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Assessing the Performance of Opuntia Ficus Indica as a Sustainable Concrete Admixture: Comparison with Sika and Darma Admixtures

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Abstract

This study examines the possibility of liquid mucilage from Opuntia ficus-indica (OFI) as a sustainable, natural concrete admixture, evaluating its effects on compressive strength, consistency, workability, and setting time. With performance comparisons versus commercial admixtures like Sika and Darma, the study uses an experimental approach that includes both direct addition (0.5%–5%) and partial replacement of mixing water (0.5%–30%). The findings show that OFI mucilage performs better than traditional admixtures in important concrete qualities, providing a sustainable building option that is also environmentally benign. This study's goal was to assess how OFI liquid mucilage, a natural additive, affected the functionality of regular concrete. Its impacts on workability, setting time, and compressive strength are assessed experimentally. According to the results, adding OFI mucilage makes it a feasible alternative for hot-climate construction since it greatly increases workability, improves moisture retention, and lengthens setting time. Optimal dosages (1% to 1.5%) outperformed traditional admixtures like Sika and Darma, increasing 28-day compressive strength by up to 9%. However, strength is adversely affected by large dosages (>2%). Reducing permeability and increasing early and long-term strength were achieved by partially substituting mucilage for cement. The environmental advantages of this natural admixture were validated by a comparative life cycle evaluation, which also showed that it might lessen carbon dioxide emissions and dependency on imported chemicals. To sum up, OFI mucilage is a multipurpose concrete admixture that excels at modifying setting times, improving workability, and optimizing strength. It also provides financial and environmental benefits for sustainable construction methods, making it an economical and resource-conscious way to develop infrastructure.

Keywords: Compressive Strength, Darma Admixture, Opuntia Ficus-Indica, Sika Admixture, Sustainable Concrete Admixture.

1. Introduction

This study investigates the potential of OFI liquid mucilage as a natural, sustainable concrete admixture, assessing its impact on workability, consistency, compressive strength, and setting time. As the need for sustainable building materials increases, researchers are looking into environmentally suitable substitutes for traditional concrete admixtures, which frequently include synthetic chemicals that can be expensive and detrimental to the environment, (Aquilina, Borg, & Buhagiar, 2018; De Souza et al., 2024). OFI, sometimes referred to as Beles or prickly pear cactus in Ethiopia, is one such substitute. The mucilage that has been removed from its cladodes, or pads, shows promise in improving the qualities of concrete and providing a sustainable and natural additive solution (Cardenas, Arguelles, & Goycoolea, 1998; Carrillo, Gómez-Cuaspud, & Suarez, 2017; Elshewy et al., 2023; Torres-Acosta, Díaz-Cruz, & Materials, 2020). Because OFI grows well in arid and semi-arid environments, it is a useful resource in places with little access to water (Al-aubadi, Hashim, & ISSN, 2015; Deshmukh & Hedaoo, 2019). Bioactive substances including proteins and polysaccharides found in its mucilage enhance the workability, durability, and water retention of concrete (Blancas-Herrera et al., 2018; Pacheco et al., 2023; Sun, 2017).

Additionally, this study has demonstrated that this natural admixture slows down the concrete's setting time, extending its workability without compromising its structural integrity (Hailu, 2020). These characteristics complement the increasing need for environmentally friendly building materials that lessen reliance on artificial additives (Hernández, Cano-Barrita, & Torres-Acosta, 2016). In addition to its technical advantages, OFI mucilage has economic and environmental benefits. This plant's abundance in Ethiopia offers a chance to encourage the use of local resources while lowering dependency on pricey, imported chemical admixtures (Sáenz Hernández et al., 2013).

Additionally, using plant-based additives in the making of concrete can reduce carbon dioxide emissions related to the transportation and manufacturing of cement (Flores-De los Ríos et al., 2015; Sánchez-Carrillo et al., 2015). Historical evidence suggests that natural admixtures, including plant-based substances, have been used in construction for centuries to enhance strength and durability (Chakraborty, Jo, & Sikandar, 2016; Shushay Welderufael Abrha, 2014). Modern research supports this approach, indicating that Opuntia ficus indica mucilage can reduce permeability and protect reinforced concrete from degradation, particularly in moisture-prone or corrosive environments (Lorika, Hamad, Yehya, Salam, & Materials, 2023; Nobel & Hartsock, 1984; Welderufael, 2015).

The impacts of OFI mucilage as a concrete admixture are examined in this study, with particular attention paid to how it affects workability, compressive strength, and setting time. This study attempts to show that it can be a good alternative to chemical admixtures by assessing its effectiveness under various circumstances (Shanmugavel, Selvaraj, Ramadoss, Raneri, & Materials, 2020) and (Azizi, Hammi, Chaouch, Majdoub, & Mnif, 2019).

Beyond Ethiopia, this research is significant because it provides insights that may impact global building trends and highlights the

potential of local resources in sustainable construction, highlighting the significance of incorporating bio-based materials into contemporary engineering applications. This project is to support the creation of long-lasting, environmentally friendly concrete solutions that are in line with international sustainability goals by fusing traditional knowledge with modern scientific discoveries. By assessing its impacts on compressive strength, setting time, and environmental sustainability, this study explores the viability of employing OFI mucilage as an additive in concrete. The study intends to help local economies, encourage green building methods, and lessen dependency on pricey imports by utilizing this domestic resource. The discovery paved the way for the incorporation of natural polymers into contemporary building methods, propelling Ethiopia's building sector closer to resilience and sustainability.

To sum up, the purpose of this study is to assess how OFI liquid mucilage, a natural additive, affects the functionality of regular concrete. With emphasis on enhancement in workability, durability, and mechanical qualities while fostering environmental and economic sustainability, the study explores its potential as a sustainable substitute for synthetic chemical admixtures.

2. Materials and Methods

2.1. Experimental Approach

This study evaluates OFI liquid mucilage's potential as a sustainable concrete admixture using an experimental methodology. In order to prove OFI mucilage as an environmentally acceptable substitute for synthetic admixtures, the methodology combines material analysis, optimal mix design, and mechanical performance evaluation.

2.2. Material Preparation & Characterization

2.2.1 OFI Mucilage Extraction & Analysis

After being gathered and skinned, the fresh OFI cladodes were mechanically blended with very little water. After the fibers were removed by filtering, the extract was subjected to phytochemical examination to ascertain its impact on cement hydration shown in Figure 1.



Figure 1. ***Beles Opuncia ficus indica (Beles) cladodes***

2.2.2 Aggregate and Cement Characterization

According to ASTM guidelines, gradation, moisture content, specific gravity, and absorption capacity of natural sand and coarse aggregates were examined as shown in Table 2. To be sure, tested the chemical

composition of Ordinary Portland Cement (OPC) as shown in Table 1.

Table 1. ***Chemical composition of Ordinary Portland cement***

Component	CaO	SiO2	Al2O3	Fe_2O_3	MgO	others
Amount (%)	64.15	21.23	5.24	3.87	1.72	3.79

Table 2. ***Properties of the fine and coarse aggregates***

Aggregate type	Property	Amount
Coarse	Maximum aggregate size(mm)	19
	Unit weight ($^{Kg}{}_3$) m	1650
	Specific gravity G_{SSD}	2.6
	Absorption capacity (%)	0.389
	Moisture content (%)	0.08 %
Fine	Fineness modulus	2.98
	Specific gravity G_{SSD}	2.89
	Water absorption (%)	0.603
	Moisture content (%)	1.42

2.3.Concrete Mix Design Preparation

The process of figuring out the ratios of the different ingredients that must be mixed to produce a concrete mix with the required qualities is known as concrete mix design. Since strength, durability, and workability were the main performance requirements for the planned application, these factors dominated the mix design in this investigation. Although concrete's appearance such as its color and surface finish is crucial in some applications, this study's goal was to assess the mechanical and performance characteristics of concrete that used OFI mucilage as an additive.

Creating a concrete mix that is affordable, compact, and easy to deploy while yet meeting performance standards for the intended usage was the aim of the mix design. To account for variations in concrete manufacturing and testing, the mix was prepared in compliance with ACI 211.4R-08, aiming for a characteristic compressive strength of 25 MPa (C-25) at 28 days and a target means strength of 30 MPa. This guarantees that the concrete satisfies the performance requirements needed for structural applications. To get the required workability and strength, the water-to-cement ratio was set at 0.491.

Two mucilage inclusion techniques were investigated in this study. Two methods were used: partial replacement, in which some of the mixing water was replaced with mucilage, and direct addition, in which mucilage was added without changing the water content. Doses varying from 0.5% to 30% (by cement weight) were assessed and contrasted with commercial admixtures such as Darma retarders and Sika Plastiment BV

40. Before testing to assess the impact of mucilage on concrete characteristics, 150 mm × 150 mm × 150 mm concrete cubes were cast and allowed to cure under usual conditions.

2.4. Experimental Testing

2.4.1 Fresh Concrete Properties

As soon as its component components are mixed, fresh concrete is created. It then goes through several chemical reactions that determine its final properties, including workability, strength and durability. Standardized testing was carried out by accepted ASTM procedures to assess the qualities of fresh concrete. To evaluate workability a crucial determinant of the concrete's compaction and ease of placement—the slump test (ASTM C143) was conducted. The Vicat device (ASTM C191), which measures the initial and final setting times and offers information on the concrete's hardening process, was also used to calculate the setting time. To determine the ideal mix proportions for the required workability and performance, the consistency test (ASTM C187) was also performed to assess the water demand and penetration depth.

2.4.2 Hardened Concrete Properties

The composition of the mixture, the curing conditions, and environmental elements all affect the hardened concrete's important characteristics, which include compressive strength, durability, and impermeability. Standardized tests were used to evaluate these attributes. By ASTM C39, the compressive strength was assessed using a Universal Testing Machine (UTM) at 3, 7, 14, and 28-day intervals to track the strength's evolution over time. Furthermore, the hardened concrete's water absorption was measured by ASTM C642, which offers vital details regarding the durability and porosity of the concrete. When taken as a whole, these tests guarantee that the hardened concrete satisfies the structural and performance requirements needed for sustainable building applications.

3 Results and Discussions

Variations in workability, strength, and durability were examined using statistical approaches. The best mucilage dosages were found using regression analysis and correlation research. Information on the efficacy of OFI mucilage was obtained through comparisons with synthetic admixtures. To evaluate cost-effectiveness, an economic feasibility study was also carried out. To measure the environmental impact of mucilage-based concrete, a life cycle assessment (LCA) was conducted with an emphasis on water savings, energy efficiency, and carbon footprint reduction. Additionally investigated was the scalability of OFI mucilage in sustainable construction methods. A thorough evaluation of OFI mucilage as a concrete additive is offered by this methodological framework. The study contributes to the development of greener building materials by shedding light on their potential for increased durability, economic viability, and environmental sustainability. The results of the cement paste consistency, compressive strength, slump, and setting time tests were used to analyze and explain the simplified results.

3.1. Setting Time Test

3.1.1. Effect of OFI (Beles) Cladode Liquid Mucilage on Setting Time

When compared to the control mix, the setting time tests showed that the addition of OFI (Beles) mucilage considerably prolonged the initial and final setting times. The initial setting time rose from 132 minutes to 276 minutes and the total setting time increased from 255 minutes to 393 minutes at a dosage of 0.5% mucilage. These durations increased to 436 and 616 minutes, respectively, at 5% dosing, indicating the

potent retardation impact of mucilage. In contrast, commercial admixtures such as Darma and Sika showed moderate increases in setting time. Sika enhanced the initial and final setup times to 168 and 325 minutes, respectively, at 0.5% and 315 & 410 minutes at 5%. Likewise, Darma observed 290 and 470 minutes at 5%, and 152 and 310 minutes at 0.5%. These findings demonstrate how well OFI mucilage works as a setting time retarder as shown in **Error! Reference source not found.**.

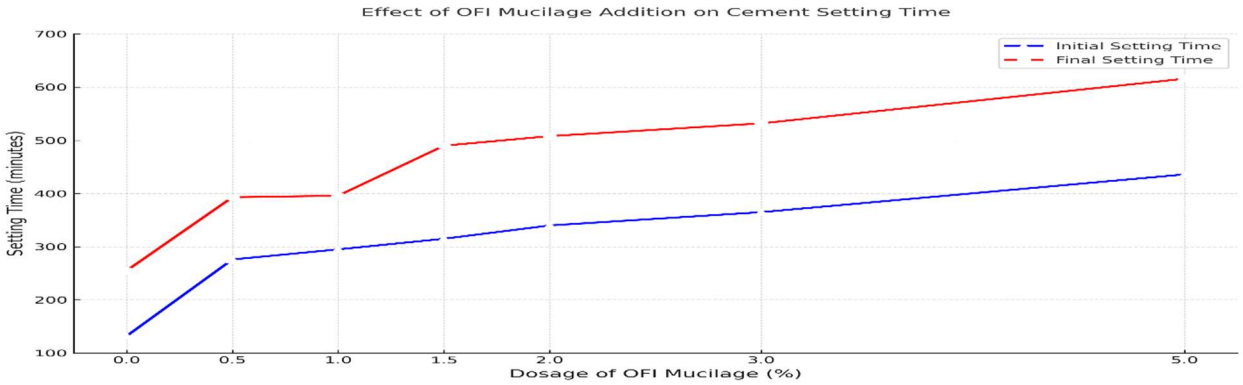


Figure 2: Setting Time Modulation OPC and OFI Cladode Mucilage

3.1.2. Effect of Partial Replacement of OFI (Beles) Mucilage on Setting Time.
Setting times were further extended by partially substituting OFI mucilage for cement. The total setting time increased from 255 minutes to 298 minutes at 0.5%, while the beginning setup time increased from 132 minutes to 142 minutes. These values increased to 230 and 445 minutes, respectively, at 5%. OFI showed better retardation than Sika and Darma, which showed modest increases as shown in **Error! Reference source not found.**.

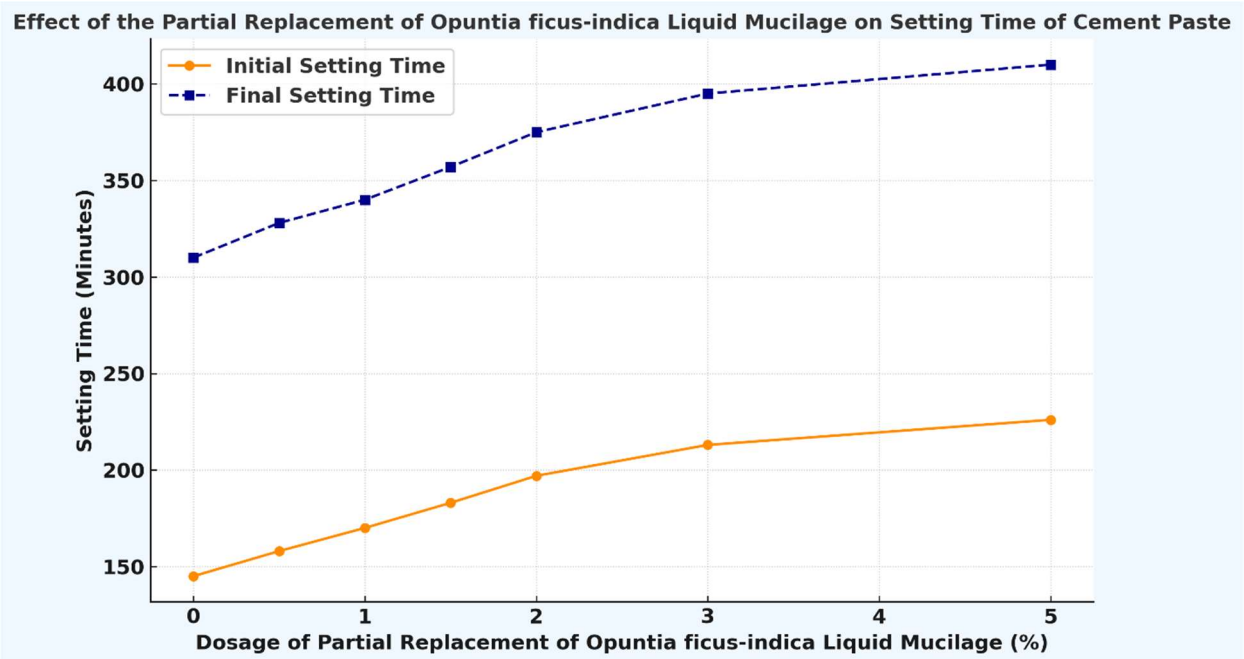


Figure3: Setting Time Modulation OPC and OFI Cladode Mucilage

3.1.3. Effect on Initial and Final Setting Time

Setting times were considerably increased by both direct addition and partial substitution of OFI mucilage. The first setting time increased to 230 minutes at 5% mucilage replacement, as opposed to 315 minutes for Sika and 290 minutes for Darma as shown in Figure 2.

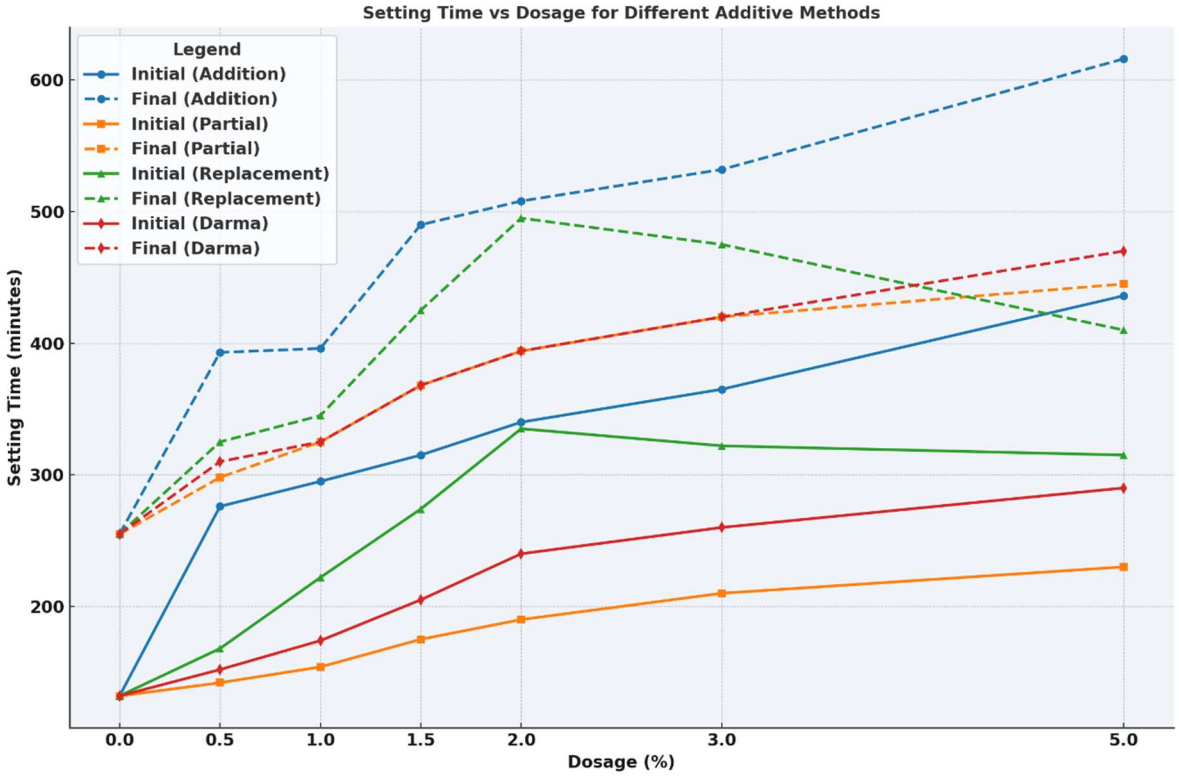


Figure 2. ***Dosage-Dependent Setting Time Delays: OFI Mucilage vs. Sika/Darma***

A similar pattern was seen in the ultimate setting time, which exceeded Sika (410 min) and Darma (470 min) by 445 min with 5% mucilage replacement. These results highlight how well mucilage works in a time-modified sustainable setting as shown in Figure 3.

3.2. Slump Test

The inclusion of OFI mucilage resulted in a considerable improvement in workability. By increasing from 24.72 mm (control) to 45.97 mm at 0.5%, the slump reached 225.28 mm at 5%, placing it in the high slump range. At greater dosages, however, workability dramatically declined when used in place of cement. The slump decreased to 1.0 mm with 30% replacement, indicating an excessive amount of stiffness. These findings imply that although mucilage improves workability as an additive, its application as a cement substitute ought to be restricted as shown in Figure 3.

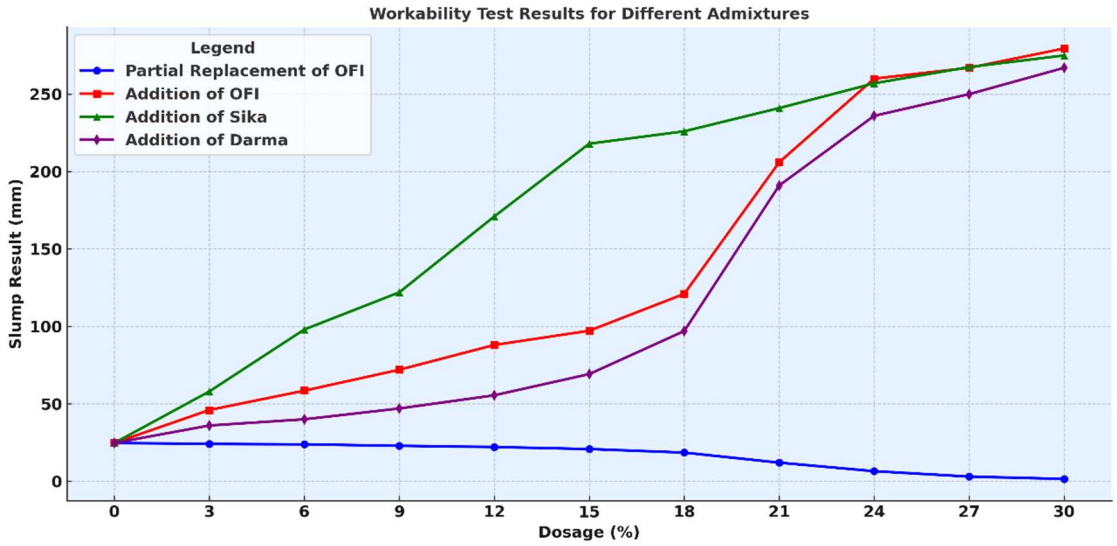


Figure 3. ***Comparative Rheological Performance of Bio-Based and Sika/Darma***

3.3. Cement Paste Consistency

Permeation depth was used to assess the consistency of the cement paste. Higher workability was observed in samples with depths of 12 mm or greater, whereas control samples with depths of 5 to 9.8 mm were categorized as stiff. With penetration depths ranging from 6 mm to 15.7 mm and a partial substitution of cement with a mucilage-reduced consistency, this material appears suitable for structural concrete as shown in Figure 4.

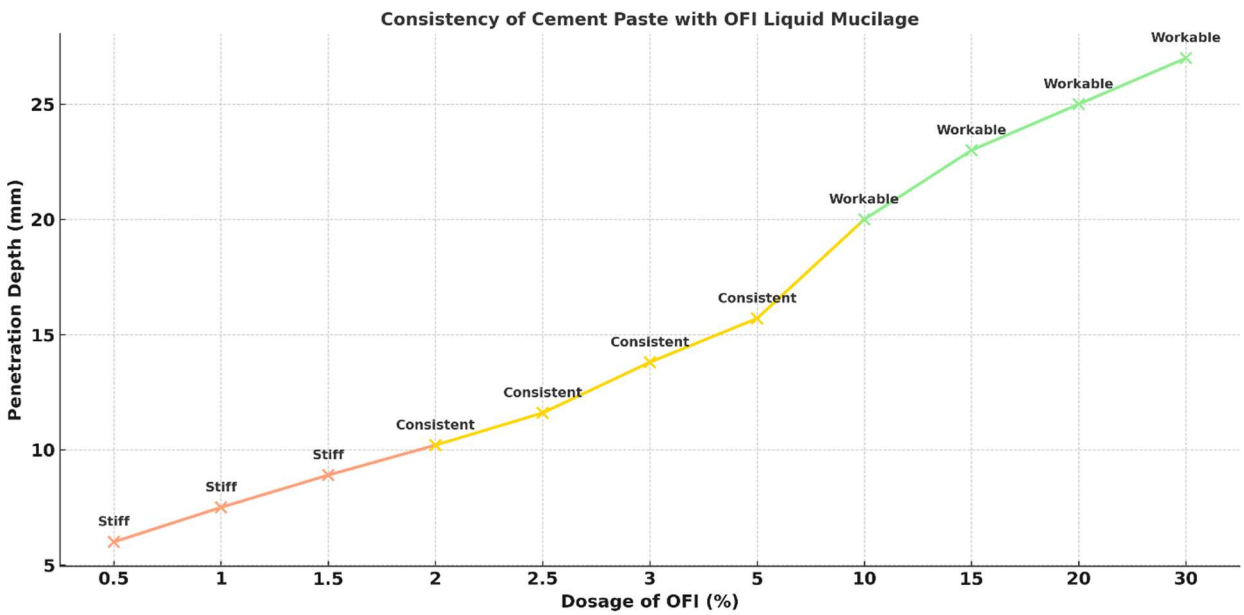


Figure 4. ***Effect of OFI Liquid Mucilage on Cement Paste Consistency***

On the other hand, the addition of mucilage improved fluidity and self-compaction qualities by greatly increasing penetration depth. It was found that the ideal range for stability and consistency was 12 mm to 15.7 mm as shown in Figure 5.

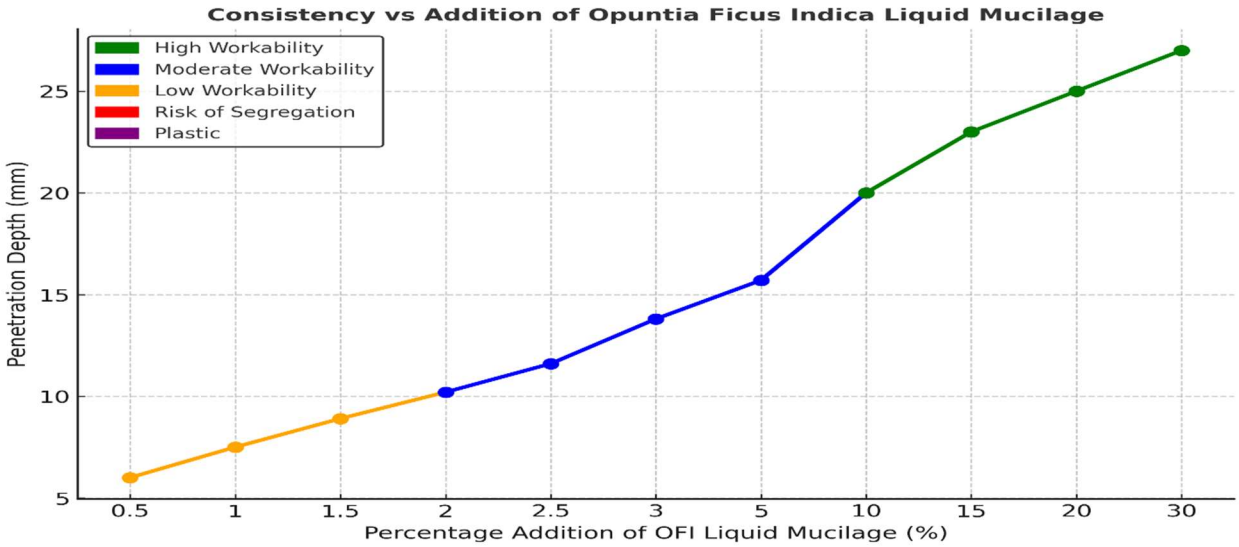


Figure 5. ***Effect of OFI Liquid Mucilage on Cement Paste Consistency***

3.4. Compressive Strength Test

3.4.1. Effect of OFI Mucilage Addition on Compressive Strength

However, excessive mucilage (≥ 2%) decreased strength, with a 5% dosage lowering it to 22.09 MPa. These results suggest that optimal enhancement occurs at 1%–1.5%. Compressive strength tests showed that low dosages of OFI mucilage increased concrete strength, increasing the 28-day compressive strength to 28.73 MPa and 29.28 MPa, respectively, compared to 26.89 MPa for the control as shown in Figure 6.

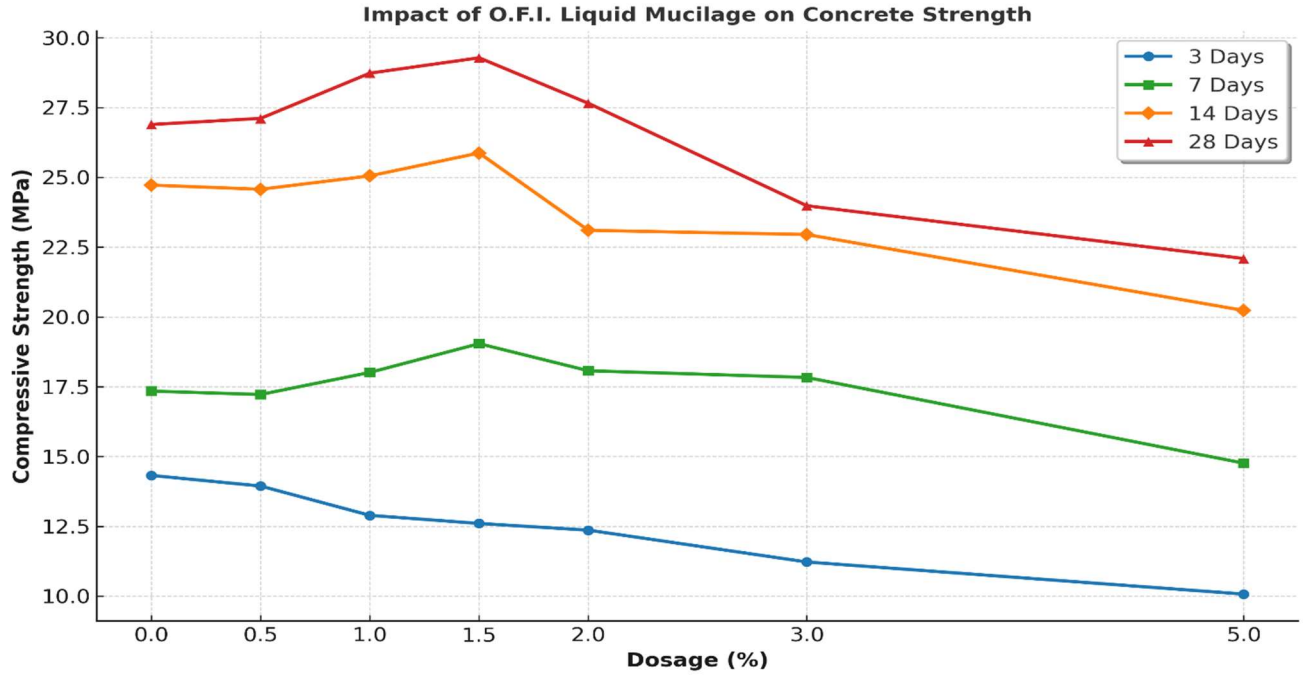


Figure 6. ***Dose-Dependent Effects of OFI Mucilage on Concrete Compressive Strength***

3.4.2. Effect of Sika Retarder and Water Reducer on Compressive Strength

At 0.5%, the Sika retarder showed very slight strength decreases, preserving its suitability for structural uses. They are not appropriate for high-strength constructions, nevertheless, because greater dosages (≥1%) resulted in noticeable strength decreases. To balance strength and workability, optimal dosages should be maintained at or below 0.5% as shown in Figure 7.

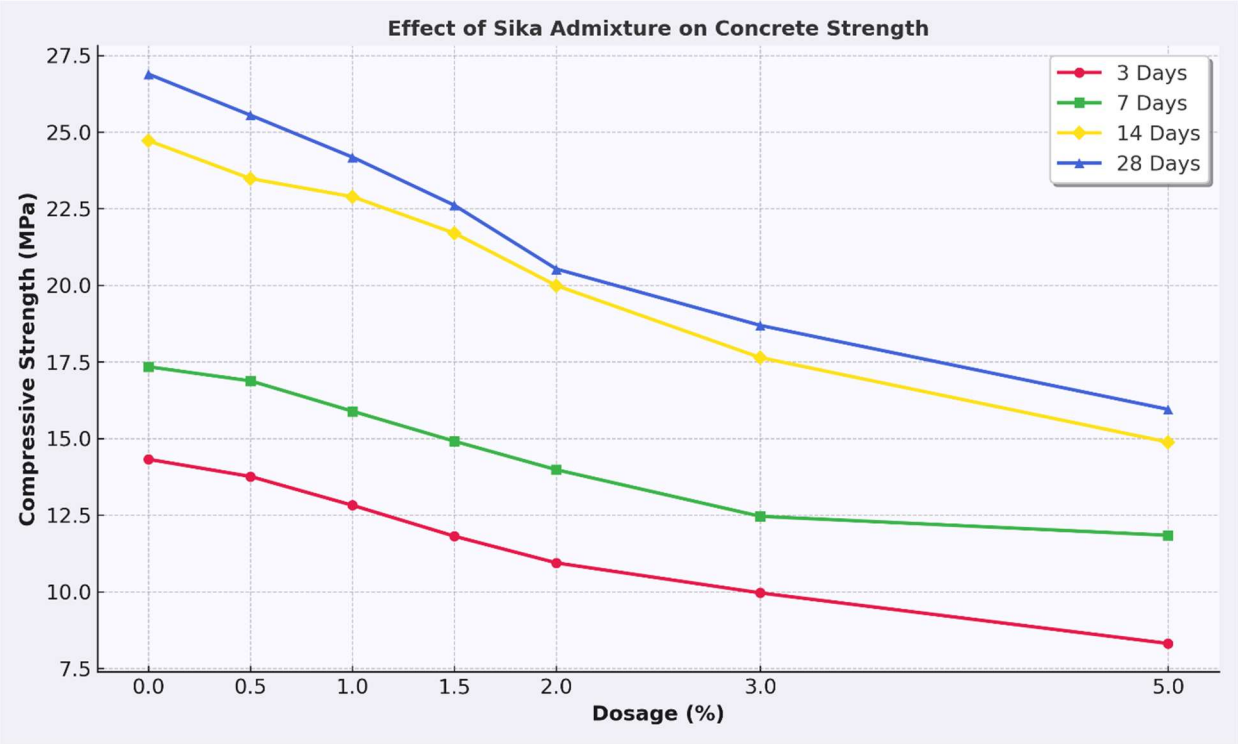


Figure 7. ***Dose-Dependent Effects of Sika on Concrete Compressive Strength***

3.4.3. Effect of Partial Replacement of OFI Mucilage on Compressive Strength

Overall curing times and compressive strength were considerably increased by partial mucilage replacement. The 28-day strength rose from 26.89 MPa (control) to 29.98 MPa at 5%, indicating improved durability and early strength development. The strength demonstrates that OFI is a useful addition for boosting strength as shown in Figure 8.

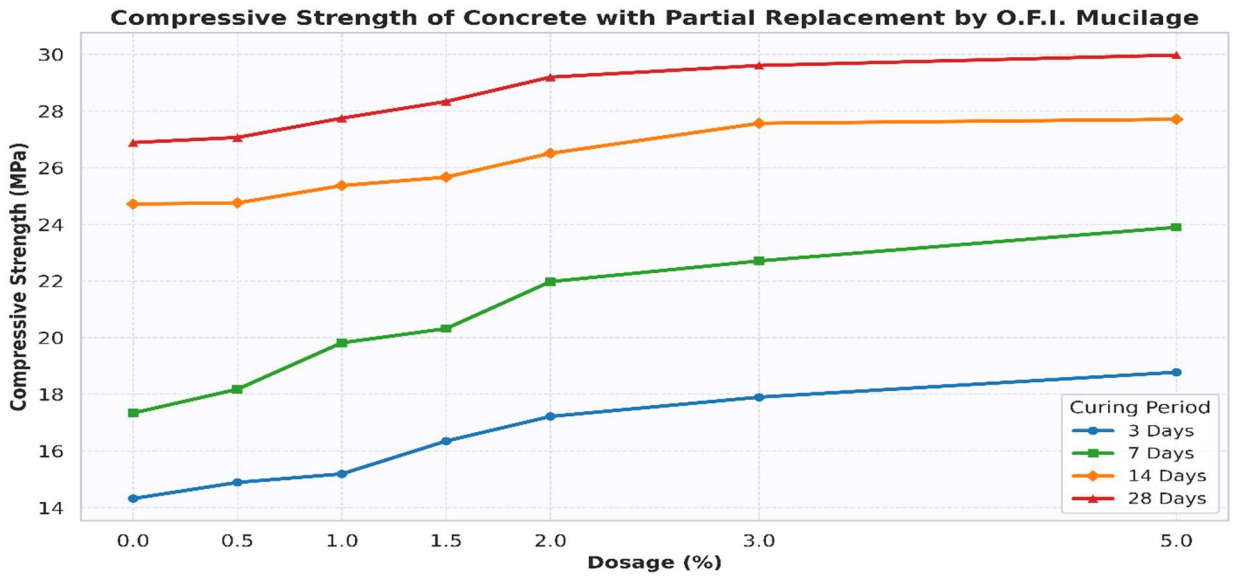


Figure 8. ***Effect of Water with OFI on Compressive Strength at Various Curing Ages***

3.4.4. Effect of Partial Replacement of Sika Retarder on Compressive Strength

Sika retarder partial replacement demonstrated modest strength gains at 0.5% and 1%, reaching 26.99 MPa after 28 days. Doses greater than 2%, however, resulted in notable strength decreases. 0.5% to 1.5% was found to be the ideal range for preserving strength without suffering undue loss shown in Figure 9.

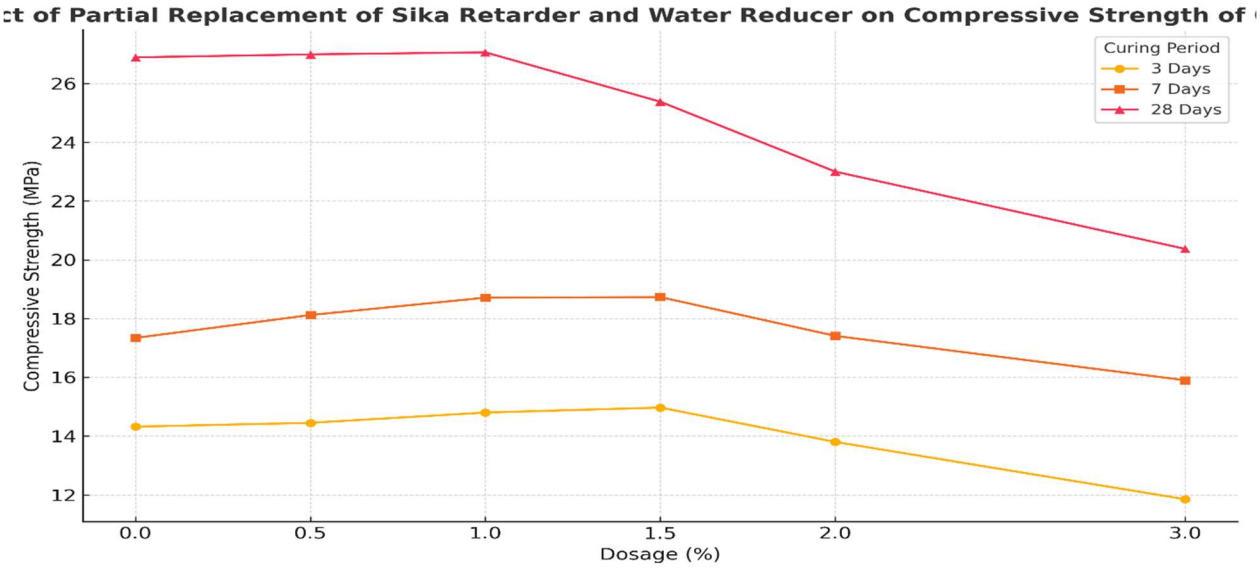


Figure 9. ***Sika retarder and water reducer effect on Compressive Strength***

According to the results, OFI mucilage is a useful natural additive for altering the characteristics of concrete. At ideal dosages (1% to 1.5%), it improves compressive strength, workability, and setting time when supplied directly. However, strength is diminished by overdosing. Although it may lessen workability at high levels, it greatly increases early and long-term strength when used in place of certain cement. Future

studies should concentrate on determining the best dosage for diverse concrete applications and evaluating the material's long-term resilience in various environmental settings.

4 Conclusions

This study compared the performance of OFI liquid mucilage with that of commercial admixtures like Sika and Darma to thoroughly examine its impacts as a sustainable concrete admixture. The results show that OFI mucilage outperforms synthetic substitutes several crucial areas, greatly improving concrete's workability, compressive strength, and setting time. Based on interpretations and discussions of the simplified results, the major findings were summarized as follows;

1. Concrete's initial and ultimate setting durations are gradually extended by OFI mucilage, which functions as a very efficient retarder. The first setup time went up from 132 minutes to 276 minutes at a 0.5% dosage and to 436 minutes at a 5% dosage. Longer working hours are made possible by this controlled delay, which qualifies OFI mucilage for certain project requirements. Furthermore, the mucilage greatly enhanced workability; at 0.5%, the slump value increased from 24.72 mm to 45.97 mm, and at higher dosages, it reached 225.28 mm.
2. According to the study, compressive strength is improved by modest dosages of OFI mucilage (0.5%–1.5%). The ideal dosage of 1.5% results in a 28-day strength of 29.28 MPa, which is 9% higher than the control mix. Strength, however, was adversely affected by larger dosages (3% and 5%), dropping to 22.09 MPa at 5%. This emphasizes how crucial exact dose control is to striking a balance between structural integrity and performance.
3. OFI mucilage continuously performed better than Sika and Darma when compared to commercial admixtures in terms of workability enhancement and setting time delays. It is also a more economical and ecologically friendly option due to its natural, plant-based composition, especially for large-scale projects. At larger dosages, OFI mucilage decreased workability but lengthened setting times when used in part lieu of water. Despite this, it is a prospective substitute for synthetic admixtures due to its eco-friendliness and beneficial effects on concrete characteristics.
4. Because it combines increased workability, longer setting periods, and greater compressive strength without sacrificing structural integrity, the ideal dosage of OFI mucilage is between 0.5% and 1.5%. Applications demanding extended working hours and environmentally friendly building techniques benefit greatly from this range.
5. The OFI liquid mucilage shows great promise as a high-performance and environmentally friendly concrete admixture. Together with its advantages for the environment, its capacity to control setting time, improve workability, and increase compressive strength makes it a competitive substitute for synthetic admixtures. Optimizing dosage levels, investigating long-term durability, and confirming its effectiveness in practical applications should be the main goals of future studies.
6. By providing a route toward more inventive and sustainable building techniques, this study adds to the expanding corpus of research on bio-based building materials. The building sector can attain both environmental

sustainability and performance excellence by using OFI mucilage in concrete technology.

5 Acknowledgment

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