IOP Conference Series: Materials
Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: A Grigorean *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **789** 012022

IOP Conf. Series: Materials Science and Engineering **789** (2020) 012022 doi:10.1088/1757-899X/789/1/012022

Considerations on the use of ultra-high performance concrete for water tanks

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Abstract. The development of ultra-high strength and high performance concrete is a relatively new field in the profile industry. The last 150 years have shown that, despite getting more and more resistance, the practical applications have been too many times due to innovations in materials science. This phenomenon seems to be caused by the increased costs per unit of volume, as resistance increases, as well as a cautious retention of using new materials in practical applications. The present study aims to be an encouragement of practical structural applications by presenting an Ultra High Performance Concrete (UHPC), developed with locally available materials. As it is known, concrete is the main building material worldwide. In the last decades, his leadership position has been strengthened by the constant concern of the researchers and by obtaining the various types of concrete with increasing performances from the point of view of the fresh and hardened state, obtaining special structural applications.

1. Introduction

In 2007, within the program PN II -IDI- ID_1053 / 2007-2010, “ULTRAPERFORMANT CONCRETE - ENVIRONMENTAL ECOLOGY”, approached the theoretical and experimental study of the ultra-high performance concrete, regarding the realization sustainable concrete, capable of maximum protection of the environment. Slim concrete elements were obtained which, for the same capable moment, are comparable with those of steel in terms of mass and geometric dimensions tested at bending and shearing [1].

At the Technical University of Cluj-Napoca, high-strength reinforced concrete has been researched since 1988. Experimental studies were carried out following the achievement of predetermined ductility factors [2] for frame nodes made with dispersed reinforced concrete (a fiber volume of at least 1% is sufficient to carry out reductions of the transverse reinforcement), for constructions located in areas with high seismicity [3].

In France, Lafarge, in collaboration with the manufacturer of chemical compounds Rhodia (www. Rhodia.com) and with the construction division of the Bouygues corporation (www.bouygues.fr), have developed a UHPC marketed under the name Ductal. It incorporates metallic or organic fibers that lead to the improved ductility of the composite material. Tests have shown that the compressive strength increases about 6-8 times (about 230 MPa without traditional reinforcement) compared to a regular concrete (RC), while the bending resistance has values of about 30-60 MPa.

A challenge for any practitioner is to use new materials and emerging technologies, in the absence of an explicit consecration at the level of the incident norm. To meet this challenge, several action groups have initiated, in recent years, transitional guidance, until the introduction of this new material in the design norm. The following list, organized by country, presents the following guidance resources for engineers:

- France - in March 1999, at the request of the Scientific and Technical Commission of the Association of Civil Engineers of France, the development of an interim code for UHPC structures began. It was published in French and English in January 2002.
- Australia - with the support of the construction company VSL (Australia), the University of New South Wales, Australia, has published ”Design Code for BPR Pre-Compressed Beams” in accordance with the methodology and spirit of the national code Australian Code AS3600-1994. This paper presents examples of design and guidance to obtain specific resistance to compression, bending, cutting force and torsion, as well as checking the crack opening, limiting arrow, fire resistance, fatigue resistance, loss of tension from pre-compression and related anchors [4].
- Japan - in sept. 2004, the Japanese Society of Civil Engineers published “Recommendations for the Design and Construction of Structures with UHPC – pre-norm”. The document includes design recommendations, rules for selecting material properties for the design, testing and obtaining the desired durability, execution technologies and examples of bridges built in the country. It is estimated that an English version will be available soon [4].
- United States – in 2002, the Federal Highway Administration (FHWA) initiated a research project in collaboration with the Massachusetts Institute of Technology (MIT) to optimize highway bridges by using UHPC. This study was based on the experience accumulated at MIT since 1999, respectively the similar one accumulated by FHWA since 2000, when a study of the potential UHPC for use on bridges began. Following this collaboration was published the report CEE Report R03-01, ”Models for optimizing bridge beams made with UHPC on highways”. The report presents the design strategy of a brittle-plastic material, with an elasto-plastic composite fibre reinforcement. Also, there is a comparison between this model, based on the maximum crack opening, and the design rules [4].

The first research programs that introduced the terminology of ”Ultra-High Performance Concrete” were initiated in 1985. The adopted definition uses the criterion of ”compressive strength” and imposes a lower limit of at least 150 MPa, Schmidt and Fehling (2005). For those UHPCs, which use constituents with very small granular dimensions (powders) and therefore have higher strengths, the term ”Concrete with Reactive Powders” (RPC) is preferred [3].

2. Technical requirements

The first part of the present research aimed at achieving high-performance concrete compositions with reactive powders (RPC), at which the resistance is between 150-200 N/mm^2.

The researches focused on two types of ultra-high performance concrete (UHPC) with reactive powders (RPC):

- concrete with and without fibers, having the medium consistency class;
- concrete with and without fibers with a workability, respectively the higher consistency class.

An important element is the selection of materials in order to obtain the concrete forms. A challenge is to succeed in achieving the performance with locally available materials.

The special properties of RPC are obtained with a high dosage of Portland cement, a small W/B ratio (water / binder), possible through the use of the latest generation of superplasticizers in large dosages, the use of high-binding pyrolastic additives – ultrafine silica and the incorporation of steel fibers as dispersed reinforcement [4].

By using ultrafine silica, a by-product of the metallurgical industry that is often considered to be a partial or added replacement for Portland cement, it achieves energy savings, reduces gas (CO_2) emissions in cement production and, finally, an environmentally friendly concrete with positive effects

IOP Conf. Series: Materials Science and Engineering **789** (2020) 012022 doi:10.1088/1757-899X/789/1/012022

in terms of compressive strength and sustainability. Thus, the waste of one industry can be the raw material for another industry. The materials used as concrete additives, having binding properties, bear, in the specialized literature, the names of additional constituents with cementitious characteristics [5].

The aggregates used are quartz sands with a maximum diameter of 1.2 mm. Although the composite mixture has an appearance close to that of a mortar matrix, it will be referred to as concrete.

The Portland cement used comes from the company Lafarge Romania, the last generation superplasticizer of polycarboxylate type is offered by BASF Romania, the metallic steel fibers with dimension of Ø0.4/25 mm (diameter / length), with bent ends and Ø0.175/6 mm - straight, are purchased from BAUM CAS FIBRES Romania, the ultrafine silica type "Elkem Microsilica Grade 940 U undensified" is offered by the company BASF Romania, and the quartz sands come from the Career company Bega Minerale Industriale Aghires [5].

At the beginning of the researches, it was started from the realization of the high compactness of the mixtures taking into account the Apollonian distribution of specific to the reactive powder concretes, the principle being that each smaller particle fills the space between the larger particles.

The mixtures were made with a mixer with forced mixture and with predetermined times (DIEM mixer with a capacity of up to 139 liters).

The principles underlying the composition of RPC are:

- increasing the homogeneity by eliminating the coarse aggregate;
- increasing the density in compacted state by optimizing the granular distribution of the mixture;
- improving the microstructure by applying a heat treatment after hardening;
- improving the ductility by incorporating steel fibers;
- establishing the technology as easy to apply in practice [5]

3. Concrete mixtures with and without fibers

In the first stage of the research, fiber-free mixtures were made, with different amounts of cement but especially of different types and different dosages of superplasticizing additives. The results were less favorable from the point of view of the resistance and the obtained workings.

The second phase of the research followed, in which mixtures were made with and without fibers, with different percentages of polycarboxylate ACE 440 BASF type superplasticizing additive and different dosages of long steel fibers. The third phase followed, in which the long fiber mixture was resumed - the most successful in the second stage (OE 23), with a short fiber mixture but also a hybrid one (1/2 fibers), long steel + 1/2 short steel fibers) [5].

These mixtures are considered representative, they fulfill the performance from the point of view of the concrete in fresh and hardened state. The quantities of the components of the recipes are related to the cement unit.

3.1. Fresh characteristics of fiber-free and long-fiber concrete mixtures - Stage II

The ME 22 mixture, also called the Witness, with the best performances, is the most fluid and falls in the second spreading class of spraying (SF2) for a self-compacting concrete, but when determining the viscosity, the values of time T500 (s) and the leakage through the V-hull exceeded the requirements. A self-compacting concrete has to meet all three requirements, therefore ME 22 is not self-compacting but concrete with very good workability. The strengthened characteristics of concrete mixtures with and without the addition of steel fibers. Are presented the values of the compressive strengths of the samples kept in water or subjected to the heat treatment immediately after removing the formwork, the samples being sealed at the casting face, by brushing with an insulating film based on Baumit type BA2 resins.

The tests were performed on 71 mm side samples and the results represent the average of 6 tests.

It is observed that the heat treated concrete up to the age of 6 days (1 day in molding and 5 days heat treatment), has higher values of the compressive strength compared to the one kept in the water until the age of the test [5].

The resistance to compression at the age of 28 days, in the case of heat treated concrete, increases very little or in some cases there is even a decrease in values compared to those from 6 days.

In concrete kept in water up to the age of 28 days, it is observed that the resistance increases over time until the last test age (28 days).

3.2. The strengthened characteristics of concrete mixtures with the addition of long steel fibers

The favorable influence of the steel fibers on the compressive strengths is observed for both modes of subsequent treatment. The true contribution of the fibers and an important feature of the dispersed reinforced concrete is reflected in the results of the bending resistance test.

3.3. Parallel between the characteristics of concrete without fibers, of those with long, short fibers and with hybrid steel fibers

The ME 22 mixture is considered a control for long, short fiber reinforced concrete and for hybrid fiber reinforced concrete, based on the OE 23 mixture, which has the best characteristics in fresh and hardened state. The hybrid fiber blend is made with 50% long fibers (Ø4/25 mm) and 50% short fibers (Ø0.175/6 mm). The fiber-free concrete scraping and scraping have values similar to those of hybrid concrete, and the long-fiber concrete has lower values, yet it is very workable. It is observed, from the values of squeezing and spreading, that long fibers influence the workability, even in smaller quantities [6].

The temperature is influenced by the large amount of cement in the composition, the amount of additive and, in some cases, the duration of mixing the concrete [5].

The occluded air content is normal for such a dense concrete, from which the air bubbles come out very hard. Analyzing the values, it is observed that the mixtures with the addition of steel fiber have a lower content of occluded air than the control concrete - without fibers. The elimination of the occluded air is obtained by vibration. The occluded air content may have much lower values for such concrete (BUIP). It has a high resistance to repeated cycles of frost - thawing, because, following the heat treatment, the microstructure of the concrete is improved by applying an optimum temperature of subsequent treatment (min. 90°C), which activates the reactivity of the microsilica and leads to a reduction in porosity [7].

Analyzing the values, it is found that, in a fresh state, the characteristics of the hybrid fiber concrete (OE 23 hybrid) are approximately the same as those of the fiber-free composition (ME 22), but better than the long fiber composition (OE 23) with fibers L, and the compressive strengths are almost identical to the compositions made only with fibers [8].

In conducting this experimental program on hybrid fiber compositions, we aimed to improve the working characteristics of ultra-high performance concrete and their behavior at complex service demands.

4. Consideration on the use of Ultra High Performance Concrete in tanks

In the particular of two 5000 m^3 water tanks (figure 1), for the intangible reserve required in case of fire, practically built in the same time, one in Buzau (noted REZ 1) and one in Bacau (noted REZ 2), we used Ultra-High Performant Concrete class C50/60 with short metallic fibers at REZ 2 and normal concrete from project class C25/30 at REZ 1. Their characteristics are according to table 1, where ND means not determined.

Figure 1. Water tank in Buzau (left) and in Bacau (right) – second phase of casting.

Table 1. Characteristics of concrete with and without fibers in fresh and hardened state.

	UHPC with heat treated fibers					Normal concrete (for REZ 1)
	ME22 with fibers	OE 23 with long fibers	OE 23 with long fibers	OE 23 with long fibers	OE 23 with long fibers	C25/30 XC4+XF1 D_{max} 16 mm, S3
Characteristics UHPC	Stage II	Stage II	Stage III with extension of mixing			
Water / Cement	0.22	0.23	0.23	0.23	0.23	0.55
Water / Binder	0.18	0.18	0.18	0.18	0.18	ND
Settling (mm)	265	247	270	270	260	ND
Spread (mm) after - 10 minutes	560	428	560	565	545	ND
- 60 minutes	-	-	508	515	500	ND
Temperatures (°C)	26.7	29.5	32.5	32.28	35.3	34.8
Occluded air (%)	4.60	4.56	4.50	4.35	4.40	5.5
Density of fresh concrete (kg/m^3)	2260	2400	2395	2437	2413	2430
Recipe density calculation (kg/m^3)	2289	2410	2410	2410	2410	2440
f_{cm} 1 day (MPa)	65.1	77.9	87.8	80.2	84.2	12.1
f_{cm} 7 days (MPa)	131	172	171.3	169.3	172.8	24.4
f_{cm} 28 days (MPa)	132	173	-	157.2	172.4	44.3

Analyzing the test values on cubes with 71 mm of the table 1, we notice a significant increase in the workability of the concrete. This is because the additive ACE 440 makes its effect more and more visible over time. With the increase of the mixing time of the concrete, of the workability, its temperature also increases, theory denied in the case of the other mixtures made with predetermined times. The increase in temperature is due to the high dosage of additive and the heat of hydration of CEM I 52.5R [8].

The value of the resistance obtained on the smaller cubes as size will always be higher and the starting mathematical relation for the equivalence of the average resistances on cubes of different dimensions is: $f_{c,\,cub200} = 0.95 \cdot f_{c\,,\,cub150} = 0.92 \cdot f_{c,\,cub100}$ [9].

The fresh concrete takes the form of the pattern, faithfully copying its imprints, reinforcing the statement related to the very good workability of these concretes, for a better filling of the pattern.

The classic technology at REZ 1, provided a four stage casting of the walls in order to eliminate the effects of the contractions and avoid the cracking of the concrete. At each casting, 3x6 samples (14.1 cm cubes) were taken, and the tests were performed at 1, 7 and 28 days, on 6 cubes.

The obtained results for REZ 1 (normal casting) reveal some disadvantages:

- the working joints (of the 4 casting stages) required special treatment like expandable cords, joint band, and careful vibration. After casting, due to cracking, corrections were made with special insulation materials to prevent leakage.
- The processing time of casted concrete (for maintaining humidity) it was four days, compared to the case of UHPC, where the time was two days.
- Subsequent works (filling, technological tests) started ten days after the last casting (stage 4) respectively 25 days after first casting (stage 1) compared to six days from the casting in the case of UHPC.

The obtained results for REZ 2 (experimental), when the casting has been done in one stage, reveal:

- the costs of renting the formwork and the costs of manpower were 60% lower;
- the costs with the concrete itself were 18% higher;
- the execution time was 50% lower than the classical solution;
- no cracks appeared;
- since the required strength has been reached 10 days earlier, the technological samples and the commissioning were also outdated by 10 days.

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5. Conclusion

- An UHPC concrete with high initial compressive strength (>170 MPa) was obtained.
- Existence of fiber influence on physical-mechanical characteristics.
- Designing the compositions of a high performance concrete (HPC) and ultra-high performance concrete (UHPC) is essential, as it will determine its structural performance.
- Obtaining these concrete is not possible without the use of materials with higher characteristics and preliminary tests.
- There are no standardized compositions – each application requires a characteristic recipe.

Some of the advantages in using UHPC for making concrete tanks are:

- complete replacement of transverse reinforcement (stirrups) or passive reinforcement (for pre-compressed concrete);
- making slimmer sections and larger openings for the same load-bearing capacity;
- increased productivity through faster reuse of formwork (high resistance in the first days);
- reduction of workmanship, transportation and materials for making formwork;
- higher rigidity for structural elements;
- low maintenance costs over the life of the structure;
- applications for prefabricated and monolithic elements;
- maximum durability for aggressive agents of any kind due to very low porosity;
- obtaining an apparent surface that does not require further finishing.
- the realization of ultra-high performance concrete by using mainly local materials is a remarkable performance in the field of structural concrete.
- brings important economic and qualitative advantages.
- however, much more attention needs to be paid to all the phases of design, transport and commissioning, because the errors are having a significant weight in the final product quality (UHPC).

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