]. Significant progress has been made in geopolymer, but the interaction of red soil, GGBFS, and agro-waste like BA and RHA is still ambiguous. This study fills this gap by evaluating the mechanical, durability, and microstructural characteristics of red soil, GGBFS, and agro-wastes-based geopolymer blocks against similar conventional cement-stabilized blocks. Applying various parameters critical for the investigation, such as compressive strength, ultrasonic pulse velocity (UPV), water absorption, spray erosion resistance, and prism efficiency, the study aims to determine the optimized mix ratio for use in construction. This research adds to the increasingly expanding body of knowledge in the field of geopolymer technology and its poise in revolutionizing construction industries by including recent findings on the usage of sustainable practices [5,1].

2. Materials and Methods:

The soil has been collected from the Dindigul district for block production. The soil properties have been calculated as a Specific gravity of 2.65, Liquid Limit of 50%, Plastic Limit of 30%, and Shrinkage Limit of 20%. The cement used is Ordinary Portland cement 53-grade cement, which conforms to IS 12269-2013[26]. The chemical and physical properties of binders are presented in Table 1. The rice husk and sugarcane bagasse were burned using an incinerator at 700°C for 6 hours to be evaluated. Ash burned was then sieved with a 75µm sieve, and only particles that passed through or retained by the 75µm sieve were used as supplementary cementitious material. Table 2 shows the mixed proportions of the proposed work. The compaction of soil blocks was done using a Hydraform semi-automatic block-making machine. The red soil and binders are mixed in the mixing unit for 5 minutes. Then, a geopolymer solution of 8 molarity and a 1:2 ratio of sodium hydroxide to sodium silicate was added to dry mix up to the optimum level and thoroughly mixed until it was uniform and lumps-free. Then, the batched fresh mix is transferred to the hydraulic press. The size of all mud blocks 220 x 220 x 115 mm can be produced under 2000-3000 psi pressure. The casted blocks are cured under ambient conditions, especially cement-stabilized blocks cured by water sprinkling and covered with plastic sheets. Cured blocks according to the IS-1725:2023 and their dry Compressive and wet compressive strength calculated at 7, 14, and 28 days. Before dry compressive strength, the Ultrasonic Pulse Velocity of the blocks is calculated as per IS 13311 (Part 1): 1992[28], a common principle for studying homogeneity or voids on solid matter.

The procedure has been followed to determine the dry compressive strength of the mud blocks as per IS 3495 (Part 1)[29]. This strength evaluation was carried out with a CTM of 1000 KN. The loading rate for testing the mud blocks was 14 N/mm^2 per minute. The compressive strength of all the blocks is noted before considering the average dry compressive strength as the respective strength of the mud block. This block efficiency test is done by stacking these mud blocks over each other for three and five numbers in each test. This test is more concerned with finding the efficiency of blocks with the strength that blocks provide in a prism manner (Block Efficiency = Masonry prism strength/Block Strength). Before the wet compression testing, blocks were soaked in water for 24 hours. After that, blocks were retrieved from the water, and all surface moisture from the blocks was wiped out with a dry cotton cloth. The subsequent experiment procedure for wet compressive strength remains the same as dry compressive strength.

The percentage of water absorption was also calculated according to IS3495 (Part2):1992[30] for blocks. A spray erosion test was conducted according to IS1725:2023[27] to determine each specimen's erosion rate. The water pressure was set at 50 kPa, and the applicability of mud blocks was evaluated based on the erosion rate in mm and mm/hour.

Table 1 The chemical and physical properties of Cement, GGBFS, Bagasse Ash and Rice Husk Ash

S.NO	Properties		Materials			
			Cement	GGBFS	Bagasse Ash	Rice Husk Ash
1	Chemical properties (compositions)	Al_2O_3	4.97	12	8.25	13
		CaO	62.60	35	6.25	22.4
		Fe_2O_3	2.55	1	3.5	0.1

		MgO	2.94	7.5	4.5	27
		Na_2O	-	1	0.5	0
		SiO_2	23.31	41	74	36.2
		SO_3	1.91	1.5	2	0.3
		LOI	1.72	1	1	1
2	Physical properties	Specific gravity	3.1	3.0	2.3	2.1
		Fineness(m^2/ Kg)	329	400	285	475
		Average particle size (μm)	7.5	11	60	9.35

Table 2 Mix Proportion

Materials	Mix ID							
	C10	G10	G8 BA2	G6 BA4	G4 BA6	G8 RHA2	G6 RHA4	G4 RHA6
Red Soil	90%	90%	90%	90%	90%	90%	90%	90%
Cement(C)	10%	-	-	-	-	-	-	-
GGBFS	-	10%	8%	6%	4%	8%	6%	4%
Bagasse Ash(BA)	-	-	2%	4%	6%	-	-	-
Rice Husk Ash(RHA)	-	-	-	-	-	2%	4%	6%

3. Results and Discussions:

(i) Dry Density of the Block:

Figure 1 illustrates the effect of Bagasse Ash (BA) and Rice Husk Ash (RHA) on the dry density of geopolymer blocks made from a red soil matrix. The system with 6% GGBFS plus 4% BA or 4% RHA has produced the highest dry densities of 1.88 g/cm³ and 1.86 g/cm³, respectively, improving general compaction and structural soundness[11]. BA and RHA have played significant roles in increasing the dry density since BA and RHA favour pozzolanic reactions, which is a considerable mechanism towards geopolymerization[12]. However, with a dosage more significant than 4% and particularly at 6%, the dry density was affected negatively due to porosity, thus causing a reduction in the overall compactness of the blocks [13]. Previous studies also support these results, which state that an optimum quantity of pozzolanic materials is required to strengthen and make the density superior, whereas excess amounts lead to negative results [14]. The conventional mud block mix results are 90% red soil and 10% cement. This dry density was lower at 1.83 g/cm³ than the results from geopolymer blocks with superior structural properties. Geopolymer blocks that contain 6% GGBFS and 4% BA or RHA showed better dry densities than these other blocks [15].

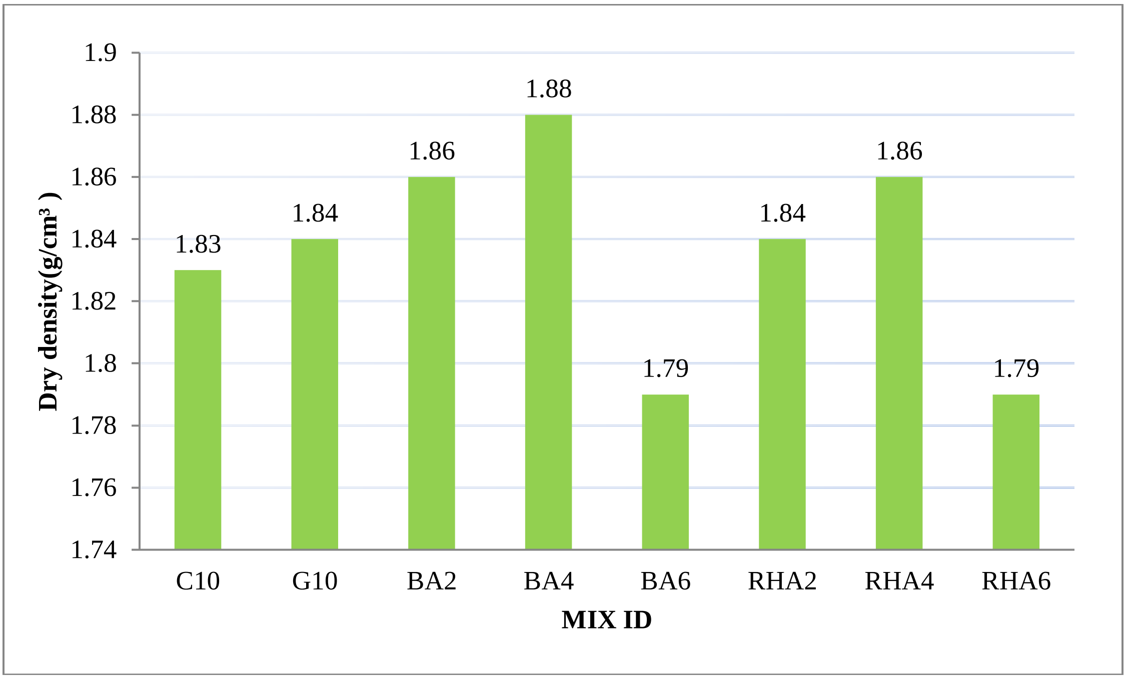

Figure 1. The effects of Bagasse Ash and Rice Husk Ash replacement on dry density

(ii) Dry Compressive strength:

This study assessed the dry compressive strength of geopolymer blocks made with 90% red soil, various percentages of GGBFS, and agro-waste (Bagasse Ash, Rice Husk Ash) with different curing ages (ambient conditions). Test results (Fig.2) showed that geopolymer blocks achieved substantially much higher compressive strength than traditional Mud Blocks (90% Red Soil plus 10% Cement) based materials after 28 days of curing. While geopolymer blocks with 6% GGBFS plus 4% BA, 6% GGBFS plus 4% RHA showed even better strength at all curing ages, such that the compressive strengths of the mixes at 3 days is 7.0 MPa, 6MPa at 7 days it is 8.5 MPa,7.5MPa, after 14 days increases to 9.5 MPa,8.5MPa and finally reaches 11.0 MPa,10.5MPa at 28 days respectively. It reflects that geopolymer blocks are better than mud house samples under mechanical properties. However, the conventional mix, 90% red soil and 10 % cement, indicates significantly less compressive strength of 2.0 MPa at 3 days, 3.5 MPa at 7 days, 4.5 MPa at 14 days, and finally up to 6.0 MPa at 28 days. Curing time was an essential aspect of achieving strength for the blocks. The long curing duration entailed the continued formation of calcium-silicate-hydrate (C-S-H) gels, which increased compressive strength [16]. At the optimal combination of 6% GGBFS and 4% BA or RHA, efficient geopolymerization and better block formations occurred. Geopolymer blocks, acquired early, exhibited rapid strength development, particularly within the first 14 days, and 28 days later, continued strengthening. Bagasse Ash (BA) and Rice Husk Ash (RHA) pozzolanic properties greatly affected how blocks improved compressive strength.

Both agronomic wastes add silica and alumina that react with the alkalinity solution and promote the creation of geopolymer gels, besides improving microstructure in the blocks. Dry density and compressive strength increased by adding BA at 4% or 4% RHA. When the agro-waste incorporation exceeded 4% into the mix, decreased compressive strength was observed with increased porosity and weak bonding between the geopolymeric components[18]. The geopolymerization process is significantly more effective than cement hydration in conventional mud blocks. Geopolymer blocks have achieved much better strength and durability in a shorter time. The alkaline activation of GGBFS with agro-waste makes them form a more muscular, compact, and chemically bound matrix [17].

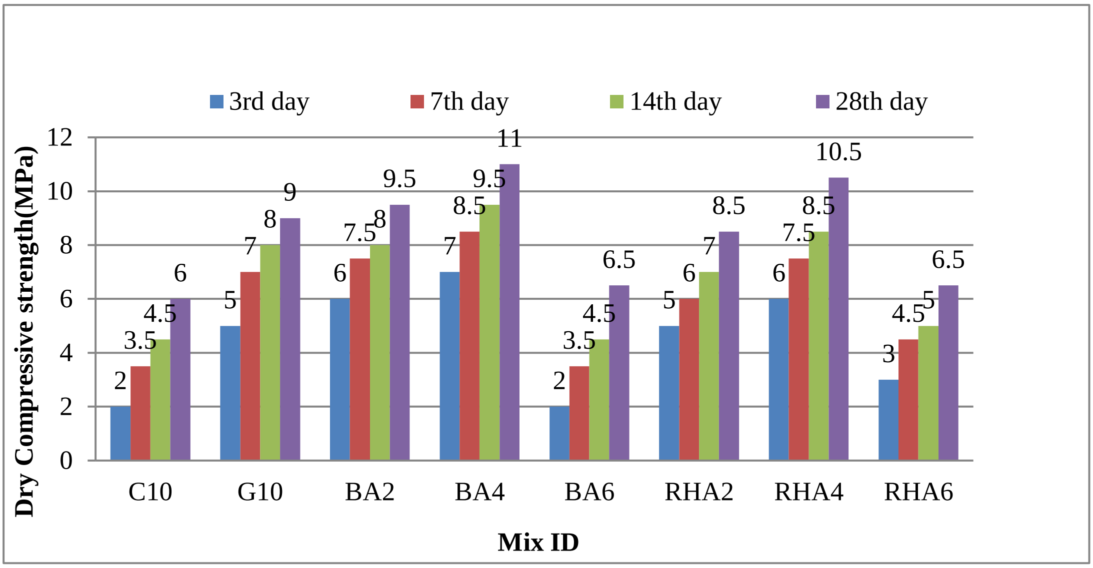

Figure 2. The effects of Bagasse Ash and RHA replacement on dry compressive strength

(iii) Wet Compressive strength:

It was found that(ref.fig.3) the combination of 6% GGBFS plus 4% BA and 6% GGBFS plus 4% RHA showed the highest values of wet compressive strength 28 days after testing, yielding results of 7.0 MPa and 6.5 MPa, respectively. These mixes could present excellent performance due to the combined function of GGBFS and agro-wastes, which presented extra silica and alumina. These substances would improve the geopolymerization into a dense, cohesive matrix that can resist weakening under wet conditions [18]. The mix with 10% GGBFS alone showed that significant increases in strength up to 5.5 MPa at 28 days could be achieved. The strength was attributed to the very high calcium and silica content in the GGBFS, as they were value-added building blocks in the formation of C–S–H (Calcium Silicate Hydrate) and N–A–S–H (Sodium Aluminosilicate Hydrate) gels that radiated a dense structure[14,17]. The absence of agro-wastes limited its potential to achieve strengths comparable to 6% GGBFS mixes with 4% BA or RHA. On the other hand, mixes with 6% agro-waste (BA or RHA) exhibited lesser wet compressive strength due to increased porosity, which weakened the matrix, thereby emphasizing the need for maintaining optimal proportions of agro-waste so that its pozzolanic advantages offset its disadvantages against excess porosity [18].

Conventional mud blocks (90% red soil and 10% cement) recorded the lowest wet compressive strength of only 4.0 MPa at 28 days. The microstructural images (Fig.4) showed that the Cement blocks often do microstructural cracks during hydration, especially under wet conditions [14, 17]. In comparison, the geopolymer blocks, especially the best mixes, offered an exceptional distance for strength and resistivity to water, which far outperformed the conventional ones[18].

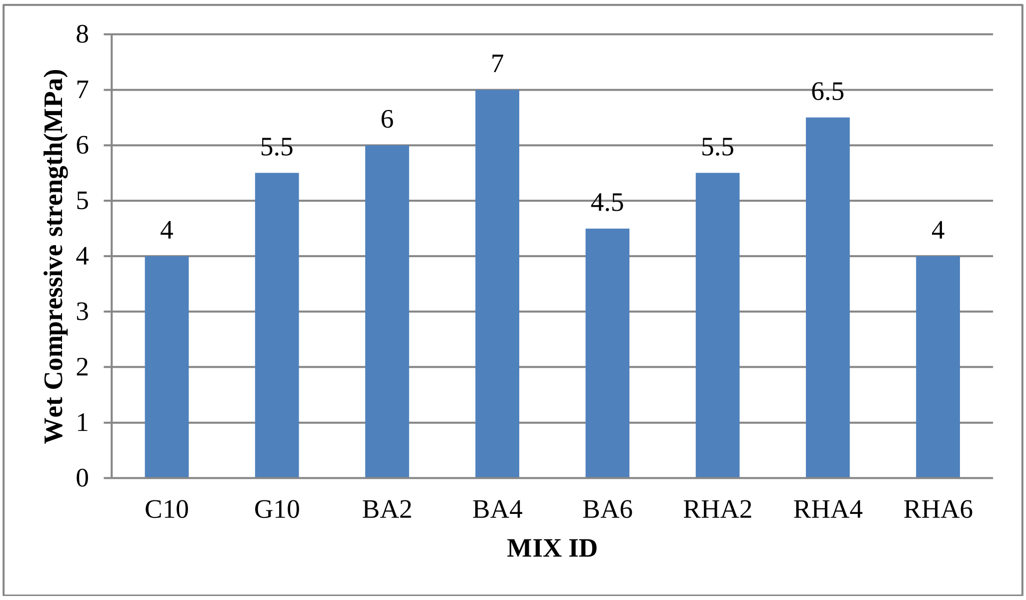

Figure 3. The effects of Bagasse Ash and RHA replacement on wet

Compressive strength

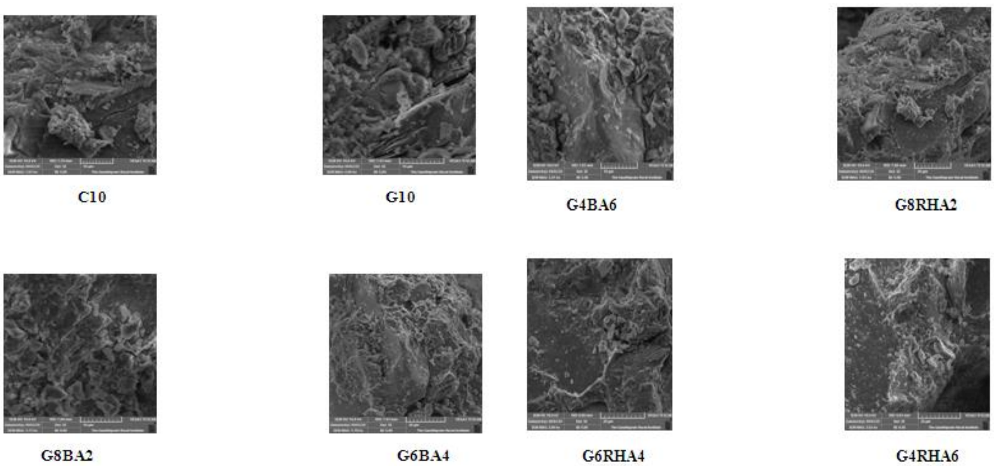

Figure 4. Scanning Electron Microscopic images of the blocks

(iv) Ultrasonic Pulse Velocity Test

In terms of the UPV values recorded at 28 days(Ref.fig.5), the highest was for six per cent GGBFS plus four per cent BA, as well as six per cent GGBFS plus four per cent RHA, showing

UPV values of 3.87 km/s and 3.82 km/s, respectively. Such data reveals a prominent internal compactness and homogeneity. The pozzolanic nature of BA and RHA improved the geopolymerization process, creating a denser and more cohesive matrix [16, 18]. A valuable finding was when 10% GGBFS alone resulted in a UPV of 3.62 km/s at 28 days. This was attributed to enhanced bonding from the considerable silica and calcium found in GGBFS, further promoting the formation of C–S–H and N–A–S–H gels. However, without incorporating agro-waste, the optimal UPV values of the mixes under consideration could not be reached [14,17]. The increasing addition of BA and RHA into the mixes improved UPV results to about 4%, beyond which 6% and above reduced UPV results. Too much agro-waste increased porosity and, therefore, internal heterogeneity and compactness decreased[16]. Conventional mud blocks (90% red soil and 10% cement) showed up to 2.82 km/s, the maximum value for 28 days, which suggested lesser compactness and more micro-cracks than the other geopolymer blocks. The best-performing geopolymer mixes with 6% GGBFS and 4% BA or RHA are far superior to the conventional blocks, thus confirming the enhanced homogeneity and structural integrity [17].

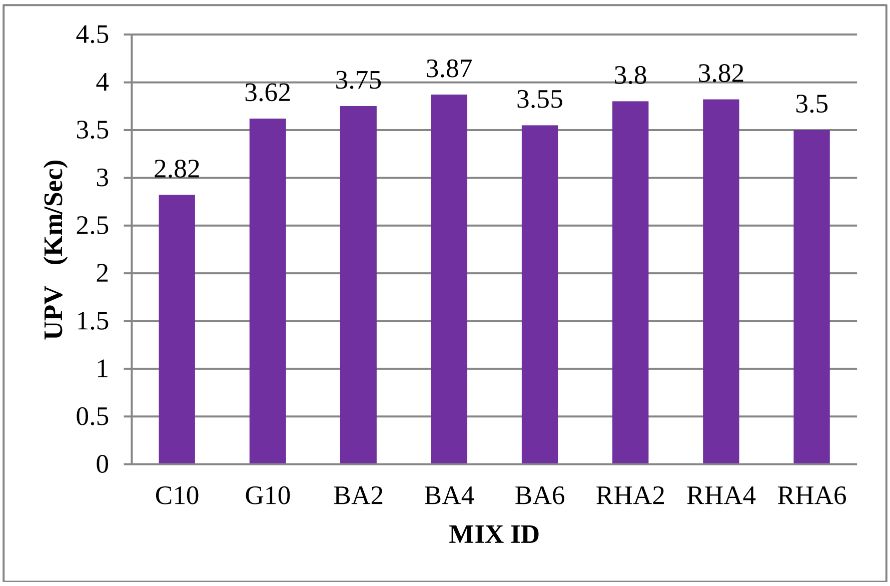

Figure 5. The effects of Bagasse Ash and RHA replacement on ultrasonic pulse velocity

(v) Prism test:

The prism test results are shown in Figure 6. An efficiency of 0.89 was obtained from the conventional mix (90% Red Soil plus 10% Cement), corroborating earlier studies on cement-stabilized mud blocks [19, 16]. Although the performance is acceptable, it can be noticed that it's lower than the optimized geopolymer mixes due to weaker mortar-block bonding. The mix of 90% red soil and 10% GGBFS had a prism efficiency of 0.91, with moderate improvement over the cement mix. This improvement in efficiency is further attributed to an understanding of improved chemical bonds and shrinkage at the block-mortar interface [20]. This composition (6% GGBFS plus 4% BA) lays extreme efficiency at 0.93, portraying stronger block-mortar interaction and transfer efficiency. The pozzolanic reactions from bagasse ashes encouraged the process of geopolymerization to strengthen structural stability [21]. The mix (6% GGBFS plus 4% RHA) imparted an almost identical efficiency of 0.92 despite the minor contribution of RHA's fine particle size and increased silica content towards further interfacial bonding [22]. A prism efficiency of 0.84 was measured in the samples containing 6% BA and 0.83 in samples containing 6% RHA. Excessive pozzolanic material would increase porosity and decrease cohesion at the block-mortar interface [23].

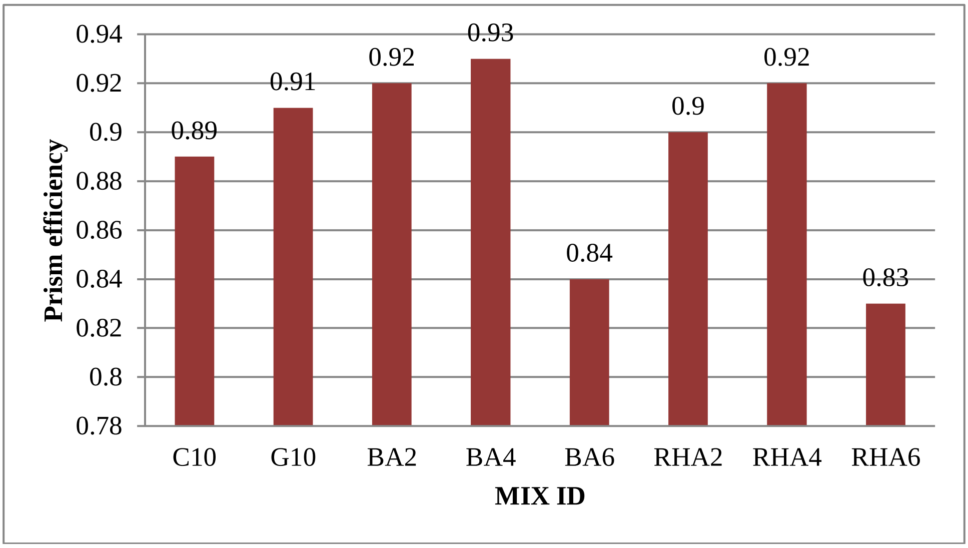

Figure 6. The effects of Bagasse Ash and RHA replacement on three-block prism efficiency

(vi) Water Absorption:

The water absorption of the conventional mix was found (Ref. Fig. 7) to be 12.2%. Even though this level is regarded as typical (<15%) according to IS 1725:2013[27], it still does not measure against the geopolymer mixes. This fact is attributed to the weaker cement matrix and larger pore structure [24]. The mix of 90% red soil and 10% GGBFS has a value of 11.5% water absorption, showing improved resistance to ingress due to the dense geopolymer matrix and enhanced pozzolanic activity. The 6% GGBFS plus 4% BA mix with 9.2% water absorption was the least among the tested mixes, indicating a superior durable shape. Incorporating BA improves the microstructure by filling voids and enhancing geopolymer gel formation[21].This mix of 6% GGBFS plus 4% RHA exhibited similarly low water absorption of 9.5%, wherein the fine particle size and high silica content of RHA contributed to the densification of the matrix, as observed[22]. Mixes of 6% BA or 6%RHA exhibited increased water absorption of 13% and 12.5%, respectively. Excessive pozzolanic materials increase porosity and micro cracking, thus reducing water resistance [20].

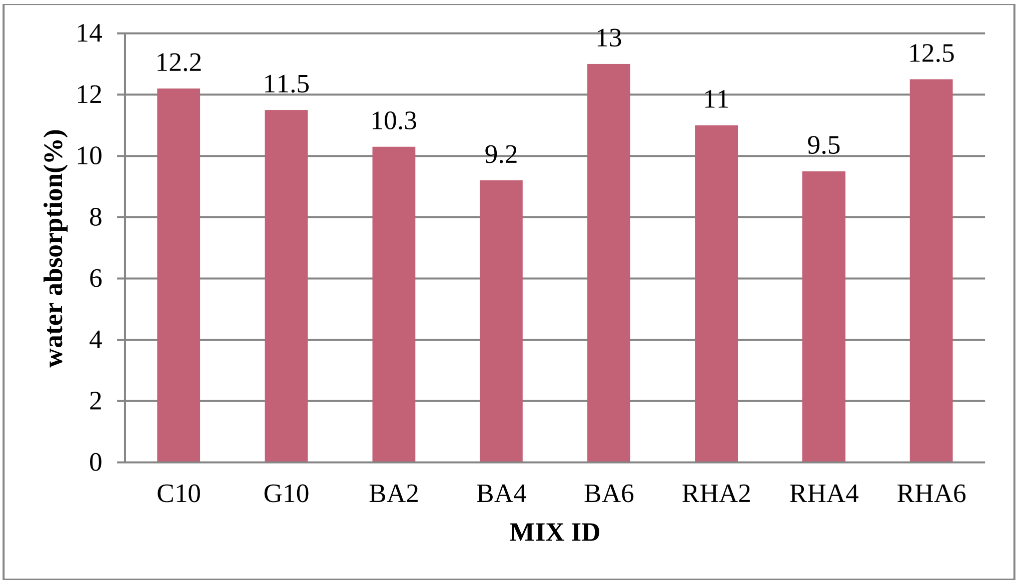

Figure 7. The effects of Bagasse Ash and Rice Husk Ash replacement on water absorption

(vii) Spray Erosion Test:

The spray erosion test results for soil blocks incorporated red soil, GGBFS and agro waste (BA and RHA) at variable dosages, as conceived in Figure 8. The spray erosion test is designed to evaluate how well these materials resist destruction by water when sprayed at controlled conditions. The most important aspect of the erosion resistance of the geopolymer blocks due to their GGBFS presence, together with BA and RHA, was confirmed, proving that the better performance was from those additives in terms of structural and functional integrity.

The control Mix containing 90% red soil and 10% cement was fairly poor-sustaining against spray erosion(14mm/h) with loss of material at a considerable level during the experiment because cement mortar has a conventional property and lacks pozzolanic properties associated with GGBFS, BA, or RHA, which would enhance the cohesion of the mass and strength of the block overall. The Mix G10 (90% Red Soil, 10% GGBFS) was better than the control mix in terms of spray erosion resistance. GGBFS provides supplementary cementitious properties that enhance structural bonds in the geopolymer matrix and reduce erosion tendency. The 10% GGBFS mix showed a lower erosion rate(13mm/h), indicating improved performance in spray conditions compared to the control mix.

Geopolymer Mixes, which comprised different proportions of BA and RHA, exhibited further improvements in wear resistance. Among these, Mix G6BA4 (90% Red Soil, 6% GGBFS, 4% BA) and Mix G6RHA4 (90% Red Soil, 6% GGBFS, 4% RHA) showed the best performances with lower quantities (10mm/h, 11mm/h) of material loss during the spray erosion test which attributed to optimal pozzolanic reactions occurring between the BA and RHA with GGBFS, which increases both strength and density of the geopolymer matrix and thus, better erosion resistance. Moderate performing mixes are Mix G8BA2 (90% Red Soil, 8% GGBFS, 2% BA) and Mix G8RHA2 (90% Red Soil, 8% GGBFS, 2% RHA), in which the addition of BA or RHA indeed contributed to the enhancement of the spray erosion resistance of the block, albeit not strictly at par as the 4% BA or RHA mixes. A higher ingredient quantity of BA and RHA in Mixes G4BA6 G4RHA6 (6% of BA or RHA) resulted to some extent of performance (19mm/h,18mm/h) because high amounts of these agro-wastes further increased porosity in the composite geopolymers matrix, which in turn weakened the bonds and reduced the strength against water erosion. The geopolymer blocks with 6% GGBFS and 4% BA or 6% GGBFS and 4%RHA revealed the highest resistance against spray erosion, which thus proved that the combination of GGBFS enhanced the bonding quality and durability and agro-wastes into the mix. These results indicate that the optimum ratio of GGBFS and agro-waste content (BA, RHA) is essential for upgrading the erosion resistance of geopolymer blocks.

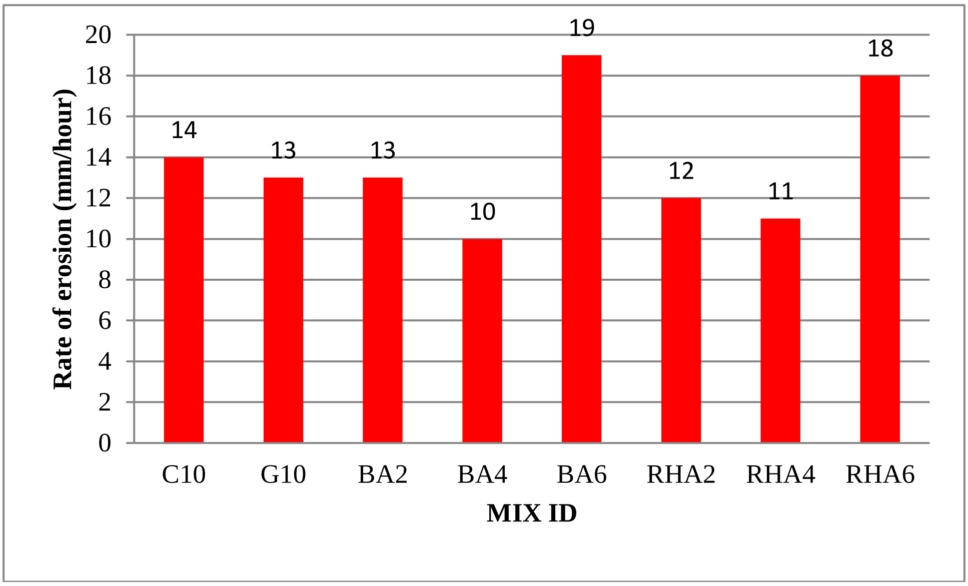

Figure 8. The effects of Bagasse Ash and Rice Husk Ash replacement on the rate of erosion

4. Conclusions:

The addition of 6% GGBFS with 4% BA or 4% RHA primarily increased the geopolymer blocks' dry density, compressive strengths, and ultrasonic pulse velocity (UPV). The dry densities of these mixes were higher than that of the conventional mix and were assigned to the pozzolanic reactions filling voids and densifying material. Geopolymer blocks at 28 days had very high compressive strength than those of the traditional blend. Preferred combination features of 6% GGBFS with 4% BA or 4% RHA maximized strength due to better bond formation and denser microstructure formation. On the contrary, increasing the amounts of BA or RHA to 6% decreases strength due to increased porosity and weak bonding in the matrix.UPV results complemented such findings, with the highest numbers recorded for the 6% GGBFS plus 4% BA or RHA mixes, suggesting fewer micro-cracks and greater integrity in the structure. This observation agrees with prior studies affirming the sound effect of GGBFS and agro-wastes on geopolymer materials. The water absorption tests showed that the GGBFS and agro-waste blended geopolymer blocks can absorb less water than the conventional mix. The densified microstructure created due to interactions between GGBFS, BA, and RHA effectively blocks water ingress. Geopolymer blocks also had the best resistance to spray erosion, particularly at 6% GGBFS plus 4% BA or RHA mixes that showed very little material loss. It was observed that high levels of BA or RHA (6%) led to reduced performance due to increased porosity. The prism efficiency test results showed that for the 6% GGBFS and 4% BA or RHA mix, the prism efficiency was highest (nearly closer to 1.0), reflecting their efficient strength-to-weight ratio. This efficiency is due to the balanced pozzolanic reactions from GGBFS and agro-wastes contributing to better structure performance. Therefore, the geopolymer blocks containing 6% GGBFS with 4% BA and 6% GGBFS with 4% RHA performed better than the conventional mix in all parameters, thus exhibiting high mechanical strength, lower water absorption, better erosion resistance, and higher microstructural integrity. Hence, the optimum amounts of red soil, GGBFS, and agro-waste-based geopolymer blocks (G6BA4, G6RHA4) can be viable and sustainable alternatives to traditional cement-based blocks, aligned with the global change towards eco-friendly construction practices.

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