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Combined effects of mineral admixtures and curing conditions on the sorptivity coefficient of concrete

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Abstract

The effect of mineral admixture and curing condition on the sorptivity of concrete are investigated. In the present work, the maximum particle size and the grading of coarse aggregate, the cement content and water/cement ratio of the concrete are kept constant. Then, in the ordinary Portland cement (OPC) 42.5 concrete, a portion of the sand is replaced by a mineral admixture such as fly ash (FA), limestone filler, sandstone filler or silica fume (SF). This paper presents the results of both the sorptivity coefficient and the compressive strength of OPC 42.5 concretes with these mineral admixtures, and concretes with OPC 32.5, blended cement (BC) or trass cement (TC). The results obtained indicate that the sorptivity coefficient of concrete decreases as the compressive strength of concrete increases. It is also shown that the sorptivity coefficient of concrete is very sensitive to the curing condition. The effect of curing condition on the sorptivity coefficient of concrete seems to be higher in low-strength concretes.

Keywords: Mineral admixture; Curing condition; Sorptivity coefficient; Compressive strength; Microfiller effect

1. Introduction

In recent years, there is a growing interest in the use of high-performance concretes, which provide overall durability and high strength [1,2]. It may not be true that concretes with identical strengths provide the same permeability. Several experimental investigations have shown that the capillary permeability is substantially affected by the curing condition. Sufficient curing is essential for a concrete to provide its potential performance [3].

It has generally been accepted that curing is more important for concrete with mineral admixtures than for normal concrete [4]. Water curing has more effect on the permeability than on the strength of concrete. Measurements of the permeability of concrete were used as an indication of durability. Dinku and Reinhardt [5] have shown that the gas permeability is sensitive to changes in curing duration, water/cement ratio, age of testing and moisture history of concrete; according to their research, it is possible to predict the gas permeability from the capillary sorptivity measurements. Blight and Lampacher [6] have indicated that there are good correlations in the relations of water sorptivity of covercrete (cover concrete) versus oxygen permeability and the carbonation depth versus oxygen permeability for the laboratory-cast specimens, but the correlations were poor or even absent when applied to in situ tests on mature concrete structures. In reinforced concrete, covercrete is defined as the least distance between the surface of the reinforcement and the outer surface of the concrete. The test results obtained by Jacobs [7] show a linear relationship between the logarithm of the gas permeability and the water content in the pores of concrete or the degree of saturation; the permeability decreases as the degree of saturation increases. Martys and Ferraris [8] have shown that the sorptivity coefficient is essential to predict the service life of concrete as a structural material and to improve its performance.

In recent years, blended cements (BCs) have attracted intensive attention. The study of Jiang et al. [9] indicates the significant contribution of these cements to the durability of the hydration products. For a wide range of cements, Parrott [10] has shown that the initial 4-day mass loss generally reduced as the strength at the end of curing period was increased. Ngala and Page [11] have shown that the diffusion resistance of some pastes such as ordinary Portland cement (OPC), OPC/30% PFA and OPC/65% BFS are adversely affected by predrying and carbonation, but the

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Table 1
Chemical properties of cements

Contents	OPC 42.5	OPC 32.5	BC 32.5	TC 32.5
SiO_2 (insoluble) (%)	0.32	0.68	7.91	14.40
SiO_2 (soluble) (%)	20.38	20.76	16.80	14.43
Al_2O_3 (%)	5.99	5.55	6.82	7.96
Fe_2O_3 (%)	3.53	3.61	4.08	4.32
CaO (%)	64.27	64.02	58.18	52.70
MgO (%)	1.30	1.19	1.28	1.35
SO_3 (%)	2.52	2.66	2.69	2.44
LOI (%)	1.39	1.20	1.46	2.18
Others (%)	0.39	0.33	0.78	0.22

effects were considerably more severe for BCs than for the OPC.

According to Khan and Ayers [12], the minimum length of curing should be optimized in terms of several properties, such as strength, permeability and the movement of aggressive gases and/or liquids from the environment. Their results show that the minimum lengths of curing for the silica fume (SF) concrete mixtures, Portland cement concrete mix and the fly ash (FA) concrete mixture were 3, 3.75 and 6.5 days, respectively. In general, it has been shown that concretes prepared with mineral admixtures are more sensitive to the water-curing producers than concretes prepared with neat Portland cement.

In the work presented here, combined effects of mineral admixtures and curing conditions on the sorptivity and compressive strength of OPC 42.5 concrete are investigated. The coefficient of sorptivity was evaluated for concretes with FA, sandstone powder (SP), limestone powder (LP) and SF. The sorptivity coefficient and the compressive strength of concretes with OPC 32.5, BC or trass cement (TC) are also discussed.

2. Materials and experiments

2.1. Materials used

2.1.1. Cements

The chemical compositions of two ordinary Portland cements (OPC 42.5 and OPC 32.5), blended cement (BC 32.5) and trass cement (TC 32.5) used, expressed in percentages by mass of the constituent oxides, are shown in Table 1. The mechanical and some physical properties of these cements are given in Table 2. BC 32.5 and TC 32.5 contain approximately 15% and 40% of natural pozzolan, respectively.

Table 2
Physical and mechanical properties of cements

Type of cement	OPC 42.5	OPC 32.5	BC 32.5	TC 32.5
Density (g/cm^3)	3.12	3.18	3.13	3.06
Fineness (cm^2/g)	3270	3190	3100	3870
Flexural strength (N/mm^2)				
7 days	6.8	6.4	4.8	4.3
28 days	8.9	7.0	7.0	6.7
Compressive strength (N/mm^2)				
7 days	36.6	30.0	24.1	22.0
28 days	51.9	45.0	38.1	35.3

Table 3
Gradings and densities of aggregates

Aggregate type	Percentage passing								Particle density (g/cm^3)
	Sieve size (mm)								
	31.5	16	8	4	2	1	0.5	0.25	
Crushed stone (8–32 mm)	100	50	1	0	0	0	0	0	2.72
Crushed stone (2–16 mm)	100	100	68	26	13	0	0	0	2.70
Sea sand	100	100	100	100	100	97	82	14	2.62

2.1.2. Aggregates

Gradings and densities of sea sand and calcareous-based crushed stone aggregates are shown in Table 3.

2.1.3. Mineral admixture

The FA of Cayırhan, sandstone microfiller kept in the filters of a quarry in the region of Ayazaga, LP brought from Cebecikoy region in Istanbul and SF provided from Eti-bank–Antalya factory were used as replacement materials. The chemical compositions and densities of these mineral admixtures are given in Tables 4 and 5.

2.2. Design of mixture proportions

The absolute volume method was used in calculating the mixture proportions. In all mixes, a cement content at 300 kg/m^3 and a water/cement ratio at 0.60 were kept constant. A superplasticizer was used to maintain approximately the same slump of 100 ± 20 mm. For each concrete mixture, the grading curve of aggregate was chosen between ISO A32–B32, closer to B32 and kept constant. Mixture proportions of aggregate were kept constant; fine aggregate: 0.30, coarse aggregate No. 1: 0.35, coarse aggregate No. 2: 0.35 expressed as percentage of total aggregate mass. In addition, in concretes with mineral admixture, the mineral admixture was 10% by mass of cement by replacing 5.5% of the fine aggregate fraction. Series A concretes without mineral

Table 4
Chemical compositions of mineral admixtures

Mineral admixture	FA	SP	LP	SF
SiO_2 (%)	42.88	57.46	9.28	94.96
Al_2O_3 (%)	16.10	18.63	3.80	0.36
Fe_2O_3 (%)	9.90	7.43	1.80	0.40
CaO (%)	15.90	3.36	42.25	0.45
MgO (%)	0.73	1.13	2.96	0.99
SO_3 (%)	6.42	0.14	1.96	0.16
LOI (%)	1.74	5.38	37.45	0.58

Table 5
Densities and average particle sizes of mineral admixtures

Mineral admixture	FA	SP	LP	SF
Density (g/cm^3)	2.34	2.71	2.68	2.56
Average particle size (μm)	71	60	7	–

admixture were designated with the code of NC, while the other concretes in this series which contain mineral admixture were designated with the following codes: CFA, CSP, CLP and CSF. The first letter (C) shows concrete, two letters following C are mineral admixtures such as FA, SP, LP and SF. Series B concretes, however, were designated as follows: CPC = concrete with OPC 32.5, CBC = concrete with BC 32.5 and CTC = concrete with TC 32.5. All mixtures were prepared in a small laboratory pan mixer. For all mixtures, the mixture compositions and the properties of fresh concrete are given in Table 6. For each mixture, 150-mm-cube specimens were kept in their molds for 24 h. After demolding, they were stored in a water tank, saturated with lime at 20 °C (± 3 °C) for 28 days. All compressive strength tests were done at 28 days. Table 7 summarizes the test results obtained for the eight concretes.

2.3. Sorptivity

For sorptivity tests, prisms of 100 × 100 × 500 mm were cast from each mixture, the specimens were demolded after 24 h. Three different curing regimes were applied to the specimens before the capillary sorption tests: (i) air curing in a room of 65% (± 5%) relative humidity and 20 °C (± 3 °C) temperature for 28 days (Curing Regime I), (ii) second curing regime (Curing Regime II) was as follows: an initial curing for 7 days under polyethylene sheet and wet burlap at 20 °C (± 3 °C) temperature, further 21 days air curing in case of Curing Regime I, (iii) water curing for 28 days in a water tank saturated with lime at 20 °C (± 3 °C) (Curing Regime III). Three test specimens for sorptivity test cut from the prisms of 100 × 100 × 500 mm were prepared for each mixture and each curing regime. Measurements of capillary sorption were carried out using specimens pre-

Table 7
Compressive strength test results

Mixture code	Compressive strength at 28 days (N/mm^2)
Series A	
NC	36.2
CFA	33.1
CSP	33.6
CLP	40.0
CSF	50.2
Series B	
CPC	31.5
CBC	29.0
CTC	24.7

conditioned in the oven at about 50 °C until constant mass. As shown in Fig. 1, test specimens of 100 × 100 × 70 mm were exposed to the water on the plane of 100 × 100 mm by placing it in a pan. The water level in the pan was maintained at about 5 mm above the base of the specimens during this experiment. The lower areas on the sides of the specimens were coated with paraffin to achieve unidirectional flow. At certain times, the mass of the specimens was measured using a balance, then the amount of water adsorbed was calculated and normalized with respect to the cross-section area of the specimens exposed to the water at various times such as 1, 4, 9, 16, 25, 36, 49 and 64 min. The sorptivity coefficient (k), was obtained by using the following expression:

$$\frac{Q}{A} = k\sqrt{t} \tag{1}$$

where Q = the amount of water adsorbed in (cm^3); A = the cross section of specimen that was in contact with water (cm^2); t = time (s); k = the sorptivity coefficient of the specimen (cm/s$^{1/2}$).

To determine the sorptivity coefficient, Q/A was plotted against the square root of time ($\sqrt{t}$), then, k was calculated from the slope of the linear relation between Q/A and $\sqrt{t}$.

Table 6
Mixture proportions and properties of fresh concrete

Mixture code	Series A					Series B		
	NC	CFA	CSP	CLP	CSF	CPC	CBC	CTC
Cement (kg/m^3)	302	301	306	305	302	302	302	303
Water (kg/m^3)	180	181	181	183	181	181	181	182
Mineral admixture (kg/m^3)	–	30	31	31	30	–	–	–
Sand (kg/m^3)	554	522	530	528	523	556	554	555
Coarse aggregate No. 1 (kg/m^3)	667	664	374	672	666	669	666	668
Coarse aggregate No. 2 (kg/m^3)	671	668	678	676	670	673	670	672
Superplasticizer (kg/m^3)	1.6	1.6	2.2	1.7	5.2	1.6	3.4	2.4
Water/binder	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Slump (mm)	80	100	80	90	120	90	80	80
Density (kg/m^3)	2376	2368	2404	2396	2379	2385	2376	2382

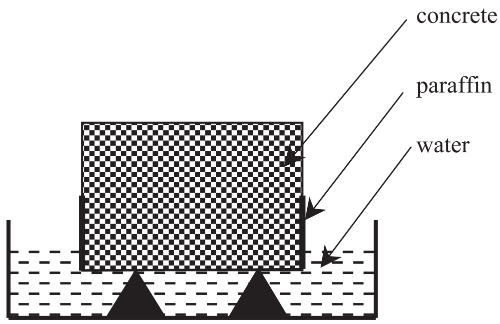

Fig. 1. The measurement of water capillary sorption.

The sorptivity coefficients obtained are shown in Table 8.

3. Discussion

3.1. Strength properties

In Series A, mixtures were produced using ordinary Portland cement. The highest compressive strength was obtained in SF concrete, and the lowest strength was obtained in FA concrete. The other compressive strength values of concretes with mineral admixture are between CFA and CSF; the order of strengths from the lowest to highest are CFA, CSP, NC, CLP and CSF.

Since the average particle size of SF is very small compared to that of cement particle, the filler effect of mineral admixture may be as important as its pozzolanic effect, according to Goldman and Bentur [13] the filler effect is more important than its pozzolanic effect as indicated in Fig. 2. Thus, the fineness of a mineral admixture is very important for the modification of aggregate–cement interface zone, which is the weakest link in concrete [14–17]. On the other hand, the average particle size of FA is very high, thus its filler effect at 28 days may not be sufficient. It is clear that the pozzolanic effect of FA is very low compared to SF. It can be concluded that compressive strength of CFA is low, because both pozzolanic activity and filler effect of FA are not as good as those of SF.

The fineness of a mineral admixture is an important parameter for filling of pores in concrete. Wee et al. [18] have shown that the use of microfiller materials combined with superplasticizers affect greatly the pore structure of concrete, and a significant reduction in the volume of pores was obtained.

Sawicz and Heng [19] have shown that the limestone filler does not only change the pore structure of concrete but the chemical structure of the cement paste. Some researchers [20,21] have concluded that the hydrocarboaluminate ($C_3A{\cdot}CaCO_3{\cdot}11H_2O$) forms between the calcareous aggregate and C_3A in cement as a result of chemical reactions. Hence, the interface is enhanced and the strength of concrete increases. There is no indication of similar reaction between siliceous SP and limestone aggregate, however, further studies are necessary to obtain reliable results. In the concrete literature, it is believed that at a room temperature of about 20 °C, there is no chemical reaction between the kuvarsit aggregate and cement paste, but it is shown that the surface of the kuvarsit aggregate becomes active above 60 °C [22].

Since the particle size of both FA and sandstone filler is significantly higher than that of both limestone filler and SF, the pores in the bulk paste and especially in the interfaces are not filled. Hence, the following conclusion rises: although CFA and CSP have the same cement content, the compressive strengths of concrete containing FA and sandstone filler is lower than that of normal concrete. The SF particles, however, may act as an ideal microfiller between the cement grains. Both pozzolanic and filling effects of FA are less than those of SF. Thus, the low compressive strength in concretes with FA is obtained compared to that of the SF concrete.

In Series B, the compressive strength of concrete with BC or TC is less than that of OPC, because the strength development in these concretes is slow compared to concrete with OPC. Especially, the compressive strength of concrete with TC is significantly lower than that of OPC. It is well known that the pozzolanic effect of microfiller materials will be significant in the later ages of concrete, thus, it is expected that the differences in the compressive strength can be changed beyond 28 days.

3.2. Evaluation of sorptivity coefficient test results

As seen from Tables 7 and 8, and Figs. 3 and 4, as the compressive strength of concrete increases, the sorptivity coefficient decreases significantly for concretes subjected to Curing Regime I. In concretes subjected to Curing Regime II, the sorptivity coefficient of concrete decreases slightly with increasing compressive strength. In concretes kept under water for 28 days (Curing Regime III), however, the sorptivity coefficient is almost constant with increasing compressive strength.

Table 8
Sorptivity coefficients

Mixture code	Sorptivity coefficient ($\times 10^{-3}$ cm/s$^{1/2}$)		
	Curing Regime I	Curing Regime II	Curing Regime III
Series A			
NC	1.53	0.75	0.46
CFA	1.67	0.97	0.60
CSP	1.65	0.91	0.54
CLP	1.47	0.67	0.47
CSF	1.28	0.70	0.44
Series B			
CPC	1.81	0.93	0.62
CBC	1.62	1.32	0.77
CTC	3.16	1.82	0.74

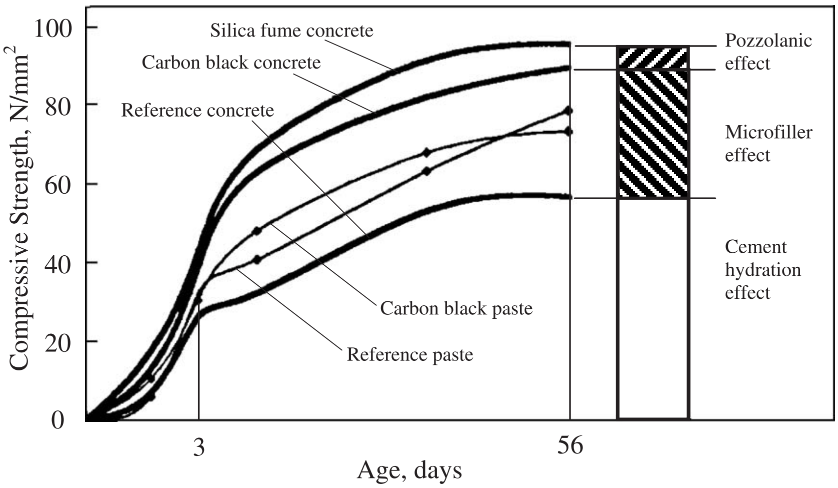

Fig. 2. Microfiller and pozzalanic effects on the compressive strength of concrete [13].

As seen in Fig. 3, the sorptivity coefficients of concretes with FA are high for all storage conditions. Recent research [23] shows that the permeability of concrete with FA is high at early ages of concrete. It is expected that the capillary sorption of concrete can be reduced with the development of pozzolanic reactions by the time. Fig. 3 also shows that the length of curing of FA concrete is insufficient compared to that of normal concrete. The same trend was obtained by Khan and Ayers [12].

Since SF and limestone filler are very fine, pores in the bulk paste or in the interfaces between aggregate and cement paste is filled by these mineral admixtures, hence, the capillary pores are reduced. The beneficial role of mineral admixture causes an increase in the strength and a reduction in the capillary sorption of concrete. The high early strength development in SF concrete can be attributed to an early pozzolanic reaction. In concretes with FA or with sandstone filler, the average particle size of the mineral admixture is higher compared to SF and LP, and the pores in bulk paste and interfaces are not filled completely. Thus, concrete has larger capillary pores, and lower compressive strength as a result of the higher capillary sorption in concrete is obtained. As seen in Fig. 4, in Series B with TC the sorptivity coefficient of concrete kept in the laboratory condition (Curing Regime I) is substantially high.

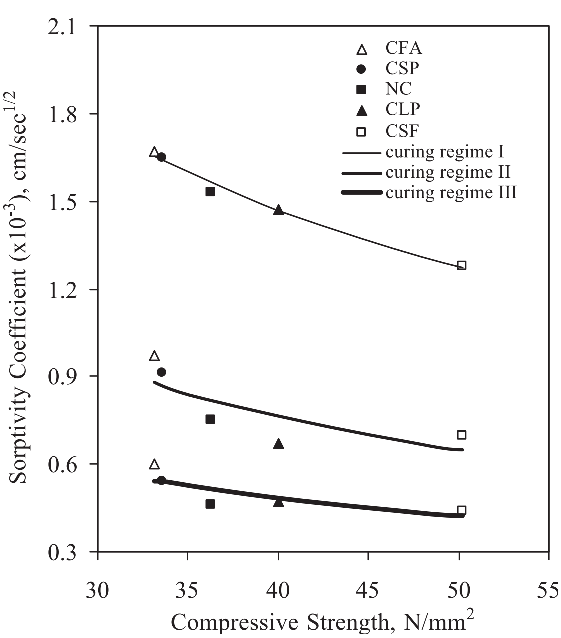

Fig. 3. Sorptivity coefficient versus compressive strength of concrete (Series A).

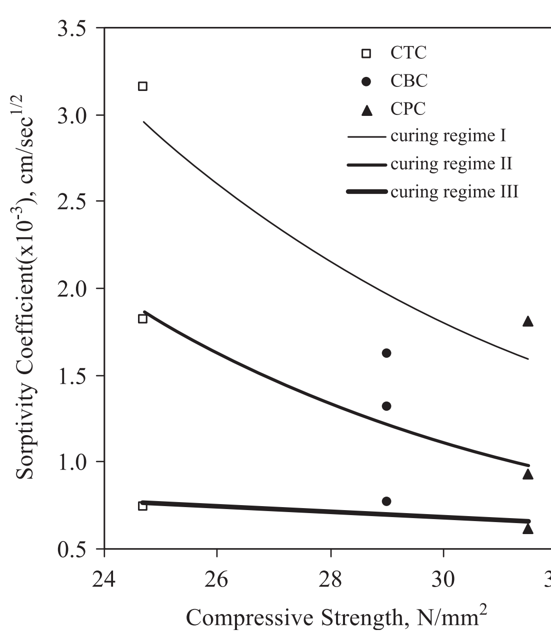

Fig. 4. Sorptivity coefficient versus compressive strength of concrete (Series B).

4. Conclusions

The following conclusions could be drawn from the results obtained in this investigation:

(1) Mineral admixtures having high values of fineness and pozzolanic activity increase the compressive strength of concrete. Mineral additives with coarse particles cause the reduction in the strength of concrete.
(2) Since microfiller materials having fine particles fill both the interfaces and the bulk paste, hence, the sorptivity coefficient of concrete decreases.
(3) For Curing Regimes I and II, the sorptivity coefficient of concrete decreases with increasing compressive strength. The sorptivity coefficients of concretes subjected to Curing Regime II are lower than those of concretes kept at laboratory conditions (Curing Regime I). In concretes subjected to Curing Regime III, however, the sorptivity coefficient is almost constant with increasing compressive strength. The addition of SF to concrete significantly reduces the sorptivity coefficient.
(4) Microfiller materials with the low value of pozzolanic activity exhibit very little cementing value in laboratory conditions. However, under water-curing conditions, the cementing activity becomes apparent.

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