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Communication

Development of high performance concrete using silica fume at relatively high water–binder ratios

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Abstract

The aim of this study was to investigate the possibility of developing high performance concrete (HPC) using silica fume (SF) at relatively high water–binder ratios. For this purpose, water–binder ratios of 0.45 and 0.50 were considered. Test specimens were air and water cured and exposed to a medium temperature range of 20°C to 50°C. The compressive strength, modulus of elasticity and initial surface absorption (ISA) of hardened concrete were determined in the laboratory. Test results indicated that concrete under water curing offers the best results. The highest level of compressive strength and modulus of elasticity and the lowest level of ISA were produced by SF concrete under water curing and at temperature of 35°C. Data collected also revealed that, under controlled curing conditions, it is possible to produce HPC at relatively high water–binder ratios.

Keywords: Medium temperature; Compressive strength; Modulus of elasticity; Initial surface absorption; Silica fume; High performance concrete

1. Introduction

The properties of concrete such as compressive strength, modulus of elasticity and initial surface absorption (ISA) are largely influenced by water–binder ratios. Most of the literature suggest that the water–binder ratio of high performance concrete (HPC) needs to be much lower than that of ordinary concrete. While ordinary concrete has a water–binder ratio of 0.50 and higher, generally it is below 0.35 for HPC [1]. However, some Japanese researchers have developed HPC at water–binder ratios higher than 0.35 [2].

The development of HPC has brought forth the need for admixtures, both mineral and chemical, to improve the performance of concrete. Silica fume (SF) is one such material. Many investigations reflecting the performance of SF were conducted in the 1970s to 1980s. Promising results were shown by Malhotra and Carette [3]. Literature on the use of SF can also be found in an informative report prepared by ACI Committee 226 [4]. This publication presents excellent performance of SF to produce high quality HPC.

The properties of hardened HPC are also influenced by curing conditions. It has been recognized that the compressive strength, modulus of elasticity and durability of concrete are improved with efficient uninterrupted curing. If curing is neglected in the early period of hydration, the compressive strength and modulus of elasticity of concrete will decrease at later ages and suffer some irreparable loss [5]. Furthermore, ISA will also increase concurrently. Efficient curing in the early period of hydration can be compared with good and wholesome feeding given to a newborn baby. However, from an economical point of view, it is not cost-effective to cure the concrete for 28 days or more. If it is possible to shorten the curing period with optimization of the properties of hardened concrete, it would minimize the cost. Curing temperature also influences the properties of hardened concrete. Elevated curing temperature hinders the hydration of cement at later ages and forms an open pore structure of cement paste and therefore affects the properties of hardened concrete [6]. This study investigates the possibility of producing HPC at water–binder

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Table 1
Chemical composition of Type I Portland cement and silica fume

Constituents	Cement (%)	Silica fume (%)
SiO_2	19.5	97.1
Al_2O_3	6.3	0.4
Fe_2O_3	2.6	0.3
CaO	63.5	0.3
MgO	3.70	0.0
SO_3	2.4	0.2
Total alkalies (Na_2O)	0.9	0.0
LOI	1.1	1.7

ratios higher than 0.35. The paper also details suitable curing methods with appropriate curing period and temperature for HPC.

2. Experimental program

2.1. Materials

Crushed stone aggregate, mining sand, Type I normal Portland cement (NPC) and SF were used in this study. The chemical compositions of cement and SF are shown in Table 1. The maximum size of coarse aggregate was 19 mm and that of fine aggregate was 4.75 mm. A naphthalene formaldehyde-based superplasticizer (SP) and an air-entraining admixture (AEA) were also used as liquid chemical admixtures. Normal tap water was used as mixing water and for curing.

2.2. Mix proportions

SF and NPC concretes were designed at water–binder ratios of 0.45 and 0.50. The Sherbrooke mix design method [7] was followed to get the optimum proportions. The details of mix proportions are presented in Table 2. Although, the water–binder ratios are high, they were insufficient to produce slumps or slump flows greater than 19 cm and 50 cm, respectively. Therefore, a SP was needed to provide the fresh concrete with the required high workability of 200 mm. In doing so, SF concrete needed higher dosages of SP, at least 2% of binder content as seen in Table 2. This is because the specific surface of SF is higher than cement particles and hence, demands greater amount of SP to reach flowability [8].

Table 3
Different curing conditions

Designation	Curing method	Curing period at 20°C (days)	Curing period in ovens at 35°C and 50°C (days)
D_3	Dry air curing	3	88
D_7		7	84
D_{14}		14	77
D_{28}		28	0
D_{91}		91	0
W_3	Water curing	3	88
W_7		7	84
W_{14}		14	77
W_{28}		28	0
W_{91}		91	0

2.3. Curing conditions

Dry air and water curing were practised. The maximum curing age was 91 days and the curing temperatures were 20°C, 35°C and 50°C. For dry air curing, after demolding, the specimens were marked and stored in an air-conditioned room at 20°C. For water curing, specimens were kept in a water bath placed in the same air-conditioned room. The average relative humidity was 65%. For specimens cured under elevated temperatures of 35°C and 50°C, they were cured initially at 20°C for 3, 7 or 14 days before being tested at 91 days. Details of the curing programme are given in Table 3.

2.4. Testing

Compressive strength and dynamic modulus of elasticity were determined at the ages of 28 and 91 days in accordance to ASTM C39 [9] and BS 1881: Part 209, respectively [10]. Both tests were carried out using 100 × 200-mm cylinders. ISA test was determined at the age of 28 days in accordance to BS 1881: Part 5 using

Table 2
The details of mix proportions

Concrete type	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Binder (B): Cement (kg/m^3)	Binder (B): Silica fume (kg/m^3)	Water (kg/m^3)	SP (%B)	AEA (%B)
Water–binder ratio = 0.45							
NPC	1038	692	440	–	198	1.25	0.05
SF	1026	684	396	44	198	2.10	0.07
Water–binder ratio = 0.50							
NPC	1055	703	400	–	200	1.00	0.06
SF	1046	697	360	40	200	2.00	0.07

Table 4
Compressive strength and dynamic modulus of elasticity of NPC and SF concrete under different curing conditions at 20°C without transfer of specimens to elevated temperature

Type of mixes	Testing age (days)	Curing conditions	Compressive strength (MPa)		Dynamic modulus of elasticity ($\times 10^4$ MPa)	
			W/B = 0.45	W/B = 0.50	W/B = 0.45	W/B = 0.50
NPC	28	D_{28}	31.8	25.1	4.16	3.99
		W_{28}	39.0	31.4	4.71	4.63
	91	D_{91}	32.3	26.4	4.19	3.96
		W_{91}	42.3	35.8	4.87	4.75
SF	28	D_{28}	35.5	29.2	4.52	4.37
		W_{28}	41.8	34.4	5.04	4.98
	91	D_{91}	37.9	31.0	4.44	4.23
		W_{91}	49.0	41.1	5.16	5.09

150-mm cubes [11]. Results presented are the average of three tested specimens.

3. Test results and discussion

The results of tests conducted on hardened concrete are shown in Tables 4, 5 and 6. The highest compressive strength and modulus of elasticity and the lowest ISA were exhibited by the water-cured specimens (Tables 4 and 5). This is expected as concrete requires continuous moisture for cement hydration. Dry air curing resulted in lower compressive strength and modulus of elasticity and higher ISA compared to water curing. This is because the hydration of cement can take place only when the water vapor pressure in the capillaries is sufficiently high, about 80% of saturation pressure [12]. Early drying of concrete may stop the cement hydration before the pores are blocked by hydration products and thus, a more continuous pore structures might be formed. In this study, it was understood that an effective way to prevent the decrease in the compressive strength and modulus of elasticity and the increase in the ISA under medium temperature is to prevent the evaporation of water from concrete at an early age. A similar opinion was expressed in an earlier work by Zain and Matsufuji [13].

Table 5
Compressive strength and dynamic modulus of elasticity of NPC and SF concrete under different curing conditions with transfer of specimens to elevated temperatures

Type of mixes	Testing age (days)	Curing age (days): Dry air (D), Water (W)	Curing age (days): Elevated temperature	Compressive strength (MPa)				Dynamic modulus of elasticity ($\times 10^4$ MPa)			
				W/B = 0.35		W/B = 0.50		W/B = 0.35		W/B = 0.50	
				35°C	50°C	35°C	50°C	35°C	50°C	35°C	50°C
NPC	28	D_3	25	30.0	24.6	25.7	21.4	4.14	3.91	3.98	3.81
		D_7	21	30.6	29.0	26.0	24.9	4.24	4.02	4.09	3.90
		D_{14}	14	33.2	29.7	29.0	25.1	4.28	4.06	4.13	3.92
		W_3	25	37.7	35.2	32.0	29.0	4.47	4.33	4.31	4.15
		W_7	21	40.0	36.1	35.0	30.0	4.57	4.38	4.37	4.19
		W_{14}	14	41.4	38.2	35.0	30.0	4.67	4.41	4.51	4.23
	91	D_3	25	29.6	24.4	25.3	20.6	4.04	3.60	3.90	3.47
		D_7	21	33.3	29.5	28.7	26.0	4.13	3.75	3.99	3.57
		D_{14}	14	35.0	31.0	30.1	28.2	4.16	3.85	4.06	3.72
		W_3	25	38.0	32.3	31.2	26.2	4.43	4.02	4.29	3.81
		W_7	21	43.3	36.3	38.6	31.4	4.51	4.10	4.35	3.88
		W_{14}	14	45.8	41.8	38.6	34.7	4.53	4.16	4.37	3.96
SF	28	D_3	25	38.4	34.5	31.5	26.4	4.30	4.15	4.17	3.96
		D_7	21	40.6	39.2	34.0	32.8	4.60	4.35	4.41	4.11
		D_{14}	14	42.1	40.3	34.6	33.1	4.60	4.35	4.43	4.13
		W_3	25	44.6	42.7	35.3	33.7	4.82	4.56	4.59	4.33
		W_7	21	50.5	47.9	42.2	39.6	4.96	4.81	4.80	4.67
		W_{14}	14	51.8	49.1	43.5	40.8	4.98	4.83	4.84	4.67
	91	D_3	25	36.8	34.4	31.7	30.2	4.34	4.05	4.23	3.90
		D_7	21	40.1	38.4	34.0	32.9	4.48	4.09	4.35	3.94
		D_{14}	14	43.1	40.1	36.4	33.7	4.52	4.18	4.39	4.02
		W_3	25	48.1	43.4	38.9	36.3	4.73	4.36	4.49	4.16
		W_7	21	56.3	47.3	49.6	41.2	4.86	4.45	4.67	4.21
		W_{14}	14	57.3	49.3	51.0	41.9	4.90	4.50	4.73	4.27

Table 6
Initial surface absorption of NPC and SF concrete under different curing conditions and at the age of 28 days

			Initial surface absorption (10^{-2} ml/m^2/s)			
Type of mixes	Water–binder ratio	Curing conditions	10 min	30 min	60 min	120 min
NPC	0.45	D_{28}	52.5	35.8	29.0	23.0
		W_{28}	47.5	30.4	23.0	18.0
	0.50	D_{28}	60.0	40.1	33.3	27.3
		W_{28}	56.3	34.6	26.5	20.9
SF	0.45	D_{28}	35.4	22.4	16.6	12.1
		W_{28}	31.4	17.7	12.7	7.9
	0.50	D_{28}	39.1	25.7	20.0	15.0
		W_{28}	34.6	20.0	14.7	9.7

Concrete specimens cured initially or continuously under water showed better gain in compressive strength at later ages than those under dry air curing. The effect of 7 and 14 days initial water curing on long-term strength is only marginal (Table 5). Therefore, this study suggests that the minimum water curing should be at least 7 days. At all ages, water curing produced higher compressive strength than dry air curing. Continued hydration is the prime reason for increased strength. Under water curing conditions, the strength continues to increase due to uninterrupted hydration of binding materials. Curing conditions W_7 and W_{14} provided higher compressive strength at the age of 28 and 91 days compared to the curing conditions W_{28} and W_{91}. Subsequent rise in compressive strength is possibly due to drying and can be explained by a hypothesis originally proposed by Waters [14]. This hypothesis suggests that, in wet concrete, water acts as a lubricant, which causes the drop in compressive strength. The specimens under curing conditions W_7 and W_{14} were partly dried at the age of 28 and 91 days and had a lower relative humidity. The removal of moisture from the interlayer of cement gel would reduce the disjoining pressure and increase the bonding forces between the particles of hydration products and thus the compressive strength of concrete. This finding was also consistent with the work of Tan and Gjørv [15].

Curing of specimens at 50°C caused lower compressive strength and dynamic modulus of elasticity and higher ISA than that at 35°C. Elevated curing temperature causes a lower degree of hydration of cement paste and thereby affects the properties of hardened concrete [6]. The effect of temperature rise on compressive strength, dynamic modulus of elasticity and ISA was more pronounced in dry air curing than water curing. Based on the present investigations, the highest level of compressive strength and dynamic modulus of elasticity and the lowest level of ISA were achieved at the curing temperature of 35°C. These results were similar to those reported earlier [16,17]. The dynamic modulus of elasticity decreased with increasing temperature and period at elevated temperature (Table 5), similar to that reported previously [13,16]. With increasing temperature and length under elevated temperatures, concrete specimens will dry out and this contributes to the reduction in the dynamic modulus of elasticity. It was seen that the concrete specimens cured under water continuously for 91 days exhibited the highest dynamic modulus of elasticity whereas their compressive strengths at this age were lower. This result indicates that the dynamic modulus of elasticity is more sensitive to moisture condition than the compressive strength.

At a particular age, the durability of concrete is largely governed by its water–binder ratio and the type of curing. The results of ISAT conducted as a measure of durability are shown in Table 6. There was a pronounced increase in the ISA-value with increasing water–binder ratio, but the influence of curing much less pronounced. This result is similar to that reported by Hilsdorf [18]. ISA of all water-cured specimens after 2 h from the start of test was less than 0.25 ml/m^2/s, which is the maximum absorptivity for low absorptive concrete [19]. The ISA values of SF concrete were much less than those of NPC concrete. The lowest ISA value was 7.9×10^{-2} ml/m^2/s, exhibited by SF concrete of w/b ratio of 0.45 under water curing.

SF concrete provided the highest compressive strength and dynamic modulus of elasticity and the lowest ISA (Tables 4, 5 and 6). The mechanism by which SF improves the performance of concrete is both physical and chemical [20]. The physical effect arises from the blocking of pores or pore refinement. SF reduces the pore volume in the concrete by the successful development of highly refined pore structure. The reduction in pore volume is also in conjunction with pore refinement, which leads to improved performance [21]. The chemical effect is due to the pozzolanic reaction [21–23]. The open channels in SF concrete are blocked by the pozzolanic reaction products. This results in the reduction in porosity and the concrete matrix becomes dense and compact [24]. Consequently, strength and impermeability of concrete are improved. It is evident from these results that HPC incorporating SF at relatively high water–binder ratios can be produced, provided that curing of the concrete is sufficient.

4. Conclusions

Silica fume concrete produced the highest level of compressive strength and dynamic modulus of elasticity and the lowest level of ISA under water curing. Incorporation of silica fume in concrete significantly increase the compressive strength and the dynamic modulus of elasticity and decreased the ISA compared to control. Curing conditions significantly influenced the compressive strength and dynamic modulus of elasticity. SF concrete subjected to dry air at 35°C after 14 days initial water curing produced the highest compressive strength and dynamic modulus of elasticity when continuously cured under water at 20°C. Provided that curing is sufficient, it is possible to develop HPC incorporating silica fume at relatively high water–binder ratios.

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