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Research Paper

Experimental Investigation of *Opuntia ficus-indica* Mucilage as a Concrete Admixture for Sustainable Construction

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Abstract

The key properties of concrete are often controlled using synthetic admixtures, despite their possible adverse environmental effects. This study tested the potential of Opuntia ficus-indica (OFI) liquid mucilage as a natural and sustainable concrete admixture, assessing its effects on setting time, workability, consistency, and compressive strength of conventional concrete. The research applied an experimental approach, incorporating both direct addition (0.5-5%) and partial replacement of mixing water (0.5-30%), with performance comparisons against the commercial admixtures Sika and Darma. The results indicated that adding OFI mucilage significantly improves workability, enhances moisture retention, and extends setting time, making it a viable alternative for hot-climate construction. Optimal dosages of 1 - 1.5 % increased the 28-day compressive strength by up to 9%, outperforming the conventional admixtures. However, excessive dosages (>2%) negatively affect the strength. Partial cement replacement with mucilage also improved early and long-term strength while reducing permeability. As a natural and locally available admixture, the findings highlight the potential of OFI to reduce reliance on imported chemicals and to lower carbon dioxide emissions. In conclusion, OFI mucilage is a multifunctional concrete admixture, excelling in setting time modification, workability enhancement, and strength optimization, while offering economic and environmental advantages for sustainable construction practices, making it cost-efficient and resource-conscious infrastructure development.

1. Introduction

Worldwide, researchers are exploring eco-friendly alternatives to conventional concrete admixtures, which often rely on synthetic chemicals that can be costly and environmentally harmful as the demand for sustainable construction materials grows (Aquilina et al., 2018). One such alternative is *Opuntia ficus-indica* (OFI), commonly known as prickly pear cactus or Beles in Ethiopia. The mucilage extracted from its cladodes (pads) exhibits promising characteristics that can enhance concrete properties, offering a natural and sustainable admixture solution (Hernandez-Carrillo et al., 2017; Elshewy et al., 2023; Torres-Acosta & Diaz-Cruz, 2020). OFI thrives in arid and semi-arid regions, making it a valuable resource in areas with limited water availability (Deshmukh & Hedaoo, 2019). Its mucilage contains bioactive compounds such as polysaccharides and proteins, which contribute to improved concrete workability, water retention, and durability (Blancas-Herrera et al., 2018; Pacheco et al., 2023).

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These properties align with the growing need for green construction materials that minimize environmental impact and reduce dependence on synthetic additives (Hernandez et al., 2016). Thus, beyond technical benefits, the use of OFI mucilage has economic and environmental advantages. Specifically, the abundance of the plant in Ethiopia presents an opportunity to reduce reliance on expensive and imported chemical admixtures while promoting local resource utilization (FAO, 2013).

Furthermore, incorporating plant-based additives into concrete production can help mitigate carbon dioxide emissions associated with cement manufacturing and transportation (Flores-De los Rios 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 et al., 2016; Shushay, 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 et al., 2023; Nobel & Hartsock, 1984; Shushay & Goitom, 2015).

In this study, the effects of OFI mucilage as a concrete admixture was investigated, focusing on its impact on compressive strength, workability, and setting time. By evaluating its performance under varying conditions, the research aims to demonstrate its potential as a viable substitute for chemical admixtures (Shanmugavel et al., 2020; Azizi et al., 2019). By leveraging this indigenous resource, the study aims to promote green construction practices, reduce reliance on expensive imports, and support local economies. Thus, it tried to provide a foundation for integrating natural polymers into modern construction techniques, advancing Ethiopia's construction industry toward sustainability and resilience. The significance of the research extends beyond Ethiopia, offering insights that could influence global construction trends and emphasize the potential of indigenous resources in sustainable construction, underscoring the importance of integrating bio-based materials into modern engineering applications. By bridging traditional knowledge with contemporary scientific advancements, the findings have the potential of contributing to the development of durable, eco-friendly concrete solutions that align with global sustainability goals.

2. Materials and Methods

2.1 Experimental approach

This study employed an experimental framework to assess the potential of OFI liquid mucilage as a sustainable concrete admixture. The methodology integrates material preparation, optimized mix design, and mechanical performance evaluation to establish OFI mucilage as an eco-friendly alternative to synthetic admixtures.

2.2 Material preparation and characterization

2.2.1 *Opuntia ficus-indica* mucilage extraction

The fresh OFI cladodes were harvested, peeled, and mechanically blended with minimal water. The extract was filtered to remove fibers before undergoing the phytochemical analysis to determine its influence on cement hydration as shown in Figure 1.

Figure 1: *Opuncia ficus-indica* (Beles) cladodes

2.2.2 Aggregate and cement characterization

Ordinary Portland Cement (OPC) was tested for normal consistency, setting time, and fineness to ensure compatibility with OFI mucilage as shown in Table 1. Natural sand and coarse aggregates were analyzed for gradation, moisture content, specific gravity, and absorption capacity per ASTM standards as shown in Table 2.

Table 1: Chemical composition of Messebo Ordinary Portland Cement

Component	CaO	SiO_2	Al_2O_3	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/m^3)	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 mix design in this study primarily focused on strength, durability, and workability, as these were the key performance criteria for the intended application. While the appearance of concrete (such as color and surface finish) is an important consideration in some applications, it was not a focus of this research, as the study aimed to evaluate the mechanical and performance properties of concrete with OFI mucilage as an admixture.

The goal of the mix design was to create a concrete mix that is cost-effective, easy to place, and compact, and that meets the performance requirements for the intended use. The mix was designed in accordance with ACI 211.4R-08, targeting a characteristic compressive strength of 25 MPa (C-25) at 28 days, with a target strength of 30 MPa to account for variability in concrete production and testing. This ensures that the concrete meets the required performance standards for structural applications. The water-to-cement ratio was fixed at 0.491 to achieve the desired workability and strength.

Two methods of mucilage incorporation were examined. The first was direct addition, where mucilage was introduced without altering the water content, and the second was with partial replacement, where mucilage was substituted for a portion of the mixing water. Dosages ranging from 0.5 to 30% (by cement weight) were evaluated and compared against commercial admixtures, namely Sika Plastiment BV 40 and Darma retarders. Concrete cubes (150 mm × 150 mm × 150 mm) were cast and cured under standard conditions before testing to evaluate the effects of mucilage on concrete properties.

2.4 Experimental testing

2.4.1 Fresh concrete properties

The fresh concrete, the immediate product of mixing its constituent materials, undergoes a series of chemical reactions that ultimately define its final characteristics, such as strength, durability, and workability. To evaluate the properties of fresh concrete, standardized tests were conducted following established ASTM protocols. The slump test (ASTM C143) was performed to assess workability, which is a critical indicator of the concrete's ease of placement and compaction. Additionally, the setting time was determined using the Vicat apparatus (ASTM C191), which measures the initial and final setting times, providing insights into the concrete's hardening process. The consistency test (ASTM C187) was also conducted to evaluate the water demand and penetration depth, ensuring optimal mix proportions for desired workability and performance.

2.4.2 Hardened concrete properties

The hardened concrete exhibits several key properties, including compressive strength, durability, and impermeability, which are influenced by the mixture's composition, curing conditions, and environmental factors. To assess these properties, standardized tests were performed. The compressive strength was evaluated following ASTM C39, using a Universal Testing Machine (UTM) at intervals of 3, 7, 14, and 28 days to monitor the strength development over time. Additionally, the water absorption of the hardened concrete was determined following ASTM C642, which provides critical information about the concrete's porosity and durability. These tests collectively ensure that the hardened concrete meets the required structural and performance standards for sustainable construction applications.

2.5 Data analysis methods

Statistical techniques were applied to examine variations in workability, strength, and durability. Comparisons with synthetic admixtures provided insights into the effectiveness of OFI mucilage.

3. Results and Discussions

3.1 Effect of *Opuntia ficus-indica* cladode liquid mucilage on setting time

The setting time tests revealed that adding OFI mucilage significantly delayed both initial and final setting times compared to the control mix. At 0.5% mucilage dosage, the initial setting time increased from 132 to 276 min, and the final setting time increased from 255 to 393 min. At 5% dosage, these times extended further to 436 and 616 min, respectively, demonstrating the strong retardation effect of mucilage. Comparatively, the commercial admixtures, Sika and Darma, exhibited moderate setting time increases. At 0.5%, Sika extended initial and final setting times to 168 and 325 min, respectively, while at 5%, they increased to 315 and 410 min. Similarly, Darma recorded 152 and 310 min at 0.5%, reaching 290 and 470 min at 5%. These results highlight the superior effectiveness of OFI mucilage as a setting time retarder. The optimal mucilage dosage for practical applications ranged from 0.5 to 1.5%, balancing workability and efficiency as shown in Figure 2.

Partial replacement of cement with OFI mucilage also prolonged setting times. At 0.5%, the initial setting time increased from 132 to 142 min, while the final setting time rose from 255 to 298 min. At 5%, these values extended to 230 and 445 min, respectively. Compared to Sika and Darma, which showed moderate increases, OFI again demonstrated superior retardation (Figure 2). Thus, both direct addition and partial replacement with OFI mucilage significantly extended setting times. These findings underscore the effectiveness of mucilage as a sustainable setting time modified.

3.2 Effect of *Opuntia ficus-indica* cladode liquid mucilage on workability

Workability improved significantly with the addition of OFI mucilage. At 0.5%, the slump increased from 24.72 mm (control) to 45.97 mm, reaching 225.28 mm at 5%, categorizing it within the high slump range.

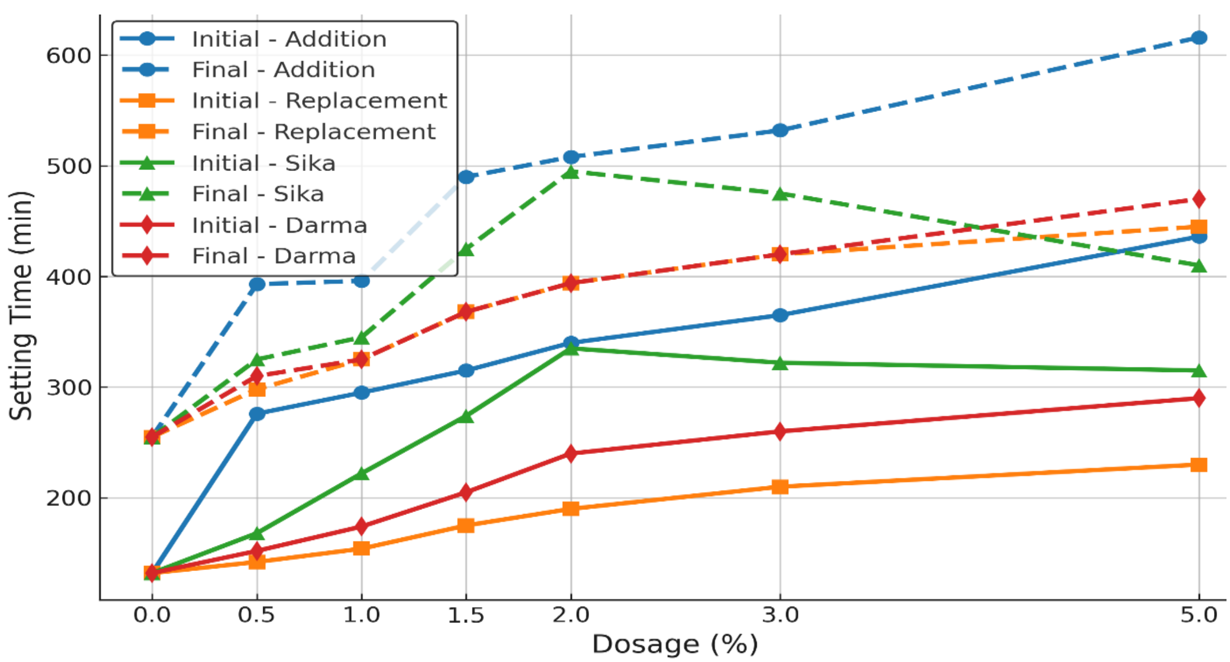

Figure 2: The initial and final setting times of the OFI, Sika, and Darma (the solid and broken lines are for initial and final setting times, respectively)

However, when used as a cement replacement, workability decreased significantly at higher dosages. At 30% replacement, the slump reduced to 1.0 mm, indicating excessive stiffness. These results suggest that while mucilage enhances workability as an admixture, its use as a cement substitute should be limited as shown in Figure 3.

3.3 Effect on cement paste consistency

Cement paste consistency was evaluated based on penetration depth. Control samples with depths of 5–9.8 mm were classified as stiff, while those with 12 mm or more exhibited higher workability. Partial replacement of cement with mucilage-reduced consistency, with penetration depths ranging from 6 to 15.7 mm (Figure 4), suggesting suitability for structural concrete.

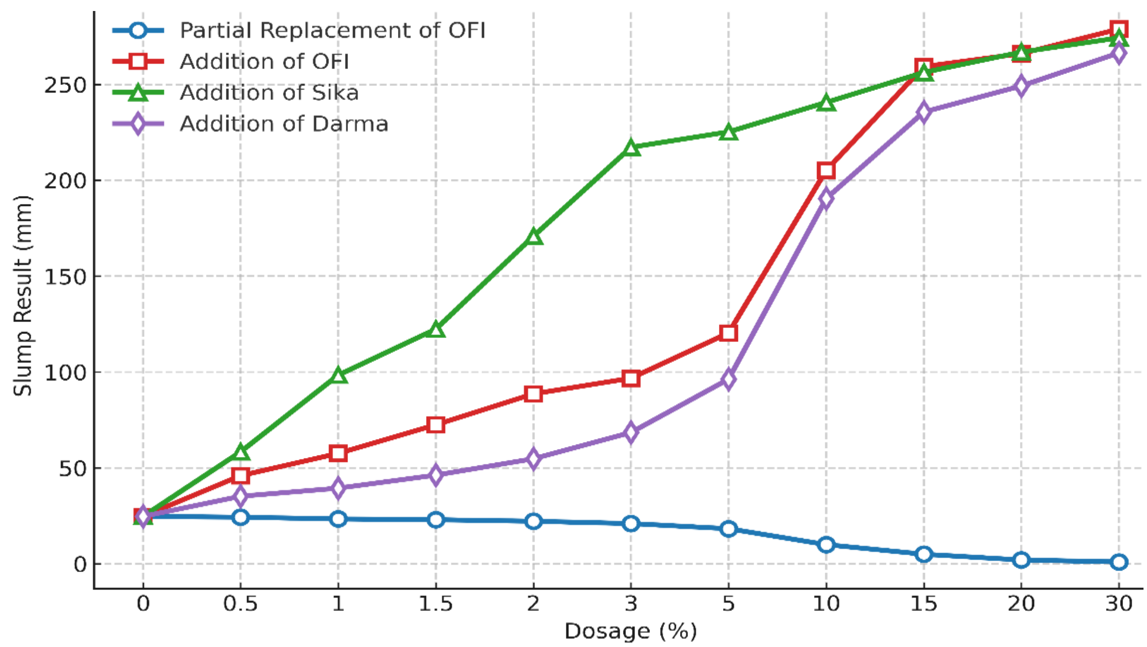

Figure 3: The slump test results

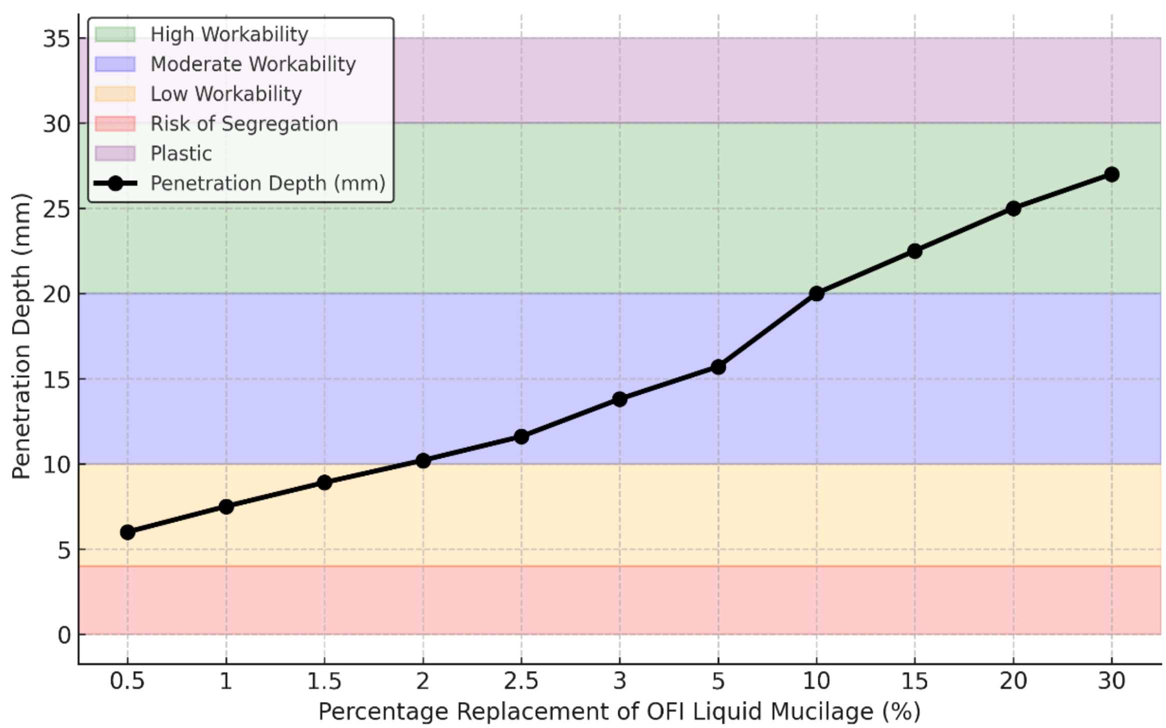

Figure 4: The consistency by partial replacement of *Opuntia ficus indica* cladodes

Conversely, adding mucilage significantly increased penetration depth, enhancing fluidity and self-compacting properties. The optimal range for consistency and stability was determined to be between 12 mm and 15.7 mm as shown in Figure 5.

3.4 Effect of *Opuntia ficus-indica* cladode liquid mucilage on compressive strength

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

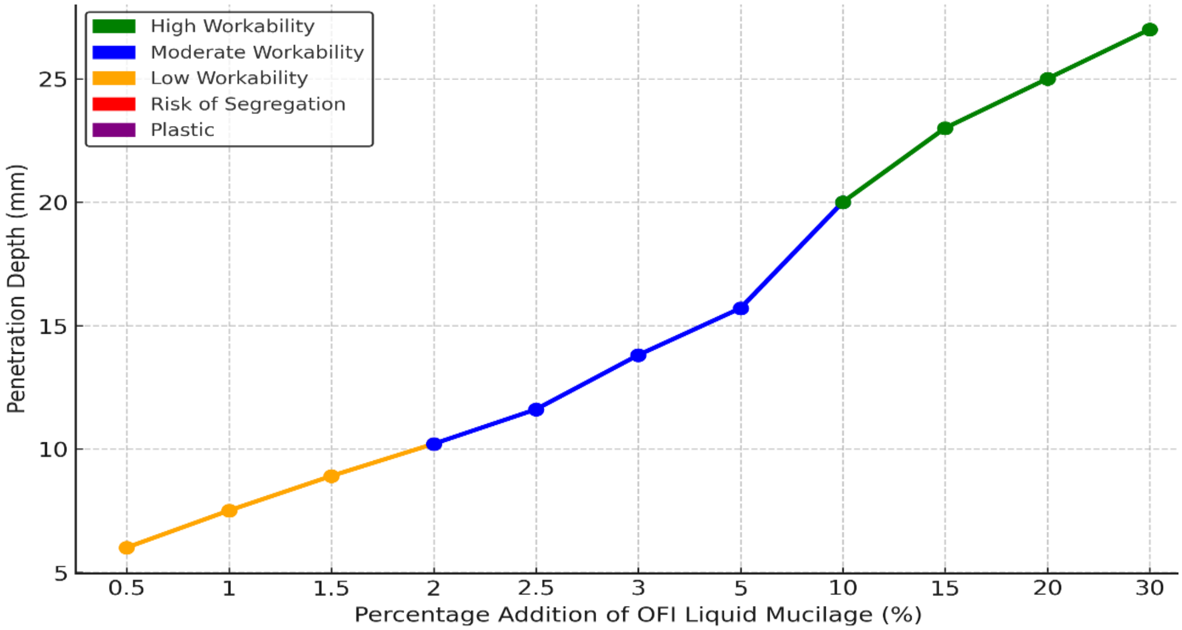

Figure 5: The consistency by addition of *Opuntia ficus indica* liquid mucilage cladodes

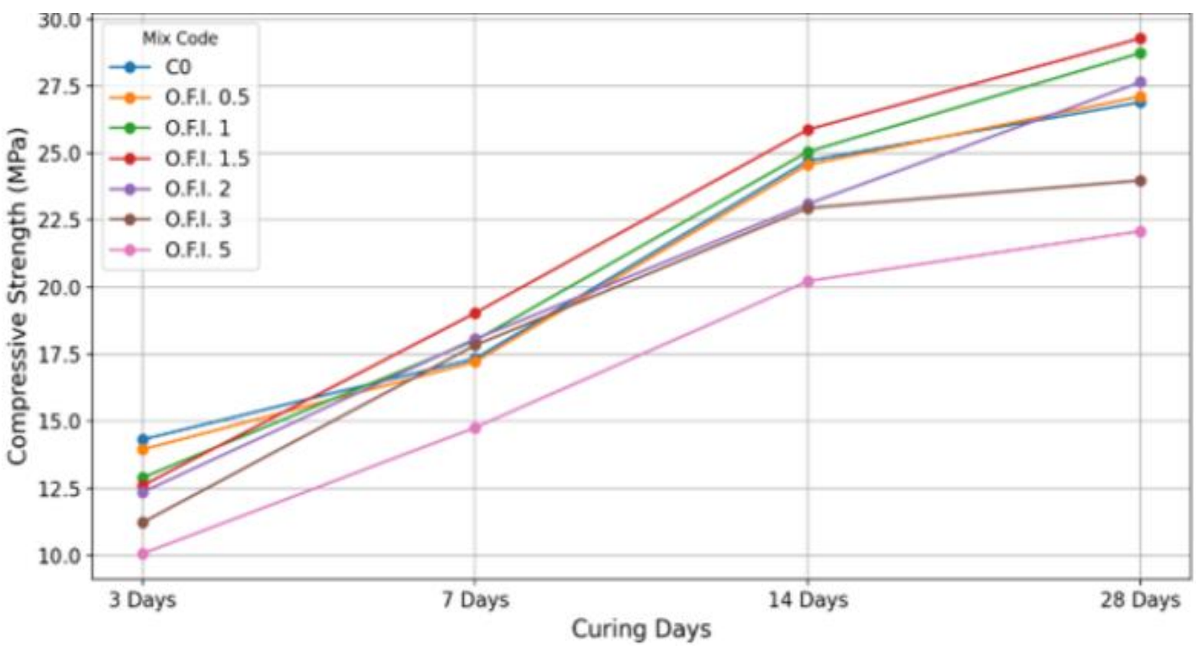

Figure 6: The effect of the addition of *Opuntia ficus-indica* Liquid Mucilage on Concrete Compressive Strength (Co and O.F.I. are for control and *Opuntia ficus-indica*, respectively)

Similarly, partial replacement with mucilage significantly improved compressive strength over all curing periods. At 5 %, the 28-day strength increased to 29.98 MPa compared to the 26.89 MPa of the control (Figure 7), demonstrating enhanced durability and early strength gain. Unlike the result of Figure 6, for the partial replacement, progressive increase of OFI between 0.5 and 5%, continuously increased the compressive strength. The strength highlights OFI as an effective strength-enhancing additive. However, the partial replacement with Sika retarder showed slight strength improvements at 0.5 and 1%, reaching 26.99 MPa at 28 days. However, dosages above 2 % led to significant strength reductions. The optimal range for Sika retarder was identified as 0.5% - 1.5% to maintain strength without excessive loss.

Overall, the findings indicate that OFI mucilage can serve as an effective natural admixture for modifying concrete properties. When added directly, it enhances setting time, workability, and compressive strength at optimal dosages (1 - 1.5%). However, excessive dosages may reduce strength. As a partial cement replacement, it significantly improves early and long-term strength but may reduce workability at high levels.

4. Conclusion

This study tried to investigate the effects of OFI liquid mucilage as a sustainable concrete admixture, comparing its performance with the commercial admixtures Sika and Darma. The study has significance to the growing body of knowledge on bio-based construction materials, offering a pathway towards sustainable and innovative building practices; by integrating OFI mucilage into concrete technology, the construction industry can achieve both performance excellence and environmental sustainability.

OFI mucilage acts as a highly effective retarder, progressively extending both the initial and final setting times of concrete. The controlled delay provides flexibility for longer working times, making OFI mucilage suitable for specific project needs. Additionally, the mucilage significantly improved workability, with a 0.5% dosage increasing the slump value from 24.72 mm to 45.97 mm, and higher dosages achieving slump values as high as 225.28 mm. Moreover, the study revealed that 0.5 to 1.5 % dosages of OFI mucilage enhance compressive strength, with the optimal dosage of 1.5% achieving a 28-day strength of 29.28 MPa, which is a 9% increase over the control mix. However, higher dosages (3 and 5%) reduced the strength, specifically to 22.09 MPa at 5%.

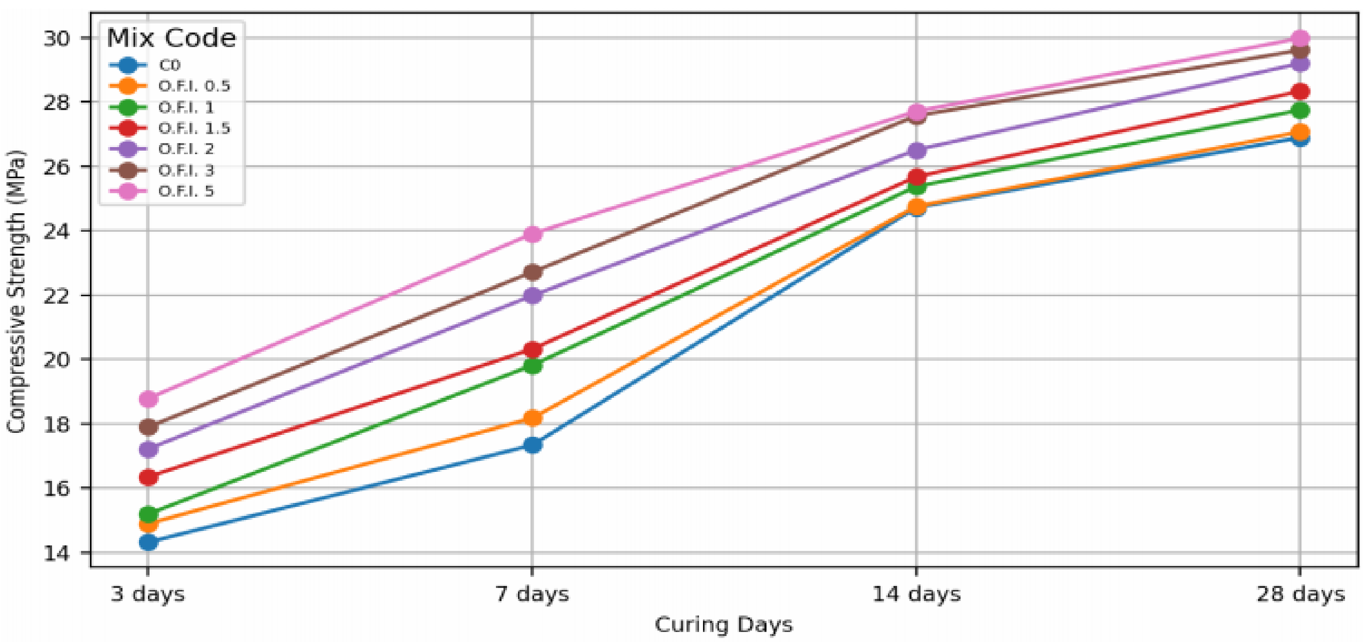

Figure 7: The partial replacement of *Opuntia ficus-indica* liquid mucilage's impact on concrete compressive (Co and O.F.I. are for control and *Opuntia ficus-indica*, respectively)

This highlights the importance of precise dosage control to balance performance and structural integrity. The optimal OFI mucilage dosage of 0.5 to 1.5 % balances improved workability, extended setting times, and enhanced compressive strength without compromising structural integrity. Thus, this range is particularly effective for applications requiring longer working times and sustainable construction practices.

When compared to the commercial admixtures, OFI mucilage consistently outperformed Sika and Darma in terms of setting time delays and workability enhancement. Its natural, plant-based composition also makes it an environmentally friendly and cost-effective alternative, particularly for large-scale projects. When used as a partial replacement for water, OFI mucilage increased setting times but reduced workability at higher dosages. Despite this, its eco-friendly nature and positive impact on concrete properties make it a promising alternative to synthetic admixtures.

Overall, the OFI liquid mucilage demonstrated significant potential as a sustainable and high-performance concrete admixture, outperforming synthetic alternatives in several key areas. Its ability to regulate setting time, enhance workability, and improve compressive strength, coupled with its environmental benefits, positions it as a viable alternative to synthetic admixtures. Future research should focus on the compositional, and microstructural characterization of OFI, optimizing dosage levels, exploring long-term durability, and validating its performance in real-world applications.

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