Analysis of the influence of excess cement paste content on the compression strength of UHPC

Análise da influência do excesso de teor de pasta de cimento na resistência à compressão do UHPC

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ABSTRACT
This research aimed to propose a rational method for dosing ultra-high performance concretes based on the association of three approaches: the definition of the ideal silica content, the use of the minimum paste volume, and the incorporation of fine basalt artificial sand. Through the combination of experimental methods and granular packing models, a robust experimental program consisting of eight steps was developed, aiming to obtain different compositions of ultra-high performance concretes, with self-compacting characteristics and compressive strength greater than 150 MPa at 28 days, after heat water treatment at 90°C. In addition, the influence of silica content, additional paste volume, different types of cure, test ages, and the addition of metallic fibers on the fluidity and strength of the composites were evaluated. Through the proposed method, the average strength of 186 MPa was achieved in the mix containing the minimum volume of paste, 484 kg/m³ of cement, and 25% silica fume. The results obtained indicate that the proposed method tends to have the best proportion among the component materials, giving rise to traits that fit the international parameters that define the UHPC, but with reduced paste volumes and consumption of binders lower than those identified in the related literature. Through a rational, economic, and sustainable approach, which aims to optimize the use of higher-cost materials and minimize the use of scarce natural resources, the method contributes positively to the technological development of the sector.
Keywords: Ultra High-Performance Concrete (UHPC), dosing method, particle packing, minimum paste volume, basalt artificial sand.

RESUMO
Esta pesquisa visou a proposição de um método racional de dosagem de concretos de ultra-alto desempenho fundamentado na associação das três abordagens: a definição do teor ideal de sílica, o emprego do mínimo volume de pasta e a incorporação do agregado miúdo artificial de basalto. Através da combinação entre métodos experimentais e modelos de empacotamento granular, um robusto programa experimental composto por oito etapas foi desenvolvido, visando a obtenção de traços de concretos de ultra-alto desempenho, com características autoadensáveis e resistência à compressão superior a 150 MPa aos 28 dias, após tratamento térmico a 90°C. Complementarmente, foram avaliados a influência do teor de sílica, do volume adicional de pasta, de diferentes tipos de cura, da idade de ensaio e da inclusão de fibras metálicas na fluidez e na resistência dos compósitos. Por meio do método proposto, a resistência média de 186 MPa foi lograda no traço contendo o mínimo volume de pasta, 484 kg/m³ de cimento e 25% de sílica ativa. Os resultados obtidos indicam que este método tende a apresentar a melhor proporção entre os materiais componentes, dando origem a traços que se enquadram nos parâmetros internacionais que definem o UHPC, porém com reduzidos volumes de pasta e consumo de aglomerantes inferiores àqueles identificados na literatura correlata. Por meio de uma abordagem racional, econômica e sustentável, que visa a otimização do emprego de materiais de maior custo e a minimização do uso de recursos naturais escassos, o método contribui positivamente para o desenvolvimento tecnológico do setor.

Palavras-chave: Concreto de Ultra-Alto Desempenho (UHPC), método de dosagem, empacotamento de partículas, mínimo volume de pasta, areia artificial de basalto.

1 INTRODUCTION
De Larrard and Sedran (1994) proposed, for the first time, the term Ultra-High Performance Concrete (CUAD) for concrete with high mechanical resistance and proved that it is possible to obtain strengths greater than 200 MPa using only common aggregates, cement, micro silica, additive superplasticizer, and low water/binder ratio, associated with simple thermal curing.

Richard and Cheyrezy (1995) developed a cementitious composite with ultra-high mechanical resistance called Reactive Powder Concrete (CPR), characterized by having a high modulus of elasticity and low creep, obtained from a densified system of ultrafine particles.

Currently, UHPC can be considered one of the most important technologies under development in the field of concrete science and has demonstrated great value in the field of civil engineering due to its excellent mechanical properties and durability (HAILE et al., 2019; MOHAMED et al., 2020; DINGQIQIANG et al., 2020).
The development of ultra-high performance concrete has evolved through techniques for improving the material's microstructure, which include optimizing the packing density of the mixture, reducing the water-binder ratio, reducing the calcium oxide/oxide ratio silicon (CaO/ SiO2), the use of siliceous materials and the microstructure of the paste due to pozzolanic reactions. (RICHARD AND CHEYREZY, 1995; CHANG et al., 2009; BUTTIGNOL et al., 2018; SOHAIL et al., 2018; IBRAHIM et al., 2020).

This work aims to contribute to the development of UHPC by analyzing the influence of paste volume on the compressive strength of ultra-high performance concretes produced with artificial basalt sand.

2 THEORETICAL FRAMEWORK

2.1 ULTRA-HIGH PERFORMANCE CONCRETE

Ultra-high-performance concrete has promoted advances in civil construction due to its characteristics that can provide greater resistance to compression, traction, ductility, and durability against the attack of aggressive agents (ACI, 2018; HAILE et al., 2019; SOHAIL et al., 2021).

ACI 239R (2018) defines ultra-high-performance concrete as a class of advanced cementitious materials with a minimum compressive strength of 150 MPa, with tensile ductility, durability, and toughness requirements. Fibers are generally included to meet specified requirements.

Perry (2018) carried out a survey based on current documentation on UHPC in countries such as the United States, Canada, Switzerland, France, Japan, Korea, China, and Spain, among others, and, based on similar specifications, proposed a global definition for the ultra-high performance concrete, namely:

Cementitious composite that has greater tensile strength, durability, and ductility compared to high-performance concrete and must contain fibers or mesh to ensure post-cracking durability and specified compressive strength of at least 120 MPa at 28 days (PERRY, 2018, p.103).

Some characteristics common to studies related to UHPC are compressive strength above 150 MPa, water/binder ratio between 0.15 and 0.25, high content of superplasticizer additive, use of very fine sand, and the presence of fibers, generally metallic (WANG et al., 2015; KANG et al., 2018; DINGQIANG, et al., 2020).
2.2 EXCESSIVE PASTE THEORY

Concrete can be considered a mixture composed of aggregates and cement paste, so it can be said that the total volume ($V_t$) is equal to the sum of the volume of paste ($V_p$) and the volume of aggregates ($V_{ag}$) (DAMINELI, 2013; ZHANG et al., 2020).

According to the excess paste theory proposed by Kennedy (1940), the paste volume is divided into two parts: the dense paste ($V_{pd}$) and the excess paste ($V_{pex}$). The dense paste is the one that fills the voids between the aggregates, while the excess paste plays a role in the dispersion and lubrication of the aggregate particles, being distributed around each particle forming a layer of constant thickness that will promote the fluidity of the concrete. (WONG AND KWAN, 2008; KWAN et al., 2012; LI AND KWAN, 2013; YURDAKUL et al., 2013; ZHANG et al., 2020).

Powers (1968) suggested that excess paste is the only parameter that influences workability. In 1999, Oh et al. incorporated the concept of paste film thickness (PFT) in the dosage of self-compacting concrete. Subsequently, Kwan and Li (2012) concluded that both excess water and excess paste increase fluidity and alter the rheology of concrete (YURDAKUL et al., 2013).

According to studies by Kwan and Li (2012), the thickness of the paste film can be defined as the average thickness of the paste film that coats aggregate particles larger than 75µm. It is worth mentioning that the methodology for determining this parameter is similar to that proposed by Kwan and Wong (2008) for determining the thickness of the water film, however, the authors consider the composition of the paste not only cementitious materials and water, but also the aggregate particles with dimensions less than 75µm.

The thickness of the paste film defined by Kwan and Li (2012) is represented by Equation 1:

$$PFT = \frac{r'_w}{A_{Fa}}$$

(1)

Where:

$r'_{w}$ is the volumetric ratio between the excess paste and the volume of solids in the remaining portion of fine aggregates; $A'_{Fa}$ is the specific surface of aggregate grains above 75 µm.
The authors observed that this parameter must be positive so that there is enough paste to fill the voids and form the film that coats the aggregates. The results also showed that higher thicknesses lead to greater fluidity, but reduce the cohesion and viscosity of the mixture, while relatively small thicknesses can lead to lower fluidity, but with high cohesion and viscosity (KWAN E LI, 2012).

In general, assuming that the packing density of the aggregates can be maximized, the amount of paste required to fill the voids and promote the required fluidity can be reduced (WONG E KWAN, 2008; KWAN et al., 2012; LI E KWAN, 2013; CAMPOS et al., 2020).

The high efficiency in the packaging of binders, characterized by the reduction of voids in the paste due to the combination of fine materials of different granulometry, associated with the optimization of the granular skeleton of the aggregates provides a reduction in paste consumption and obtaining better performance concretes, both in the state plastic and in the hardened state. In this way, determining the ideal paste content helps to optimize concrete properties (KWAN E WONG, 2008; LI E KWAN, 2013; DAMINELI, 2013; CAMPOS, 2019).

3 MATERIALS AND METHODS
3.1 SELECTION AND CHARACTERIZATION OF MATERIALS

For the development of this research, the use of high initial strength Portland cement, silica fume, artificial basalt sand, natural sand, quartz powder, and superplasticizing additive was specified.

3.1.1 Fine aggregates

The artificial sand used comes from fine-grained rock, consisting essentially of labradorite, augite, and opaque crystals, with the presence of labradorite and augite microphenocrysts, being classified as basalt. The material has a specific mass of 2,910 kg/m³, determined according to NBR NM 52 (ABNT, 2009), a loose unit mass of 1,820 kg/m³ and a void index of 37.5%, established according to the prescriptions of NBR NM 45 (ABNT, 2006).

The results of the granulometric composition of the material, determined by NBR NM 248 (ABNT, 2003), indicate that the aggregate has a maximum characteristic diameter of 4.75 mm and a fineness modulus of 3.49.
Natural sand has 98% silica in its microstructure. Its specific mass is equal to 2,640 kg/m³, established according to NBR NM 52 (ABNT, 2009). The loose unit mass is equal to 1,470 kg/m³ and its void content is 44.3%, parameters determined according to NBR NM 45 (ABNT, 2006).

The results of the particle size analysis test of the material, carried out according to NBR NM 248 (ABNT, 2003) indicate that the aggregate has a maximum characteristic diameter of 0.60 mm and a fineness modulus of 0.90. In Figure 1 it is possible to check the particle size curve of the two aggregates.

![Figure 1 - Particle size curve of aggregates](image)

3.1.2 Binders

The binders used were high initial strength Portland cement (CP V-ARI) and silica fume. According to the test report issued by the manufacturer, the cement has a specific mass of 3,090 kg/m³, a specific surface of 4,363 cm²/g, a compressive strength of 46.3 MPa at seven days, and 56.1 MPa at 28 days of age.

The silica fume used as a pozzolanic addition has a non-densified specific mass of 2,220 kg/m³, SiO₂ content greater than 90%, specific surface area (B.E.T.) of 19,000 m²/kg, and spherical particles with an average diameter of 0.20 μm ($d_{50}$).

Table 1 presents the chemical compositions of cement and microsilica, according to information from the manufacturers.
Table 1 - Chemical composition of binders

<table>
<thead>
<tr>
<th>oxide</th>
<th>CP V - content (%)</th>
<th>Silica fume – content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>19.02</td>
<td>93.02</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.80</td>
<td>1.65</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.28</td>
<td>1.22</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.68</td>
<td>0.98</td>
</tr>
<tr>
<td>MgO</td>
<td>2.90</td>
<td>--</td>
</tr>
<tr>
<td>CaO</td>
<td>62.72</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Source: Manufacturer (2020)

3.1.3 Quartz powder

The quartz powder used is sold as ground silica quartz sand #400 and has a specific mass of 2,620 kg/m³, determined by NBR 16605 (ABNT, 2017), and a loose unit mass of 0.913 kg/m³, according to NBR NM 45 (ABNT, 2006).

The chemical analysis of the material indicated that the SiO₂ content is greater than 99% and the particle size analysis carried out on the laser particle analyzer model Bettersize/S3 Plus shows an average diameter (d₅₀) of 17.4 μm.

3.1.4 Chemical admixture

The polycarboxylate-based superplasticizing ADVA 458 was used. According to the manufacturer, this product has a density of 1,095 kg/m³ and a solids concentration of 47%.

3.2 EXPERIMENTAL METHOD

The experimental program of this research included the molding of 120 specimens, 6 specimens per mix, which were subsequently subjected to the test to determine the resistance to simple axial compression.

For analysis purposes, 4 different levels of silica fume (15, 20, 25, and 30%) and 5 levels of additional paste volume (0, 20, 40, 60, and 80) were tested, verifying the influence on fluidity and compressive strength.

3.2.1 Determination of minimum paste volume

Initially, a packing curve was determined using the modified Andreasen and Andersen model, later a granular mixture of natural sand, basalt sand, and quartz powder was determined, using linear programming techniques, to define a granulometric curve similar to the...
granulometric curve given by the modified Andreasen and Andersen model, where the percentage to be used of each material was defined.

After defining the percentages of aggregates, the modified Toufar model was used to define the packing density and void ratio of the granular mixture. The results of the analysis indicate that the granular packing density of the mixture of the three materials ($\alpha_{tm}$) is 0.66741 and that the minimum volume of paste ($V_p \text{min}$) required to fill the voids between the aggregates is 33.3%.

### 3.2.2 Determination of mix

The first step in determining the UHPC mix consisted of establishing the volume of each of the components of the mixture, based on the respective paste volumes. The results for the levels of 15, 20, 25, and 30% silica fume are presented in Table 2.

<table>
<thead>
<tr>
<th>Silica fume content</th>
<th>parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Additional paste volume</td>
<td>0%</td>
</tr>
<tr>
<td>15%</td>
<td>Paste volume $V_p$ (m$^3$)</td>
<td>0.33259</td>
</tr>
<tr>
<td></td>
<td>Aggregate volume (m$^3$)</td>
<td>0.66741</td>
</tr>
<tr>
<td></td>
<td>Cement volume (m$^3$)</td>
<td>0.17310</td>
</tr>
<tr>
<td></td>
<td>Silica fume volume (m$^3$)</td>
<td>0.03647</td>
</tr>
<tr>
<td>20%</td>
<td>Quartz poder volume (m$^3$)</td>
<td>0.10095</td>
</tr>
<tr>
<td></td>
<td>Artificial sand volume (m$^3$)</td>
<td>0.44000</td>
</tr>
<tr>
<td></td>
<td>Natural sand volume (m$^3$)</td>
<td>0.12646</td>
</tr>
<tr>
<td></td>
<td>Water volume (m$^3$)</td>
<td>0.12302</td>
</tr>
<tr>
<td></td>
<td>Total volume (m$^3$)</td>
<td>1.00000</td>
</tr>
<tr>
<td>20%</td>
<td>Paste volume $V_p$ (m$^3$)</td>
<td>0.33259</td>
</tr>
<tr>
<td></td>
<td>Aggregate volume (m$^3$)</td>
<td>0.66741</td>
</tr>
<tr>
<td></td>
<td>Cement volume (m$^3$)</td>
<td>0.16445</td>
</tr>
<tr>
<td></td>
<td>Silica fume volume (m$^3$)</td>
<td>0.04619</td>
</tr>
<tr>
<td>20%</td>
<td>Quartz poder volume (m$^3$)</td>
<td>0.10095</td>
</tr>
<tr>
<td></td>
<td>Artificial sand volume (m$^3$)</td>
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<td>0.12646</td>
</tr>
<tr>
<td></td>
<td>Water volume (m$^3$)</td>
<td>0.12195</td>
</tr>
<tr>
<td></td>
<td>Total volume (m$^3$)</td>
<td>0.66741</td>
</tr>
</tbody>
</table>
From the combination of different paste volumes and silica fume contents, 20 traces of UHPC were determined and identified according to the following nomenclature: TR-S.V, where TR indicates trace, S the silica content, and V the additional volume of paste.

### 3.3 CHARACTERIZATION OF CONCRETE IN THE FRESH STATE

The fluidity of UHPC in the fresh state was determined through an adaptation of the procedures followed by Okamura and Ouchi (2003), Kwan and Wong (2008), Fung and Kwan (2010); Kwan and Chen (2012) and Ibrahim et al. (2020) who used a frusto-conical mold with reduced dimensions (upper diameter of 70 mm and lower diameter of 100 mm) to carry out the test.

For this research, the truncated cone specified in the test to determine the specific mass of fine aggregate (NBR NM 52:2009) was used, which has an upper diameter of 40 mm, a lower
diameter of 90 mm, and a height of 75 mm. The test was carried out on a previously moistened glass plate to eliminate any friction that could affect the result.

To carry out the test, the UHPC was poured freely into the cone, which, after being filled, was carefully removed to allow the material to flow only under the influence of gravity. The time specified for measuring the diameters of the spread paste was set at 20 seconds after removing the cone.

It is also noteworthy that the determination of diameters followed the procedure adopted by Ibrahim et al. (2020) in which the fluidity value of the mixtures was determined by the average of the spread of the values of four diameters.

3.4 CHARACTERIZATION OF CONCRETE IN THE HARDENED STATE

In the hardened state, the samples were subjected to the axial compression test at 28 days of age. To determine the compressive strength of the concrete, the specimens were tested according to the procedures of NBR 5739 (ABNT, 2007). Before carrying out the test, the samples were rectified to ensure the flatness of the base and its perpendicularity to the longitudinal axis.

The tests were carried out in a hydraulic compression press with a capacity of 100 tons, Class 1 measurement accuracy according to NM ISO 7500-1 (ABNT, 2016), and a device with a ball joint suitable for compression testing of 5x10 cm specimens in concrete presses, at a loading rate of 0.45 MPa/s, as prescribed in NBR 5739 (ABNT, 2018).

4 RESULTS

4.1 ANALYSIS OF MIX FLUIDITY

The fluidity of the different mix was established through the use of a frusto-conical mold with reduced dimensions, as can be seen in Figure 2 (a). The scattering result was determined from the average of four diameters (Figure 2(b)).
It is important to mention that in mixes with higher silica fume contents and larger volumes of paste, it was decided to reduce the additive content to avoid segregation, exudation, or incorporation of air into the mixture, thus justifying the decrease or discreet increase in the spread value about the mixture with an immediately lower paste volume. A similar procedure was adopted in the research by Soliman and Tagnit-Hamou (2016).

In Figure 3, it is possible to evaluate the spreading behavior depending on the silica fume content and the additional volume of paste.

For the same volume of paste and considering only the variation in the amount of silica fume, it is possible to observe that the maximum difference between the spreads is 6.8%. After
the analysis of variance, it was verified that this difference is not significant so the increase in sílica fume content does not significantly affect the fluidity of the mixtures.

It is necessary to highlight that the sílica fume added to the mixture was proportioned in mass to the cement and that its specific mass is lower than that of the cement. Therefore, the volume of solid particles about the water present in the different traces increases as the sílica fume content increases, causing opposite effects, which, when combined, alter the fluidity of the mixtures.

It is known that with the increase in silica fume content, there is an increase in the specific surface area of the assembly ($A_{CM}$), increasing the water demand necessary to wet the particles and reducing the available water film thickness (WFT), which will imply reducing the fluidity of the mixture. The high fineness of the particles promotes an increase in the packing density of the mixture and, consequently, the portion of excess water ($\mu'_w$) available to lubricate the paste and promote fluidity decreases. On the other hand, the spherical shape of the sílica fume particles reduces the interlocking of the granular skeleton and improves fluidity, while its high fineness increases cohesion and, consequently, reduces fluidity.

Although the effect of silica content was not significant on fluidity, a pattern can be observed. The series with 30% sílica fume was the one that presented the lowest scattering values, followed, in this order, by the series with the contents of 25%, 20%, and 15%, indicating that the increase in the specific surface area and the cohesion of the mixture were preponderant, impairing fluidity. Similar behavior was identified in research by Henche (2013) and Li, You and Brouwers (2018) carried out with sílica fume contents of 5%, 10%, and 15%.

In turn, the increase in paste volume promoted an increase in the fluidity of the mixture. Figure 4 (a) represents the mix with the minimum paste content. It can be observed that this mixture does not have self-compactting characteristics, however, from 20% additional paste volume (Figure 4 (b)), the fluidity of the UHPC increases.
This behavior is a consequence of the reduction in the volume of aggregates and the increase in the paste content available to lubricate the aggregate grains, promoting an increase in mobility between them, and, consequently, greater fluidity. This fact was also observed by NG et al. (2016).

The results obtained here are congruent with the considerations of Kwan and Li (2012), who highlight that higher thicknesses of the paste film produce greater fluidity, reducing the cohesion and viscosity of the mixture, while relatively small thicknesses can lead to fluidity, lower, but with high cohesion and viscosity.

The influence of the additional paste volume on fluidity is confirmed by the results of the analysis of variance where it was observed that the p-value is lower than the significance level of 0.05, indicating a statistical difference between the values obtained.

To compare means, the Tuckey-Kramer test was used. Data analysis allows us to conclude that only when comparing the results of the minimum paste volume of 60% with that of 80%, the
effect is not significant. For the other values, there is a statistical difference between the results, with a significance level of 5%.

Similar results were also observed by Yu, Spiesz and Brouwers (2014) and Soliman and Tagnit-Hamou (2016).

4.2 ANALYSIS OF COMPRESSION STRENGTH

Table 6 presents the results of the average compressive strength ($f_{cm}$) of the mixes subjected to thermal curing and tested at the age of 28 days. Standard deviation (Sd) values are also presented.

<table>
<thead>
<tr>
<th>Additional paste volume</th>
<th>0%</th>
<th>20%</th>
<th>40%</th>
<th>60%</th>
<th>80%</th>
<th>$f_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix</td>
<td>$f_{cm}$ (Sd)</td>
<td>$f_{cm}$ (Sd)</td>
<td>$f_{cm}$ (Sd)</td>
<td>$f_{cm}$ (Sd)</td>
<td>$f_{cm}$ (Sd)</td>
<td>$f_{cm}$ (Sd)</td>
</tr>
<tr>
<td>TR-15</td>
<td>137.1 (6.4)</td>
<td>145.5 (7.4)</td>
<td>148.6 (4.4)</td>
<td>146.4 (4.6)</td>
<td>150.4 (12.9)</td>
<td>145.6</td>
</tr>
<tr>
<td>TR-20</td>
<td>180.8 (3.9)</td>
<td>170.1 (8.1)</td>
<td>166.7 (5.3)</td>
<td>147.4 (8.3)</td>
<td>131.8 (10.3)</td>
<td>159.4</td>
</tr>
<tr>
<td>TR-25</td>
<td>186.1 (10.5)</td>
<td>167.9 (9.9)</td>
<td>162.3 (12.2)</td>
<td>151.3 (9.2)</td>
<td>161.9 (2.9)</td>
<td>165.9</td>
</tr>
<tr>
<td>TR-30</td>
<td>172.2 (16.7)</td>
<td>169.8 (11.0)</td>
<td>165.9 (12.7)</td>
<td>142.0 (5.0)</td>
<td>146.3 (11.7)</td>
<td>159.2</td>
</tr>
<tr>
<td>$f_{cm\text{avg}}$</td>
<td>169.1</td>
<td>163.3</td>
<td>160.9</td>
<td>146.8</td>
<td>147.6</td>
<td>--</td>
</tr>
</tbody>
</table>

Source: authors

It is possible to observe that the average resistance of the 20 mixes evaluated is 157.0 MPa, varying from 131.8 MPa to 186.1 MPa. The general coefficient of variation, on average, is 5%, indicating that production and testing operations can be classified with a good level of rigor for the general variation of experimental mixtures in the laboratory, according to ACI 363 (2010).

4.2.1 Analysis of the influence of silica fume content on compressive strength

It is possible to observe that the average compressive strength values corresponding to the different additional volumes of paste ($f_{cm\text{avg}}$) indicate that as the additional volume of paste increases, the compressive strength tends to decrease, except for the series containing 15% silica fume.

Regarding the behavior of compressive strength depending on the silica fume content, it can be stated that the series with 15% silica fume, despite containing the highest cement consumption, was the one that presented the lowest average compressive strength ($f_{cm\text{avg}}$), while the one containing the 25% content was the one that reached the highest levels.
In this table, it is also possible to observe that as the silica fume content increases, the average compressive strength value of the series increases, however, when it reaches the level of 25%, the compressive strength value starts to decrease. In this case, it is believed that the excess silica fume may be causing the distancing effect between the other particles, contributing to the drop in compressive strength.

Similar behavior was identified by Biz (2001) but with silica fume contents varying between 10 and 30%. The maximum compressive strength was obtained with 20% silica fume and the author considers that this result can be partially attributed to the agglomeration effect and the greater difficulty in dispersing high silica fume contents.

The action of silica fume in UHPC can be explained as a function of the pozzolanic reaction with calcium hydroxide released by the hydration of the cement and the filling effect on the voids between the cement grains or other powdered materials (MA E DIETZ, 2008). Therefore, about the 15% silica fume content, it is believed that the fact that the results obtained here are lower than those of the other contents can be justified by the fact that this percentage, in terms of stoichiometric calculation, is very close to the necessary to react with all the calcium hydroxide resulting from the cement hydration reaction. That said, in these quantities, it is estimated that there is no more calcium hydroxide to be consumed, and there is also no silica left to act as a filler and fill the small voids existing in the granular skeleton (TUTIKIAN, ISAÍA and HELENE, 2011; SOHAIL et al., 2018).

To evaluate the joint influence of silica fume content and additional paste volume on the average compressive strength, a double-factor analysis of variance without repetition was employed. The results indicate that there is no significant difference between the resistance values either as a function of the silica content or the additional volume of paste since the resulting p-value is higher than the significance level of 0.05 for both cases.

4.2.2 Analysis of the influence of additional paste volume on compressive strength

Analyzing the compressive strength results, it is observed that for the contents of 20, 25 and 30% silica, as the additional volume of paste and, consequently, the cement consumption ($C_{cp}$) increase, the volume of aggregates decreases and the average compressive strength tends to reduce.
This behavior was expected since the 0% volume corresponds to the amount of paste necessary to fill the voids between the aggregates, and increasing this volume causes the effect of distancing between the aggregates. In this case, the transmission of effort no longer occurs directly between the aggregates and starts to occur through the paste, contributing to the drop in compressive strength.

The results indicate that the minimum volume of paste is sufficient to obtain the highest compressive strength for UHPC and that, from this level onwards, any additional increase in paste will probably not promote relevant benefits in terms of resistance, since there is the possibility that not all cementitious materials are participating in pozzolanic reactions, as observed by Liu et al. (2020) and Yurdakul et al. (2013).

It is also possible to observe that as the silica fume content increases, the difference between the compressive strength average values of adjacent volumes is minimized. Similar behavior was identified by Meleka et al. (2013). In their research, the authors noted that as the cement and silica fume content increases, the percentage gain in compressive strength decreases.

In 1990, Popovics proved that for the same w/agl ratio, an increase in the binder content resulted in a decrease in compressive strength. Li, Yu and Brouwers (2018) reached the same conclusion based on trace analysis with binder consumption varying between 750 and 900 kg/m³. A similar pattern can also be seen in the research by Vatannia et al. (2020), in which the cement consumption of the mixtures studied ranged from 900 kg/m³ to 595 kg/m³. The authors also demonstrated that higher levels of resistance were achieved in mixes with higher aggregate consumption.

The analysis of variance for the series containing 20%, 25% and 30% silica fume contents indicates that the increase in paste volume in strength was statistically significant for the three contents.

For the 15% silica content, the results indicate a tendency towards an increase in the value of compressive strength as a function of the increase in additional paste volume and cement consumption, with the mix with the minimum paste volume being the one that presented the highest lowest average resistance, while the mix with 80% additional paste volume was the one that achieved the highest results. The difference between the two extremes is 10%. However, it is important to highlight that the results of the analysis of variance indicate that this increase is also not statistically significant.
The results indicate that the mixes with the minimum volume of paste are those that present the best binder index and that this value increases as the additional volume of paste increases, regardless of sílica fume consumption, resulting in more expensive and less sustainable concrete.

Table 7 presents the average compressive strength values of each series ($f_{cems}$), as well as the average of the respective cement ($C_{cp}$) and silica fume ($C_{sa}$), consumption, in addition to the binder index of the series ($BIs$).

<table>
<thead>
<tr>
<th>Series</th>
<th>$f_{cems}$ MPa</th>
<th>$C_{cp}$ Kg/m³</th>
<th>$C_{sa}$ Kg/m³</th>
<th>$BIs$ Kg/m³/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR-15</td>
<td>145.6</td>
<td>749</td>
<td>112</td>
<td>5.91</td>
</tr>
<tr>
<td>TR-20</td>
<td>154.9</td>
<td>711</td>
<td>142</td>
<td>5.36</td>
</tr>
<tr>
<td>TR-25</td>
<td>165.9</td>
<td>678</td>
<td>169</td>
<td>5.10</td>
</tr>
<tr>
<td>TR-30</td>
<td>159.2</td>
<td>647</td>
<td>194</td>
<td>5.28</td>
</tr>
</tbody>
</table>

Source: authors

It is worth noting that the TR-25.0 mix was the one that presented the highest individual resistance, with one of the samples reaching 199.1 MPa, with a total consumption of 605 kg/m³ of binders. As a consequence, this mix also has the highest average resistance among the five mixes produced with the minimum volume of paste, in addition to the best individual binder index (3.25 Kg/m³/MPa for 0% additional paste volume) among the 20 traits studied. For comparison purposes, Vatannia et al. (2020) obtained a binder index of 3.77 kg/m³/MPa and resistance of 206.0 MPa in a mix containing 595 kg/m³ of cement, 30% sílica fume and w/agl ratio of 0.20.

Another relevant point is the fact that the average strength of 186.1 MPa of the TR-25.0 mix was achieved with the consumption of 484 kg/m³ of cement, a value 36% lower than the average identified in the survey of related parameters. However, given the minimum volume of paste, this mix presents reduced fluidity and, therefore, may not be considered the best mix from workability. Therefore, the choice of the ideal paste volume requires the establishment of a balance point at which the properties in the fresh state and the hardened state can be satisfactorily achieved.
5 CONCLUSION

The general objective of this research was to analyze the excess paste content in the compressive strength of UHPC.

A highlight of this research was the incorporation of artificial basalt sand in natura (without any additional sieving or washing) into the UHPC matrix, as a larger fine aggregate, aiming not only to reduce the consumption of cement, such as maximizing mechanical properties and reducing the use of scarce natural resources and/or more expensive, such as natural sand and quartz powder.

The results obtained indicated that it is possible to obtain concrete with self-compacting characteristics and compressive strength levels greater than 150.0 MPa, with all mixes containing 20%, 40% or 60% additional paste volume.

The analysis of the percentages of silica fume stipulated in this research proved to be relevant in proving that the ideal content (25%) was what promoted the best average results in compressive strength and binder index. Through the tests carried out, it was possible to observe the influence of different silica fume contents on fluidity and compressive strength.

The use of an optimized granulometric curve for the aggregates led to the determination of the minimum paste volume, and the obtaining of better performing concrete, both in terms of mechanical properties and in relation to the consumption of binders. The analysis of additional volumes of paste made it possible to prove that excess binders do not promote benefits in compressive strength, nor in the binder index of the mixes.

With the exception of the 15% silica fume content, the best results in terms of resistance were obtained in mixes with 33% paste volume, without excess paste, a value 76% lower than the average identified in related works, which is 51%. However, the mixes that were produced with the minimum volume of paste did not present adequate fluidity. However, in subsequent mixes (20% additional paste volume), which contain 40% paste volume, this problem was minimized.
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