Sustainable development of an Ultra-High Performance Fibber Reinforced Concrete (UHPFRC): Towards partial replacement of cement by slags

Maria Dolores Rubio Cintas[1], Miguel José Oliveira[2], Elisa M. J. Silva[2], Maria Eugenia Parron[1], Francisca Pérez García[3], Manuel Alejandro Fernandez Ruiz[1]

1 University of Cadiz, Spain
2 Institute of Engineering, University of Algarve, Portugal
3 University of Malaga, Spain
mariadolores.rubio@uca.es

Abstract. The global production of concrete represents, every year, more than 5% of the anthropogenic emissions of carbon dioxide, mainly from the production of cement. This negative factor can be improved by incorporating supplementary cementitious materials in order to replace cement.

In the last few decades, research has been conducted on what it is known as Ultra High Performance Fibber Reinforced Concrete (UHPFRC). The term includes a broad range of materials such as defect-free, dense particle, engineered composite, multi-scale particle and fibber-reinforced cementitious materials, with enhanced properties. UHPFRC has better mechanical and durability properties compared to normal strength concrete. Other benefits of using UHPFRC on a structure includes the reduction of concrete sections, concrete formwork, labour, equipment and time of construction. Despite of the benefits associated to this material, the UHPFRC is still struggling to be universally applied, mainly due to its high cost and its high environmental impact. UHPFRC cost is higher than normal concrete, due to a very high powder content and steel fibber addition. However, the production of UHPFRC using locally available materials, under normal curing conditions, should reduce its cost and turned it into a more attractive construction product.

In this paper, the fresh and hardened properties of a specific UHPFRC composition are presented. The mixture replaces a significant percentage of cement by slags, and the results reveal the viability of the proposed mix. The environmental performance of the mixture confirmed the improvement on the material sustainability and allowed the identification of some potential future studies.

Keywords: Ultra High Performance Fibber Reinforced Concrete (UHPFRC), Concrete Sustainability, Circular Economy, Slags Reuse.

1 Introduction

Ultra High Performance Concrete (UHPC) and Ultra High Performance Fibber Reinforced Concrete (UHPFRC) are recent cement based materials, and they have attracted the attention of researchers since they were introduced in the 1990s. UHPC can have a compressive strength ranging from 150 MPa to 810MPa[1], approximately 3 to 16 times as that of Conventional Concrete (CC). This material is almost impermeable to carbon dioxide, chlorides and sulphates. These excellent properties give a high durability, that leads to a long life service, with reduced maintenance. The improved corrosion resistance provides protection against adverse environmental exposure classes[2]. Due to the high compressive strength, UHPC structures weight only one-third or one-half of the corresponding conventional concrete structures under the same load. This weight reduction leads to lighter structures. Although UHPC possesses excellent properties, its high binder content, of about 800 to 1000 kg/m^3, affects not only the production costs, but also the shrinkage[3]. In general, UHPC has a high economic cost and it cannot replace CC in most applications where the conventional mixtures can economically meet the performance criteria. UHPC requires a high content of energy intensive materials including cement, which has a negative environmental impact.

The sustainability of the cement and concrete industries is imperative to the well-being of our planet and to human development. However, the production of Portland cement, an essential constituent of concrete, leads to the release of a significant amount of CO_2 and other greenhouse gas (GHGs). The production of one ton of Portland cement produces about one ton of GHGs [4]. Considering the continuous increase of cement production, it is estimated that, nowadays, cement and concrete industry are responsible for about 7% to 8% of global CO_2 emissions [5]. Also, one of the main problems in the iron and steel industry concerns the by-products waste, which must be properly processed or reused to promote environmental sustainability. One of these by products is steel slag. The cement substitution with slag strategy achieves two goals: raw materials consumption reduction and waste management.

In UHPFRC the elimination of steel reinforcement bars reduces labour costs and provides greater architectural freedom, allowing different shapes and smaller thicknesses of the concrete elements.

Regarding sustainable development, durability of construction and building materials are a key issue for civil engineering design. So, the development of a material with improved durability would be of great significance, particularly for infrastructures in aggressive environments. UHPC and UHPFRC are examples of this promising construction materials.

Results of laboratory essays, developed to reduce the three main UHPC constraints described, namely, high cost, unfavourable environmental impact and potential shrinkage problems, are presented on this paper. The work is being developed by the research group "Use of Industrial, Construction and/or Demolition Waste for the Construction of Structural and Non-Structural Concrete (TEP-951)", from Cadiz University.

2 Materials and experimental methodology

A UHPC reference mixture and a UHPFRC mixture were produced and tested on laboratory. The UHPFRC mixture contains steel fibbers and 50% of the cement were replaced by slags. The UHPC reference mixture was developed and validated by the TEP-951 research group in previous works.

2.1 Materials

The materials used to produce the mixtures are listed below. Cement was partially replaced by weight with Ground Granulated Blast Furnace Slag (GGBFS).

- ✓ Aggregates - siliceous sand (0 to 0.5mm and 0.6mm to 1.2mm);
- ✓ Cement - Portland cement CEM I 42.5R/SR;
- ✓ Silica flour - SIKRON U-S500 with a specific surface of 20000m^2/kg and microsilica grade 940-D;
- ✓ Fibbers - short steel fibbers (13/0.2mm, density of 7800kg/m^3) and superplasticizer SIKA with solid content of 40%;
- ✓ GGBFS from Estabisol, S.A. with density of 2910kg/m^3 and specific surface area 4920cm^3/g.

The chemical composition of GGBFS depends of the raw materials in the iron production process. Table 1 presents the chemical composition of the GGBFS used on the mixture (given by the supplier).

Table 1. Chemical composition of GGBFS.

Ground Granulated Blast Furnace Slag (GGBFS) chemical composition			
Parameter	Concentration	Parameter	Concentration
CaO	45.72	MnO	0.42
SiO_2	32.30	Fe_2O_3	0.29
Al_2O_3	10.70	SrO	0.12
MgO	7.64	Na_2O	0.08
SO_3	1.52	ZrO_2	0.04
TiO_2	0.67	NiO	0.04
K_2O	0.45	Cr_2O_3	0.01

2.2 Mix design and mixing procedure

The different materials proportions used on the production of UHPC and UHPFRC mixtures are presented in Table 2.

Table 2. Materials proportions used on the production of UHPC and UHPFRC mixtures.

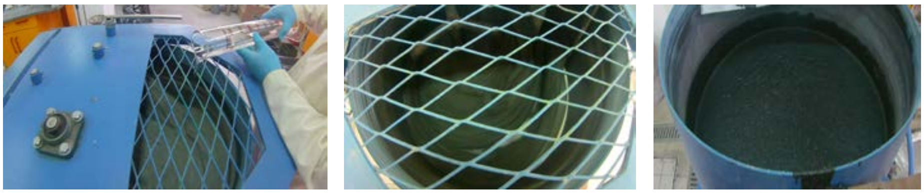
Materials	Commercial reference	UHPC mixture	UHPFRC mixture
Cement	CEM I 42.5R/SR	800 kg/m^3	400 kg/m^3
GGBFS	GGBFS	-------------	400 kg/m^3
Silica fume	Microsilica grade 940-D	175 kg/m^3	175 kg/m^3

Silica power	U-S500 SIBELCO	225 kg/m^3	225 kg/m^3
Fine Sand 1	Silica Sand 0 to 0.5mm	302 kg/m^3	302 kg/m^3
Fine Sand 2	Silica Sand 0.6 to 1.2mm	568 kg/m^3	568 kg/m^3
Water	Tap water	181 kg/m^3	181 kg/m^3
Admixture	Sika viscocrete	35 kg/m^3	35 kg/m^3
Straight steel fibres	13/0.20mm	--------------	160 kg/m^3
Water in the admixture	--------------	19 l/m^3	19 l/m^3
Total of water	--------------	200 l/m^3	200 l/m^3
Water / Binder	--------------	0.205	0.205

The dosage of the fibbers was established between 3% and 8% of the proportions of cement addition and for the mixture studied it correspond to 8%.

The concrete mixing was performed in two different equipment's. The UHPFRC mixture was done in a 50 litters mixer and for the UHPC it was used a 1.5 litters mixer, with the same characteristics as described in EN 196-1. The total mixing time recorded for the UHPFRC and UHPC mixtures were, respectively, of 32 minutes and 18 minutes. The different mixing times observed are due, probably, to different rotation speeds and volumes.

Fig. 1a, Fig. 1b and Fig.1c shows the mixing process for the UHPFRC mixture and Fig. 2a, Fig. 2b and Fig.2c for the UHPC reference mixture.



1a 1b 1c

Fig. 1. 50 litters mixer used for the mixing process of the UHPFRC mixture.

2a 2b 2c

Fig. 2. 1.5 litters mixer used for the mixing process of the UHPC reference mixture.

2.3 Test methodologies for fresh properties

Taking into account the characteristics of the concrete studied, it was considered appropriate to evaluate its properties as Self-Compacting Concrete (SCC). SCC is a highly flowable, non-segregating concrete that can be spread into place, fill formwork, and encapsulate even the most congested reinforcement by means of its own weight, with little or no vibration. In addition, mechanical and durability properties of the resultant concrete are maintained (or even enhanced). SCC is a technically advanced material, which has a high potential in the areas of productivity, working conditions and even in matters arising from their inherent characteristics. The advantages of SCC over normally vibrated concrete are the following [6]:

a. Reducing manpower;
b. Reducing noise pollution;
c. Reducing energy consumption;
d. Easier to place;
e. Safer working environment;
f. Better surface finish;
g. Complex member sections;
h. Great freedom in design;
i. Accelerating construction;
j. Improving durability.

The filling ability and stability of self-compacting concrete in the fresh state can be defined by four key characteristics [7]. Each characteristic can be addressed by one or more test methods.

Table 3. Characteristics of Self-Compacting Concrete (SCC) and related test methods.

Characteristic	Preferred test method(s)
Flowability	Slump-flow test
Viscosity (assessed by rate of flow)	T_{500} Slump-flow test or V-funnel
Passing ability	L-box test
Segregation	Segregation resistance (sieve) test

The recommended test for characterizing SCC on site is slump-flow. This gives a good indication of the uniformity of concrete supply. Slump-flow is a measure of the total fluidity and therefore filling ability of the concrete. A visual assessment for any indication of mortar/paste separation at the circumference of the flow, and any aggregate separation in the central area also gives some indication of segregation resistance.

2.4 Measurements of compressive and flexural strength

Compressive and flexural strength tests were performed according to EN 196-1 [8] in specimens with the dimensions 40mm x 40mm x 160mm. The tests were carried out in two different servo-controlled testing machines. The compressive strength tests were performed in testing machine with a maximum capacity of 3000kN (see Fig. 3a) and flexural strength tests in a universal machine prepared to perform flexural tests with a maximum capacity of 100kN (see Fig. 3b).

3a. Compressive strength test equipment. 3b. Flexural strength test equipment.

Fig. 3. Compressive and flexural strength equipment's.

Specimens were tested at 7 and 9 hours, 1 day, 3 days, 7 days, 14 days, 28 days and 150 days after T0 (time concerning the mixing of water with cement) for the UHPFRC and at 28 days for the UHPC mixture.

2.5 Shrinkage

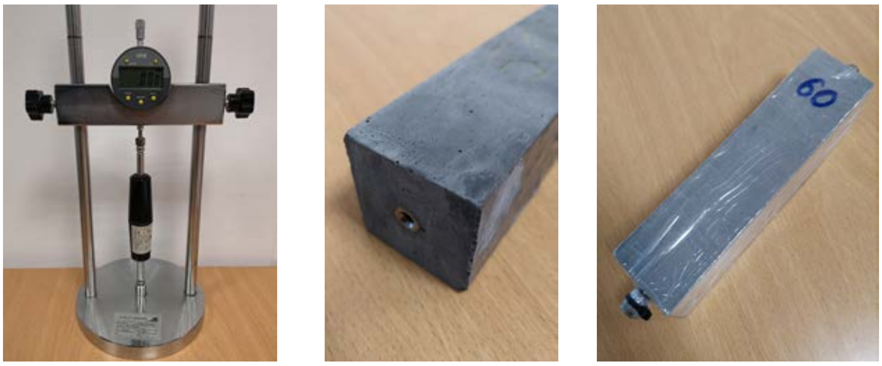
The estimation of time-dependent behaviour is still one of the most difficult aspects in designing a concrete structure. The structural concrete codes which deal with time dependent behaviour provide general rules for standard concrete, but the validation of some established stress-strain-relations have to be confirmed via laboratory testing when special mixtures are used [9-11].

Shrinkage is the sum of the autogenous and the drying shrinkage. Autogenous shrinkage occurs during setting and is caused by the internal consumption of water during hydration. The volume of the hydration products is less than the original volume of un-hydrated cement and water. This reduction in volume causes tensile stresses and results in autogenous shrinkage. Drying shrinkage is caused by the loss of water from the concrete to the atmosphere. Drying shrinkage is relatively slow and the stresses that it induces are partially balanced by tension creep relief.

The aggregate restrains the shrinkage of the cement paste and so the higher the volume of the aggregate and the higher the E-value of the aggregate, the lower the shrinkage. A decrease in the maximum aggregate size, which results in a higher paste volume, increases the shrinkage.

The variation of the Water/Powder (W/P) ratio produces a clear effect on the autogenous shrinkage. Low W/P ratios result in a high autogenous shrinkage [12, 13]. According to [14], the low W/P ratios lead to a rapid autogenous shrinkage due to the existence of a finer porous structure and lower humidity. The high autogenous shrinkage observed in concretes with low W/P ratio (less than 0.40) is mostly recorded in the first days.

In this research, and in order to limit the amount of work and materials used, it was decided to use small specimens (40x40x160)mm, since the ratio between the smallest size of the specimen and the largest aggregate size is about 33. The preparation of specimens was performed according to NP EN 196-1, using a different mixture proportion, in a room with a temperature of 20±2ºC and a relative humidity of 55±5%. The test specimens were not compacted mechanically since this material exhibits a self-compacting behaviour. The removal of moulds took place approximately 7 hours after mixing. This time was defined as the minimum necessary to ensure concrete strength between 1MPa and 2MPa, in order to avoid specimens damage. Thereafter, the specimens were weighed, their length registered and, in the case of the samples used for the measurement of autogenous shrinkage, they were sealed with a plastic film. Shrinkage deformations of each specimen were measured using a length comparator with a sensitivity of 1µm (see Fig. 4a) and gage studs on the end sections of the concrete prisms (see Fig. 4b). Stability of the length comparator was checked by a reference invar bar. Samples for measurement of autogenous and total shrinkage were placed on two thin supports and samples for measurement of autogenous shrinkage were also kept sealed (see Fig. 4c). Others samples were immersed in water to control the expansion in saturated conditions. At the ages of 1 day, 3 days, 7 days, 14 days and 28 days, and 2 months, 3 months, 4 month and 5 months, the samples were weighed and the length variation was measured.



4a. Length comparator. 4b. Concrete prisms. 4c. Sealed sample.

Fig. 4. Length comparator and specimen used for the measurement of shrinkage deformations.

3 Test Results

3.1 Workability

The properties measured on the UHPFRC mixture, associated to its fresh state, are presented in table 4.

Table 4. Self-compacting ability of UHPFRC mixture.

Method	Value	classification
Flow (EN 12350-8)	690 mm	SF2
V funnel (EN 12350-9)	36 s	--
L Box (3 bars) (EN 12350-10)	0.83	PL2

Regarding the flowability a slump-flow class of SF2 was obtained. According to [7], SF2 (660mm to 750mm) is suitable for many normal applications. Regarding the viscosity, the value of 36 seconds is above the last class (VF2). Slump-flow class VF2 has no upper class limit, but with increasing flow time it is more likely to exhibit thixotropic effects, which may be helpful in limiting the formwork pressure or improving segregation resistance. Negative effects may be experienced regarding surface finish (blow holes) and sensitivity to stoppages or delays between successive lifts. This aspect may raise questions regarding pumping placement. Pumping is the most common method of placing SCC, but a high resistance to movement and a very high cohesion can block the pipes especially if there are prolonged stops.

The result obtained on the L box test indicates good passing ability. Passing ability describes the capacity of the fresh mix to flow through confined spaces and narrow openings such as areas of congested reinforcement without segregation, loss of uniformity or causing blocking.

Lastly, segregation resistance is fundamental for SCC in-situ homogeneity and quality. SCC can suffer from segregation during placing and also after placing, just before stiffening. Although it was not performed the segregation test itself, the analysis of the flowability and L box test indicated a high segregation resistance capacity.

Fig. 5a shows the UHPFRC mixture flow, Fig. 5b the V funnel test equipment and Fig. 5c the L box test equipment, used on laboratory.

5a. Flow of mixture. 5b. V funnel test. 5c. L box test.

Fig. 5. Self-compacting ability tests of UHPFRC mixture.

3.2 Compressive and Flexural strength

The compressive and flexural strength test results for UHPFRC and UHPC mixtures are presented in Table 5. For the UHPC mixture only 28 days' test were performed since the main objective was to have reference values. The compression values result from test of three samples, while for flexural strength the values were obtained only from one test.

At the end of five months the mixture with fibbers and slag (UHPFRC) reaches more than 150MPa. Looking at the values at 28 days and comparing the values of flexural strength with compression, it can be seen that the Flexural Traction/Compression ratio is equal to 0.184 for the UHPFRC mixture and 0.182 for the UHPC mix. There is no evidence of the added value of the use of fibbers in the flexural strength.

Table 5. Compressive and flexural strength test results.

Mixture	Strength	days

		1	3	7	14	28	150
UHPFRC	Compressive (MPa)	36,6 SD=0.3	79,4 SD=1.6	102,3 SD=1.5	119,2 SD=1.7	130,2 SD=1.0	157,0 SD=0.8
	Flexural (MPa)	--	17,5	18,7	20,3	24,0	24,3
UHPC	Compressive (MPa)	--	--	--	--	100,3 SD=3.8	--
	Flexural (MPa)	--	--	--	--	18,2	--

3.3 Mass change and Shrinkage

The graphics associated to Fig. 6a and Fig. 6b, shows the mass variation for, respectively, the UHPC reference mixture and the UHPFRC mixture during 5 months of age. Each curve represents the average value obtained for the 3 specimens. The mass variation presented was calculated as a percentage of the initial mass, recorded immediately after mould removal. The individual results deviation was very small (SD≤0.11%). As expected, sealed specimens show almost no mass change and immersed specimens show mass gain. Regarding the substitution of 50% of cement by slag, there are differences in the mass variation for the studied mixtures. Around 7 days, the values for the loss of mass to the air dry specimens are smaller in about 0.5%. For immersed tests specimens the differences are smaller.

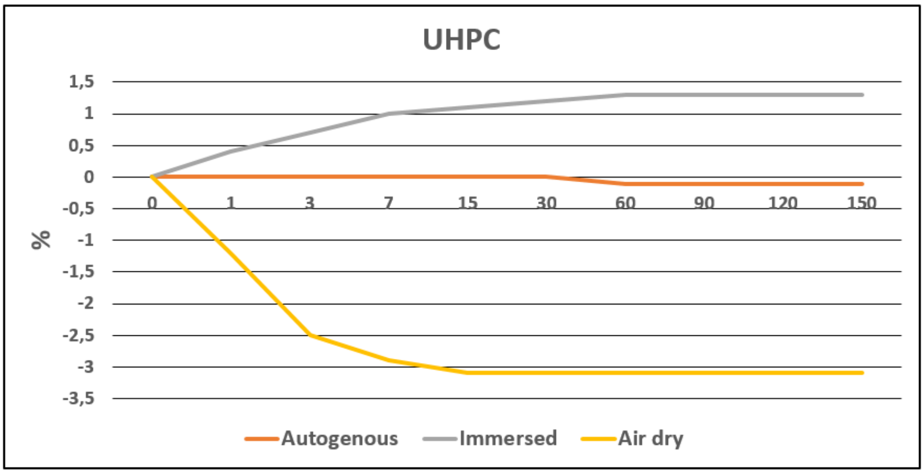


Fig. 6a. Mass change of UHPC mixture.

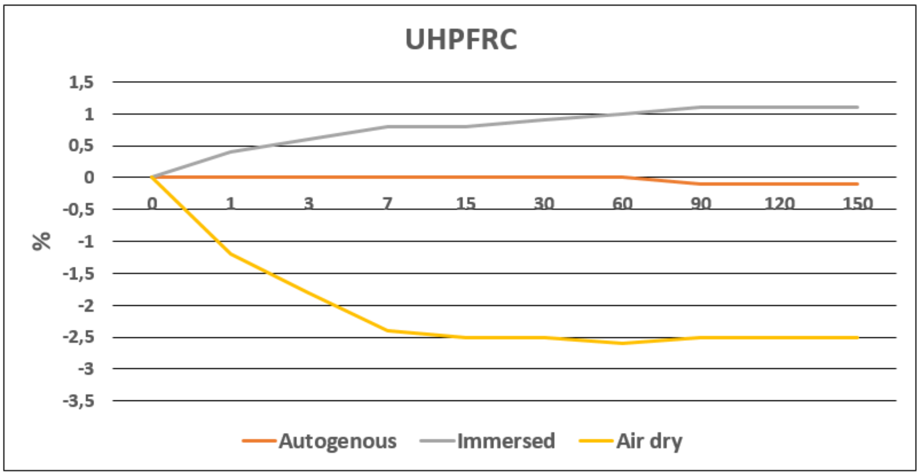


Fig. 6b. Mass change of UHPFRC mixture.

Graphics associated to Fig. 7a and Fig. 7b illustrate the autogenous and total shrinkage (air-dried and immersed in water), recorded for the same lapse time as mentioned above. The results were obtained using the average measurements of tree specimens. For each mixture the solid curve represents the average value and the dashed curves present the average plus or minus one standard deviation.

Immersed specimens show expansion due to mass gain, and sealed specimens show low shrinkage values, due to the absence of drying. When comparing the values of the two mixtures a significant decrease is visible in the early ages and in the long term for the mixture containing slags and fibbers. For example, for 1 day of age the expansion for UHPC reaches $455x10^{-6}$ while for UHPFRC the value is $308x10^{-6}$. For 1 day, but for samples subject to air drying, the values go from a reduction of $-1260x10^{-6}$ to $-531x10^{-6}$. After two months the differences are also substantial. Performance improvement with the introduction of slags and fibbers is evident, however, it was not possible to detect the contribution of each of these changes.

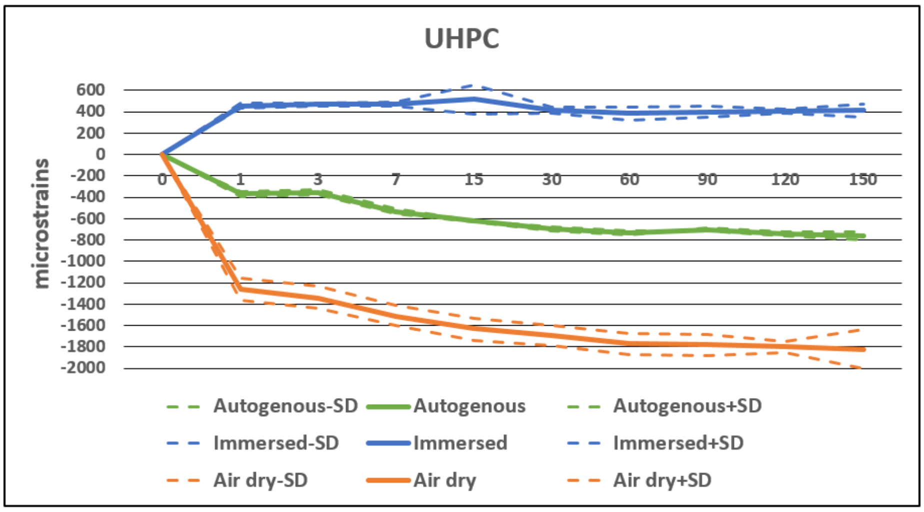


Fig. 7a. Shrinkage of UHPC mixture.

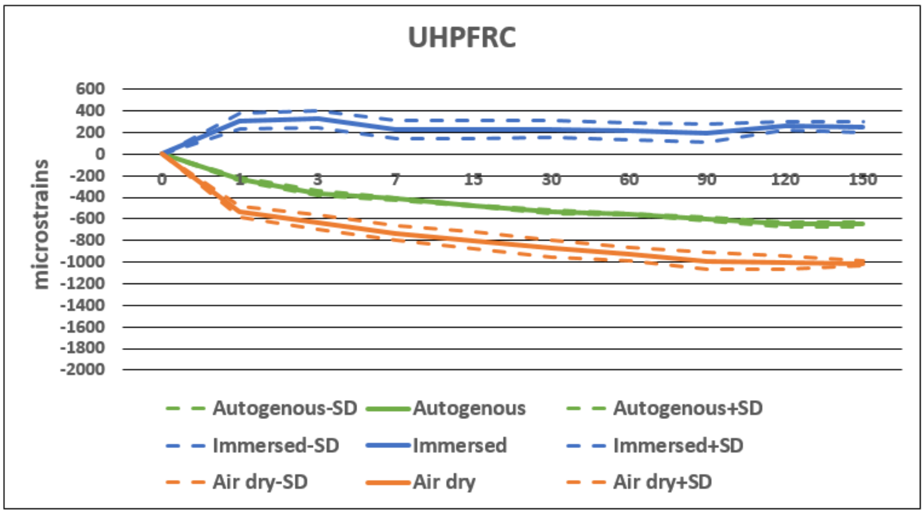


Fig. 7b. Shrinkage of UHPFRC mixture.

4 Economic viability of the designed UHPFRC mixture

As already pointed out, the high cost of UHPFRC is a huge constrain for their use. Table 5 presents the different material used for the production of the UHPFRC, their cost per cubic meter without VAT taxes, on march of 2019 for Portugal, and the estimated cost of the overall product.

Table 5. Estimated UHPFRC overall price per cubic meter.

Materials	Commercial reference	Price (*)	UHPFRC	Partial cost/m^3
Cement	CEM I 42.5R	0.10€/kg	400 kg/m^3	40.0€
GGBFS	GGBFS	0.06€/kg	400 kg/m^3	24.0€
Silica fume	Grade 940-D	0.15€/kg	175 kg/m^3	26.3€
Silica power	U-S500 SIBELCO	0.50€/kg	225 kg/m^3	112.5€
Fine Sand 1	Silica Sand 0 to 0.5mm	0.10€/kg	302 kg/m^3	30.2€
Fine Sand 2	Silica Sand 0.6 to 1.2mm	0.10€/kg	568 kg/m^3	56.8€
Water	Tap water	0.0007€/kg	181 kg/m^3	0.1€
Admixture	Sika viscocrete	1.10 €/kg	35 kg/m^3	38.5€
Straight steel fibbers	13/0.20 mm	1.20€/kg	160 kg/m^3	192.0€
Total cost of materials /m^3				520.4€

(*) prices indicated by suppliers not including transport cost and VAT.

The cost percentage of each component, considering the overall price of the UHPFRC, is easily perceptible on the pie chart (see Fig. 8). Some components have a high contribution on the final price and alternatives must be studied. Nevertheless, and despite the cost problem, there are two aspects to take into account: a) this concrete can, for certain applications, dispense the use of conventional steel reinforcements bars; b) this concrete has a much higher durability than conventional concrete and therefore has a considerably longer life time.

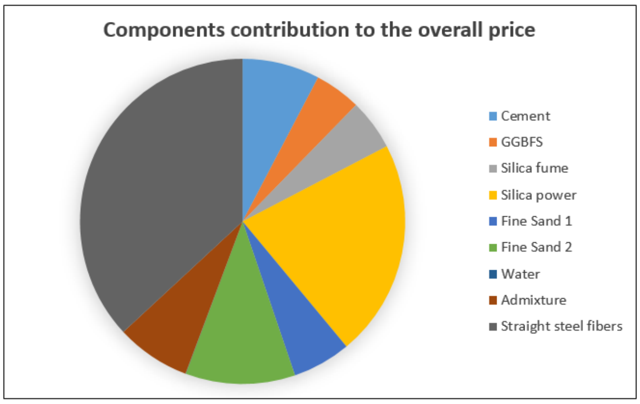


Fig. 8. Percentage of cost material contribution to the UHPFRC overall price.

5 Conclusions

Starting from on reference composition of a UHPC previously studied, a composition comprising the replacement of 50% of the cement by slag and inclusion of metal fibers was developed in order to answer three of the main constraints associated to this type of product, namely, unfavourable environmental impact, potential shrinkage problems and high cost.

The results obtained in the tests performed show some improved behaviours. The UHPFRC mixture, when compared to the UHPC, used as reference, have better performances, namely on the following aspects:

a. High mechanical resistance (Compressive strength of 157MPa and Flexural strength of 24MPa at the age of 5 months);
b. Better shrinkage performance for both air dry and submersible test specimens.
c. Improved environmental performance because part of the cement was replaced by a by-product of the industry (steel production slags);
d. Good self-compacting ability (Flowability, passing ability and segregation).

Despite the improvements, there are still negative aspects that will be taking into account in future studies. In particular:

e. High cost of the mixture, in particular of some of the components;
f. Very large mixing times, which adds even more to the cost due to energy consumption;
g. High shrinkage values when compared to conventional concrete;
h. High ecological footprint, even with the replacement of the cement by slags.

Acknowledgments

The authors express their sincerely acknowledgments to the technical team of the “Laboratório de Materiais de Construção (LMC)” and “Laboratorio de Materiales de Construcción”, from, respectively, Engineering Institute of Algarve University and “Escuela Politécnica Superior de Algeciras” of Cádiz University. This work has been supported by the Fundação para a Ciência e a Tecnologia (FCT), Portugal under the grant SFRH/BSAB/142874/2018.

References

1. M. Richard, Cheyrezy, Composition of reactive powder concretes, Cem. Concr. Res. 25 (7) 1501–1511 (1995).
2. C.M. Tam, W.Y. Tam Vivian, K.M. Ng, Assessing drying shrinkage and water permeability of reactive powder concrete produced in Hong Kong, Constr. Build. Mater. 26 79–89 (2012).
3. Dehui Wang, Caijun Shi, Zemei Wu, Jianfan Xiao, Zhengyu Huang, Zhi Fang, A review on ultra high performance concrete: Part II. Hydration, microstructure and properties, Construction and Building Materials 96 368–377 (2015).
4. MALHOTRA, V M. Role of Supplementary Cementing Materials and Superplasticizers in Reducing Greenhouse Gas Emissions, Proceedings of ICFRC International Conference on Fiber Composites, High-Performance Concrete, and Smart Materials, Chennai, India, , pp. 489-499, January (2004).
5. P. Hajek, C. Fiala, M. Novotna, Sustainable Concrete - on the way towards sustainable Building. In proc World SB14 Barcelona – Creating New Resources, (2014).
6. P.L. Domone, A review of the hardened mechanical properties of self-compacting concrete. Cement Concr. Compos. 29(1), 1–12 (2007).

7. ERMCO, European Guidelines for Self-Compacting Concrete: Specification, Production and Use, May, Available at: www.efca.info or www.efnarc.org, (2005).
8. EN 196-1: 2016. Methods of testing cement. Determination of strength.
9. CEN, Eurocode 2, Design of Concrete Structures, Part1: General Rules for Building. Europen Standard. European Committee for Standardization, pp. 28-31 (1992).
10. ACI 318-11: Building Code Requirements for Structural Concrete and Commentary.
11. Oliveira, Miguel José; Ribeiro, António Bettencourt; Branco, Fernando Garrido; Shrinkage of self-compacting concrete. A comparative analysis, Journal of Building Engineering 9 117-124 (2017).
12. Baroghel-Bouny, V. “Texture and moist properties of ordinary and high-performance cementitious materials”, in Proceedings of Séminaire RILEM “Betón: du Matérial à la Structure”, Arles, France, (1996).
13. Toma G.,Pigeon, M., Marchand, J., Bissonnette, B. e Barcelo L., “Early age restrained shrinkage: Stress buid up and relaxation”, in International research seminar: “Self-desiccation and its importance in Concrete Technology”, Lund, Sweden, pp 61-71, (1999).
14. Bjontegaard, O. e Sellevold, E. J.,”Autogenous and thermal deformation”, in “Early Age Cracking in Cementitious Systems”, RILEM TC 181-EAS, pp.65-88, July (2002).