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Communication

Physical properties of high-performance concrete with admixtures exposed to a medium temperature range 20°C to 50°C

M.F. Mohd Zain[a,*], S.S. Radin[b]

[a]Department of Civil and Structural Engineering, Universiti Kebangsaan Malaysia, Faculty of Engineering, UKM Bangi, 43600 UKM Bangi, Selangor, Malaysia
[b]Faculty of Civil Engineering, Universiti Teknologi Malaysia, Malaysia

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Abstract

This paper discusses two physical properties, namely, compressive strength and modulus of elasticity of high-performance concrete made with four types of concrete mixes exposed to temperatures within the range 20°C to 50°C under three types of curing methods. The results showed that the compressive strength of concrete incorporating mineral admixtures practically reached above 100 MPa from the age of 7 days. The highest levels of strength and modulus of elasticity were produced by silica fume (SF) concrete under water and wrapped curing at temperature of 35°C. This indicates that the high pozzolanic reactivity and microfiller effect of SF at medium temperature has modified the open channels at the transition zone in SF concrete. The medium temperature environment associated with proper curing has played an important role in the hydration process that produced the hardened concrete with higher strength and elasticity.

Keywords: Medium temperature; High-performance concrete; Silica fume; Compressive strength; Dynamic modulus of elasticity

1. Introduction

The development of high-performance concrete has brought forth the need for admixtures, both mineral and chemical. Mineral admixtures are siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [1]. These admixtures, being extremely fine materials, fill the microvoids in grain packing and thereby improves the compactness of the concrete matrix and at the same time the rheological properties of the fresh mix.

Among the chemical admixtures, superplasticizers (SPs) come first because their volume of use in concrete is the largest of all. This type of admixture causes deflocculation of cement grains and this is the process by which the cement grains in suspension of water can recover their initial grain size. The incorporation of SP leads to an appreciable reduction in the quantity of mixing water because a lot of this water is no longer entrapped in the cement grain flakes [2]. This property, coupled with the addition of mineral admixture particularly silica fume (SF), enables concrete to achieve high strength without loss of workability [3]. The other chemical admixture, which is often used in cold region concreting, is air-entraining admixture. Theoretically, there is no need for air-entraining agent (AEA) to be used in concrete in non-freezing environment such as in Malaysia. However, in order to improve handling, placeability, and finishability of concrete, it is strongly recommended to utilize a small amount of AEA in fresh concrete.

Curing condition and curing temperature also influence the properties of hardened concrete. 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 [4]. 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 [5]. This paper presents two physical properties, namely, compressive strength and modulus of elasticity of high-performance

* Corresponding author. Tel.: +60-3-8929-6223; fax: +60-3-8929-6147.
E-mail address: fauzi@eng.ukm.my (M.F.M. Zain).

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Table 1
A summary of physical and chemical analysis of cement, GGBS, SF, FA, AEA and SPs

Item	GGBS	SF	FA	AEA	SP	Cement
Specific gravity	2.89	2.24	2.47	–	–	3.15
Surface area (m^2/g)	0.836	26	0.48	–	–	0.326
Chemical analysis (%)						
SiO_2	34.20	97.70	2.47	–	–	–
Al_2O_3	13.90	0.40	16.10	–	–	–
Fe_2O_3	0.20	0.30	2.90	–	–	–
CaO	42.70	0.30	1.70	–	–	–
TiO_2	–	–	1.10	–	–	–
MgO	6.10	0.00	0.70	–	–	1.40
SO_3	–	0.20	0.30	–	–	2.00
P_2O_5	–	–	0.70	–	–	–
Na_2O	–	–	1.70	–	–	0.61
K_2O	–	–	1.60	–	–	–
S	0.30	–	–	–	–	–
Solid content (%)	–	–	–	8	40	–
Moisture (%)	–	0.40	1.65	–	–	–
Loss on ignition (%)	–	–	–	–	–	1.30

concrete incorporating SF, fly ash (FA), ground granulated blast-furnace slag (GGBS) under three types of curing conditions exposed to medium temperature.

2. Experimental programme

2.1. Materials

Crushed stone aggregate, mine sand, Type-I normal Portland cement (NPC), GGBS, FA and SF were used in this study. The chemical compositions of those materials 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 SP and air-entraining admixture were also used as liquid chemical admixtures. Besides, normal tap water (pH = 6.9) was used as mixing water and for curing.

2.2. Mix proportions

SF, GGBS, FA and NPC concrete were designed at 25% water–binder ratios. The Sherbrooke mix design method [6] was followed to determine the optimum proportions. The details of mix proportions are shown in Table 2.

2.3. Curing conditions

Water, wrapped and dry air curing were practiced. The maximum curing age was 91 days and the curing temperatures were 20°C, 35°C, and 50°C. After demolding, the specimens were marked and immersed in water for full water curing at a temperature of 20°C. Under wrapped curing, after demolding, the specimens were marked and wrapped with wet burlaps before subjected to temperatures of 20°C, 35°C, and 50°C. The specimens for dry air curing were marked and stored in the curing chambers at temperatures of 20°C, 35°C, and 50°C.

2.4. Testing

Compressive strength and dynamic modulus of elasticity were determined at the age of 7, 28, 56 and 91 days. Compressive strength test was carried out according to the ASTM standard [7]. British standard was followed to determine dynamic modulus of elasticity [8]. The test specimens for compressive strength and dynamic modulus of elasticity were 7.5-cm diameter × 15-cm height cylinders. All specimens were cast in a standard manner. The compressive strength and dynamic modulus of elasticity were computed as the average values given by the three specimens.

3. Test results and discussion

3.1. Compressive strength

The results of tests conducted on hardened concrete are shown in Table 3. All pozzolanic concretes show better compressive strength performance than NPC concrete. The compressive strengths generally increase from the age of 7 days to 28 days for all types of concrete specimens except for GGBS concrete under 35°C and 50°C of dry air curing at age of 28 days. There are two possible reasons for the strength losses of slag concrete at this point. First, the rate and the degree of hydration are affected by the loss of moisture at an early age, with a

Table 2
Detail of mix proportions

Type of mix	Water–binder (%)	s/a (%)	Unit weight (kg/m^3) Water	Cement	GGBS	SF	FA	Fine aggregate	Coarse aggregate	SP (× C%)	AEA (× C%)
NPC	25	39	160	640	–	–	–	627	993	1.35	0.40
GGBS	25	39	160	320	320	–	–	616	977	1.10	0.30
SF	25	39	160	576	–	64	–	616	979	1.80	0.48
FA	25	39	160	576	–	–	64	619	985	3.00	0.80

s/a = Sand-aggregate ratio.

Table 3
Compressive strength and dynamic modulus of elasticity of NPC, GGBS, SF and FA concrete under different curing condition and temperatures

Type of mixes	Curing temperature (°C)	Curing methods	Compressive strength (MPa)				Modulus of elasticity ($\times 10^4$ MPa)			
			7 days	28 days	56 days	91 days	7 days	28 days	56 days	91 days
NPC	20	Water	85	105	114	119	4.69	5.04	5.14	5.27
		Wrapped	85	103	116	125	4.88	5.05	5.10	5.23
		Dry air	71	74	83	81	4.22	4.38	4.27	4.17
	35	Wrapped	89	107	104	115	4.78	4.88	4.96	4.99
		Dry air	72	74	78	77	4.19	4.13	4.10	4.02
	50	Wrapped	86	112	102	110	4.73	4.91	4.82	4.65
		Dry air	70	73	70	78	4.16	3.95	3.85	3.77
GGBS	20	Water	85	119	119	127	4.61	5.15	5.16	5.18
		Wrapped	92	113	113	120	4.65	4.86	4.97	4.80
		Dry air	65	77	74	78	3.90	4.05	4.11	3.90
	35	Wrapped	104	112	115	123	4.74	4.88	4.75	4.94
		Dry air	71	77	76	80	3.95	3.92	3.82	3.74
	50	Wrapped	111	108	112	114	4.85	4.80	4.55	4.37
		Dry air	76	72	81	84	4.01	3.87	3.70	3.67
SF	20	Water	93	123	118	130	4.32	5.21	5.24	5.28
		Wrapped	91	124	123	128	4.78	5.07	5.16	5.22
		Dry air	73	93	92	97	4.20	4.23	4.19	4.17
	35	Wrapped	106	126	126	130	4.89	4.82	4.84	4.84
		Dry air	80	97	98	95	4.17	4.12	3.99	4.05
	50	Wrapped	111	116	100	113	4.75	4.65	4.48	4.45
		Dry air	87	87	91	93	3.92	3.92	3.82	3.74
FA	20	Water	99	107	120	121	4.81	5.12	5.17	5.34
		Wrapped	97	108	112	111	4.86	5.10	5.15	5.26
		Dry air	82	86	92	94	4.34	4.32	4.28	4.40
	35	Wrapped	113	125	114	131	5.00	5.00	5.15	5.20
		Dry air	93	100	95	98	4.41	4.30	4.30	4.22
	50	Wrapped	108	125	116	110	4.96	4.97	4.71	4.66
		Dry air	93	95	93	96	4.17	4.12	4.08	3.99

decrease in strength gain. Secondly, may be the heat of generation was decreased in slag concrete after being exposed to these temperatures for 10 days [9]. Furthermore, from the age of 7 days, the strength of slag, SF, and FA concrete practically reached above 100 MPa. This seems to indicate that the open channels in concrete are blocked by their high pozzolanic reaction products at medium temperature to form the stable cementitious compound calcium silicate hydrate (C-S-H). Also, the influences of microfiller effect of mineral admixture especially SF and the consequences of SPs action on the structure of hardened pastes of low water–binder ratio are also reflected on the results of FA and SF concretes. The SF concrete shows an early strength up to 28 days. This also indicates that the process of SF dissolution begins early, within 1 day, followed by the formation of silica-rich gel at 7 days, and its final transformation into dense C-S-H gel within 28 days [10].

The highest compressive strength values were achieved by the water cured and wrapped cured concrete specimens. The reason is that water curing provides the required moisture for the hydration. Dry air curing resulted in lower compressive strengths compared to wrapped curing. This is because the hydration of cement can take place only when the vapor pressure in the capillaries is sufficiently high, about 80% of saturation pressure [11]. Therefore, early drying of concrete may stop the cement hydration before the pores are blocked by hydration products and thus, a more continuous pore structures may be formed. In this study, it was understood that an effective way to prevent the decrease in the compressive strength under medium temperature is to prevent the evaporation of water from concrete at an early age. A similar opinion was made by Zain and Matsufuji [12] in their experimental study.

Concrete specimens which were transferred to the elevated temperature regimes showed better gain in compressive strength. Subsequent rise in compressive strength is possibly due to drying and can be explained by a hypothesis originally proposed by Samarai [13]. This hypothesis suggests that in wet concrete, water acts as a lubricant which causes the drop in compressive strength. The specimens under wrapped curing at 35°C were partly dried at the age of 28, 56, 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 is also consistent with the work of other researchers [14].

Curing of specimens at 50°C caused lower compressive strength than at 35°C. It is well known that an elevated curing temperature causes a lower degree of hydration of cement paste and thereby affects the properties of hardened concrete. The effect of temperature rise on compressive strength was more pronounced in dry air curing than water or wrapped curing. Based on the present investigations, the highest levels of compressive strength were achieved at the curing temperature of 35°C under wrapped curing. This indicates that the concrete strength is not significantly influenced by the overall water content but rather by the water movement in the concrete specimen. Similar results were found in one earlier study [12].

SF concrete achieved the highest compressive strength. The mechanism by which SF improves the performance of concrete is both physical and chemical. The physical effect is due to its ultrafineness. It acts as a filler of the spaces between the cement grains [15]. SF reduces the pore volume in the concrete by the successful development of highly refined pore structure. The reduction in pore volume goes side by side with pore refinement, which leads to improved performance [16]. The chemical effect is the secondary pozzolanic reaction [17,18]. The open channels in SF concrete are blocked by the high pozzolanic reaction products and therefore, the porosity is reduced. Besides, improved interfacial bond between aggregates and cement paste develops in SF concrete.

3.2. Dynamic modulus of elasticity

Table 3 show that the dynamic modulus of elasticity increased continuously with age under 20°C of water and wrapped curing but decreased from the age of 28 days under dry air curing. However, under 50°C of dry air and wrapped curing, the dynamic modulus of elasticity of all concrete mixes decreased continuously with age. It might be due to the insufficiency of water for full hydration.

The dynamic modulus of elasticity generally decreased with the increase in curing temperature and also dropped continuously with the length of exposure. A similar observation was made in one previous work [12]. These phenomena are also related to the moisture loss from the specimens. Since moisture moves out with increasing age and the concrete specimens begin to dry up with increasing temperature and length of exposure, dynamic modulus of elasticity tends to decrease. It was seen that the concrete specimens cured by water continuously for 91 days exhibited the highest dynamic modulus of elasticity, whereas their compressive strengths at 91 days were lower. Thus, it is understood that the dynamic modulus of elasticity largely depends on moisture condition. At early age, the difference between the results for SF, FA concrete, and NPC concrete is small. However, at the age of 91 days, the specimens from SF and FA concrete show higher dynamic modulus of elasticity. This indicates that the role-played by SF as an effective filler and the porosity reducer are more pronounced at later ages.

4. Conclusions

The main conclusions, which can be drawn from this investigation, are given below.

The compressive strength of wrapped curing at early age is usually greater than dry air curing. Compared to the wrapped curing specimen, the loss of strength of the dry air specimen from the age of 7 days, was around 70%. This may suggest that the medium temperature environment associated with proper curing has played an important role in the hydration process that produced the hardened concrete with higher strength and durability.

The concrete specimens incorporated with mineral admixtures produced greater strengths from the age of 7 days. This indicated that the significant acceleration of pozzolanic reaction of those admixtures especially SF at medium temperature will increase strength.

The dynamic modulus of elasticity of all concrete mixes increased continuously with age under 20°C of water and wrapped curing but decreased from the age of 28 days under dry air curing. SF and FA concrete show higher dynamic modulus of elasticity values at the age of 56 and 91 days. This indicates that the role-played by SF as an effective filler and porosity reducer are more pronounced at later age.

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