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Properties of Portland Cement-Silica Fume Pastes II. Mechanical Properties

by R.F. Feldman and Huang Cheng-yi

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RÉSUMÉ

On a mesuré la résistance en compression, le module de Young et la microdureté en fonction de la porosité de pâtes ne contenant que du ciment ou contenant du ciment et 10 ou 30 pour cent de silice fine dans des rapports $e/(c+sf)$ de 0,25 et 0,45. Les porosités sont plus faibles pour les pâtes sans silice fine, mais les résistances sont supérieures pour un rapport $e/(c+sf)$ de 0,25 après 180 jours de cure. Toutefois, pour un rapport $e/(c+sf)$ de 0,45, l'incorporation d'une grande quantité de silice n'augmente que légèrement la résistance. Le module d'élasticité est plus élevé sans silice fine. On montre que pour un rapport $e/(c+sf)$ de 0,45, l'addition de silice fine donne un E_0 relativement faible mais un S_0 élevé. Ce phénomène est dû à la combinaison d'un hydrate dispersé de faible masse volumique qui contient peu de CaO/SiO_2 , et d'une faible teneur en $Ca(OH)_2$, ce qui donne un composite relativement homogène. Les corrélations entre les caractéristiques mécaniques (à l'échelle logarithmique) et la teneur en eau captive sont bonnes pour tous les échantillons, avec ou sans silice fine.

PROPERTIES OF PORTLAND CEMENT-SILICA FUME PASTES
II. MECHANICAL PROPERTIES

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ABSTRACT

Compressive strength, Young's modulus, and microhardness are measured as a function of porosity for pastes of silica fume-cement blends made with silica fume contents of 0, 10 and 30 per cent at $w/(c+sf)$ ratios of 0.25 and 0.45. Porosities are lower for pastes without silica fume addition, but strengths are greater at $w/(c+sf)$ of 0.25 at 180 days curing. At a $w/(c+sf)$ of 0.45, however, strengths are marginally greater with large additions of silica fume. Modulus of elasticity is greater without addition. It is shown that silica fume addition at a $w/(c+sf)$ of 0.45 results in a relatively low E_o but high S_o . This is due to a combination of low-density dispersed hydrate of low CaO/SiO_2 and low $Ca(OH)_2$ content, leading to a relatively homogeneous composite. Correlations between log mechanical property and non-evaporable water content are good for all specimens, with and without silica fume.

Introduction

The first paper of this series (1) reported an investigation of the development of pore-size distribution, measurement of surface area by different techniques, and measurement of the drying shrinkage of various mixes of portland cement-silica fume blended pastes. It demonstrated that the properties of blended pastes are quite different from those of pure pastes or blended mortars. Calcium hydroxide, which is deposited in mortars at the interface of inclusions such as sand, subsequently reacts with silica fume (2). In blended pastes, silica fume reacts with calcium hydroxide only in the matrix phase (3).

In order to understand the factors that affect mechanical properties, the total porosity of the blends has been measured. Mechanical properties such as microhardness, Young's modulus, and compressive strength were determined for the paste blends at 0, 10 and 30 per cent silica fume content prepared at $w/(c+sf)$ of 0.25 and 0.45 and cured for up to 180 days. Correlations were also investigated for mechanical properties, non-evaporable water, and porosity.

Experimental

Details of materials, mixes, and curing procedure have been given in part one of this series (1).

Porosity

Damp-dry specimens (1.3 mm thick) were placed in desiccators conditioned with salt solution to 11% RH. The weight change from the damp-dry condition was recorded as a percentage of the volume of the specimen in the d-dried state. (D-drying was achieved by heating the samples in a vacuum at 100°C for 8 - 14 h.) Apparent volumes were determined by measuring the thickness and diameter of the disc samples.

Compressive Strength, Young's Modulus and Microhardness

Strength was measured in compression on 51 × 51-mm cubes, three cubes for each preparation, at each of the curing times (1, 3, 7, 14, 18, 90 and 180 days).

Young's modulus was measured on 32-mm diameter paste discs 1.3 mm thick, using seven discs to obtain an average value (4). Deflection was measured by loading a saturated paste specimen at its centre while supported at three points on the circumference of a circle 25 mm in diameter.

Microhardness was measured by means of a Leitz microhardness machine with a Vickers pyramid indenter on the same discs as were used for determining the modulus of elasticity. Measurements were carried out in a conditioned box free of CO₂. Each value was the average of 40 readings taken on two discs (4).

Results

Compressive Strength

The results of the development of compressive strength with time for the six mixes, together with the nomenclature for each mix, are presented in Fig. 1 and Table I. At a w/(c+sf) of 0.25 the strength for P₁₀^L is greatest (of the three mixes) to between 28 and 90 days of curing, while S^L and P₃₀^L are similar up to 14 days. By 90 days, S^L has the highest strength, i.e., 124 MPa after 180 days of curing; P₃₀^L is lowest, at 106 MPa. The rate of strength development after 28 days is much greater for S^L than for the other two mixes. At a w/(c+sf) ratio of 0.45, the strength of P₃₀^H is highest between one and 180 days; but the rate of strength development is greatest for S^H after 28 days, exceeding the strength of P₁₀^H between 90 and 180 days.

Microhardness

The development of microhardness with time is illustrated in Fig. 2. The spread of results for the three silica fume contents at both values of w/(c+sf) is much less than that for compressive strength. At a w/(c+sf) of 0.25, P₃₀^L develops maximum hardness, i.e., 688 MPa after 180 days, while S^L and P₁₀^L have similar values of hardness of about 650 MPa after the same period.

At a w/(c+sf) of 0.45, P₁₀^L shows the greatest microhardness up to 14 days. At 180 days, S^H and P₃₀^H both exceed P₁₀^H, which has the lowest microhardness.

TABLE I
Nomenclature for Mixes

Per cent silica fume	w/(c+sf)*	
	0.25	0.45
0	S ^L	S ^H
10	P ₁₀ ^L	P ₁₀ ^H
30	P ₃₀ ^L	P ₃₀ ^H

*Water-to-cement plus silica fume ratio by weight

At both values of $w/(c+sf)$ the specimens without silica fume show the greatest rate of increase in hardness between 28 and 180 days.

Young's modulus

The results for Young's modulus, all mixes, as a function of curing time are presented in Fig. 3. At a $w/(c+sf)$ of 0.25 the rate of increase of modulus is similar for the three mixes after seven days of curing; values at 180 days are 2.92, 2.83 and 2.58×10^4 MPa for P_{10}^L , S^L and P_{30}^L , respectively.

At a $w/(c+sf)$ of 0.45 the rate of modulus development for S^H is maximum between 28 and 180 days, as for compressive strength and microhardness, and the value at 180 days is also the highest of the three mixes: 1.75, 1.64 and 1.55×10^4 MPa for S^H , P_{10}^H and P_{30}^H , respectively. Microhardness and compressive strength values for P_{10}^H are, however, lowest.

Porosity

The porosity values for different mixes are presented as a function of curing time in Fig. 4. In all cases porosity decreases as curing time increases. At a $w/(c+sf)$ of 0.25, the porosity decrease is greatest for S^L and P_{10}^L prior to 28 days. After 28 days S^L shows the greatest decrease and the porosities for P_{30}^L and P_{10}^L become similar; at 180 days the values are approximately 18.9, 18.9 and 16.3 for P_{30}^L , P_{10}^L and S^L , respectively.

FIG. 1
Compressive strength of cement pastes with different silica fume contents versus hydration time

FIG. 2
Microhardness of cement pastes with different silica fume contents versus hydration time

At a $w/(c+sf)$ of 0.45, the pastes without silica fume, S^H and P_{10}^H , are similar for the first 14 days, but S^H again shows the largest decrease in porosity after 28 days; values at 180 days are 28.8, 31 and 32.2 for S^H , P_{10}^H and P_{30}^H , respectively. Prior to 28 days, P_{10}^H , S^H and P_{30}^H have lowest porosities in that order. These are trends very similar to those of the Young's modulus.

Porosity/Mechanical Property Relation

Several expressions have been used to describe the porosity dependence of strength, fracture energy, and Young's modulus. The following equation has often been used for mechanical properties:

$$M = M_0 e^{-b_M P}$$

where M = mechanical property, M_0 = mechanical property at zero porosity, P = porosity, and b_M is a pore shape factor.

Plots of log mechanical property against porosity were made for specimens cured from 3 to 180 days; the plots developed six straight lines for each mechanical property. The results for linear regression analysis, recorded in Table II, show the intercept, the mechanical property at zero porosity (S_0 , H_0 , E_0 , i.e., strength, microhardness, and Young's modulus, respectively), and the shape factor (b_S , b_H and b_E) for each specimen. The correlation coefficient for each line is also given.

Compressive Strength

The values of S_0 derived from compressive strength analysis at a $w/(c+sf)$ of 0.25 decrease with increase in silica fume content. This system is very complex, especially since a large amount of unhydrated cement remains for S^L even at 180 days, and b_S values decrease with S_0 values. At a $w/(c+sf)$ of 0.45, S_0 values for P_{10}^H and P_{30}^H are much higher than that for S^H , i.e., 746.5, 669.9 and 448.7 MPa, respectively. This is consistent with the fact that in P_{10}^H and P_{30}^H , $Ca(OH)_2$ content is greatly reduced, and despite the higher porosity for P_{10}^H and P_{30}^H at 180 days the strength for P_{30}^H was higher than that for S^H .

Microhardness

The values of H_0 and b_H are also presented in Table II. P_{10}^L has the largest H_0 value at a $w/(c+sf)$ of 0.25, but it is not much different from that of S^L . b_H changes in the same manner as H_0 . At a $w/(c+sf)$ of 0.45, H_0 varies as $P_{10}^H > P_{30}^H > S^H$, in the same order as for b_H , S_0 and b_S . This is consistent with the compressive strength results and shows that, despite the higher porosity of P_{10}^H and P_{30}^H in relation to S^H , the microhardness values after 180 days of curing do not differ from each other to any large extent.

Young's modulus

The values for E_0 presented in Table II show a different trend from those of compressive strength and microhardness. At a $w/(c+sf)$ of 0.45, $S^H > P_{10}^H > P_{30}^H$. In this case modulus values for S^H are also greater than P_{10}^H and P_{30}^H at 180 days. At a $w/(c+sf)$ of 0.25, no particular trend is evident, the values being $P_{10}^L > S^L > P_{30}^L$. The results appear to be dominated by the residual unhydrated cement.

Mechanical Property - Non-evaporable Water Relation

Plots of the logarithm of the three mechanical properties versus non-evaporable water content at a $w/(c+sf)$ of 0.45 are presented in Figs. 5-7. All are for specimens cured from 3 to 180 days. Correlation coefficients from

FIG. 3 Young's modulus of cement pastes with different silica fume contents versus hydration time

FIG. 4 Porosity determined by adjusted water technique for cement pastes with different silica fume contents versus hydration time

TABLE II
Linear Regression Analysis of Compressive Strength, Microhardness, and
Modulus of Elasticity Versus Porosity Results

Sample	S_o (MPa)	b_s	Correlation coefficient r
S^L	610.94	0.0960	0.98
P_{10}^L	371.5	0.0682	0.94
P_{30}^L	252.3	0.0539	0.92
S^H	448.7	0.0668	0.98
P_{10}^H	746.45	0.0804	0.96
P_{30}^H	669.88	0.0693	0.91
	H_o (MPa $\times 10^{-1}$)	b_H	
S^L	114.29	0.0329	0.91
P_{10}^L	117.49	0.0316	0.87
P_{30}^L	94.84	0.0199	0.90
S^H	137.09	0.0438	0.94
P_{10}^H	212.81	0.0555	0.87
P_{30}^H	182.39	0.0481	0.96
	E_o (MPa)	b_E	
S^L	4.35×10^4	0.0245	0.93
P_{10}^L	5.25×10^4	0.0311	0.95
P_{30}^L	4.16×10^4	0.0269	0.95
S^H	6.01×10^4	0.0417	0.93
P_{10}^H	4.90×10^4	0.0381	0.91
P_{30}^H	4.86×10^4	0.0363	0.88

linear regression analysis are all over 0.93, and for compressive strength and microhardness are above 0.95. The larger amount of non-evaporable water associated with specimen S^H for a similar gain of compressive strength or microhardness is evident from increased slope for P_{10}^H and P_{30}^H ; P_{10}^H has the greatest slope in the plot of strength and microhardness (Figs. 5 and 6, respectively). Similar results may be observed for Young's modulus, except that the slopes for P_{10}^H and P_{30}^H are similar. At a $w/(c+sf)$ of 0.25 there is relatively less difference between the slopes for S^L , on the one hand, and P_{10}^L and P_{30}^L , on the other, for the plot of the three mechanical properties. This is due to the increased influence of the unhydrated phase and the influence of the initial low $w/(c+sf)$ on degree of hydration.

Mechanical Property Interrelation

Linear plots of microhardness versus compressive strength, Young's modulus versus compressive strength, and Young's modulus versus microhardness are presented in Figs. 8-10, respectively, for a $w/(c+sf)$ of 0.45. Figure 8 shows good linear correlation between microhardness and compressive strength, and the slope of the line is independent of silica fume content. On the other hand, correlations between Young's modulus and compressive strength or microhardness, although good, show slopes dependent on silica fume content. It is clear that the response of the Young's modulus measurement to changes brought on by silica fume is different from that of compressive strength and microhardness measurements.

Discussion

Porosity measurements (Fig. 4) show that pastes without additions of silica fume have lower porosity values because hydration reactions between 28 and 180 days continue at a faster rate. This difference was discussed in a previous paper (3) in which it was suggested that the decrease in permeability of the hydration products in the presence of silica fume is due partly to low $Ca(OH)_2$ content. The difference in porosity, however, is not so large as would be expected from the difference in the extent of the reaction (assessed from the non-evaporable water content) because of the offsetting effect of density of products. The density of C-S-H formed in the presence of silica fume is 2.05 g/mL, whereas its value when formed in the absence of silica fume is 2.24 g/mL. The C-S-H formed in the presence of silica fume would thus be more effective, per unit weight of non-evaporable water, in filling pores of the matrix (1).

The value of the mechanical property of porous composite bodies such as cement-silica fume blends is dependent on several factors, including porosity, density of product, bonding between reaction products, and homogeneity (6). Although lower porosity could indicate a higher value for a mechanical property, other factors might have a countering influence. At a $w/(c+sf)$ of 0.45, S^H does not have the highest compressive strength or microhardness after 180 days curing despite the lower porosity. It is clear that the lower $Ca(OH)_2$ content of P_{10}^H and P_{30}^H (giving a more homogeneous body, possibly with fewer areas for crack initiation) can increase the strength of these paste blends. This factor is not so dominant with regard to Young's modulus, as may be seen in the results at a $w/(c+sf)$ of 0.45 where the value for S^H is greater than either P_{10}^H or P_{30}^H ; in this case the higher density product with the lower porosity results in a higher Young's modulus.

The values of S_o , H_o and E_o at a $w/(c+sf)$ of 0.45 illustrate the response of the properties of the various composites to different mechanical stresses. For S_o and H_o , $P_{10}^H > P_{30}^H \gg S^H$, but for E_o , $S^H > P_{10}^H$ and P_{30}^H . In previous work on autoclaved cement-silica systems (6), values of E_o , S_o , H_o and b_E , b_S and b_H were obtained; the values for the autoclaved 20% silica-cement mixture were similar to those for S^H obtained here, but the values of the three properties, E_o , S_o and H_o , of P_{10}^H and P_{30}^H were not similar to those of any of the autoclaved mixtures. The values of the ratio E_o/S_o for S^H , P_{10}^H and P_{30}^H are 133.9, 65.6 and 72.6, respectively; but this value varies from 110 to 186 for autoclaved cement-silica mixtures containing 10 to 50% silica. Silica fume addition results in the combination of a relatively low E_o , probably due to the low density hydrate product, and a high S_o , due to low $Ca(OH)_2$ content (7) and possibly to pore shapes leading to low stress intensities.

The high values of mechanical properties for P_{10}^H and P_{30}^H , with relatively low non-evaporable water content (8), as shown in Figs. 5-7, are surprising. They are probably due to the combination of a low-density, dispersed-hydrate

FIG. 5 Compressive strength versus non-evaporable water content for cement pastes containing silica fume ($w/(c+sf) = 0.45$)

FIG. 6 Microhardness versus non-evaporable water content for cement pastes containing silica fume ($w/(c+sf) = 0.45$)

FIG. 7 Young's modulus versus non-evaporable water content for cement pastes containing silica fume ($w/(c+sf) = 0.45$)

FIG. 8 Microhardness versus compressive strength for cement pastes containing silica fume ($w/(c+sf) = 0.45$)

FIG. 9 Young's modulus versus compressive strength for cement pastes containing silica fume ($w/(c+sf) = 0.45$)

FIG. 10 Young's modulus versus microhardness for cement pastes containing silica fume ($w/(c+sf) = 0.45$)

product of low CaO/SiO_2 ratio (7,9) and to low Ca(OH)_2 content, leading to a relatively more homogeneous composite.

Conclusions

1. Porosity of pastes without silica fume is lower than that of pastes of blends, especially at longer periods of curing.
2. Young's modulus of elasticity for paste without silica fume is higher than that for pastes with silica fume, but compressive strength is lower.
3. Good correlations are found between log mechanical property and porosity or non-evaporable water.
4. Silica fume addition results in the combination of a relatively low E_0 , due to a low density product, and a high S_0 , due to low Ca(OH)_2 content.
5. Silica fume addition also results in the combination of a low-density, dispersed-hydrate product of low CaO/SiO_2 and low Ca(OH)_2 content, leading to a relatively homogeneous composite.

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