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Mechanical and Fracture Mechanics Properties of Ultra-High-Performance Concrete

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***Abstract**: This paper presents the results of an experimental study conducted to develop and evaluate the compressive strength, flexural strength and drying shrinkagewhich are three important properties of ultra-high-performance concrete (UHPC). In this study, sixteen mixtures with different ratios of silica fume, crushed quartz powder, steel fibers, sand typeand different aggregate size were prepared. The effect of utilized materials on mechanical properties of UHPC was experimentally concludedand analyzed by ANOVA test.*

***Keywords**: Compressive strength, Drying shrinkage, Flexural strength, Steel fibers, Ultra-high performance concrete.*

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I. Introduction

Ultra-high performance concrete (UHPC) is one of the modern concrete technologies that appeared at the 21st century to make a great improvement in the conventional concrete properties. UHPC has some advantages such as high ductility, high durability,high compressive strength that exceeded 150 MPa, flexural strengths higher than 10 MPa at 28 days**,** high toughness and high resistance against chloride diffusion and chemical attacks **[1].**UHPC is distinguished by using low water to cementitious ratio (W/C), replacing coarse aggregate by fine aggregate and adding pozzolanic materials. Steel fibers are used to enhance the tensile strength, the flexural strength and ductility of UHPC thus **[2]** investigated that adding 2% steel fibers by concrete volume is the most suitable ratio to produce UHPC with high ductility and high tensile strength. Strength performance remains the most important property of structural concrete; from this point of view, the relation between UHPC composition and mechanical properties has long been a matter of research concern.

II. Experimental investigation

1.1. Materials and mixture design

UHPC is designed according to absolute volume methodusing Portland cement, silica fume, crushed quartz powder, steel fibers, water and superplastlizers. All mixtures contain Portland cement (CEM I 52.5 N) with amount 900 Kg/m^{3}complying with the Egyptian standard specification **(ES 4756-1/2013)[3]** and the chemical properties are shown in Table 1. Silica fume was usedwith an average particle size of 8 µm confirming to **ASTM C1240-97 (1997) [4]** and the chemical properties are shown in Table 1.Crushed quartz powderwith specific gravity 2.85 t/m³ was used and the chemical properties are shown inTable 1.Superplasticizerof type (ViscoCrete-3425) was used to enhance the workability of mixtures.Four sizes of sand were used (0.15: 1.18 mm), (0.15: 2.36 mm), (0.15: 4.75 mm) and (0.15: 0.6 mm) and their specifications are according to**(ES 1109:2008) [5].** Corrugated round steel fibers with aspect ratio 25.2 were used at all mixtures. The ratio of W/C was 0.2 at all mixtures.Table 2 illustrated the ratios of produced mixtures.

Table1 Chemical properties of UHPC components.

Component	MgO (%)	K_2O (%)	Na_2O (%)	Fe_2O_3 (%)	SiO_2 (%)	CaO (%)	AL_2O (%)	Loss on ignition L.O.I (%)	SO_3 (%)	CL_2 (%)
Cement	1.65	0.18	0.50	3.56	21.58	61.09	4.94	2.60	3.22	---
Quartz powder	0.21	0.22	0.05	0.35	97.0	1.02	0.83	---	0.33	0.05
Silica fume	0.18	0.35	0.14	0.52	96.02	---	1.01	---	0.26	0.16

Table 2 Mixture Proportions of UHPC by weight.

Material	Mix No	Description	Mix proportions (with respect to cement)						
			C	SF	S_tf (Kg/m^3)	S	CQ/S	SP	W/C
CQ	1	0.0	1	0.25	157	1.58	0.0	0.04	0.2
	2	10%	1	0.25	157	1.42	0.16	0.04	0.2
	3	20%	1	0.25	157	1.26	0.32	0.04	0.2
	4	30%	1	0.25	157	1.11	0.47	0.04	0.2
Aggregate Size	5	0.15 to 1.18 mm	1	0.25	157	1.26	0.32	0.04	0.2
	6	0.15 to 2.36 mm	1	0.25	157	1.26	0.32	0.04	0.2
	7	0.15 to 4.75 mm	1	0.25	157	1.26	0.32	0.04	0.2
SF	8	0.0%	1	0.0	157	1.26	0.32	0.04	0.2
	9	10%	1	0.10	157	1.26	0.32	0.04	0.2
	10	20%	1	0.20	157	1.26	0.32	0.04	0.2
	11	30%	1	0.30	157	1.26	0.32	0.04	0.2
S_tf	12	0.0%	1	0.25	0.0	1.26	0.32	0.04	0.2
	13	1.4%	1	0.25	107	1.26	0.32	0.04	0.2
	14	2%	1	0.25	157	1.26	0.32	0.04	0.2
Sand Type	15	Natural Sand	1	0.25	157	1.26	0.32	0.04	0.2
	16	Combined Sand (50% natural sand +50% limestone)	1	0.25	157	1.26	0.32	0.04	0.2

Where: C: Cement; **CQ/S**: Ratio between crushed quartz and sand; **S**: Sand; **SF**: Silica fume; **S_tf**: Steel fibers; **SP**: Superplastlizers.

1.2. Mixing, casting procedure and curing

At mixer with capacity 15 liters, all materials were mixed with the following sequence:

- Cement, crushed quartz powder, silica fume and fine sand were carefully mixed at a slow speed (140 ± 5 rpm) for 3 minutes.
- Half of used superplasticizer was dissolved in half amount of water and continue mixing for 3 minutes at slow speed.
- Adding the remaining half of superplasticizer with the remaining half of water and continue mixing at a slow speed for approximately 3 other minutes.
- Steel fibers were added and continue mixing for 5 minutes at medium speed.
- Mixer was stopped when UHPC mixtures became homogenous.
- Moldswere filled with fresh concrete and vibrated for 30 seconds.
- The specimens were left in a room at 23 ºCand covered using plastic sheets.
- After 24 hours, all specimens were demolded and cured in water at a temperature (21 ± 2 ºC) until the testing age.

1.3. Testing process

The experimental program contains measuring compressive strength, flexural strength and drying shrinkage. At 7, 28 and 56 days, compressive strength was measured using cubes 50 × 50 × 50 mm. The compressive strength test was measured according to **ASTM C109, (2004) [6]**.

The flexural strength was measured at 7, 28 and 56 days using prisms 40 × 40 ×160 mm in compliance with **ASTM C293, (1994) [7]**.

Beams 25 × 25 × 285 mm were used to measure the drying shrinkage at 7, 14, 28, and 56 days according to **ASTM C490/C490M (2011) [8]**. Three prisms were used at each age and averages were reported as tested results.

III. Results and discussion

Duncan's multiple range test was used to make a comparison of means for the effect of each variable at each age at level 0.05. By using the linear model, ANOVA test was applied to the experimental results.

1.4. Compressive strength

Compressive strength test was conducted at 7, 28 and 56 daysand results are shown in Fig. 1.

1.4.1 Discussion of compressive strength results

1.4.1.1 Effect of silica fume

Increasing silica fume has a great effect on increasing the compressive strength results. As shown in Fig. 1, adding 30% silica fume by cement weight resulted in compressive strength exceeded 150 MPa at 56 days. ANOVA test showed that silica fume has a significant effect on compressive strength results; meanwhile, the interaction between each of age and silica fume is insignificant, that means increasing the ratio of silica fume with the improvement of age doesn't have a great effect on increasing compressive strength.

1.4.1.2 Effect of steel fibers

Increasing steel fibers resulted in increasing compressive strength results at all ages as shown in Fig. 1. This tracked back to increasing steel fibers resulted in delaying the propagation of cracks **[9]**. From ANOVA results, steel fibers have a significant effect on compressive strength results; meanwhile, the interaction between each of age and steel fibers is insignificant.

1.4.1.3 Effect of aggregate size

As shown in Fig. 1, when increasing aggregate size, the compressive strength decreases; from an engineering view point, the reason for this incremental tracked back to decreasing the dynamic flow of UHPC **[10]**. ANOVA test showed that aggregate size has a significant effect on compressive strength results; meanwhile, the interaction between each of age and aggregate size is insignificant.

1.4.1.4 Effect of sand type

Combined sand resulted in compressive strength higher than using natural sand only as shown in Fig. 1.This because of combined sand contains limestone which is a good filler material and produced a dense microstructure**[11]**. According to ANOVA results, sand type has a significant effect on compressive strength results; meanwhile, the interaction between each of age and sand type is insignificant.

1.4.1.5 Effect of crushed quartz powder

Four ratios of crushed quartz powder were used and it was found that the higher compressive strength was obtained at 20% quartz as a partial replacement of fine sand by weightbecause quartz is a good filler material but with increasing crushed quartz powder from 20 to 30%, slightly reduction was noticed in compressive strength results as shown in Fig. 1. ANOVA test showed that crushed quartz powder has a significant effect on compressive strength results; meanwhile, the interaction between each of age and crushed quartz powder is insignificant.

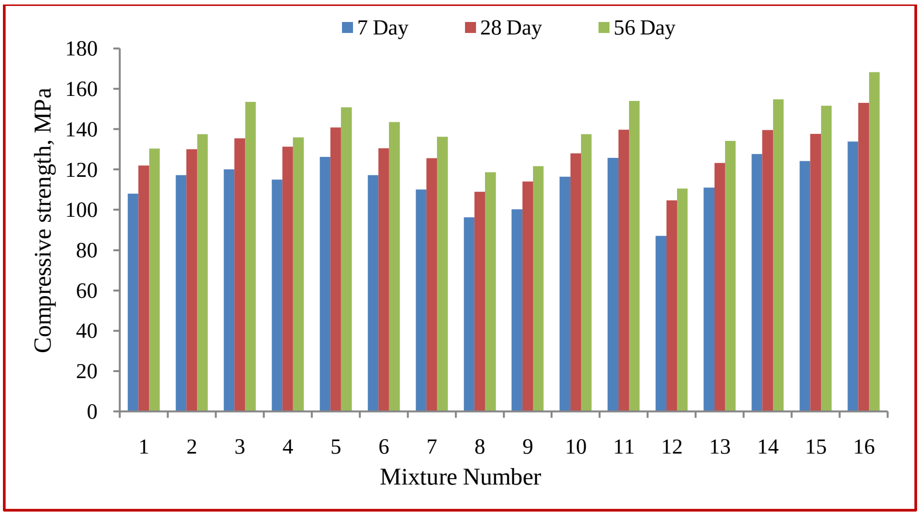


Fig. 1 Compressive strength results for UHPC

1.5. Flexural strength

The results of the flexural strength test at 7, 28 and 56 days are shown in Fig. 2. ANOVA results showed that adding steel fibers, crushed quartz powder, silica fume, combined sand and aggregate size have a significant effect on flexural strength results.

1.5.1 Discussion of flexural strength results

1.5.1.1 Effect of steel fibers

As expected, a mixture without steel fibers resulted in low flexural strength but with increasing steel fibers to 2 % by concrete volume resulted in flexural strength exceeded 30 MPa at 56 days as shown in Fig. 2(a). These results are in agreement with **[12]**.From ANOVA test, the interaction between each of age and steel fibers is significant, that means increasing the ratio of steel fibers with the improvement of age has a great effect on increasing flexural strength.

1.5.1.2 Effect of silica fume

Mixture without silica fume resulted in low flexural strength; meanwhile, the flexural strength increased to 32.6 MPa at 56 days when increase silica fume from 10 to 20 % by cement weight but showed no significant change between 20 and 30 % as shown in Fig. 2(b).The interaction between each of age and silica fume is significant according to ANOVA results.

1.5.1.3 Effect of crushed quartz powder

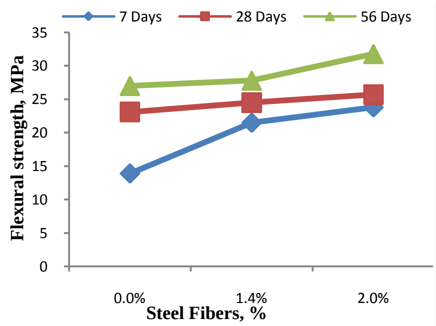
Without adding crushed quartz powder, the flexural strength was less than 30 MPa at all ages but with increasing the crushed quartz powder up to 20% as a partial replacement of fine sand by weight resulted in increasing the flexural strength as shown in Fig. 2(c). ANOVA test showed that the interaction between each of age and crushed quartz powder is insignificant.

1.5.1.4 Effect of aggregate size

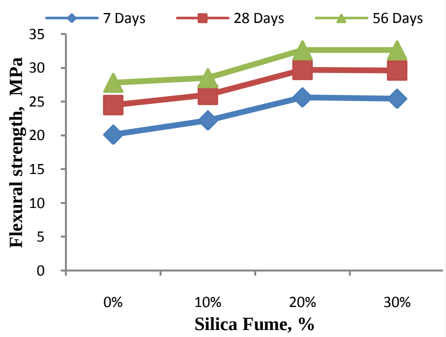
Adding fine aggregate size (0.15:1.18 mm) increased the flexural strength to 34.2 MPa at 56 days but with increasing maximum fine aggregate size to 4.75 mm, the flexural strength decreased at all ages as shown in Fig. 2(d). ANOVA test showed that the interaction between each of age and aggregate size is insignificant.

1.5.1.5 Effect of sand type

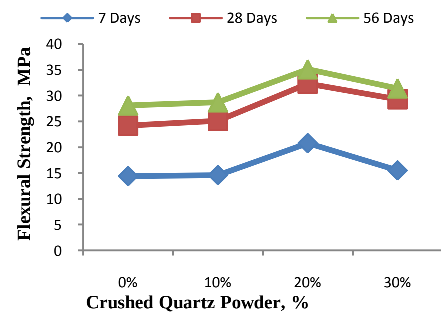
Adding combined sand resulted in flexural strength higher than adding natural sand only as shown in Fig. 2(e). Based on ANOVA results, the interaction between each of age and sand type is insignificant.



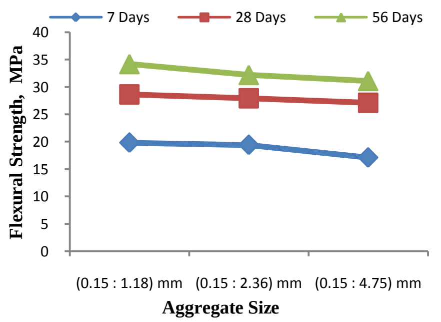
(a) Effect of steel fibers



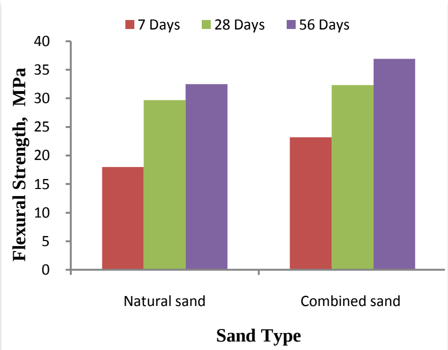
(b) Effect of silica fume



(c) Effect of crushed quartz



(d) Effect of aggregate size



(e) Effect of sand type

Fig. 2 Flexural strength results for UHPC: (a) Effect of steel fibers; (b) Effect of silica fume; (c) Effect of crushed quartz powder; (d) Effect of aggregate size; (e) Effect of sand type.

1.6. Drying shrinkage
The results of drying shrinkage test at 7, 14, 28 and 56 days are shown in Fig. 3. ANOVA results showed that adding steel fibers, crushed quartz powder, silica fume, combined sand and varying aggregate size have a significant effect on drying shrinkage results.
1.6.1 Discussion of drying shrinkage results
1.6.1.1 Effect of steel fibers
As shown in Fig. 3(a), the drying shrinkage decreased with increasing steel fibers. This reduction in drying shrinkage is tracked back to the generation of the shear stresses along the fibers thus fibers were exposed to compression and resisted the tensile strain in concrete **[13]**. Based on ANOVA results, the interaction between each of age and steel fibers is significant, that means increasing the ratio of steel fibers with the improvement of age has a great effect on increasing drying shrinkage.
1.6.1.2 Effect of silica fume
Drying shrinkage increased with increasing silica fume from 0 to 30% by cement weight as shown in Fig. 3(b). This tracked back to the pozzolanic reaction and pore size refinement mechanism of silica fume**[14]**.The interaction between each of age and silica fume is significant according to ANOVA results.
1.6.1.3 Effect of crushed quartz powder
Adding 30% crushed quartz powder as a partial replacement of fine sand by weight recorded the lowest drying shrinkage as shown in Fig. 3(c) because the quartz powder is a filler material and the refinement in the pores plays a notable role in reducing the shrinkage. ANOVA test showed that the interaction between each of age and crushed quartz powder is insignificant.
1.6.1.4 Effect of aggregate size
Increasing the maximum fine aggregate size from 1.18 to 4.75 mm resulted in decreasing drying shrinkage as shown in Fig. 3(d). This reversal relationship between aggregate size and drying shrinkage was supported by [13] who reported that the reduction in drying shrinkage is due to the restraining action of the aggregate in the mortar. From ANOVA test, the interaction between each of age and aggregate size is significant.
1.6.1.5 Effect of sand type
Natural sand resulted in lower drying shrinkage than combined sand by about 14% at 56 days as shown in Fig. 3(e). This reduction is due to limestone is a good filler material thus accelerate the process of hydration and produce high shrinkage at an early age. Based on ANOVA results, the interaction between each of age and sand type is significant.

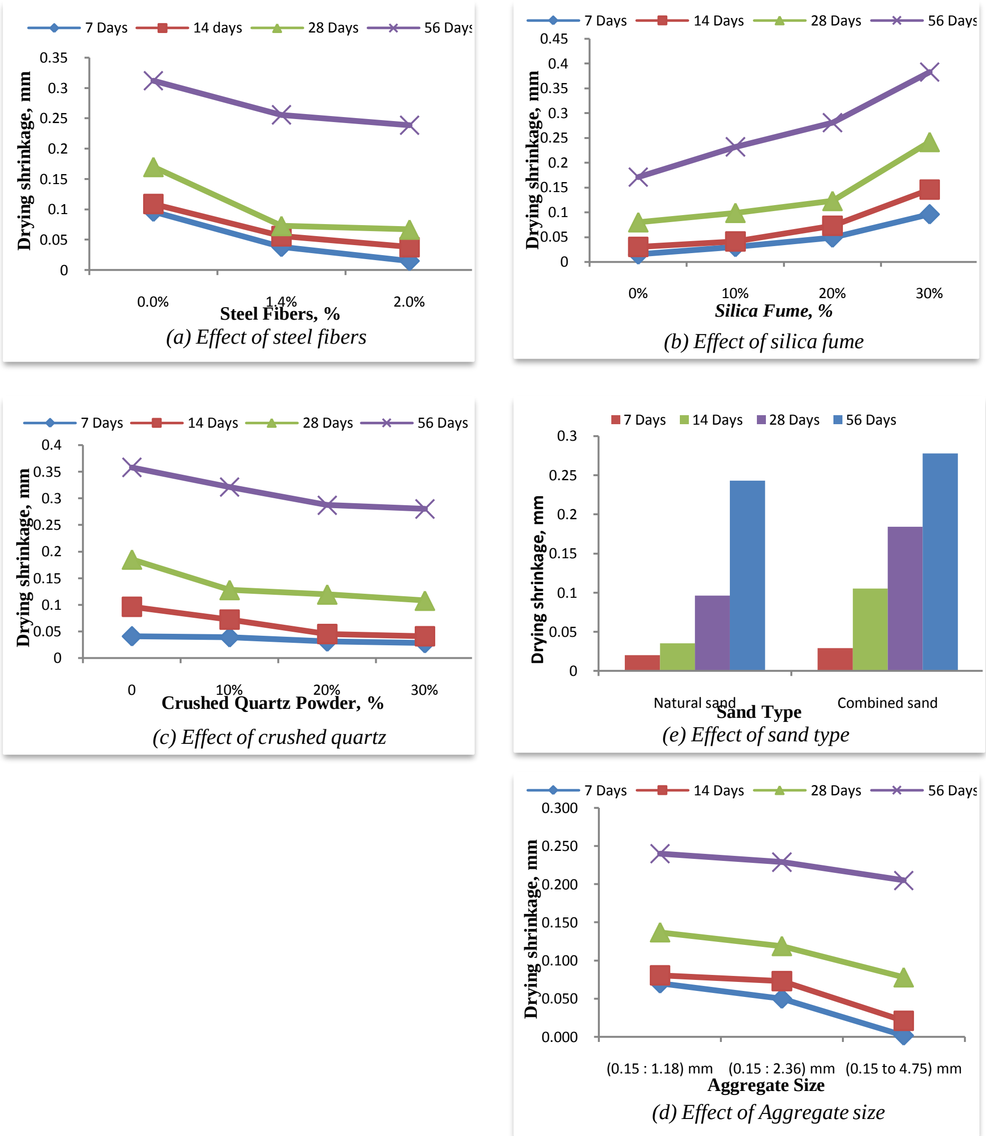


Fig. 3 Drying shrinkage results for UHPC: (a) Effect of steel fibers; (b) Effect of silica fume; (c) Effect of crushed quartz powder; (d) Effect of aggregate size; (e) Effect of sand type.

IV. Conclusions

An experimental program of UHPC was conducted to present the effect of using a different ratios of silica fume, crushed quartz powder, steel fibers, maximum aggregate size and sand type on the mechanical properties of UHPC and the results were analyzed by ANOVA test. The following conclusions were concluded from the experimental program:

- Using limestone with natural sand was beneficial to produce UHPC with high compressive strength and flexural strength.
- Adding 2% steel fibers by concrete volume was the optimum ratio to produce UHPC with high compressive strength and flexural strength at all ages.
- Using 30% silica fume by cement weight improved the compressive strength of UHPC.
- Increasing crushed quartz powder up to 20% as a partial replacement of sand by weight was useful in improving the compressive strength and flexural strength test.
- The inclusion of steel fibers, different maximum size, silica fume and sand type resulted in different drying shrinkage. Moreover, adding 0% silica fume was found to produce the minimum drying shrinkage, in turn, 30% silica fume by cement weight resulted in the highest drying shrinkage.
- The smallest used aggregate size (0.15:1.18 mm) resulted in the highest compressive strength, flexural strength and drying shrinkage among used sizes of aggregate in this study.

- The analysis in this study provides simple and economic values of mechanical properties of UHPC as affected by different constituents of the material.

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