Influencia del volumen de fibras y curado posterior sobre el comportamiento post – fisura de un concreto de ultra alto desempeño

Influence of fiber volume and subsequent curing on post - crack behavior of an ultra high performance concrete (UHPC)

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Resumen

En el presente artículo se evalúa el desempeño de un concreto de ultra alto desempeño reforzado con diferentes contenidos de fibras metálicas, el cual fue elaborado utilizando materiales accesibles en Colombia y con técnicas de fabricación convencional, es decir no se utilizaron presiones o temperaturas elevadas en la fabricación de los diferentes especímenes. A este concreto de ultra alto desempeño se le realizaron pruebas de resistencia a la compresión uniaxial, resistencia a la flexión y de igual forma se evaluó el comportamiento de viguetas fisuradas a diferentes edades, las cuales fueron sometidas a diferentes tiempos de curado, con el fin de determinar la resistencia residual a flexión de las mismas. Se ha observado que el contenido en fibras y la adherencia que se genere entre las mismas y la matriz de concreto son aspectos de gran importancia, con el fin de garantizar que no haya pérdida de la resistencia a la flexión, independientemente de la edad de fisuración.

Palabras claves: Concreto de ultra alto desempeño, resistencia a la compresión, post-fisura, concreto reforzado con fibras, resistencia a la flexión

Abstract

In this paper the performance of an Ultra-High Performance Concrete (UHPC) reinforced with different contents of metal fibers is evaluated. This concrete was produced using materials available in Colombia and conventional manufacturing techniques; ie no high temperatures or pressures in the manufacturing of different specimens were used. This UHPC was tested for uniaxial compressive strength and flexural strength. Furthermore, we evaluated the behavior of different ages cracked joists of different ages, which were subjected to different curing times in order to determine the residual bending strength., was evaluated. It has been observed We observed that the fiber content and adhesion to be generated between them the fibers and the concrete matrix are matters of great importance, in order to ensure no loss of flexural strength, regardless of the age of the cracking.

Keywords: Ultra high performance concrete (UHPC), compressive strength, postcracking, fiber reinforced concrete, flexural strength

1. Introduction

In the 90's, authors such as Bouygues (Resplendido, 2004) or Reda et al. (1999) took the first steps in research of Ultra High Performance Concrete (UHPC). The first application of UHPC in civil engineering was in 1997 for a pedestrian bridge in Sherbrooke, Canada (Resplendido, 2004; Acker et al., 2004). Later, it was used in other areas such as in the construction of the Cattenom and Civaux power plants (Resplendido, 2004) or research about the performance of steel tubes filled with UHPC (Tue et al., 2004).

While improvements have been made in concrete's ability to withstand compression, the definition of high-strength concrete has been changing over time. This is why the American Concrete Institute's Committee 363 recognizes that the definition of high-strength concrete is based on the specific geographical area, since it depends on the compression strengths that are produced in each region (ACI Committee 363, 2010).

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Today, there are only a few methodologies for the design of concrete mixtures with compression strength levels above 83MPa, with the exception of the model developed by De Larrard (1999), to measure various types of concrete, both conventional and high performance concrete. Given that there are no simplified methodologies for high-strength concrete mixtures, research in this area is very attractive, so as to find relationships that can be used to support the implementation of these materials in the industry.

One of the main characteristics of these mixtures is the high concentration of cement material. Some authors recommend that the content of cement material be above 900 kg., which is composed of between 20% to 25% of silica fume and cement (Wang et al., 2012). Likewise, it is important to use high doses of super-plasticizers so as to proportionately reduce the ratio of water/cement. (Yang et al., 2010).

If metallic fibers are added into the process of the concrete mixture, they considerably improve the impact, fatigue and bending strengths, offering a large variety of applications, as well as technical and economic advantages. The ultra-high performance concrete, reinforced with metallic fibers, is a viable candidate to overcome low tensile strength and a lack of ductility of the concrete which are inherent characteristics of conventional concrete.

Adding metallic fibers to the concrete mixture increases ductility (Oh, 1992; Oh, 1994), weight-bearing capacity (Ashour et al., 1993), and shear stress strength (Campione et al., 2008). On the other hand, multiple authors (Ashour et al., 2000; Chunxiang et al., 1999) researched the flexural performance of beams made of concrete that was reinforced with high strength fibers.

To determine the optimal combination of materials for the concrete reinforced with metallic fibers, experimental compression strength tests were required, in addition to fluidity trials of the mixture, while considering that the maximum volume of fibers that can be used without an impact to handling is 2%. (Markovic, 2006).

Many authors have researched multiple self-healing methods (Jonkers et al., 2010; Van Tittleboom et al., 2010). It is believed that the self-healing properties of cement materials are a combination of physical and chemical processes, including (a) the formation of calcium carbonate or calcium hydroxide, (b) the loss of concrete particles in the cracking of the concrete, (c) an additional hydration process of the cement that was not hydrated, and (d) the expansion of the concrete matrix in the cracked area given the high cement content and the low ratio of water and cement (Wu et al., 2012). The self-healing benefits include not only the reduction of maintenance and repair costs, but also the reduction of CO₂ emissions, since concrete production is very harmful to the environment.

The objective of this research is to develop a UHPC with compression strength above 150 MPa, using materials that are easy to obtain in Colombia and preparation methods that do not require high pressure nor do they create additional heat which generating hydration. The implementation of these techniques is difficult to control and to provide to structures once the different structural and non-structural elements in a conventional engineering project have been poured.

The goal was also to evaluate the mechanical behavior in response to the flexing of cracked UHPC, after submitting it to different curing periods, so as to evaluate if there is self-healing of the concrete.

2. Methodology

2.1 Description of the Materials

So as to characterize the components of the mixture, we conducted physical-chemical tests that are described below:

- Morphological characterization of the granular materials used in the mixture's design with granulometry using the sieve technique (ASTM C117).
- Implementation of the granulometry of the fine-grained inputs (cement, silica fume, and quartz dust) of the mixture, by using the laser technique for dust.
- Physical-mechanical characterization of the cementing materials, using compression cube tests (ASTM C109) and strength activity index (ASTM C311).
- Chemical and mineral characterization of the cement, using x-ray diffraction (DRX).

2.2 Analysis of the material's mechanical performance

To study the mechanical performance of the UHPCs, we conducted compression strength tests in accordance with standard ASTM C39. Then a modulus of rupture test was implemented, in line with standard ASTM C580; finally, a test of sudden residual flexural strength in accordance with standard ASTM C1399.

2.3 Post-cracking performance of the UHPC

We evaluated the flexural mechanical performance of the cracked UHPC, after subjecting them to different periods of humid curing. To achieve that, prismatic samples were taken to a controlled crack in a universal machine until a deflection of 0.2 mm. (ASTM C1399). Those samples were stored for periods of 7 to 28 days, and then the responses of the samples were determined with a post-curing flexural strength test (ASTM C1399).

3. Analysis of results

The high performance concrete (UHPC) created in this research is a type of reactive powder (Aitcin, 2000; Richard et al., 1995). The Fuller distribution method was used to determine the dosages of materials composing the concrete. The concrete mixtures produced were made with high levels of cement material (cement and silica fume) and a low water/cement ratio. Fine-grain sand, with a maximum diameter of 500 μm , and quartz powder, with an average diameter of 18 μm , were used as dry ingredients.

3.1 Characterization of the Materials

The properties of the individual materials, such as the granulometric distribution, specific mass and experimental compactness, were determined using an experimental method.

The materials used to manufacture the ultra-high resistant concrete were: Portland cement; silica fume; a super-plasticizer additive based on modified polycarboxylics, and two types of sand: the first (quartz powder) has granular dimensions between 2.4 to 85 μm and the second type (sand-60) between 140 to 500 μm ; steel fibers (diameter of 18 μm , length of 13 mm and density of 7.90 g/cm^3).

The density values of the cement and silica fume, presented in Table 1, were determined with the Le Chatelier Flask, in line with standard ASTM C188. The specific gravity and absorption values for sand-60 and quartz powder were determined in line with the procedures established in standard ASTM C128.

Tabla 1. Densidad de los materiales
Table 1. Density of the materials

Material	Densidad/Density (g/cm^3)
Cemento/Cement	3.17
Humo de Sílice/Silica Fume	2.65
Arena/Sand – 60	2.59
Polvo de Cuarzo (Arena – 100)/Quartz Powder (Sand – 100)	2.51

The fineness of the Portland cement was determined using the Blaine Fineness Apparatus, in line with the procedure described in standard ASTM C204. Its specific surface area was 3796.41 cm^2/g . It is important to note that this value is not specified in standard ASTM C1157 for Portland Cement. The amount of water required to prepare hydraulic cement paste, of normal consistency for later tests, was 26.1 %.

This value was determined by following the procedure described in ASTM C187. Once the water/cement ratio was established, the setting time of this paste was measured, following the parameters outlined in ASTM C191. Given the results obtained from the tests of set times, initial and final set times of 170 min. and 210 min. respectively were measured. Table 2 presents a summary of the physical parameters of the Portland cement.

Tabla 2. Parámetros físicos del Cemento Portland
Table 2. Physical Parameters of Portland Cement

Parámetros Físicos/ Physical Parameters	Resultados Proyecto/ Project Results	NTC - 121	ASTM C1157
Tiempo de fraguado inicial, mínimo (min)/ Initial set time, minimum (min)	60	60	45
Tiempo de fraguado final, máximo (min)/ Final set time, maximum (min)	150	600	420
Blaine, mínimo (cm ² /g)/ Blaine, minimum (cm ² /g)	3796.41	2800	2800

The method used to evaluate compatibility, as well as the saturation point of the plasticizer on the cement particles and silica fume, was the fluidity test of the pastes with a slump test ; for this type of concrete, we must verify that the diameter of the mixture is over 60 cm.

The percentage of voids in the sand was determined by the test of compactness and vibration, in line with the procedures described in standard ASTM C29. The procedure was done with Sand-60 and Quartz Powder (Sand-100), with the results shown in Table 3.

Tabla 3. Porcentaje de vacíos de las Arenas
Table 3. Percentage of voids in the Sand

Material		Polvo de Cuarzo/ Quartz Dust	Arena/Sand – 60
Porcentaje de Vacíos/ Percentage of Spaces	Varillado/ Measurement	46.08 %	41.06 %
	Vibrado/ Vibration	39.20 %	36.53 %

The granulometric distribution of the cement, silica fume, quartz powder (sand-100) and sand-60 that make up the concrete mixture was determined with laser granulometry. Figure 1 shows the results of these particle size measurements, together with the mixtures that were made as part of the experimental design, so as to evaluate different properties, such as handling and compression strength.

Figura 1. Granulometría láser de los materiales y mezclas propuestas
Figure 1. Laser granulometry of the proposed materials and mixtures

The silica fume available in Colombia is not as finely grained; therefore, differing from the literature, the most finely grained input in our mixtures was quartz sand. This material is a component with a small enough diameter to fill the spaces between the cement and the silica fume. Also, when designing the mixture it was important to keep in mind the gradation of Sand-60.

Using a Scanning Electron Microscope (SEM), we observed the detail of the characteristics of each of the materials in the concrete mixture.

As shown in Figures 2 and 3, the particles of the inputs in the mixture are very angular and their surfaces are not well defined. Therefore, the water/cement ratio used in the mixture cannot be further reduced.

Figura 2. MEB, Arena - 60. (a) 50x, (b) 10000x
Figure 2. MEB, Sand - 60. (a) 50x, (b) 1000x

Figura 3. MEB, Polvo de cuarzo (Arena – 100). (a) 50x, (b) 10000x
Figure 3. MEB, Quartz powder (Sand – 100). (a) 50x, (b) 1000x

In contrast with stone inputs, silica fume has the desired spherical form (Figure 4), allowing us to work with lower water/cement ratios. This material, due to its high silica content, plays an important role in the structure of the cement paste. It acts like a physical filler, increasing the compactness of the mixture. It considerably reduces the oozing of the fresh cement due to its large surface area and its ability to hold water, and it favors the Pozzolan activity that is generated (Espinoza Montenegro, 2010).

Figura 4. MEB, Humo de sílice. (a) 50x, (b) 10000x
Figure 4. MEB, Silica fume (a) 50x, (b) 1000x

As shown in Figure 5(a), cement is the most finely grained material in the mixture, with an average diameter of 7 µm. In Figure 5(b), we can see that the surface of the cement grains is very well defined. They show a softened texture, and they are not totally spherical, whereas silica fume is spherical.

Figura 5. MEB, Cemento Tipo III. (a) 50x, (b) 10000x
Figure 5. MEB, Cement Type III. (a) 50x, (b) 10000x

3.2 Study of the material's mechanical behavior

3.2.1 Test mixtures

We proposed an ideal mixture, as supported by the Fuller distribution and in line with the aspects already mentioned in this paper. By varying the proportions of the materials included in the mixture, we created 4 mixtures with different proportions, so as to evaluate ease of handling and the compression strength of the different mixtures.

The UHPC mixture was designed to optimize the density of the packaging of the dry ingredients. The goal for this mixture is achieved by trying to independently optimize two major phases until the optimal final combination is achieved; the first phase is the paste phase, composed of cement, silica fume, water and the super plasticizing additive; the second is the inert particles phase, which in this case is composed of quartz dust and sand-60.

Table 4 shows the dosages of the mixtures, indicating the proportion of the different components in relation to the amount of cement.

Tabla 4. Dosificación de las mezclas en función de la cantidad de cemento

Table 4. Dosages of the mixtures in relation to the amount of cement

Material	Mezcla 1/ Mixture 1	Mezcla 2/ Mixture 2	Mezcla 3/ Mixture 3	Mezcla 4/ Mixture 4
Cemento/ Cement	1.00	1.00	1.00	1.00
Humo de sílice/ Silica fume	0.25	0.25	0.25	0.20
Arena – 60/ Sand – 60	1.00	1.00	1.50	1.00
Polvo de cuarzo/ Quartz dust	0.50	0.25	0.25	0.20
Agua/ Water	0.31	0.31	0.31	0.30
Aditivo/ Additive	0.09	0.075	0.075	0.07

Using a Fuller granulometric composition, we observed the optimal proportion of sand-60 and quartz powder, approximately 80% and 20% respectively. This result is due to the improved accommodation of the materials used in the mixtures in these proportions.

Figure 6 shows typical curves for the 4 mixtures, for the uniaxial compression strength test at 1, 7 and 28 days. The tested specimens were cubes with sides of 50 mm; these cubes were created following the parameters established in standard ASTM C109. The speed of the application of weight was 0.13 mm/min.

Figura 6. Resultados del ensayo de resistencia a compresión de las diferentes mezclas planteadas
Figure 6. Compression strength test results of the different mixtures proposed

As seen in Figure 6, the compression strength obtained on day 1 was above 75 MPa in all of the mixtures; these results are quite high when accounting for the early age when the tests were done.

Once the compression strength tests were done, we used mixture number 4 since, as shown in Figure 6, it is the mixture with the greatest uniaxial compression strength at an age of 28 days, in addition to fulfilling the handling requirements.

3.2.2 Mixtures with fibers

Given the mixture's strong performance, specifically in compression strength, we proceeded to test the concrete mixture by adding different quantities of metallic fibers, which were implemented based on percentages of the total volume of the mixture. We chose to do handling, compression strength and modulus of rupture tests, adding 0.5%, 1.5% and 2.0% of fibers.

The size of the fibers that were added into the mixture is very important. The ductility level and the traction strength of the concrete mixture are also important; they depend not only on the size of the fibers, but also on the percentage of fibers used per m^3 . The steel fibers proposed for this mixture are 13 mm long and 0.018 mm in diameter.

To estimate the UHPC's modulus of rupture with different contents of metallic fibers, we implemented a series of flexural strength tests, following the recommendations of standard ASTM C580, applying the weight at one third of the clear span.

Figure 7 shows the trend presented by the Maximum Flexural Strength of the joists with different amounts of metallic fibers, tested at 1, 7 and 28 days. We observed that on day 1, the fibers were not yet sufficiently attached and the flexural strength is practically the same for the different amounts of fibers. The samples tested at 7 and 28 days show that mixtures with metallic fiber amounts lower than 2.0% have increased performance when there is a higher fiber content, so the performance of the joists with 2.0% of fibers was superior to the rest.

Figura 7. Comparación esfuerzo de flexión, según la edad de las viguetas
Figure 7. Comparison of flexural strength, according to the age of the joists

3.2.3 Post-crack behavior of fiber-reinforced UHPC

Given the low water/cement ratio, and the high levels of cement material in the mixture, we assumed that not all of the cement material was able to be hydrated during the mixing process.

To evaluate a possible self-healing process of the concrete, the test specimens were cracked and then subjected to a subsequent curing process to measure average residual flexural strength, keeping in mind the weight registered at deflections 0.50, 0.75, 1.00 y 1.25 mm, as indicated in standard ASTM C1399. The test specimens were cracked at 1, 7 and 28 days, and the re-test was done at 7 and 28 days after the cracking date.

Table 5 shows a summary of the results, comparing the Maximum Flexural Strength obtained in the test specimens that were not cracked, against the test samples that were cracked, on different days. This allowed us to measure their Average Residual Strength (ARS), which was obtained with a re-weighted deflection curve of 0.50, 0.75, 1.00 y 1.25 mm, as shown in Formule 1.

$$ARS = \frac{L}{b \cdot d^2} (P_A + P_B + P_C + P_D) \quad (1)$$

Where,

L : is the element's clear span (mm)

b : is the average width of the element (mm)

d : is the average height of the element (mm)

$(P_A + P_B + P_C + P_D)$: is the sum of the weights of the deflections of 0.50, 0.75, 1.00 y 1.25 mm (N).

Tabla 5. Dosificación de las mezclas en función de la cantidad de cemento
Table 5. Maximum flexural strength and ARS of the test cases of cracked UHPC with fibers

		Sin fisura/ Without cracks	Fisura 1 día/1 day Crack		Fisura 7 días/7 day Crack		Fisura 28 días/28 day Crack	
Porcentaje fibras/ Percentage fibers	Ensayo/Test	Esfuerzo máximo a flexión (MPa)/ Maximum Flexural Strength (MPa)	Esfuerzo máximo a flexión (MPa)/ Maximum Flexural Strength (MPa)	ARS (MPa)	Esfuerzo máximo a flexión (MPa)/ Maximum Flexural Strength (MPa)	ARS (MPa)	Esfuerzo máximo a flexión (MPa)/ Maximum Flexural Strength (MPa)	ARS (MPa)
0.5%	7 días/days	9.05	7.74	7.55	6.81	6.50	7.76	7.41
	28 días/days	11.72	8.16	7.99	8.57	8.36	9.24	7.32
1.5%	7 días/days	9.82	9.85	7.51	11.11	10.60	13.28	12.57
	28 días/days	12.73	11.84	11.43	12.34	12.05	13.95	13.43
2.0%	7 días/days	14.15	16.93	16.88	20.05	17.95	26.77	25.16
	28 días/days	17.82	17.68	15.46	20.74	18.35	30.63	22.82

Table 5 shows that the cracked test specimens reach the modulus of rupture in most cases, even going past that in some cases. We therefore observe that the process of self-healing is effective, since the material is able to withstand the same load as before the cracking, or even increase the breaking load, with ductile behavior.

When the analysis is focused on the amount of fibers in the test specimen, we observe that the joists with contents equal to 0.5% gained the least flexural strength, while the ones with 2% of fibers showed approximately 100% more flexural strength. Given these results, it is possible to see that the gains in flexural strength and self-healing are highly correlated with the contribution of the fibers and how well they are attached

4. Conclusions

Ultra-high performance concrete reinforced with metallic fibers, manufactured with conventional techniques and materials available in Colombia, have features that excel in many different aspects; these characteristics are evident when compared with the performance of a concrete matrix without fibers. Given the high uniaxial compression strength, together with the good flexural performance that can be achieved, fewer sections are required in constructions, and they are therefore lighter.

To obtain the desired performance, we carefully studied the relationship between packaging density and flow capacity in the fresh phase of the concrete, based on the granulometric distribution proposed by Fuller. The dosages proposed in this research were based on the packaging of the inputs, using finely graded material with different average diameters so as to achieve the highest compactness possible. By eliminating larger sized inputs, together with the optimization of the mixture, we were able to create a more homogeneous and denser concrete, which positively influenced its mechanical properties.

For the proposed mixture, we conclude that when creating a dosage with a higher content of metallic fibers, the uniaxial compression as well as flexural strength are notably better. The addition of metallic fibers creates an increase in the concrete to withstand deformation, reducing the most relevant characteristic when it is subject to bending (fragile cracking). The use of silica fume in the mixture's dosage increases the compactness of the mixture, while considerably reducing the exuding of fresh concrete due to its large surface area, allowing us to work with a low water/concrete ratio.

We saw that in all of the proposed analyses, there was a self-healing process of the concrete, which is composed of a curing process after the cracking of the concrete.

As observed in the analyses indicated above, the adherence of the fibers to the concrete matrix plays a fundamental role in the joist's flexural strength. In fact, for joists that cracked at 28 days of aging, where a large part of the cement material was already hydrated, mechanical abilities improved after the next curing. Likewise, the self-healing of the concrete's flexural strength is directly related to the fiber content of the concrete. The fiber content must be greater than 1.5% to ensure that, independent of the age of the cracking, the concrete can maintain, and not lose, its flexural strength.

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