ISSN 1996-3394

Asian Journal of Materials Science

Knowledgia SCIENTIFIC
A Place to Publish Outstanding Research

http://knowledgiascientific.com

Asian Journal of Materials Science 2 (3): 137-146, 2010
ISSN 1996-3394

Effects of Silica Fume, Ultrafine and Mixing Sequences on Properties of Ultra High Performance Concrete

S. Shihada and M. Arafa
Department of Civil Engineering,
The Islamic University of Gaza, P.O. Box, Gaza, Palestine

Abstract: The aim of this study is to investigate the effects of changing silica fume content, amount of crushed quartz powder as ultra fine aggregate and the sequence of mixing procedure on the main properties of Ultra High Performance Concrete (UHPC), with particular emphasis on 28 days compressive strength, density and slump. Several concrete mixes involving different contents of Silica fume and crushed quartz powder are prepared and tested for this purpose. Based on the results of this study, it is concluded that the optimum silica fume content necessary for producing UHPC is about 15% of cement mass. At this percentage, compressive strength is about 60% more than the strength for the zero content of silica fume. Added to this, the results show that adding 40% of the quantity of superplastisizer to the UHPC mixture at the first stage of the mixing with all dry materials has a positive effect on the 28 days compressive strength, while enhancing the workability. Moreover, as the ultrafine content increases, the compressive strength increases with the highest compressive achieved using ultrafine to cement ratio of 0.50.

Key words: UHPC, silica fume, crushed quartz, mixing sequence, Gaza strip

INTRODUCTION

Ultra High Performance Concrete (UHPC) is one of the latest developments in concrete technology. The UHPC refers to materials with a characteristic compressive strength in excess of 120 MPa (Hugues *et al*., 2008). The UHPC is made by using coarse, fine and ultrafine aggregates, very low amounts of water, silica fume and high amounts of cement. Silica fume is an ultrafine powder whose particle sizes are 50 to 100 times finer than cement and can fill up the voids created by the free water in the cement matrix. Chemically, it reacts with Calcium Hydroxide (CH) to produce additional Calcium Silicate Hydrate (CSH). The reaction between hydrated Portland cement compounds and Silica fume produces a very dense microstructure and thus improves the bond between the cement and the aggregates.

The influence of silica fume content on the performance of UHPC is studied by Park *et al*. (2008), Duval and Kadri (1998) and Mazloom *et al*. (2004). They conclude that the compressive strength of UHPC is dependent on silica fume content since the additional amount of silica fume decreases the water demand which, in turn, needs more superplasticizer to make the concrete mix workable.

The effect of mixing methods on fresh and hardened UHPC is also studied by Schachinger *et al.* (2004) where the results indicate that adding 40% of the amount of the

Corresponding Author: S. Shihada, Department of Civil Engineering,
The Islamic University of Gaza, P.O. Box, Gaza, Palestine

superplasticizer to the water at the beginning of the mixing procedure avoids agglomeration of silica fume and reduces the air content of concrete. Chopin *et al*. (2004) shows that mixing time can be reduced by increasing the fine particle content with a constant w/c ratio. Furthermore, Chang and Peng (2001) indicated that first mixing the binder with a portion of the superplasticizer and part of the water before adding the aggregate with the remaining part of superplasticizer dissolved in the rest of the water requires less mixing time and increases the compressive strength.

Ultra high performance concrete associated with very dense matrix is characterized by the use of high volumes of ultrafine particles which are usually quartz powders with a maximum size of 150 μm. The effect of filling powders is studied by Long ***et al.*** (2002) and Tafraoui ***et al.*** (2009) where the results show that increasing the amount of ultrafine powder results in increasing the compressive strength UHPC.

This particular research work, which is a continuation to a study previously carried by Arafa ***et al.*** (2010) is to evaluate the effects of changing silica fume content, amount of crushed quartz powder and mixing sequences on the main properties of UHPC. Accordingly, series of laboratory experiments are carried out to investigate the influences of the above-mentioned parameters on the properties of UHPC. The most appropriate silica fume content, ultrafine content and mixing sequence are to be specified based on the results of the experimental program.

MATERIALS AND METHODS

The UHPC constituent materials used in this research include High Strength Portland Cement CEM I 52.2R. The cement meets the requirements of ASTM C150/C150 M (2009), quartz sand and basalt aggregate. The nominal size of crushed basalt ranges from 0.6 to 6.3 mm while that of quartz sand is in the range of 0.2 to 0.4 mm. The specific gravity is 2.8 and absorption is 1.48% for basalt. For quartz sand, the specific gravity is 2.66 and the absorption is 0.62%. Crushed quartz powder of a maximum size of 150 μm is used as ultrafine aggregate. Grey silica fume with SiO_2 as main chemical component (95%) conforming to the requirements of ASTM C 1240-05 (2005) is used. In addition, a superplasticizer is used to ensure suitable workability. Proportions of these constituent materials are carefully chosen to optimize the packing density of the mixture.

Test Program

The UHPC mixes are prepared in the Soil and Material Lab at IUG-Gaza. The carried tests include 28-day compressive strength, unit weight and slump.

- For compressive strength tests, 100×100×100 mm cubes are tested according to ASTM C109/C109 M (2008). The prepared cubic specimens are covered with plastic sheeting and left in the laboratory for 24 h before being removed from the moulds and stored in a curing water tank at room temperature until the time of testing in 28 days. The water/cement ratio is set at 0.30 and the superplastisizer weight per cement weight is kept as 0.03 for all mixes. The presence of any moisture in the aggregate is measured directly before mixing and the balanced water is added at the time of mixing
- Unit weights are measured according to ASTM (2006)
- For determination of workability of fresh concrete, slumps are measured according to ASTM (2009)

Table 1: Mix proportions for different silica fume contents

Materials	Unit	Mix A	Mix B	Mix C	Mix D
Cement CEM I52.2 R	kg m^{-3}	693	660	630	600
Water	kg m^{-3}	207.9	198	189	180
Silica fume	kg m^{-3}	0	33	63	93
Silica fume per cement weight	%	0	5	10	15.5
Quartz powder	kg m^{-3}	300	300	300	300
Quartz sand (0.2-0.4 mm)	kg m^{-3}	315	315	315	315
Basalt aggregate (0.6-1.18 mm)	kg m^{-3}	460	460	460	460
Basalt aggregate (2.36-6.3 mm)	kg m^{-3}	530	530	530	530
Superplasticizer	kg m^{-3}	20.7	19.8	18.8	18.0

Table 2: Sequence (1)

Description	Step No.
Mixing of all dry materials (cement, aggregate coarse, fine, ultrafine, silica fume)	1
Adding water with, 40% of superplastisizer, to the mixture, slowly	2
3 min break	3
Adding the remaining 60% of the superplastisizer to the mixture	4
Continuation of mixing until UHPC changes from a dry mixture to thick fresh concrete	5

Table 3: Sequence (2)

Description	Step No.
Mixing of all dry materials (cement, aggregate (coarse, fine, ultrafine, silica fume)	1
Adding water, with all of the superplastisizer, to the mixture, slowly	2
Continuation of mixing until UHPC changes from a dry mixture to thick fresh concrete	3

Table 4: Sequence (3)

Description	Step No.
Mixing cement, aggregate (coarse, fine, ultrafine)	1
Adding water, with 40% of the superplastisizer, to the mixture slowly	2
Adding the silica fume	3
3 min break	4
Adding the remaining 60% of the superplastisizer to the mixture	5
Continuation of mixing so until UHPC changes from a dry mixture to thick fresh concrete	6

Effect of Changing Silica Fume Content

Four different silica fume contents of 0, 5, 10 and 15.5%, by cement mass are used to explore the influence of silica fume content on the mechanical properties of UHPC. Each of the four mixes shown in Table 1 has water to cement ratio of 0.30, superplastisizer to cement weight of 0.03 and the remaining ingredients are kept constant. The maximum silica content is limited to 15.5% since the workability beyond this content becomes very low.

Effect of Changing Mixing Sequences

The effects of changing the mixing sequences on the main properties of UHPC, including density, slump and compressive strength are investigated. Four mixing sequences are papered with quantities of cement, aggregates, silica fume and superplasticizer are kept constant and proportions of Mix D, detailed above, are used in preparing these four mixes. In sequence (1), the dry materials are mixed first followed by adding all of the mixing water to 40% of the superplasticizer. Then the mixer is put to hold for 3 min, followed by adding the remaining part of the superplasticizer to the mixture, as shown in Table 2.

Sequence (2) is similar to sequence (1) with the exception of adding the entire amount of superplasticizer to the mixture in the second step, as shown in Table 3. Sequence (3) is similar to sequence (1) with the exception of adding the silica fume before the 3 min

Table 5: Sequence (4)

Description	Step No.
Mixing cement, aggregate (coarse, fine, ultrafine)	1
Adding water, with all of superplastisizer, to the mixture, slowly	2
Adding the silica fume	3
3 min break	4
Continuation of mixing until UHPC changes from a dry mixture to thick fresh concrete	5

Table 6: Mix proportions for different crushed quartz contents

Materials	Unit	Mix E	Mix F	Mix G	Mix H
Cement CEM I52.2 R	kg m^{-3}	600	600	600	600
Water	kg m^{-3}	180	180	180	180
Silica fume	kg m^{-3}	93	93	93	93
Quartz powder	kg m^{-3}	300	240	180	120
Quartz powder/cement	%	50	40	30	20
Quartz sand (0.2-0.4 mm)	kg m^{-3}	315	323	339	354
Basalt aggregate (0.6-1.18 mm)	kg m^{-3}	460	460	460	460
Basalt aggregate (2.36-6.3 mm)	kg m^{-3}	530	530	530	530
Superplasticizer	kg m^{-3}	18	18	18	18

break, as shown in Table 4. Sequence (4) is similar to sequence (2) with the exception of adding the silica fume to the mixture before the 3-minute break, as shown in Table 5.

Effect of Changing Crushed Quartz Powder Content

Four different ultrafine to cement of 20, 30, 40 and 50% are used to explore the influence of crushed quartz powder content on the mechanical properties of UHPC. Details of these mixes are shown in Table 6.

RESULTS AND DISCUSSION

Effect of Changing Silica Fume Content

Compressive Results

The results in Table 7 show that it is possible to produce high strength concrete with compressive strengths up to 81 MPa without using silica fume at all. For 5 and 10% silica fume content, very high strength concretes with 92 MPa, 107 MPa respectively, can be achieved. Generally, the increase in the silica fume content effectively increases the compressive strength of concrete, where the increase in compressive strength for the 15% silica fume content is about 60% larger than the 0% mix. This increase in compressive strength for the 15% silica fume content is much larger than the 20% increase obtained by Mazloom *et al*. (2004), more than the 15% increase obtained by Duval and Kadri (1998) and less than the 80% increase reported by Köksal *et al.* (2008).

The hydration of Portland cement produces many compounds including Calcium Silicate Hydrates (CSH) and Calcium Hydroxide (CH). When silica fume is added to fresh concrete, it reacts with the CH to produce additional CSH which improves the bond between the cement and the surface of the aggregate. Moreover, the silica fume particles can fill the voids created by free water in the matrix. This function is called particle packing which refines the microstructure of the concrete, thus creating a much denser pore structure. The benefit of this reaction is twofold: increasing compressive strength and decreasing total pores volume. Figure 1 shows the relationship between compressive strength of UHPC and silica fume content.

Table 7: Compressive strength test results at 28 days for different silica fume contents

Mix	No. of specimens	Silica fume content (%)	Mean compressive strength (MPa)	SD	Coefficient of variation (%)
Mix A	4	0	81	3.1	3.8
Mix B	4	5	92	2.64	2.8
Mix C	4	10	107	3.8	3.6
Mix D	6	15.5	128	3.55	2.8

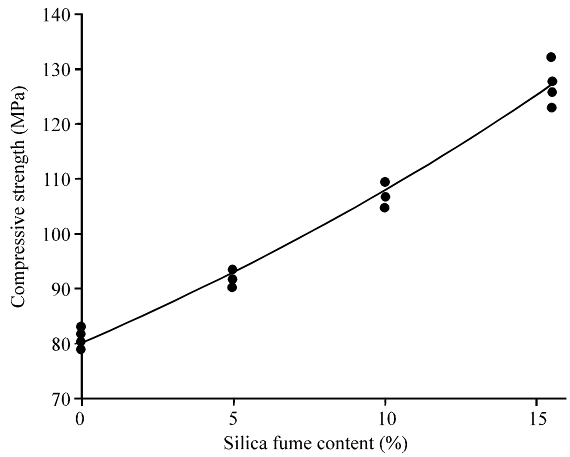

Fig. 1: Relationship between 28-day compressive strength and silica fume content

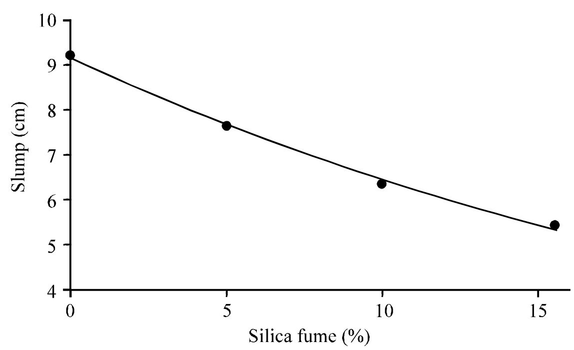

Fig. 2: Relationship between slump and silica fume content

Slump Test Results

It is observed that as the silica-fume content increases the concrete loses slump, as shown in Fig. 2. It is observed that as the silica-fume content increases, the concrete becomes sticky. The loss in slump of fresh concrete is primarily attributed to the high surface area of the silica f ume which absorbs more mixing water, while slumps resulting using silica-fume contents of 0 to 5% silica-fume are considered plastic. Slumps resulting from using silica-fume contents of 10 to 15.5% are considered stiff-plastic. The slump value for the 15% silica fume mix is about 40% smaller than the 0% mix. The results reported by Mazloom *et al*. (2004) and Köksal *et al*. (2008) are in agreement with the findings of this study, while the results obtained by Duval and Kadri (1998) are in contradiction with. This maybe be attributed to the changes in mix ingredients and mixing sequence.

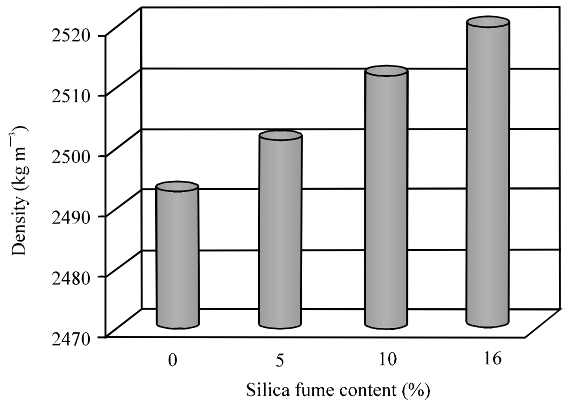

Fig. 3: Average density for different silica fume contents

Table 8: Compressive strengths at 28 days for the mixing sequences

Mix	No. of specimens	Mean compressive strength (MPa)	SD	Coefficient of variation (%)
Sequence (1)	6	128	3.55	2.8
Sequence (2)	4	100.63	9.05	8.9
Sequence (3)	4	92.35	7.80	8.4
Sequence (4)	4	88.23	4.80	5.4

Density Results

The density of concrete increases as the silica fumes content increases, as shown in Fig. 3. The increase in density for the 15% silica fume mix is about 1% larger than the 0% mix. This increase in concrete density is attributed to the continuous hydration of main cement compounds. Köksal *et al.* (2008) findings are in contradiction with the results of this study, where they reported a 2% decrease in density at 15% silica fume content.

Effect of Mixing Sequence

Compressive Strength Results

Table 8 shows that sequences (1) and (2) which involve adding silica fume to the mixtures at the first stage of mixing increase the compressive strength compared to sequences (3) and (4) which entail adding silica fume to mixtures at the final stage of the mixing. This may be attributed to two factors; first the suffusion contact between the cement, silica fume and the aggregates which is necessary for improving the effectiveness of the silica fume. Second, the micro fine silica particles properly disperse themselves so that they separate from each other and pack individually between and around the cement grains.

The compressive strength for the sequence (1) is 28, 37 and 45% higher than sequences (2), (3), (4), respectively.

Slump Results

Figure 4 shows that sequences (1) and (3) increase workability compared with sequences (2) and (4). The reason for this result is attributed to two factors; first, when that superplastisizer is added after full absorption of the water by the aggregates, the superplastisizer will act to facilitate the movement of the aggregates. Second, adding the superplastisizer after appreciable mixing time to of all constituents will cause it to function efficiently instead of working with poorly blended ingredients in the case of adding 100% of

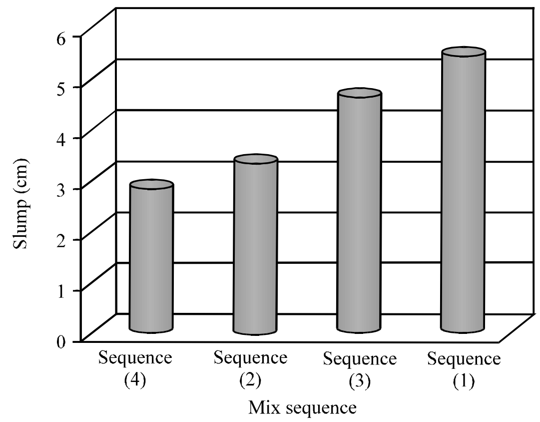

Fig. 4: Effect of mixing sequences on slump values

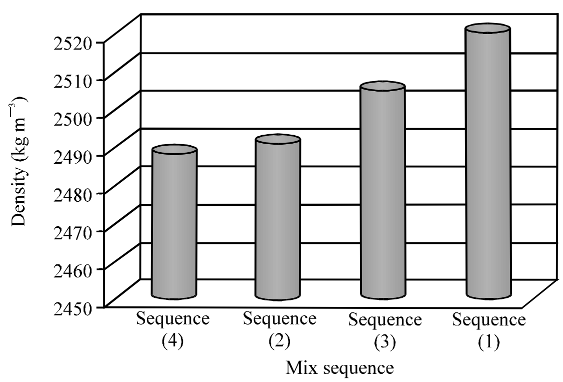

Fig. 5: Effect of mixing sequences on density

Table 9: Effect of crushed quartz powder content on 28-day compressive strength

Mix	No. of specimens	Ultrafine content (%)	Mean compressive strength (MPa)	SD	Coefficient of variation (%)
Mix E	6	50	128	3.55	2.8
Mix F	3	40	111.03	4.00	3.6
Mix G	3	30	97.77	2.30	2.8
Mix H	3	20	90.93	3.40	3.7

the superplastisizer to the mixing water. Chopin *et al*. (2004) reported results in agreement with this study, while Chang and Peng (2001) reported results in contradiction with.

Density Results

Figure 5 shows that the density of concrete increases in this order; sequence (4), sequence (3), sequence (2) and sequence (1).

Effect of Amount of Crushed Quartz Powder (Ultrafine Aggregate)

Compressive Strength Results

Compressive strength test results for different contents of crushed quartz at 28 days of age are shown in Table 9 and Fig. 6, where these results demonstrate that the compressive

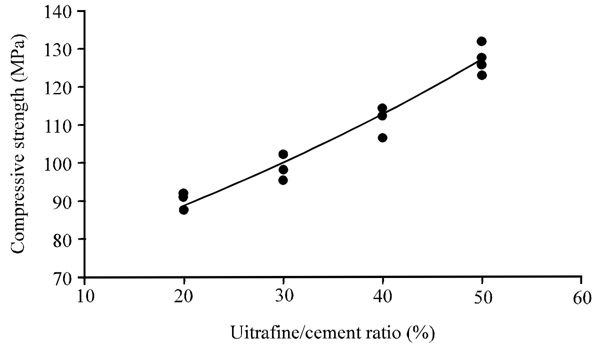

Fig. 6: Relationship between 28 day compressive strength and ultrafine to cement ratio

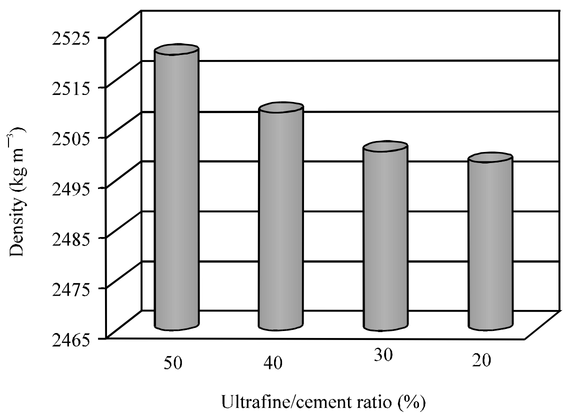

Fig. 7: Average density for different ultrafine to cement ratio

strength decreases as the content of ultrafine decreases. The increase in compressive strength of concrete with the increase of crushed quartz content is due to the finer particles that fill-up the hollow spaces between the cement and the coarse grains. From the results shown in the same table, one can easily conclude that Mix E with 50% of crushed quartz powder content filling has the highest compressive strength. The other three mixes undergo drops in compressive strengths ranging from about 13 and 29% compared with Mix E. Tafraoui *et al.* (2009) findings are in general agreement with the results of this study.

Density Results

Based on the results shown in Fig. 7, one can easily conclude that densities of concrete specimens increase with increasing the percent of ultrafine. The quartz powder acts as a filler between the aggregate and cement grains. This means that the smaller particles of fine aggregate are able to provide a denser concrete matrix.

CONCLUSION

Based on the results of the experimental program, the following conclusion may be drawn out:

- Compressive strength of UHPC increases with increasing silica fume content. The increase in compressive strength for the 15% silica fume content is about 60% larger than the 0% mix. Also, the increase in silica fume content increases the dry density. On the other hand, the increase in silica fume content reduces slump values, where the slump for the 15% silica fume mix is about 40% smaller than the 0% mix
- Sequence (1) which involves adding silica fume content at the first stage of mixing produces compressive strengths that are 45% larger than sequence (4). Also, sequence (1) enhances the workability and increases the dry density better than the other three sequences
- The increase in ultrafines increases the compressive strength, as well as the density of UHPC. Using ultrafine powder to cement ratio of 0.5 is the most appropriate for achieving a minimum compressive strength of 120 MPa at 28 days, while achieving the highest dry density at the same time, using materials available at Gaza Strip local markets

REFERENCES

ASTM C 1240-05, 2005. Standard Specification for Silica Fume Used in Cementitious Mixtures. American Society for Testing and Materials Standard Practice, Philadelphia, Pennsylvania, USA.

ASTM C109/C109M, 2008. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). American Society for Testing and Materials Standard Practice, Philadelphia, Pennsylvania.

ASTM C150/C150M, 2009. Standard Specification of Portland Cement. American Society for Testing and Materials Standard Practice, Philadelphia, Pennsylvania.

ASTM, 2006. Standard Test Method for Density, Absorption and Voids in Hardened Concrete. American Society for Testing and Materials Standard Practice C642, Philadelphia, Pennsylvania.

ASTM, 2009. ASTM C143, Standard Test Method for Slump of Hydraulic Cement Concrete. American Society for Testing and Materials, Philadelphia, Pennsylvania, pp: 4.

Arafa, M., S. Shihada and M. Karmout, 2010. Mechanical properties of ultra high performance concrete produced in the Gaza strip. Asian J. Mater. Sci., 2: 1-12.

Chang, P.K. and Y.N. Peng, 2001. Inflence of mixing techniques on properties of high performance concrete. Cem. Concr. Res., 31: 87-95.

Chopin, D., F. Larrard and B. Cazacliu, 2004. Why do HPC and SCC require a longer mixing time?. Cem. Concr. Res., 34: 2237-2243.

Duval, R. and E.H. Kadri, 1998. Influence of silica fume on the workability and the compressive strength of high-performance concretes. Cem. Concr. Res., 28: 533-547.

Hugues, V., D. Shahryar and N. Martin, 2008. Evaluation of properties of high strength concrete for prestressed concrete prisms. Proceeding of the 2nd Intenational Symposium on Ultra-High Performance Concrete, March 5-7, Kassel, Germany, Kassel University Press, pp: 278-294.

Köksal, F., F. Altun, I. Yiğit and Y. Şahin, 2008. Combined effect of silica fume and steel fiber on the mechanical properties of high strength concretes. Construction Build. Mater., 22: 1874-1880.

Long, G., X. Wang and Y. Xie, 2002. Very-high-performance concrete with ultrafine powder. Cem. Concr. Res., 32: 601-605.

Mazloom, M., A.A. Ramezanianpour and J.A. Brooks, 2004. Effect of silica fume on mechanical properties of high-strength concrete. Cem. Concr. Composites, 26: 347-357.

Park, J., G. Ryu, S. Kang and S. Kim, 2008. The influence of the amount of silica fume on the mechanical property of ultra-high performance concrete. Key Eng. Mater., 385-387: 701-704.

Schachinger, I., J. Schubert and O. Mazane, 2004. Effect of mixing and placement methods on fresh and hardened ultra high performance concrete (UHPC). Proceedings of the International Symposium on Ultra-High Performance Concrete, Sept. 13-15, Kassel, Germany, pp: 575-586.

Tafraoui, A., G. Escadeillas, S. Lebaili and T. Vidal, 2009. Metakolin in the formulation of UHPC. Construction Build. Mater., 23: 669-674.