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Performance of Concrete with Different Types of Cactus as Admixtures-A Comprehensive Review

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Abstract

The use of cactus extracts, mostly *Opuntia ficus-indica*, as bio-admixtures in construction materials offers a sustainable approach to enhancing concrete and mortar performance. Studies tell that cactus mucilage improves compressive strength, durability, and resistance to water and freeze-thaw cycles while reducing carbon footprints and mitigating steel corrosion. Applications include lightweight concrete, bio-enhanced lime mortars, and sustainable blocks. Cactus-based additives also effect setting times, microstructure, and mechanical properties, representing flexibility and environmental benefits. Despite challenges in mix design optimization and long-term assessments, these advancements highlight the potential of cactus biopolymers in creating eco-friendly, high-performance construction materials.

Keywords: Cactus, *Opuntia ficus-indica, Euphorbia tortilis, Nopal cactus,* Mucilage, Mechanical properties, durability

1. Introduction

The construction sector, a significant contributor to global carbon emissions, faces increasing pressure to adopt sustainable practices. One innovative method is integrating renewable and natural materials into concrete preparations. Among these, cacti, particularly *Opuntia ficus-indica* and *Euphorbia tortilis*, stand out for their unique properties and widespread availability in arid regions. These plants produce mucilage, a viscous, water-absorbing compound, and strong fibers, both of which offer important benefits when used in cement-based composites. This is not only improves material properties but also promotes the development of cost-effective, environmentally friendly, and sustainable eco-materials.

Recent studies have verified the positive impact of cactus-based additives on concrete. cactus mucilage improves workability, enhances durability, and reduces cracking in cementitious materials[1][2]. Calcium oxalate present in the mucilage creates a protective film, safeguarding the surface and structure from exposure to acidic gases[3]. Also mucilage enhances hydration and decreases permeability, and can also be used as a green alternative to synthetic admixtures[4][5]. In addition to mucilage, fibers derived from cacti provide notable mechanical benefits. Which enhanced flexural strength, ductility, and load-bearing capacity[6][7]. The historical use of cactus in lime mortars, also suggests its potential for modern restoration applications[8][9].

While these developments are promising, challenges persevere in normalizing the use of cactus-based bio-admixtures for diverse construction needs. This paper reviews existing research to explore how cactus-derived additives impact the mechanical properties, durability, and sustainability of concrete, providing valuable visions for the adoption of greener construction practices.

2. Types of cactus

Several studies have explored different species of cactus for their applications as bio-admixtures in concrete and mortar. The following summarizes the primary types of cactus referenced in these studies:

Fig1:Types of cactus; a)Opuntia ficus-indica; b) *Euphorbia tortilis; c) Nopal cactus*

2.1 Opuntia ficus-indica (Prickly Pear Cactus)

The *Opuntia ficus-indica* species, commonly known as prickly pear cactus, is extensively studied for its mucilage, a viscous biopolymer that significantly enhances the properties of concrete and mortar. The key benefits of incorporating *Opuntia ficus-indica*(fig1.a) into construction materials include improved durability, reduced carbon footprint, corrosion mitigation, and the creation of lightweight concrete. The mucilage improves concrete's resistance to water penetration, cracking, and freeze-thaw cycles[1][4]. Additionally, it is used as a partial replacement for calcium-based binders, helping to produce low-carbon cement.The mucilage also helps to prevent steel corrosion in reinforced concrete exposed to aggressive environments[10]. Furthermore, the fibers and mucilage derived from *Opuntia ficus-indica* contribute to the development of lightweight concrete with improved soundness and reduced setting times[7][8]

2.2 Euphorbia tortilis

The *Euphorbia tortilis* species, also known as the Tortilla Cactus(fig1.b), has also been studied for its potential use as a natural additive in concrete, enhancing its mechanical properties. This cactus is primarily used to improve the flexural strength, load-carrying capacity, and ductility of concrete. The cactus extract is typically added in amounts ranging from 0.5% to 2% by weight of the cement[6][11]. The incorporation of *Euphorbia tortilis* helps in improving the concrete's toughness, making it more resistant to cracks and fractures under stress.The concrete specimens incorporating *Euphorbia tortilis* extract are commonly tested at 28 days to assess their mechanical properties, including compressive strength, flexural strength, and overall durability[12]. This age is used to evaluate how well the cactus extract improves the concrete's performance over the curing period. Additionally, *Euphorbia tortilis* has been found to contribute to sustainable construction practices by enhancing the material's mechanical properties without requiring significant alterations to the standard concrete mix.

2.3 Nopal Cactus

The *Nopal cactus* (mainly from the *Opuntia* genus) has been extensively studied for its potential as a bio-admixture in concrete and mortar. The mucilage and fibers extracted from *Nopal* cactus(fig1.c) are used to enhance various properties of concrete, including durability, microstructure, and soundness. The mucilage, rich in natural biopolymers, improves the concrete's resistance to water penetration, cracking, and freeze-thaw cycles[11][13]. Also, *Nopal cactus* fibers contribute to the reinforcement of concrete, enhancing its tensile strength and preventing cracks.The typical dosage of *Nopal cactus* mucilage in concrete ranges from 1% to 3% by weight of the cement. The cactus fibers are generally added at similar dosages, typically between 0.5% and 1% by weight of the total concrete mix. Concrete specimens are usually tested at 28 days to evaluate key properties, such as compressive strength, durability, and microstructural changes[11][14]. In addition to improving durability and strength, *Nopal cactus* also contributes to sustainable construction practices by reducing the environmental impact of cement production. This is achieved by replacing part of the conventional cement with the natural cactusderived materials.

Cactus Species	**Application**
Opuntia ficus-indica	Mucilage and fibers for concrete & mortar
Euphorbia tortilis	Flexural strength, ductility
Nopal Cactus	Durability, microstructure enhancement
Opuntia spp. (Fibers)	Reinforcement in concrete
Opuntia ficus-indica (Fibers in Lime Mortar)	Historical building restoration

3 Methods of cactus extraction

3.1 Manual Cold Extraction

This method involves manually cutting cactus pads (*Opuntia ficus-indica* or similar species) into small pieces and soaking them in cold water. After 24–48 hours, the mucilage melts into the water. The resulting mixture is filtered to remove any solid particles ,seen on Figure 2. This low-energy technique is used for its simplicity and preservation of mucilage properties[1] [11][15].

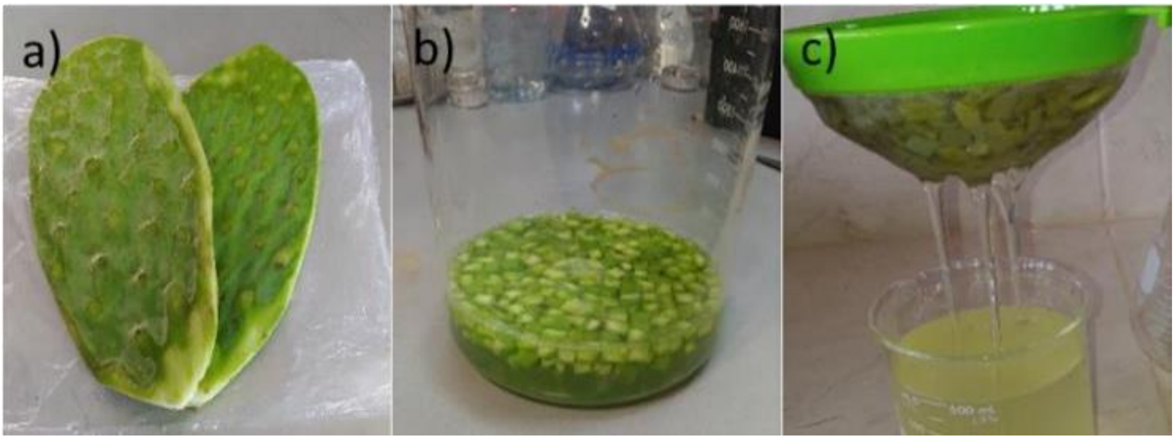

Fig2. a) Fresh cactus leaves, b) Prickly pear cactus mixed with water c) Filtration process of Nopal mucilage[15]

3.2 Hot Water Extraction

In this method, the cactus pads are boiled in water for 2–3 hours, which accelerates the release of mucilage. The hot mixture is strained and cooled to extract the bio-admixture. The heating process reduces viscosity, making it easier to blend with cement paste[16][17]. Several studies indicate that treating vegetable fibers with hot water before use improves their performance[18].

3.3 Mechanical Blending Extraction

Mechanical blending contains crushing or grinding cactus cladodes using a blender or industrial crusher. Water is added during the process to separate mucilage. The resulting slurry is then filtered and purified for use in concrete. This method is efficient for large-scale applications[2][8][19].

3.4 Fiber Extraction Through Maceration

Cactus fibers are extracted by soaking the pads in water for an lengthy period, allowing the softer material to break down. The remaining fibrous content is then stripped manually or using mechanical tools. These fibers are washed, dried, and sometimes chemically treated to improve bonding with cement [6][7].

3.5 Solvent-Assisted Extraction

For laboratory-grade applications, solvents such as ethanol or acetone are used to separate and purify cactus mucilage. This method ensures a highly concentrated and refined bio-admixture but is generally limited to research due to cost [5][15].

3.6 Freeze-Drying Technique

Once the mucilage is extracted using any of the above methods, it can be freeze-dried to form a powder. This approach is ideal for preserving the material for long-term storage and transportation. Freeze-dried mucilage can later be reconstituted with water for use in concrete mixes[4][13].

3.7 Microwave-Assisted Extraction

Microwave energy is used to heat and rupture the cells of cactus pads, releasing mucilage. This rapid and energy-efficient method allows for a controlled extraction process, ideal for industrial-scale operations [20].

3.8 Alkali Treatment for Fiber Extraction

Cactus fibers are treated with an alkaline solution, such as sodium hydroxide, to remove lignin, hemicellulose, and other impurities. This chemical process improves the fiber’s adhesion properties when combined with cement, enhancing concrete’s mechanical strength [6][21].

3.9 Natural Drying and Powder Conversion

In traditional practices, cactus pads are sun-dried until they harden. Once dry, the pads are ground into powder and added directly to cement or mortar. This approach minimizes energy use and is suitable for rural or small-scale construction[22][23].

3.10 Biological Pre-Treatment

In some studies, bacterial or enzymatic pre-treatment is used to extract mucilage and other bio-polymers from cacti. This approach leverages biological processes to break down plant materials while maintaining the integrity of the bio-admixture [14]

4 Properties of Cactus

4.1 Durability and Water Resistance

Cactus mucilage, particularly from *Opuntia ficus-indica*, has been shown to improve the durability of concrete by enhancing its resistance to water penetration, cracking, and freeze-thaw cycles. The mucilage acts as a water repellent, filling voids in the concrete matrix, which reduces its permeability and helps resist water ingress. This makes cactus-based concrete more durable in harsh environments.

In addition, cactus-infused concrete has been shown to perform better under freeze-thaw conditions, as the mucilage contributes to the reduction of microcracks, thus prolonging the lifespan of structures exposed to dangerous weather conditions[1][4]

4.2 Compressive Strength

Concrete incorporating cactus mucilage has been found to exhibit increased compressive strength compared to conventional concrete. This is because the mucilage acts as a binder, improving the adhesion between cement particles and filling voids in the concrete matrix. As a result, the mixture is more cohesive and stronger. Studies have shown that the compressive strength of cactus-based concrete is significantly enhanced, especially when tested at 28 days of curing, which is the standard testing period for concrete[1]. Compressive strength increased 20.4% at 15% replacement[16]. Compressive strength up to 76 kg/cm² higher than conventional bricks[24].

4.3 Flexural Strength and Toughness

The addition of cactus fibers to concrete significantly improves its flexural strength and toughness. The fibers help distribute stresses within the concrete, preventing cracks from spreading and enhancing the material's ability to withstand bending forces. This is especially beneficial in structural applications where concrete may be subjected to bending. At 28 days of curing, concrete with cactus fibers demonstrates improved performance under load, exhibiting higher flexural strength and better resistance to crack propagation, making it more durable under stress[6][12].

4.4 Corrosion Mitigation

Opuntia ficus-indica mucilage has been found to serve as an effective corrosion inhibitor for steel reinforcement in concrete, particularly in aggressive environments such as those containing chlorides. The mucilage forms a protective layer around the steel reinforcement, preventing the formation of rust and thereby reducing the risk of corrosion. This helps extend the lifespan of reinforced concrete, especially in coastal areas or regions using de-icing salts. Studies indicate that cactus-infused concrete exhibits a significantly reduced rate of corrosion compared to conventional concrete[10].

4.5 Microstructural Improvement

The incorporation of cactus mucilage improves the microstructure of concrete, leading to denser and less porous concrete. Concrete without additives typically has a network of voids, which can reduce its strength and durability. Cactus mucilage helps fill these voids, creating a smoother, more cohesive matrix. This leads to enhanced strength and water resistance, as the improved microstructure results in lower permeability. As a result, cactus-based concrete demonstrates better long-term durability and resistance to environmental degradation[13].

4.6 Lightweight Concrete

Cactus fibers, when incorporated into concrete, help produce lightweight concrete with reduced overall density while maintaining strength and durability. This is especially beneficial for applications where weight reduction is a critical factor, such as in facades, precast elements, or high-rise buildings. The reduction in weight also leads to lower transportation costs and easier handling during construction. Additionally, cactus fibers help reduce the setting time of concrete, which increases the efficiency of construction projects. Studies have shown that concrete containing cactus fibers remains strong, durable, and lightweight[7][8]

4.7 Reduced Carbon Footprint

Cactus-based concrete contributes to sustainability by reducing the carbon footprint of concrete production. Cement production is a significant source of CO2 emissions, but by replacing part of the cement with cactus mucilage, the environmental impact is lowered. Research indicates that cactus-based concrete not only offers similar, if not superior, performance compared to conventional concrete but also contributes to a more sustainable construction process. This makes cactus-infused concrete an ecofriendly alternative to traditional concrete, aligning with the growing demand for low-carbon construction materials[16].

5 Conclusion

1. Cactus-derived materials, such as mucilage and fibers, enhance compressive strength, durability, and corrosion resistance in concrete.
2. Cactus mucilage improves the water resistance of concrete, reducing permeability and enhancing freeze-thaw durability by filling voids in the matrix.
3. Cactus fibers increase flexural strength, toughness, and resistance to cracking, improving the concrete's performance under dynamic loads.
4. Cactus materials can replace a portion of traditional cement, reducing the carbon footprint of concrete production and promoting sustainability.
5. Cactus mucilage acts as a natural corrosion inhibitor for steel reinforcement, improving the concrete’s lifespan in CO2 and chloride-contaminated environments.
6. Cactus-based additives are renewable, cost-effective, and eco-friendly, offering a sustainable alternative to traditional concrete admixtures.
7. Cactus materials are a renewable and sustainable resource, contributing to the reduction of environmental impact in the construction industry.
8. Continued research into cactus-based concrete mixtures has the potential to revolutionize the construction industry, making concrete stronger, more durable, and environmentally friendly.
9. The use of cactus materials supports sustainable construction practices by creating low-carbon, efficient building materials.

Sl. no	Author &Year	Type of Cactus	Grade	Ratio/ Dosages	Tests	Compressive Strength(28 Days)	Fexural strength	Remarks
1.	Shanmugavel et al.2020	Nopal Cactus (Opuntia Ficus-Indica)	M20	2% 4% 6% 8% 10%	Slump, compressive strength, flexure, Young's modulus, UPV, RCPT, acid/sulfate resistance	21 21.5 22 23 22.8 25	6.2 6.9 7.2 7.9 8.1 8.9	Improved workability, water retention, mechanical properties, durability with increasing CEX dosage
2.	MartínezMolina et al.2014	Dehydrated Nopal	_	0% 1% 2% 4%	Compressive strength, porosity, ultrasonic pulse velocity, resistivity	37.1 36.4 36 29	_	Enhanced strength, reduced voids, and improved durability with up to 2% cactus addition; above 2%, reduced performance
3.	Velumani et al.2023	*Euphorbia tortilis*	M25	1% 3% 5% 7% 9%	Compressive strength, porosity, RCPT, SEM analysis, drying shrinkage	26 27.2 28.8 30 31.2	_	Improved durability, reduced porosity, enhanced workability
4.	Hernández et al.2016	*Opuntia ficus índica* cactus	Motor-1:1 W/C 0.30	0.5% 1% 1.82%	Compressive strength, chloride permeability, carbonation tests	_	_	Reduced carbonation and chloride permeability, enhanced durability.
5.	Pattusamy et al.2023	Euphorbia tortilis cactus	M20	1% 3% 5% 7% 9%	Compressive strength, flexural strength, sorptivity, durability tests	23.3 25.6 26.5 27.1 28.4	7.03 7.51 7.96 8.06 8.76	Strength increase by 29% with 9% extract, reduced porosity.
6.	BlancasHerrera et al.2018	*Opuntia ficus-indica*	Motor-1:2.75 W/C 0.68	_	Ultrasonic pulse velocity, electric resistivity,	_	_	Improved matrix densification

					sulfate attack tests			, enhanced durability.
7.	Ramírez-Arellanes et al.2012	nopal cactus	W/C 0.30, 0.45, 0.60	3%	SEM analysis, XRD, capillary absorption, chloride diffusion	_	_	Significant reduction in chloride diffusion, improved microstructure.
8.	Chandra et al.1998	nopal cactus	Motor-1:3 W/C 0.50	50% 100%	Compressive and flexural strength, water absorption, freeze-thaw tests	48.5 43.5	10.1 10	Enhanced water resistance, increased long-term strength.
9.	Lorika et al. 2023	*Opuntia ficus-indica*	W/C 0.58	15% 25% 50%	Compressive strength, durability, SEM, FTIR, freeze-thaw resistance	33.3 32.6 32.3	5 4.2 4.1	Compressive strength increase (20.4% at 15% replacement), reduced fluid ingress by 39%, improved durability.
10.	Cárdenas et al. 2015	Opuntia ficus-indica	_	0.65% 1% 1.95%	Mechanical tests, impermeability tests	_	_	Improved impermeability, homogeneous network formation at higher mucilage ratios.
11.	Aparicio et al. 2019	Opuntia ficus-indica	Various mixtures	_	Compressive strength, water absorption, SEM	_	_	Compressive strength up to 76 kg/cm² (higher than conventional bricks), 17% water absorption reduction, weight reduction by 25%.

12.	Mendoza-Goden et al. 2024	Nopal Mucilage	Motor1:10	2.8 kg of nopal and 2.3 kg of aloe vera	Compressive strength, water absorption, thermal conductivity, fractal analysis	_	_	Improved compressive strength (up to 12.2 MPa), lower bulk density, enhanced thermal properties.
13.	Torres-Acosta et al. 2021	Opuntia ficus-indica	Motor1:3	0% 1.5% 4% 8% 42% 95%	Corrosion resistance, polarization resistance, water absorption	_	_	Corrosion inhibition of up to 90%, reduced cracking, enhanced durability in CO2 environments.
14.	Kammoun et al. 2019	Prickly Pear Fiber	_	2cm - 5kg/m3 10kg/m3 15kg/m3 3cm - 5kg/m3 10kg/m3 15kg/m3 5cm - 5kg/m3 10kg/m3 15kg/m3	Compressive strength, flexural strength, shrinkage, thermal conductivity	2cm- 30 27.5 24 3cm- 28 26.5 23.5 5cm- 27.5 26 23	2cm- 4.5 5.2 6.2 3cm- 5.8 6.2 6.8 5cm- 6.2 6.6 6.9	Reduced density (up to 25%), 42% decrease in thermal conductivity, 170% improvement in flexural strength, slight compressive strength reduction.
15.	Gallegos-Villela et al. 2021	Nopal mucilage	_	_	Compressive and flexural strength, thermal conductivity, UPV, surface roughness, ED-XRF	96% increase	72% increase	96% increase in compressive strength, 72% increase in flexural strength, 50% reduction in thermal conductivity.

16.	Ramdoss et al. 2015	Opuntia ficus Indica	Cactus/water- 1:3	25% 50% 75% 100%	Compressive and flexural strength, SEM, XRD, FT-IR, water absorption, salt crystallization	4.1 4 3.8 4	1.25 1.2 1.35 1.5	75% mucilage showed optimal strength (3.4× after 360 days), reduced water/salt absorption, and resistance to salt crystallization.
17.	Ferriz-Papi 2015	Prickly Pear	Up to 100% water replacement	_	Compressive and flexural strength, water absorption, freeze-thaw, capillarity tests, XRD	_	_	Improved impermeability, reduced porosity, delayed setting time, enhanced durability.
18.	Anne Aquilina et al. 2018	Opuntia Ficus-Indica(liquid and powder)	_	OFI Water Replacements- 10% 20% 40% 60% OFI Powder Replacements- 0.5% 1% 1.5% 2%	Compressive strength, flexural strength, water absorption, ultrasonic pulse velocity	OFI Water Replacements- 27 28 26 32 OFI Powder Replacements- 32 30 27 28	_	Increased setting time, improved compressive and flexural strength at lower replacements, reduced porosity and water absorption.
19.	Díaz-Blanco et al. 2019	Nopal mucilage	W/C 0.45	Mucilage/ water 1:1 1:2 1:3	Compressive strength, open circuit potential, electrochemical noise, linear polarization resistance	223.5 kg/cm2 234.9 kg/cm2 246.5 kg/cm2	_	Corrosion delay and lower corrosion rates, reduced early-age compressive strength, enhanced durability against chloride exposure.

20.	Chiraz El Azizi et al. 2019	Opuntia FicusIndica Cladodes	M32 W/C-0.5	Portland cement replacement- 1% 2.5% 4%	Compressive strength, acid resistance, setting time, SEM, XRD	42.8 54.52	–	Compressive strength improvement up to 54 MPa (2.5% replacement), enhanced acid resistance, reduced setting time.
21.	M. Arreola Sanchez et al. 2015	Opuntia cactus fibers	W/C 1.01	0.5% 1% 1.5% 2% 4%	Compressive strength, flexural strength, setting time, water demand, SEM	9.5 8.9 8.5 7.5 6.5	2.3 2.2 1.95 1.85 1.85	1.5% substitution showed optimal performance, increased compressive and flexural strength, improved setting time.
22.	R. Mohanraj et al. 2024	Euphorbia Tortilis Cactus	M20 and M25	1% 3% 6% 9%	Flexural strength, stiffness, ductility, energy absorption	–	5 5.8 6.2 6.65	Improved loadcarrying capacity (47.9% increase at 9% ETC), enhanced stiffness and ductility, reduced crack widths.

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