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From Waste to Resource: Valorization of Dimensional Stone Waste in Geopolymer Mortars for the Circular Economy in Construction

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A B S T R A C T

The cement industry is a major source of global CO_2 emissions, highlighting the need for sustainable alternatives that balance performance with reduced environmental impact. Geopolymers offer a promising low-carbon substitute to OPC, with reported emission reductions of up to 80%. Simultaneously, dimensional stone processing in India generates over 30 million tons of waste annually, causing serious air, water, and land pollution. Valorizing this waste in geopolymer binders provides dual benefits of waste mitigation and sustainable material development. The present study explores the use of dimensional stone waste with GGBS for geopolymer mortar production, focusing on optimizing strength and physical properties through mix design variables such as activator molarity and NaOH:Na_2SiO_3 ratios. Characterization of materials was conducted using XRF, XRD, and SEM. Results showed maximum compressive strength at 8 M NaOH with a 1:2.5 NaOH:Na_2SiO_3 ratio, along with higher density, and lower porosity and water absorption. The novelty lies in systematic optimization of activator parameters for stone waste-based geopolymers, which have not been studied in detail previously. Findings confirm the feasibility of converting challenging waste into high-performance binders, supporting circular economy goals. Beyond structural performance, the natural colour of stone waste enhances the aesthetic appeal of geopolymer products without synthetic pigments.

Keywords: Dimensional stone waste; geopolymer mortars; circular economy; green concrete technology; waste valorization.

1. Introduction

The construction industry is one of the largest contributors to global environmental challenges [1]. The construction sector faces two pressing sustainability challenges: the high carbon emissions associated with cement production and the ecological burden of unmanaged industrial waste [2,3]. Cement production alone is estimated to account for 7-8% of global carbon dioxide (CO_2) emissions, largely due to the calcination of limestone and the burning of fossil fuels [4,5]. In India, the cement sector releases approximately 177 million tons of CO_2 annually. This highlights the urgent need for low-carbon alternatives that can reduce the environmental footprint of construction [6]. In parallel, the extraction and processing of dimensional stones such as granite, marble, sandstone, and slate are highly waste-intensive. Globally, quarrying and processing can result in material losses of up to 60-70%, while in India, more than 30 million tons of dimensional stone waste are generated annually [7]. This waste is often dumped near quarrying and processing sites, where it contributes to dust pollution, groundwater contamination, and land degradation, as shown in Fig. 1.

In states like Rajasthan, accumulated deposits already exceed 100 million tons [8]. Addressing both challenges together opens opportunities for circular economic solutions. Recycling dimensional stone waste into new construction materials reduces the demand for virgin resources and diverts large volumes of waste from disposal sites. Geopolymer technology offers one such route. Geopolymers are inorganic binders formed through the reaction of aluminosilicate precursors with alkaline activators [9]. Compared with ordinary Portland cement (OPC), geopolymers can lower greenhouse gas emissions by up to 80% and can incorporate a wide range of industrial by-products, including fly ash, slag, and stone dust [10,11].

Several studies have reported the use of dimensional

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stone waste and related materials in geopolymer systems, primarily to demonstrate feasibility and explore alternative construction products. Gupta et al. [12] developed coloured bi-layer bricks incorporating stone processing waste, where the emphasis was placed on product development and aesthetics rather than on controlling geopolymer reaction mechanisms through activator chemistry. Shilar et al. [13] investigated granite waste powder as a geopolymer binder and observed improvements in fresh and hardened properties at selected alkaline conditions; however, their study did not involve a systematic evaluation of NaOH molarity or NaOH-Na_2SiO_3 ratio, nor did it relate these parameters to physical characteristics such as density, porosity, or water absorption. Luhar et al. [14] examined geopolymer composites incorporating waste-based materials, focusing mainly on mechanical and durability properties, without isolating dimensional stone waste as an active precursor or examining how variations in activator composition affect early-age mix densification under ambient curing conditions. Although the previous studies confirm the suitability of stone waste for geopolymer applications, they provide limited understanding of how activator molarity and silicate availability control physical performance and strength development measured at 7 and 28 days, particularly in hybrid stone waste-GGBS systems. The present study addresses this gap through a systematic investigation of NaOH molarity and NaOH-Na_2SiO_3 ratio, linking activator chemistry with strength development, physical properties, and microstructural characteristics.

Fig. 1 Dimensional stone waste generation at the factory stage (Bayana village in Rajasthan)

This approach moves beyond feasibility-oriented studies and offers performance-based insights for optimising stone waste-based geopolymer mortars under practical ambient curing conditions. The present study focuses on the development of geopolymer mortars that combine dimensional stone waste with ground granulated blast furnace slag (GGBS). The influence of two key factors, activator molarity and the sodium hydroxide (NaOH) to sodium silicate (Na_2SiO_3) ratio, was examined. The focus is on understanding how activator molarity and the NaOH: Na_2SiO_3 ratio influence strength development and microstructural densification. By optimizing these mix parameters, the study demonstrates how dimensional stone waste can be transformed into a valuable resource for geopolymer mortars. The results contribute to sustainable material development by reducing cement consumption, lowering CO_2 emissions, and promoting the reuse of industrial waste in construction within a circular economy framework.

2. Materials and Methods

2.1 Materials Used

Table 1 Elemental composition of stone waste & GGBS

Elements	Mass %	
	Dimensional Stone Waste	GGBS
Na	0.28	0.53
Mg	0.79	3.97
Al	9.24	22.04
Si	70.23	21.10
P	0.04	0.03
S	0.25	0.87
Cl	0.14	0.07
K	9.16	1.04
Ca	6.16	42.33
Cr	0.12	0.35
Mn	0.21	3.84
Fe	2.41	2.66

Dimensional stone waste was collected from Bayana, in the Bharatpur district of Rajasthan (India), where cutting and polishing operations generate large volumes of slurry and powder. The waste was dried and sieved before use. GGBS, procured from Suyog Elements India Pvt Ltd, Gujarat (India), was used as a supplementary precursor owing to its high calcium and alumina content. Locally available river sand was used as fine aggregate. Furthermore, the alkaline activator consisted of NaOH and Na_2SiO_3 procured from LOBA Chemicals Pvt Ltd., India. NaOH pellets were dissolved in distilled water to prepare solutions of different molarities (4-10 M). The solutions were left to stabilize for 24 hours before use. Na_2SiO_3 solution was used in its supplied form, and the NaOH: Na_2SiO_3 ratio varied between 1:1 and 1:2.5. The chemical composition of the precursors was determined by X-ray fluorescence (XRF) (Table 1). As shown in Table 1, stone waste contained mainly silica ($\approx$ 70%) and alumina ($\approx$ 9%), while GGBS was found to be rich in calcium oxide ($\approx$ 42%) and alumina ($\approx$ 22%). These oxide proportions indicate that both the materials can

balance each other in a geopolymer system, with stone waste providing silica and alumina for network formation and GGBS contributing calcium for strength development. Mineralogical analysis was carried out using X-ray diffraction (XRD), and particle morphology was examined with scanning electron microscopy (SEM). The results of these tests are discussed in the following section.

2.2 Methodology

The experimental program was carried out in two stages. In the first stage, the effect of NaOH molarity was investigated. Mortar mixes were prepared with NaOH solutions of 4 M, 6 M, 8 M, and 10 M molarities, while keeping the activator solution to binder ratio fixed at 30% and the binder-to-fine aggregate ratio constant at 1:2. These proportions were selected based on preliminary investigations, which indicated that they provided workable mortar mixes without segregation or excessive stiffness. Physical properties, including water absorption, porosity, and bulk density, were determined at 28 days, and compressive strength was measured at 7 and 28 days, and flexural strength at 28 days. Based on these results, the mix with optimum molarity was identified. In the second stage, this optimum molarity from the first stage was adopted to study the effect of the NaOH: Na_2SiO_3 ratio. Ratios of 1:1, 1:1.5, 1:2, and 1:2.5 were examined, and the same set of tests as done for molarity was repeated. For all mixes, stone waste and GGBS were used in equal proportions as binder, with river sand as the fine aggregate. Table 2 presents the mix design adopted for the brick specimens in the study.

The dry materials were thoroughly blended before the pre-prepared alkaline solution was added gradually. Fresh mortar was placed into the brick production machine to fabricate compressed geopolymer bricks with dimensions of 190 mm x 90 mm x 90 mm. Subsequently, 50 mm cubes and 40 mm x 40 mm x 160 mm beam specimens were prepared by sectioning the brick specimen. All specimens were cured under ambient laboratory temperature conditions until the age of testing, as shown in Fig. 2. Testing procedures followed standard protocols. Compressive strength was determined at 7 and 28 days in accordance with ASTM C109 [15]. Flexural strength tests were performed in accordance with ASTM C78. Water absorption was measured following IS 2250: 1981 [16]. Bulk density and porosity were calculated using gravimetric methods. These tests enabled systematic evaluation of how activator molarity and activator ratio influenced both the physical and mechanical performance of stone waste-GGBS geopolymer mortars.

(a) (b) (c)

Fig. 2 Casting and preparation of specimens (a) Brick specimens, (b) Cubes and beams specimens, and (c) Testing of cube specimens.

3. Results and Discussion

3.1 Characterization of Raw Materials

The chemical composition of the precursors, already summarized in Table 1, highlights the complementary role of the two binders. Stone waste is silica-rich with moderate alumina, providing the base framework for geopolymerization, while GGBS contributes significant calcium and alumina, which are known to accelerate reaction kinetics and improve early strength. XRD analysis provided further insights into the mineralogical characteristics of the raw materials. Stone waste showed sharp crystalline peaks dominated by quartz, confirming its low amorphous content and limited direct reactivity.

Table 2 Mix proportion of brick specimens used in the study

Mix ID	GGBS (gm)	Stone Waste (gm)	Sand(gm)	NaOH (gm)	Na_2SiO_3(gm)	Molarity	NaOH: Na_2SiO_3	Binder: Sand
4M, 1:1	750	750	1500	225	225	4	01:01	01:01
6M, 1:1	750	750	1500	225	225	6	01:01	01:01
8M, 1:1	750	750	1500	225	225	8	01:01	01:01
10M, 1:1	750	750	1500	225	225	10	01:01	01:01
8M, 1:1.5	750	750	1500	180	270	8	01:1.5	01:01
8M, 1:2	750	750	1500	150	300	8	01:02	01:01
8M, 1:2.5	750	750	1500	129	321	8	01:2.5	01:01

In contrast, GGBS showed a broad hump in the range of 25-35 ° 2θ, which is representative of amorphous phases, along with minor crystalline reflections. The presence of this reactive amorphous phase in GGBS makes it an essential component in the blended system, ensuring effective dissolution and gel formation under alkaline activation (Fig. 3).

Morphological features observed under SEM also reflected this contrast. Stone waste particles were irregular, angular, and rough-textured, increasing the surface area available for reaction but potentially reducing workability at higher replacement levels. On the other hand, GGBS particles were smoother and denser, allowing better packing and contributing to matrix densification during geopolymerization (Fig. 4). Together, these observations confirm that combining stone waste with GGBS can produce a binder system with both chemical reactivity and microstructural compactness.

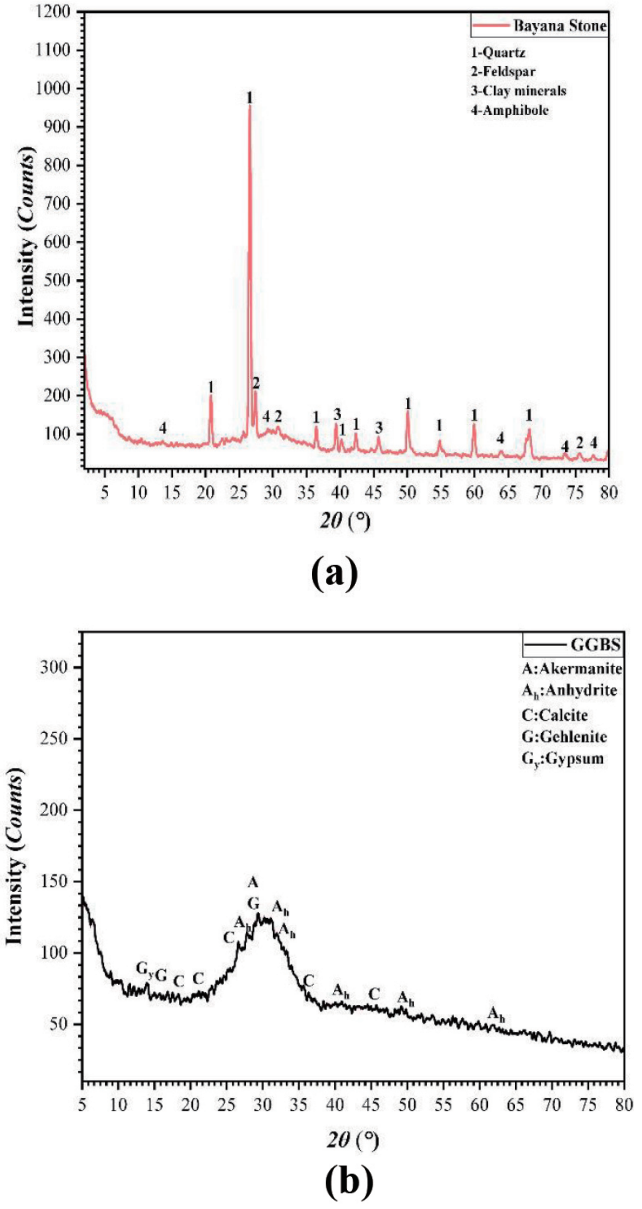

Fig. 3 Mineralogical characterization of (a) Dimensional stone waste and (b) GGBS using XRD

3.2 Effect of NaOH Molarity

3.2.1 Density

The bulk density of the GGBS-stone waste geopolymer mortars exhibited a significant dependency on the NaOH molarity, with values ranging from 1734 kg/m^3 at 4 M to 1965 kg/m^3 at 8 M, followed by a decline to 1798 kg/m^3 at 10 M (Fig. 5). The maximum density achieved at 8 M molarity represents a 13.3% increase compared to the 4 M specimens, indicating enhanced consolidation and gel formation within the geopolymer matrix. The increase in density with rising molarity from 4 M to 8 M can be attributed to the enhanced dissolution of aluminosilicate species from both GGBS and stone waste precursors under higher alkaline conditions. Increasing the NaOH concentration typically increases geopolymer density due to the complete dissolution of Si and Al species, resulting in greater gel formation [17]. The GGBS component, rich in calcium oxide, readily reacts with the alkaline activator to form calcium-aluminum-silicate-hydrate (C-A-S-H) gel. At the same time, stone waste contributes silica and alumina for the formation of sodium-aluminum-silicate-hydrate (N-A-S-H) gel. This combined gel formation in the hybrid system creates a denser microstructure by filling inter-particle voids and reducing porosity. However, the decline in density at 10 M molarity suggests that excessive alkalinity has adverse effects. At very high NaOH concentrations, rapid precipitation and gelation occur, which can trap excess water and create microcracks due to rapid setting and autogenous shrinkage.

3.2.2 Water Absorption and Porosity

Water absorption and porosity are critical indicators of the durability and microstructural integrity of geopolymer materials. In this study, water absorption decreased from 12% at 4 M to a minimum of 9% at 8 M, then increased to 11% at 10 M. Similarly, porosity exhibited a parallel trend, decreasing from 19.5% at 4 M to 15% at 8 M, representing a 23.1% reduction, before increasing to 18.5% at 10 M, as shown in Fig. 6.

The reduction in both water absorption and porosity at 8M molarity is directly related to the enhanced geopolymerization reaction and the formation of a denser gel network. At optimal alkalinity (8 M), sufficient hydroxide ions are available to break Si-O-Si and Al-O-Al bonds in the precursor materials, releasing reactive monomers that subsequently undergo polycondensation to form 3D aluminosilicate networks. The hybrid C-A-S-H and N-A-S-H gels formed in this system create a more homogeneous and interconnected matrix, effectively filling capillary pores and reducing permeability. The inverse relationship between density and porosity confirms that the 8 M specimens possess the most compact microstructure. These findings align closely with Ahmad et al. [18], higher porosity leads to higher water absorption, which lowers the density of geopolymer concrete, while less porosity leads to higher density and decreased water absorption. The increased porosity at 10 M can be attributed to incomplete gelation, rapid water evaporation during curing, and the formation of

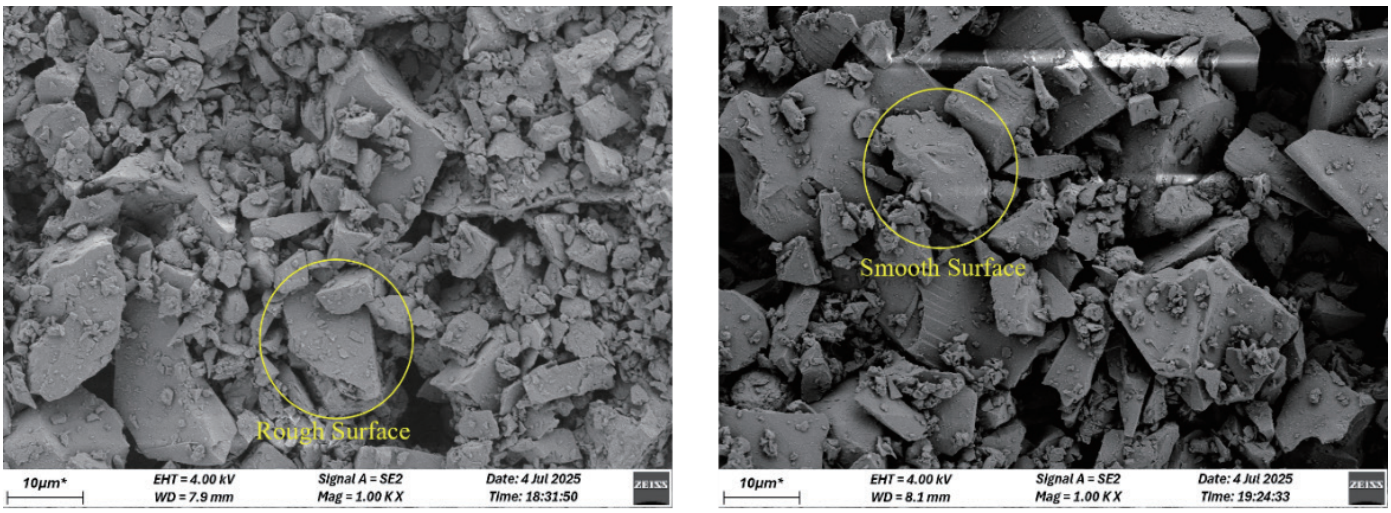

Fig. 4 Microscopic characterization of (a) Dimensional stone waste and (b) GGBS using SEM micrograph

interconnected pore networks resulting from excess alkali. Also, increasing NaOH concentration beyond optimal levels increases apparent porosity due to increased viscosity and water evaporation during polymerization, resulting in linked pores and high permeability [19].

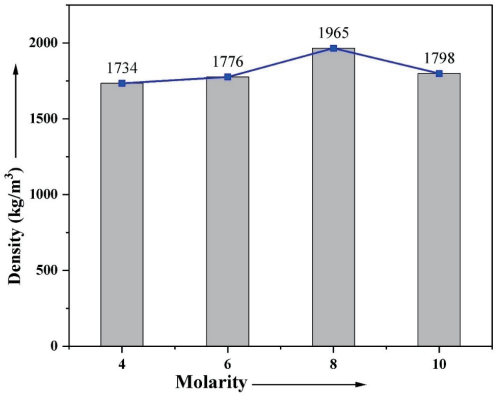

Fig. 5 Effect of NaOH molarity on the density of geopolymer mortars.

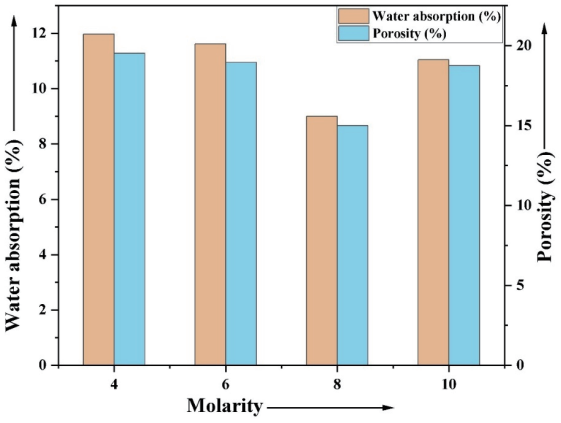

Fig. 6 Effect of NaOH molarity on water absorption and porosity.

3.2.3 Compressive Strength

Compressive strength is the most critical mechanical property for evaluating the performance of geopolymer mixes. The results demonstrate a noticeable effect of NaOH molarity on strength development at both 7 and 28 days. At 7 days, compressive strength increased from 19.95 MPa at 4 M to 51.96 MPa at 8 M, then decreased to 41.82 MPa at 10 M. At 28 days, the trend continued with values of 22.51 MPa, 41.42 MPa, 73.85 MPa, and 52.7 MPa for 4 M, 6 M, 8 M, and 10 M, respectively (Fig. 7), indicating an optimum NaOH molarity of 8 M for strength development.

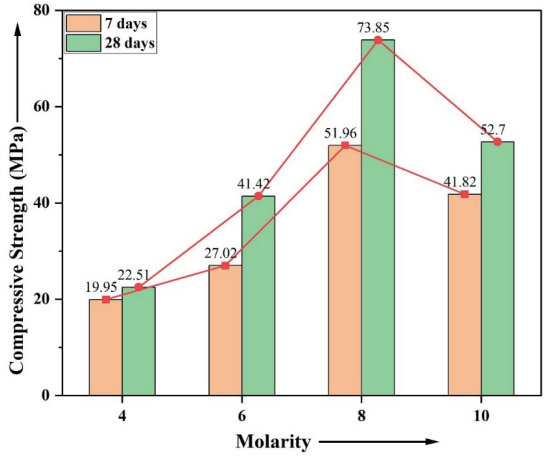

Fig. 7 Compressive strength values at 7 and 28 days for different NaOH molarities.

These strength trends are further clarified by the microstructural features observed in SEM images (Fig. 8). SEM observations show a clear effect of NaOH molarity on mix morphology. At 4 M NaOH (Fig. 8a), the microstructure is relatively loose, with a high proportion of unreacted particles and visible voids, consistent with the low compressive strength measured at this molarity. At 6 M NaOH (Fig. 8b), partial gel formation and improved particle bonding are observed,

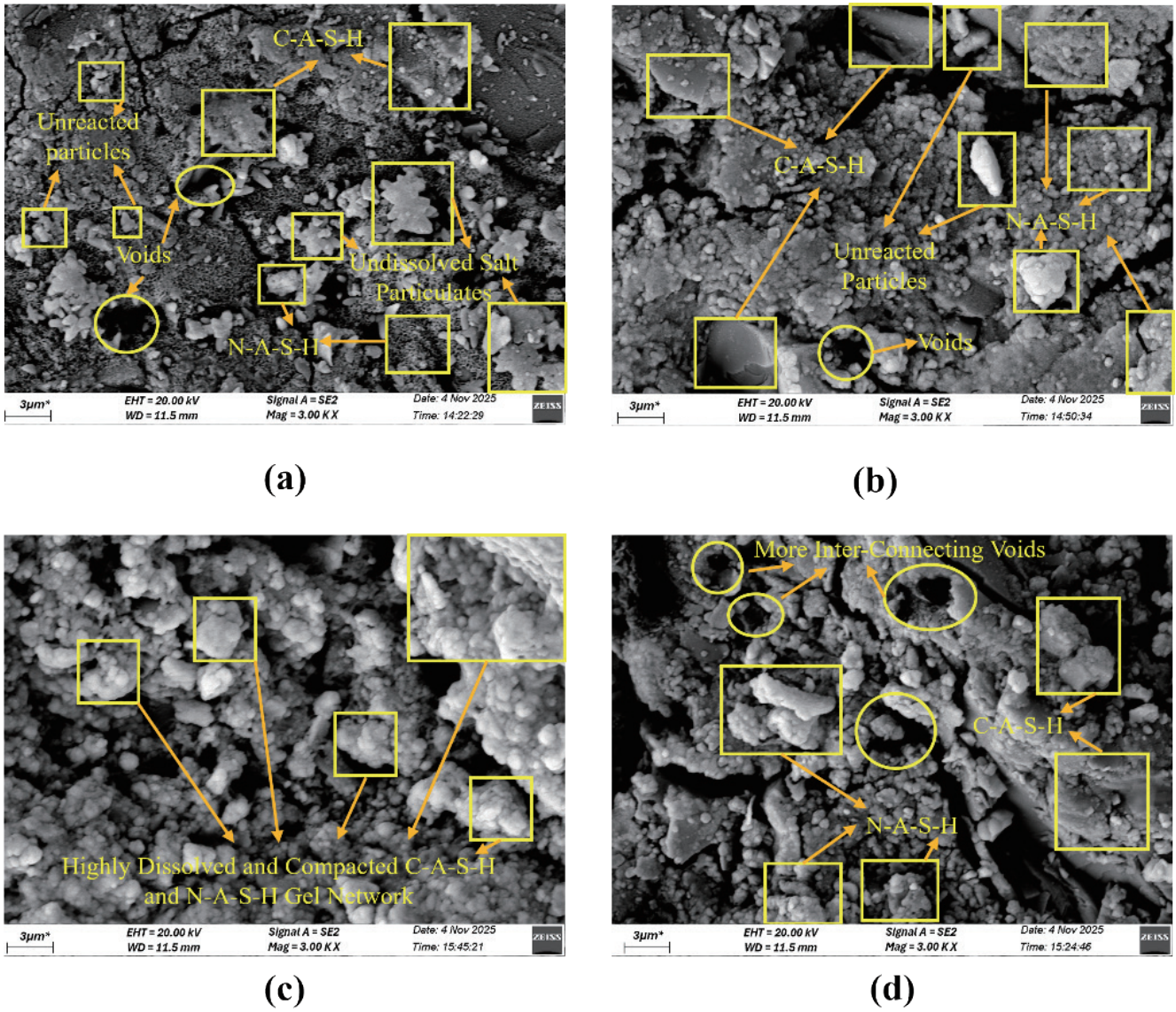

Fig. 8 SEM images of geopolymer mixes at (a) 4M, (b) 6 M, (c) 8 M, and (d) 10 M

although isolated pores and unreacted regions remain. The specimen activated with 8 M NaOH (Fig. 8c) shows the most compact and homogeneous microstructure, characterized by a dense and continuous C-A-S-H/N-A-S-H dominated matrix with minimal visible porosity. This dense matrix structure directly corresponds to the maximum compressive and flexural strength achieved at this molarity.

The significant strength gain observed at 8 M is primarily due to the combined effect of the GGBS-stone waste blend under optimal alkaline activation. At this molarity, the alkaline environment is sufficiently strong to dissolve both the highly reactive GGBS (containing CaO, SiO_2, and Al_2O_3) and the less reactive crystalline stone waste (predominantly quartz with aluminosilicate minerals), enabling the formation of a well-connected binder matrix. In similar stone-cutting waste-based geopolymer systems, the development of crystalline phases such as mullite and anorthite under alkaline activation has been reported to coexist with the geopolymer gel and to contribute to matrix densification and strength development [20]. In the present study, the identification of quartz, mullite, and anorthite in the XRD patterns of stone waste-GGBS mortars is consistent with these observations and suggests that stone waste acts not only as a silica-alumina source but also as a contributor to the overall microstructural compactness. Comparable strength levels achieved in other hybrid geopolymer systems with optimized activator chemistry further support this interpretation [21,22].

In contrast, the reduction in compressive strength observed at 10 M NaOH, despite the higher alkalinity, corresponds well with the SEM features shown in Fig. 8d, where a more heterogeneous matrix with increased interconnected voids is evident. These microstructural characteristics suggest that excessive alkalinity promotes non-uniform gel precipitation and reduced matrix continuity, rather than further densification, even though dissolution potential is enhanced [23]. Such heterogeneity limits effective stress transfer within the matrix and explains the decline in mechanical performance at this molarity. Nevertheless,

strength development from 7 to 28 days across all molarities indicates continued geopolymerization, with percentage increases ranging from 12.8% at 4 M to 42.1% at 8 M. The highest relative strength gain recorded at 8 M confirms that this activator concentration provides the most favorable balance between dissolution and stable binder formation, resulting in sustained strength development over time.

3.2.4 Flexural Strength

Flexural strength, which reflects the material's resistance to bending and tensile stresses, shows a similar pattern to compressive strength but with less variation. The flexural strength increased from 8.91 MPa at 4 M to a peak of 12.11 MPa at 8 M (35.9% increase), then decreased to 10.13 MPa at 10 M, as shown in Fig. 9.

The enhanced flexural strength at 8 M is indicative of improved gel homogeneity and reduced microcracking in the geopolymer matrix. Flexural strength is susceptible to microcracks, voids, and interfacial transition zones, which act as stress concentrators and initiation points for crack propagation [24]. The optimal alkalinity at 8 M promotes uniform gel distribution and stronger bonds between the gel phase and unreacted particles, improving tensile and flexural performance. The reduction in flexural strength at 10 M can be attributed to the same factors affecting compressive strength: microcracking from rapid setting, incomplete polymerization, and non-uniform gel distribution.

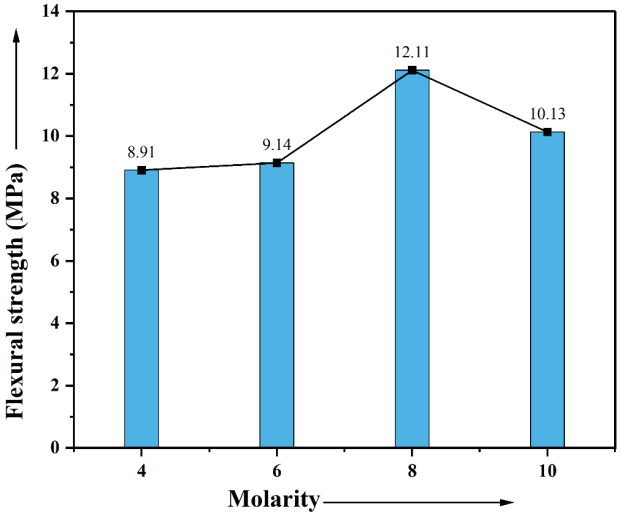

Fig. 9 Effect of NaOH molarity on flexural strength at 28 days.

3.3 Effect of NaOH: Na_2SiO_3 Ratio

Based on the findings from Section 3.2, 8 M NaOH was identified as the optimal molarity for achieving maximum compressive strength. Subsequently, the ratio of NaOH to Na_2SiO_3 was varied at this fixed molarity to optimize the geopolymer properties further. The ratios examined (1:1, 1:1.5, 1:2, and 1:2.5) were chosen to study the combined effect of alkalinity and soluble silica concentration. Adjusting this ratio is significant as it directly affects the matrix's strength development, gel formation, and compactness.

3.3.1 Density

The bulk density showed a consistent increase in values with higher Na_2SiO_3 content, varying from 1798 kg/m^3 at a 1:1 ratio to 1908 kg/m^3 at a 1:2.5 ratio, representing a 6.1% increase (Fig. 10). This gradual increase in density indicates progressive densification of the geopolymer matrix with increasing Na_2SiO_3 content.

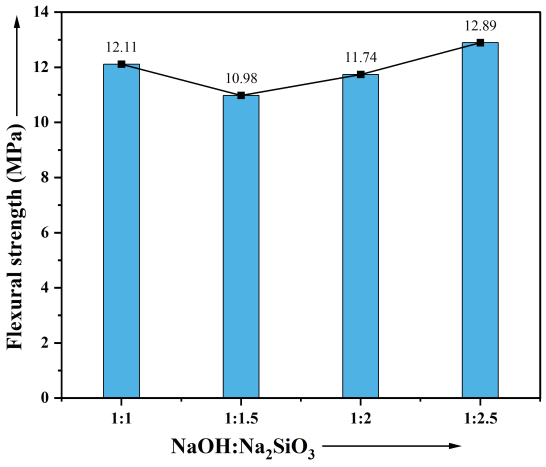

Fig. 10 Effect of NaOH: Na_2SiO_3 on the density of geopolymer mortars.

Na_2SiO_3 serves a dual role in geopolymerization: it provides additional soluble silica (SiO_2) for polymer chain formation and contributes to the alkaline environment necessary for precursor dissolution. The increase in density with a higher Na_2SiO_3 ratio can be attributed to enhanced availability of silicate species, which promotes more extensive polycondensation reactions and the formation of longer, more interconnected silicate chains in the geopolymer gel. This results in a denser matrix with reduced void content. The current findings align with research done by Yilmazoglu et al. [25], which shows that GGBS-based geopolymer concrete results in increased density and more homogeneous microstructure with optimized activator compositions. The higher silicon content from Na_2SiO_3 also facilitates the formation of both C-A-S-H and N-A-S-H gels in the hybrid GGBS-stone waste system. The C-A-S-H gel, formed predominantly from GGBS activation, incorporates additional silica into its structure, resulting in lower Ca/Si ratios and more polymerized gel structures [26]. The N-A-S-H gel formed from stone waste dissolution similarly benefits from increased silica availability, promoting higher degrees of polymerization (Q^4 structures) and greater structural integrity [27].

3.3.2 Water Absorption and Porosity

Both water absorption and porosity decrease with increasing Na_2SiO_3 content. Water absorption decreased from 11% at 1:1 to 10% at 1:2.5, while porosity decreased from 18.5% to 17%, representing an 8.1% reduction (Fig. 11).

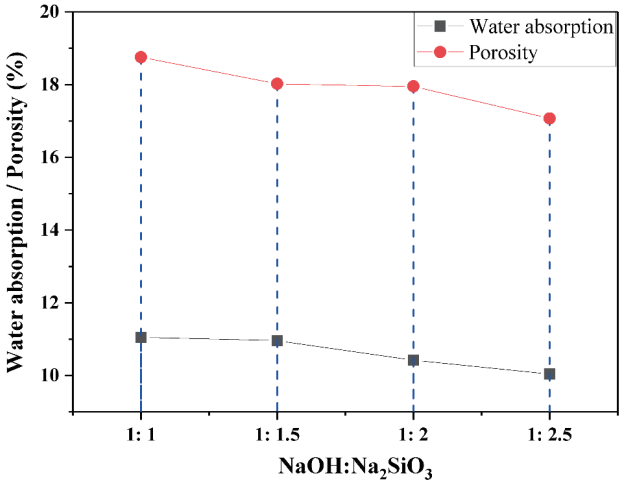

Fig. 11 Effect of NaOH: Na_2SiO_3 on water absorption and porosity.

The reduced water absorption and porosity at higher Na_2SiO_3 ratios reflect improved microstructural compactness and reduced pore network connectivity. The additional soluble silicate accelerates the geopolymerization reaction by providing readily available silicon tetrahedra ($[SiO_4]^{4-}$), which rapidly condense with aluminium tetrahedra ($[AlO_4]^{5-}$) released from the GGBS and stone waste precursors. This rapid reaction kinetics results in a more homogeneous gel phase with fewer unreacted particles and discontinuous pores. Also, the increased viscosity of the alkaline activator solution at higher Na_2SiO_3 ratios improves workability and reduces the tendency for segregation and bleeding during mixing and casting [28]. This leads to a more uniform distribution of the geopolymer gel and reduces the formation of large capillary pores that contribute to high water absorption. The current findings are consistent with previous studies, Nadeem et al. [29], Ibrahim et al. [30], which confirms that higher Na_2SiO_3 content improves strength, reduces permeability, and enhances its durability properties.

3.3.3 Compressive Strength

The compressive strength results at varying NaOH: Na_2SiO_3 ratios revealed a remarkable non-linear pattern. At 7 days, strength values were 51.82 MPa (1:1), 45.8 MPa (1:1.5), 50.13 MPa (1:2), and 58.02 MPa (1:2.5). At 28 days, the corresponding values were 73.85 MPa, 68.75 MPa, 71.24 MPa, and 75.78 MPa (Fig. 12). The maximum strength was achieved at the 1:2.5 ratio, representing a 2.6% increase over the 1:1 ratio at 28 days.

The slight decrease in strength at the 1:1.5 ratio and a gradual increase at 1:2 and 1:2.5 ratios indicate a change in the governing gel formation mechanism. At the 1:1 ratio, the alkalinity is mainly due to NaOH, which provides an intense hydroxide ion concentration for the rapid dissolution of precursors. However, the limited availability of soluble silicate may restrict the formation of highly polymerized gel structures. At the 1:1.5 ratio, there may be a temporary imbalance between the precursors' dissolution rate and silicate availability for polycondensation, resulting in slightly lower strength. As the Na_2SiO_3 content increases to 1:2 and 1:2.5, the enhanced availability of silicate species advances more extensive polymerization and cross-linking, resulting in a denser and stronger gel network. The superior performance at the 1:2.5 ratio is attributed to the optimal balance between alkalinity (from NaOH) and silicate availability (from Na_2SiO_3). The present study is comparable to that of Ansari et al. [27], who explained that when NaOH and Na_2SiO_3 are used together, Na_2SiO_3 provides $[SiO_4]^{4-}$ to facilitate geopolymerization, while NaOH offers an alkaline environment to leach $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$for subsequent reactions. However, excess $[SiO_4]^{4-}$can adsorb on reactant particle surfaces and slow the reaction. The 1:2.5 ratio appears to reach the optimal balance for the GGBS-stone waste system. The strength development from 7 to 28 days (42.5% for 1:1, 50.1% for 1:1.5, 42.1% for 1:2, and 30.6% for 1:2.5) indicates that higher Na_2SiO_3 ratios promote earlier strength development, as evidenced by the lower percentage increase for the 1:2.5 specimens. This is consistent with the accelerating effect of soluble silicate on geopolymerization kinetics [31].

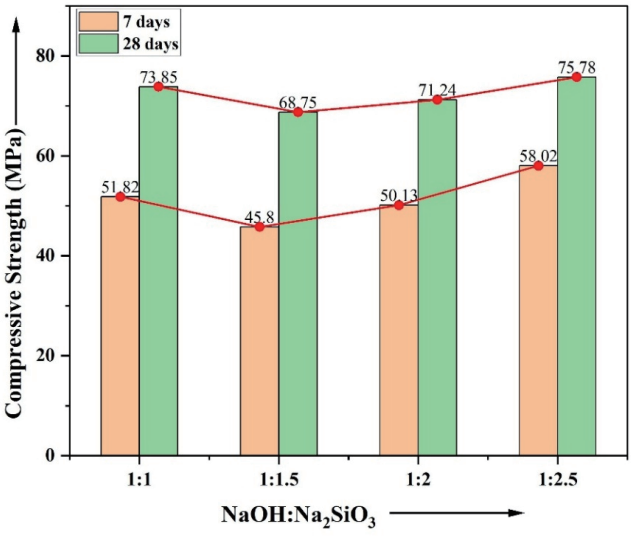

Fig. 12 7 and 28 day compressive strength test results for different NaOH to Na_2SiO_3 ratios at 8 M mix.

3.3.4 Flexural Strength

Flexural strength exhibited a pattern consistent with that of compressive strength, with values of 12.11 MPa (1:1), 10.98 MPa (1:1.5), 11.74 MPa (1:2), and 12.89 MPa (1:2.5). The maximum flexural strength at the 1:2.5 ratio represents a 6.4% increase compared to the 1:1 ratio, as shown in Fig. 13.

The improved flexural strength at higher Na_2SiO_3 nanoparticle ratios indicates enhanced matrix homogeneity and improved interfacial bonding between the gel phase and unreacted particles. The increased silicate content promotes more complete geopolymerization, resulting in fewer weak zones and discontinuities that could serve as crack initiation sites. These results align with a study done by Ibrahim et al. [30], who reported that Na_2SiO_3 combined with 10 M NaOH increased flexural strength and fracture toughness by 81.6% in rice husk ash based geopolymers, demonstrating the critical role of soluble silicate in enhancing mechanical performance.

The flexural to compressive strength ratio in the current study (approximately 17%) is consistent with typical values for geopolymer concretes and indicates balanced mechanical properties. The improvement in flexural strength at higher Na_2SiO_3 ratios can be explained through the interaction of geopolymeric gels. In the GGBS-stone waste mix system, C-A-S-H gels derived from GGBS contribute to ductility and deformation resistance, while N-A-S-H gels from sandstone offer rigidity and suppress crack growth. At the 1:2.5 ratio, these gels work together, producing a dense, well-bonded matrix that combines both toughness and strength [26,32].

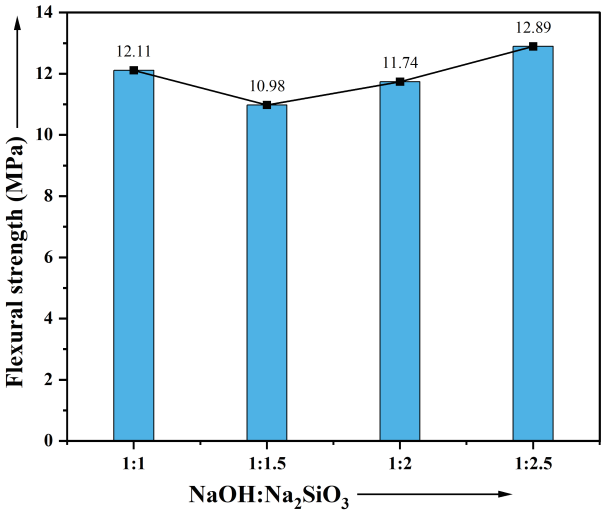

Fig. 13 Effect of NaOH: Na_2SiO_3 ratios on flexural strength for 8M mix at 28 days.

4. Conclusion

The present study focused on valorizing dimensional stone waste in combination with GGBS for the development of geopolymer mortars. The study systematically examined the influence of NaOH molarity and NaOH: Na_2SiO_3 ratio on physical properties and mechanical properties. This dual focus addressed technical optimization and established the feasibility of turning stone waste into a functional binder material. The critical findings from the present study are as follows:

(1) Dimensional stone waste, when used in equal proportion with GGBS, was successfully utilised to produce geopolymer mortars under ambient curing, achieving compressive strengths above 70 MPa at 28 days, along with low water absorption and porosity.

(2) NaOH molarity affected both physical and mechanical properties significantly. Increasing molarity from 4 M to 8 M improved density and strength and reduced porosity and water absorption, while a further increase to 10 M resulted in reduced performance. An optimum NaOH molarity of 8 M was identified for the studied system.

(3) At 8 M NaOH, the NaOH: Na_2SiO_3 ratio governed mortar performance. Increasing the ratio from 1:1 to 1:2.5 led to progressive improvement in density, compressive strength, and flexural strength, with the 1:2.5 ratio giving the best overall results within the investigated range.

(4) The optimised mix (8 M NaOH, NaOH: Na_2SiO_3 = 1:2.5, binder-to-sand ratio = 1:2) provides a reproducible activator composition for producing dense, high-strength stone waste-GGBS geopolymer mortars suitable for masonry units and compressed brick applications under ambient curing conditions.

The novelty of this research lies in its systematic optimization of activator chemistry for stone waste-based geopolymer mortars, moving beyond earlier feasibility studies. The results highlight how dimensional stone waste, typically considered a disposal challenge, can be transformed into a reliable precursor for sustainable binder systems. From a sustainability perspective, the study demonstrates the technical feasibility of reutilizing dimensional stone waste as a geopolymer binder component, supporting waste valorization and resource efficiency. The findings highlight the potential of stone waste-based geopolymers as alternative binder systems within circular construction practices. Future research can extend towards durability assessment, scale-up studies for structural applications, and life-cycle analysis to quantify carbon savings. Such investigations will further validate the potential of stone waste-based geopolymers as practical, sustainable alternatives in modern construction.

CRediT authorship contribution statement

Akash Paradkar: Conceptualization, Data curation, Investigation, Methodology, Visualization.

Astha Sharma: Writing – Original draft, Formal Analysis, Validation.

Sandeep Chaudhary: Conceptualization, Funding Acquisition, Resources, Writing – review & editing, Supervision.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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