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Factors effecting on the compressive and tensile strength of reactive powder concrete made with local materials

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Abstract. Ultra High Performance Concrete (UHPC) represent as one of the most concrete progressive development so that it can be improved the strength, durability, reliability, and resilience of the concrete structures. The availability of local materials play the main role in the major step in making the economic mix jobs by saving their materials and effort and decrease the concrete cost. So in this paper, the parameters including the curing regimes, of sand gradation, binder type, and content, and steel fiber content were investigated to show their effect on concrete's compressive strength. The obtained results showed that the curing regime that consists of 5 days (2 days at 60°, 3 days at 80°) given the highest strength than other curing regimes. Finer sand, Silica Fume, steel fibers cause a considerable increasing in compression strength. Various relationship were obtained illustrating the effect of studied parameters with concrete strength.

Keywords: Reactive powder concrete; Ultra-high strength concrete; High range water reducers; Hot water curing; Silica fume; Steel fiber.

1. Introduction

Reactive Powder Concrete (RPC) was developed in 1990's by a French company was known as Bouygues so that the new concrete technology gives an ultra-high strength and more ductility composite material with enhancing of mechanical properties. The basic idea of RPC type is the behavior optimization of microstructure by making a precise mix gradation for most particles in the concrete skeleton to achieving the maximum concrete density. RPC consists of very fine sand, super plasticizers, silica fume, steel (reinforcement) fiber, and cement that are resulting in a cementation mixture with the very low water-cement ratio (w/c). Briefly, it is not considered as concrete materials because of the nonexistence of the coarse aggregate in the cement mixture.

The non existence coarse aggregate can be represented as a big feature relating the microstructure system of RPC so that enhancement the performance behavior of RPC in order to trim down the heterogeneity between the cement base medium and the aggregate. Today, RPC is represented as an advanced technological progressive for the buildings construction industry. RPC is already prefer used for a special applications such as bearing units of a bridge girder, end block of pre-stress units, finder systems in port engineering, base units in power plants, medium to long span bridge project, highway structures subjected to a harmful environmental condition, etc…[1].

Since the task of RPC function is the removal of coarse aggregates causing an optimization of the granular framework by increasing the ratio of surface area over particles volume, leading to increasing the cementation matrix density by away of a post set heat treatment. The using of UHPC available local materials can make further choices and opportunities for the applications of UHPC in the buildings, transportations, in addition to the underground structures. The investigation of UHPC constituent materials will contribute to improving the concrete mechanical properties as discussed in this work so that this will easily lead to more practical development and to simplify UHPC mixture proportions as specified by the experimental new program. According to the composition of UHPC mixture, the mode of failure can be explosive, and this result can be recognized to the higher compressive strength resulting from the brittle nature of UHPC. The additional steel fibers will be used to eliminate this mode of failure in which the steel fibers enhance and increase the flexural capacity in addition to the performance of UHPC [1,2].

The estimated stress-strain curves of UHPC display a linear elastic response to 90% of the ultimate concrete strength compared to 45% of the ordinary concrete so this property is essentially so useful in practice for reducing deformation, including both deflection and cracking, as the concrete structure can be better to resist the applied external or internal loads. In the manufacturing of UHPC, the temperature is considered as one of the most important factors during the curing process which means the curing system has an influence effect on the mechanical properties such as a heat-curing system can largely raise the in the early days the age compressive strength and improve the ultimate compressive strength. A usual system of UHPC curing consists of two stages so that in the first stage the concrete is treated by placing it in an appropriate temperature for avoiding moisture losing until researching the required situate while in the second stage, the temperature of curing could be increased for accelerating the compressive strength.

Hence, different UHPC mixes have been employed with several ratios and various filler material, high range water reducers (HRWR), steel fibers, and accelerator means. The UHPC filler material is considered as an important component that represents closely about 50% by weight, therefore, the filler material type is straightforwardly affect the cost of UHPC as its compressive strength. Consequently, using the available local materials leads to decrease in the cost and give confidence in using UHPC in the practice. But in sometimes, according to the nature of the material location, using of these local materials may be lower the mix strength. For present work, the researchers employed UHPC mixtures using available local fine sand as a filler material. Thus, the mix quantities of the UHPC constituent materials are based on the recommended values associated to the subject which make the resulting UHPC mixtures have a compressive strength at least equal to 150 MPa [3,4].

2. Literature review

During a few years since the 2000s, a sensible number of studies had been conducted to deal with the mixture properties and proportions to increase the mechanical properties of UHPC. As an example in the United States, the Federal Highway Administration [5] which is one of many organizations that interesting to investigate UHPC development applications. In the literature of this subject area, there are two main progresses in the UHPC field. The first one interest on the improved UHPC mechanical properties such as the resulting mixture strength (compressive, tensile, shear, and flexure), and the durability correlated properties so these developed properties are achieving using enhancing the UHPC mixture proportion. The second development focuses on the UHPC applications to raise its use in many types of both design and construction stages related to different concrete structures. Below some researchers work relate to high performance concrete.

Richard [6] found 35 kg/m^3 of super plasticizer was suitable to give a slump flow of 360 mm in which this amount of HRWR was closely larger than the allowance amount used in the Ductal which equal to 30.7 kg/m^3. However, using large dosages of super plasticizer may be producing a large setting time value of UHPC, hence for solving this potential undesired effect, an accelerator agent may be applied to reduce the setting time. The accelerator disbands the cement particles in water which make accelerating the reaction processes leading to reducing the concrete setting time. As mentioned to Lafarge, an accelerator dosage of 30 kg/m3 is recommended for UHPC which used as a considerable amount of super plasticizer.

Tayfun [7] work with the microstructure and flexural behavior of reinforced (steel-fiber) concrete formed with the different volume fraction of steel fibers and specimens aspect ratio. Concrete specimens of the prismatic shape of dimensions 100×100×350 mm were employed with and without steel fiber (two different steel fiber types each one was hooked-end). The flexural strength had been distinct for each age while the crack widths had been calculated after the greatest bearing loads. The microstructure of steel fiber reinforced concrete (SFRC) had been considered by two means (scanning electron microscopy and optical microscopy). The results indicated that the microcopy images could be used for demonstrated the characteristic of SFRC bond where a good bond was illustrated between the concrete matrix interface zone and steel fiber by using polarizing microscopy. SFRC flexural strength became enlarger with increasing both the concrete age and fiber volume fraction.

Kumar et. al. [8] work with a very dense matrix mix of Reactive Powder Concrete (RPC) that composed of very fine powders (cement, sand, quartz powder and silica fume), steel fibers (optional), and a super plasticizer and using these components to give the ultra-high strength and durability properties. The performance of reactive powder concrete had been investigated in which RPC was made containing fly ash Ground Granulated Blast Furnace Slag (GGBS) as a replacement for cement at three percentages of 5%, 10%, and 15% and in order to compare these result of cement replaced mixture, a specimen without cement replacement (RPC) were also cast. The obtained results showed that a development related to the strength (compressive and flexural) in addition to the elastic modulus for cement replaced mixes.

3. Paper Plan

This paper consists of an experimental program which carried out to investigate the suitability amount of silica fume, and steel fiber in the production of high strength concrete with using of available local materials to reach a new approach in producing UHPC from available local materials. Hence, the first step focus on the investigating of the influence of the curing regimes on the concrete behavior (strength types) measured by different ages so that the curing regimes are conducted that including 6 curing types which given as follows: 2 days at 80°C, 3 days at 80°C, 4 days at 80°C, 7 days at 20°C, 3days at 80°C, and 2 days at 60°C followed by 3 days at 80°C. Then, the experimental procedures with their results are presented to UHPC mixtures. Moreover, the obtained results are summarized in tables and figures given by the different relationship with the deep discussion.

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4. Experimental program

The experimental program consists of many different stages beginning from the selection of the job materials followed by mixing them and casting them into their cubes and prisms molds and finally subjected to the curing system.

4.1 Materials

RPC compose of extremely fine powder materials such as cement, sand, and silica fume in addition to steel fibers (added as mix specified), and super plasticizer material that used at its best possible dosage to decrease the water cement ratio (W/C) and getting better the concrete workability.

4.1.1 Cement

In this research, Portland cement Type V (Aljisir sulfate resisting) which produced in Iraq was used in which its chemical and physical properties satisfy the requirements of Iraqi specification No.5.

4.1.2 Fine aggregate

Natural sand with four maximum sizes of 2.63, 1.18, 0.6 and 0.3 mm was used. The content of Sulfate of fine aggregate was found within the permissible limits of the Iraqi specification No. 45.

4.1.3 Silica fume

Silica fume is consequential from the reduction of high purity quartz with coal or coke, and wood chips in an electric arc furnace during the silicon metal or silicon alloys production. Using silica fume in concrete has engineering potential and economic. It added to the UHPC mixes of this work. The percentages used were 10%, 15%, 20%, 25%, and 30% as partial replacement of cement weight. The tested silica fume is conformed and satisfy the physical and chemical requirements of ASTM C1240 specifications.

4.1.4 Steel fibers

In general, the using of this specific steel fiber enhances the initial values of the compressive and tensile strength of RPC. Hooked steel fibers used throughout the experimental program as shown in figure 1 in which hooked type has enlarged the connection of hydrated cement paste around steel fibers surfaces. Here, the steel fiber has the following properties diameter 0.5mm, length 30mm, density 7800 kg/m³, and the ultimate tensile strength not less than 850 MPa.

Figure 1. Hooked steel fibers.

4.2 Testing procedure

Test procedure is divided into two categories such that the first one relates to a suitable selection of mix properties and proportion while the second deals with the mixing operation in the laboratory.

4.2.1 Mix proportions

Table 1 shows the UHPC mixes proportion which is essential for getting the minimum compressive strength at least 150 MPa. In this table, silica fume accounts 10% to 30 % of the binder for mix non contain steel fiber and 25% for mixes without steel fiber. Using silica fume is essential to reach an excessive compressive strength in addition to the high durability because silica fume makes accelerating to the pozzolanic reactions which produce additional calcium silicate hydrates (C-S-H) that consequently fill the voids exist in the paste matrix. Since the present work focuses on finding the most effectual silica fume content for developing UHPC by using the locally available materials achieve two main goals, the first goal is to obtain a mix satisfy the adequate compressive strength and the second goal is to minimize the cost of UHPC.

4.2.2 Mixing procedure

The following mixing procedure was employed for each patch of (HPC) under specified laboratory circumstances: The quantity of silica fume in dry condition state was mixed with the necessary cement for period 5 minutes to make sure that silica fume was carefully dispersed through cement particles. Then, the fine sand was added to the mixer and mixed for 5 minutes. Later, the super plasticizer was dissolved in pure water and the liquid of super plasticizer and water was added to the rotary machine mixer so that the whole mix ingredients by mixing for a sufficient time. After that, the mixer was stopped, and the mixing was continued by hand particularly for parts which not reached by the mixer blades. Finally, the mixer was operated for 5 minutes to attain sensible fluidity. Steel fibers were slowly distributed in the uniform state through the for 5 minutes for the period of the mixing process, and later the mixing process was continued for an additional 3 minutes. Finally, the total times requires for the mixing one batch is approximately 30 minutes. Two types of test samples are required in which the first one is cubed specimens to estimate the concrete compressive strength and the second is the prisms specimens to determine the flexural (tensile)concrete strength.

Table 1. Mix materials proportions

Sample	Cement [a]	Fine Sand [a]	Silica Fume [b]	Super Plasticizer [b]	Water-Cement ratio (w/c) [c]	Steel Fiber [d]
1	1	1	10	6	18	---
2	1	1	15	6	18	---
3	1	1	20	6	18	---
4	1	1	25	6	18	---
5	1	1	30	6	18	---
6	1	1	25	6	18	0.5
7	1	1	25	6	18	1.0
8	1	1	25	6	18	1.5
9	1	1	25	6	18	2.0
10	1	1	25	6	18	2.5

[a] Cement an fine sand are expressed by fraction weight proportion of total mix such as 1:1.
[b] Silica fume and superplastisizer are expressed as percent weight of cement.
[c] Water-cement ratio was expressed as percentage ratio.
[d] Steel fiber is expressed as percent volume of total mix.

5. Results and discussion

The study result is divided into four sections, so each section focuses on the required investigated parameter in order to illustrative its effect on the strength gained.

5.1. Curing regime

Table 2 shows the effect of different methods of hot curing on the compressive strength. Herein results indicate that the highest compression strength that can be obtained by increasing the curing period which reaches to 90 days and this value of strength can be obtained in hot curing with 2 days at 60°C + 3 days at 80°C.

Table 2. Compression of UHPC strengths for different curing conditions.

Curing regime	Compression Strength (MPa)
2 days at 80°C	56.3
3 days at 80°C	63.5
4 days at 80°C	66.2
7 days at 20°C + 3 days at 80°C	50.1
2 days at 60°C + 3 days at 80°C	89.0

5.2. Sand gradation

Table 3 describes the results of four graded of sand with corresponding compressive strength in which these results were shown in figure 2. It can be observed that the mixture compressive strength become lesser with the increase of the maximum size of fine aggregate used that given as logarithm relationship. Also, it is observed that 0.3 mm maximum size exhibited 39% increase in compressive strength compared with the maximum size of fine aggregate equal to 2.36 mm. According to the obtained results, the following expression was found between the concrete compressive strength (f_{cu}), here known as grade strength, with the size of fine sand (S_{pass}) which given as:

$$f_{cu} = 16.48\log_e(S_{pass}) + 100.8 \quad (1)$$

with a modulus of correlation equals to 0.9305

Table 3. Compression strength of concrete mixture with a gradation of fine sand.

Sieve size passing (mm)	Compression Strength (MPa)
2.36	89.00
1.18	97.17
0.60	104.00
0.30	124.41

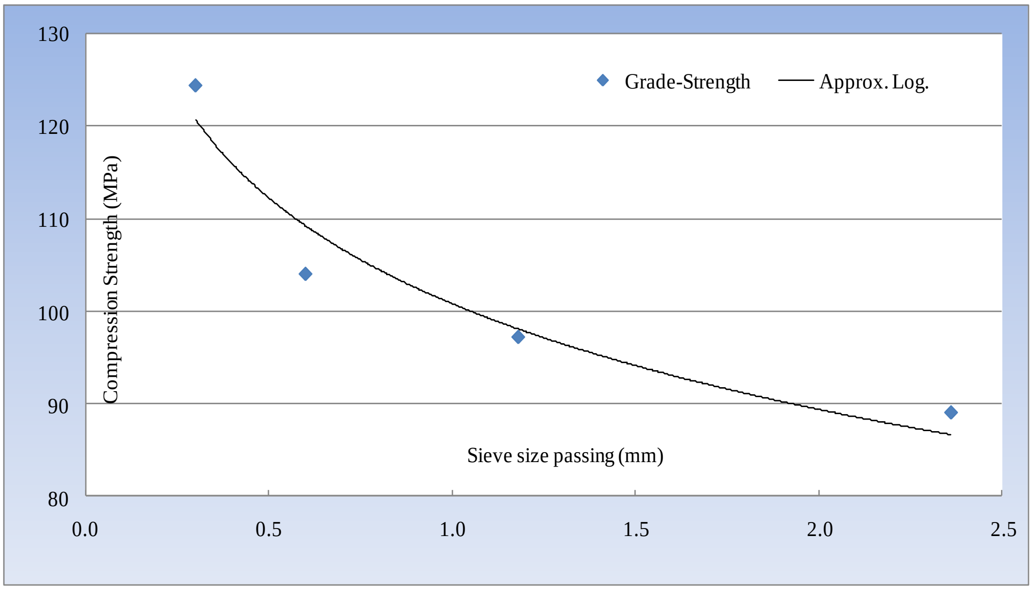


Figure 2. The relationship between compression strength of concrete mixture with a grade of fine sand.

5.3. Silica fume

Different proportions of silica fume were selected, and their result is given in Table 4, and their effect is shown in figure 3. It is noticed from Table 4 that the increasing of silica fume ratios increases the compressive strength but with less amount in which a small compressive strength had been gained after 25% ratio of Silica Fume. The effect of Silica fume is well recognized in figure 3 that display a nonlinear relationship between the concrete compressive strength (f_{cu}) and the silica fume contents (S_i) which given as:

$$f_{cu} = 0.008S_i^3 - 0.3311S_i^2 + 9.9607S_i + 23.88 \quad (2)$$

so that this relationship gives value for the modulus of correlation equals to 0.9972.

Table 4. Compression strength of concrete mixture with different silica fumes content.

Silica Fume (%)	Compression Strength (MPa)
10	94.0
15	112.3
20	120.0
25	126.0
30	127.1

It is so clear that the effect of silica fume is enhancing the mechanical characteristics of the hardened concrete by to make these properties better than the case without using it noting that the basic physical principle of its action in the concrete mix is a closely similar to that of the filler action. Due to its fineness, silica fume can well be placed into the interval between the cement particles as the similar pattern of sand that filling the voids between coarse aggregate and cement particles to enclose these voids, in addition, the space between sand grains.
Generally, the silica fume used to increase the concrete strength of considerable amount. In addition, since silica fume has high surface area and high content of amorphous silica , therefore the chemical reaction of silica fume is huge active pozzolan reacts more rapidly than usual pozzolans. Consequently, from Table 4, it can be found that the optimum dose of silica fume is 25% (by weight) when used as partial replacement of ordinary Portland cement (OPC).

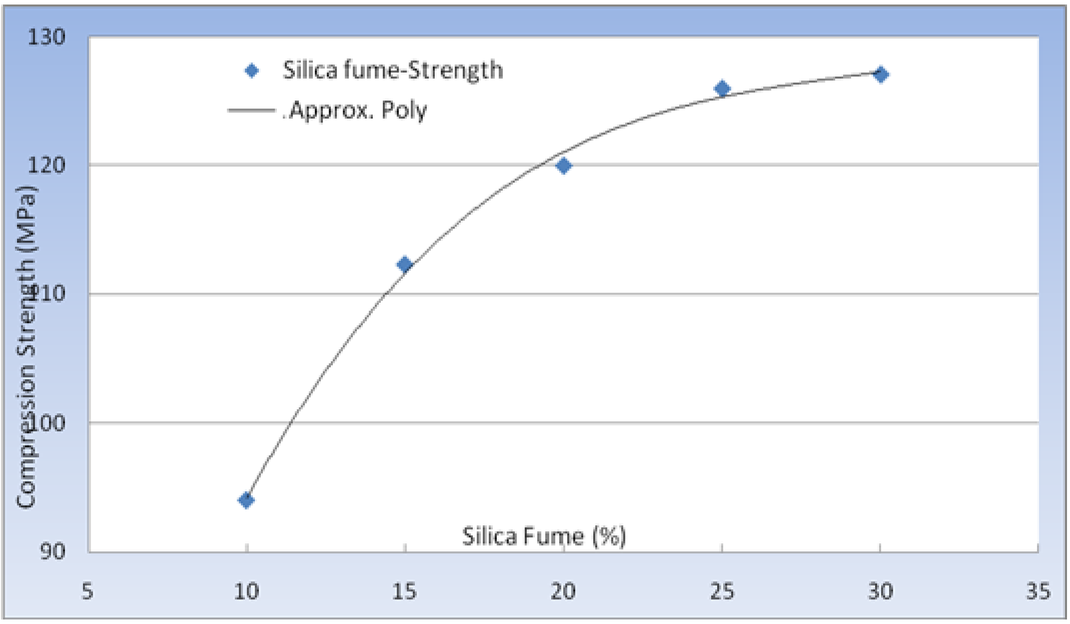


Figure 3. Relationship between compression strength of concrete mixture with silica fume ratio.

5.4 Steel Fiber

Six steel fiber ratios were used and their results with high performance concrete (HPC) and UHPC strength (more than 150 MPa) are given in Table 5. These results indicate a large benefit of the steel fiber in the high performance concrete (both HPC and UHPC) strength types and it is important to conclusion that steel fiber more than 1.6% change the concrete type to UHPC which has a high effect on both compression and tension strength The microstructures of RPC at early ages in the young and mature pastes state can be shown in various figures that given by Tayfun [8] and ACI 234 [9].

Figure 4 shows the trend of steel fiber of high performance concrete (UHPC-HPC) strength relationship which takes a linear nature regardless strength type with the modulus of regression equals 0.99. Two relationships are obtained here in which the first between the compressive concrete strength and the steel fiber content (S_f) while the second between the flexural concrete strength (f_{ct}), sometimes known as the tensile concrete strength, with the steel fiber content and these two relationship are given below as:

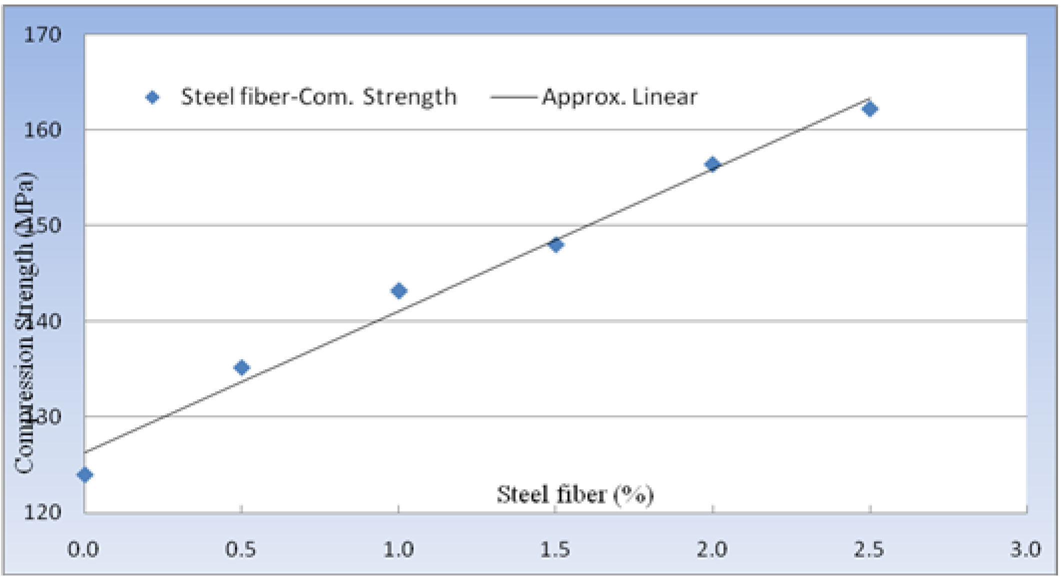
$$f_{cu} = 14.823 S_f + 126.3 \tag{3}$$

$$f_{ct} = 8.9714 S_f + 7.7524 \tag{4}$$

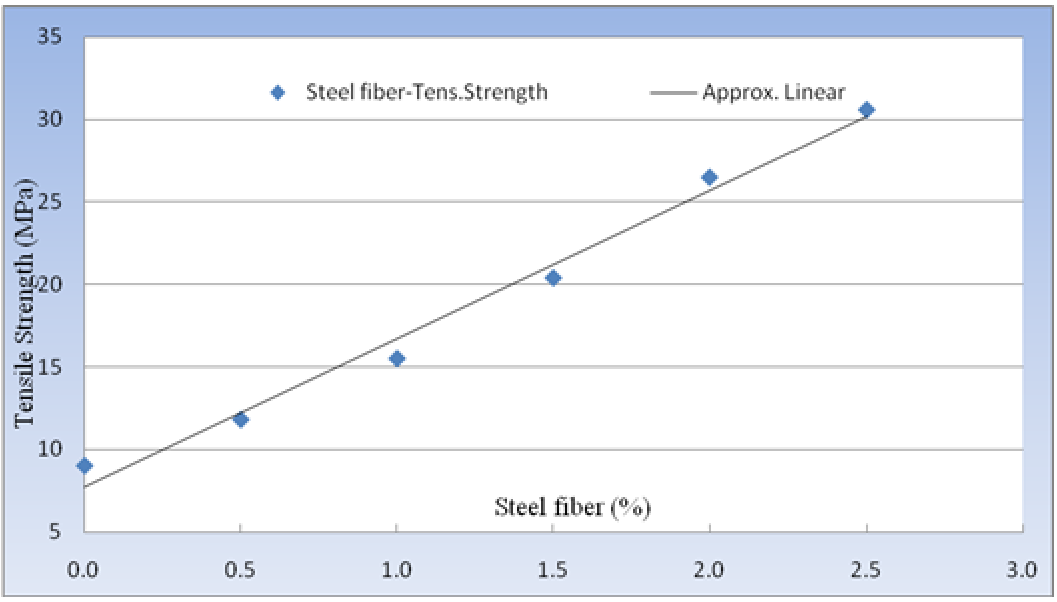
Table 5. Steel fiber ratio with compression and tensile strength of UHPC

Steel Fiber %	Compression Strength (MPa)	Tensile Strength (MPa)
0.0	124.0	9.0
0.5	135.2	11.8
1.0	143.2	15.5
1.5	148.0	20.4
2.0	156.4	26.5
2.5	162.2	30.6

The effect of the presence of steel fibers on the concrete strength can be illustrated as a very dense matrix is satisfied by optimizing the granular packing of the fine dry powders and this state of microstructure concrete is achieved by increasing the steel fiber content regardless of the economic point of view.
For tensile strength, the UHPC mixture steel fibers of ratio 2.5% increase the strength by 240 % than mixture without steel fibers while this ratio is 31% corresponding to compression strength. These results can be attributed to the action of steel fibers as the interception of steel fibers to the development and growth of cracks formed in the hardened concrete paste, which leads to the suspension of growth of these cracks in addition to not generating additional cracks within the ultra high performance concrete (UHPC) paste. Also, it seen that there is a good quality attachment in interface zones of cement concrete medium and steel fiber which alter in this situation by increasing the bonding between steel and concrete [10].
The above results are so clear as depicted in Figure 5 which displays two samples of crushing concrete cubes with and without steel fibers. These results may comparable with those when using polypropylene fibbers as a solution for sapling resistance despite fiber behavior in high temperature while PP melt and create channels through which the water vapour pressure built-up within HPC as temperature rises is released, which significantly reduces the sapling tendency of HPC under fire conditions [4].



(a)



(b)

Figure 4. Relationship between steel fiber ratio with (a) concrete compressive strength; (b) Tensile strength

With steel fiber Without steel fiber

Figure 5. Concrete cubes crushing samples with and without steel fiber.

6. Conclusions

According to the receiving results, the following conclusions are specified as :

1. The curing regime had an influenced effect on the concrete compressive strength in which curing regime C that consists of 2 days at 60°C followed by 3 days at 80°C, giving the maximum concrete compressive strengths.
2. The added steel fibers cause a considerable increasing in the tensile strength (flexural) than compression strength with a linear relationship.
3. It is achievable for producing UHPC mixtures containing availably local materials to obtain 150MPa compressive strength with the following mixture proportion by weight (cement 1, fine Sand 1, silica fume 25%, water / cementations material ratio 18%, and steel fiber 2.0% by volume).
4. The finer sand causes an increasing in the concrete compressive strength than using the usual gradation sand.
5. Using amount of silica fume larger than 25% had insignificant special effects on the concrete compressive strength so that this ratio of silica can be considered the optimal value.

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