STUDY OF AMORPHOUS METALLIC FIBERS AS ALTERNATIVE CONSTITUENTS IN A REFERENCED INDUSTRIAL UHPFRC MIX: CONDITIONS OF OPTIMIZED APPLICATIONS

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Abstract

The purpose of this research is to identify an optimal composition of a UHPFRC based on a referenced industrial mix reinforced with amorphous metallic fibers (AMF). Amorphous metals, also called metallic glass alloys, are obtained through a fast cooling of a molten metal resulting in a non-crystalline structure. Combining this process to fibers results in AMF bring together strength, flexibility, thinness, durability and rustproof properties. The final aim of this study is to analyse the feasibility and the advantages of replacing steel fibers (SF) by AMF in UHPFRC. Compressive and three-point bending tests were carried out for two parameters: the length of the AMF of 20 mm, 15 mm, 10 mm (for a width of 1mm and a thickness of 24 μm); and the volume fraction of AMF between 1 % and 2 %. Based on experimental results, the optimal composition consists in a volume fraction of 1.5 % of 15 mm-long AMF. The comparison with a UHPFRC composed of 2 % SF leads to similar mechanical resistances. Non-referenced tests using salt water in the composition of the UHPFRC as well as for the storage water show a potential use of non-fresh water when using UHPFRC with AMF.

Résumé

Cet article présente la recherche d'une formulation optimale d'un BFUP basé sur l'utilisation de fibres métalliques amorphes (FMA) en tant que constituant alternatif dans un BFUP référencé. Un métal amorphe est obtenu à la suite d'un refroidissement rapide du métal en fusion. En combinant ce procédé aux fibres métalliques on obtient des fibres métalliques amorphes regroupant résistance, flexibilité, finesse, durabilité et résistance à la corrosion. L'objectif final de cette étude est d'évaluer la possibilité de remplacer les fibres acier (SF) par des FMA dans un BFUP et les avantages qu'il en découlerait. Des essais mécaniques en compressions et en flexion trois points ont été menés suivant deux paramètres : la longueur des FMA (20 mm, 15 mm et 10 mm) pour une largeur et épaisseur constantes, de respectivement 1 mm et 24 μm; et le pourcentage volumique en FMA variant entre 1 % et 2 %. La composition optimale, fondée sur les résultats expérimentaux, est composée de FMA de 15 mm de long pour un dosage volumique de 1.5 %. La comparaison avec un BFUP dosé à 2 % en fibres aciers présente des résistances mécaniques semblables. Des essais non référencés utilisant de l'eau salée dans la composition des BFUP ainsi que dans l'eau de cure évoquent une utilisation potentielle d'eau non douce lors de l'utilisation de FMA dans des BFUP.

1. INTRODUCTION

For several years, steel fibers (SF) have been used in Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) and problems have risen from their use, especially for architecture purposes. This study, carried out in an Industrial Entrepreneurship and Research Project (PIER) within the ESTP (École Spéciale des Travaux Publics) evaluates the possible use of a UHPFRC composed of amorphous metallic fibers (AMF).

The referenced industrial mix used throughout this research project is currently used with steel fiber. The objective of the study was to evaluate the possibility of replacing these fibers by flat and thin AMF. The project was divided into two phases. The first aimed at an optimal composition of a UHPFRC based on a referenced industrial mix using different percentages and types of AMF. The second phase of the study compared this selected mix, to the commercialized mix, using steel fibers. This study led to possible benefits and drawbacks of the use of amorphous metallic fibers instead of steel fibers in a referenced UHPFRC.

2. RESEARCH OF AN OPTIMAL COMPOSITION

The research of an optimal composition was based on two criteria: the type of AMF (length and width) and the volume fraction of fibers in the mix. Thereafter, the volume fraction of fibers will be given in volumetric percentage for one cubic meter of stored concrete.

The workability and the mechanical resistances of the different UHPFRC are the criteria under which the optimal composition was selected. The optimal composition uses 15 mm long, 1 mm wide and 24 μm thick AMF in a volume fraction between 1.25 % and 1.50 %.

Table 1: Characteristics of the optimal composition using 15 mm long AMF

Volume fraction	1.25%	1.50%
Specific surface: m^2/m^3	0.9	1.1
Density: kg/m^3	2389	2381
Air content: %	1.05	2.13
Diameter of the flow table test: mm	280	249
Three-point bending test (4x4x16 cm): MPa	18.86	20.71
Compression test (4x4x16 cm): MPa	119.2	128.7

3. COMPARATIVE STUDY

The second phase of the project presents the comparative study of two UHPFRC: the one dosed with 1.5 % of 15 mm long AMF, and a marketed UHPFRC using 2.0 % in volume of 12.5 mm long SF.

The study was conducted through several comparison tests: fluidity; workability; concrete shrinkage; durability; mechanical resistance; influence of fibers orientation. Due to a comparison study between two UHPFRC, some tests are experimental protocols. The research process was based on the ability to find new vantage points for the study of UHPFRC with protocols which are not listed in any standard.

3.1 Concrete shrinkage

The test described by the standard NF P 18-427 was carried, it consists in measuring the variation of distance between two opposite faces on 7 x 7 x 28 (cm) prismatic samples of hardened concrete equipped with measuring pins.

This test started 24 hours after the cast and was reiterated several times on the six samples:

- three samples composed of 2 % of SF
- three samples composed of 1.5 % of AMF

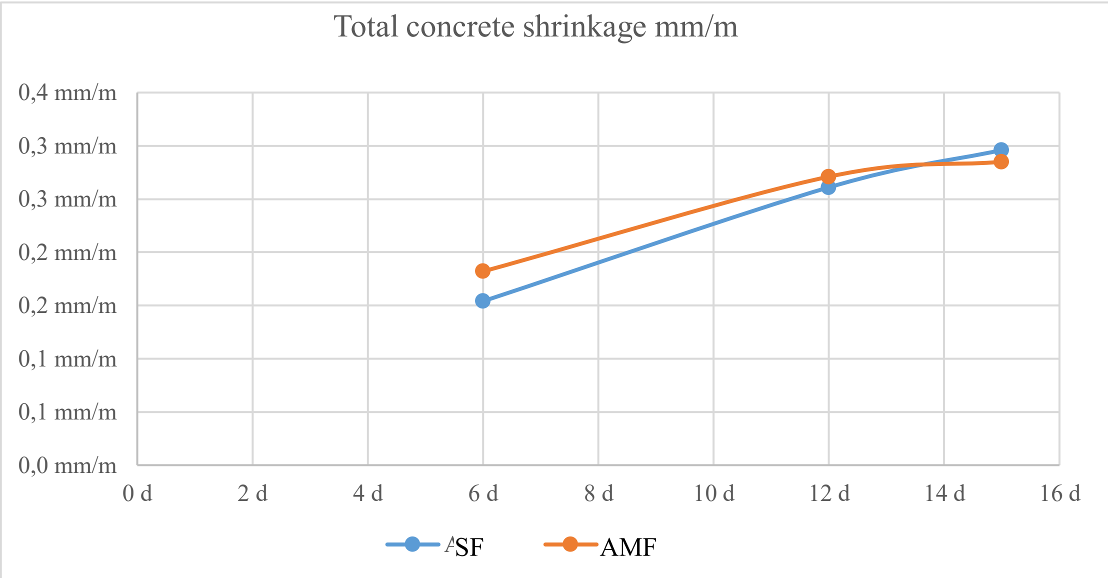


Figure 1: Concrete shrinkage curves of UHPFRC with AMF and SF

During the first 12 days a more important shrinkage can be observed (Fig. 1) for the AMF samples, yet later the trend reverses. In the long term, the concrete composed of AMF is less subject to shrinkage, meaning it is more reliable and stable than the one composed of SF.

3.2 Durability

Testing the durability of the two concretes in a saline environment appears interesting due to the non-corrosive aspect of the AMF. This test seemed relevant because of potential future UHPFRC construction on the sea shore. Because a specific protocol was not followed, salt water was also in the mixture of the concrete in order to analyze the possible differences.

A singular experimental protocol was adopted (Fig. 2). The Mediterranean Sea salinity level was chosen as the salinity reference. Hence, the concentration determined was to be 38.5 g/L in salt for the water used to store the samples as well as for the mixture water. Eight types of samples (4 x 4 x 16 (cm)) were designed depending on the type of fibers, the type of mixture water and the type of water used for the storage of the samples.

AMF 1.5%

Storage water / Mixture water	Fresh water	Salt water
Fresh water	9 samples	9 samples
Salt water	9 samples	9 samples

SF 2.0%

Storage water / Mixture water	Fresh water	Salt water
Fresh water	9 samples	9 samples
Salt water	9 samples	9 samples

Figure 2: Diagram of the different types of samples for the salt water experiment

The salinity of the curation tank has been regularly measured and adjusted during the six months of cure of the seventy-two samples. After six months of cure two conclusion aspects were drawn. On the one hand there is an aesthetic aspect and a mechanical aspect.

On an aesthetic point of view, AMF react in a better way than the SF when exposed to salt water, especially on the surface of the samples (Photos 1-3). The SF have a tendency to rust and cavities were also found only on the samples designed with SF. The AMF offer a significant architectural and architectonic advantage; it is even truer for light color concretes with which points of rust would result in rust drops on the surface.

Photo 1: Sample with steel fibers showing rust spots

Photo 2: Sample with steel fibers showing cavities

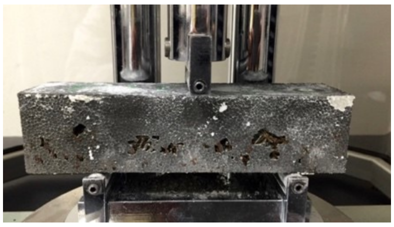


Photo 3: Sample with AMF, no rust found (after compression test)

Concerning the mechanical aspects, compressive tests (Fig. 3) as well as three-point bending tests (Fig. 4) were conducted. On average there is little difference between all samples for both bending and compression tests. With regard to the comparison, between the UHPFRC designed with AMF and the one with SF, results are close, between 11 kN and 12 kN (respectively) for the three-point bending test and between 130 and 150 MPa in compression. Using AMF allows to achieve mechanical performances comparable to classic UHPFRC with a lower percentage of fibers (1.5 % of AMF while the UHPFRC composed of SF is dosed with 2 %).

3.3 Influence of the fibers' orientation

In order to study the influence of the fibers orientation with respect to the mechanical resistances of the two analyzed UHPFRC, concrete slabs of 70 x 70 x 3 (cm) were designed in order to have a significant dimension reflecting the concrete flow during the pouring. The objective of these slabs was to cut samples in the same direction as the pouring direction as well as perpendicular to its flow. These samples were tested during a three-point bending test and compared.

Design of a specific experimental protocol in order to obtain an orientation of the fibers principally in the flow direction resulted in the following:

1. Preparation of the mixture according to the usual protocol
2. Addition of the fibers
3. Pouring of the concrete on a "transfer" board
4. Filling of the mold through a natural flow of the concrete (Photo 4).

In each of the slabs, three strips of 45 cm by 15 cm were cut. These samples were centered on the slabs to avoid edge effects.

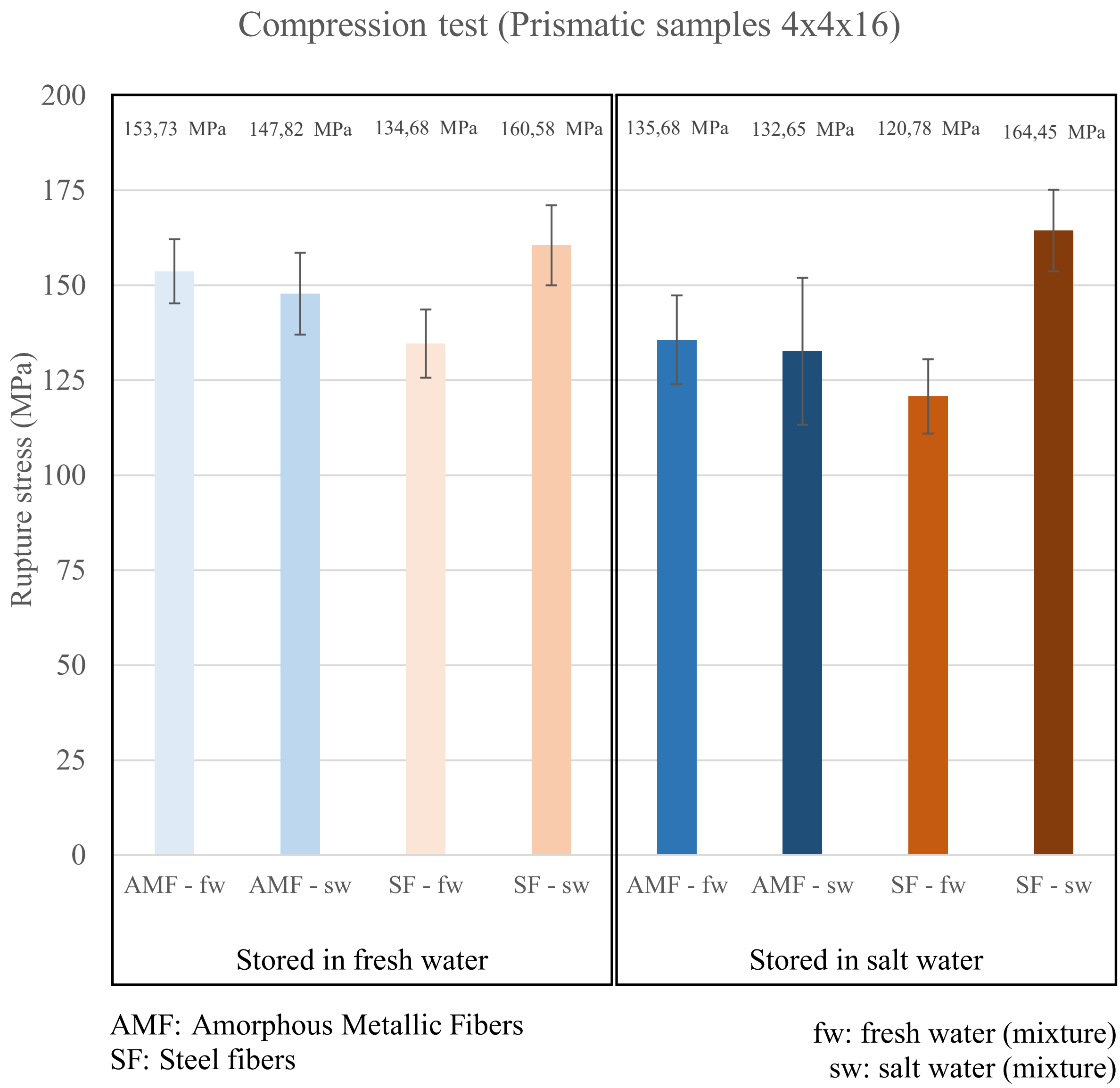
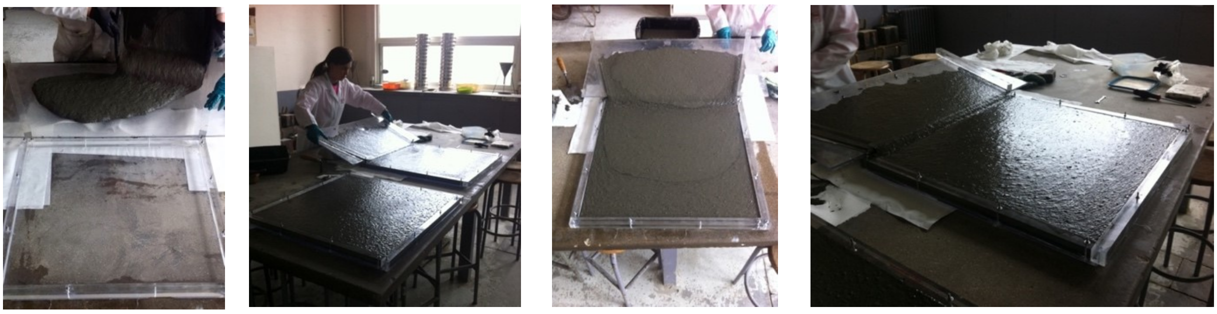


Figure 3: Compression test carried out on samples stored in clear and salt water

Photo 4: Preparation of the concrete slabs



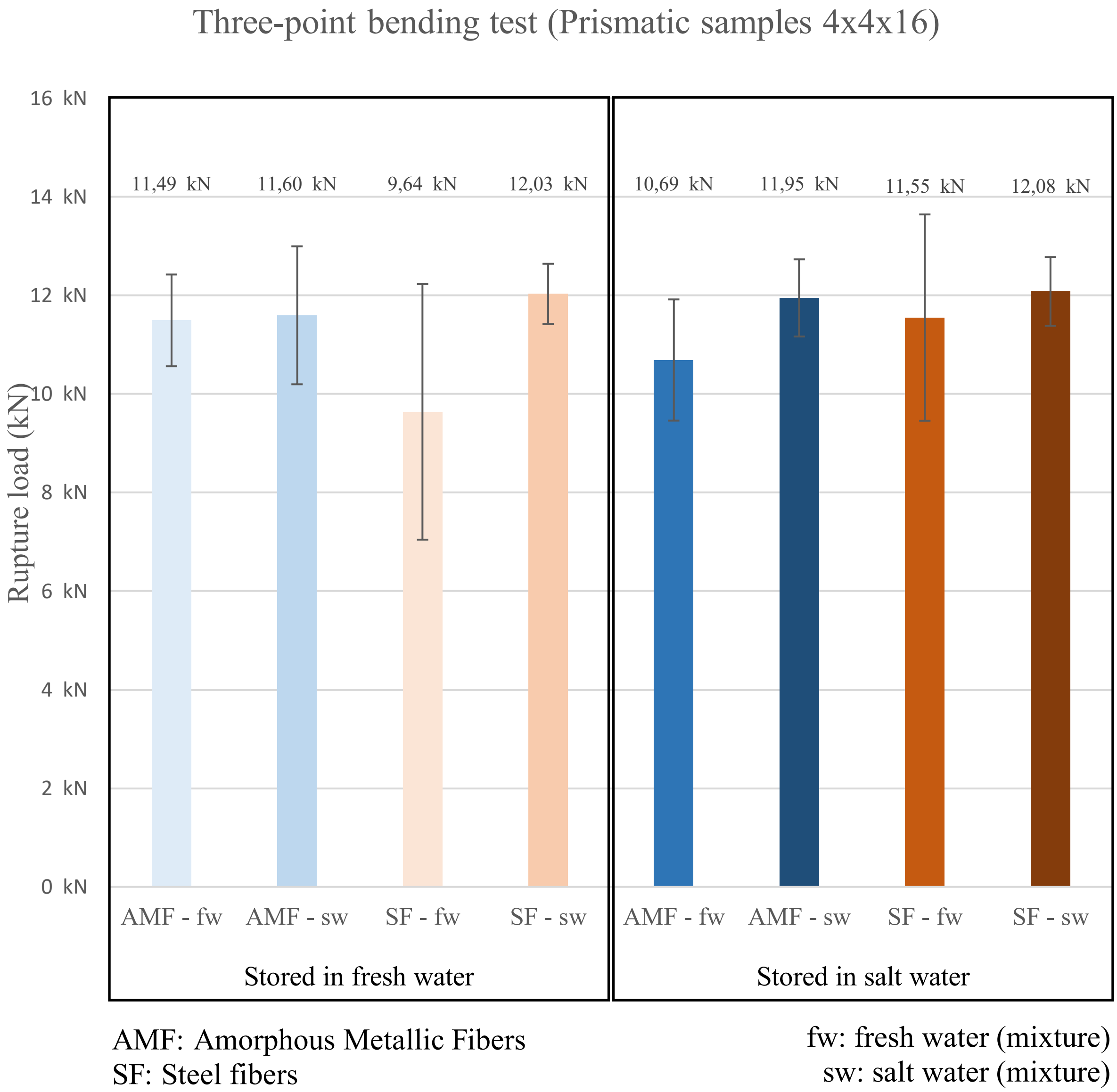


Figure 4: Bending test carried out on samples stored in clear and salt water

The following final samples were obtained:

- 3 samples of 45x15x3 (cm) composed with AMF cut in the flow direction
- 3 samples of 45x15x3 (cm) composed with AMF cut perpendicular to the flow direction
- 3 samples of 45x15x3 (cm) composed with SF cut in the flow direction
- 3 samples of 45x15x3 (cm) composed with SF cut perpendicular to the flow direction

Once cut, the samples were stored in water for 28 days before being tested in flexion through a three-point bending test. For the samples composed of SF, the fibers were mainly oriented within the flow direction on the bottom of the slab and perpendicularly to it on the surface. This observation can be explained by the creation of a concrete wave forming during the pouring in the mold. Thus, fibers are not oriented in the same direction at the top and at the bottom of the samples. During a bending test, the bottom fibers are the one under stress, hence the sample were tested on both side in order to obtain an average resistance of the samples in flexion.

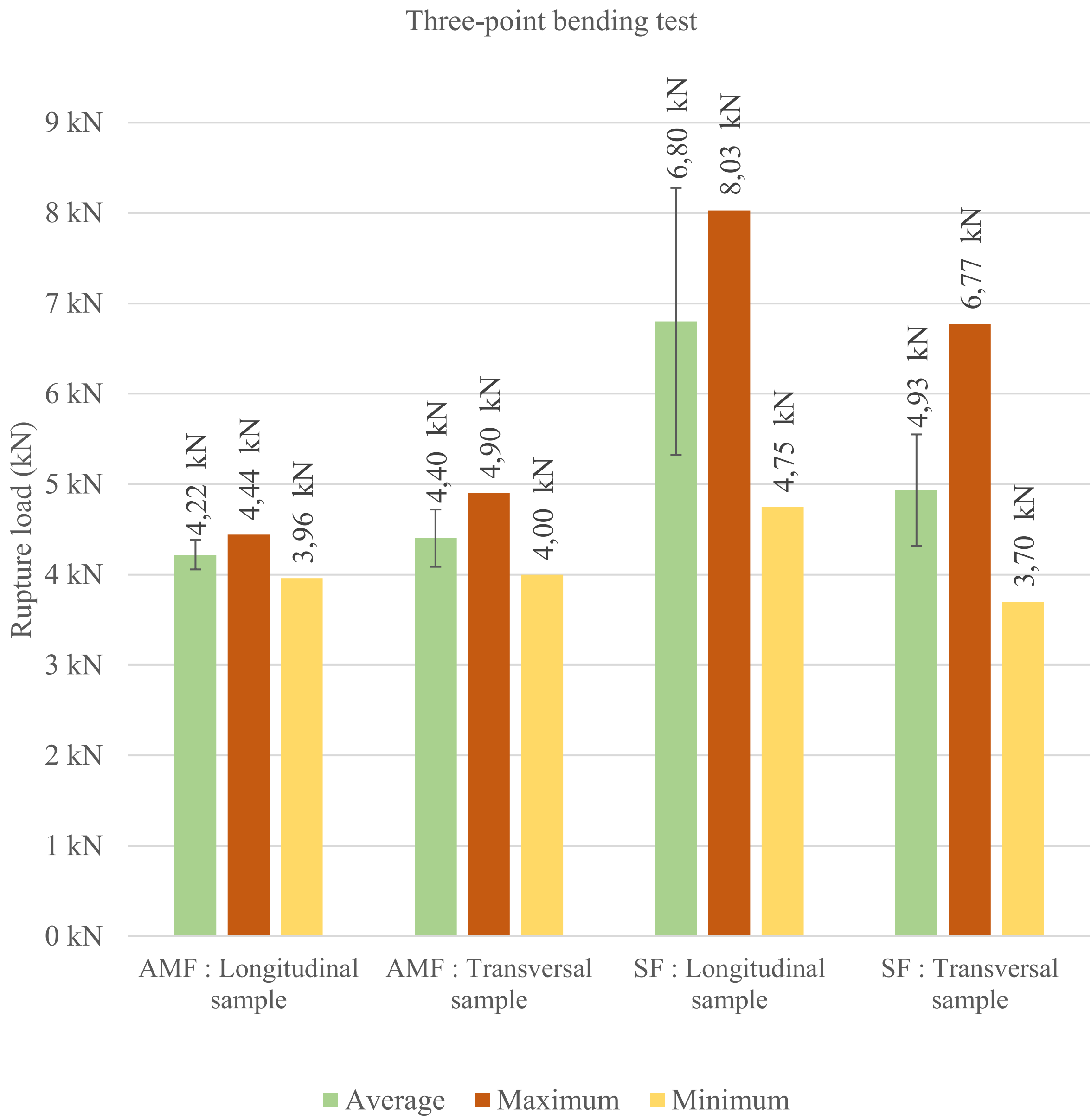


Figure 5: Three-point bending test of the 45x15x3 (cm) samples

Preferential orientations were not observed with the AMF; the average results (Fig. 5) are similar for the two orientations (5.0 % difference). It allows us to conclude that the method of placing the UHPFRC composed with AMF should not affect the mechanical resistance of the concrete. It is a technical advantage that allows the composition of much more complex molds.

In contrast, the SF seem to be much more affected by the pouring method (27.5 % difference). Two layers of fibers can be identified: on the bottom, the fibers are oriented in the same direction as the concrete flow and on the surface their direction is perpendicular.

By comparing the results of these tests, samples composed with SF present a higher bending resistance. Yet, when comparing the deformation to the force applied, the concrete composed of AMF presents a better rigidity which may be searched (for a force of 4.3 kN applied, the deformations are: AMF: 0.6 mm, SF: 1.27 mm). For the same load, the deformation can be doubled by using SF. This rigidity may be looked for if other supporting elements are linked to the UHPFRC structure in a way that a too important deformation could lead to a deformation on the overall structure. This rigidity could also be searched for bracing elements.

4. CONCLUSION

The referenced tests showed similar performance levels between the UHPFRC dosed with 1.5 % of amorphous metallic fibers and the one dosed with 2 % of steel fibers. We can notice that the results seem more homogeneous with the AMF for the different mixes (with fresh and salt water) and for the different curing environments (in fresh and salt water). The use of sea water in the composition of UHPFRC could be a new approach, especially in areas where fresh water is scarce. On an aesthetic point of view, differences were obvious as amorphous metallic fibers do not corrode. This characteristic is a major asset in architectural design and opens new design possibilities, as rust is not an issue, especially for projects exposed to extreme humid climate such as the sea shore.

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