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# ANALYSIS OF THE INFLUENCE OF STEEL FIBER CONTENT RELATED TO EXCESS VOLUME OF ULTRA-HIGH-PERFORMANCE CONCRETE PAST

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**ARTIGO ORIGINAL**

## RESUMO

O Concreto de Ultra-Alto Desempenho (UHPC) é conhecido por suas propriedades excepcionais. O objetivo desta pesquisa foi analisar a influência do teor de fibras de aço e do volume de pasta nas propriedades do UHPC e avaliar seu desempenho no estado fresco e endurecido. Foram realizados ensaios com diferentes teores de fibras de aço (0% a 5%) e volumes de pasta (20%, 40%, 60% e 80% de excesso de pasta), considerando espalhabilidade, trabalhabilidade e resistência à compressão. No estado fresco, observou-se que a adição de fibras reduziu a espalhabilidade, com uma diminuição entre 6% e 21%. Por outro lado, o aumento da quantidade de excesso de pasta melhorou a fluidez e trabalhabilidade das misturas. No estado endurecido, não houve diferença estatisticamente significativa entre as misturas com diferentes teores de pasta. No entanto, verificou-se que o aumento do teor de fibras reduziu a resistência à compressão do UHPC. O aumento da quantidade de pasta em excesso não teve efeito significativo na resistência, mas melhorou a fluidez e a consistência da mistura quando fresca. A pesquisa mostrou que o teor de fibras afeta a trabalhabilidade e a resistência do UHPC, enquanto o volume da pasta favorece a fluidez sem comprometer a resistência à compressão no estado endurecido.

**Palavras-chave:** concreto de ultra-alto desempenho; fibras de aço; pasta; dosagem; mistura.

## ABSTRACT

Ultra-High-Performance Concrete (UHPC) is known for its exceptional properties. The objective of this research was to analyze the influence of steel fiber content and paste volume on the properties of UHPC and to evaluate its performance in the fresh and hardened state. Tests were carried out with different steel fiber contents (0% to 5%) and paste volumes (20%, 40%, 60% and 80% excess paste), considering spreadability, workability and compressive strength. In the fresh state, it was observed that the addition of fibers reduced the spreadability, with a decrease between 6% and 21%. On the other hand, increasing the amount of excess paste improved the flowability and workability of the mixes. In the cured state, there was no statistically significant difference between the mixes with different paste contents. However, it was found that increasing the fiber content reduced the compressive strength of UHPC. Increasing the amount of excess paste did not have a significant effect on strength, but did improve the flowability and consistency of the mix when fresh. The research showed that the fiber content affects the workability and strength of the UHPC, while the paste volume favors the flowability without compromising the compressive strength in the hardened state.

**Keywords:** ultra-high-performance concrete; steel fibers; paste; dosage; mix.

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# 1 INTRODUCTION

Ultra-High-Performance Concrete (UHPC) is characterized by mechanical and physical properties such as high compressive strength, ductility, workability and durability (Richard and Cheyrezy 1995, Meng *et al*. 2020). These properties are the result of its dense microstructure with low porosity and high compactness (Larrard and Sedran 1994) and the use of components such as microsilica, quartz powder and superplasticizing, in addition to a low water/binder ratio (Shi *et al*. 2015, Alkaysi *et al*. 2016). This combination of factors gives UHPC superior performance compared to conventional concretes (Du *et al*. 2021).

In particular, the addition of metal fibers increases the toughness and ductility of concrete (Shi *et al*. 2015, Perry 2018). Studies show that the addition of steel fibers increases the flexural strength of UHPC (Bajaber and Hakeem 2021). The influence of fibers on the mechanical properties of UHPC depends on factors such as fiber type and content, shape factor, and fiber orientation in the mix (Christi *et al*. 2022). However, the addition of fibers can also cause difficulties in production, such as air entrapment and loss of workability, and affect the rheology of the mix (Sohail *et al*. 2018). Therefore, it is necessary to optimize the fiber content and paste volume to ensure adequate workability and performance of the UHPC, balancing the fluidity and cohesion of the mix (Kwan *et al*. 2012).

The slump flow test is used to evaluate the workability of UHPC, where in addition to obtaining the opening of the concrete mix, the apparent plastic viscosity for free flow of this mix can also be observed (Hung *et al*. 2020).

The mix design of UHPC is a critical factor in achieving the desired properties (Damineli *et al*. 2017). Particle packing is an important step in the compaction process, ensuring a dense microstructure with minimal voids (Vanderlei 2004, Dingqiang *et al*. 2020). There are several models for particle packing, such as the Alfred model (Funk and Dinger 1994) and the Toufar model (Toufar *et al*. 1976).

Paste volume is an important factor in UHPC design, affecting the workability, strength and durability of the material (Piasta and Zarzycki 2017). The excess paste theory, proposed by Kennedy (Kennedy 1940), divides the paste volume into dense paste and excess paste (Wong and Kwan 2008). The excess paste acts to disperse and lubricate the particles, while the dense paste fills the intergranular voids (Zhang *et al*. 2020). Control of the paste volume is essential to ensure the flowability and cohesion of the UHPC and to avoid problems such as segregation and exudation (Kwan and Li 2012).

Fiber content affects the mechanical properties of the material, such as tensile and flexural strength, but excessive levels can affect the workability and performance of the concrete (Kusumawardhaningsih 2015).

Considering the main challenges in the study of UHPC, the main objective of this research is to analyze the influence of the steel fiber content in relation to the excess paste volume in UHPC, evaluating its performance in the fresh and hardened state. The relevance of this research is justified by the growing importance of UHPC in civil engineering and the need to improve the knowledge of its formulation, especially in relation to the influence of fibers and paste on its properties.

## 2 MATERIALS AND METHODS

### EXPERIMENTAL PROGRAM

The concrete mix was defined using the Alfred, Toufar, and wet packing methods, based on the material properties. The minimum paste volume required to fill the aggregate voids was then determined. The amount of microsilica and additives was determined using parameters from the literature and specific tests.

After defining the minimum paste content, the amount of material for blends with excess paste from 20% to 80% was calculated. The maximum spread allowed by the standard, 850 mm, was selected and fibers were added up to the minimum spread limit (550 mm) or the maximum recommended content (5%). A total of 30 different mixes with 5 excess paste contents (0%, 20%, 40%, 60% and 80%) and 6 fiber contents (0%, 1%, 2%, 3%, 4% and 5%) were analyzed in the fresh and hardened state, resulting in more than 180 test specimens. These mixes had a nomenclature defined by X.YY, where X is the fiber content and YY is the paste content of the mix, for example, mix 5.60 is the one that contains 5% fibers and 60% excess paste.

## SELECTION AND CHARACTERIZATION OF MATERIALS

The materials used to develop the research were a superplasticizer additive based on polycarboxylate polymers, fine and medium sands, quartz powder, Portland cement CP V-ARI, silica fume and steel fibers with low carbon contente.

### *Cement*

Portland cement CP V-ARI is a cement certified according to NBR 16697, consisting of 95% to 100% clinker. Its specific gravity is 3.12 g/cm3. Some chemical, mechanical and physical properties are given in Table 1.

Tabel 1 – Characteristics of CPV – ARI cement

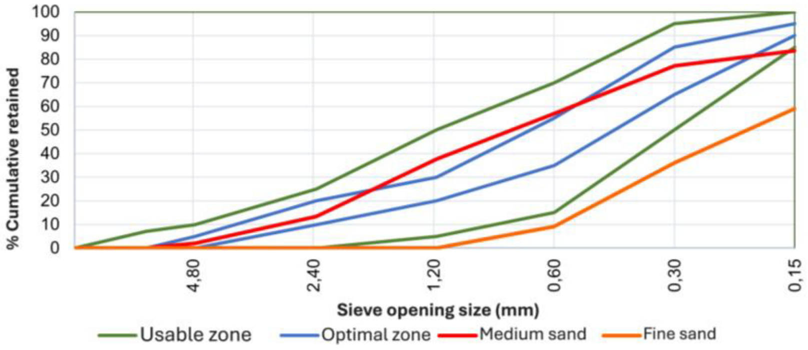
| **Properties** | **Loss on ignition** | **Insoluble residue** | **Magnesium oxide content** | **Reference strength at 28 days** | **Initial setting time** |
|---|---|---|---|---|---|
| **Standard ref. (NBR 16697)** | ≤ 6.5% | ≤ 3.5% | ≤ 6.5% | ≥ 34 MPa | ≥ 60 min |
| **Value specified by the manufacturer** | 5.4% | 2.5% | 5.8% | 42.1 MPa | 238 min |

Source: Adapted from the manufacturer's technical data sheet

### *Fine Aggregate*

The fine sand had a specific gravity of 2703 kg/m$^3$, unit mass of 1521 kg/m$^3$, fineness modulus of 1.04 and maximum diameter of 0.6 mm. The medium sand had a specific gravity of 2381 kg/m$^3$, a unit mass of 1486 kg/m$^3$, a fineness modulus of 2.71, and a maximum grain diameter of 2.4 mm. Figure 1 shows the particle size curves of the sands.

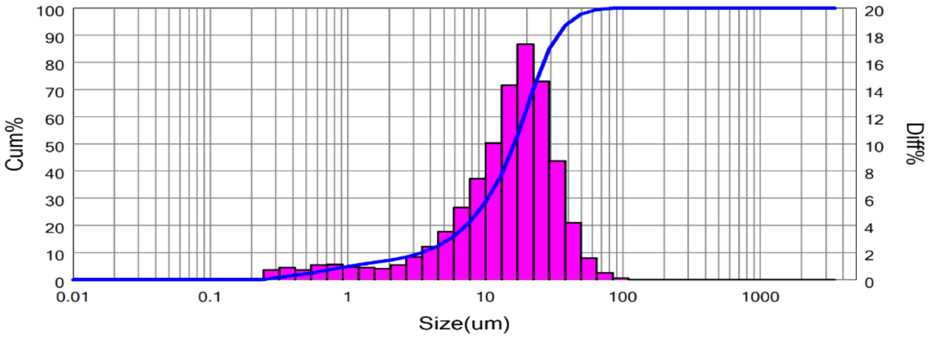
Figure 2 – Particle size curves of sands



*Quartz Powder*

The specific mass value obtained was 2620 $kg/m^3$ and the unit mass was 913 $kg/m^3$. Laser particle size analysis gave the results shown in Figure 2, where the largest diameter particle is 0.15 mm and the smallest diameter is 0.005 mm, with an average particle diameter ($d50$) of 16.31 µm.

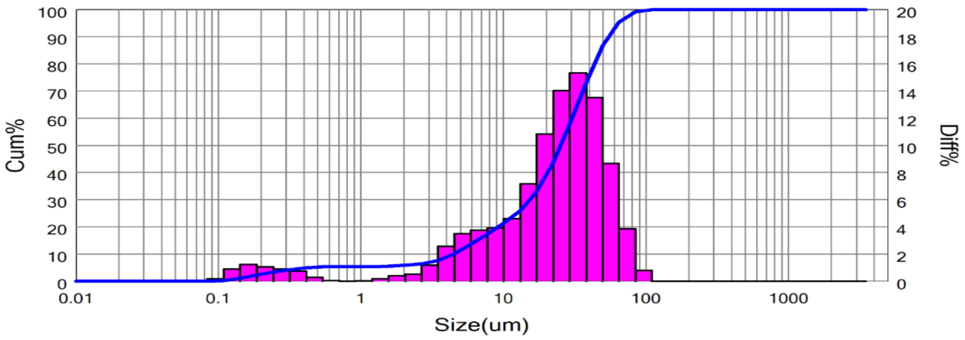
Figure 2 – Particle size curves of quartz powder



*Silica Fume*

In this work, the silica fume selected has the characteristics of a specific mass of 2220 $kg/m^3$ and a unit mass of 350 $kg/m^3$. It has a $SiO_2$ content of more than 90%. The particle size curve is shown in Figure 3, where the particle with the largest diameter is 0.063 mm and the smallest diameter is 0.005 mm, presenting an average particle diameter ($d50$) of 25.28 µm.

Figure 3 – Particle size curves of sílica fume



*Chemical Admixture*

Due to the low water/binder ratio characteristic of ultra-high-performance concretes, the use of a Chemical admixture based on polycarboxylate polymer technology (PCE) was chosen. According to the manufacturer, this product has a density of 1.12 kg/m³. Recommended contents range from 0.2% to 5% of the cement mass.

*Steel Fibers*

The manufacturer's technical data for the fibers used in this work can be found in Table 2.

Tabel 2 – Properties of steel fibers

| Steel type | Form factor | Dimension (mm) | Area (mm²) | Density (kg/m³) | Maximum tensile load (N) | Maximum tensile stress (MPa) |
|---|---|---|---|---|---|---|
| **Carbon steel** | 39 | 0,75 x 30 | 22,5 | 7840 | >22500 | >1000 |

Source: Adapted from the manufacturer's technical data sheet

## STUDY OF QUANTITIES AND DEVELOPMENT OF UHPC MIX DESIGN

### *Granular Packing*

For granular packing, Alfred's models were used to determine the ideal curve and, based on the ideal curve, a granular mixing procedure was performed by matrix analysis according to Maia et al (2024) to define the real curve, trying to approximate the real granulometric curve to the ideal one. The Packing Deviation Index (PDI) (Christ et al 2022) was calculated to evaluate the difference between the real and ideal curves.

The Toufar method was used to determine the void volume of the aggregate mix, which is the minimum volume of paste required to fill the voids between the aggregates.

Wet Packing Method

The wet packing method was used to determine the appropriate water/binder (w/b) ratio for UHPC as described in (Maia *et al*. 2025). The silica fume content was set at 25% of the cement mass based on literature and previous research (Hamad *et al*. 2024, Zheng *et al*. 2022). The chemical admixture content was determined experimentally by defining the saturation point of the chemical admixture, aiming for a stable and self-compacting paste. The ideal w/b ratio was defined as that which gave the highest concentration of solids and the lowest void index in the mix.

### *Determination of UHPC Mix Design*

The Toufar packing method also defines the percentage by volume of each aggregate used and the quartz powder. In the wet packing method, where the silica fume content is set at 25%, the w/b ratio and the cement volume are defined.

The reference mix was defined with 0% excess paste, which is exactly the amount of material calculated earlier. The material quantities were then defined for 20%, 40%, 60% and 80% excess paste. Table 3 shows the calculated material consumption.

Tabel 3 – Material consumption in kg/m$^3$ of the mixtures

| **Excess paste** | **0%** | **20%** | **40%** | **60%** | **80%** |
|---|---|---|---|---|---|
| **Cement (kg/m$^3$)** | 590.10 | 708.12 | 826.14 | 944.15 | 1062.17 |
| **Silica fume (kg/m$^3$)** | 147.52 | 177.03 | 206.53 | 236.04 | 265.54 |
| **Quartz powder (kg/m$^3$)** | 532.35 | 464.74 | 397.14 | 329.54 | 261.94 |
| **Medium sand (kg/m$^3$)** | 849.56 | 741.67 | 633.79 | 525.91 | 418.02 |
| **Fine sand (kg/m$^3$)** | 139.61 | 121.88 | 104.15 | 86.42 | 68.69 |

| | | | | | |
|---|---|---|---|---|---|
| **Water (kg/m$^3$)** | 132.77 | 159.33 | 185.88 | 212.43 | 238.99 |
| **Chemical admixture (kg/m$^3$)** | 36.88 | 44.26 | 51.63 | 59.01 | 66.39 |

*Increase of Steel Fibers*

The metallic fiber contents used were 0% to 5%, in relation to the mass of binders (Xue *et al*. 2024). The limit of 5% was chosen because it is the first value above the maximum content recommended by the equation proposed by Christ et al (2022).

With the definition of the quantity of fibers and the UHPC mix, the mixtures indicated in Table 4 were made.

Tabel 4 – Mixtures to be manufactured

| **Excess paste** | **0%** | **20%** | **40%** | **60%** | **80%** |
|---|---|---|---|---|---|
| **Fiber content** | | | | | |
| **0%** | Mix 0.00 | Mix 0.20 | Mix 0.40 | Mix 0.60 | Mix 0.80 |
| **1%** | Mix 1.00 | Mix 1.20 | Mix 1.40 | Mix 1.60 | Mix 1.80 |
| **2%** | Mix 2.00 | Mix 2.20 | Mix 2.40 | Mix 2.60 | Mix 2.80 |
| **3%** | Mix 3.00 | Mix 3.20 | Mix 3.40 | Mix 3.60 | Mix 3.80 |
| **4%** | Mix 4.00 | Mix 4.20 | Mix 4.40 | Mix 4.60 | Mix 4.80 |
| **5%** | Mix 5.00 | Mix 5.20 | Mix 5.40 | Mix 5.60 | Mix 5.80 |

## TESTS IN THE FRESH STATE

### *Slump Flow Test*

The UHPC mix for the slump flow test was prepared with a mechanical mixer. The concrete spread was measured and classified, being as SF1 for spreads between 550 mm and 650 mm, SF2 for spreads between 660 mm and 750 mm, and SF3 for spreads between 760 mm and 850 mm.

### *Mini Slump Test*

The mini slump test was conducted using a mortar mixer. The purpose of this test was to correlate with the results of the slump flow test in order to convert the mini slump spread values to slump flow test values.

The mini slump test was performed in two stages: MS1 and MS2. In the first stage, with the production of MS1 mixes, the test was carried out with the same w/b ratios used in the slump flow test, with the aim of comparing the results obtained at different scales. In the second stage, with the production of MS2 mixes, the test was performed with new w/b ratios, adjusted to ensure adequate workability of the UHPC at the reduced scale of the mini slump test.

### TESTS IN THE HARDNED STATE

After analyzing the mixes in the fresh state, the hardened state was evaluated by the compressive strength test. For the concrete made with the mechanical mixer, 10x20cm cylindrical molds were used, which were cast after the slump flow test. For the concrete made in the mortar mixer, 5x10cm metal molds were used, which were cast after the mini slump test. The analysis of the properties of the hardened state was done in three parts: analysis of the results of the concrete made in the mechanical mixer (SF); analysis of the concrete made in the mortar mixer with the same w/b ratio as SF (MS1); and analysis of the concrete made in the mortar mixer with a different w/b ratio than in the previous tests (MS2).

For SF concrete, 4 specimens were made per mix (0% to 80% excess paste, always with 5% fibers) for a total of 20 specimens. These were cured for 28 days in a controlled environment, rectified and crushed. For MS1 and MS2 concretes, 6 test specimens were prepared per percentage of fibers associated with excess paste, for a total of 36 specimens per mix and 180 specimens in total. The specimens were subjected to wet and thermal curing. After 24 hours of molding, they were demolded and wet cured for 48 hours. The thermal cure temperature gradually increased to 90ºC, where they remained for 72 hours. The specimens then continued in the wet cure until the 28-day molding was completed for the compressive strength test.

## 3 RESULTS AND ANALISYS

### UHPC MIX DESIGN

#### *Aggregate Properties*

The Alfred packing model was used to evaluate the ideal mix, which resulted in a modulus of fineness (MF) of 1.89, suitable for fine mixes. The percentages of fine sand

(8.44%), medium sand (58.34%), and quartz powder (33.22%) in the mix were then calculated. The new particle size distribution curve showed a fineness modulus of 1.80 and a Packing Deviation Index (PDI) of 41.5, indicating a high proximity between the ideal and actual curves calculated by the Alfred packing method.

### *Determination of minimum paste volume*

The second stage of the dosage method consisted of determining the minimum volume of paste required in the mixture to fill the voids between the aggregates. Based on the results of the Toufar method, the minimum amount of paste required for the mixture was determined to be 38.84%.

### *Definition of the water/binder ratio (w/b)*

The third step of the dosage method was to determine the water/binder (w/b) ratio of the mix. For this purpose, the wet packing method was used with different w/b ratios ranging from 0.10 to 0.24.

The results of the wet packing test allowed us to determine the ideal w/c ratio of 0.52 by volume. This ratio corresponds to the highest packing density and the lowest void ratio. The w/c ratio of 0.52 by volume corresponds to a w/c content of 0.18. The w/c ratio of 0.18 was therefore defined as the ideal, allowing further research to obtain the other necessary parameters.

### *Determination of UHPC mix design*

Each mix was adjusted by adding water to achieve a maximum spread of 850 mm in the slump flow test, which characterizes a self-compacting concrete (SCC). Based on the quantities of materials, Table 5 shows the mixes of ultra-high-performance concrete, with the quantities of each material for each mix, including the reference mix and the mixes with excess paste.

Tabel 5 – Ultra-high performance concrete mixes

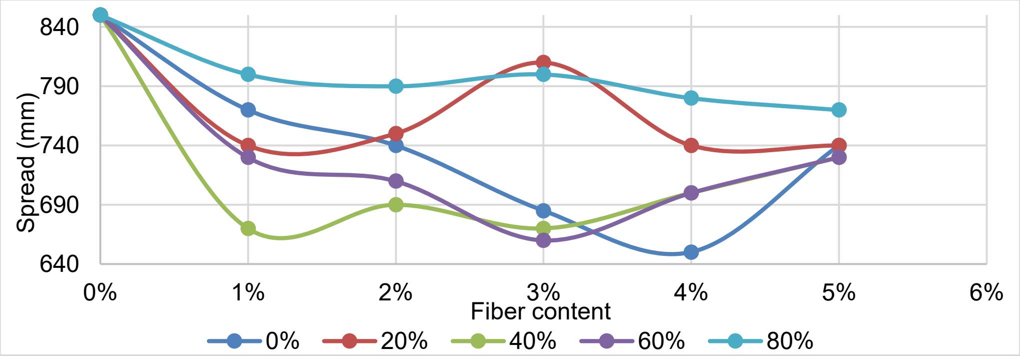
| Excess paste | Cement | Silica fume | Quartz powder | Medium sand | Fine sand | Water | Chemical admixture |
|---|---|---|---|---|---|---|---|
| **0%** | 1 | 0.25 | 0.9 | 1.44 | 0.24 | 0.18 | 0.05 |
| **20%** | 1 | 0.25 | 0.66 | 1.05 | 0.17 | 0.18 | 0.05 |
| **40%** | 1 | 0.25 | 0.48 | 0.77 | 0.13 | 0.18 | 0.05 |
| **60%** | 1 | 0.25 | 0.35 | 0.56 | 0.09 | 0,.18 | 0.05 |
| **80%** | 1 | 0.25 | 0.25 | 0.39 | 0.06 | 0.18 | 0.05 |

## ANALYSIS OF PROPERTIES IN THE FRESH STATE

### *Slump flow test*

Slump flow tests were carried out to evaluate the workability of the mixes, using a spread of 850 mm as the initial parameter. The addition of water was progressively adjusted until this value was reached, with the first w/b ratios analyzed ranging from 0.18 to 0.25. It was observed that the mix with no excess paste (0.00) required a greater amount of water due to the high aggregate content, while the mixes with a greater paste volume (0.40, 0.60 and 0.80) reached the parameter with lower w/b ratio. The inclusion of fibers reduced the spread of the mixes in a non-linear manner, varying between 6% and 21% for the 1% fiber content compared to the mix without fibers, and showing a tendency to converge to 740 mm for the 5% fiber content mixes. These facts can be observed in Figure 4.

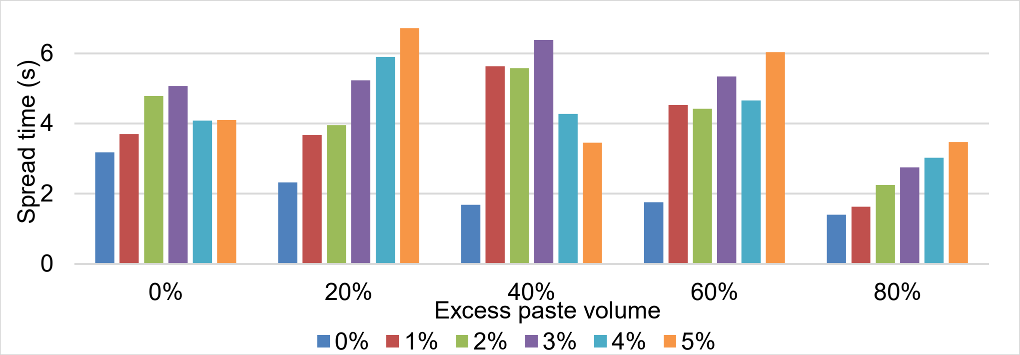
Figure 4 – Performance of all mixtures in the slump flow test



Of the five compounds analyzed, 56.7% were classified as SF2 and 40% as SF3, with only one compound classified as SF1. The T500 time showed a tendency for the viscosity increase with the addition of fibers, especially for the mixes with 20% and

80% excess paste, while the others showed clear variations, as can be seen in Figure 5.

Figure 5 – Apparent plastic viscosity (T500) of the studied mixtures



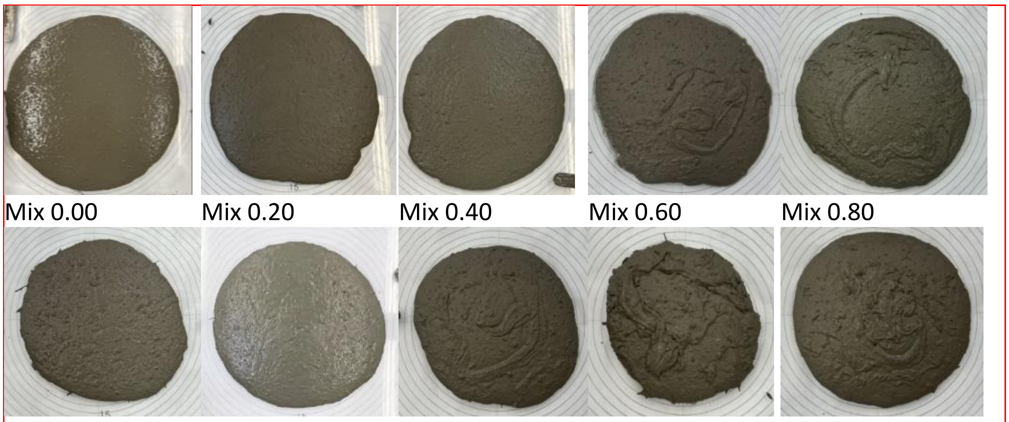
These results confirm the influence of excess paste volume and fiber content on the workability and fluidity of ultra-high-performance concretes.

*Mini slump test MS1*

In the second part of this research, the mixes were analysed on a reduced scale with the aim of later correlating with the values obtained from the slump flow test. Table 6 shows the results of the mini slump test for the first scale, MS1. The results show that the spread of UHPC decreases as the steel fibre content increases, confirming the trend observed in the slump flow test.

Figure 6 shows the visual appearance of some mixes after the mini slump test for the first stage, MS1. The images show that in some cases the amount of water used was insufficient to ensure adequate workability of the UHPC, particularly for mixes with higher fiber content and lower excess paste.

Figure 6 – Fresh appearance of the mixtures after mini slump test (MS1)



Mix 0.00 Mix 0.20 Mix 0.40 Mix 0.60 Mix 0.80

Mix 5.00 Mix 5.20 Mix 4.40 Mix 5.60 Mix 5.80

By visual analysis of the mixes, it can be confirmed that although the slump flow test gave different w/b ratios to those obtained by the wet packing method, in the reduced scale test (mini slump) the amount of water in some mixes was almost insufficient to give the concrete a self-compacting appearance. This effect is noticeable in mixes below the w/c ratio suggested by the method. On the other hand, in other cases the w/b values appear to be higher than necessary, making the concrete excessively self-compacting and almost exuding, as is the case with mixes containing 0% and 20% excess paste. A new mini-slump test was therefore carried out, adjusting the w/b ratios so that there was neither too much nor too little water in the mixes.

*Mini slump test MS2*

In the second stage of the mini-slump test, the test (MS2) was repeated to ensure a self-compacting UHPC, adjusting the amount of water and setting an initial spread of 290 mm. This approach was based on the mix with 40% excess paste, which showed good consistency in the first test and had the w/b defined by the wet pack. With the updated w/b ratios, the mixes were re-evaluated.

Table 6 - Spread in MS1 mini slump test (mm)

| **w/b ratio** | | 0.25 | 0.23 | 0.18 | 0.16 | 0.16 |
|---|---|---|---|---|---|---|
| **Fiber content** | | **Excess paste** | | | | |
| | | **0%** | **20%** | **40%** | **60%** | **80%** |
| | **0%** | 330 | 295 | 290 | 220 | 225 |
| | **1%** | 320 | 270 | 250 | 200 | 205 |
| | **2%** | 315 | 260 | 230 | 190 | 195 |
| | **3%** | 290 | 250 | 215 | 200 | 200 |

Table 7 - Spread in MS2 mini slump test (mm)

| **w/b ratio** | | 0.23 | 0.21 | 0.18 | 0.18 | 0.18 |
|---|---|---|---|---|---|---|
| **Fiber content** | | **Excess paste** | | | | |
| | | 0% | 20% | 40% | 60% | 80% |
| | 0% | 290 | 290 | 290 | 290 | 290 |
| | 1% | 280 | 275 | 260 | 275 | 285 |
| | 2% | 270 | 275 | 245 | 260 | 280 |
| | 3% | 265 | 260 | 235 | 250 | 270 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **4%** | 255 | 240 | 210 | 190 | 200 |
| | **5%** | 230 | 235 | 205 | 175 | 185 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 4% | 250 | 255 | 230 | 255 | 260 |
| | 5% | 255 | 250 | 230 | 245 | 250 |

The results showed that the opening decreased with increasing steel fiber content, but without compromising the self-compacting properties, even in mixtures with 5% fibers. Visual analysis confirmed that all mixes maintained the expected consistency. Mixes with 0% and 20% excess paste remained more homogeneous, while those with 40% or more showed reduced workability. When comparing the two batches, the adjustment of the water content and the initial standardization of the spread resulted in a better performance of the MS2 mixes compared to MS1.

### *Correlation between tests*

After performing the slump flow and mini slump tests, an analysis was performed to correlate the results obtained in both tests. The objective of the correlation was to determine whether the mini slump test, which is simpler and faster to perform, could be used as an alternative to the slump flow test to evaluate the workability of UHPC.

To perform the correlation, the results of the Mini Slump Test were converted to the Slump Flow Test scale using a conversion factor that considers the dimensions of the moulds used in both tests. This conversion was based on the difference in volume between the truncated cones used in each test and the difference between the maximum spread of each test. The volume of the slump flow test truncated cone (Vsf) is 549778.72 $mm^3$, while the volume of the mini slump test truncated cone (Vms) is 344.00 $mm^3$. The maximum spread for the slump flow test (Δsf) is 850 mm and the maximum spread for the mini slump test (Δms) is 290 mm.

A change factor (Δ) has been established to convert the mini slump spread values to slump flow equivalent values, allowing comparison between tests.

$$\Delta = \frac{\left(\frac{V_{sf}}{V_{ms}}\right)^2}{\frac{\Delta_{sf}}{\Delta_{ms}}} \qquad (1)$$

The conversion was made using the MS2 data (Table 8), which showed better workability and uniformity, giving greater confidence in the comparison. This conversion factor was then used to convert the mini slump test spread values to the slump flow test scale, called mini slump factored (MSF). Thus, Table 8 shows the values obtained for SF and Table 9 shows the values obtained for MSF. From Table 9 it can be seen that none of the MSF mixes fit into the SF1 slump class, 12 of the 30 MSF samples were classified as SF2 and 18 as SF3

Table 8 - Slump flow spreading values (mm)

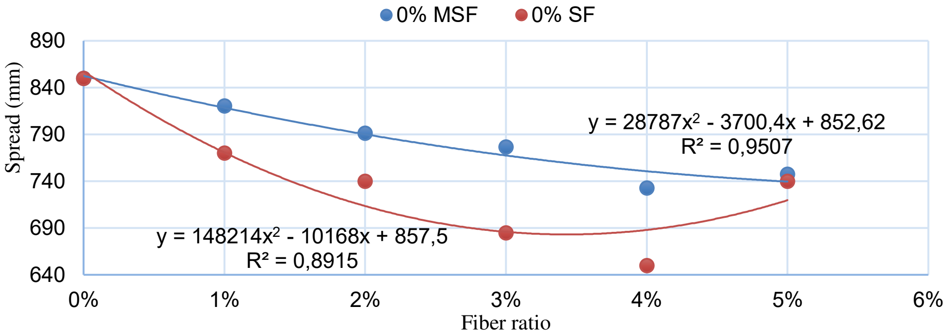
| | | **Excess paste content** | | | | |
|---|---|---|---|---|---|---|
| | | **0%** | **20%** | **40%** | **60%** | **80%** |
| **iber content** | **0%** | 850 | 850 | 850 | 850 | 850 |
| | **1%** | 770 | 740 | 670 | 730 | 800 |
| | **2%** | 740 | 750 | 690 | 710 | 790 |
| | **3%** | 685 | 810 | 670 | 660 | 800 |
| | **4%** | 650 | 740 | 700 | 700 | 780 |
| | **5%** | 740 | 740 | 730 | 730 | 770 |

Table 9 - Spread in MS2 mini slump test (mm)

| | | **Excess paste content** | | | | |
|---|---|---|---|---|---|---|
| | | 0% | 20% | 40% | 60% | 80% |
| **Fiber content** | 0% | 850 | 850 | 850 | 850 | 850 |
| | 1% | 821 | 806 | 762 | 806 | 835 |
| | 2% | 791 | 806 | 718 | 762 | 821 |
| | 3% | 777 | 762 | 703 | 733 | 791 |
| | 4% | 733 | 747 | 689 | 747 | 762 |
| | 5% | 740 | 740 | 730 | 730 | 770 |

The comparison between the MSF and SF mixes, shown in Figure 7, shows that the spread values converge to the same end point in mixes with high fiber content, indicating that both tests capture similar trends in the behavior of concrete with fiber addition.

Figure 7 – Spreads of the mixtures without excess paste from the mini slump factored (MSF) test and the slump flow (SF) test



The differences in spread can be justified by the lower amount of water used in the mini slump, which was adjusted relative to the first mix, proving the importance of the w/b ratio in the performance of the concrete. The Student's t-test confirmed that the mixes were statistically similar, taking into account the variation in fiber content and excess paste, demonstrating that the mini-slump and slump flow tests can be used in a complementary manner to evaluate the behavior of SCC and UHPC.

The analysis of the properties in the fresh state showed that the addition of steel fibers has a significant influence on the workability of UHPC, reducing the spreading and increasing the viscosity of the material. This effect is more pronounced for the mixes with lower paste overruns, suggesting that the paste overruns can partially compensate for the loss of workability caused by the fibers. The mini-slump test proved to be a viable alternative to the slump flow test for evaluating the workability of UHPC, especially in situations where the amount of concrete available is limited or when the test needs to be performed more quickly and economically.

## ANALYSIS OF PROPERTIES IN THE HARDENED STATE

### *Compressive strength for SF specimens*

The compressive strength test was carried out on the slump flow test specimens and the results are shown in Table 10. For each mix, 4 specimens with 5% fibers were prepared and they were not subjected to thermal curing, but only to wet curing.

Tabel 10 – Ultra-high performance concrete mixes

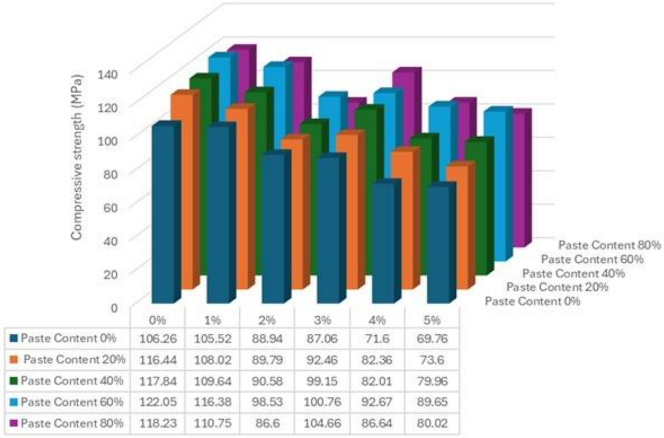
| **Mixs** | **Sample 1** | **Sample 2** | **Sample 3** | **Sample 4** | **Media** | **$\sigma_p$** | **VC** |
|---|---|---|---|---|---|---|---|
| **5.00** | 64.9 | 60.9 | 41.2 | 55.9 | 55.8 | 10.4 | 19% |
| **5.20** | 65.5 | 57.7 | 89.2 | 61.4 | 68.5 | 14.2 | 21% |
| **5.40** | 81.9 | 78.4 | 55.1 | 81.7 | 74.3 | 12.9 | 17% |
| **5.60** | 92.6 | 62.7 | 79.3 | 65.3 | 75.0 | 13.8 | 18% |
| **5.80** | 75.6 | 67.8 | 56.7 | 48.6 | 62.2 | 11.9 | 19% |

The results indicate that mixes with up to 60% excess paste showed increasing strength, but there was a significant drop in mix 5.80. The average strength was statistically the same for all mixes at the 5% level, except for mix 5.40 which had an average strength of 80.7 MPa after eliminating spurious data, which was statistically different.

### *Compressive strength for MS1 specimens*

Analysis of the mini slump test results showed that the mixes had significantly higher compressive strength than those produced in the conventional mixer (Mix SF), with an average increase of 50%. The compressive strength results, obtained from 6 samples per mix, were analyzed after spurious data analysis. Figure 8 shows, in addition to the corrected strength averages, that the increase in fibers reduces the strength of the concrete.

Figure 8 – Compressive strength (MPa) of MS1 samples after spurious data analysis



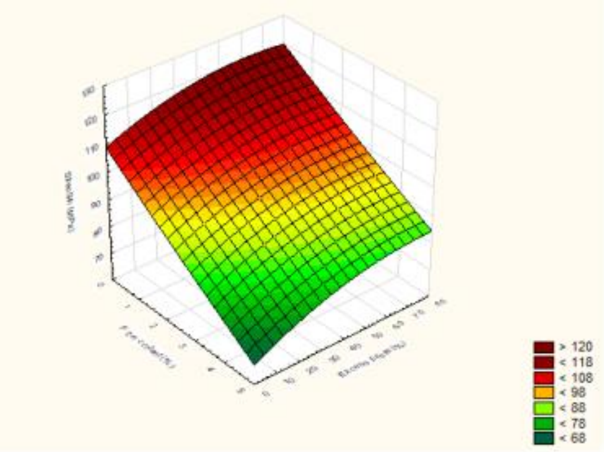
| | 0% | 1% | 2% | 3% | 4% | 5% |
|---|---|---|---|---|---|---|
| ■ Paste Content 0% | 106.26 | 105.52 | 88.94 | 87.06 | 71.6 | 69.76 |
| ■ Paste Content 20% | 116.44 | 108.02 | 89.79 | 92.46 | 82.36 | 73.6 |
| ■ Paste Content 40% | 117.84 | 109.64 | 90.58 | 99.15 | 82.01 | 79.96 |
| ■ Paste Content 60% | 122.05 | 116.38 | 98.53 | 100.76 | 92.67 | 89.65 |
| ■ Paste Content 80% | 118.23 | 110.75 | 86.6 | 104.66 | 86.64 | 80.02 |

The inferential statistical analysis resulted in a regression model expressed in equation (2):

$$RC = 108.6636 + (0.3686 * ep) - (8.7552 * fc) - (0.0029ep^2) + (0.0147 * ep * fc) + (0.0964 * fc^2) \quad (1)$$

Where RC is the compressive strength (MPa), ep is the excess paste, and fc is the fiber content, both given as percentages. The coefficient of 0.3686 indicates a minor influence of excess paste, while the negative coefficient of -8.7552 shows that increasing fiber content reduces compressive strength. The other coefficients reflect a small influence of the remaining terms. Statistical analysis revealed a strong correlation between the variables, with a correlation coefficient of 0.9576 and a coefficient of determination of 0.9171, meaning over 91% of the variation in compressive strength is explained by the independent variables. Analysis of Variance (ANOVA) confirmed the model's statistical significance, with a regression sum of squares of 5809.578 and an F-value of 138.2. Figure 9 displays the response surface illustrating the impact of fiber content and excess paste on compressive strength. The surface analysis shows a steep slope along the RC x fiber content axis, while the RC x excess paste axis exhibits a smoother variation, confirming the dominant influence of fiber content on compressive strength.

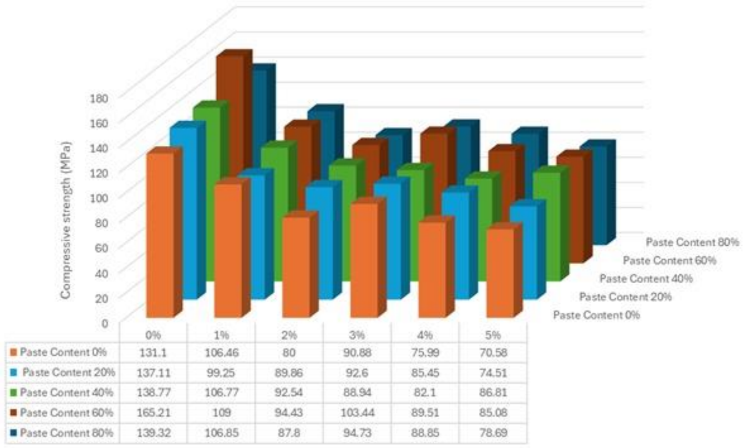
Figure 9 – Response surface for MS1 samples



*Compressive strength for MS2 specimens*

For the second batch of mixes, Figure 10 shows the results after analyzing the spurious data, indicating that the paste content had no effect on the compressive strength at the 5% significance level. The fiber content, on the other hand, showed an inverse relationship with a decrease in strength.

Figure 10 – Compressive strength (MPa) of MS2 samples after spurious data analysis



| | 0% | 1% | 2% | 3% | 4% | 5% |
|---|---|---|---|---|---|---|
| Paste Content 0% | 131.1 | 106.46 | 80 | 90.88 | 75.99 | 70.58 |
| Paste Content 20% | 137.11 | 99.25 | 89.86 | 92.6 | 85.45 | 74.51 |
| Paste Content 40% | 138.77 | 106.77 | 92.54 | 88.94 | 82.1 | 86.81 |
| Paste Content 60% | 165.21 | 109 | 94.43 | 103.44 | 89.51 | 85.08 |
| Paste Content 80% | 139.32 | 106.85 | 87.8 | 94.73 | 88.85 | 78.69 |

Based on the compressive strength data in Figure 10, a regression equation, shown in equation (3), was generated for the MS2 samples, taking excess paste and fiber content as independent variables.

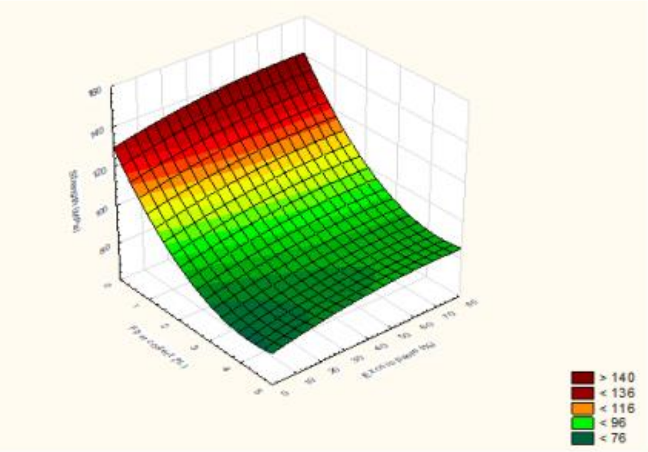
$$RC = 129.5008 + (0.3037 * ep) - (25.432 * fc) - (0.002 * ep^2) - (0.0055 * ep * fc) + (2.9629 * fc^2)$$

**4** (2)

The correlation between the variables is very strong, with a coefficient of 0.8757, indicating that the model explains a large proportion of the variability in the data. The analysis of variance confirmed the significance of the model, with a calculated F-value of 41.13, which is higher than the tabulated F-value, with a confidence level higher than 99.99%.

Partial correlations show that excess paste has a weak correlation with compressive strength, while fiber content has a very strong correlation. Finally, the generated response surface (Figure 11) shows that although excess paste initially increases the compressive strength, after a certain point it no longer contributes significantly to the strength. Furthermore, compared to the response surface of MS1, the strength of MS2 samples was superior due to the appropriate w/b ratio.

Figure 11 – Response surface for MS2 samples



*Correlation between tests*

When comparing the compressive strength results of the SF, MS1 and MS2 tests it was found that at 5% fiber content, the SF and MS1 tests are statistically equal with a p-value of 0.05075, which is above the significance level, indicating that there is no difference between the means. The t-statistic of -2.2965 is within the 95% acceptance interval, strengthening the rejection of the null hypothesis. This suggests that the change in mixing medium, which varied between the mixer (SF) and the mortar mixer

(MS1), did not affect the compressive strength, although it did affect the fresh state of the mixes.

The results of SF and MS2 for 5% fibers are statistically different, with a p-value of 0.03654 and a t-statistic of -2.507, which is outside the acceptable range. The difference between the means was -11.99 and the effect size was large (1.59), indicating that the change in w/b ratio and mixing medium affected the compressive strength.

Finally, when analyzing the MS1 and MS2 mixes, statistical analysis indicated that there was no significant difference between the compressive strength means, with a p-value of 0.9096, well above the significance level. The t-statistic of -0.1172 is within the 95% acceptance interval, indicating that the change in w/b ratio between tests did not have a negative or positive effect on the compressive strength of the hardened concrete.

## 5 CONCLUSIONS

This research, whose main objective was to analyse the influence of the addition of steel fibers in ultra-high-performance concretes (UHPCs) with different paste contents, was successful in its objectives and revealed some important aspects about the behavior of UHPCs in fresh and hardened states. The main conclusions of the study are presented in the following topics:

- The addition of steel fibers reduced the workability of fresh UHPC, which affected the spread ability and flow time. A 6% to 21% reduction in flowability was observed for mixes containing 1% fiber compared to those without fibers. In addition, increasing fiber content resulted in a slower flow time.
- Excess paste increased the workability of fresh UHPC but had no significant effect on compressive strength. Mixtures with higher paste content showed better spread ability and shorter flow time. However, the compressive strength was not significantly affected by excess paste.
- The addition of fibers had a negative effect on the compressive strength of

UHPC, and it is crucial to optimize the fiber content to find a balance between workability and mechanical strength. The mix with 3% fibers showed a slight increase in compressive strength compared to the other contents, indicating that there is an ideal fiber content to maximize strength.

- Adjusting the water/binder (w/b) ratio in the mini slump test (MS2) resulted in higher compressive strength values than those obtained in the slump flow (SF) test. The optimum w/b ratio should be determined for each test method to maximize the strength of the UHPC.
- Changing the mixing method (mixer vs. mortar mixer) did not significantly affect the compressive strength of UHPC. The compressive strength values obtained with the mixer (SF) were statistically equal to those obtained with the mortar mixer (MS1).

The conversion factor developed to convert the results of the mini slump test to the slump flow test will allow cost savings in future research. By converting the results of the mini slump test, which is cheaper and easier to perform, to the slump flow test, researchers can obtain information about the behavior of UHPC under different conditions without having to perform the slump flow test on a large scale, which can result in significant savings in time and resources.

## 6 REFERENCES

AHMAD, S. et al. Fracture toughness of UHPC mixtures: Effects of w/b ratio, cement and silica fume contents. **Construction and Building Materials**, v. 417, p. 135327, 2024. https://doi.org/10.1016/j.conbuildmat.2024.135327

AITCIN, P. C. Cements of yesterday and today concrete of tomorrow. **Cement and Concrete Research**, v. 30, p. 1349-1359, 2000. https://doi.org/10.1016/S0008-8846(00)00365-3

ALKAYSI, M.; EL-TAWIL, S.; LIU, Z.; HANSEN, W. Effects of silica powder and cement type on durability of ultra high performance concrete (UHPC). **Cement and Concrete Composites**, v. 66, p. 47-56, 2016. https://doi.org/10.1016/j.cemconcomp.2015.11.005

BAJABER, M. A.; HAKEEM, I. Y. UHPC evolution, development, and utilization in construction: A review. **Journal of Materials Research and Technology**, v. 10, p. 1058-1074, 2021. https://doi.org/10.1016/j.jmrt.2020.12.051

CHRIST, R.; TUTIKIAN, B.; HELENE, P. **Concreto de ultra-alto desempenho – UHPC: Fundamentos, propriedades e dosagem**. 1ª edição. São Paulo: Editora LEUD, p.176, 2022.

DAMINELI, B.; PILEGGI, R. G.; JOHN, V. M. Influence of packing and dispersion of particles on the cement content of concretes. **Revista IBRACON de Estruturas e Materiais**, v. 10, n. 05, p. 998-1024, 2017. https://doi.org/10.1590/S1983-41952017000500004

DINGQIANG, F. et al. Novel approach for developing a green Ultra-High Performance Concrete (UHPC) with advanced particles packing meso-structure. **Construction and Building Materials**, v. 265, p. 120339, 2020. https://doi.org/10.1016/j.conbuildmat.2020.120339

DU, J. et al. New development of ultra-high-performance concrete (UHPC). **Composites Part B: Engineering**, v. 224, p. 109220, 2021. https://doi.org/10.1016/j.compositesb.2021.109220

FUNK, J.E., DINGER, D. **Predictive process control of crowded particulate suspensions: applied to ceramic manufacturing**. New York, Springer Science & Business Media, 1994.

HUNG, C. C.; CHEN, Y. T.; YEN, C. H. Workability, fiber distribution, and mechanical properties of UHPC with hooked end steel macro-fibers. **Construction and Building Materials**, v. 260, p. 119944, 2020. https://doi.org/10.1016/j.conbuildmat.2020.119944

KANG, S. T.; KIM, J. K. The relation between fiber orientation and tensile behavior in an Ultra High Performance Fiber Reinforced Cementitious Composites (UHPFRCC). **Cement and Concrete Research**, v. 41, n. 10, p. 1001-1014, 2011. https://doi.org/10.1016/j.cemconres.2011.05.009

KENNEDY, C. H. The design of concrete mixes. **ACI Proceedings**, v. 36, p. 373-400, 1940. https://doi.org/10.14359/8528

KUSUMAWARDHANINGSIH, Y. et al. Tensile Strength behavior of UHPC and UHPFRC. **Procedia Engineering**, v. 125, p. 1081-1086, 2015. https://doi.org/10.1016/j.proeng.2015.11.166

KWAN, A. K. H.; LI, L. G. Combined effects of water film thickness and paste film thickness on rheology of mortar. **Materials and Structures**, v. 45, n. 9, p. 1359-1374, 2012. https://doi.org/10.1617/s11527-012-9837-y

KWAN, A. K. H.; CHEN, J. J.; LI, L. G. Effects of condensed silica fume and superfine cement on flowability of cement paste. In: APPLIED MECHANICS AND MATERIALS, Trans Tech Publications Ltd., v. 121, p. 2695-2700, 2012. https://doi.org/10.4028/www.scientific.net/AMM.121-126.2695

LARRARD, F.; SEDRAN, T. Optimization of ultra-high performance concrete by the use of a packing model. **Cement and Concrete Research**, v. 24, p. 997-1009, 1994. https://doi.org/10.1016/0008-8846(94)90022-1

MAIA, A. T.; MAZER, W.; FERREIRA, E. O. Granular packaging analysis for UHPC production. **Australian Journal of Civil Engineering,** 2024. https://doi.org/10.1080/14488353.2024.2419674.

MAIA, A. T.; FERREIRA, E. O.; MAZER, W. The Determination of the Content of Addition of Silica Fume and the Relationship of Water/Binder in UHPC Through the Wet Packing Method. **Revista Desafios**, v. 12, n. 4, 2025. https://doi.org/10.20873/2025_jul_17225

MENG, Q. et al. Steel/basalt rebar reinforced Ultra-High Performance Concrete components against methane-air explosion loads. **Composites Part B: Engineering**, v. 198, p. 108215, 2020. https://doi.org/10.1016/j.compositesb.2020.108215

PERRY, V. H. What really is ultra-high-performance concrete?—Towards a global definition. In: Proceedings of the 2nd International Conference on Ultra-HighPerformance Concrete Material & Structures UHPFRC, 2018.

PIASTA, W.; Zarzycki, B. The effect of cement paste volume and w/c ratio on shrinkage strain, water absorption and compressive strength of high performance concrete. **Construction and Building Materials**, v. 140, p. 395-402, 2017. https://doi.org/10.1016/j.conbuildmat.2017.02.033

RICHARD, P.; CHEYREZY, M. Composition of reactive powder concretes. **Cement and Concrete Research**, v. 25, n. 7, p. 1501-1511, 1995. https://doi.org/10.1016/0008-8846(95)00144-2

SHI, CAIJUN et al. A review on ultra high performance concrete: Part I. Raw materials and mixture design. **Construction and Building Materials**, v. 101, p. 741-751, 2015. https://doi.org/10.1016/j.conbuildmat.2015.10.088Get rights and content

SOHAIL, M. G. et al. Advancements in concrete mix designs: High-Performance and Ultrahigh-Performance Concretes from 1970 to 2016. **Journal of Materials in Civil Engineering**, v. 30, n. 3, ASCE 04017310-1, 2018. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002144

TOUFAR, W., BORN, M., AND KLOSE, E. Contribution of optimization of components of different density in polydispersed particle systems, **Freiberger Booklet** A, v. 558, 29-44, 1976.

VANDERLEI, R. D. **Análise experimental do Concreto de Pós Reativos: dosagem e propriedades mecânicas**. PhD Thesis. Universidade de São Paulo, 2004. https://doi.org/10.11606/T.18.2004.tde-23082006-095043

WONG, H. H. C.; KWAN, A. K. Rheology of cement paste: role of excess water to solid surface area ratio. **Journal of Materials in Civil Engineering**, v. 20, n. 2, 189-197, 2008. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:2(18

XUE, JUNQING et al. Experimental evaluation of the effectiveness of fiber orientation methods on the mechanical performance of UHPFRC. **Construction and Building Materials**, v. 448, 138184, 2024. https://doi.org/10.1016/j.conbuildmat.2024.138184

ZHANG, Y. et al. Experimental study on flexural behavior of damaged reinforced concrete (RC) beam strengthened by toughness-improved ultra-high performance concrete (UHPC) layer. **Composites Part B: Engineering**, v. 186, 107834, 2020. https://doi.org/10.1016/j.compositesb.2020.107834

ZHENG, QIAOMU et al. Revealing the effect of silica fume on the flexural behavior of ultra-high-performance fiber-reinforced concrete by acoustic emission technique. **Cement and Concrete Composites**, v. 131, 104563, 2022. https://doi.org/10.1016/j.cemconcomp.2022.104563

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