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Effect of Sand Content on Strength and Pore Structure of Cement Mortar

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Abstract: The effects of four sand contents on the compressive, flexural and splitting-tensile strength of cement mortars were evaluated. Moreover, we experimentally investigated the pore structure of cement mortar brought about by changing the sand content and water/cement ratio. The changes in the pore structure were quantified by measuring the porosity and pore size distribution obtained by using mercury intrusion porosimetry (MIP) technique. The test results show that the strengths of cement mortar increase with increasing sand content. It is also suggested that the traditional water/cement ratio law can be applied to cement mortar with different sand contents, provided that a slight modification is introduced. Sand content is an important parameter influencing the pore structure of cement mortar. Moreover, there is a good relationship between the pore structure and strength of cement mortar.

Key words: sand content; strength; cement mortar; pore structure

1 Introduction

The strength of mortar or concrete is generally considered to be its most important property, although in practice, other characteristics such as durability and permeability are of equal importance. Much previous work has concerned the development of strength in mortar or concrete. Investigations on various strength properties of mortar or concrete can be traced back to the work of Feret who first recognized the importance of water/cement ratio on the strength of cement-based materials. This was about two decades before the pronouncement of well-known Abrams' law on the effect of water/cement ratio on concrete strength[1,2]. However, it is not strictly true that the strength is controlled only by the water/cement ratio because the effects of aggregate quantity[3-5], maximum particle size[6-8], and surface condition[9,10] on the strength have also been reported. Yet, numerous empirical formulas-so called strength formulas-have been developed for the strength versus water/cement ratio relationship. Abrams' formula is an example that estimates concrete strength from water/cement ratio only. These formulas are usually simple but have restricted limits of validity. For improvement, new strength formulas are offered in this paper.

Although the water/cement ratio is one of the basic tools of concrete technology, it is definitely not sufficient for a comprehensive mastery of strength. Due to the large volume fraction they occupy in concrete, aggregates exert a major influence on the mechanical behavior of concrete. Stock *et al*[11] published a comprehensive review concerning the effect of aggregate volume on concrete compressive strength. De Larrad and Belloc[12] also performed some original experiments, in which they produced a series of concretes having different aggregate contents, keeping the same grading and matrix and avoiding segregation in fluid mixtures by continuously rotating the specimens before setting. Unfortunately, only compressive tests were performed. Giaccio *et al*[13] investigated the effects of various parameters of the concrete mix design including water/cement ratio, size of coarse aggregate, weight ratio of coarse to fine aggregate, and volume content of coarse aggregate. Strange and Bryant[14] conducted a series of tests (compression, tension, and three-point bending) to study the influence of the various aggregate shapes on the fractural behavior of concrete. From multiple

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regression analyses on compressive strength, Kaplan[15] found that the surface texture of the aggregate was on the average more important than its elastic modulus whereas Swamy and Rigby[16] found the elastic modulus of the coarse aggregate to be more significant, exceeded only by the expected large influence of the water/cement ratio. Yang and Huang[17] demonstrated that the compressive strength of concrete is mainly affected by the properties and volume fraction of aggregate. Giaccio and Zerbino[18] pointed out that the compressive strength of high strength concrete is limited by the strength of aggregate. Fu *et al*[19] indicated that the compressive, splitting tensile and flexural strength increased as the amount of binder used increased but decreased with the aggregate size. Perry and Gillott[20] and Chen *et al*[21] provided some experimental results for the strength of concrete with different aggregate and mortars. Chi *et al*[22] demonstrated that the influence of aggregate characteristics on concrete strength increases in lightweight concrete. However, no basic and universally accepted conclusions exist on the effect of coarse or fine aggregate on the strength of cement-based materials.

It is well known that the mechanical behavior of cement-based materials is predominately dependent on its composite structure. The presence of pores can adversely affect the material's mechanical behavior[23-25]. This paper also reports an experimental investigation in the pore structure of cement mortar brought about by changing the sand content and water/cement ratio. The changes in the pore structure were quantified by measuring the porosity, and pore size distribution obtained by using mercury intrusion porosimetry technique.

The contribution of this paper is to offer an idea for consideration of further research on the improvement of the relationship between mortar strength and its composition. In this study an effort has been made to understand the Abrams' law for cement mortars with different water/cement ratios and sand/cement ratios.

2 Experimental

2.1 Materials and mix proportions

ASTM Type I portland cement was utilized in preparing the mortar specimens. Natural river sand available in nearby stream was used for preparing the test specimens. The specific gravity and the bulk density of sand were 2.59 and 1570 kg/m^3, respectively. Potable water available in the laboratory was used. No water-reducing agents were used for improving the workability of mortar in this program. Fig. 1 shows the particle size distribution of the sand used in the experimental work. Mortar mixes were designed to study the strength with different water/cement (*w/c*) ratios and sand/cement (*s/c*) ratios. The *w/c* ratios of 0.4, 0.5, and 0.6 were adopted. At each *w/c* ratio, four proportions of *s/c* ratios, *i e*, 0.6, 1.0, 1.5, and 2.0, were adopted.

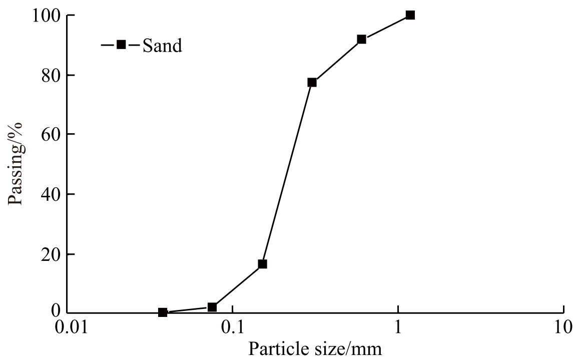

Fig.1 Particle size distribution of sand

2.2 Preparation and casting of test specimens

Standard metallic cube moulds (70.7 mm) were used for the preparation of the mortar specimens for compressive strength. Cylindrical moulds measuring 50 mm×100 mm were used for split tensile strength. 40 mm×40 mm×160 mm beams with 120 mm span and central loading was adopted to evaluate the flexural strength. After casting, all the test specimens were finished with a steel towel. Immediately after finishing, the specimens were covered with plastic sheets to minimize the moisture loss from them. All the specimens were stored at a temperature of about 23 ℃ in the cuing room. They were demolded after 24 h and put into a water-curing tank. For all three mechanical tests, six specimens were used for the determination of average strength. All specimens were tested for strength at the age of 90 days.

2.3 Determination of porosity

After the flexural tests, three pieces from each specimen were weighed under water and in the saturated surface-dry (SSD) condition, thus enabling the bulk volume to be calculated. It was assumed that any volume change during drying or re-saturation was negligible. This volume was used to calculate the bulk density of each sample after drying (in the worst case, the bulk volume change due to drying would be approximately 1.5%[26]). Each specimen was then dried in a carbon-dioxide free oven at 105 ℃ until constant weight was obtained. The difference in weight between in the water-saturated and oven-dry conditions was used to calculate the porosity expressed as a percentage of the bulk specimen volume. The data which are presented are the average of three replicates. The porosity was calculated using Eq.(1):

$$p=\frac{(W_{\mathrm{ssd}}-W_{\mathrm{d}})}{(W_{\mathrm{ssd}}-W_{\mathrm{w}})}\times 100\% \quad (1)$$

where, p is the porosity (100%), W_{ssd} is the specimen weight in the saturated surface-dry (SSD) condition (gm), W_{d} is the specimen dry weight after 24 h in oven (gm), and W_{w} is the weight of saturated specimen (gm).

This method has been used to measure the porosity of the cement-based materials successfully[27,28].

2.4 Mercury intrusion porosimetry (MIP)

Mercury intrusion porosimetry (MIP) is a widely used method for measuring the pore size distribution of cement-based materials. In MIP test, a sample is placed into a chamber, and surrounded by mercury, and then the pressure applied on the mercury is gradually increased. So as the pressure increases the mercury is forced into the pores of the sample. The fact that the test is based on is that for filling a non-wetting fluid into a pore of the diameter d, a pressure p that is inversely proportional to the diameter of this pore must be applied[29]. The data which are presented are the average of four replicates. This pressure is given by the Washburn equation as below[30]:

$$d=\frac{-4\gamma\cos\phi}{P} \quad (2)$$

where, d is the apparent pore diameter, γ is the surface tension of the mercury, and ϕ is the contact angle between the mercury and the pore wall. The values for γ and ϕ were assumed to be 0.480 N/m and 140°, respectively.

The MIP tests were done on a Quantachrome Autoscan 33 porosimeter with a maximum intrusion pressure of 414 MPa used. The weights of the samples were approximately 3 g. The cube specimens were removed from their curing environment at the age of the test. They were cored and the cores were then immediately placed in ethanol solution to stop hydration. The samples for the MIP tests were then obtained by carefully breaking the core with a chisel. Small pieces of mortar, 3-6 mm, were taken from the middle of the core by a hand clipper. Before testing, the samples for the MIP tests (which require total removal of moisture) were dried in an oven at 105 ℃ until a constant mass was reached. The oven drying time was determined by repeated heating and cooling of several preliminary samples, which was found to take about 3 hours. The mass variation was considered negligible when the change was in the region of 5%. Further drying of these small samples did not yield any further mass loss. To obtain the critical pore size of the specimens with different *w/c* and curing period, differential curves at the cumulative intruded pore volume versus pore diameter diagrams were also used.

In this investigation, the highest pressure used in these experiments was 212 MPa, according to a minimum pore diameter of 0.006 9 μm. The higher the pressure is, the smaller the pores which can be intruded. However, one has to keep in mind that the increase in volume obtained at high pressure can be partly caused by bigger capillary pores which can only be reached by small pores[31,32]. As the pressure increases, the mercury is forced into the pore system on the surface of the sample. If the pore system is connected, a pressure may be reached at which mercury can penetrate the smallest pore necks of the system and penetrate the bulk sample volume. If the pore system is not connected, mercury may penetrate the sample volume by breaking through pore walls. As reported by various researchers[32,33], however, the MIP technique has some limitations. First, the Washburn equation was derived based on the assumption that the intruded pores are cylindrical. A second problem is known as the ink bottle effect, in which a larger pore is preceded in the intrusion path of the mercury by a smaller neck. This may produce pore-size distribution curves with somewhat exaggerated high volumes of smaller pores and small volumes of larger pores. Another nuisance lies in the fact that the sample must be dried prior to the intrusion. It has been indicated that some microstructural damage may occur during the drying process[33]. Despite these limitations, the MIP technique is still considered an invaluable tool and the appropriate method for comparing the pore structure and pore network characteristics of different types of cement-based materials[34].

3 Results and discussion

3.1 Strength

The compressive, flexural and splitting-tensile strengths are shown in Fig.2. From Fig.2, it can be found that the strength of cement mortar increases with an increase in sand/cement ratio. The compressive strengths of cement mortar with a fixed sand/cement

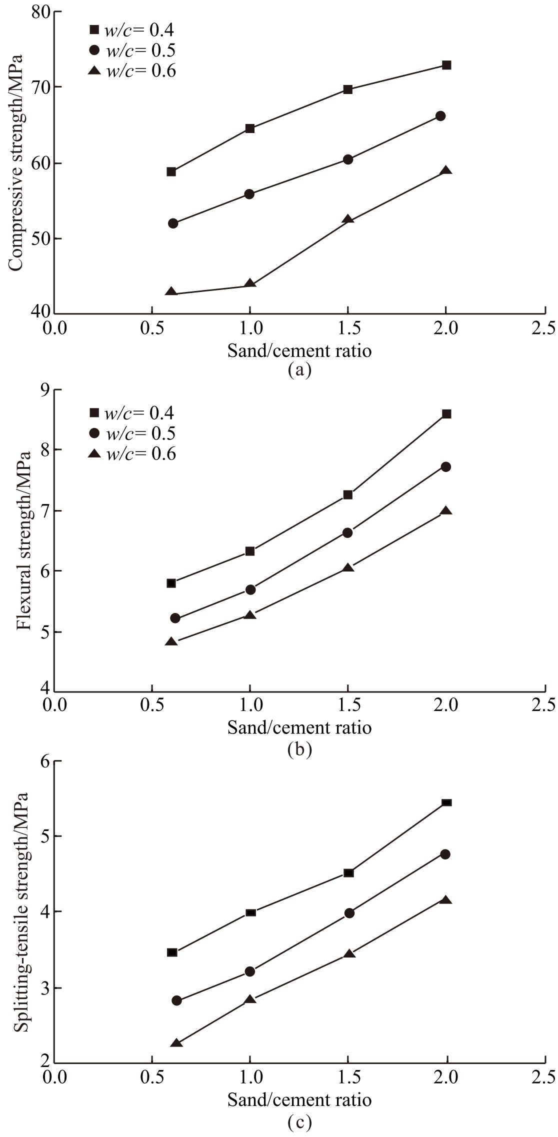

Fig.2 Effect of sand-cement ratio on strength of mortar

ratio have significant difference among water/cement ratios. All strengths decrease with an increase in water/cement ratio. From the test results, it is clear that the water/cement ratio is still a key factor to determine the strength of cement mortar. The flexural and splitting-tensile strengths also show the similar trend. The enhancement of strength of mortar due to added sand particles can be explained by several mechanisms. One of them is the microcrack shield, which causes a reduction of stress in the fracture process zone (FPZ)[35-37]. Another one is the crack bridging, which provides closing pressure in the FPZ. Also, the interlocking particles between the crack surfaces consume energy and thus enhance the fracture resistance[18,38]. The most generally accepted mechanism is that when a crack meets an array of impenetrable obstacles it becomes pinned. In order to pass the cracks have to bow out and thus make the crack surface rougher. This would lead to an increase in strength. This is true, however, only for static loading. Under dynamic loading with different loading rates, the roughness of the fracture surface of materials varies[39].

Analysis on strength results of mortar is carried out to examine the relationship between compressive and tensile strengths. From a large number of tests, a simple 1.5 power law model has become one of the most widely used analytical models for describing the relationship between the indirect tensile strength (splitting-tensile and flexural strengths) and compressive strength of cement-based materials. In this study, the indirect tensile strength of cement mortar is assumed to be proportional to their compressive strength. Eqs.(3) and (4) have been derived for describing a relationship between the indirect tensile and compressive strengths of cement mortar in this study:

$$f_{fl}=0.013\,9\cdot(f_c)^{3/2} \tag{3}$$

$$f_{sp}=0.008\,3\cdot(f_c)^{3/2} \tag{4}$$

These equations are plotted in Fig.3 with experimental data. It can be seen that the regression lines from Eqs.(3) and (4) show a relatively good

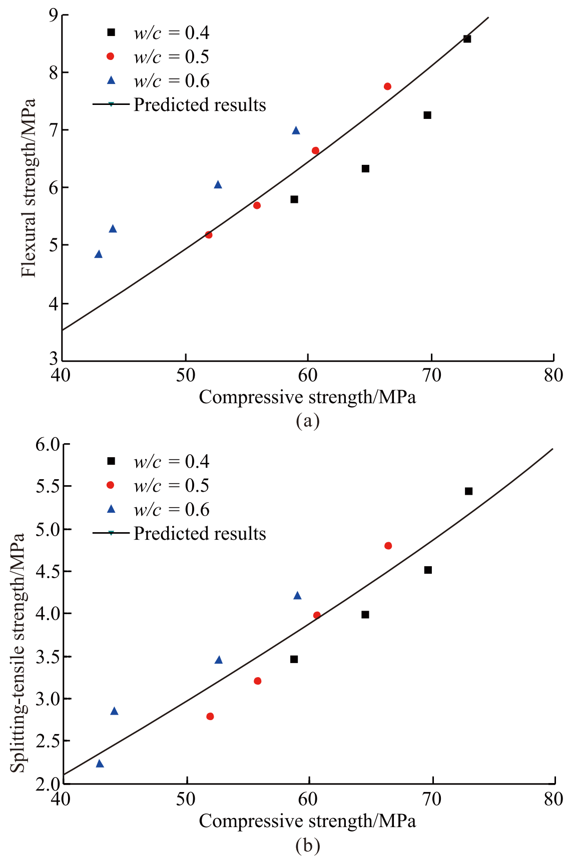

Fig.3 Relationship between tensile and compressive strengths of mortar

relationship between the indirect tensile strength and compressive strength of cement mortar. The coefficient of determination (COD=R^2), which indicates how much of the total variation in the dependent variable can be accounted for by the regression equation, was obtained as 0.821 and 0.888 for Eqs. (3) and (4) in this study, respectively. Most statisticians consider a COD of 0.7 or higher for a reasonable model[40]. Therefore, the derived 1.5 power equations may be successfully used to represent the relationship between the indirect tensile strength and compressive strength of cement mortar.

3.2 Porosity and pore size distribution

Aggregates of the same type affect the microstructure mainly by their volume in the mortar mass and their gradation. In the series of mortars composition, the gradation curve of the aggregates used was selected to be even. The influence of the cement/sand ratio on porosity is given in Fig.4. The high total porosity, which occurs for higher water-cement ratio and lower sand-cement ratio mortars, implies that such mortars contain both higher quantity of pore spaces and coarser pores. It seems that in mortars of low volume of sand (*s/c* 0.6:1), the porosity ranges from 27%-39% while in those with high volume (*s/c* 2:1) the porosity is 17%-27%.

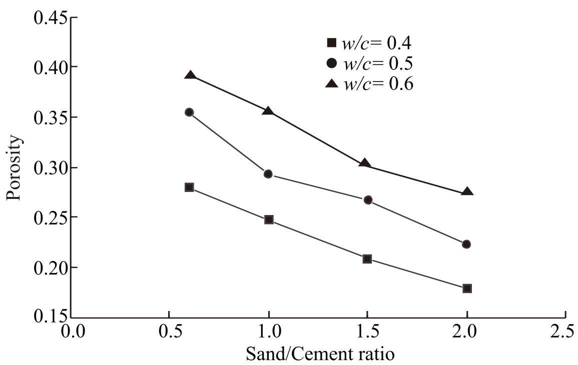

Fig.4 Effect of sand-cement ratio on porosity of mortar

Results for pore size distribution of mortars with different sand/cement ratios and water/cement ratios are shown in Fig.5. The pore size distribution curve (Fig.5) shifts to the left with increasing sand content, *i e*, the pores become finer with sand addition. The higher water/cement ratio seems also to have an effect on the pore size distribution. Larger pores are favored in high water/cement ratio mortars (Fig.5). The marked difference in the pore size distribution of mortars as a function of sand/cement ratio appears to be an interfacial effect. As the sand/cement ratio increases, the amount of interface per volume of specimen should increase and larger pores may be formed around the sand grain during mixing. However, other factors may contribute to this phenomenon. It has been shown that during hydration a preferential deposition of $Ca(OH)_2$ occurs in the interfacial zone (less than 50 microns) around aggregates in concrete and around sand in

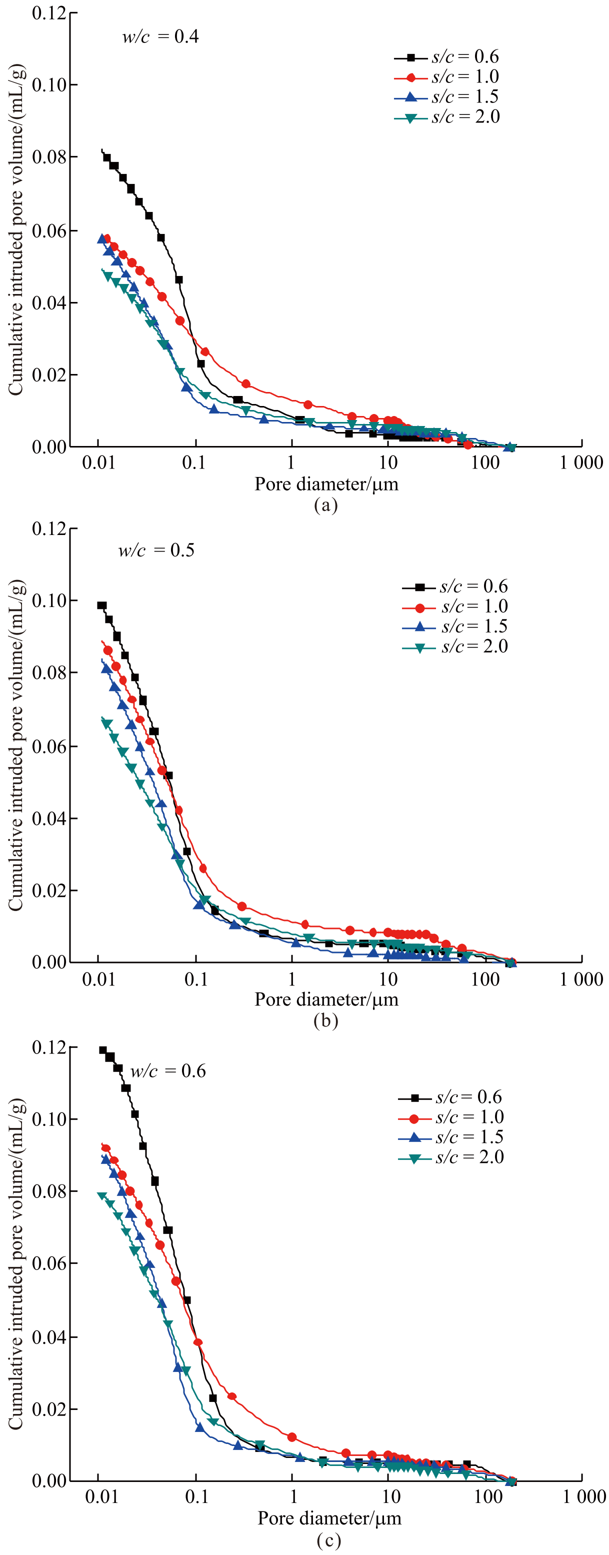

Fig.5 Cumulative intruded pore volume *vs* pore diameter for mortar

mortars[41,42]. The layer of $Ca(OH)_2$ may be covered with a layer of elongated C-S-H gel particles. These layers have been referred to as a duplex film and the zone nearest to the film is only sparsely occupied at early stages of hydration[43]. Larger $Ca(OH)_2$ crystals may develop in this zone after a few days of hydration[44]. This modified form of deposition of products is likely to cause changes in the pore size distribution.

4 Modified water/cement ratio law for cement mortar

Abrams' water/cement ratio, pronounced during 1918, has been described as the most useful and significant advancement in the history of cementitious materials technology, particularly in the concrete technology. The mathematical relationship between concrete strength and water/cement ratio, according to Abrams', is shown in the following equation:

$$f = \frac{A}{B^{w/c}} \tag{5}$$

where, f is the strength of cementitious materials, w/c is the water-cement ratio, and A, B is experimental parameters.

Eq. (5) can be rewritten in the following form:

$$\log f = \log A - {}^{w}\!/_{c} \log B = b_0 + b_1 \left({}^{w}\!/_{c}\right) \tag{6}$$

where, b_0 and b_1 are constants of regression analysis.

The change in strength due to added particles has been correlated to a quantity called inter-particle separation D_s for composites, which is a function of both the particle diameter d_p and the volume fraction of particles V_p[37]:

$$D_s = \frac{2d_p\left(1-V_p\right)}{3V_p} \tag{7}$$

Spanoudakis and Young[45] and Langley *et al*[46] suggested that the strength of composites is actually related to the ratio d_p/D_s, which is a simple function of the volume fraction given by:

$$\frac{d_p}{D_s} = \frac{3V_p}{2\left(1-V_p\right)} \tag{8}$$

Quantitatively, the above theory supports the following empirical equation:

$$f \propto \frac{d_p}{D_s} \tag{9}$$

The sand volume concentration (V_p) is determined using the standard equation:

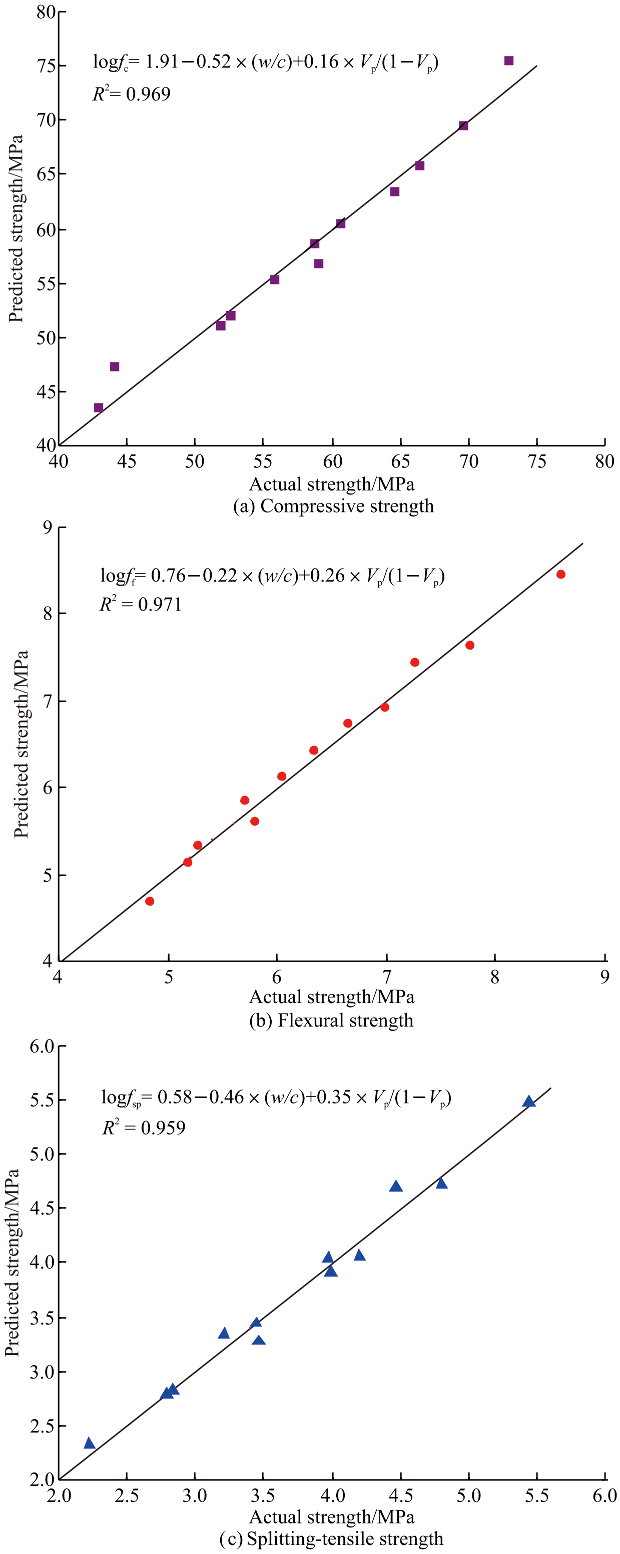

Fig.6 Comparison of experimentally obtained strength to corresponding predicted values

$$V_p = \left\{ \frac{x}{\rho_s} \Big/ \left[\frac{x}{\rho_s} + \frac{1}{\rho_{hcp}} \right] \right\} \times 100\% \quad (10)$$

where, x is the sand/cement ratio by weight; ρ_s is the dry density of sand (g/cm^3), and ρ_{hcp} is the dry density of hardened cement paste (g/cm^3).

Based on the aforementioned results, a new strength model was formulated as a function of *w/c* and volume content of sand following the format of Eq.(11):

$$\log f = b_0 + b_1 \left({}^{w}\!/_{c} \right) + b_2 \left[\frac{3V_p}{2\left(1 - V_p\right)} \right] \quad (11)$$

For all three series of strengths (compressive strength, flexural strength and splitting-tensile strength) studied it has been tested statistically how accurate the experimental test results conform to the predictions by Eq.(11). A multi-linear regression analysis, based on the least-squares method, has been used to calculate the best model as well as the best estimates for the constants b_0, b_1, and b_2 in each case. Results of regression analysis are presented in Fig.6 concerning the best estimates of b_0, b_1, and b_2 in the modified Abrams' law Eq.(10). Results coefficients of correlation R^2 is also included in Fig.6. Considering that all the R^2 values in our experiments are 0.96 or above, it may be concluded that there is a very good correlation with Eq.(10) and therefore between the predictions based on the proposed theory of strength of mortar on the one hand, and experimental data on the other. Thus, it is suggested that the modified water/cement ratio law may be accepted as reasonable working hypotheses.

5 Influence of pore structure on strength of cement mortar

5.1 Effect of porosity

The general validity of the close relation between strength and porosity in mortars was intuitively or empirically known even from historic times. This relationship was scientifically proved by numerous researchers who have numbered the factors influencing it[27]. Robler and Odler[47] used four expressions that had been derived by other workers to express the relationship between the porosity and strength of porous materials; Furthermore, they concluded that the Bashin[48] model fit their results best. In this study, the Bashin equation was carried out on the relationship between the porosity and strength of cement mortar:

$$f = f_0 (1 - p)^n \quad (12)$$

where, f is the compressive, flexural and splitting-tensile strengths of cement mortar, f_0 is an intrinsic strength, namely, the strength at zero porosity, p is the porosity and n is the power coefficient.

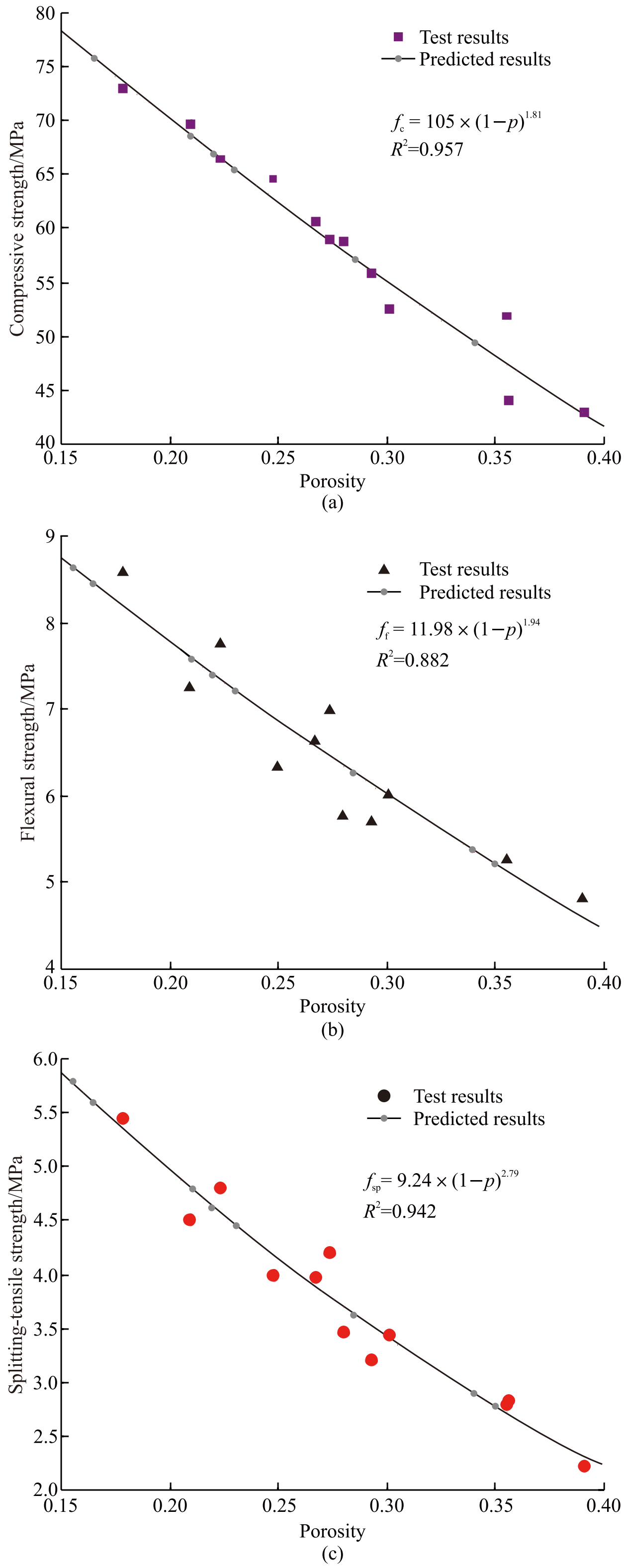

Fig.7 Effect of porosity on strength of mortar

Balshin equations and regression coefficient of the equations were calculated and are listed in Fig.7. It can be found that the model could describe the strength and porosity of cement mortar with acceptable accuracy.

5.2 Effect of pore size

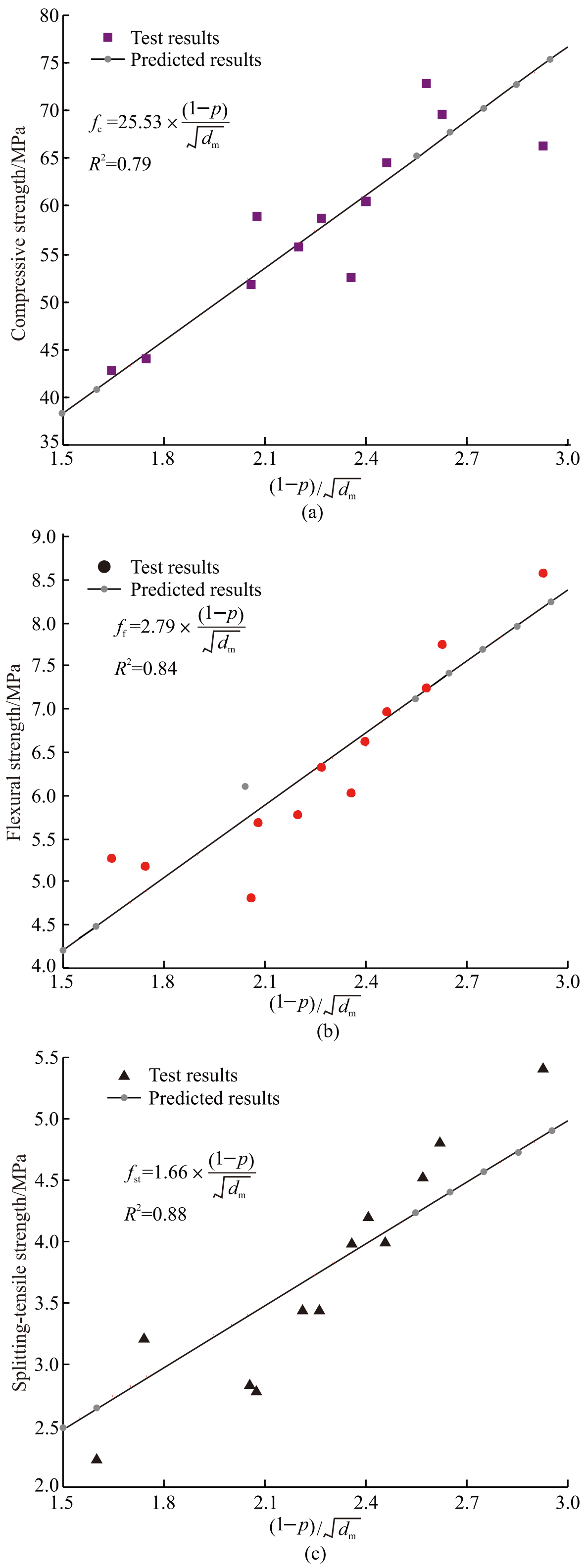

Fig.8 Effect of pore size on strength of mortar

From the instruction curves, the values of mean distribution diameter d_m (μm) were estimated according to the equation given below[50]:

$$\ln d_m=\frac{\sum_{i=1}^{i=n} V_i \ln d_i}{\sum_{i=1}^{i=n} V_i} \tag{13}$$

where, for the continuous intrusion curve divided into n discrete radii ranges, V_i is the incremental intrusion of mercury corresponding to ith radius range represented by the mean diameter d_i.

The best correlation between the strength and pore structure of cement mortar is therefore achieved by combing the porosity and mean distribution radius and incorporating the strength, which leads to the relation as follows[25]:

$$f=K\frac{f_0(1-p)}{\sqrt{d_m}} \tag{14}$$

where, K is empirical constants. Kumar and Bhattacharjee[49] advocated the estimation of f_0 from strength-porosity relationship. Fig.8 shows the results obtained and as can be observed the regression line gives a good fit.

6 Conclusions

The water/cement ratio and sand content are two important factors determining the strength and pore structure of cement mortar. The strength of cement mortar increases with an increase in sand/cement ratio. The strength of cement mortar with a fixed sand/cement ratio has significant difference among water/cement ratios. Increasing sand content reduces the total porosity of cement mortar. The pore size distribution curve shifts to the left with increasing sand content, *i e*, the pores become finer with sand addition.

It is also suggested that the traditional water/cement ratio law can be applied to cement mortar with different sand contents, provided that a slight modification is introduced. This will be of assistance in the design of cement-based materials for strength.

The present investigation also shows that pore structure is a primary factor influencing the strength of cement mortar. The Balshin equation fits the results of strength and porosity of all mixes and there is a relatively strong quantitative relationship between the strength and pore size distribution of cement mortar.

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