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Artículos de Investigación

Mechanical, Thermal, and Acoustic Properties of Mortars and Concretes Modified with *Furcraea Cabuya* Trel Juice (Fique Juice)*

Propiedades mecánicas, térmicas y acústicas de morteros y concretos modificados con jugo de *Furcraea cabuya* trel (jugo de fique)

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Abstract:

Currently, the use of synthetic additives for mortar and concrete is widespread; in contrast, the alternative use of plasticizers and pore generators from plants or natural waste is not common. In this work, the effect of the addition of fique juice on mortars and concretes was evaluated. The compression strength, thermal conductivity, and acoustic impedance of the mortars were calculated. Furthermore, the compressive strength of concrete (added with fique juice) was evaluated under fire conditions. Mortars were manufactured with several fique juice dosages ranging from 3% to 9% by weight of cement, and concretes were cast with 5%, 7%, and 10% fique juice at a water-cement ratio of 0.40. The results showed a reduction in the thermal conductivity of the modified mortars and an increase in their acoustic absorption for frequencies lower than 1000 Hz with respect to the control (unmodified mortar). On the other hand, concrete modified with fique juice was subjected to temperatures of 200, 600 and 1000 °C, obtaining greater thermal insulation. The loss of compressive strength due to fire revealed an inversely proportional relationship with the percentage of natural additive used. This means that for the same fire temperature, the concrete without juice lost 11% of its resistance, while the concrete modified with 10% juice only decreased its compression strength by 5%.
Keywords: Concrete, *Fique* Juice, Thermal Properties, Acoustic Properties.

Resumen:

Hoy en día el uso de aditivos sintéticos para morteros y concretos es generalizado; por el contrario, el uso alternativo de plastificantes y generadores de poros de plantas o residuos naturales no es común. En el presente trabajo se evaluó el efecto de la adición de jugo de fique sobre morteros y concretos. Se calculó la resistencia a la compresión de los morteros, también su conductividad térmica y la impedancia acústica. Además, la resistencia a la compresión del concreto (agregado con jugo de fique) se evaluó en condiciones de incendio. Los morteros se fabricaron con varias dosis de jugo de fique que iban del 3 % al 9 % en peso de cemento, y los concretos se fabricaron con un 5 %, 7 % y 10 % de jugo de fique a una relación agua-cemento de 0.40. Los resultados mostraron una reducción de la conductividad térmica de los morteros modificados y un aumento en su absorción acústica para frecuencias inferiores a 1000 Hz con respecto al control (mortero sin modificar). Por otro lado, el concreto modificado con jugo de fique fue sometido a temperaturas de 200, 600 y 1000 °C, obteniendo un mayor aislamiento térmico. La pérdida de resistencia a la compresión, debida al fuego, mostró una relación inversamente proporcional con el porcentaje de aditivo natural utilizado. Esto significa que para la misma temperatura de incendio, el concreto sin jugo perdió 11 % de su resistencia, mientras que el concreto modificado con 10 % de jugo solo disminuyó su resistencia a la compresión en un 5 %.
Palabras clave: concreto, jugo de fique, propiedades térmicas, propiedades acústicas.

Author notes

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Introduction

Due to its employment generation capability and its share of gross domestic product (GDP), the construction industry is one of the main players in the global economy [1]. Additionally, to reduce energy consumption, the application of sustainability criteria is essential in this and in any other industry. For these reasons, the use of raw materials from agricultural products or natural waste has increased in recent years in concrete production, with the usual practice [2, 3, 4] being the use of chemical additives to modify some physical and mechanical properties of mortars and concretes. In this context, the use of plant extracts (in this case, fique juice) as an additive for cementitious materials could be a sustainable alternative. Fique juice is an organic byproduct of the Cabuya fiber production process from the *Furcraea Cabuya* Trel plant [5]. Fique is mainly cultivated in some regions of Colombia (Departmentos), such as Cauca, Nariño, Santander, and Antioquia, where 30,000 tons of fibers are produced every year [5]. Fique juice contains water, cellulose, minerals, saccharose, proteins, nitrogen, phosphorus, calcium, potassium, saponins and sapogenins [7]. The fiber is mainly used in the production of handicrafts (hats, sacks and packages for agriculture, ropes, and strings); nevertheless, it represents only 4% of the full weight, and the remaining 96% corresponds to industrial waste (70% fique juice and 26% bagasse) without adequate treatment. This subproduct becomes waste deposited in rural areas (affecting soil and water sources), becoming a highly polluting and toxic material [6].

Currently, the additives used in concrete and mortar mixes are synthetic. Natural extracts of plant origin have been studied as additives in cementitious materials, including fique juice, due to their saponin content. Comparatively, these studies are few since most tend to use fique juice for the production of drugs and surfactants [8].

Lightweight concrete is commonly used as thermal and acoustic insulation due to its internal porous matrix, for example, aerated concrete or foamed concrete [9]. Aerated or foamed concrete requires very expensive machines and equipment that in turn require considerable energy. Recent studies have shown an improvement in thermal and low-density behavior when lightweight aggregates with air are used [10]. The aim of this work was to obtain a porous matrix in mortars and concretes (based on Portland cement), avoiding considerable losses of mechanical strength and fire resistance, that should be used as a thermal and acoustic insulating material. On the other hand, the acoustic and thermal conductivities of the cement mortars (modified with fique juice) were determined. The obtained results indicated that in the fresh state, the fique juice improved the fluidity and workability of the cement mortars. In the hardened state, the density and compressive strength decreased for both modified mortars and concretes. Additionally, the test of thermal conductivity in mortars and the test of fire conditions in concretes demonstrated insulating behavior, apparently because of the porosity increase. Finally, the acoustic impedance of the mortars increased with the addition of fique juice.

This work is organized as follows: materials and methods, results and conclusion.

Materials and methods

To achieve the abovementioned results, the protocol conducted is shown in Figure 1.

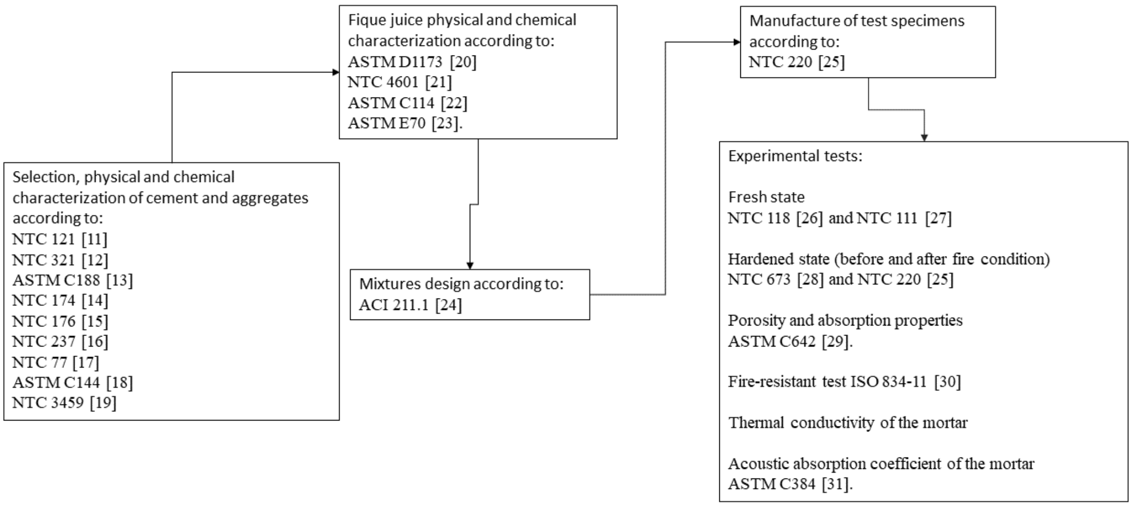

FIGURE 1.
Flow chart-Proposed protocol for selecting materials, casting and testing mortars and concretes modified with *Furcraea cabuya* trel
Source: Authors' own creation.

Every step of the flow chart that allowed us to characterize the mortars and concretes modified with *Furcraea cabuya* trel juice (fique juice) is explained in the following sections. At the end of this work, the conclusions are presented.

Selection, physical and chemical characterization of cement and aggregates

Type I Portland cement, sand and river gravel were used for casting the concrete. Type I Portland cement was made according to the physical and mechanical specifications of the Colombian technical standard (Norma Técnica Colombiana) NTC 121 [11] and chemical specifications of NTC 321 [12]. The specific weight of the cement was 3080.57 kg/m^3, which was determined following the specification in the standard ASTM C188 [13]. Gradation and quality requirements by the standard NTC 174 [14] were satisfied by the aggregates, and density and absorption of the coarse and fine aggregates were determined by NTC 176 [15] and NTC 237 [16], respectively. Following the procedure in the standard NTC 77 [17], granulometric and sieve analyses were performed to obtain the sand fineness modulus. The fine aggregate satisfied the standard ASTM C144 [18] for mortars. The potable water used for mixing was provided by Acueducto Metropolitano de Bucaramanga (AMB), which satisfies all the physicochemical properties (amount of sulfate and chloride) and the biological standard NTC 3459 [19]. Table 1 shows the results of the constituent material characterization.

TABLE 1.
Aggregate properties

Parameter	Sand	Gravel
Specific Gravity (kg/m^3)	2662,49	2671,18
Absorption (%)	2,23	1,40
Voids (%)	39,80	39,49
Fineness modulus	3,00	-------
Nominal max size (mm)	-------	19

Source: Author's own creation.

Physical and chemical characterization of fique juice

The fique juice composition was determined by performing four physicochemical tests: foam formation, conventional dry extract, losses by calcination, and pH. The foam formation test was conducted following the requirements in the standard ASTM D1173 [20], measuring intervals of 0, 30, 180, and 300 seconds. The conventional dry extract was performed by following the standard NTC 4601 [21] applying Equation 1.

$$Es(\%) = \frac{R}{M} * 100\% \tag{1}$$

where *Es* is the dry extract percentage, *R* is the mass residue in grams and *M* is the additive mass in grams.

The fique juice pH test was determined by following the standard ASTM E70 [23]. Losses by calcination were tested by using the loss of mass calculation (Equation 2) that a liquid suffers when it is exposed to 1050±25 °C of temperature (ASTM C114 [22]).

$$Pc(\%) = \frac{M3 - M1}{M2 - M1} * 100\% \tag{2}$$

where *Pc* is the loss by calcination expressed as a percentage, *M1* is the capsule mass in grams, *M2* is the capsule mass with the dry residue at 105 °C and *M3* is the capsule mass with the leftover from the additive at 1050 °C.

Mixture design

The concrete mixture design was performed by following the standard ACI 211.1 [24] using a water-cement ratio of 0.4 and 462 kg/m^3 of cement. The maximum aggregate size used was 19 mm. The concrete design strength was 21 MPa at 28 days. Without changing the water-cement ratio, the concrete was modified by adding 5, 7 and 10% mass fique juice. The mortar mix was designed using a water-cement ratio of 0.5 with a design strength of 19 MPa at 28 days. In this case, the fique juice was provided in proportions equal to 3%, 6%, and 9% mass juice. Tables 2 and 3 show the mix design parameters of concrete and mortar.

TABLE 2.
Dosage of concrete

Parameter	Results values			
Fique juice (%)	0	5	7	10
Water (kg/m^3)	186	163	153,70	139,80
Cement (kg/m^3)	462			
Sand (kg/m^3)	804,20			
Gravel (kg/m^3)	916,50			
a/c Ratio	0,40			
f'c (MPa)	21			

Source: Authors' own creation.

TABLE 3.
Dosage of mortar

Parameter	Results values			
Fique juice (%)	0	3	6	9
Water (kg/m^3)	277,50	260,90	244,20	227,60
Cement (kg/m^3)	555			
Sand (kg/m^3)	1393,38			
a/c Ratio	0,50			
f'c (MPa)	19			

Source: Authors' own creation.

Casting of test specimens

To perform the exposure to fire test, cubic test specimens were used (Figure 2). For this test, 12 samples were manufactured. The compressive strength of the mortars was determined in 60 samples according to the standard NTC 220 [25] using cubes of 50 mm length. For the thermal conductivity test, cylindrical specimens 160 mm in diameter and 15 mm in thickness were implemented. Porosity measurements were performed in 12 cylindrical specimens with 100 mm diameter and 50 mm thickness. For the acoustic impedance test, 12 cylindrical specimens were implemented, with a diameter of 100 mm and a thickness of 20 mm. In each test, the mean value and the standard deviation were obtained.

FIGURE 2.
Cubic shape fire specimen (100 mm x100 mm x100 mm)
Source: Authors' own creation.

Experimental tests

Setting time tests were performed through Vicat's apparatus. For mortar, the setting time test and fluidity test were conducted according to NTC 118 [26] and NTC 111 [27], respectively. The compressive strength (f'c) test was performed before and after fire conditions using the standards NTC 673 [28] and NTC 220 [25] for concrete and mortar, respectively. The porosity and absorption properties were determined by following the standard ASTM C642 [29].

The concrete fire-resistance test was performed by applying a fire load as standard ISO 834-11 [30] requires. Thermocouples were positioned on the exposed external face and on the opposite face (Figure 3). The magnitude and exposure time of those fire loads were 200, 600, and 1000 °C at 32, 54, and 105 minutes, respectively.

FIGURE 3.
Fire resistance test
Source: Authors' own creation.

The thermal conductivity and acoustic absorption (ASTM C384 [31]) tests were carried out in mortars. The thermal conductivity coefficient was determined by the thermal conductivity test in the steady state assuming a uniform temperature distribution in the test bank. The mortar was considered an infinitely rigid ceramic, homogeneous and isotropic material. The test consists of applying heat, by an electrical resistance, on the bottom face of the specimen. The equipment consists of a thermic insulated cylinder to reduce the lateral heat losses and allows a unidimensional flow through the material (Figure 4). Thermocouples were located in both faces of the specimen to measure the temperature when it reached its steady heat transference state. The average temperature on the top face was calculated by using Equation 3, and the mortar thermal conductivity coefficient was calculated by using the adapted Fourier equation (Equation 4).

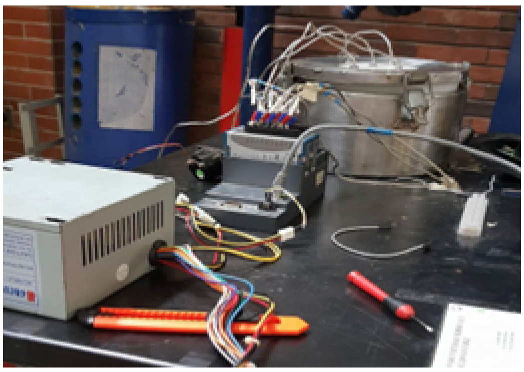

FIGURE 4.
Thermal conductivity test
Source: Authors' own creation.

$$T = Ti - \frac{(T2 - T3)^2 + (T4 - T5)^2}{4(T2 + T3 + T4 + T5 - 4T1)} \tag{3}$$

$$K = \frac{QL}{A(T - T_R)}\left[\frac{W}{m * k}\right] \tag{4}$$

where *Ti* is the temperature at point I, *K* is the thermal conductivity, *A* is the effective area perpendicular to the heat flow, *TR* is the electrical resistance temperature, *L* is the recipient thickness and *Q* is the electrical potential consumed by the resistance (*W*).

The mortar acoustic absorption coefficient was obtained using an impedance tube (ASTM C384 [31]). The frequencies employed were 250, 500, 700, and 1000 Hz. These frequencies were measured when the maximum and minimum amplitudes were displayed on an oscilloscope (Figure 5). With these values and using Equations 5 and 6, the stationary wave relationship (SWR) and the absorption coefficient were calculated.

As illustrated in Figure 5, the system consists of a mobile microphone, a speaker located at one end, which is connected to a frequency generator and to an oscilloscope where the waves produced inside the specimen are observed graphically.

FIGURE 5.
Acoustic absorption test
Source: Authors' own creation.

$$SWR = \frac{P_{\max}}{P_{\min}} \tag{5}$$

where *SWR* is the maximum and minimum ratio in a stationary wave, P_{max} is the maximum voltage amplitude and P_{min} is the minimum voltage amplitude.

$$a_n = \left[\frac{SWR - 1}{SWR + 1}\right]^2 \tag{6}$$

where a_n is the acoustic absorption coefficient.

Results

Fique juice characterization

The pH, the conventional dry extract (indicates the water content in the fique juice) and the calcination losses (shows the organic material contained in the fique juice) results are shown in Table 4. The foam heights at 0 s and 300 s were 13.3 mm and 2 mm, respectively. These values represent the foam content in the juice and allow determining the pore distribution into the hardened mix and its homogeneous distribution [31, 32]. Since the factor of greatest influence on foam formation is the age of the juice (the elapsed time since juice extraction until its use), it is indispensable to use the juice before achieving fermentation. Finally, the organic material content is less than 10%, and the water content in the juice is 90.23% (high content).

TABLE 4.
Fique juice properties

Parameter	Value
pH	4,33
Dry Extract conventional	9,77%
Losses by calcination	6,15%

Source: Authors' own creation.

Setting time

The initial and final setting times for the hydraulic cement paste modified by different dosages of fique juice are shown in Figure 6. In this figure, 0% dosage was defined as the control dosage (without any natural additive). The setting time of the hydraulic cement paste was shorter when the fique juice dosage was increased, which means that both parameters, setting time and fique juice dosage, have an inverse relationship, which could catalog the fique juice as a kind of accelerating additive.

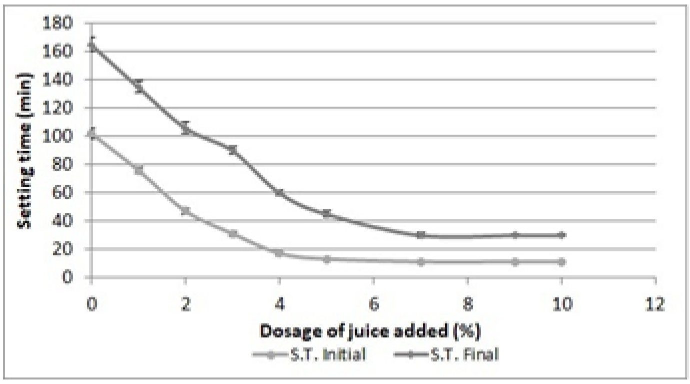

FIGURE 6.
Initial and final setting times
Source: Authors' own creation.

Settlement of the concrete

The test was carried out in concrete with a water content of 186 kg per cubic meter of concrete (without additive), and the settlement was 21 mm, which is a representative value for dry mixes. As the percentage of fique juice (additive) increased from 0% to 10%, settlement also increased. The maximum settlement measured was 40 mm for the highest additive percentage of 10%. According to these results, the juice contributed to the workability and plasticity of the mixture. From this point of view, fique juice could be classified as a possible plasticizer additive, even as an air occluder additive.

Fluidity of the mortar

The obtained values from the fluidity test for all dosages of fique juice are presented in Figure 7. Based on the results, it is observed that when fique juice is added to the mixture and the water-cement ratio is kept constant, the effect is a gradual increase in fluidity. The fluidity increase allowed a reduction in the amount of water needed to obtain determinate workability, causing some segregation of the aggregates as a minor consequence (side effect).

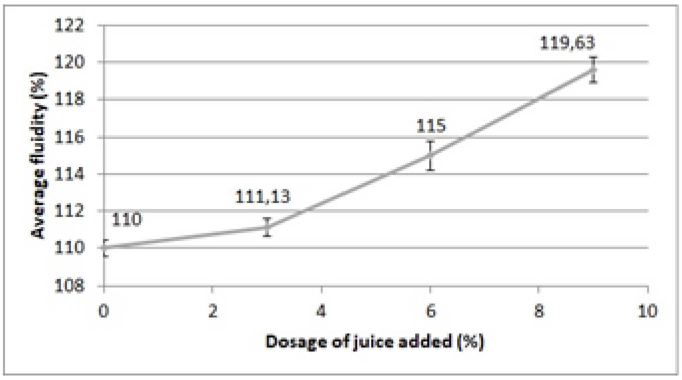

FIGURE 7.
Average fluidity of the mortar based on the amount of juice added
Source: Authors' own creation.

Porosity of the concrete

The percentage of permeable pores increased as the juice dosage increased. As shown in Figure 8, the porosity without additive was 12.3%, and it increased to 19.3% when 10% additive was added. This behavior confirmed the use of fique juice as an air occluder additive. These results are in accordance with Jaramillo [32] and Ochoa [33].

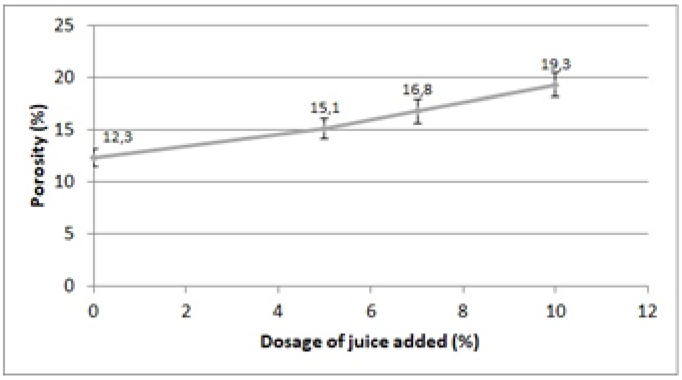

FIGURE 8.
The porosity of concrete with and without a natural additive
Source: Authors' own creation.

Porosity of the mortar

The density of the dry mortar and the average volume of permeable pores (voids) for every dosage are shown in Figure 9 and Figure 10, respectively. Because of the increasing juice dosage, the volume of permeable pores increased, and the dry density was depleted. Both effects are due to the addition of air to the mortar matrix, which in turn is a product of adding the fique juice. The increase in the porosity and the absorption indicates that there is a connection between the pores of the mortar matrix so that the absorbed water is distributed among them. Figure 11 shows the results.

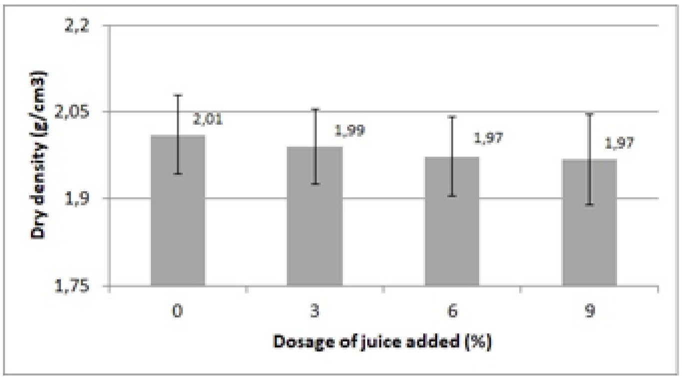

FIGURE 9.
Dry density for each dosage of fique juice
Source: Authors' own creation.

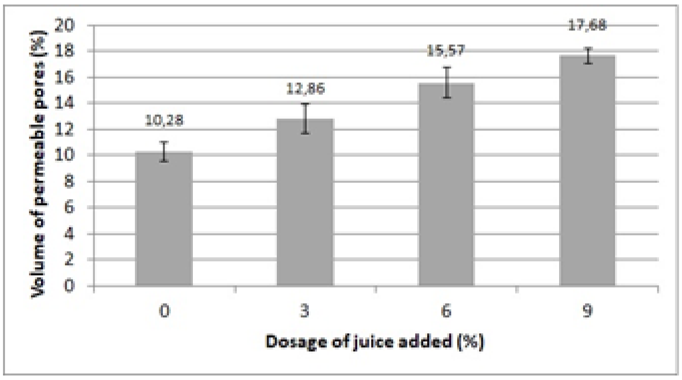

FIGURE 10.
Average volume of permeable pores (voids) of each dosage
Source: Authors' own creation.

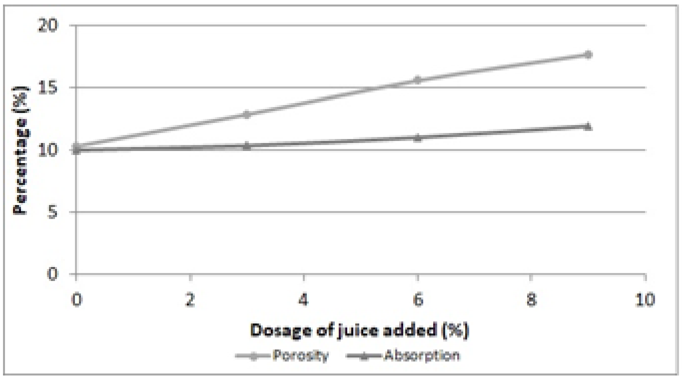

FIGURE 11.
Percentage of absorption and porosity according to the dosage of juice
Source: Authors' own creation.

Concrete behavior under fire conditions

All the concrete test specimens showed a typical black color on exposed fire surfaces. Concrete faces under temperatures between 200 °C and 600 °C did not show any surface damage, although samples exposed to 1000 °C suffered surface peeling (particularly test specimens without additive). Figures 12, 13 and 14 show the temperature registered by the thermocouples located in the interior of concrete samples with 0%, 5%, 7% and 10% added fique juice and subjected to fire temperatures of 200 °C, 600 °C and 1000 °C, respectively. The dotted vertical line indicates the end of the fire exposition. Once the fire load was suspended, the temperature at the interior of the furnace increased for some minutes, and then its cooling process started. In the case of the fire temperature test at 200 °C, all the samples revealed that the time elapsed between the fire load ending and the maximum temperature reached was 11 minutes, as shown in Figure 12. The cooling time was higher in the specimens subjected to the same external temperature and highest additive content. The results show an increase in fire isolation related to the higher fique juice content (see Figures 12, 13 and 14).

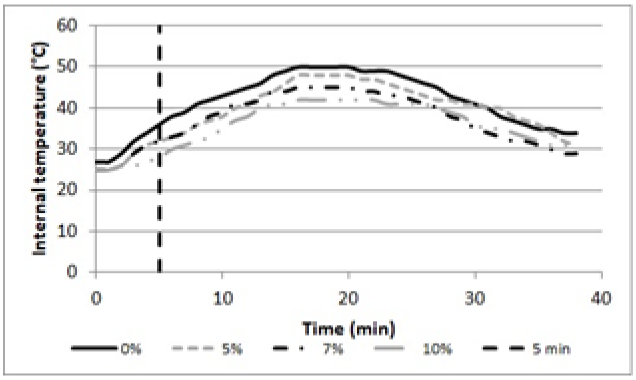

FIGURE 12.
Test at an external temperature of 200 °C
Source: Authors' own creation.

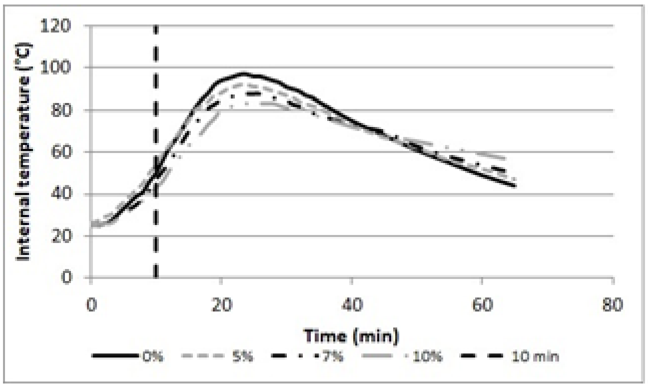

FIGURE 13.
Test at an external temperature of 600 °C
Source: Authors' own creation.

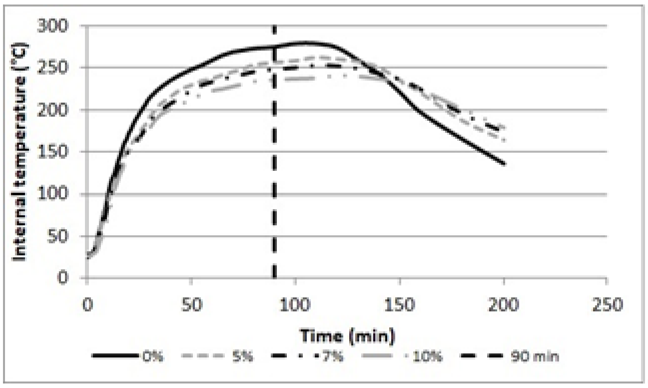

FIGURE 14.
Test at an external temperature of 1000 °C
Source: Authors' own creation.

Compressive strength (f'c) of the concrete under fire conditions

The compressive strength was determined at 7 and 28 days of curing in 3 test samples for each percentage of fique juice added. Figure 15 shows a considerable loss of compressive strength (f'c) of the specimens proportional to the increment of the added additive percentage.

The loss of compressive strength related to the percentage of additive for each fire temperature is observed in Table 5. However, despite this compressive resistance loss due to the fique juice content, a lower loss was evidenced for each fire temperature compared to the pattern concrete. Observing the sample behavior during the 200 °C fire temperature, the concrete without additive had a loss of compressive strength of 11% compared to a loss of only 5% for the concrete with the addition of 10% fique juice. This tendency was observed in all the modified samples (Table 6).

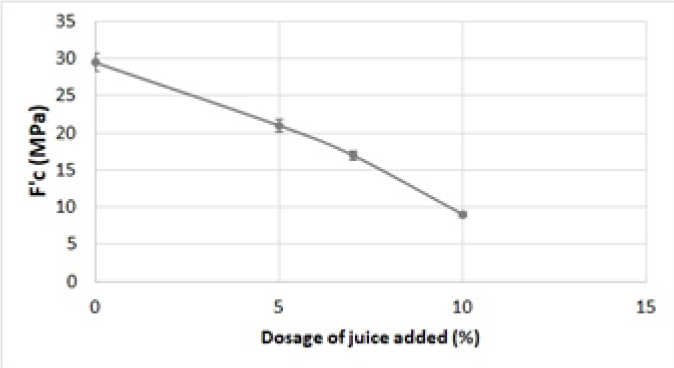

FIGURE 15.
Effect of the additive on f'c at 28 days
Source: Authors' own creation.

TABLE 5.
Compressive strength of test specimens subjected to fire conditions

Additive (%)	0%	5%	7%	10%
f'_c Room (MPa)	29,40	21,10	16,90	9,10
f'_c a 200° C (MPa)	26,30	19,20	15,90	8,60
f'_c a 600° C (MPa)	20,20	14,80	12,00	6,80
f'_c a 1000° C (MPa)	7,80	6,70	5,70	3,20

Source: Authors' own creation.

TABLE 6.
Loss of strength (f'c) under fire conditions

Additive (%)	0%	5%	7%	10%
Loss of f'_c at 200° C (%)	11	9	6	5
Loss of f'_c at 600° C (%)	31	30	29	25
Loss of f'_c at 1000° C (%)	74	68	66	65

Source: Authors' own creation.

Compressive strength (f'c) of the mortar fire condition

The compressive strength for each percentage of juice addition was evaluated in 3 mortar specimens for each dosage. Just as for concrete, the mortar showed a similar behavior under fire conditions, since the compressive strength had a reduction with the increment in fique juice percentage.

Comparing the compressive strength, porosity, and percentage of fique juice, it can be recognized that (Figure 16) the compressive strength is inversely proportional to porosity, which is reduced by the addition of fique juice. These results are in accordance with those of Chen et al. [34], Carreño [35] and Benmansour [36].

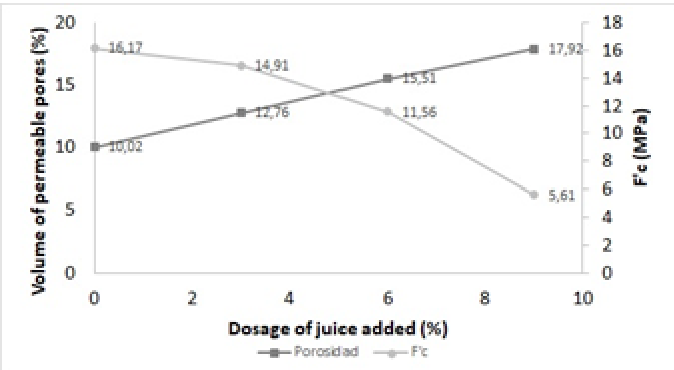

FIGURE 16.
Relationship between the resistance to compression and the volume of permeable pores for each dosage
Source: Authors' own creation.

Thermal conductivity of the mortar

Table 7 shows the effect of the fique juice addition on the thermal conductivity. The amount of fique juice and the thermal conductivity coefficient (K) are inversely proportional, but the values are not remarkable compared with those of the pattern mortar. The reduction in thermal conductivity can be due to the higher porosity of the modified mortars (Figure 17), but the value of K=0.74 $W.m^{-1}. K^{-1}$ corresponds to a normal mortar. Similarly, it was reported by Benmansour [36].

TABLE 7.
Average thermal conductivity coefficient for each dosage

Dosage (%)	Thermal Conductivity (*K*) (W/m*K)
0	0,74
3	0,74
6	0,73
9	0,73

Source: Authors' own creation.

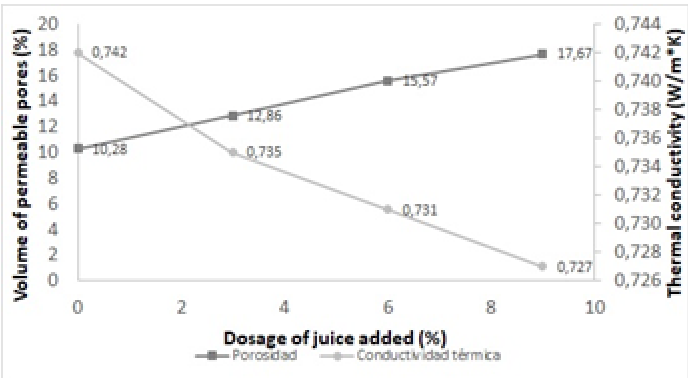

FIGURE 17.
Relationship between the amount of additive, thermal conductivity and number of pores
Source: Authors' own creation.

Acoustic impedance of the mortar

The absorption coefficient was calculated for four different frequencies within the audible range. The value of the coefficient of absorption α varied for each frequency, being a unique value for each material. The calculated data are shown in Figure 18.

The modified mortars (with fique juice added) showed that the material absorbed a large part of the sound waves for low frequencies (250 Hz to 500 Hz). On the other hand, at high frequencies (750 Hz to 1000 Hz), the acoustic absorption coefficient showed a moderate increase (almost constant). Because the sound wave came into contact with the air (trapped by the pores formed by the addition of juice), part of the acoustic energy was converted into heat caused by the movement of the air produced [37]. For Kim, it is mainly due to increased porosity [38].

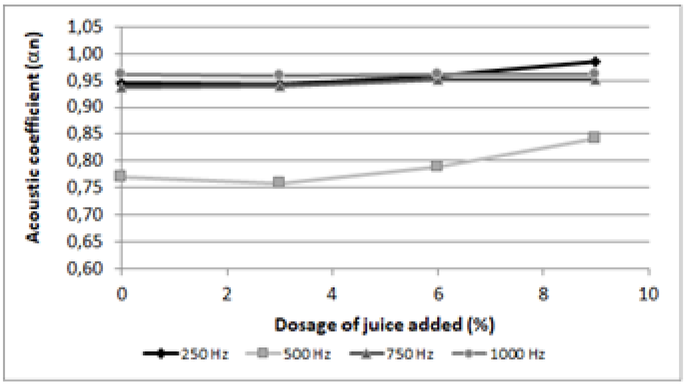

FIGURE 18.
The acoustic absorption coefficient for each dosage
Source: Authors' own creation.

Conclusions

Characterization of the fique juice showed that it is composed of 90.23% water and 9.77% dry extract. The juice was also found to be a large foam producer and has an acidic pH of 4.33, indicating that it could harm concrete (basic pH 11-12).

The fique juice acted as a setting accelerator additive, considerably reducing the initial and final setting times. This characteristic increased as the dosage increased. The decrease in setting times provided a good development of compressive strength.

The modified concrete in the fresh state improved its fluidity and workability. On the other hand, in the hardened state, the density decreased because the juice behaved as an air-occluding additive.

The mixture fluidity increase provided by the fique juice is not a determining parameter for characterizing it as a plasticizer additive because it did not present a compressive strength improvement or a decrease in porosity.

The compressive strength of the concrete specimens with fique juice was reduced compared with the standard sample without a natural additive. This loss increased as the additive percentage increased.

The concrete mixture with fique juice in the hardened state increased the percentage of permeable pores, providing insulating behavior. In the fire test, the increase in permeable pores caused the maximum internal temperatures to decrease as the amount of additive increased. Likewise, during the cooling time, the internal temperature reached is better preserved for the samples with a higher percentage of additive.

Increasing the amount of juice in the mortar mixture caused the entrained air to increase. The increase in the porosity and the absorption indicated that there is a connection between the pores of the mortar matrix so that the absorbed water is distributed among them. This condition causes the compressive strength to have bad behavior.

The mortar mixtures with doses equal to 6% and 9% show a high decrease in compressive strength; thus, it is not possible for practical application.

The results obtained from the thermal conductivity test reveal a decrease in the coefficient (K) when a high amount of juice is added, making the material more porous and better insulated against heat.

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Notes

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