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Evaluation of Expanded Clay and Tuff as Lightweight Agents in Concrete Stabilized with Nopal Mucilage and Aloe Vera

Daniel Mendoza-Goden [1,2], Rocio Rafaela Gallegos-Villela [1], Pedro Flores-Becerra [1], Josue Francisco Perez-Sanchez [1,*], Edgardo Jonathan Suarez-Dominguez [1] and Arturo Palacio-Perez [3]

1 Facultad de Arquitectura, Diseño y Urbanismo, Universidad Autónoma de Tamaulipas, Centro Universitario Sur, Tampico 89337, Tamaulipas, Mexico; l18200093@pachuca.tecnm.mx (D.M.-G.); rafaela.gallegos@uat.edu.mx (R.R.G.-V.); pedro.flores@uat.edu.mx (P.F.-B.); edgardo.suarez@docentes.uat.edu.mx (E.J.S.-D.)
2 Instituto Tecnológico de Pachuca, Tecnológico Nacional de México, Blvd. Felipe Ángeles km 84.5, Venta Prieta, Pachuca de Soto 42083, Hidalgo, Mexico
3 Instituto de Ingeniería, Universidad Nacional Autónoma de México, Circuito Interior, Ciudad Universitaria, Mexico City 04510, Mexico; apalaciop@iingen.unam.mx
* Correspondence: josue.perez@uat.edu.mx

Abstract: Objectives: This study aims to evaluate the potential of lightweight concrete mixtures incorporating sustainable materials, such as nopal mucilage and aloe vera, to enhance thermal and structural performance while promoting eco-friendly construction practices. The objective is to analyze their effects on physical, mechanical, and thermal properties to optimize mixture design. **Methods/Analysis:** Six lightweight concrete mixtures were prepared using varying dosages of tuff, expanded clay, nopal mucilage, and aloe vera as lightweight and stabilizing agents. To assess their performance, a series of physical tests (bulk density, water absorption, and slump), mechanical tests (compressive strength), and thermal characterizations (conductivity, heat capacity, and resistivity) were conducted. Fractal analysis was employed to evaluate the structural complexity of the mixtures. **Findings:** The results revealed significant differences based on the materials used. Mixtures with aloe vera exhibited extreme water absorption (up to 11.472%) and varying consistency, from fluid ("spreads") with tuff to workable with expanded clay. When combined with expanded clay, Nopal mucilage-based mixtures showed lower workability but higher compressive strengths (up to 11.447 MPa). Expanded clay increased bulk density and enhanced thermal efficiency, with mixtures incorporating aloe vera or nopal mucilage demonstrating high heat retention and structural complexity. The compressive strengths ranged from 7.343 MPa (aloe vera-tuff) to 12.207 MPa (water-tuff), highlighting the impact of stabilizing agents on mechanical performance. **Novelty or Improvement:** This study introduces a novel evaluation of lightweight concrete mixtures using nopal mucilage and aloe vera, focusing on their synergistic effects with lightweight aggregates such as tuff and expanded clay. The findings provide valuable insights into optimizing eco-friendly concrete mixtures with improved thermal retention, workability, and mechanical properties, offering a sustainable alternative for modern construction.

Keywords: lightweight concrete; sustainable materials; thermal analysis; mechanical properties

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1. Introduction

Concrete, with its excellent mechanical properties and durability, is one of the most widely used materials in the construction industry. However, its high density and the environmental impact of its production have prompted the search for more sustainable and lightweight alternatives. In this context, lightweight concrete has emerged as a promising solution, not only allowing for a reduction in structural weight without significantly compromising its mechanical properties but also reducing the environmental impact of construction.

The use of organic materials as lightweight agents and stabilizers in concrete is a trend that is under increasing exploration. Among these, nopal mucilage and aloe vera stand out for their adhesive properties and ability to improve the workability of concrete [1,2]. Mucilage, a natural polysaccharide, acts as a binding agent and contributes to water retention, which is crucial for concrete curing [3]. On the other hand, Aloe vera has demonstrated properties that enhance the plasticity and strength of concrete and offer antimicrobial benefits that can prolong the material's lifespan [4,5].

Beyond the benefits above, including organic materials in lightweight concrete positively impacts environmental sustainability. Reducing the carbon footprint and using renewable resources are critical in mitigating climate change [2,6–8]. Specifically, expanded clay and tuff, used as lightweight agents, not only decrease the weight of concrete but also improve its thermal and acoustic insulation, contributing to the energy efficiency of buildings [9,10]. Multiple studies have explored various approaches to enhance its properties by incorporating sustainable and natural additives. However, many of these studies focus on individual components or limited combinations, leaving a gap in understanding the synergies between sustainable agents and lightweight aggregates.

In previous works, materials were crushed to obtain particles of suitable size for use in concrete mixtures. Granulometric analyses, density tests, and chemical composition studies were conducted using energy-dispersive spectroscopy (EDS) and X-ray diffraction (XRD) [1,5]. Extracts were obtained from fresh plants through dehydration and cold extraction processes. Their rheological and chemical properties were analyzed, determining their viscosity and polysaccharide content [2,3]. Based on these material characteristics, several concrete mixtures were formulated by substituting specific percentages of coarse aggregate with volcanic tuff and expanded clay. The mixtures were prepared with varying proportions of nopal mucilage and aloe vera extract as additives [6,10].

Concrete samples were cured and tested at different ages (7, 14, and 28 days) using a hydraulic press to measure their compressive strength [9,11]. The density and specific weight of fresh and hardened concrete were determined to evaluate the lightweight effect of the materials used [12,13]. Slump and water retention tests were performed to assess the workability and behavior of the concrete during curing [4,5]. Some studies conducted life cycle assessments (LCA) to determine the environmental impact of concrete mixtures, considering the reduction of CO_2 emissions and the use of renewable materials [6,14–21]. According to the literature, adding nopal mucilage and aloe vera significantly increased the compressive strength of lightweight concrete. Samples incorporating these additives showed an increased strength of 15–20% compared to control mixtures without additives [2,4]. The partial replacement of conventional aggregates with volcanic tuff and expanded clay reduced the concrete density by 25–30%, considerably reducing structural weight without adversely affecting mechanical properties [9,10].

One study by [22] investigates the use of expanded clay in lightweight concrete, focusing on its effects on thermal and mechanical properties. The researchers also explore using aloe vera as a natural additive to enhance the material's hydration and workability. While the results promise to improve specific characteristics, this work does not consider the interaction between expanded clay, tuff, and organic materials such as nopal mucilage. To fill this gap, it is crucial to examine how combinations of these agents can influence both the physical and mechanical properties of lightweight concrete, which is one of the objectives of this study.

Another significant contribution comes from [23], which explores innovative methods to improve the strength and durability of lightweight concrete. The work primarily focuses on inorganic lightweight aggregates and their effects on the material's structural integrity. Despite its comprehensive analysis, it overlooks the potential of natural additives like nopal mucilage and aloe vera, which can improve mechanical performance and enhance concrete's environmental sustainability. This study aims to bridge this gap by incorporating these natural additives into various concrete mixtures, assessing their combined effects with expanded clay and tuff to achieve a more sustainable and efficient material.

Regarding microstructural analysis, Refs. [24,25] provide valuable insights into the relationship between specific surface area, fractal dimension, and compressive strength in lightweight concrete added with volcanic tuff. The authors discuss how changes in the internal structure of concrete can influence its overall performance. However, their investigation is limited to synthetic additives, leaving the role of plant-based materials unexplored. These studies extend the previous work by analyzing the fractal dimension of concrete mixtures containing these natural agents. It offers a deeper understanding of how their addition impacts the material's internal complexity and strength.

Some works investigate lightweight concrete's mechanical, thermal conductivity, and insulation properties with natural additives, emphasizing the benefits of materials like expanded clay [26–28]. However, the studies do not explore the combined effects of expanded clay and other sustainable agents. This research addresses this gap by evaluating mixtures' thermal performance and mechanical properties, providing a comprehensive understanding of how these additives contribute to heat retention, stability, and overall material efficiency.

Similarly, Ref. [29] explores using natural fiber additives in lightweight concrete, evaluating their influence on strength and flexibility. While this paper offers valuable findings on fiber-based reinforcement, it does not examine the broader category of natural additives such as nopal mucilage and aloe vera. This study extends the scope by investigating the impact of these agents on concrete's workability, compressive strength, and thermal properties, contributing to a more holistic approach to sustainable concrete formulation.

Mixtures with nopal mucilage and aloe vera exhibited better workability and water retention, facilitating curing and reducing surface cracks [1,3]. Improvements in the thermal and acoustic insulation properties of lightweight concrete were observed, especially in mixtures that included expanded clay. This suggests potential energy-efficient construction applications [9,13]. Sustainability assessments indicated a significant reduction in the carbon footprint of lightweight concrete mixtures due to using renewable materials and a decrease in the required cement [6,14].

Combining expanded clay, tuff, and organic stabilizers such as nopal mucilage and aloe vera presents an innovative solution for the construction industry. This approach addresses the need for lighter and more sustainable materials and offers improvements in concrete's physical and mechanical properties, such as higher compressive strength and better durability [11,13]. The present research aims to evaluate the performance of these combinations, providing a scientific basis for their practical application in the construction sector.

The present work makes significant contributions by investigating the synergistic effects of nopal mucilage and aloe vera alongside lightweight aggregates, like expanded clay and tuff, in concrete mixtures. It bridges the gaps identified in the existing literature by offering a comprehensive analysis of their combined impact on compressive strength, thermal properties, and internal structure while emphasizing sustainability. This approach improves lightweight concrete's mechanical and thermal properties and advances eco-friendly practices in the construction industry.

2. Materials and Methods

This study collected 2.8 kg of nopal and 2.3 kg of aloe vera. These materials were cleaned and cut into quadrangular elements measuring 1 to 2 cm on each side. Each material was macerated in water for 24 h at a 1:10 (kg/L) ratio of distilled water. After this period, the organic materials were ground and filtered, recovering the supernatant containing the extract. This viscous liquid product was left to stand for 24 h. The extracted mucilage and aloe vera were evaluated for extract concentration in the maceration solution through liquid-liquid extraction. 80 mL aliquots were taken, and 40 mL of ethyl acetate (Merck, reagent grade) were added. Three washes were performed in a separation funnel, recovering the organic material and adding anhydrous sodium sulfate (Merck, reagent grade) to eliminate moisture residues. Subsequently, the solvent was evaporated, and the amount of organic material in the mixture was determined by gravimetry. This procedure was performed in triplicate, and the concentration of nopal mucilage extract was 1035.42 $\pm$ 27.88 mg/L, while the aloe vera extract concentration was 526.25 $\pm$ 11.92 mg/L.

The selection of material proportions for the experimental lightweight concrete mixtures was based on the characterization of fine and substitute aggregates (river sand, expanded clay, and tuff), following standard procedures to evaluate moisture content [30], water absorption capacity [31], density, and bulk density [32]. These properties significantly influenced the mix design, which was determined using the ACI method to achieve optimal workability, structural integrity, and performance in each mixture. Table 1 provides critical insights into the physical properties of the materials. The expanded clay exhibited high water absorption (16.43%) and low bulk density (360 kg/m^3), confirming its lightweight nature and suitability as a substitute aggregate for reducing overall mixture density. However, its high absorption requires careful water content adjustment to avoid excessive workability or drying issues, as observed in past studies [29]. Volcanic tuff, with an absorption of 46.61% and bulk density of 480 kg/m^3, displayed an even greater capacity to retain moisture. This behavior necessitated higher water content or the inclusion of stabilizing agents such as nopal mucilage or aloe vera to balance workability while maintaining strength. Regional sand, characterized by its relatively high bulk density (1400 kg/m^3) and moderate absorption (6.3%), served as the primary fine aggregate. Its consistent properties ensured a stable base for all mixtures, contributing to their mechanical stability and compatibility with lightweight substitutes. The ACI method developed six distinct mixtures, each tailored to evaluate the effects of tuff, expanded clay, and stabilizing agents such as nopal mucilage and aloe vera. The mix proportions, shown in Table 2, illustrate a systematic approach to incorporating these materials while considering their unique physical properties:

- LCAT (Cement-Sand-Water-Tuff): This baseline mixture was designed to evaluate the performance of tuff as a lightweight aggregate without additional stabilizers. Tuff's high absorption, including water at 4.86 L, ensured adequate hydration and workability.
- LCNT (Cement-Sand-Nopal Mucilage-Tuff): Nopal mucilage replaced water in this mixture to investigate its role as a natural stabilizer. The mucilage's high viscosity reduced workability, necessitating precise adjustments to aggregate proportions. The combination aimed to improve compressive strength and reduce permeability, aligning with findings by [3].
- LCST (Cement-Sand-Aloe Vera-Tuff): Aloe vera replaced water in this mixture to explore its effects on hydration and thermal properties. As observed in previous

studies [1], the high fluidity of aloe vera-modified mixtures required careful balancing of sand and tuff proportions to maintain consistency.

- LCAAE (Cement-Sand-Water-Expanded Clay): Expanded clay was introduced as the primary lightweight aggregate in this mixture. Its low bulk density (360 kg/m^3) allowed for a significant reduction in mixture weight, while its high absorption necessitated precise water content (4.86 L) to ensure proper hydration and workability.
- LCNAE (Cement Sand, Nopal Mucilage, Expanded Clay): This mixture combined nopal mucilage and expanded clay to assess their synergistic effects on thermal insulation and strength. The reduced sand content (17.92 kg) and the expanded clay's lower density contributed to a lightweight and cohesive mixture.
- LCSAE (Cement-Sand-Aloe Vera-Expanded Clay): Aloe vera and expanded clay were paired to evaluate their combined impact on thermal conductivity and structural efficiency. The mixture's proportions emphasized maintaining low density while enhancing heat transfer properties.

Table 1. Results of the moisture, absorption, bulk density, and density Tests.

Material	Moisture (%)	Absorption (%)	Bulk Density (kg/m^3)	Density (kg/m^3)
Expanded Clay	1.82	16.43	360	616
Volcanic Tuff	29.95	46.61	480	768
Regional Sand	4.0	6.30	1400	2300

Table 2. Mix design (tuff and expanded clay) using the ACI Method.

Mix	Cement (kg)	Water (L)	Mucilage (L)	Aloe (L)	Tuff (kg)	Expanded Clay (kg)	Sand (kg)	MAS *
LCAT	6.92	4.86	0	0	6.98	0	18.66	¾″
LCNT	6.92	0	4.86	0	6.98	0	18.66	¾″
LCST	6.92	0	0	4.86	6.98	0	18.66	¾″
LCAAE	6.92	4.86	0	0	0	3.55	17.92	½″
LCNAE	6.92	0	4.86	0	0	3.55	17.92	½″
LCSAE	6.92	0	0	4.86	0	3.55	17.92	½″

* MAS—Maximum Aggregate Size.

The proportions of cement, aggregates, and stabilizing agents were carefully calibrated to balance workability, density, and strength. The high absorption rates of tuff and expanded clay required water and stabilizer content adjustments to prevent excessive dryness or fluidity. Including nopal mucilage and aloe vera, based on their demonstrated ability to modify cementitious materials' viscosity and thermal properties, as highlighted in previous research [5,33]. The maximum aggregate size (¾″ for tuff mixtures and ½″ for expanded clay mixtures) reflects the need to optimize particle packing while maintaining lightweight characteristics. For each mix mentioned in Table 2, three cylindrical specimens of 15 cm diameter and 30 cm height were produced. The specimens were cured by total immersion for nine days and tested after 28 days.

Once the mixes were prepared and the lightweight concrete specimens obtained, they were subjected to various characterization tests. The fresh concrete consistency test was used to determine its consistency and viability, verifying that the correct amount of water had been added to the mix. This test was conducted according to [34].

In the water absorption test by immersion, the volume of a sample in both wet and dry states was determined by calculating the amount of water absorbed by the difference in weights. The specimens were submerged in water for seven days, weighed, left to stand for 24 h at room temperature, and dried in an oven at 75 °C for 24 h to accelerate the drying process. The compression test evaluated the material's behavior under a compressive load, measuring deformation, stress, and strain variables. The results were used to verify that the concrete mix met the specified strength requirements for the determined structure. This test was performed according to [33] using a CONTROLS Automax Model C13C04 machine (CONTROLS Group, Milan, Italy).

Using Image J software (Version 1.54m), a HiView 1600x digital microscope (NOYAFA, Kwun Tong, Hong Kong) was used to analyze the concrete morphology and obtain images, which were later used to determine its fractal dimension. For measuring thermal properties, the KD2 Pro equipment (Decagon Devices Inc., Washinton, USA) with a dual-needle sensor was employed, measuring thermal conductivity (K, [W/(mK)]), thermal resistivity (ρ, [°C(cm/W)]), volumetric heat capacity (C, [MJ/(m^3*K)]), and thermal diffusivity (D, [mm^2/s]).

3. Results and Discussion

Table 3 shows the absorption, bulk density, and slump test results.

Table 3. Absorption, bulk density, and slump test results indicate the standard deviation values.

Mix	Volumetric Weight (kg/m^3)	Water Absorption (%)	Slump (cm)
LCAT	1612.14 ± 95.76	4.501 ± 1.06	2
LCNT	1612.14 ± 95.76	4.509 ± 0.44	0
LCST	1632.26 ± 7.85	11.472 ± 2.89	Spreads
LCAAE	1803.28 ± 22.64	6.252 ± 0.17	Spreads
LCNAE	1706.46 ± 24.55	4.897 ± 0.45	0
LCSAE	1657.41 ± 14.28	4.200 ± 0.12	2

The results presented in Table 3 and Figure 1 provide valuable insights into the performance of the six lightweight concrete mixtures tested. They reveal significant variations in bulk density, water absorption, slump, and compressive strength, essential indicators of the mixture's workability, durability, and potential structural applications. According to the results, the LCAT mixture has a bulk density of 1612.14 kg/m^3, a water absorption of 4.501%, and a slump of 2 cm. These values indicate that this mixture has moderate water absorption and adequate consistency with an acceptable slump. The relatively low water absorption suggests that this mixture effectively retains moisture, which is critical for maintaining hydration during curing and service. The slump of 2 cm indicates that the mixture possesses adequate workability for typical construction processes, which is expected for lightweight concrete with tuff as the primary lightweight aggregate. In contrast, the LCNT mixture shares the same bulk density as LCAT (1612.14 kg/m^3) but has slightly higher water absorption (4.509%) and a slump of 0 cm, suggesting a drier and less workable mix. Incorporating nopal mucilage, which replaces part of the water, results in a mixture that is less fluid and more difficult to handle, potentially limiting its application in scenarios requiring ease of placement and shaping. This behavior was also observed in the LCNAE mixture with a bulk density of 1706.46 kg/m^3 and water absorption of 4.897%. This suggests that using nopal mucilage with expanded clay yields a slightly denser mixture, though its workability remains low, as indicated by the zero slump.

The LCST mixture has a higher bulk density than the previous ones (1632.26 kg/m^3) and significantly high water absorption (11.472%). The slump is described as "spreads", indicating that the mixture is excessively fluid, possibly unworkable for specific applications. The high water absorption suggests that aloe vera, while providing some benefits in terms of sustainability and workability, also leads to an excessively wet mixture that might pose challenges for handling and structural stability. The LCAAE mixture has the highest bulk density of all the mixtures (1803.28 kg/m^3) and a water absorption of 6.252%. The "spreads" slump further emphasizes that this mixture is highly fluid, likely due to the combination of expanded clay and water. While the high bulk density suggests that this mixture could be helpful in applications requiring enhanced weight-bearing capacity, the low workability and excess water absorption may limit its applicability in projects where consistency and ease of use are prioritized [24–29].

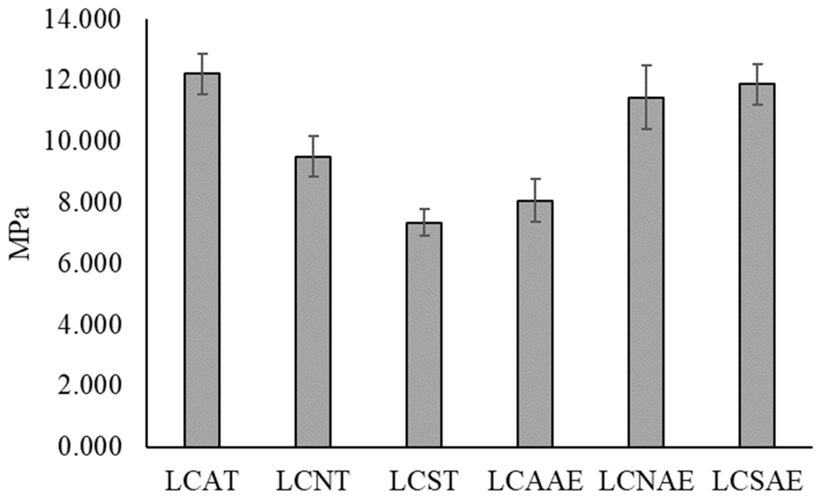


Figure 1. Results from compression strength test.

Lastly, the LCSAE mixture, combining aloe vera with expanded clay, has a bulk density of 1657.41 kg/m^3 and the lowest water absorption (4.2%). The 2 cm slump indicates good workability and consistency, making it suitable for construction applications where ease of handling is essential. This mixture balances reduced water absorption and adequate fluidity, making it a promising candidate for practical use in lightweight concrete applications.

As shown in Figure 1, the LCAT mixture, which uses tuff as the lightweight aggregate and water as the stabilizing agent, achieves the highest compressive strength of 12.207 MPa. This indicates that tuff, in combination with water, provides the best structural integrity, making it suitable for high-strength applications. On the other hand, the LCNT mixture, which replaces water with nopal mucilage, shows a significantly lower compressive strength of 9.503 MPa. While this value remains within the acceptable range for some applications, adding nopal mucilage reduces the compressive strength, likely due to the mix's drier, less workable nature. The lower strength of LCNT may limit its application in load-bearing structures, though it could still be suitable for non-structural elements.

The LCST mixture, which substitutes water with aloe vera, exhibits the lowest compressive strength of all the mixtures at 7.343 MPa. The high water absorption and excessive fluid consistency likely contribute to its poor structural performance. Although aloe vera can have benefits in terms of sustainability and workability, its use in concrete appears to compromise the mixture's strength, making it unsuitable for structural applications where high compressive strength is required. In contrast, the LCAAE mixture uses expanded clay and water, achieving a compressive strength of 8.063 MPa. While this value is lower than LCAT's, it still indicates moderate strength, suggesting that expanded clay, although not as strong as tuff, can provide adequate structural performance when combined with water. This mixture's relatively high slump and fluidity may limit its use in specific structural applications. Still, they could be helpful in applications where ease of handling is more important than strength.

The LCNAE mixture, which combines nopal mucilage with expanded clay, shows a compressive strength of 11.447 MPa, close to LCAT. This suggests that nopal mucilage can positively affect lightweight concrete's strength when combined with expanded clay. The higher strength of LCNAE compared to LCNT further supports the idea that nopal mucilage enhances compressive strength when paired with a more suitable aggregate, such as expanded clay.

Finally, the LCSAE mixture, incorporating aloe vera with expanded clay, presents a compressive strength of 11.870 MPa, nearly equivalent to LCNAE. Despite the presence of aloe vera, which in LCST significantly lowered strength, the combination with expanded clay results in a solid mixture with a compressive strength close to that of the best-performing mixtures. This suggests that the synergy between expanded clay and aloe vera can counterbalance the negative effects of aloe vera on strength, resulting in a more robust and workable concrete mixture.

Table 4 presents the results of the thermal evaluation of the tested lightweight concrete mixtures, highlighting the influence of various additives on their heat transfer, storage, and retention capabilities. These properties are critical in determining the suitability of concrete for specific applications, particularly in environments where thermal efficiency is a priority. The LCAT mixture, composed of cement, sand, water, and tuff, demonstrates moderate thermal conductivity (0.563 W/(m·K)) and heat diffusivity (0.178 mm^2/s), indicating stable thermal performance. These characteristics make LCAT an appropriate candidate for applications where a balance between heat retention and transfer is essential. Its moderate heat storage capacity (2.183 MJ/(m^3·K)) further supports its use in structures requiring thermal stability, such as insulation layers or passive heating systems [13,17].

Table 4. Thermal properties of evaluated materials.

Mix	°C	ρ [°C(cm/W)]	K [W/(m·K)]	C [MJ/(m^3·K)	D [mm^2/s]	Error
LCAT	25.7100	177.7000	0.5630	2.1833	0.1780	±0.0042
LCNT	25.5233	165.2000	0.6110	2.0083	0.3047	±0.0041
LCST	28.9133	109.6733	0.9543	2.8333	0.3410	±0.0066
LCAAE	27.4733	121.1067	0.8430	1.9827	0.4307	±0.0070
LCNAE	27.2733	206.2333	0.4853	2.0717	0.2397	±0.0052
LCSAE	27.1767	213.5000	0.4743	2.0153	0.2347	±0.0047

The LCNT mixture, which replaces water with nopal mucilage, exhibits slightly higher thermal conductivity (0.611 W/(m·K)) and diffusivity (0.305 mm^2/s) than LCAT. These results suggest that nopal mucilage enhances the mixture's ability to transfer heat, potentially making it more suitable for applications requiring rapid heat dissipation. However, its lower heat storage capacity (2.008 MJ/(m^3·K)) might limit its effectiveness in applications demanding prolonged thermal stability. In contrast, the LCST mixture, incorporating aloe vera instead of water, shows significantly higher thermal conductivity (0.954 W/(m·K)) and diffusivity (0.341 mm^2/s) than LCAT and LCNT, alongside the highest heat capacity among all mixtures (2.833 MJ/(m^3·K)). These properties indicate that LCST excels in heat transfer and storage, though its low thermal resistivity (109.67 °C·cm/W) suggests limited resistance to temperature variations. This mixture may be more suitable for applications involving rapid heat distribution, such as underfloor heating or thermal panels, where its ability to transfer and store heat is advantageous.

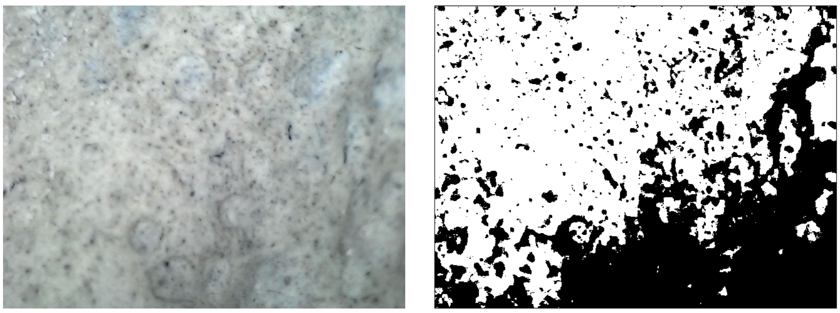
The LCAAE mixture, using expanded clay as the lightweight aggregate, exhibits high thermal diffusivity (0.431 mm^2/s) and conductivity (0.843 W/(m·K)) but has the lowest heat capacity (1.983 MJ/(m^3·K)) among the mixtures. These results indicate that LCAAE facilitates rapid heat transfer but retains less heat, making it suitable for scenarios requiring quick thermal response rather than prolonged heat retention. The relatively high thermal diffusivity positions it as a candidate for applications that require fast cooling or heating cycles. The LCNAE mixture, which combines nopal mucilage and expanded clay, demonstrates unique thermal properties with higher resistivity (206.23 °C·cm/W), lower conductivity (0.485 W/(m·K)), and moderate diffusivity (0.240 mm^2/s). These values suggest that LCNAE is more efficient in heat retention, as it transfers heat more slowly while maintaining a high heat capacity (2.072 MJ/(m^3·K)). These characteristics make this mixture particularly effective for applications requiring thermal insulation or energy-efficient designs, where reducing heat loss is a priority.

Similarly, the LCSAE mixture, incorporating aloe vera and expanded clay, shows the highest resistivity among the mixtures (213.50 °C·cm/W) and the lowest thermal conductivity (0.474 W/(m·K)). Its heat capacity (2.015 MJ/(m^3·K)) and diffusivity (0.235 mm^2/s) align closely with those of LCNAE, highlighting its suitability for thermal insulation applications. Combining aloe vera and expanded clay creates a mixture that effectively retains heat while minimizing thermal conductivity, making it an excellent choice for energy-efficient buildings or thermal barriers [7,10,28,29].

The results indicate that different additives significantly influence the thermal performance of lightweight concrete mixtures, offering diverse solutions for various construction needs. Mixtures with tuff (LCAT) exhibit balanced thermal properties and are suitable for general-purpose applications requiring stable heat transfer and storage. Nopal mucilage-enhanced mixtures (LCNT and LCNAE) improve heat retention, making them ideal for insulation applications. Mixtures with aloe vera (LCST and LCSAE) excel in heat transfer and storage, but their reduced resistivity may limit their use in applications where thermal resistance is crucial.

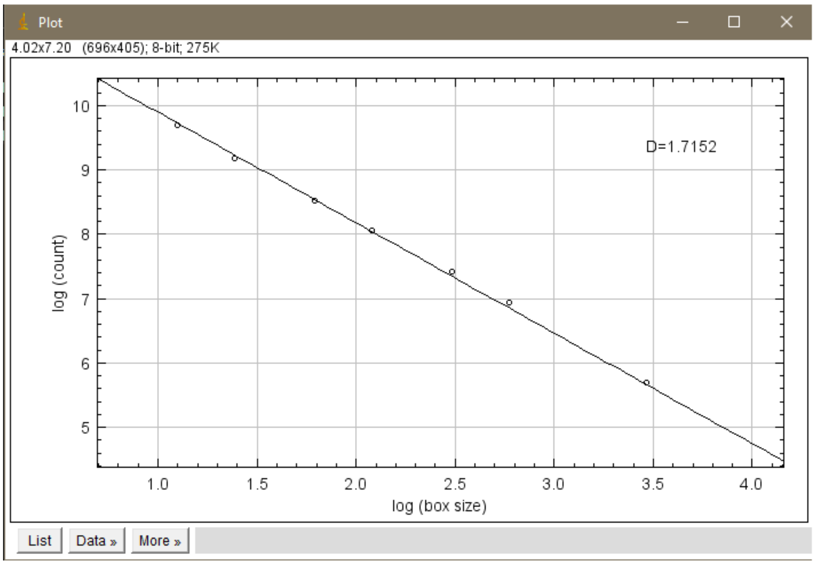
Micrographs obtained from the samples were used for a fractal dimension analysis to determine the probable homogeneity of the mixture components. Figure 2 shows an example of the analysis performed for all specimens, and Table 5 shows the fractal dimension values. The fractal dimension of the surface refers to the measure of the roughness or complexity of a material's surface and does not necessarily characterize its internal structure. However, the surface fractal dimension can be related to specific internal structure properties, especially in porous or heterogeneous materials, where surface complexity may reflect internal network characteristics.

The LCAT mixture (Cement-Sand-Water-Tuff) has a fractal dimension of 1.71787 ± 0.0024, indicating a relatively complex internal structure, which may contribute to its high compressive strength and good thermal stability. The LCNT mixture (Cement-Sand-Nopal Mucilage-Tuff) shows a higher fractal dimension compared to LCAT, suggesting a more complex and heterogeneous internal structure, possibly due to the incorporation of nopal mucilage, which can affect the material's internal distribution.



(**a**) (**b**)

Figure 2. *Cont.*



(c)

Figure 2. Example of the micrographic analysis process of the LCAT mixture for obtaining the fractal dimension value using ImageJ software: (**a**) original micrograph, (**b**) binary image, and (**c**) fractal dimension analysis.

Table 5. Fractal Dimension values (D) and standard deviation.

Mix	D
LCAT	1.71787 ± 0.0024
LCNT	1.7628 ± 0.0124
LCST	1.6907 ± 0.0039
LCAAE	1.7094 ± 0.0079
LCNAE	1.7515 ± 0.0049
LCSAE	1.7206 ± 0.0129

The LCST mixture (Cement-Sand-Aloe Vera-Tuff) shows a fractal dimension of 1.6907 ± 0.0039, the lowest among the tuff mixtures. This suggests a less complex internal structure, which could be related to its lower compressive strength. The LCAAE mixture (Cement, Sand, Water, Expanded Clay) has a fractal dimension of 1.7094 ± 0.0079. This slightly lower fractal dimension than LCAT indicates a moderately complex internal structure consistent with its intermediate compressive strength and thermal properties.

The LCNAE mixture (Cement-Sand-Nopal Mucilage-Expanded Clay) presents a fractal dimension of 1.7515 ± 0.0049. This high fractal dimension suggests a highly complex and heterogeneous internal structure, which may contribute to its high compressive strength and good heat retention. The LCSAE mixture (Cement-Sand-Aloe Vera-Expanded Clay) shows a fractal dimension of 1.7206 ± 0.0129. This fractal dimension, similar to LCAT's, indicates a complex and robust internal structure, reflected in its high compressive strength and good thermal properties.

The experimental results obtained in this study highlight the diverse impacts of tuff, expanded clay, nopal mucilage, and aloe vera on the physical, mechanical, and thermal properties of lightweight concrete mixtures. Comparing these results to findings from previous studies achieves a more nuanced understanding of these materials and their interactions. The water absorption, bulk density, and slump tests reveal significant workability and moisture behavior variations among the mixtures. For instance, the LCST mixture, which incorporates aloe vera, shows extremely high water absorption and a fluid consistency ("spreads"), aligning with findings by [1], who report that aloe vera's hydrophilic properties increase water retention and improve fluidity in concrete mixtures. This property enhances workability but compromises structural integrity due to excessive water content.

In contrast, the LCNT mixture, which substitutes water with nopal mucilage, demonstrates lower water absorption and a dry consistency. This corroborates the findings by [3], who identify cactus mucilage as an agent that reduces water permeability and increases viscosity in cementitious materials. These properties make LCNT less workable but potentially more durable in low-permeability environments. The LCAAE and LCNAE mixtures, which use expanded clay, show higher bulk densities due to their inherent properties, as confirmed by [21,22]. Expanded clay increases density while contributing to the lightweight nature of the material. However, the din workability between the two mixtures suggests that nopal mucilage enhances cohesion, whereas water alone produces greater fluidity.

The compressive strength results indicate that mixtures with tuff, such as LCAT, achieve the highest strength, consistent with findings by [25], who report that volcanic tuff enhances the mechanical properties of concrete due to its pozzolanic activity and fine particle size. The substitution of water for aloe vera in LCST reduces compressive strength significantly, aligning with observations by [5], who note that aloe vera can disrupt cement hydration and reduce structural rigidity. Interestingly, the combination of lay with nopal mucilage or aloe vera, as in LCNAE and LCSAE, improves compressive strength relative to mixtures with tuff. This suggests a synergistic interaction between expanded clay and these organic stabilizers, supporting the findings of [1,3,21] on the complementary roles of lightweight aggregates and natural additives in enhancing the mechanical performance of concrete.

The thermal characterization reveals that mixtures with expanded clay, such as LCAAE, exhibit high thermal diffusivity and conductivity, as [10] reported in their study of lightweight aggregates. However, their lower heat capacity limits their ability to heat, making them suitable for applications requiring rapid heat transfer rather than thermal insulation. Mixtures with aloe vera, such as LCST and LCSAE, demonstrate higher heat transfer and storage efficiencies. These findings align with [26,27], who highlight aloe vera's ability to enhance thermal conductivity while increasing the mixture's heat capacity. The low thermal resistivity observed in these mixtures suggests aloe vera is less effective in insulation applications. The LCNAE mixture, which combines nopal mucilage and expanded clay, exhibits high thermal resistivity and heat retention. This corroborates the report by [3], who found that nopal mucilage improves insulation properties by forming a dense, cohesive matrix that limits heat transfer. This mixture is particularly suitable for applications where energy efficiency and stability are a priority.

4. Conclusions

This study evaluated six concrete mixtures with different dosages of tuff, expanded clay, nopal mucilage, and aloe vera as lightweight and reinforcing agents. Physical and mechanical tests were conducted to determine if these elements can be used in the construction industry when lightweight concrete is required.

The results show that mixtures including aloe vera (LCST and LCSAE) exhibit extreme water absorption and consistency behaviors, with LCST being very fluid and LCSAE showing good workability. Mixtures with nopal mucilage (LCNT and LCNAE) tend to be drier and less workable. In contrast, mixtures with expanded clay (LCAAE and LCNAE) have higher bulk density and variations in consistency and water absorption. Mixtures with water, such as LCAT and LCAAE, tend to have variable strength depending on the lightweight agent, either tuff or expanded clay. Mixtures that include nopal mucilage, such as LCNT and LCNAE, show improved strength when expanded clay is used instead of tuff. On the other hand, mixtures with aloe vera, LCST, and LCSAE exhibit a notable difference in strength, being considerably lower with tuff and higher with expanded clay. This suggests combining expanded clay with nopal mucilage or aloe vera can offer excellent compressive strength in lightweight concrete mixtures.

According to the literature, the lightweight concrete mixtures studied in this work present mechanical strength properties ranging from low to moderate in the following order:

- LCST (Cement, Sand, Aloe Vera, Tuff): 7.343 MPa (Low strength)
- LCAAE (Cement, Sand, Water, Expanded Clay): 8.063 MPa (Low strength)
- LCNT (Cement, Sand, Nopal Mucilage, Tuff): 9.503 MPa (Low strength)
- LCNAE (Cement, Sand, Nopal Mucilage, Expanded Clay): 11.447 MPa (Moderate strength)
- LCSAE (Cement, Sand, Aloe Vera, Expanded Clay): 11.870 MPa (Moderate strength)
- LCAT (Cement, Sand, Water, Tuff): 12.207 MPa (Moderate strength)

The observed results of the study can be attributed to the unique physical and chemical properties of the materials used, as well as the influence of mix proportions and experimental conditions. The high absorption rates of tuff and expanded clay are consistent with their porous structures, contributing to reduced bulk density and lightweight characteristics. However, these high absorption levels necessitate precise water or stabilizer content adjustments to ensure adequate hydration and workability. Nopal mucilage improved cohesion and reduced permeability but led to drier mixtures with lower slump values due to viscosity. On the other hand, Aloe vera increased fluidity and thermal conductivity while reducing compressive strength when combined with tuff, suggesting an incompatibility in achieving structural stability with this combination.

Compressive strength varied across the mixtures, with water-tuff (LCAT) achieving the highest strength due to its balanced hydration and compactness. Mixtures with expanded clay showed moderate strength, with nopal mucilage (LCNAE) or aloe vera (LCSAE) positively influencing the internal matrix. These results align with the thermal properties, where expanded clay combinations demonstrated enhanced heat retention and resistivity, indicating suitability for insulation. Conversely, aloe vera-modified mixtures' high heat transfer efficiency suggests potential applications in energy-efficient designs requiring rapid thermal exchange.

The results also reflect the influence of curing conditions and sample size. The nine-day immersion curing and 28-day testing ensured consistent hydration, but small-scale specimens may limit the generalization of findings to large-scale construction applications. Using cylindrical samples provided reliable compressive strength results but may not capture the full scope of thermal and mechanical interactions in real-world structures. The findings are subject to the limitations of laboratory conditions, small sample sizes, and specific curing methods, which may differ from field conditions. Further research is recommended for practical applications to validate these results under real-world conditions, including long-term durability studies and performance evaluations in full-scale structural elements. Based on the results, mixtures with expanded clay and nopal mucilage (LCNAE) or aloe vera (LCSAE) show significant promise for sustainable and efficient construction projects, particularly in scenarios prioritizing thermal performance and reduced environmental impact.

This research provides a more holistic understanding of the interactions between lightweight aggregates and sustainable additives compared to prior studies. While earlier works focus on the individual effects of aloe vera and nopal mucilage, this study evaluates their combined impacts, highlighting synergistic benefits in mechanical and thermal performance. Furthermore, including fractal analysis and its correlation with compressive strength adds a novel dimension to understanding the internal structure of lightweight concrete, advancing the methodologies for further studies. The observed results underscore the potential of incorporating sustainable materials such as nopal mucilage and aloe vera into lightweight concrete mixtures. When used with aggregates like tuff and expanded clay, these additives offer tailored solutions for diverse applications, from high-strength structural components to energy-efficient thermal barriers. The findings complement and extend prior research by providing a comprehensive analysis of these materials' combined effects, emphasizing their role in developing eco-friendly and performance-optimized construction materials. Future studies should further explore the long-term durability and environmental impact of these mixtures to solidify their position as viable alternatives in sustainable construction.

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