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THE EFFECT OF BRITTLENESS ON STRENGTH OF CONCRETE

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Abstract

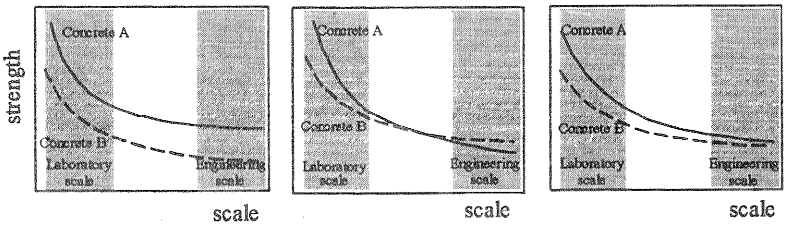
High-strength cement paste with higher brittleness and polymer cement concrete with lower brittleness are selected to compare their size effect on strength. Tentative works performed in experiment and numerical analysis are presented in this paper. It is shown that brittleness affects the size effect on strength of concrete. According to experimental and numerical results, there is a possibility that at laboratory scale a high-strength concrete with high brittleness displays higher strength than a normal concrete with low brittleness, nevertheless, the high-strength concrete displays lower strength than the normal concrete at larger scale.
Key Words: brittleness, size effect, strength, numerical method

1 Introduction

Brittleness of concrete is commonly regarded as a property that only affects failure mode of concrete, so it is a quite general view to improve strength of concrete prior to brittleness of concrete. Recently, some experimental results and theoretical analyses have indicated that the size effect on strength varies with brittleness of concrete. Therefore, brittleness of concrete may affects not only the failure mode, but also the bearing capacity of a concrete structure.

To test the strength of concrete, we must use a certain size of specimen. All experimental results show that there exists size effect on strength of concrete. Therefore, the strength that we usually deal with is actually related to the size of specimen. In general, small specimens are used to test strength of concrete at laboratory scale, but concrete structures at engineering scale are usually very huge. Therefore, the size effect is important problem for concrete.

There are three typical cases in Fig. 1 for the size effect of certain concrete in comparison with each other. Obviously, people worry about case (b) in Fig.1 and even case (c) in Fig. 1. Although at laboratory scale the strength of concrete A is much higher than that of concrete B, at engineering scale the strength of concrete B is higher than that of concrete A due to different size effect on strength. The size effect law may be influenced by brittleness of concrete. The greater the brittleness is, the stronger the size effects on strength may be. For the case (b) in Fig.1, the brittleness of concrete A is higher than that of concrete B. It is necessary to compare size effects of different concrete within greater size range, especially to establish the relation between the size effect on strength and brittleness.



(a) (b) (c)

Fig. 1 A schematic diagram of comparison of size effect on strength between two different concrete

Based on the experimental results and the numerical analysis, this paper exhibits the possibility of brittleness effect on strength of concrete and the significance of modifying the brittleness of concrete.

2 Review of size effect on strength of concrete

In 1925, Gonnerman first noticed the size effect on strength of concrete and since than many researchers have studied the phenomenon experimentally and theoretically.

Early researches were focused on establishing some relations between water-cement ratio, or aggregate-cement ratio, or aging, and the size effect on compressive strength or flexural strength. And, in most cases, the size of specimen was varied only within the range required by standards or codes, and some empirical relations between non-standard size and the standard size had been established. The results have shown that the size effect is affected by many factors. In other word, any concrete has its own characteristic size effect on strength. Sabnis et al.(1979a) had summarized the achievement.

Much progress in experiment and theory in this field have been made for recent two decades. Many researchers have begun to consider how the size effect had been treated in codes and design standards (Okamura et al 1994, Sabnis 1994).

Traditionally, the phenomenon of size effect on strength had been explained in Weibull theory. But in most cases, especially when the size span is large, it is difficult to predict correctly the size effect law. More and more researchers realize that the size effect has to be explained in views of fracture mechanics. Bazant et al. (1991a) have examined the shortcomings of the classical Weibull theory and they (1991b) have proposed the nonlocal theory based on fracture mechanics and the classical Weibull theory.

There are two ways to obtain the size effect on strength.

The first way is through test. However, it is very difficult only by the way. First, the size of specimen used to test a size effect must be within a very limited range because of experimental conditions. Second, because there is great deviation in experimental results of strength, the number of specimen at every scale must be large enough to obtain a correct size effect law. However, this is more difficult for that at larger scale.

The next way is by means of numerical methods. Many studies have shown that numerical method is very useful in analyzing the size effect. However, the validity of numerical results depends on adequate model and parameters. It is necessary to study the way further.

3 Experimental results

For an important structural material, compressive strength of concrete should be paid more attention to. Therefore, this paper emphasizes on the size effect in uniaxial compression. The geometry of specimen is described in Fig. 2. In order to vary the size in greater range as possible as we can and to perform numerical analysis easily, specimens are notched. According to Jayatilaka' results (1979), the most unfavorable case is when the angle between direction of notch and that of load is 30-50° in uniaxial compression, so the angle is 45° in this study. Four different sizes are considered. They are 70×70×70, 100×100×100, 200×200×100, 400×400×100 mm and the number of specimens at each size is not less than 6.

In this paper, the brittleness of concrete is described as the characteristic length l_{ch} as defined in equation (1).

$$l_{ch} = \frac{EG_F}{f_t^2} \tag{1}$$

where

E = modulus of elasticity;
G_F = fracture energy;
f_t = tensile strength.

Because there are size effects on the fracture energy and the tensile strength, it is very difficult to measure the brittleness index experimentally. This paper intends to study the effect of brittleness on strength of concrete qualitatively, so we may select some kinds of concrete with as higher or lower brittleness as possible. Therefore high-strength cement paste and polymer cement concrete are both used in our study.

The transversal geometry of the specimen used to test tensile strength is 50×100 mm. Elastic modulus E and Possion's ratio are performed according to Chinese Standard GB81-85. Fracture energy is determined by three-point bend. The size of specimen is 100×100×400 mm and the ratio of notch to height is 0.5. The flexural strength is also determined by three-point bend and the size of specimen is similar to that used in testing the fracture energy.

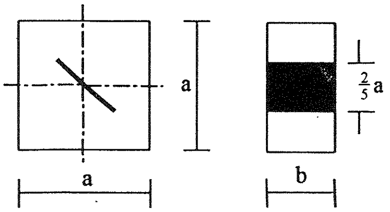


Fig. 2 The geometry of specimen

Mark 525 ordinary Portland cement and super fine sand are used. The polymer is acrylate emulsion. Mix proportion of polymer cement concrete is 1.0 cement: 0.1 polymer: 1.2sand: 3.6 gravel: 0.45 water (weight). The material properties of the polymer cement concrete and the cement paste are listed in Table 1.

Table 1 Properties of polymer cement concrete (PCC) and cement paste

Mix	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Fracture energy (N/m)	Possion's ratio	Flexural strength (MPa)	Characteristic length (m)
PCC	41.4	1.58	34.3	241.6	0.314	6.32	3.32
Cement paste	79.3	1.16	21.4	48.2	0.211	6.14	0.767

The experimental results of brittleness effect on strength are shown in Fig. 3. The strength at each scale is obtained using the maximum load divided by the effective area, which is 0.6ab(see in Fig. 2). Instron machine is used and load rate is about 1.0×10^4 s/mm.

The failure mode of all cement paste specimens is abrupt and it is difficult to record the whole descending part of the load-displacement curve, including the test of fracture energy, whereas fracture of the polymer cement concrete is quite stable. Therefore, the experimental result of the fracture energy of the cement paste in Table 1 may be on the higher side.

It is shown that the strength of cement paste is two times greater than that of polymer cement concrete at 70 mm scale, whereas the strength of cement paste is close to that of polymer cement concrete at 400 mm scale. According to the size effect on strength in Fig. 3, it is possible for the strength of polymer cement concrete to exceed that of cement paste with the specimen size increasing. When specimens fracture, there appear two pairs of antisymmetric cracks. The first pair of cracks form in the direction vertical to the notch and the second pair of cracks form along with the notch. When cement paste is destroyed completely, there are just the two pairs of cracks in specimen. However, when polymer cement concrete is destroyed completely, the specimen is usually crushed.

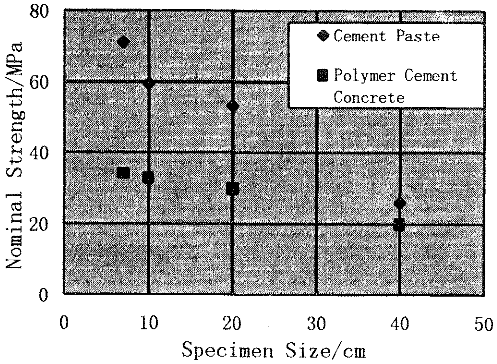


Fig. 3. Experimental results of brittleness effect on strength

4 Numerical study

To experimentally investigate the size effect on strength is inevitably limited by the specimen size. Numerical method is one of the most useful means. Many researchers have made great progress in studying size effect by using numerical method.

The accuracy of numerical calculation depends not only on the fracture model but also on the fracture parameters. And, the fracture parameters are keys to guarantee the accuracy of numerical results. Most fracture models used to analyze mechanical behavior of concrete are based on the concept of strain softening. Thus, fracture parameters of most fracture models can come from the strain softening relation. The strain softening relation may be assumed as $\sigma(\delta)$, and $\sigma(\delta)$ is related to f_t and G_F(see in Fig. 5). Because there are size effect on f_t and G_F in experiment, it is difficult to determine the strain softening relation through experiment. However, the relation can be determined by using numerical method

4.1 Functional form of the strain softening relation

Compared with the linear, bilinear and other forms of softening relations, it is best to describe $\sigma(\delta)$ as following equation proposed by Reinhardt and coworkers (1986a),

$$\sigma(\delta)/f_t = (1+(c_1\frac{\delta}{\delta_0})^n)\exp(-c_2\frac{\delta}{\delta_0}) - (\frac{\delta}{\delta_0})(1+c_1^n)\exp(-c_2) \qquad (2)$$

where

δ_0 is ultimate displacement,

c_1, c_2 and n are coefficients.

Reinhardt and coworkers have given values of c_1, c_2, n, δ_0 for normal and lightweight concrete respectively. In this paper, c_1, c_2, n, δ_0 are assumed to be determined. When f_t, G_F are known, following equation can be obtained from Fig.4.

$$G_F = \int_0^{\delta_0} \sigma(\delta)\mathrm{d}\delta \qquad (3)$$

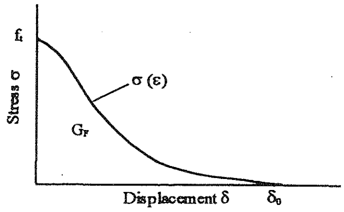


Fig. 4. A typical strain softening curve of concrete

Thus, there are three unknown quantities left in equation (2). Because c_1, c_2, n in equation (2) have not physical meanings, they are assumed to be variable. With c_1, c_2, n varying, there are many forms of curves described by equation (2), including all possible shapes of the strain softening curve of concrete. Some typical curves are shown in Fig.5.

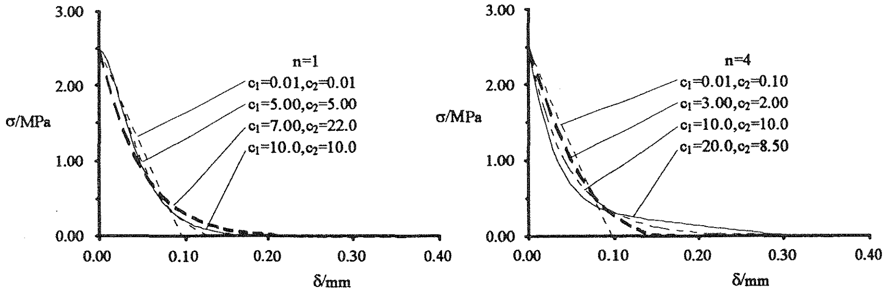


Fig. 5. Some typical curves described by equation (2) with c_1, c_2, n varying (f_t=2.5 MPa, G_F=100 N/m)

4.2 How to determine f_t, G_F, c_1, c_2 and n

The procedure is based on some experimental results of mechanical behavior of concrete. First, f_t, G_F, c_1, c_2 and n are given initial values respectively and vary with an increment. The strain softening relation expressed in equation (2), together with suitable fracture model, is used to analyze a certain mechanical behavior of concrete. Next, the numerical results are compared with corresponding experimental results. Finally, when the error between numerical and experimental results is minimal, corresponding f_t, G_F, c_1, c_2 and n are determined as the fracture parameters. It is worth pointing out that it is imperative to use a series of experimental results to compare with numerical results. Only when all the experimental results are agree with the numerical results can the strain softening relation be considered to set. Generally, a mechanical behavior is expressed using a whole load-displacement curve.

4.3 Numerical calculation

The strain softening relations used in numerical analysis are listed in Tab.2. f_t in Tab. 2 is much higher than that in Tab. 1, which may be considered as a result of the size effect on strength. It is difficult to keep stable in the whole range when the test of fracture energy of cement paste is performed, so fracture energy of cement paste in Table 2 may be less than that in Tab. 1. According to Qian and coworkers' view (1997a), reference value of fracture energy is that tested using small specimen and fracture energy used in the numerical analysis is considered as a constant.

Table 2 The strain softening relations used in numerical calculation

Mix	f_t (MPa)	G_F(N/m)	C_1	C_2	n
Polymer cement concrete	4.6	241	0.50	9.50	2
Cement paste	8.2	43	0.01	0.05	1

Finite Element Method (FEM) and Damaged Band Crack Model (Qian, J. et al. 1995) (DBCM) are used in numerical analysis. For DBCM, the fracture zone is assumed to be a damaged band with a certain width. Forming and propagating of a crack are considered as beginning and accumulating of damage respectively. By means of the characteristic of FEM, when the model is used in numerical analysis, the width of the damaged band is equal to that of an element. Having been adapted, the strain softening relation is given in a form of stress vs. strain.

An example of numerical analysis of brittleness effect on strength is shown in Fig.6. It is shown that numerical results are agreed with experimental results at four scales. Therefore, the numerical results extrapolated to larger scale in Fig.6 are reliable relatively.

In addition, it is shown from Fig. 6 that although the high-strength paste displays higher strength than polymer concrete within 60cm, the high-strength paste displays lower strength than the polymer concrete over 70cm.

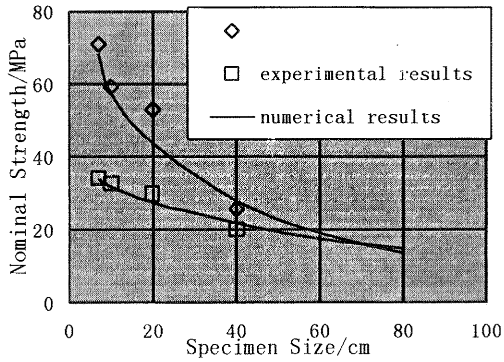


Fig.6. Numerical results of brittleness effect on strength

5 Discussion and Conclusion

Some experimental results have been investigated in the brittleness effect on strength. However, we have noticed that most of the studies focus on tension and bend. Owing to the characteristic mechanical properties of concrete, the compressive strength is more important. Therefore, study on brittleness effect on compressive strength at different scales is more significant. If cases illustrated in Fig. 1 (b), (c) would be confirmed, it must be paid more attention to improving brittleness of concrete.

Experimental and numerical results in this paper bring it to light that there exists the possibility shown in Fig. 1. In order to meet the needs of experiment and numerical analysis, the specimens are notched. Obviously, it is very important to study the brittleness effect on strength using unnotched specimen. Besides, the study on size effect is certainly limited by experimental conditions. Therefore, numerical method will play more important role and some available fracture models must be developed.

6 Acknowledgements

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