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INFLUENCE OF SODIUM LIGNOSULPHONATE ON WORKABILITY AND STRENGTH DEVELOPMENT IN GGBS-BASED GEOPOLYMER CONCRETE

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ABSTRACT

This study investigates the use of sodium lignosulphonate (NaLS), an eco-friendly lignin-based admixture, to enhance the workability and strength of M30-grade GGBS-based geopolymer concrete (GPC) produced under ambient conditions. The experimental program involved mixes containing GGBS (413.79 kg/m³), fine and coarse aggregates, alkaline activators (sodium hydroxide and sodium silicate), and varying NaLS dosages (0–3% by binder weight). Results showed that adding NaLS significantly improved workability and mechanical properties, with an optimum performance at 2% dosage—slump increasing from 50 mm to 98 mm, compressive strength from 34.0 MPa to 43.5 MPa, split tensile strength to 4.22 MPa, and flexural strength to 5.85 MPa. Beyond 2%, a slight reduction in performance occurred due to excess air entrainment. The study concludes that 2% NaLS optimally enhances the microstructural density, bonding, and overall performance of GGBS-based GPC, establishing it as a sustainable, cost-effective solution for low-carbon concrete development in ambient curing environments.

1. INTRODUCTION

The construction industry faces increasing pressure to reduce its carbon footprint and environmental impact. Conventional Portland cement (OPC), the primary binder in concrete, is responsible for approximately 7–8% of global carbon dioxide (CO_2) emissions, primarily due to the calcination of limestone and the high energy demands of clinker production. The search for sustainable alternatives to OPC has led to the development of geopolymer concrete (GPC), an eco-friendly material that utilizes industrial by-products rich in aluminosilicates, such as fly ash and ground granulated blast furnace slag (GGBS). These materials, when activated with alkaline solutions, form a polymeric Si–O–Al network that provides comparable or even superior mechanical and durability performance to conventional cementitious systems while significantly reducing embodied carbon emissions.

Among various geopolymeric systems, GGBS-based geopolymer concrete has gained prominence due to its high calcium content, which promotes early-age strength development and enables curing under ambient conditions. This characteristic makes GGBS geopolymers particularly attractive for practical applications, as they overcome the limitations of heat curing often required for fly-ash-based geopolymers. However, despite these advantages, GGBS-based geopolymer concretes often suffer from low workability and rapid setting, mainly due to the high reactivity of GGBS and the strong alkalinity of the activating solution. Consequently, the use of chemical admixtures has been proposed to enhance workability and control setting behavior without compromising mechanical performance.

In conventional OPC concrete, chemical admixtures such as superplasticizers and water reducers play a vital role in improving the fresh and hardened properties of the mix. Among these, sodium lignosulphonate (NaLS)—a lignin-derived, anionic surfactant—is one of the most widely used first-generation water-reducing agents. Derived from the sulfite pulping process of wood, NaLS is eco-friendly, biodegradable, and cost-effective. It functions primarily by adsorbing onto binder particle surfaces, imparting electrostatic repulsion and dispersion, which enhances flowability at reduced water content. However, the effectiveness of NaLS in geopolymer systems is still uncertain because of the different chemical environment compared to Portland cement. The high pH and complex ionic interactions in alkaline-activated systems can alter the adsorption behavior and stability of organic admixtures, potentially leading to varied or even adverse effects on workability and strength.

Previous studies have explored the incorporation of various admixtures—such as naphthalene-based and polycarboxylate-based superplasticizers—in geopolymer systems, with mixed outcomes. While some admixtures improve flow and setting control, others have been found incompatible with high-alkali environments, resulting in thickening or reduced strength. Limited research has specifically investigated sodium lignosulphonate in GGBS-based geopolymer concrete, particularly under ambient curing conditions. Some reports indicate that lignosulphonate may improve workability at low dosages but retard polymerization and reduce strength at higher concentrations due to delayed gel formation or increased air entrainment. However, most available studies focus on paste or mortar systems, leaving a knowledge gap in concrete-level applications that include aggregates and realistic curing conditions.

Addressing this gap is crucial because understanding the behavior of NaLS in geopolymer concrete can enable the design of mixes that are both workable and structurally reliable for field use. For M20-grade ambient-cured GGBS geopolymer concrete, establishing the relationship between NaLS dosage and key mechanical parameters such as compressive, splitting tensile, and flexural strengths will contribute to optimizing mix design for practical implementation.

Therefore, the present study aims to evaluate the effect of sodium lignosulphonate on the mechanical properties of GGBS-based geopolymer concrete. The investigation involves preparing concrete mixes with varying NaLS dosages, assessing fresh properties (slump and setting behavior), and determining mechanical properties at different ages under ambient curing. The results are expected to provide insights into the dosage–performance relationship, helping to identify an optimal NaLS range that balances workability and strength. Furthermore, this research contributes to the broader understanding of organic admixture compatibility within geopolymer systems, advancing the sustainable utilization of industrial by-products for low-carbon construction materials.

2. LITERATURE REVIEW

Mathur et al. (2017) compared straight and spiral earth air tunnel heat exchangers in cooling and heating modes at MNIT Jaipur, as one example of the many experimental and computational studies conducted on the subject of earth air tunnel heat exchangers. We assumed a total of 60m for the buried tubes. The pipe's thickness was determined to be 0.003 m and its inner diameter to be 0.10m. Pipe material was selected as High Density Poly Ethylene, or HDPE. Based on their calculations, they determined that the EATHE spiral system takes up less room than the straight system. Additionally, compared to the straight EATHE technique, the spiral EATHE system is more effective [2]. Using thermal imaging, Sanjeev Jakhar et al. (2014) studied experimental results of a solar air heating duct connected to an earth air tunnel heat exchanger for the dry environment of Ajmer city were recorded. They found that using EATHE in conjunction with a solar air heating duct was much more successful than using EATHE alone. The polyvinyl chloride (PVC) material was used for the pipes. The specified length of the tubes is 60 meters.The earth tube's inner diameter was determined to be 0.010 m, while its thickness was 0.003 m, according to reference [3]. The size of the pipe, the radius of the pipe, the air velocity inside the tube, and the depth to which the pipe was buried were the variables in the parametric model that Mihalakakou et al. (1995) created [4]. The effectiveness of both single and multiple parallel earth-to-air heat exchanger systems was studied by Santamouris et al. (1997) in relation to various ground surface boundary conditions [5]. An earth-air-pipe system linked with a building without air conditioning was assessed by Kumar et al. (2003) for its potential conservation [6]. The thermal performance of EATHE linked to a room with 100% fresh air and covered in PVC for winter heating was quantitatively evaluated by Bansal et al. (2009). According to their findings, the material of the pipe does not significantly affect the air temperature at the exit [7]. A parametric research testing the novel notion of a "derating factor" for the thermal performance of an earth air tunnel heat exchanger was conducted by Rohit Misra et al. (2012) using computational fluid dynamics (CFD) [8]. The power output of gas turbines was improved by S. Barkat et al. (2016) at Esypt by use of an earth-air tunnel heat exchanger cooling system [9]. The influence of soil thermal conductivity and operating time on the efficiency of an earth air tunnel heat exchanger was investigated by Bansal et al. (2012) at Govt. Engineering College Ajmer [10]. Using several locations for air conditioning in a room coupled with an earth air tunnel heat exchanger, Rahul Khatr et al. (2016) created a computational fluid dynamics (CFD) model to identify the best temperature distribution [11].

In 2014, O.P. Jakhar and Rajendra Kukana used a computational fluid dynamics (CFD) method to conduct a transient thermal study on an earth air tunnel heat exchanger throughout the summer. According to their findings, sandy soil has a greater cooling impact than sandy loamy soil [12]. In this study, a water-cooled heat exchanger is connected to a single unit of an earth air tunnel heat exchanger at the system's output end in order to increase the system's cooling capacity when used independently. Inside the water-cooled heat exchanger, the waste water from the water cooler was used for cooling purposes. Three distinct input air velocities (10, 12, and 14 m/s) were tested experimentally. Under the hot and dry summer weather of Chittorgarh city, operations were carried out for nine hours every day.

3. MATERIALS

3.1. Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) was used as the primary binder in this study. It is an industrial by-product obtained from the steel manufacturing process, consisting mainly of calcium, silica, and alumina. The GGBS used conformed to IS 12089:1987 specifications. The specific gravity was found to be around 2.9, with a Blaine fineness of approximately 400 m^2/kg.

3.2. Fine Aggregate

River sand conforming to IS 383:2016 Zone II grading was used as the fine aggregate. The sand had a specific gravity of 2.65 and fineness modulus of 2.65.

3.3. Coarse Aggregate

Crushed granite aggregates with a nominal maximum size of 20 mm were used. The aggregates were surface dry prior to batching. The specific gravity was 2.70.

3.4. Alkaline Activator Solution

The alkaline activator comprised a combination of sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) solution.

- NaOH: 98% purity pellets dissolved in distilled water to obtain an 8M concentration.
- Sodium silicate: Commercial-grade solution with SiO_2 = 28–30%, Na_2O = 8–10%, and a modulus (Ms = SiO_2/Na_2O) of approximately 2.5.

A fixed Na_2SiO_3/NaOH ratio of 2.0 by mass was adopted across all mixes to maintain uniform reaction conditions.

3.5. Sodium Lignosulphonate (NaLS)

Sodium lignosulphonate, a brown, water-soluble organic powder, was used as a dispersing agent. It contains sulfonated lignin fragments that act as anionic surfactants. The admixture was added in varying dosages (0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3%) by weight of GGBS to evaluate its effect on fresh and mechanical properties.

3.1.6 Water

Potable water was used for NaOH solution preparation and minor adjustments to the activator liquid-to-binder ratio.

4. MIX PROPORTION DETAILS

The mix proportions adopted for the development of geopolymer concrete in this study are presented in the table, illustrating the quantities of each constituent material per cubic meter of concrete. The binder used in the mix comprises Ground Granulated Blast Furnace Slag (GGBS) at a dosage of 413.79 kg/m³, serving as the primary aluminosilicate source responsible for geopolymerization. The fine and coarse aggregates were incorporated at 540 kg/m³ and 1260 kg/m³, respectively, maintaining a suitable aggregate-to-binder ratio to ensure desired workability and strength characteristics. The alkaline activator system consisted of sodium hydroxide (NaOH) pellets and sodium silicate solution, which are essential for dissolving the reactive components in GGBS and facilitating the formation of geopolymeric gels.

Table 3.1. Different quantities for making geopolymer concrete

Component	Quantity (kg/m³)
GGBS	413.79
Fine Aggregate	540.00
Coarse Aggregate	1260.00
NaOH Pellets	15.04
Sodium Silicate Solution	124.14
Extra Water	14.00 L
Sodium Lignosulphonate	0.5%, 1%, 1.5%, 2%, 2.5%, 3% (by wt. of binder)

The NaOH pellets were used at 15.04 kg/m³, while 124.14 kg/m³ of sodium silicate solution was added to maintain an appropriate activator modulus and ensure adequate alkalinity for effective polymerization. Additionally, 14 liters of extra water were introduced to adjust the workability and maintain a consistent mix consistency without compromising the mechanical performance. To study the influence of chemical admixtures on the fresh and hardened properties, sodium lignosulphonate (NaLS), a water-reducing and dispersing agent, was incorporated at varying dosages of 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% by weight of the binder. This variation was designed to evaluate its impact on workability, setting characteristics, and mechanical strength development of the geopolymer concrete, thereby optimizing admixture dosage for superior performance.

5. MIX DESIGN PROCEDURE

The mix design for GGBS-based geopolymer concrete was developed considering the target mean strength for M20 grade concrete and ambient curing conditions. The procedure followed was as per the guidelines proposed by previous geopolymer studies (e.g., Hardjito & Rangan, 2005; IS 10262:2019 as reference for aggregate proportioning). The total aggregate content was fixed at 1800 kg/m³, with the fine-to-total aggregate ratio of 0.3. The alkaline activator-to-binder ratio and the Na_2SiO_3/NaOH ratio were optimized based on trial mixes to ensure adequate workability and strength.

6. TESTING OF FRESH AND HARDENED CONCRETE

6.1 Workability Test

The slump cone test (as per IS 1199:1959) was conducted to assess the workability of each mix. The influence of sodium lignosulphonate dosage on flowability was noted.

6.2 Compressive Strength Test

Compressive strength tests were performed on 150 mm cube specimens at 7, 14, and 28 days in accordance with IS 516:2018.

6.3 Split Tensile Strength Test

150 mm × 300 mm cylindrical specimens were tested for split tensile strength as per IS 5816:1999 to evaluate the tensile behavior of geopolymer concrete.

6.4 Flexural Strength Test

Beam specimens of 100 mm × 100 mm × 500 mm were tested for flexural strength under two-point loading as per IS 516:2018.

7. RESULTS AND DISCUSSION

7.1. Slump cone test

The workability of GGBS-based geopolymer concrete incorporating different dosages of Sodium Lignosulphonate (NaLS) was assessed using the slump cone test, and the results are presented in Fig. X. The slump value of the control mix (0% NaLS) was 50 mm, indicating a relatively stiff consistency typical of ambient-cured GGBS geopolymer concrete due to its fast-reacting calcium-rich matrix. With the incorporation of NaLS, a progressive increase in slump was observed up to a dosage of 2%, beyond which the slump value decreased.

At 0.5% NaLS, the slump improved to 65 mm, reflecting the onset of dispersing action caused by the anionic sulfonate groups in NaLS, which adsorb onto GGBS particle surfaces and promote electrostatic repulsion. A further increase to 1% NaLS resulted in a slump of 78 mm, indicating enhanced flowability due to improved particle separation and reduced internal friction within the mix.

The optimum workability was observed at 2% NaLS, where the slump reached a maximum of 98 mm. This substantial improvement can be attributed to effective dispersion of binder particles and the ability of NaLS to break down initial flocculated structures, facilitating better lubrication within the matrix. This confirms that moderate dosages of NaLS significantly enhance the fresh properties of geopolymer concrete by delaying early coagulation tendencies associated with high-calcium GGBS activation.

Beyond this optimum point, a decline in slump was recorded. The slump at 2.5% NaLS reduced to 88 mm, and further decreased to 75 mm at 3% NaLS. Excess NaLS likely leads to over-adsorption on particle surfaces, increased viscosity of the pore solution, and potential entrainment of air, all of which reduce the free flowability of the concrete. Additionally, higher concentrations of organic molecules may temporarily disrupt the geopolymer gelation process, causing inconsistent dispersion and reduced workability.

Overall, the results indicate that NaLS is effective in enhancing the workability of GGBS-based geopolymer concrete, with 2% identified as the optimum dosage for achieving maximum slump under the given mix proportions and ambient curing conditions. Beyond this level, the diminishing workability suggests that excessive NaLS incorporation adversely affects the rheological behavior of the mixture.

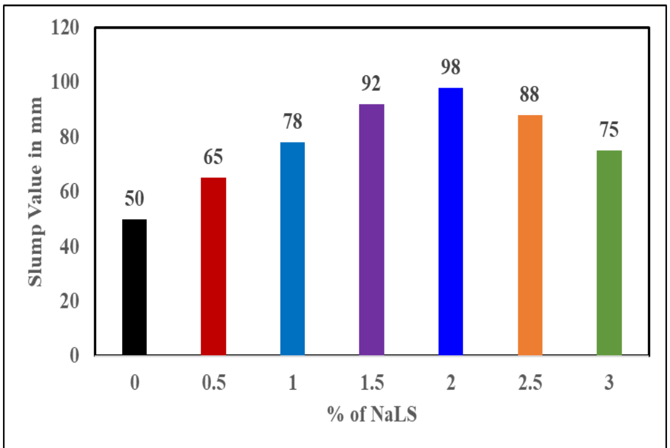

Figure 1. Slump values of geopolymer concrete with varying dosages of NaLS

7.2. Compressive strength

The compressive strength of GGBS-based geopolymer concrete incorporating different dosages of Sodium Lignosulphonate (NaLS) was evaluated at 7, 14, and 28 days, and the results are illustrated in Fig. X. The strength development trend clearly demonstrates that NaLS influences both early-age and long-term performance, with an optimum dosage observed at moderate concentrations.

The control mix (0% NaLS) achieved a compressive strength of 22.5 MPa, reflecting the typical early-age behavior of ambient-cured, calcium-rich geopolymers. With the addition of NaLS, an increase in strength was observed up to 1.5% dosage. The strengths at 0.5%, 1%, and 1.5% NaLS were 24.0 MPa, 25.8 MPa, and 27.6 MPa, respectively. This enhancement is attributed to improved workability and packing density, which enables more uniform dispersion of the binder and reduces microvoids. The maximum early-age strength occurred at 2% NaLS, reaching 29.8 MPa, representing a 32% improvement over the control. However, further increase to 2.5% and 3% resulted in a decline to 28.2 MPa and 25.6 MPa, respectively, likely due to excess organic content interfering with the early geopolymerization kinetics.

At 14 days, a similar trend persisted. The control mix exhibited 28 MPa, and the strength increased progressively with NaLS addition, peaking at 35.8 MPa for the 2% dosage. This corresponds to a 27.8% improvement compared to the control. Mixes containing 0.5%, 1%, and 1.5% NaLS achieved 29.6 MPa, 31.5 MPa, and 33.4 MPa, respectively, demonstrating positive synergy between enhanced workability and geopolymeric gel formation. Strength reduction was again observed beyond the optimum value, with the 2.5% and 3% mixes recording 34.2 MPa and 31.0 MPa, respectively. The decrease indicates possible retardation or incomplete polymerization at higher NaLS concentrations.

At 28 days, all mixes exhibited significant strength gain, consistent with the continuous formation and densification of N–A–S–H and C–A–S–H type gels in GGBS-based geopolymers. The reference concrete achieved 34 MPa, meeting M20-grade requirements. All NaLS-modified mixes surpassed this strength, with 2% NaLS again exhibiting the highest compressive strength of 43.5 MPa, marking a 28% improvement over the control. Mixes with 0.5%, 1%, and 1.5% NaLS reached 36.5 MPa, 38.8 MPa, and 40.9 MPa, respectively. Slight reductions were observed at higher dosages, with 41.6 MPa at 2.5% and 38.0 MPa at 3% NaLS. Although still higher than the control mix, the reduction confirms that excessive lignosulphonate content disrupts optimal gel formation, possibly due to delayed dissolution of GGBS or increased entrapped air.

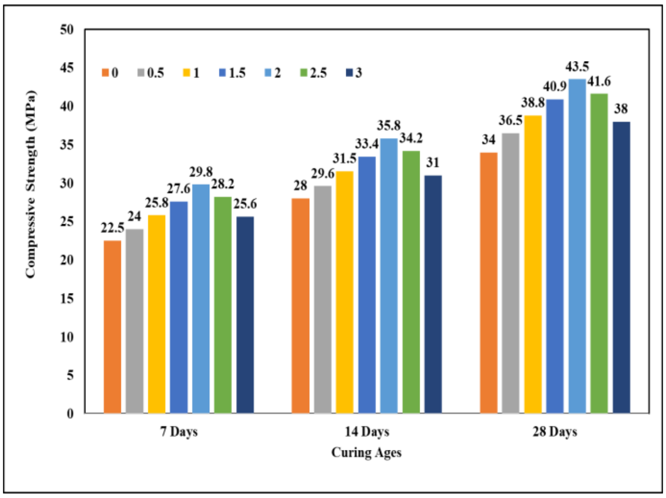

Figure 2. Compressive strength of geopolymer concrete with varying dosages of NaLS for different curing ages

Across all curing ages, 2% NaLS consistently produced the highest compressive strength, indicating that this dosage achieves an optimal balance between improved workability, better particle dispersion, and effective geopolymer gel development. Lower dosages provided moderate improvement, while higher dosages showed diminishing returns due to interference with the reaction mechanism. The consistent trend across 7, 14, and 28 days suggests that NaLS influences both early-stage kinetics and long-term structural development of the geopolymer matrix.

7.3. Split tensile strength

The split tensile strength of GGBS-based geopolymer concrete incorporating different dosages of Sodium Lignosulphonate (NaLS) was evaluated at 7 days and 28 days. The results presented in Fig. X show that NaLS significantly influences the tensile behavior of the concrete, with strength values improving up to an optimum dosage and subsequently declining beyond it.

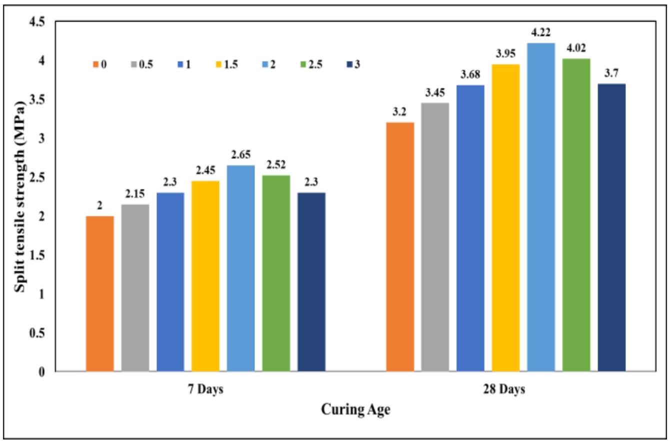

Figure 3. Split strength of geopolymer concrete with varying dosages of NaLS for different curing ages

The 7-day split tensile strength of the control mix (0% NaLS) was 2.00 MPa. The addition of NaLS led to a gradual increase in strength, with mixes containing 0.5%, 1%, and 1.5% NaLS achieving 2.15 MPa, 2.30 MPa, and 2.45 MPa, respectively. The maximum strength at this age was recorded for the mix with 2% NaLS, reaching 2.65 MPa, which represents a 32.5% improvement over the control. This trend reflects the beneficial role of NaLS in improving particle dispersion and enhancing the cohesion of the geopolymer matrix, enabling stronger tensile load transfer across the specimen.

Beyond the optimum dosage, the strengths at 2.5% and 3% NaLS declined to 2.52 MPa and 2.30 MPa, respectively. The reduction is attributed to excess NaLS interfering with the binding mechanism, likely due to the introduction of additional organic content, increased air entrainment, or disturbed gel formation at early ages.

At 28 days, all mixes showed substantial improvement in tensile performance due to the progressive formation of N–A–S–H and C–A–S–H type geopolymeric gels. The control mix recorded 3.20 MPa, while mixes with NaLS demonstrated consistent strength enhancement up to the 2% dosage. Strengths of 3.45 MPa, 3.68 MPa, and 3.95 MPa were achieved for mixes containing 0.5%, 1%, and 1.5% NaLS, respectively. The highest tensile strength was again obtained for the 2% NaLS mix, reaching 4.22 MPa, corresponding to a 31.8% increase compared to the control.

A slight reduction was observed for the 2.5% and 3% NaLS mixes, which recorded 4.02 MPa and 3.70 MPa, respectively. Despite being higher than the control, the decline from the optimum value suggests that excessive NaLS adversely affects the tensile mechanism by disrupting the integrity of the fiber-like gel network responsible for tensile resistance in geopolymer concrete.

7.4. Flexural Strength

The flexural strength of GGBS-based geopolymer concrete incorporating different dosages of Sodium Lignosulphonate (NaLS) was evaluated at 28 days, and the results are shown in Fig. X. The trend demonstrates that NaLS positively influences the flexural performance up to an optimum dosage, beyond which a decline is observed.

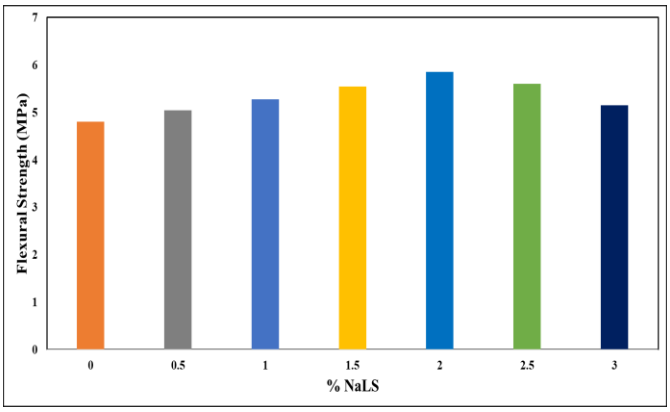

Figure 4. Flexural strength of geopolymer concrete with varying dosages of NaLS for different curing ages

The control mix (0% NaLS) recorded a flexural strength of 4.8 MPa. The introduction of NaLS led to a consistent improvement in strength, with the mixes containing 0.5% and 1% NaLS achieving 5.0 MPa and 5.3 MPa, respectively. This enhancement is attributed to improved workability and uniform distribution of GGBS particles, enabling better formation of continuous geopolymer gel networks. Additionally, the presence of NaLS at these dosages likely facilitates better fiber-like gel connectivity, promoting higher tensile bridging capability under flexural loading.

A significant increase was observed at 1.5% NaLS, where the flexural strength reached 5.5 MPa, followed by the maximum recorded strength of 5.9 MPa at 2% NaLS. This optimum dosage corresponds well with the trends observed in compressive and split tensile strengths, indicating that 2% NaLS provides the most favorable microstructural and rheological conditions for developing a dense and cohesive geopolymer matrix. Improved dispersion and reduced microvoid content at this dosage enhance the material's ability to resist bending stresses.

Beyond the optimum, a slight reduction in strength was observed. Mixes with 2.5% NaLS and 3% NaLS showed flexural strengths of 5.6 MPa and 5.2 MPa, respectively. While these values remain higher than the control, the reduction indicates that excessive NaLS may introduce unwanted effects—such as increased entrapped air, excess organic residues, or inhibited gel formation—which can weaken the interfacial transition zones and reduce the material's bending resistance.

The results confirm that flexural strength follows a similar pattern to compressive and tensile strengths, with 2% NaLS emerging as the optimum dosage that balances improved workability, enhanced gel formation, and better crack-bridging capability. The decline at higher dosages reinforces the importance of controlled NaLS incorporation to prevent adverse microstructural effects.

8. CONCLUSION

This study investigated the influence of Sodium Lignosulphonate (NaLS) on the fresh and mechanical properties of GGBS-based geopolymer concrete cured under ambient conditions. Based on the experimental results obtained from slump, compressive strength, split tensile strength, and flexural strength evaluations, the following conclusions can be drawn: The slump values increased steadily with NaLS addition and reached a maximum at 2% NaLS, indicating a significant enhancement in workability due to improved particle dispersion and reduced internal friction. Beyond 2%, the slump decreased, suggesting that excess NaLS increases mix viscosity and may introduce air entrainment.

NaLS had a notable positive effect on compressive strength up to an optimum dosage. At all curing ages (7, 14, and 28 days), the 2% NaLS mix consistently achieved the highest strength, with a 28-day strength of 43.5 MPa, representing a substantial improvement over the control. Higher dosages (2.5% and 3%) caused strength reduction due to interference with the geopolymerization process. Similar to compressive behavior, the split tensile strength increased with NaLS content up to 2%, reaching 4.22 MPa at 28 days, which is 31.8% higher than the control. This improvement is attributed to enhanced gel continuity and better stress transfer within the matrix. Tensile strength declined at higher dosages due to potential microvoid formation and gel disruption. Flexural performance followed a consistent trend with the other mechanical properties. The highest flexural strength of 5.9 MPa was recorded at 2% NaLS, demonstrating improved crack-bridging capability and enhanced matrix cohesion. Strength reductions at 2.5% and 3% NaLS confirm that excessive admixture disrupts the structural integrity of the geopolymer matrix. Across all fresh and hardened properties, 2% Sodium Lignosulphonate emerged as the optimum dosage for achieving maximum performance in GGBS-based geopolymer concrete under ambient curing.

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