Effect of Nanosilica on shrinkage strain of low-binder ultrahigh performance cementitious composites

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Abstract—This study demonstrated the effect of using nano silica (NS) on the shrinkage properties of low binder ultra-high performance cementitious composites (UHPCCs). For this, UHPCC mixtures were designed with water/binder ratio of 0.20 and total binder of 800 kg/m³. Commercially available NS was used in partial substitution of cement at 0, 0.5, 1, 2 and 3% by weight. The samples produced were tested for compressive strength, autogenous and drying shrinkage as well as weight loss. The results showed that replacing of NS with cement decreased both dry and autogenous shrinkage of UHPCCs. Furthermore, among different NS contents ranging from 0.5 to 3%, UHPCCs containing 2% NS exhibited better results of compressive strength at 180 days.

Keywords— Nanosilica; ultrahigh performance composite; shrinkage; compressive strength

I. Introduction

During the last 20 years, Ultra-High Performance Concrete cementitious composites (UHPCC) has become an introduction of the most favorable ingenious high technology types of concrete [1-3]. In order to obtain the desired properties of UHPCC, enhancing the interfacial transition zone (ITZ) to a level comparable to that of bulk paste aggregate. This might be achieved by using silica materials such as nano silica (NS) [4]. Nano-scale SiO₂ seems to be the most popular nano-particle in the researches because of its big benefits in the concrete. Nano SiO₂ cannot only fill the voids between cement and silica fume particles; its high specific surface area to the volume ratio yields a high rate of pozzolanic reaction that leads to the potential for tremendous chemical activity. Recent studies revealed that addition of nano-silica provided many significant improvement in mechanical [5], durability [6], physical [7] and micro structure of concretes [8]. Nevertheless, there are divergent opinion and poor vision about the optimum percentage of the nano-sized particles when replaced with cement to produce concrete. There are little studies on shrinkage properties of UHPCC containing nano materials in which the effect of such material is varying and contradictory. On the other hand, concerning to the effect of NS on UHPCC, there is no doubt of increasing mechanical properties among researchers especially compressive strength [9, 10].

II. Experimental study

A. Materials and mixture proportioning

The cementitious materials used in concrete production were ordinary portland cement (CEM I 42.5 R) conforming to the TS EN 197 [11] and nano silica (NS). Chemical composition, physical and mechanical properties of them are given in Table 1. Quartz aggregate with a specific gravity of 2.65 was utilized in three fractions, namely 0–0.4, 0.6–1.2, and 1.2–2.5 mm. A new-generation superplasticizer (SP) of polycarboxylate type was used to fulfill the workability specifications in ASTM C 494 [12].

A comprehensive experimental program has been carried out and demonstrated in Table 2 with a NS content of 0, 0.5, 1, 2 and 3 %. Superplasticizer was used in varying amounts to adjust the workability for the mixtures. The mixtures in Table 2 were designated according to NS replacement level, for example, NS1 indicates the mixture containing 1% of nano silica.

B. Concrete mixture proportioning, casting, and sample preparation

The mixtures were prepared by means of a special designed, vertical axis, high speed mixer which has mixing speed of as high as 470 rpm. Dry powders and aggregates were mixed with the speed of 100 rpm for about three min. After a half of water addition, mixture was remixed for about five minutes with the speed of 100 rpm. Finally, SP and remaining water were added to premixed material and mixing was resumed at 470 rpm for about five minutes. Fresh concretes were then poured into the molds and compacted by using a vibrating table. The specimens were then covered with polyethylene sheets and kept in the moulds for 16 h at room temperature of 22 ±2 °C. Thereafter, they were cured in standard conditions of water curing until the testing age. In addition to 50-mm cubes to determine compressive strength, a typical mixture consists of 70x70x280 mm dimensions for measuring each of weight loss, dry and autogenous shrinkage.

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III. Test results and discussions

A. Compressive strength

Effects of using nano silica (NS) on the compressive strength development of the UHPCC are shown in Figures 1. Interestingly compressive strength of the concretes continuously increased up to 2% NS content beyond which strength began to decrease at 180 days. The control UHPCCs had 180-day compressive strengths of 136.5 as seen in Fig. 1. In addition, 2% NS replacement caused 10.5 % higher strengths than the companion reference mixtures. Furthermore, slightly lower compressive strength of UHPC containing 3% NS may be attributed to improper dispersion of nano particles in the mixture. Nanoparticles have a pronounced tendency towards agglomeration because they have high inter-particle van der Waal's forces due to their much smaller sizes [15-17]. The disagglomeration of nanoparticles is crucial to achieve the ideal composite materials and the amount of SiO₂ nano particles in the mixture can also have been exceeded the quantity for consuming the calcium hydroxide compounds to form C-S-H gel. Therefore, it did not contribute to enhance the strength of UHPCC more [18]. Moreover, Table 2 presents the superplasticizer demand of the mixtures to provide the target workability. It was also evident in Fig. 2 that the mixtures with NS required greater amount of superplasticizer, especially at higher replacement levels of NS. The quite limited strength enhancement with the use of NS was also attributed to the increase in the superplasticizer for the sake of constant workability (Fig. 2).

Fig. 1. Compressive strength versus Nano silica and water cured

Fig. 2. Nano silica effective on flow and superplasticizer

B. Free shrinkage, weight loss and flow

The obtained dry shrinkage and weight loss results are demonstrated in Figs. 3 and 4, respectively. Though the dry

Table 1 PROPERTIES OF CEMENT AND NANO SILICA

Constituent (%)	Cement	Nano silica
CaO	62.12	-
SiO ₂	19.69	99.8
Al ₂ O ₃	5.16	-
Fe ₂ O ₃	2.88	-
MgO	1.17	-
SO ₃	2.63	-
K ₂ O	0.88	-
Na ₂ O	0.17	-
Cl	0.0093	-
Loss on ignition	2.99	-
Insoluble residue	0.16	-
Free CaO	1.91	-
Specific surface (m ² /kg)	394 ^a	150000 ^{b*}
Specific gravity	3.15	2.2

^a Blaine specific surface area.

^b BET specific surface area.

TABLE 2 MIXTURE PROPORTIONS OF UHPCC CONTAINING NS

Codes	Cement (kg/m ³)	Nano Silica (kg/m ³)	Water (kg/m ³)	SP* (kg/m ³)	Quartz aggregate (kg/m ³)
NS0	800	0	160	21.6	1471.3
NS0.5	796	4	160	25.2	1461.1
NS1	792	8	160	28.8	1450.8
NS2	784	16	160	36.0	1430.2
NS3	776	24	160	43.2	1409.7

*Superplasticizer

C. Testing Methods

Compression test was conducted on 50 mm cubes at 180 days with respect to ASTM C39 [13]. Free shrinkage specimens were exposed to drying in a room at 23 ±2 °C and 50 ±5% relative humidity for about 60 days, according to ASTM C157-75 [14]. A dial gage extensometer with a 200 mm gage length was used to measure the length change. Measurements were carried out every 24 hrs for the first three weeks continuously and then three times a week. Variations in the free shrinkage strain and the weight loss were monitored at the same time on the same specimens. Free shrinkage measurements and weight loss of UHPCC were conducted on three prisms samples from each mixture. Like the dry shrinkage, the same size of prisms (70x70x280 mm) and dial gage extensometer were used for measuring autogenous shrinkage test. Unless, a teflon sheet was placed inside the mold to prevent the restraint of concrete from the frictional force between the molds and UHPCCs. The top surface of the specimen was sealed with polyester film after the mold was filled completely to prevent moisture evaporation. After 24 hours, specimens were demolded immediately and sealed with aluminum adhesive tape to be performed in the equivalent constant temperature and indicated humidity room.

shrinkage strains were comparable for the early ages of drying period, a clear distinction was observed at the later periods for UHPCC with different amount of NS content (Fig.3). The mixture that with no contribution of NS (NS0), had the highest shrinkage strain of about 519 microstrain at the end of the 60 days. In all UHPCCs mixes, the dry shrinkage reduces with an increase in the amount of NS. The use of NS with the amounts of 0.5%, 1%, 2% and 3.0% causes a reduction in dry shrinkage about 3%, 6%, 9% and 12%, respectively. These dry shrinkage reduction effects of NS in UHPCC have also observed for normal concretes as reported [19-21] and were related with the main compound of NS which is assumed causing to reduce the surface force tension of pore water and consequently reducing the dry shrinkage [10/22].

As presented in Fig. 4, the weight loss values for UHPCCs containing more silica nano particles were slightly higher than that of lower nano silica content. The maximum difference of weight loss values between the mixture with zero and 3% of nano silica content (NS0 and NS3) was equal to only 4.5 g. The reason of faintly more loss of weight with the contribution of NS may be related to high superplasticizer used to achieve target workability for the mixes with high NS used, as noticed in Fig 2. On the other hand, this contradiction between dry shrinkage and weight loss was also explained by the other researchers like Wiegink et al. [23], that the some other factors will interfere to this intimate relation.

Fig. 3. Dry shrinkage measurements for UHPCC with different NS content.

Fig. 4. Weight loss measurements for UHPCC with different NS content.

C. Autogenous shrinkage

The reduction of the macroscopic volume of cementitious composite by the hydration process, namely autogenous shrinkage, is strongly affected by admixtures and W/B [24, 25]. The measurement of autogenous shrinkage start with the starting of the initial setting time because this type of shrinkage usually used for the prediction of cracking so that the reduction of volume in the fresh state (before initial set) is excluded [26].

Typical autogenous shrinkage versus time curves for the UHPCCs with different amount of silica nano particles are displayed in Fig. 5. The lowest autogenous shrinkage (252 microstrain) was measured in the UHPCC with 3% of nano silica, followed by the concretes with lower NS content and it's finally reached to 320 microstrain for zero nano silica content. Furthermore, using autogenous type will cause an extra improvement of shrinkage than the dry one, it is reached to 45% with a 3% incorporation of NS with UHPCC, as shown in Figs. 4 and 5.

Fig. 5. Autogenous shrinkage measurements for UHPCC with different NS content.

IV. Conclusions

The following conclusions can be excluded from this study:

1-NS increases the packing density, particularly interface between the pastes and aggregate. 3 %, the results were still higher than those of the control concrete (0 % NS).

2-UHPCC with low binder content (800 kg/m^3) and with no contribution of micro silica and steel fiber gave a compressive strength about 136.5 MPa, with only 2% of NS used in the mixture. Additionally, the quite limited strength enhancement with the use of NS was attributed to the increase in the superplasticizer for the sake of constant workability.

3-In all UHPCCs mixes, the dry shrinkage reduces with an increase in the amount of NS. The mixture that with no contribution of NS had the highest shrinkage strain is about 519 microstrain at the end of the 60 days drying period.

4-The weight loss values for UHPCCs containing more silica nanoparticles were slightly higher than that of lower nanosilica content. The maximum difference of weight loss values between the mixture with zero and 3% of nano silica content (NS0 and NS3) was equal to only 4.5g.

5-The reason of faintly more loss of weight with the contribution of NS, may related to high super plasticizer

used to give enough workable for the mixes with high NS used and the some other factors will interfere to this intimate relation (shrinkage and weight loss).

6-The lowest autogenous shrinkage (252 microstrain) was measured in the UHPCC with 3% of nano Silica type, followed by the concretes with lower NS content and it's reached to 320 microstrain for zero silica content. Furthermore, using autogenous type will cause an extra improvement of shrinkage than the dry one, it is reached to 45% with a 3% incorporation of NS with UHPCC.

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