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Evaluation of Rheological Properties of Cashew Nutshell Liquid Superplasticizer with Portland Cement

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ABSTRACT

This study investigates the rheological performance of Portland cement paste modified with a novel bio-based superplasticizer synthesized from cashew nutshell liquid (CNSL), an agro-industrial byproduct rich in phenolic compounds. The use of bio-derived admixtures is gaining attention in sustainable construction practices, offering a greener alternative to conventional petrochemical-based additives. In this work, the synthesized CNSL-based superplasticizer (CNSL-SP) was evaluated for its effectiveness in enhancing the flow behaviour of cement paste across various water-to-cement (w/c) ratios ranging from 0.2 to 0.4. Rheological properties were measured using a Brookfield CAP 1000+ viscometer under different shear rates, and CNSL-SP was dosed at concentrations between 0.5% and 3.0% by weight of cement. The results demonstrate a consistent decrease in shear stress with increasing CNSL-SP content, indicating improved dispersion and workability of the cement paste. The most effective dosage was observed between 1% and 2%, where the reduction in yield stress was substantial without compromising paste stability. At higher dosages, particularly beyond 2%, over-fluidity and potential segregation were observed, especially at elevated w/c ratios. These findings highlight the potential of CNSL-SP as a sustainable and cost-effective superplasticizer for concrete technology, particularly in regions with abundant cashew production. Moreover, the results provide a foundation for further investigations into the long-term mechanical performance and durability characteristics of CNSL-modified concrete. The use of renewable resources such as CNSL for performance-enhancing admixtures aligns with the broader goals of green engineering and environmentally conscious construction practices.

Keywords: Rheology, Viscometer, Superplasticizer, cashew, cement

INTRODUCTION

Concrete is an essential material in modern construction, serving as the backbone for infrastructural development globally. Its widespread adoption is largely due to its versatility, excellent mechanical strength, long-term durability, and relatively low production cost when compared to alternative materials such as steel or timber. The global consumption of concrete is estimated to exceed 30 billion tonnes annually, making it the second most consumed substance on Earth after water (Mehta & Monteiro, 2014). Despite its impressive performance in hardened states, the quality of concrete in its fresh state significantly determines its ease of handling, workability, and ultimate structural performance. In particular, the rheological properties of fresh concrete—which describe its flow and deformation under applied stress—are critical during mixing, transportation, placement, and compaction. These properties are primarily influenced by the water-to-cement (w/c) ratio, the presence of mineral and chemical admixtures, the characteristics of cement and aggregates, and the ambient conditions during casting

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(Neville, 2011; Aïtcin, 2000). Among various chemical admixtures, superplasticizers (SPs) play a vital role in enhancing the flowability and workability of concrete without increasing its water content, thereby maintaining or even improving its mechanical properties and durability (ASTM C494, 2019).

Superplasticizers, also known as high-range water-reducing admixtures (HRWRAs), are polymers that improve the dispersion of cement particles, reduce yield stress, and delay flocculation. The mechanism by which SPs operate typically involves steric hindrance and electrostatic repulsion, both of which prevent agglomeration of cement grains in the early stages of hydration (Plank *et al*., 2009). Commonly used superplasticizers include sulfonated naphthalene formaldehyde (SNF), sulfonated melamine formaldehyde (SMF), lignosulfonates, and more recently, polycarboxylate ethers (PCEs). Despite their effectiveness, the production of synthetic SPs is energy-intensive and often relies on petrochemical resources, raising environmental concerns about carbon emissions and sustainability (Jiang *et al*., 2017). In light of increasing global emphasis on sustainable construction practices, there has been a surge in research aimed at developing eco-friendly admixtures from renewable and biodegradable sources. These include plant-derived polymers, lignin, tannins, and oils extracted from agricultural byproducts. Among such alternatives, Cashew Nutshell Liquid (CNSL) has emerged as a promising raw material for bio-based admixtures due to its chemical richness, availability, and industrial underutilization (Lubi & Thachil, 2000; Habib *et al*., 2021). CNSL is a reddish-brown viscous liquid extracted from the pericarp of cashew nuts (*Anacardium occidentale*), primarily comprising cardanol, cardol, and anacardic acid. These compounds are phenolic in nature and possess reactive functional groups—such as hydroxyl, carboxyl, and alkyl chains—that can be chemically modified to enhance solubility and dispersing power (Hassan *et al*., 2019). The global cashew industry produces millions of tonnes of nutshell waste annually, especially in West Africa and Southeast Asia, providing a potentially large and renewable source of CNSL (FAO, 2022).

Previous studies have successfully demonstrated the use of modified CNSL derivatives in polymer synthesis, surface coatings, friction linings, and insulation materials (Lubi & Thachil, 2000; Aigbodion *et al*., 2010). More recently, researchers have explored CNSL's application in concrete technology. Habib *et al*., (2021) synthesized CNSL-based superplasticizers through sulfonation and formaldehyde polycondensation processes, showing favourable dispersion in cement pastes. Habib *et al*., (2021) findings indicated improvements in fluidity and mechanical strength comparable to commercial SPs, albeit with reduced environmental impact. Similarly, Refaie *et al*., (2020) highlighted the potential of plant-oil-based superplasticizers in achieving targeted rheological performance while maintaining compatibility with cementitious systems. The rheological evaluation of cement paste is a vital tool in understanding the action of superplasticizers, especially those derived from novel or bio-based sources. Rheology, broadly defined, is the study of deformation and flow of matter under applied stress. In the context of cementitious materials, it focuses on key parameters such as yield stress, plastic viscosity, and thixotropy, which directly influence workability, segregation resistance, and pumpability (Xu et al., 2025). Cement pastes and mortars are non-Newtonian, time-dependent fluids; they often exhibit shear-thinning behaviour, where viscosity decreases with increasing shear rate—a behaviour significantly modified by SPs.

Evaluating the rheological performance of superplasticizer-enhanced cement paste

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typically involves the use of rotational viscometers or rheometers. These instruments apply controlled shear rates and measure the corresponding torque or resistance, thereby determining the flow curves of the paste (Ferraris & Brower, 2000). The Brookfield CAP 1000+ viscometer, used in this study, is one such device capable of accurately capturing the flow behaviour of viscous fluids like cement paste. By testing a range of water-cement ratios and SP dosages, researchers can map out optimal compositions for both practical workability and long-term performance. In this context, the present study investigates the effects of varying CNSL-based superplasticizer dosages on the rheological behaviour of Portland cement paste. The focus is to determine how CNSL-SP influences shear stress under different shear rates and water-cement ratios, thereby establishing its viability as a sustainable admixture. Understanding these relationships is vital because overdosage of SPs, especially with novel or untested formulations, can lead to undesirable effects such as segregation, bleeding, and delayed setting (Aïtcin, 2000; Yamada *et al*., 2000). The motivation for this work is twofold. Firstly, it contributes to the ongoing search for sustainable construction materials by exploring a low-cost, locally available byproduct in a high-value application. Secondly, it addresses the gap in current literature regarding the rheological characterization of CNSL-derived admixtures, which is still limited despite promising early studies. Additionally, there is an environmental dimension: the utilization of CNSL, a non-edible agricultural waste, supports circular economy principles and reduces the reliance on fossil-derived chemicals in construction.

Moreover, understanding the relationship between SP dosage and cement rheology is not just of academic interest—it has real-world implications for concrete production, especially in resource-constrained settings where controlling water content, improving pumpability, and minimizing energy use during mixing are critical. With urbanization accelerating in many parts of Africa and Asia—where cashew processing is also prevalent—there is strong alignment between regional agricultural waste generation and infrastructure needs. This study builds upon existing knowledge of plant-based admixtures and rheological modelling by integrating empirical testing with practical mix design considerations. It also provides foundational data for future work involving performance testing of CNSL-SP in mortar and concrete, including setting time, strength development, shrinkage, and durability under aggressive exposure conditions. In summary, the research presented herein offers a comprehensive evaluation of a bio-based superplasticizer derived from cashew nutshell liquid and its effect on the flow behaviour of cement paste. The objectives are to quantify the changes in shear stress across multiple dosages and water-cement ratios, to identify optimal conditions for use, and to demonstrate the environmental and technical viability of CNSL-SP. Ultimately, this work contributes to the broader discourse on green engineering and the transition toward more sustainable concrete technologies.

MATERIALS AND METHODS

Materials

The primary materials used in this study included Ordinary Portland Cement (OPC), distilled water, and Cashew Nutshell Liquid (CNSL), which was locally sourced from cashew processing waste in Nigeria. The OPC complied with ASTM C150 Type I specifications, commonly used in general concrete construction. For the synthesis of the CNSL-based superplasticizer (CNSL-SP), the following analytical-grade reagents were employed: methanol, tetraoxosulfate (VI) acid (H_2SO_4), sodium hydroxide (NaOH), and formaldehyde (37%). All reagents were

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obtained from Sigma-Aldrich and used without further purification.

Synthesis of CNSL-Based Superplasticizer

The CNSL was extracted from cashew shells using a controlled thermal process, as described by Lubi and Thachil (2000). The extracted CNSL predominantly contained cardanol and anacardic acid, which provided active sites for subsequent chemical modification. The superplasticizer was synthesized through sulfonation and formaldehyde polycondensation, a method adopted from Habib *et al*., (2018) and optimized in later studies (Habib *et al*., 2021; Refaie *et al.,* 2022). In the first step, CNSL was sulfonated by the gradual addition of concentrated sulfuric acid at 80°C under continuous stirring. This process introduced sulfonic acid groups into the CNSL molecule, enhancing its water solubility and dispersion potential. Next, a condensation reaction was initiated by adding formaldehyde and sodium hydroxide to the sulfonated CNSL, yielding a polymeric compound with surface-active properties. The reaction was allowed to proceed at 80°C for 2 hours under reflux conditions. Upon completion, the product was cooled and neutralized using dilute NaOH to a pH of approximately 7. The synthesized CNSL-SP was stored in an airtight container at room temperature for further use.

Rheology Testing Procedure

The rheological performance of cement paste was evaluated using a Brookfield CAP 1000+ rotational viscometer, equipped with cone-plate spindle size 4. The tests were designed to assess the shear stress response of cement pastes modified with varying dosages of CNSL-SP.

Experimental Design

Cement paste samples were prepared with water-to-cement (w/c) ratios of 0.20, 0.25, 0.30, and 0.40, and superplasticizer dosages of 0.5%, 1.0%, 2.0%, and 3.0% by weight of cement. The dosage range was selected based on previous works by Habib *et al*., (2018), Ajay *et al*., (2020), and Habib *et al*., (2021), which reported optimum dispersing performance for plant-based admixtures within this range. Each paste was mixed thoroughly for 3 minutes to ensure uniform dispersion and was immediately tested within 15 minutes of preparation to minimize the effects of early hydration. Rheological measurements were conducted at shear rates of 0.2 s^{-1}, 0.5 s^{-1}, and 1.0 s^{-1}, capturing the non-Newtonian behaviour of the pastes under controlled flow conditions.

Mix Proportion

The mix proportions for each w/c ratio and CNSL-SP dosage are presented in Table 1. The water content was fixed at 10 mL across all batches to maintain consistent test volume in the viscometer. The amount of cement and superplasticizer was adjusted accordingly to meet target w/c ratios and dosage percentages. The rheological test setup is shown in Figure 1. Subfigure (a) illustrates the preparation process, including cement paste mixing and dosing of CNSL-SP, while subfigure (b) shows the Brookfield viscometer used for the testing.

Table 1: Mix Proportions for Rheology Testing

Water-Cement ratio (w/c)	Cement (g)	Water (mL)	CNSL-SP at the percentage of cement (mm^3)			
			0.5%	1%	2%	3%
0.2	50	10	1.1	2.2	4.3	6.5
0.25	40	10	0.9	1.7	3.5	5.2
0.3	33	10	0.7	1.4	2.9	4.3
0.4	25	10	0.5	1.1	2.2	3.3

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(a) (b)

Figure 1: Experimental Setup for Rheology Testing
(a) Cement Paste Preparation; **(b)** Brookfield CAP 1000+ Viscometer in Operation

RESULTS AND DISCUSSION

Effect of CNSL-SP on Rheology of Cement Paste

The primary objective of the rheological investigation was to evaluate the dispersing performance of cashew nutshell liquid-based superplasticizer (CNSL-SP) in Portland cement paste. The influence of CNSL-SP dosage on shear stress was assessed at various water-to-cement (w/c) ratios and shear rates. The results are presented in Figures 2 through 8 and reveal distinct trends in flowability enhancement with increasing SP content. At a shear rate of 1.0 s^{-1} and 0.5% CNSL-SP dosage (Figure 2), the shear stress of cement paste was observed to be 48.25 N/mm^2, indicating moderate flow resistance. As shown in Figure 3, when the CNSL-SP dosage was increased to 1%, shear stress values decreased progressively across all w/c ratios—specifically 47.25 N/mm^2 (w/c = 0.2), 45.03 N/mm^2 (w/c = 0.25), and 43.77 N/mm^2 (w/c = 0.3). A further increase in CNSL-SP to 2% led to additional reductions in shear stress, yielding values of 44.95 N/mm^2, 42.90 N/mm^2, and 40.80 N/mm^2 for w/c ratios of 0.2, 0.25, and 0.3 respectively (Figure 4). At the highest dosage level of 3% (Figure 5), the shear stress for the 0.3 w/c ratio dropped further to 37.0 N/mm^2, reflecting the maximum effect of dispersion. These trends confirm that CNSL-SP effectively lowers the yield stress of cement paste, likely due to steric hindrance and electrostatic repulsion imparted by its sulfonated molecular structure. This behaviour is consistent with results reported by (Habib *et al*., 2021 & Ajay *et al*., 2020), who demonstrated similar shear stress reductions with plant-based or phenolic superplasticizers.

However, the performance at the 0.4 w/c ratio deviates slightly. The rheological profiles at this ratio showed an abrupt reduction in shear stress approaching near-zero values, suggesting over-fluidization. This indicates that while CNSL-SP improves flow, excessive water and SP content combined may promote segregation, a common limitation observed in high-range water-reduced pastes (Plank *et al*., 2009).

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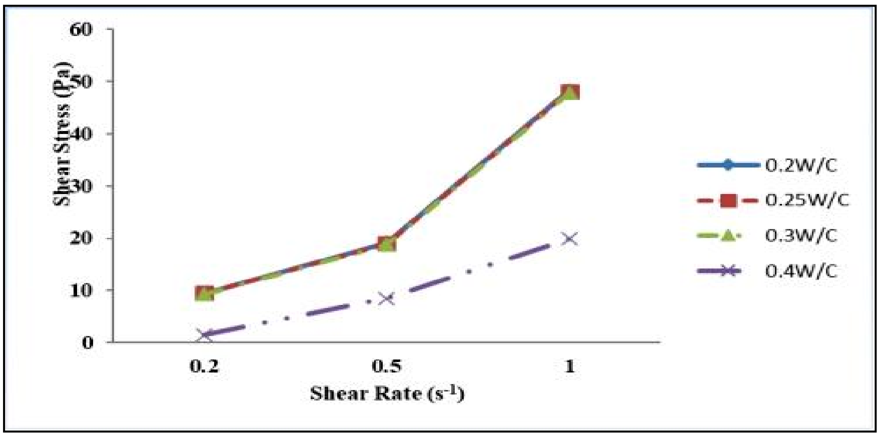

Figure 2: Rheology of CNSL-SP and Cement at 0.5% Addition of CNSL-SP.

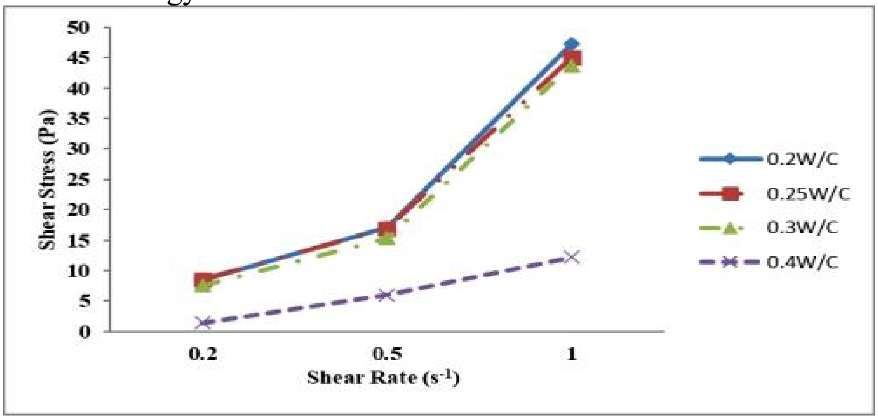

Figure 3: Rheology of CNSL-SP and Cement at 1% Addition of CNSL-SP.

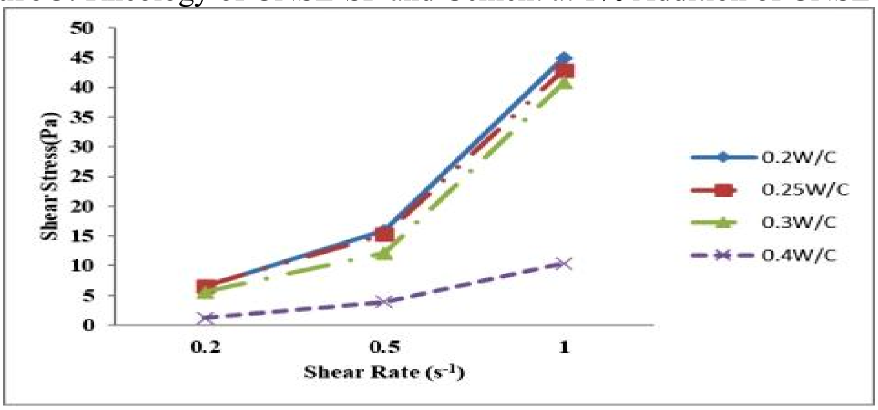

Figure 4: Rheology of CNSL-SP and Cement at 2% Addition of CNSL-SP.

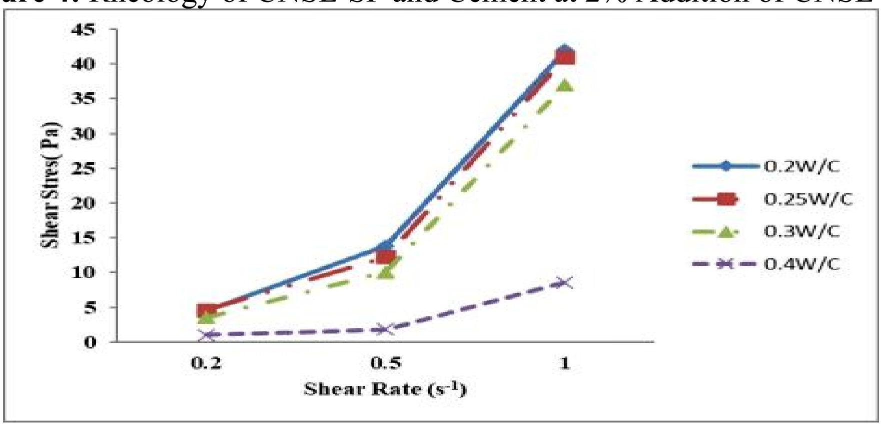

Figure 5: Rheology of CNSL-SP and Cement at 3% Addition of CNSL-SP.

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Shear Stress Versus Superplasticizer Dosage at Varying Shear Rates

Figures 6 through 8 illustrate the relationship between shear stress and w/c ratio at varying CNSL-SP dosages for shear rates of 0.2 s^{-1}, 0.5 s^{-1}, and 1.0 s^{-1} respectively. At 0.2 s^{-1} (Figure 6), a clear reduction in shear stress was observed with increasing CNSL-SP content. Specifically, the shear stress at 0.2 w/c ratio declined from 48.25 N/mm² at 0.5% SP dosage to 41.95 N/mm² at 3% dosage. The pattern continues in Figure 7, where increasing the shear rate to 0.5 s^{-1} resulted in significantly lower shear stress values: 19.18 N/mm² at 0.5% CNSL-SP and 13.8 N/mm² at 3% dosage. The most pronounced effect was observed at the highest shear rate of 1.0 s^{-1} (Figure 8), where the shear stress values dropped further to 9.46 N/mm² (0.5% SP) and 4.51 N/mm² (3% SP). These results indicate that CNSL-SP is particularly effective under dynamic mixing or pumping conditions, where higher shear rates are encountered. As the SP dosage increases, the enhanced dispersion of cement particles disrupts flocculated structures, reducing internal friction and thus lowering shear resistance.

This behaviour aligns with previous findings by Yamada *et al*., (2000) and Xu et al., (2025, who attributed such rheological improvements to improved dispersion mechanisms at high shear rates. However, beyond a certain dosage and w/c threshold, the paste becomes excessively flowable and susceptible to segregation, particularly evident in the 0.4 w/c ratio curves approaching the x-axis (Figures 6–8).

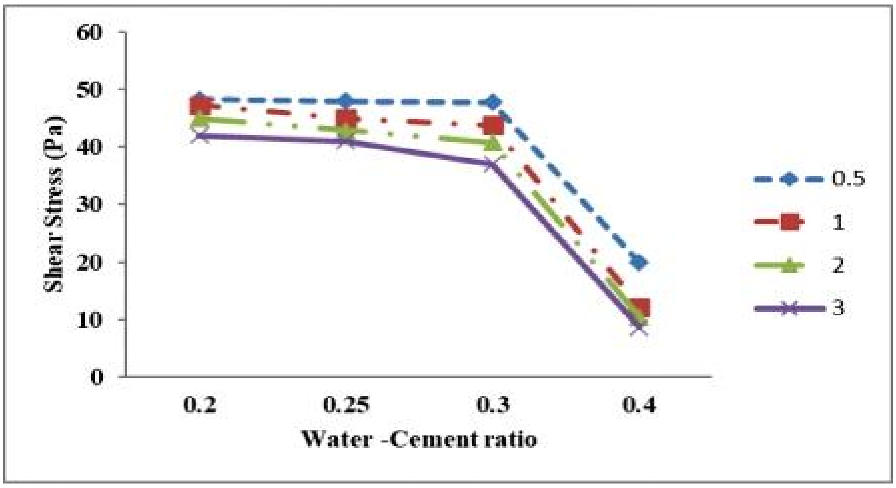

Figure 6: Rheology of Shear Stress against Water Cement Ratio at Shear Rate of 0.2s^{-1}

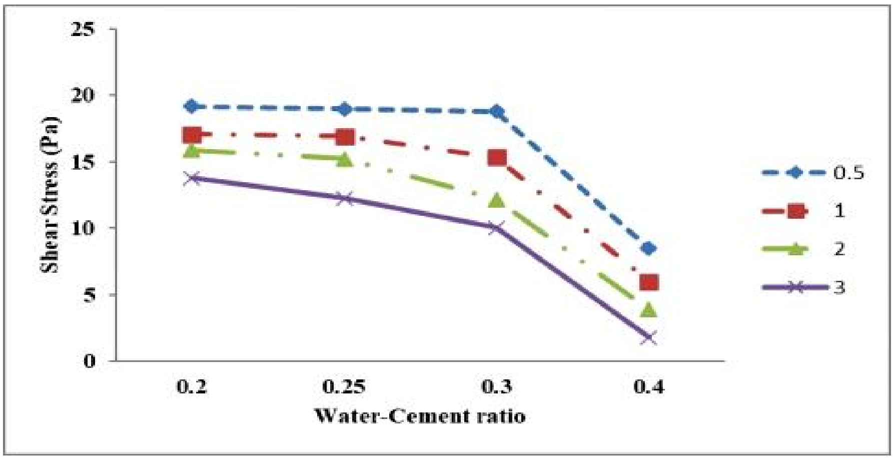

Figure 7: Rheology of Shear Stress against Water Cement Ratio at Shear Rate of 0.5s^{-1}

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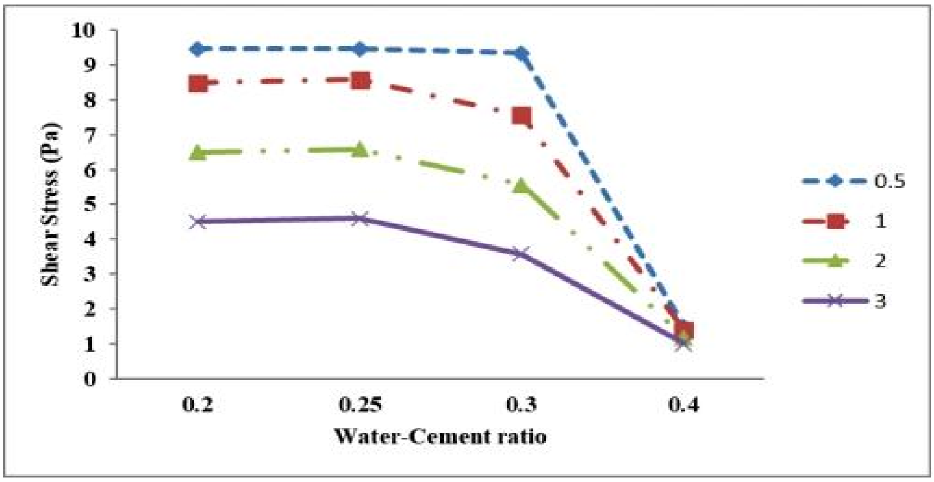

Figure 8: Rheology of Shear Stress against Water Cement Ratio at Shear Rate of $1s^{-1}$

Benchmarking and Practical Implications

From the data obtained, it is evident that 0.3 w/c ratio yields the most stable and balanced rheological behaviour across all SP dosages. This aligns with optimal performance benchmarks observed in commercially available superplasticizers (Aïtcin, 2000). It also reflects the saturation point beyond which additional CNSL-SP contributes to diminishing returns in shear reduction and risks paste instability. Furthermore, the increased rate of shear stress decline with rising shear rates demonstrates the non-Newtonian, shear-thinning nature of CNSL-modified cement pastes. This is typical of systems influenced by effective superplasticizer action, where the network of flocculated particles is broken down more efficiently under high mechanical agitation (Plank *et al*., 2009; Ferraris & Brower, 2000). Therefore, in practical applications, CNSL-SP shows promise for enhancing flow in concrete mixtures that require high workability, such as self-compacting concrete or pumped concrete, especially in regions with limited access to synthetic admixtures.

CONCLUSION

This study has successfully examined the rheological behaviour of Portland cement paste modified with a novel bio-based superplasticizer synthesized from cashew nutshell liquid (CNSL-SP). The experimental results demonstrated that CNSL-SP effectively enhances the flowability of cement paste by significantly reducing shear stress. This effect was most pronounced at dosage levels between 1% and 2% by weight of cement, suggesting an optimal range for improving fresh-state workability without compromising paste stability. The results also identified a benchmark water-cement (w/c) ratio of 0.3 as the most effective for achieving a balanced combination of workability and structural cohesion. Notably, the influence of CNSL-SP became more evident at higher shear rates, indicating its potential suitability for applications involving mechanical mixing, pumping, or machine placement—where high shear environments are common. However, at a w/c ratio of 0.4 combined with a 3% CNSL-SP dosage, the paste exhibited excessive fluidity, approaching segregation. This observation underscores the importance of controlling both water content and superplasticizer dosage to maintain optimal rheological performance. Furthermore, the performance of CNSL-SP was found to align with the behaviour of conventional synthetic superplasticizers, operating through mechanisms such as electrostatic repulsion and steric hindrance. These findings validate CNSL-SP as a promising, sustainable alternative to petroleum-based admixtures in concrete technology.

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To further establish its practical relevance, future research is recommended in several key areas. These include assessing the influence of CNSL-SP on setting time, compressive strength development, and long-term durability of hardened concrete. Investigations should also explore its compatibility with supplementary cementitious materials such as fly ash, silica fume, and slag, which are commonly used in sustainable concrete mix designs. Additionally, the long-term storage stability of CNSL-SP and its scalability for industrial production warrant thorough examination. Finally, conducting a comprehensive Life Cycle Assessment (LCA) would provide valuable insights into the environmental benefits of CNSL-SP compared to conventional synthetic superplasticizers, supporting its adoption in green construction initiatives. This research contributes valuable knowledge toward the development of environmentally friendly admixtures, paving the way for more sustainable concrete practices in the construction industry.

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