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Developing Geopolymer Mixes For Producing Eco-Friendly Lightweight Concrete

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ABSTRACT

This study presents a preliminary investigation into the optimization of normal weight geopolymer concrete (NWGPC) mixes as a foundation for developing eco-friendly lightweight geopolymer concrete. Nine mixes were prepared using GGBFS as the sole binder, with systematic variation in sodium oxide (Na_2O) content (8%, 9%, 10%) and solution modulus (Ms = 0.9, 1.0, 1.1). All mixes were evaluated for compressive strength, splitting tensile strength, flowability, and dry density. The results showed that increasing Na_2O content significantly improved both compressive and tensile strengths due to enhanced slag dissolution and accelerated geopolymerization, with the highest strengths obtained at 10% Na_2O for all Ms levels. Conversely, higher Na_2O reduced workability as rapid gel formation increased mix stiffness. The solution modulus also played a critical role, where Ms = 1.0 produced the most favorable mechanical performance, while both lower (Ms = 0.9) and higher (Ms = 1.1) values resulted in inferior strengths and reduced consistency. Dry density values remained within the normal-weight range (2179–2250 kg/m^3) with limited sensitivity to mix variables. The findings establish Ms = 1.0 and Na_2O = 10% as optimal parameters for achieving high-performance NWGPC, forming a robust baseline for future production of lightweight geopolymer concrete.

Keywords: Geopolymer concrete, Normal weight geopolymer, Mix design optimization, Geopolymer mortar

1. INTRODUCTION

Concrete remains the most widely used construction material worldwide, but its environmental impact particularly the carbon emissions associated with Portland cement production continues to raise serious sustainability concerns. Cement manufacturing is responsible for approximately 7% of global CO_2 emissions, making it a major contributor to climate change [1]. As the demand for eco-friendly and sustainable building solutions increases, researchers are placing greater emphasis on developing alternative binders that can partially or fully replace conventional cement without compromising structural performance.

Geopolymer concrete has gained significant attention as one of the most promising sustainable alternatives. It is produced using industrial by-products rich in aluminosilicate materials, such as fly ash, metakaolin, slag, rice husk ash, and silica fume [2]. When activated with alkaline solutions typically a combination of sodium hydroxide and sodium silicate these materials form a stable, dense matrix with excellent mechanical properties. Geopolymer concrete has demonstrated superior early strength, improved durability, reduced shrinkage, and enhanced chemical resistance compared to traditional Portland cement concrete, making it highly attractive for structural applications [3], [4], [5]

Despite its promising properties, the practical use of geopolymer concrete still faces challenges, especially regarding workability, setting time, and mix consistency. These issues become even more critical when geopolymer concrete is intended for large-scale structural or masonry applications that require predictable behavior, sufficient open time, and reliable handling. Unlike conventional concrete, geopolymer mixtures are sensitive to activator concentration, the sodium silicate-to-hydroxide ratio, binder characteristics, and water content all of which strongly influence strength development and fresh properties.

For this reason, optimizing normal weight geopolymer concrete (NWGPC) is an essential preliminary step before extending geopolymer technology to specialized products such as lightweight blocks, precast units, or insulating elements. Establishing a stable and well-balanced normal-weight mix ensures that the mechanical and physical performance is reliable enough to serve as a foundation for future modifications.

In this study, Ground Granulated Blast Furnace Slag (GGBFS) is used as the primary binder due to its availability, cost-effectiveness, and superior mechanical performance. GGBFS is a by-product of the steel manufacturing industry and is highly valued for its high silica content, which contributes to increased compressive strength, reduced permeability, and improved durability [6], [7], [8]. These characteristics make it a suitable choice for normal weight geopolymer concrete, where achieving high compressive strength and consistency is essential [9].

The objective of this research is to identify optimal mix proportions for normal weight geopolymer concrete by systematically evaluating the effects of key variables, including activator concentration, sodium silicate-to-hydroxide ratio, binder content, and additional water. The goal is to produce geopolymer mixes with balanced mechanical and workability properties that meet structural requirements while maintaining sustainability. The outcomes of this study provide a clear basis for future development of lightweight geopolymer mixtures and other specialized geopolymer-based construction materials.

2. Experimental Program

2.1. Materials Properties

2.1.1. GGBFS and aggregate

Ordinary Portland Cement (OPC) was fully replaced with Ground Granulated Blast Furnace Slag (GGBFS) as the primary binder in this study, as illustrated in Figure 1. The chemical composition of the slag was determined through XRD analysis, and the results are presented in Table 1. Natural sand was used as the fine aggregate, with a specific gravity of approximately 2.50 and a fineness modulus of about 2.75, while no coarse aggregate was included in any of the mixtures.

Table 1: Chemical composition of GGFBS.

Component	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**K_2O**	**Na_2O**	**TiO_2**	**Mn_2O_3**	**Other oxides**
% of Mass	41.66	13.96	1.49	34.53	5.53	0.97	0.49	0.58	0.35	0.44

2.1.2. Activators

The slag binder was activated using a combination of sodium silicate solution (SS) and sodium hydroxide flakes (SH). To identify the chemical composition of these activators, XRD analysis was carried out, and the obtained results are summarized in Table 2.

Table 2: Chemical composition of sodium silicate and sodium hydroxide.

Component	SiO_2	Na_2O	H_2O
Sodium Silicate (% of Mass)	31	12	57
Sodium Hydroxide (% of Mass)	-----	60.25	39.75

Figure 1:Ground granulated blast furnace slag

2.2. Test Program

Before advancing to more specialized application a comprehensive preliminary investigation was carried out on normal weight geopolymer concrete to establish a reliable baseline mix with optimized mechanical performance, as recommended by previous research [17]. In this study, the binder content was held constant at 450 kg/m³ to ensure consistency across all mixtures. The solution modulus (Ms) which is defined as the ratio of SiO_2 to Na_2O in the alkaline activator was examined at three levels: 0.9, 1.0, and 1.1, as these ranges are known to significantly influence both reaction kinetics and final strength development. Similarly, the sodium oxide (Na_2O) content in the activator was varied at 8%, 9%, and 10% of the binder mass to evaluate its impact on the geopolymerization process and the resulting mechanical properties. Throughout the experimental program, the water-to-binder ratio was kept constant at 0.50, and the corresponding amount of additional water necessary for each mix was included to achieve acceptable workability. Table 3 presents the complete test matrix used in this phase. For every combination of Ms and Na_2O content the compressive strength, tensile strength, and flowability were measured to determine the most balanced and effective mix. The results of this preliminary optimization provide a clear understanding of how activator composition influences the behavior of normal weight geopolymer concrete.

This optimized mix design will serve as the foundation for the subsequent stage of research, in which the same principles will be applied to the development of lightweight geopolymer concrete.

Table 3: Test Matrix for Normal weight geopolymer concrete per cubic meter.

Mix.	Slag (Kg)	Sand (Kg)	SH (Kg)	SS (Kg)	Additional Water (Kg)	Percentage of Na_2O in the mix.	Solution Modulus (Ms)
N1	450	1390	45	131	147	10%	0.9
N2	450	1390	40	124	152	9%	
N3	450	1390	36	108	161	8%	
N4	450	1390	45	145	140	10%	1
N5	450	1390	40	138	147	9%	
N6	450	1390	36	120	156	8%	
N7	450	1390	45	160	135	10%	1.1
N8	450	1390	40	152	141	9%	
N9	450	1390	36	132	152	8%	

2.3. Specimens' preparation

The preparation process began by dissolving the sodium hydroxide (SH) flakes in water and allowing the solution to cool to approximately 30 °C. Once cooled, the sodium silicate (SS) solution was added, and the combined activator was left to reach the same temperature before use in the mixing process [18], [19]. The slag and sand were first placed in the mixer and blended in their dry state. The prepared activator solution was then introduced, followed by the addition of extra water to enhance workability. Mixing continued for about 60 seconds. A flow table test was performed for all mixes to verify the mixture's workability in the fresh state according to ASTM C1437 [10], as illustrated in Figure 2. The fresh geopolymer mix was subsequently poured into 100 × 100 × 100 mm molds as shown in Figure 3 and allowed to rest for 24 hours prior to demolding. The specimens are left to be cured in the ambient temperature. The specimens were then tested at 3, 7, and 28 days for compressive strength test and were tested at 28 days for tensile strength test.

Figure 2: Flow table test for the fresh mix.

Figure 3: Cast specimens

3. Testing of the specimens

For the normal weight geopolymer concrete evaluation, each mix was tested in compression at 3, 7, and 28 days, and in splitting tensile strength at 28 days. A load-controlled testing machine with a capacity of 200 tons was used for all tests, applying load at a constant rate of 0.50 N/s.

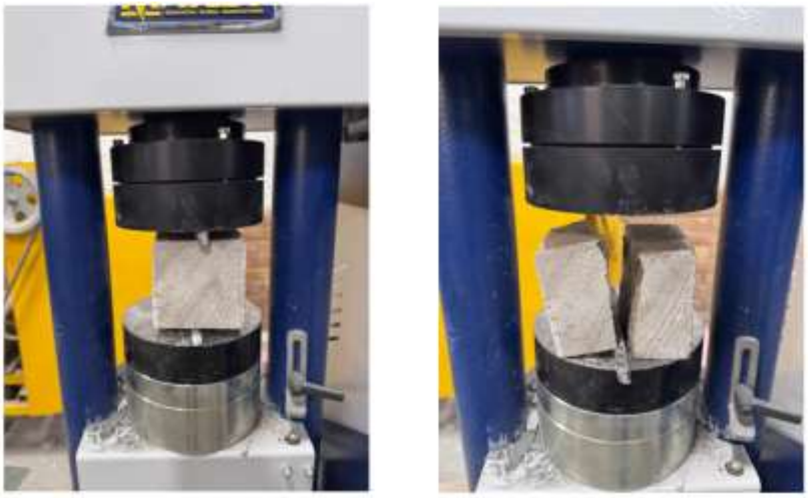
Each mix included twelve cube specimens measuring 100 × 100 × 100 mm, prepared in sets of three for each testing age for the compressive strength test and three more for the splitting tension test. After casting and demolding at 24 hours, all specimens were stored under identical laboratory conditions until testing. Before loading, the cube faces were cleaned and positioned to ensure proper alignment in the testing machine The compressive strength test was performed according to ASTM C39 as shown in Figure 4 [11], while the splitting tensile test was performed according to ASTM C496 as shown in Figure 5 [12]. The complete test results for compressive and tensile strength for all mixes are provided in Table 4.

Table 4: Test results for the tested specimens

Mix No.	Average Compressive strength (MPa)			Average tensile strength (MPa)	Flowability (%)	Average Dry Density (Kg/m^3)
	3 Days	7 Days	28 Days	28 days		
N1	28.7	35.1	42.6	3.83	65	2188
N2	23.1	30.0	36.2	2.21	70	2210
N3	19.8	26.8	33.9	2.05	90	2198
N4	33.1	39.0	45.2	3.90	70	2250
N5	25.8	34.9	40.8	2.83	80	2200
N6	23.3	30.4	39.2	2.47	100	2195
N7	21.8	27.9	33.3	3.00	90	2235
N8	18.9	24.6	30.6	2.07	100	2179
N9	16.9	23.7	28.1	1.53	100	2222

a) Test Setup b) Mode of Failure

Figure 4: Test setup and mode of failure for compressive strength test.



a) Test Setup b) Mode of Failure

Figure 5: Test setup and mode of failure for splitting tensile strength test.

4. Discussion of test results

4.1. Effect of Sodium Oxide (Na_2O)

The test results demonstrate that the Na_2O content has a pronounced influence on both the mechanical and fresh properties of the normal weight geopolymer concrete mixtures. As shown in Figure 6 and Figure 7, Increasing the Na_2O percentage from 8% to 10% consistently enhanced the compressive and tensile strength across all solution modulus levels, with 10% Na_2O mixtures (N1, N4, N7) achieving the highest strength values at 28 days. This improvement is attributed to the higher alkalinity, which promotes faster dissolution of slag particles and accelerates the geopolymerization reaction, resulting in a denser and stronger matrix. However, this increase in Na_2O content was accompanied by a reduction in flowability, as the mixes became stiffer due to rapid gel formation and higher reaction heat. The 8% Na_2O mixes exhibited the highest workability but lower strength, while the 9% Na_2O mixes provided intermediate performance. Variations in dry density were relatively minor, though slightly higher densities were generally observed in mixes with higher Na_2O content, reflecting a more compact microstructure. Overall, the Na_2O concentration played a critical role in balancing strength development and workable consistency in the geopolymer mixtures [13].

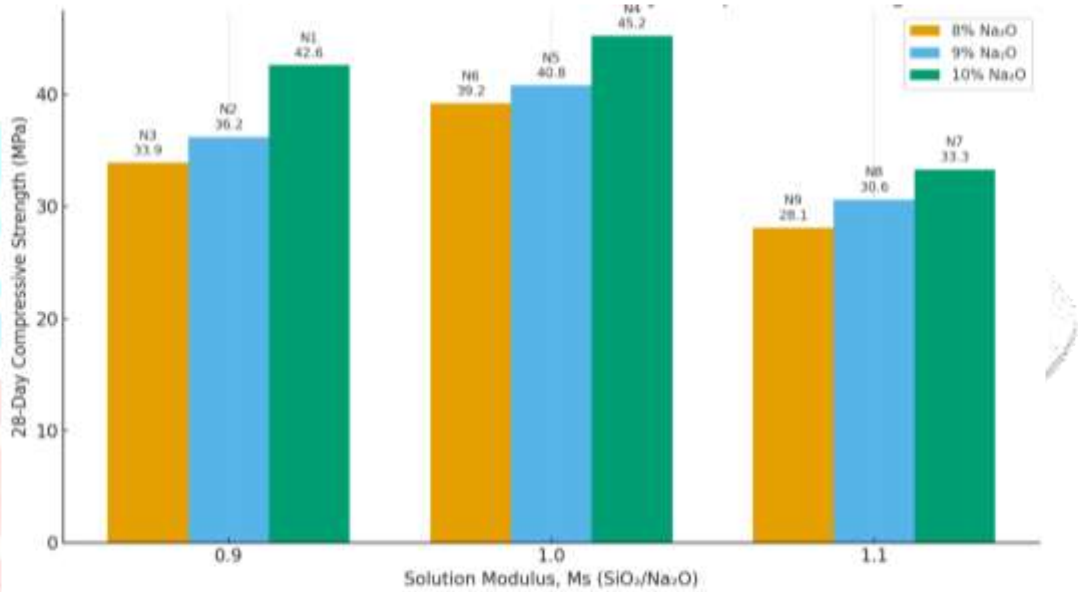


Figure 6: Effect of Na_2O percentage on compressive strength.

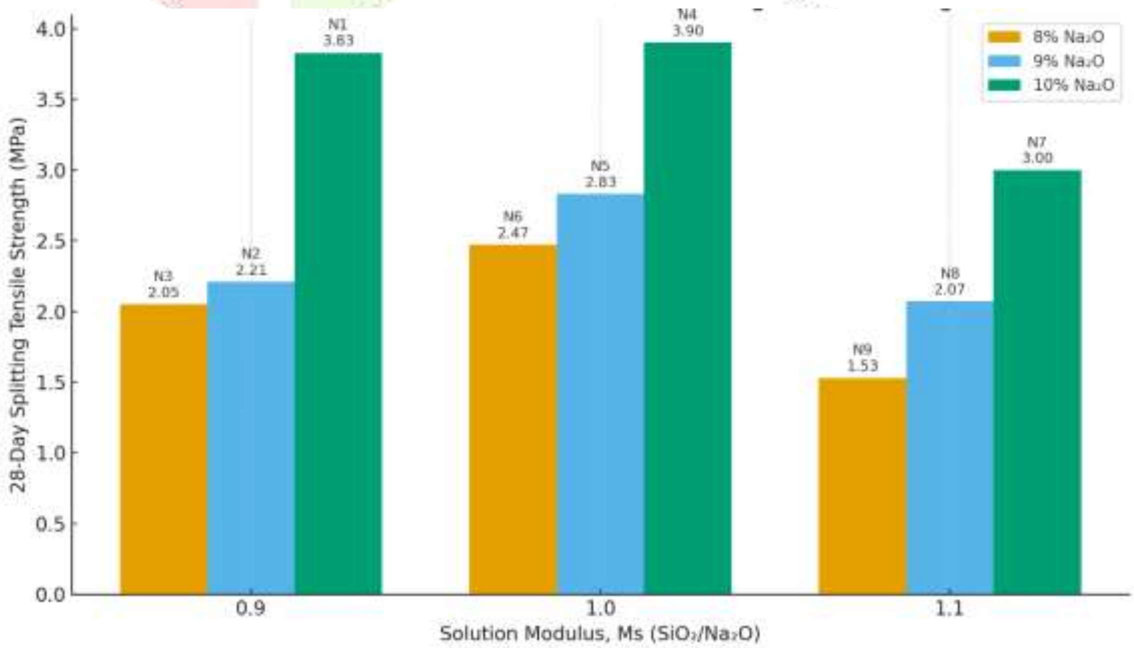


Figure 7: : Effect of Na_2O percentage on splitting tensile strength.

4.2. Effect of solution modulus (Ms)

As Illustrated in Figure 8 and Figure 9, the solution modulus (Ms) had a noticeable impact on the mechanical performance and workability of the normal-weight geopolymer concrete mixes. Increasing Ms from 0.9 to 1.0 improved both the compressive and splitting tensile strengths for all Na_2O levels, indicating that a balanced ratio of SiO_2 to Na_2O enhances gel formation and produces a denser geopolymer matrix. This is evident in the strength increase from mixes N1–N3 (Ms = 0.9) to mixes N4–N6 (Ms = 1.0). However, further increasing the modulus to Ms = 1.1 resulted in a reduction in strength for all corresponding mixes (N7–N9). The higher silicate content at Ms = 1.1 likely increased the viscosity of the activator and slowed slag dissolution, which limits the formation of reaction products and leads to lower strength. Flowability also decreased at higher Ms values due to increased solution viscosity and faster structural buildup. Overall, an Ms value of 1.0 yielded the most favorable combination of strength development and workable consistency, while excessively low or high moduli resulted in suboptimal geopolymerization behavior [8], [14].

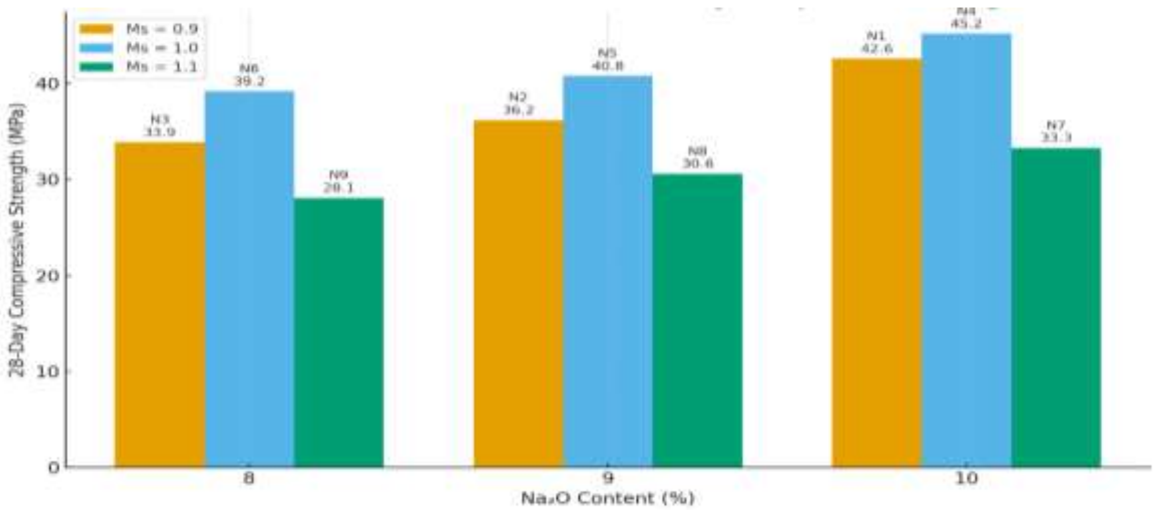


Figure 8: Effect of Ms on Compressive strength.

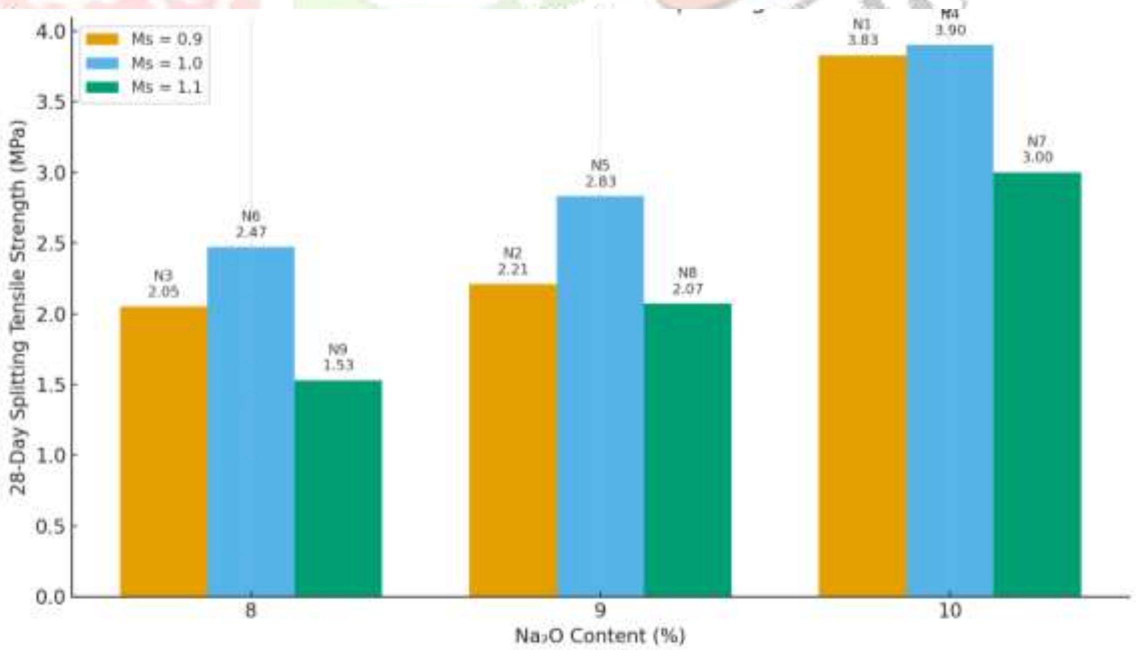


Figure 9: Effect of Ms on Splitting tensile strength.

4.3. Effect of Na2O and Ms on workability

The workability of the geopolymer mixtures was strongly influenced by both the sodium oxide content and the solution modulus. Increasing Na_2O from 8% to 10% consistently reduced flowability, as the higher alkalinity accelerated the dissolution of slag particles and promoted rapid gel formation, leading to faster stiffening of the fresh mix. Similarly, increasing Ms raised the viscosity of the activator due to the higher silicate content, which further limited flow and reduced the mixture's ability to spread during the flow table test. Mixes with low Na_2O (8%) and lower Ms (0.9) exhibited the highest workability, while those containing 10% Na_2O and Ms = 1.1 showed the lowest flow percentages, confirming that both parameters significantly accelerate geopolymerization reactions and reduce mixture fluidity. The results are indicated in Figure 10.

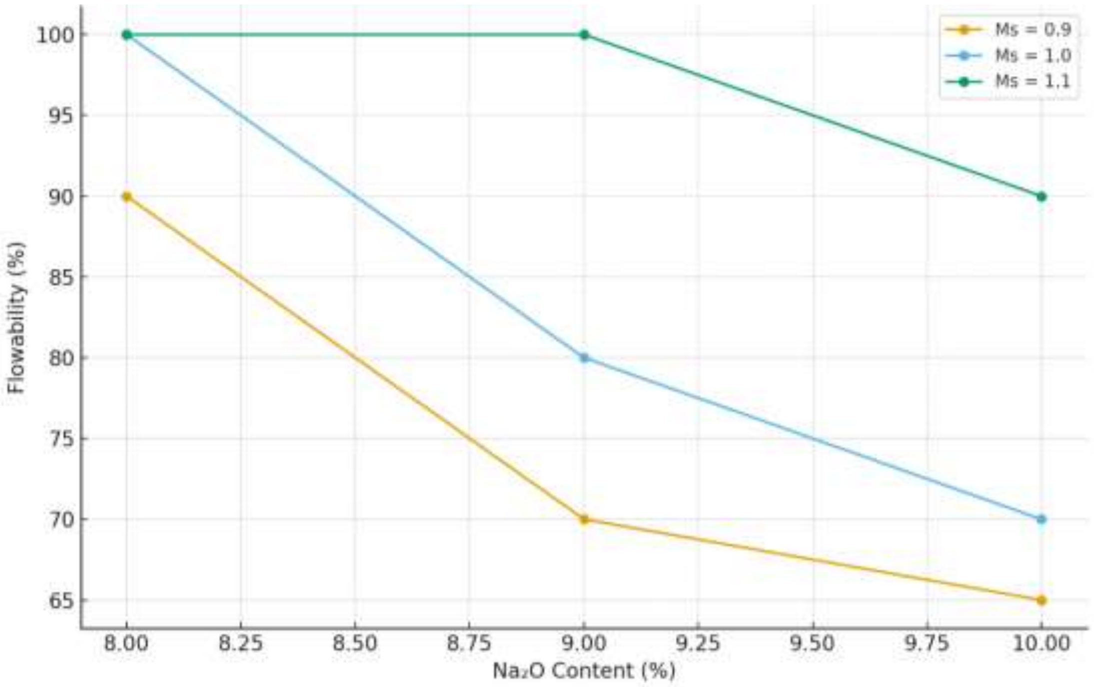


Figure 10: Effect of Ms and Na2O on workbility.

5. Summary and Conclusions

This study optimized normal-weight geopolymer concrete by evaluating the combined effects of sodium oxide content (8%, 9%, 10%) and solution modulus (Ms = 0.9, 1.0, 1.1) on the mechanical and fresh properties of GGBFS-based mixes. Results showed that increasing Na_2O enhanced both compressive and tensile strengths but reduced flowability due to faster geopolymerization. The solution modulus significantly influenced strength development, with Ms = 1.0 producing the highest performance across all activator levels, while both lower and higher Ms values resulted in reduced strength. Dry density remained within the normal-weight range for all mixes. Overall, the findings identify Na_2O = 10% and Ms = 1.0 as optimal conditions for achieving a balanced, high strength geopolymer mix that serves as a reliable baseline for future lightweight geopolymer concrete development. The results in this research can be summarized as following:

- Increasing the Na_2O content from 8% to 10% significantly improved both compressive and splitting tensile strengths due to enhanced slag dissolution and accelerated geopolymerization.
- Higher Na_2O levels reduced flowability, while lower Na_2O improved workability at the expense of strength.
- The solution modulus had a strong influence on performance, with Ms = 1.0 providing the highest mechanical strength and most balanced behavior.
- Both low (Ms = 0.9) and high (Ms = 1.1) modulus values resulted in reduced strength, the latter due to increased activator viscosity and slower dissolution.
- All mixes maintained normal weight density, and the results identify 10% Na_2O and Ms = 1.0 as the optimal combination for developing high-performance geopolymer concrete and for serving as a baseline for future lightweight formulations.

- Workability decreased with increasing Na_2O content and deviating from the optimal modulus, with the lowest flow observed at high alkalinity (10% Na_2O, Ms = 0.9) and the highest flow achieved at lower alkalinity and higher Ms levels.

Future work: It will extend the optimized normal-weight geopolymer mixes to develop lightweight geopolymer concrete and evaluate its mechanical, durability, and microstructural performance.

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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This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. All experimental data supporting the findings have been organized in tabular and graphical formats as presented in the manuscript.

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