MECHANICAL ENGINEERING | SHORT COMMUNICATION

Effect of natural additives on concrete mechanical properties

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Abstract: The construction industry commonly uses steel-reinforced concrete despite the high levels of pollution in its production process. In this research, it was studied the dosing effect of nopal mucilage and Ixte fiber as additives for the enhancement of concrete’s mechanical properties: compression strength, flexural strength, heat transfer coefficient, ultrasonic pulse rate, ED-XRF, and roughness by fractal dimension analysis. It was found a remarkable improvement in mechanical properties when both natural additives are used. It was observed an increase of potassium and calcium ions concentration after additive dosing. This behavior determines the suitability of the blend for its application in the engineering and construction industry to reduce cement or steel use.

Subjects: Stress Analysis; Technology; Concrete & Cement

Keywords: concrete with organic compounds; nopal mucilage and Ixte fiber; thermal analysis; flexural and compressive strengths

1. Introduction

Concrete is the primary construction material used worldwide due to its versatility and durability (Carrillo et al., 2017; León-Martínez et al., 2014). Nowadays, the pursuit of environmental impact reduction due to its production and usage leads to applying sustainable solutions. The use of recycled polymers as concrete aggregate has shown an increase of tenacity, a property that implies the higher energy absorption capacity before the material failure (Behera et al., 2014; Gunasekar et al., 2019; Liguori et al., 2014; Verdelotti et al., 2014; Zhang et al., 2019). Properties like diffusion and penetration coefficients are related to material durability (Binić & Aksogan, 2018). Therefore, adding fine aggregates or mineral compounds increases the abrasion resistance and strength (McNeil & Kang, 2013; Tosun & Şahin, 2015).

Other works have proposed methods to improve concrete performance: avoiding the entrance of chlorine ions, increasing the failure strength, or reducing the shaping time. Among these methods, organic components’ addition to the mixture is one of the most recently studied. One of the

PUBLIC INTEREST STATEMENT

The construction industry constitutes one of the significant sources of pollution. Nowadays, plenty of research has been conducted to obtain eco-friendly materials that achieve the same characteristics as standard materials. One of the main topics is the addition of organic compounds into concrete to reduce cement quantities used in constructive elements. This research studied the dosing effect of nopal mucilage and Ixte fiber as additives for enhancing concrete’s mechanical properties. The combination resulted in a 96% increase of the flexural-compressive strength and conferred to the materials the capacity of retard heat transfer without compromise the mechanical properties. The nopal mucilage increases calcium and potassium ion concentration, accelerating the crystallization processes for the best mechanical properties. This behavior determines the blend’s suitability for its application in the engineering and construction industry to reduce cement or steel use.
applied materials is mucilage extracted from different cacti sources, as nopal (Alpizar-Reyes et al., 2017; Hernández et al., 2016).

Nopal (Opuntia ficus Indica) is a plant cultivated for commercial and consumption purposes in Chile, Argentina, Morocco, Italy, and the USA; and it is, along with corn, a staple food in Mexico (Arreola-Nava et al., 2017; López-León et al., 2019; Martínez et al., 2018). Different nopal species have been studied to determine their chemical composition to understand its properties and applications (Aquilina et al., 2018; Carrillo et al., 2017; González-Sandoval et al., 2019; Madera-Santana et al., 2018).

The addition of nopal mucilage improves the electrical resistivity, effective porosity, and chloride permeability for different contents of the extract substituting the water in the concrete blend (Aquilina et al., 2018; Blanco et al., 2019; Torres-Acosta & Díaz-Cruz, 2020). However, compressive strength needs more extended periods to be positive, and the average time is seven days until the compressive strength is equal to the blend with no extract and 28 days to reach at least 20% more.

Besides, not only the water is substituted, but also the cement powder. In these cases, almost an increase of 75% of the compressive strength is achieved for an average substitution of 2%. However, the cladode’s powders’ obtention is more expensive than the obtention process of the mucilage extract, which could not be profitable for industrial applications (Aquilina et al., 2018; El Azizi et al., 2019; Madera-Santana et al., 2018).

Nowadays, the combination of ancient construction technics has re-evolved for a widespread application of natural materials. For example, in earth-based construction, natural fibers are used to prevent shrinkage or wall cracking, improving their binding force with positive effects on the tensile and compressive strength of the final material (Giada et al., 2019; Ortega-Lerma et al., 2016).

This research proposes the dosing effect of Nopal mucilage and Ixtle fiber as additives for concrete, studying the generation of green materials for the construction industry. Besides the following of the compressive and flexural strength behavior, it was considered the natural aggregates’ effect on the heat transfer coefficient.

2. Materials and methods

The materials were analyzed from twenty specimens (ten beams and ten cylinders) of three different blends: a blank conformed by the conventional elements of concrete (CB), a blend whit nopal mucilage substituting water (CM), and a mixture of CM and Ixtle fiber (CMI). Regular Portland cement was used (CPC-30, Holcim Company), and the sand was river type with granulometry #4. For the obtention of nopal mucilage, 20 kg of nopal were cleaned and blended to get 8 kg of the organic material. Sodium benzoate was added at five g/L as an antioxidant. The mucilage was aged for 48 h and then used in the tests (Figure 1(a,b)). Ixtle fiber was hand-extracted from Agave Lechuguilla Torrey, applying rural techniques (Figure 1(c,d)). After mechanical treatment, the fibers were set to a 2 mm average thickness to promote concrete strength enhancement (Suárez-Domínguez, Aranda-Jiménez, Fuentes-Pérez et al. 2017a; Suarez-Domínguez, Aranda-Jiménez, Zuñiga-Leaf et al., 2017b). It is worth mentioning that all of the plants were produced within the university campus facilities.

Figure 1. Representative specimens of the plants for the obtention of natural additives: Nopal plant (a), obtention of mucilage (b), Agave Lechuguilla torrey plant (c), and Ixtle fibers (d).
In similar works, the authors have estimated that concrete gets its best properties around ninety days after fabrication (Aquilina et al., 2018; Hernández et al., 2016; Torres-Acosta & Díaz-Cruz, 2020). The mixtures were added with an accelerator (8 ml/kg of cement) to perform tests after fourteen days of curing (Sika Set accelerator). The accelerator did not influence the natural additive’s behavior, and it is also useful to streamline the unmolding process. Table 1 shows the specifications of the sample conformations.

Figure 2 shows the samples and molds used in this work for beams (2a) and cylinders (2b). The compression tests followed the ASTM-C93 method (under the Mexican Standard NMX-C-083-ONNCCE, 2010) with cylinder dimensions of 10 cm in diameter and 20 cm in height. The flexural strength test was performed for beams of 15 cm x 15 cm x 60 cm with a Controls E-48 Universal Machine under the ASTM-C293 Standard (Mexican Standard NMX-C-303-ONNCCE, 2010).

The heat transfer test followed the procedure described in ASTM-C177-19 with a KD2 Thermal Analyzer. The samples’ porosity was determined from the ultrasonic analysis (UPV) following the ASTM-C597 (NMX-C-275-ONNCCE, 2004). For the UPV analysis, 7.5 x 7.5 x 15 cm prisms were cut from the beam probes. Finally, for the surface roughness analysis, a set of pictures was taken with a 10x digital microscope, and ImageJ software was used to analyze the samples’ surfaces. The Energy dispersive X-ray fluorescence analysis (ED-XRF) was performed to determine the natural aggregates’ presence in the samples. After compression tests, remained pieces of the cylinders and beams were tested in an ED-XRF Analyzer (Xenemetrix, P-Metrix) at 50 kV/10 W/400 μA with Rh anode and Ti filter for 300 counts/min. All of the experiments were performed in triplicate with a mean average error of 5%.

3. Results and discussion
Table 2 shows the results of the flexural and compression strength experiments. The CMI had a flexural strength of 2,62 ± 0.131 MPa (72.36% higher than CB) and compression strength of 20,75 ± 1,038 MPa (96.5% higher than CB). This behavior is a clear indication of the positive effect of the mucilage-fiber combination. The effect of these materials can be abided from two points of view. The first one is related to the water retention capacity of the nopal

| Table 1. Mixture fabrication ratios (CB = blank, CM = concrete with mucilage, and CMI = concrete with mucilage and Ixtle fiber) |
|-------------------------------------------------------------|
|                | Cylinders |                      | Beams      |
|                |           | CMI                  | CB         | CM       | CMI       |
| Cement (%)     | 14,37     | 14,37                | 11,86      | 14,3     | 14,3      |
| Gravel (%)     | 40,15     | 40,15                | 33,14      | 40,07    | 40,07     | 40,07 |
| Sand (%)       | 30,02     | 30,02                | 30,56      | 36,98    | 36,98     | 36,98 |
| Mucilage (%)   | -         | 8,45                 | 24,42      | -        | 8,64      | 8,64  |
| Water (%)      | 8,45      | -                    | -          | 8,64     | -         | -     |
| Fiber (ppm)    | -         | -                    | 100        | -        | -         | 100   |
| Accelerator (ppm) | 10      | 10                   | 10         | 80       | 80        | 80    |

Figure 2. Examples of molds and samples for beams (a) and cylinders (b).
mucilage, which results in a better watering effect that enhances the setting process and reduces the water-to-cement ratio, achieving higher strength values (Aquilina et al., 2018; El Azizi et al., 2019; Madera-Santana et al., 2018; Torres-Acosta & Diaz-Cruz, 2020). Moreover, the porosity and total void content are related to excess water or air trapping during the fabrication and setting process. Ixtle fiber works as a filler material that promotes the homogeneity of the materials and reduces the zones of weakness in the final structures (Giada et al., 2019; Marie, 2016; Ortega-Lerma et al., 2016).

The results of the compression test showed a direct relation to the physical changes of the samples. The control sample CB (Figure 3(a)), water-based cylinders, had a characteristic behavior compared to the natural-modified samples. It showed a linear failure distribution due to the possible low homogeneity of the mixture. The opposite effect is observed for CM and CMI samples (Figure 3(b,c)).

Surface image analysis was applied to study the rugosity of the samples. Figure 4 shows pictures in which the roughness profile is very similar for all samples, and Table 3 shows the fractal dimension analysis results. The values obtained indicate that the addition of natural additives did not compromise the surface morphology.

Typically, for higher density values, better mechanical properties are obtained. Therefore, the high compression and flexural strengths are related to this property, as well as the thermal conductivity (K). The K results are shown in Table 3, and it is observed a reduction of about 50% when Ixtle fiber is added, which indicates the proportional relation of these variables. These results agree with the natural fibers’ filler function because it is a poor heat conductor and as a replacement of air in the pores reduces the heat transport within the materials (Asadi et al., 2018; Maneewan et al., 2019; Suarez-Dominguez et al., 2017b).

Table 3 also shows the UPV analysis of the samples. For the mucilage and mucilage-fiber mixtures, the UPV remains in good quality concrete level, as indicated in the reference standard: high quality 3001< UPV<4000, durable UPV>4000 (ASTM-C597, NMX-C-275-ONNCCE; Nogueira & Rens, 2018). These values are higher than the CB mixture and indicate

| Table 2. Compression and flexure results after 14 days of curing |
|---------------------------------------------------------------|
| **Beams** | **Cylinders** |
|-----------|----------------|
| CB        | 1.52 ± 0.076   | 10.56 ± 0.053 |
| CM        | 1.98 ± 0.099   | 9.57 ± 0.048  |
| CMI       | 2.62 ± 0.079   | 20.75 ± 0.125 |
To identify the presence of mucilage, it was carried out an ED-XRF analysis. Results are shown in Figure 5, where it is possible to appreciate an increase of potassium and calcium ions that are characteristic of nopal mucilage (Aquilina et al., 2018; El Azizi et al., 2019; Carrillo et al., 2017; Madera-Santana et al., 2018).

Calcium and Potassium accelerate the hydration rate of freshly paced concrete and decrease its free water content faster (Jianming et al., 2019); this change may favor the crystallization of concrete and bonds between components.

4. Conclusions
This research aimed to analyze the effect of dosing nopal mucilage and Ixtle fiber on concrete’s mechanical properties. It was found that the addition of nopal mucilage in concrete...
mixtures generate a remarkable increase of the flexural and compressive strength in comparison with a typical concrete mix. On the other hand, it can be concluded so far that the Ixtle fiber improves the nopal mucilage effect (72 and 96% increase of the flexural and compressive strength, respectively) and confers to the materials the capacity of retard heat transfer without compromising the mechanical properties. It was found that nopal mucilage addition increases organic calcium and potassium ion concentration. This could promote the crystallization processes, potentializing the mechanical properties on shorter setting periods.

The materials and mixtures proposed in this work can be used as sustainable materials in the construction industry. Along with the anticorrosion functionality studied by other authors, it is now possible to increase the mechanical and physicochemical properties of concrete structures.

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