Concrete Cracking Control in *Underwater Marine Structures* using Basalt Fiber

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Abstract. The construction of coastal ports requires the use of materials that meet the demands of the marine environment, to prevent underwater concrete structures from cracking and spalling easily; basalt fiber is used to delay the expansion of concrete and prevent the formation of cracks. This research studies the behavior of concrete for prefabricated piles with Portland Cement Type I and basalt fibers added in 0.1%, 0.3% and 0.6%; the results indicate that the fiber is suitable for concrete, the slump decreases, the compressive strength increases for specimens cured in tap water and sea water, the relationship between resistances does not vary, and the depth of carbonation decreases.

1. Introduction

Constructions located in marine environments are exposed to attack by different agents, such as: sulfates, acids, seawater, chlorides, microorganisms, algae and mollusks, so they require the use of a concrete with greater durability [1], which presents low permeability to reduce the appearance of cracks (micro and macro) and voids produced during its manufacturing and commissioning [2]. This reduction has been carried out through the application of fibrous materials such as: glass fibers, polypropylene, steel, and carbon, among others; because with them compact and more efficient concretes are produced [3], being these suitable for marine infrastructures, as is the case of tourist ports located on the beaches of coastal coastlines.

Ports are built to generate economic development in society, but due to social needs for recreation or tourism they are remodeled, including stalls and modern ornaments [4], which increase existing loads, requiring that their supporting structural elements, such as the reinforced concrete piles, are in a good state of preservation to guarantee the strength of the structure. These piles, being submerged under water, are affected by microorganisms, salts and chlorides, the latter producing an increase in cracks in the covering [5]; the same ones that cause cracks and spallings, leaving the reinforcing steel exposed [6] and affecting the load capacity due to the reduction of its cross section [7].

An alternative solution to the reduction of cracking consists of reinforcing the concrete with Basalt Fiber (BF), which comes from an igneous rock and that through a winding process fibers of Ø 5-20 μm; its characteristics include: rigidity, durability, high resistance to acids and solvents, contributes to workability, increases tensile strength, is resistant to chloride attack and is more tenacious in alkaline
environments [8]; and that when incorporated into the mix it requires avoiding the formation of agglomerations so as not to affect the final strength of the concrete [8]. Interesting investigations have been reported on the characteristics of BF and its behavior in concrete, thus we have [9], [10], [11] analyzed the chemical composition of BF by means of the X-ray fluorescence test and found that 53% corresponds to silicon dioxide; on the other hand, with the addition of BF the slump decreases [12], [13], [14]; the compressive strength for concrete cured in tap water and sea water increases [14], [15], [16], [17], [18], [19]; the relationship of the compressive strength of concrete cured in sea water and concrete in tap water is similar [20], [21], [22]; and the depth of carbonation decreases [23], [24], [25].

The present work is related to the tourist ports in the bay of the city of Pisco where there are reinforced concrete piles with different pathologies on their surface, highlighting cracking and spalling; Portland Cement Type I has been used because the type of cement is of little importance compared to the low permeability requirements of concrete in water [26]. This research addresses the problem of surface cracking of precast reinforced concrete piles of tourist ports submerged in tidal zones; to do this, we study the chemical composition of the BF, the slump, the compressive strength of the cured concrete in tap water and sea water, the relationship between the cured with sea water and cured with tap water, and the depth of carbonation.

2. Materials and methods

2.1 Materials
It was used Portland cement type I [27]; the fine and coarse aggregates were natural, the coarse ones being a maximum size of Ø ½” [28]; the BF used are circular in shape, of Ø 16 μm, length 24 mm and density 2650 Kg/m³, the image of which is shown in figure 1; and the water was tap [29].

![Figure 1. Basalt fiber.](image1.png)

![Figure 2. Chemical composition of BF.](image2.png)

2.2 Methods
The concrete design was made according [30] to a $f_{c,l} = 280$ kg/cm². The different mixtures made with their component materials, tests and number of test tubes used are shown in table 1 and table 2. The mixture was prepared according to [31], then they were cured for 7 and 28 days [32] and then they were tested in a fresh and hardened state. The composition of the BF was made at 3 days with the X-ray fluorescence assay [33]; the slump with [34]; for resistance specimens of Ø 15 x 30cm [35]; and the depth of carbonation with phenolphthalein in specimens of Ø 15 x 30cm curing with sea water [36].

| Materials (kg)        | BF-0 standard | BF-0.10 | BF-0.30 | BF-0.60 |
|-----------------------|---------------|---------|---------|---------|
| Type I cement         | 415.05        | 415.05  | 415.05  | 415.05  |
| Fine Aggregate        | 764.59        | 764.59  | 764.59  | 764.59  |
| Coarse Aggregate      | 1010.55       | 1010.55 | 1010.55 | 1010.55 |
3. Results and analysis

3.1 X-ray fluorescence

In figure 2, the chemical compounds of the BF of 24 mm length and Ø 16 µm are presented, showing that Silicon dioxide (SiO$_2$), Aluminum oxide (Al$_2$O$_3$), Iron oxide (Fe$_2$O$_3$) and Oxide of calcium (CaO) are the 4 compounds that represent 85.60% of the fiber composition, where the amount of SiO$_2$ is equal to 51.40%. [37] and [38] study BF of 21mm and 25mm in length, and of Ø 11 µm and 17 µm, finding that SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$ y CaO represent 81.17% and 88.84%, with SiO$_2$ being 51.82% and 50.90% respectively. In this regard [39] indicates that a SiO$_2$ content higher than 42% determines that the rock belongs to an alkaline type basalt.

3.2 Slump

Figure 3 shows the influence of the amount of BF on the slump of concrete with type I cement for three types of mixes BF-0.10, BF-0.30 y BF-0.60, prepared with Ø 16 µm fibers, length 24 mm. In it, it is seen that the slump decreases when the amount of BF increases, reaching values lower than 3.10", 2.30" and 1.50" for the mixtures BF-0.10, BF-0.30 and BF-0.60 that represent 11.43%, 34.29% and 57.14% less compared to the BF-0 mixture (standard). [40] and [41] studied mixtures with BF for additions with 0.1%, 0.3% and 0.4%, 18 mm in length and Ø 17 µm, and with 0.05%, 0.10%, 0.15% and 0.20%, length 18 mm and Ø 15 µm; finding a decrease of 15.25%, 20.00% and 47.46%, and of 29.71%, 49.43%, 44.86% and 60.71% respectively. [42] indicates that this behavior is due to the increase in the coefficient of friction between the cement and the fiber during mixing and the moisture contained in the fiber, causing a decrease in workability.

| Test type           | BF-0     | BF-0.10  | BF-0.30  | BF-0.60  |
|---------------------|----------|----------|----------|----------|
| Compressive strength|          |          |          |          |
| Curing time (days)  | 7        | 7        | 7        | 7        |
| Number of specimens | 4        | 4        | 4        | 4        |
| Tap water, Sea water|          |          |          |          |
| Carbonation depth   |          |          |          |          |
| Curing time (days)  | 28       | 28       | 28       | 28       |
| Number of specimens | 4        | 4        | 4        | 4        |
| Sea water           |          |          |          |          |

| | | | |
|---|---|---|---|
| Compressive strength | BF-0 | BF-0.10 | BF-0.30 | BF-0.60 |
| Curing time (days)   | 7    | 7        | 7        | 7        |
| Number of specimens  | 4    | 4        | 4        | 4        |
| Tap water, Sea water |       |          |          |          |
| Carbonation depth    | 90   | 2        | 2        | 2        |
| Curing time (days)   | -    | 90       | 90       | 90       |
| Number of specimens  | 90   | 2        | 2        | 2        |
| Sea water            |       |          |          |          |

Table 2. Number of specimens per test.
3.3 Compressive Strength of specimens cured in tap water
Figure 4 shows the influence of the BF test age on the compressive strength of 3 concrete mixes BF-0.10, BF-0.30 and BF-0.60, prepared with fibers of length 24 mm and Ø 16 μm and cured tap water. It can be seen that the resistance increases for 7 and 28 days, reaching values greater than 286.08 kg/cm² and 305.04 kg/cm² for the BF-0.60 mixture, which represent 44.48% and 8.01% more than the BF-0 sample (standard). [43] and [44] studied mixtures with 0.10%, 0.25%, 0.40% and 0.50% addition, 13 mm in length and Ø 12 μm, and with 0.50%, 0.75% and 1.00%, length 24 mm and Ø 16 μm; finding an increase in resistance at 7 and 28 days of 15.97% and 13.15% and of 22.41% and 26.79% respectively. [45] indicates that this behavior may be due to the presence of sufficient moisture to continue hydration of the cement.

3.4 Compressive Strength of specimens cured in sea water
Figure 5 shows the influence of the BF test age on the compressive strength of 3 concrete mixes BF–0.10, BF–0.30 and BF-0.60, prepared with fibers of length 24 mm and Ø 16 μm and cured in sea water. It can be seen that resistance increases for 7 and 28 days, reaching values greater than 281.20 kg/cm² and 310.81 kg/cm² for the BF-0.60 mixture, which represent 69.80% and 13.00% more than the BF-0 sample (standard). [46] and [47] studied mixtures with 0.10%, 0.20% and 0.30% addition, 20 mm in length and Ø 15 μm, and with 0.15%, 0.20% and 0.25%, length 35 mm and Ø 13 μm; finding an increase in resistance at 7 and 28 days of 8.43% and 4.76% and 44.68% and 7.03% respectively. [48] indicates that this behavior is due to the development of hydration products to block the interior pores of concrete.
3.5 Relationship of curing with sea water vs curing with tap water

Figure 6 shows the relationship of seawater cure to potable water cure of concrete specimens with BF. In it, it can be seen that the cylindrical 150 x 300 mm specimens cured in seawater have a greater linear relationship and very similar with slightly higher values in 0.17%, 0.45% and 1.89% for BF-0.10, BF-0.30 and BF0.60 that represent an average of 0.84% more. [49] and [50] studied 150x150mm cubic specimens made with fly ash with additions of 25%, 30%, 45%, and 100x200mm cylindrical specimens with 44Kg/m$^3$ silicate fume; finding an increase of 6.98% and 0.35% respectively. [51] indicates that this behavior is due to the entry of chloride, sulfate and sodium into the microstructure of the cement paste, clogging the pores and decreasing porosity.

3.6 Carbonation

Table 3 shows the influence of BF on the carbonation depth of concrete with type I cement for a ratio $a/c = 0.47$ and an exposure time of 90 days. In it, it is seen that by increasing the amount of fiber the carbonation depth decreases, reaching the average values of 150, 136 and 125mm for the addition percentages of 0.10%, 0.30% and 0.60%, which means a decrease in the depth of the 16.67% for BF-0.60 compared to BF-0.10. Figure 7, Figure 8 and Figure 9 show the different carbonation zones for the samples tested. [52] and [53] studied mixtures with addition of 20%, $a/c = 0.50$ and exposure time of 42 days, and with 25% and 50%, $a/c = 0.46$ and exposure time of 70 days, finding a decrease in carbonation depth of 40% and 38.88% 11.11% respectively. [54] indicates that this behavior may be related to the lower water-cement ratio of the mix, which influences the uniformity of the porosity of the concrete.

| Identification | Zone              | Carbonation Depth $d_k$(mm) | Minimal | Maximum | Average |
|----------------|-------------------|----------------------------|---------|---------|---------|
| BF-0.10        | Colorless         | 150                        | 150     | 150     | 150     |
| BF-0.30        | Purple-red        | 135                        | 138     | 136     |         |
| BF-0.60        | Purple-red        | 125                        | 126     | 125     |         |
4. Conclusions
With the incorporation of the basalt fiber and Type I cement, the formation of cracks in the surface of the piles is delayed because the fibers improve the brittle behavior of the concrete.

The higher composition of SiO$_2$ in basalt fiber provides better stability under alkaline conditions. The slump when decreasing produces a drier consistency of the mixture, generating a greater difficulty for mixing.

The compressive strength of specimens cured in tap water is increased by constant humidity, vapor retention and protection from contaminating agents.

The higher compressive strength of sea water cured concrete specimens is due to the presence of calcium chloride in seawater, which accelerates the hardening process of the concrete.

The slightly higher relationship between sea water cure over tap water cure is due to the fact that sea salts slightly increase the density of concrete.

The decreasing carbonation depth indicates that the fiber improves the micro-pore structure of the concrete, delaying the penetration of sea water.

5. References
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