Effect of binder content, pozzolanic admixtures and SiO2 nanoparticles on thermal properties and capillary water absorption of high performance concrete

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Abstract: This paper investigates the effects of some admixtures including silica nanoparticles, silica fume and Fly Ash along with binder content on thermal properties and capillary water absorption of high performance concrete (HPC). For this purpose, a fraction of Portland cement was replaced by silica fume, silica nanoparticles, blend of silica fume and silica nanoparticles and three percentages of fly ash as 10, 2, 10+2% and 5, 10 , 15% respectively. Specimens were prepared with two binder contents as 400 and 500 kg/m^3. Thermal properties were investigated via thermogravimetric analysis (TGA). Capillary water absorption tests of the specimens were carried out at the age of 90 days. The results showed that the pozzolanic admixtures especially blend of silica fume and SiO_2 nanoparticles have an significant effect on thermal properties and particularly capillary water absorption.

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1. Introduction

High performance concrete (HPC) offers high strength, better durability properties, and good construction. High strength is one of the important attributes of HPC. High strength concrete, according to American Concrete Institute Committee ACI 363 R [1], is the concrete which has specific compressive strength of 41 MPa or more at 28 days. The HPC offers significant economic and architectural advantages over NSC in similar situations, and is suited well for constructions that require high durability. On one hand it is known that high cement content usually introduces high hydration heat, high autogenous shrinkage and high cost. Moreover, the consumption of natural resources and carbon dioxide emissions associated with cement production can cause serious environmental impacts. On the other hand, it is worldwide accepted that energy saving in building technology is one of the most important problems in the world. Reduction of energy usage can be taken place even by design methods [2,3] or using waste materials [4–6].

Nowadays, most industrial wastes are being used without taking full advantages of their characteristics or disposed rather than used. Among these materials, fly ash (FA), a by-product of thermal power plants, and ground granulated blast furnace slag (GGBFS) have been reported to improve the mechanical properties and durability of concrete when used as a cement replacement material [7, 8]. It is worth mentioning that for example in Turkey, more than 13 million tons of FA has been produced per year, however, because of insufficient data on the properties of fly ash and concrete incorporating FA, only 5% of this amount is utilized in construction industry [9]. Therefore, one solution to reuse such industrial wastes and reduce the cost of SCC is the use of mineral admixtures such as limestone powder, natural pozzolans, GGBFS and FA.

The amount of FA in concrete for structural use is generally limited to 15–25% of the total cementitious materials. Concretes containing large amounts of FA were initially developed for mass concrete applications to reduce the heat of hydration [10]. Canada Centre for Mineral and Energy Technology first developed high volume FA concrete for structural use by the late 1980's [11]. In a study undertaken by Bouzoubaâ and Lachemi, it was shown that it was possible to design SCC with high volumes of FA by replacing up to 60% of cement with Class F FA [12]. Moreover, Nehdi et al. also studied the durability of SCC with high volume replacement materials (FA and ground granulated blast furnace slag), and concluded that SCC with 50% replacement with Portland cement of FA and slag can improve the workability and durability [13]. With this respect, it should be mentioned that a 50% replacement of each ton of Portland cement would result in a reduction of approximately 500,000 t of CO2. Using GGBFS or FA as a partial replacement takes advantage of the energy saving in Portland cement which is governed by AASHTO M302 [14].

Kulakowski et al. [15] reviewed the silica fume influence on reinforcement corrosion in concrete and the effect of metakaolin on transport properties of concrete were also investigated by Shekarchi et al

[16]. There are also some works on incorporating nanoparticles into concrete specimens to achieve improved physical and mechanical properties which most of them have focused on using SiO2 nanoparticles in normal concrete [17], generally cement mortars and cement-based materials [18–20], self compacting concrete (SCC) [21] and high performance self compacting concrete (HPSCC) [22].

Production and application of HPC containing nanomaterials and mineral admixtures seems to be a promising and energy saving step toward sustainable construction and building technology. However, this would not be achieved without studying its performance before being widely adopted in construction. Also, the behavior of structural elements made with HPC needs better understanding, together with design provisions. This paper investigates the effects of silica nanoparticles, silica fume and Class F fly ash on thermal properties of HPC with different binder contents.

2. Materials

An ASTM Type II Portland cement (PC) was used to produce the various HPSCC mixtures. In addition, silica nanoparticles, silica fume and class F fly ash were used as admixtures which are hereafter named as Nano Silica (NS), Silica Fume (SF) and Fly Ash (FA) respectively. Table 1 summarizes physical properties and chemical composition of the cement and Silica Fume. The nanoparticles' properties are presented in table 2.

Table 1. Chemical composition and physical properties of cement and Silica Fume

Chemical analysis (%)	Cement	Silica Fume
Sio_2	20<	93.6
Al_2O_3	6<	1.3
Fe_2O_3	6<	0.9
CaO	<50	0.5
MgO	<5	1
SO_3	<3	0.4
K_2O	<1	1.52
Na_2O	<1	0.45
Loss of ignition	<3	3.1
Specific gravity	3.15	2.2
Blaine fineness (cm^2/g)	3260	21090

Table 2. Properties of silica nanoparticles

Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Purity (%)
15±3	165±17	<0.15	>99.9

Table 3. Chemical and physical properties Fly Ash

Constituent	Percent by weight
Sio_2	52
Fe_2O_3	3.5
Al_2O_3	30
CaO	6.5
MgO	5
SO_3	1.6
Loss of ignition	3.7
Na_2O	0.58
K_2O	1.27
Color	Gray
Specific gravity	2.13

Class F fly ash was used in this study which its physical and chemical properties are given in table 3. Scanning electron microscopy (SEM) of Class F fly ash is also shown in Fig 1.

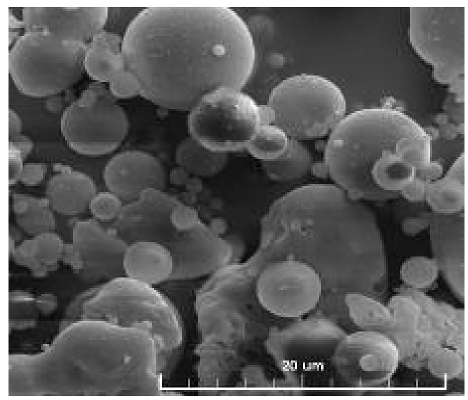

Fig. 1. SEM micrograph of Class F fly ash particles

The coarse aggregate used was limestone gravel with a nominal maximum size of 12.5 mm. As fine aggregate, a mixture of silica aggregate sand and crushed limestone (as filler) was used with a maximum size of 4.75 mm. All aggregates in this research were used in dry form and the aggregates are a mixture of eight particle sizes of fine and coarse aggregates. A polycarboxylic-ether type superplasticizer (SP) with a specific gravity of between 1.06 and 1.08 was employed to achieve the desired workability in all concrete mixtures. Furthermore viscosity modifying agent (VMA) for better stability was used.

3. Mix proportions

A total number of 14 concrete mixtures were designed with a constant water/binder (w/b) ratio of 0.38 and total binder content of 400 and 500 kg/m^3. Concrete mixtures were prepared with 10%, 2% and 10%+2% (by weight) replacement of Portland cement by SF, NS and blend of SF + NS respectively. Also some mixtures were designed with 5%, 10% and 15% replacement of Portland cement by FA. The mixture proportions of concrete and binder paste are given in table 4.

Table 4. Mix proportions of the concrete specimens

No	Concrete ID	w/b	Cement	Silica Fume	Nano silica	Fly Ash	Filler	Fine aggregate	Coarse aggregate	Sp	VMA
			(kg/m^3)								
1	HPC400	0.38	400	-	-	-	177	1003	578	2.5	2
2	HPC500	0.38	500	-	-	-	177	1003	578	3.12	2.5
3	HPC400FA5%	0.38	380	-	-	20	177	1003	578	2.5	2
4	HPC400FA10%	0.38	360	-	-	40	177	1003	578	2.5	2
5	HPC400F15%	0.38	340	-	-	60	177	1003	578	2.5	2
6	HPC500FA5%	0.38	475	-	-	25	177	1003	578	3.12	2.5
7	HPC500FA10%	0.38	450	-	-	50	177	1003	578	3.12	2.5
8	HPC500FA15%	0.38	425	-	-	75	177	1003	578	3.12	2.5
9	HPC400NS2%	0.38	392	-	8	-	177	1003	578	2.5	2
10	HPC400SF10%	0.38	360	40	-	-	177	1003	578	2.5	2
11	HPC400SF10NS2%	0.38	352	40	8	-	177	1003	578	2.5	2
12	HPC500NS2%	0.38	490	-	10	-	177	1003	578	3.12	2.5
13	HPC500SF10%	0.38	450	50	-	-	177	1003	578	3.12	2.5
14	HPC500SF10NS2%	0.38	440	50	10	-	177	1003	578	3.12	2.5

The abbreviations used in the study for labeling the mixtures were adopted in such a way that they clearly show the main parameters and their amount. HPSCC stands for high performance self compacting concrete which is followed by the binder content. NS, SF and FA denote Nano Silica Silica Fume and Fly Ash respectively which are followed by their percentages.

5. Thermogravimetric analysis test

Thermogravimetric analysis (TGA) test was conducted so that the weight loss of the concrete specimens due to heating can be determined. A simultaneous thermal analyzer equipped with a Data Acquisition System was used for the tests. Specimens which were cured for 28 days were heated from 110 to 650 ◦C, at a heating rate of 4◦C/min and in an inert N2 atmosphere.

4. Capillary test

When a non-saturated concrete element is in contact with water at one side and absorbed water evaporation is possible from the other side, a permanent flowing regime through capillary absorption is established [37]. The test carried out in this study for determination of capillary water absorption is based on RILEM CPC 11.2, TC 14-CPC for testing capillary absorption in hardened concrete. The 100×100×100 mm specimens were dried in the oven at 40±5ºC. They were put on rods in a water bath in such a way that they were immersed in water for no more than 5 mm. In this test, unidirectional flow depths of the specimens were measured and results of capillary depths were reported.

6. Results and discussion

6.1. TGA results

Table 5 shows the thermogravimetric analysis results of different HPSCC specimens measured in the 110–650 ◦C range in which dehydration of the hydrated products occurred. The results show that after 28 days of curing, the loss in weight of the specimens is increased by decreasing the PC content in concretes.

The results also showed that the loss in weight of the specimens is increased by increasing NS and SF in concrete mixtures. Increasing the FA percentage in the binder resulted in weight loss increase, however the weight losses were not as significant as those occurred in the specimens containing NS and SF. The most noticeable weight losses belonged to the mixtures containing 10%SF + 2%Ns with binder content of 500 kg/m3. the increase in weight loss could be due to more formation of CH and C_3H compounds in the cement paste. Furthermore, more rapid formation of hydrated products in presence of silica nanoparticles and silica fume could be the reason of more weight loss.

Table 5. Thermogravimetric analysis results of HPC specimens

No	ID	Weight loss in the range of 110–650 ◦C (%)
1	HPC400	13.5
2	HPC500	14.5
3	HPC400FA5%	14.2
4	HPC400FA10%	14.9
5	HPC400F15%	15.6
6	HPC500FA5%	14.8
7	HPC500FA10%	15.9
8	HPC500FA15%	16.3
9	HPC400NS2%	17.8
10	HPC400SF10%	18.1
11	HPC400SF10NS2%	19.3
12	HPC500NS2%	18.8
13	HPC500SF10%	19.2
14	HPC500SF10NS2%	19.9

6.2. Capillary Water absorption

The capillary water absorption results of the HPSCC samples at different time intervals are presented in table 6. The results show that the height of absorbed water in the concrete samples has decreased by increasing the binder content from 400 to 500 and addition of NS, SF and FA admixtures. Increase in binder content from 400 to 500 lead to capillary water absorption from 2.8 to 2.5 mm during three hours and from 8.6 to 6.6 mm during 72 hours respectively, which the capillary water height decreases seem more significant at longer times. It may be due to the fact that the samples fully dried in the oven have more tendency to absorb water at earlier times, however at longer times the effect of binder content, NS, SF and especially FA admixtures comes to be revealed more and the results considered to be more realistic and reliable. Addition of 2% NS resulted in capillary water absorption of 3.6 and 3 mm for binder content of 400 and 500 respectively during 72 hours for which the reductions of 58 and 54% compared to the mixtures without any admixture can be considered. Addition of 10% SF with binder content of 400 and 500 resulted in capillary water absorption decrease by 60 and 53% respectively during 72 hours compared to the mixtures without any admixture. The same reductions observed for mixtures containing blend of 2% NS + 10% SF were 66 and 66% respectively. As can be seen, the water proofing effects of SF and NS on HPSCC tend to appear more obviously in the mixtures containing both SF and NS with higher binder content. As can be inferred from the water absorption results, this performance may be attributed to the more packed and refined microstructure and pore structure of the concrete achieved by addition of SF + NS.

Table 6. Results of capillary absorption by time

No	Concrete ID	Capillary water absorption (mm)			
		Time (hour)	Time (hour)	Time (hour)	Time (hour)
		3	6	24	72
1	HPC400	2.8	2.82	6.5	8.6
2	HPC500	2.5	3.4	5.5	6.6
3	HPC400FA5%	2.7	3.7	6.2	8.3
4	HPC400FA10%	2.4	3.2	5	6.3
5	HPC400F15%	2	2.9	4.3	5.8
6	HPC500FA5%	2.4	3.2	5.3	6.3
7	HPC500FA10%	2	2.9	4.3	5.8
8	HPC500FA15%	1.9	2.4	3.3	3.8
9	HPC400NS2%	2.2	2.7	3.4	3.6
10	HPC400SF10%	2.1	2.5	3.3	3.4
11	HPC400SF10NS2%	1.9	2	2.8	2.9
12	HPC500NS2%	1.8	2.3	2.9	3
13	HPC500SF10%	1.7	2.16	2.9	3.1
14	HPC500SF10NS2%	1.5	1.7	2.1	2.2

Addition of 5% fly ash resulted in capillary water absorption of 8.3 and 6.3 mm for cement content of 400, 450 and 500 respectively during 72 hours for which the reductions of 3.5 and 4.7% compared to the mixtures without any pozzolan can be considered. By increasing the fly ash percentage more significant results were recognized. Addition of 10 and 15% FA with binder content of 400 and 500 resulted in capillary water absorption decrease by 27 and 12% and 44 and 42.5% respectively during 72 hours compared to the mixtures without any FA. As can be seen, the water proofing effects of fly ash on high performance self compacting concrete tend to be revealed more obviously at higher percentages of FA addition. As observed in water absorption results, this performance may be attributed to the more packed microstructure and pore structure of the concrete by addition of fly ash.

7. Conclusion

Based on the results obtained in this experimental study, the following highlights can be concluded:

- Addition of the admixtures generally reduced the capillary water absorption and increase in binder content led to reduced capillary absorption.
- The mixtures containing pozzolanic admixtures showed more weight loss and it was particularly apparent for nanoparticles blended mixtures.
- The results showed that the mixtures containing blend of silica fume and SiO2 nanoparticles have more packed microstructure, less capillary absorption and more thermal weight loss.

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