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Materials

Effects of binder strength and aggregate size on the compressive strength and void ratio of porous concrete

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Abstract: To test the influence of binder strength, porous concretes with 4 binder strengths between 30.0-135.0 MPa and 5 void ratios between 15%-35% were tested. The results indicated that for the same aggregate, the rates of strength reduction due to the increases in void ratio were the same for binders with different strengths. To study the influence of aggregate size, 3 single size aggregates with nominal sizes of 5.0, 13.0 and 20.0 mm (Nos. 7, 6 and 5 according to JIS A 5001) were used to make porous concrete. The strengths of porous concrete are found to be dependent on aggregate size. The rate of strength reduction of porous concrete with small aggregate size is found to be higher than that with larger aggregate size. At the same void ratio, the strength of porous concrete with large aggregate is larger than that with small aggregate. The general equations for porous concrete are related to compressive strength and void ratio for different binder strengths and aggregate sizes.

Key words: cement paste; porous concrete; compressive strength; void ratio

1. Introduction

Porous or pervious concrete is a special concrete with continuous voids intentionally incorporated into the concrete mass. It can be used in numerous applications such as permeable concrete for pavement, concrete bed for vegetation or living organism, noise absorbing and thermal insulated concrete. It is important that suitable void ratio is obtained in order to acquire adequate strength and other desired functions such as permeating water, growing vegetation and absorbing sound.

Numerous factors influence the compressive strength and void ratio of porous concrete [1-3]. These factors include binder strength, flow of binder, aggregate size and shape, and specimen size. However, the important factors affecting the relationship of strength and void ratio of porous concrete are binder and aggregate characteristics. Two of the most common factors used in porous concrete are binder strength and aggregate size.

It has been shown that the relationship between compressive strength and void ratio of a porous brittle material suggested by Ryshkewitch [4] and Duckworth [5] shown in the following Eq. (1) can be used to describe porous concrete with single binder [6]. At one end, the strength of the material is zero when the whole material consists of air void. At the other end, the whole material consists of very low or zero air void *i.e.* a well compacted cement paste. For porous concrete, paste covers aggregate and acts as one unit with air voids formed within the paste matrix [6].

$$\sigma=\sigma_0\exp(-BV) \tag{1}$$

where σ is the compressive strength, MPa; σ_0 the compressive strength at zero void, MPa; B the strength reduction parameter; and V the void ratio, %.

In this system, cement paste is treated as the homogenous and continuous matrix. Voids in the gel and the capillary systems are, therefore, part of the continuous cement matrix. Therefore, the void of the porous concrete system consists of the intentionally designed air void.

It would be beneficial to extend this equation to

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cover the other important factors *viz.*, binder strength and aggregate size in order that it can be used as a more general formula to estimate the compressive strength of porous concrete.

2. Materials and testing

For this study, two sets of tests were planned. The first set dealt with the effect of binder strength on the relation of strength and void ratio of porous concrete. The second set dealt with the effect of aggregate size.

2.1. Series I: Effect of binder strength

In this experiment, pastes with 4-designed compressive strength levels of 30, 70, 110 and 135 MPa and porous concrete with void ratios of 15%, 20%, 25%, 30% and 35% were used. The concrete with a certain air void is designed by assigning the amount of air void volume in the unit so that the remaining volume is occupied by cement paste and aggregate. Once the volume of the aggregate pile is known, the volume of the paste can be calculated.

$$V_p=V_a-V_v \quad (2)$$

where V_p is the volume of paste, V_a the volume of aggregate pile, and V_v the volume of air void.

(1) Materials and mix proportion

Normal Portland cement Type 1 (PC) with a Blaine fineness of 3150 cm^2/g, 5.0-13.0 mm crushed limestone (No. 6 according to JIS A 5001 [7]) with a specific gravity of 2.65 and an aggregate pile void content of 42.6%, and polycarbon Type F superplasticizer (SP) were used in this experiment. The mix proportions are given in Table 1.

Table 1. Mix proportions of series I

Ratio of water to cement	Flow / mm	Void ratio / %	Unit weight / (kg·m^{-3})				
			Water	Cement	Fly ash	Aggregate	SP
0.225	190±10	0	412	1832	0	0	18.0
		15	114	506	0	1521	4.3
		20	93	414	0	1521	3.5
		25	73	322	0	1521	2.7
		30	52	231	0	1521	2.0
		35	31	139	0	1521	1.2
0.300	190±10	0	412	916	916	0	0
		12	114	253	253	1521	0
		17	93	207	207	1521	0
		23	73	161	161	1521	0
		28	52	116	116	1521	0
		34	31	70	70	1521	0

(2) Details of pastes

For this series, pastes with a flow value of 190±10 mm were used. For the designed strengths of 70, 110 and 135 MPa, pastes with a water/cement ratio (W/C) of 0.225 were used. The required strengths were obtained for the pastes at the ages of 2, 7 and 28 d respectively as shown in Fig. 1. For the 30 MPa paste, the W/C of 0.3 and the 50% fly ash replacement of PC were used. The specific gravity of fly ash (FA) was 2.20. The designed target strength of 30 MPa was obtained at the age of 6 d. The compressive strengths of pastes were measured with ϕ50 mm×100 mm cylinders.

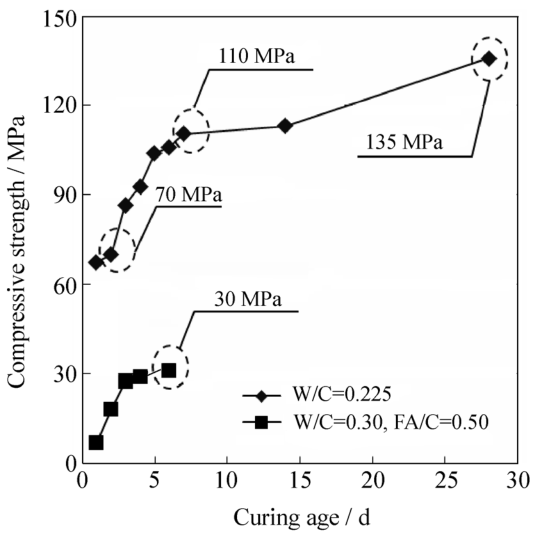

Fig. 1. Compressive strength development of pastes.

2.2. Series II: Effect of aggregate size

In this series, porous concrete with 3 single size aggregates and 4-designed void ratios of 15%, 20%, 25% and 30% were used. For this series, the obtained strength of paste of 129.0 MPa was slightly lower than the designed value of 135.0 MPa.

(1) Materials and mix proportion

Normal Portland cement Type 1 with a Blaine fineness of 3150 cm^2/g, and 3 aggregate sizes of 2.5-5.0, 2.5-5.0, 5.0-13.0 and 13.0-20.0 mm diameter crushed limestone (Nos. 7, 6 and 5 according to JIS A 5001 [7]) with a specific gravity of 2.65 and aggregate pile void contents of 42.4%, 42.6% and 43.9% respectively, and polycarbon Type F superplasticizer (SP) were used in this experiment. The mix proportions are given in Table 2. The fineness moduli of the 2.5-5.0, 5.0-13.0 and 13.0-20.0 mm diameter aggregates were 5.0, 6.4 and 7.0, respectively.

Table 2. Mix proportions of series II

Aggregate No.	Void ratio / %	Unit weight / (kg·m^{-3})					
		Water	Cement	Aggregate	SP		
					Flow / mm		
					150±10	190±10	230±10
5	15	113	500	1526	2.00	3.00	3.75
	20	92	409	1526	1.64	2.45	3.07
	25	72	318	1526	1.27	1.91	2.38
	30	51	226	1526	0.91	1.36	1.70
6	15	113	504	1521	2.01	3.02	3.78
	20	92	413	1521	1.65	2.47	3.09
	25	72	321	1521	1.28	1.93	2.41
	30	52	230	1521	0.92	1.38	1.72
7	15	119	527	1487	2.11	3.16	3.96
	20	98	436	1487	1.74	2.62	3.27
	25	78	345	1487	1.38	2.07	2.59
	30	57	254	1487	1.01	1.52	1.90

(2) Details of pastes

For this series, pastes with a W/C of 0.225 and flow values of 150±10, 190±10 and 230±10 mm were used. The SP was incorporated to obtain the designed flows of the pastes. The compressive strengths of the pastes were measured at the age of 28 d with ϕ50 mm×100 mm cylinders.

2.3. Mixing of paste

A 30-L dual action (tilting and rotating) concrete mixer was used for the mixing of paste and concrete as it was quite efficient in mixing cement and caused minimum damage to the aggregate. For mixing of paste, the mixing method was set at 50 r/min for the first 30 s after the addition of cement, water and admixture followed by the mixing speed of 200 r/min for 240 s (total mixing time of 270 s). The paste specimens were poured into ϕ50 mm×100 mm cylinders. They were demoulded at 1 d and kept in water until testing age.

2.4. Testing of cement paste

(1) Flow value

Right after the mixing of cement paste, flow value was determined using flow table with a flow cone of 70 mm in top diameter, 100 mm in bottom diameter, 60 mm in height with 15 impacts in 15 s in accordance with JIS R 5201 [8].

(2) Compressive strength

The compressive strength of paste was determined in accordance with ASTM C 39 [9]. The reported results were an average of 3 tests. The test was done within ±30 min of the designed age to get accurate and comparable results.

2.5. Mixing of concrete

For mixing of concrete, coarse aggregate was added to the cement paste (prepared from section 2.3) and the mixture was mixed at 200 r/min for 90 s. The mixture was then placed into a ϕ100 mm ×200 mm cylindrical mould in 3 layers with each layer receiving tamping of 15 times. At the final stage, the surface vibrator was applied for 10 s to top surface of the cylinder. Top surface vibration was used successfully for the preparation of porous concrete [6]. The specimens were demoulded at 1 d and kept in water until testing age.

2.6. Testing of concrete

(1) Void determination

The void of hardened concrete was measured using test method for porous concrete as suggested by the Committee for Eco-concrete Research [10-11]. The reported results were an average of 2 tests.

(2) Compressive strength

The compressive strength of concrete was determined in accordance with ASTM C 39. The reported results were an average of 3 tests. The tests were also done within ±30 min of the designed age to get accurate and comparable results.

3. Results and discussion

3.1. The influence of binder strength

The results on the compressive strengths of paste and concrete and the total void ratio are plotted in Fig. 2. The relationship between compressive strength and void ratio of porous concrete was influenced by binder strength. As the total void ratio became larger, the compressive strength of porous concrete was reduced. The strengths of pastes were used as the strengths at very low or zero void of porous concrete [6]. The relationships between binder strengths and void ratios for the 4 sets of results could be expressed as:

$$\sigma_1=135\exp(-0.0860V),\ R^2=0.962 \tag{3}$$

$$\sigma_2=110\exp(-0.0841V),\ R^2=0.971 \tag{4}$$

$$\sigma_3=70\exp(-0.0757V),\ R^2=0.963 \tag{5}$$

$$\sigma_4=30\exp(-0.0752V),\ R^2=0.954 \tag{6}$$

The correlation coefficient of the results was high with R^2 ranging between 0.954-0.971. The value of strength reduction parameter *B* was within a narrow range of 0.0752-0.0860 despite a very large range of binder strength of 30 to 135 MPa. This suggested that the parameter *B* could be considered independent of the binder strength. The average strength reduction parameter *B* could be used to estimate the relationship between strength and void ratio of porous concrete with a single aggregate size. To generalize the equation, the average *B* value of 0.080 was, therefore, used for all the 4 equations.

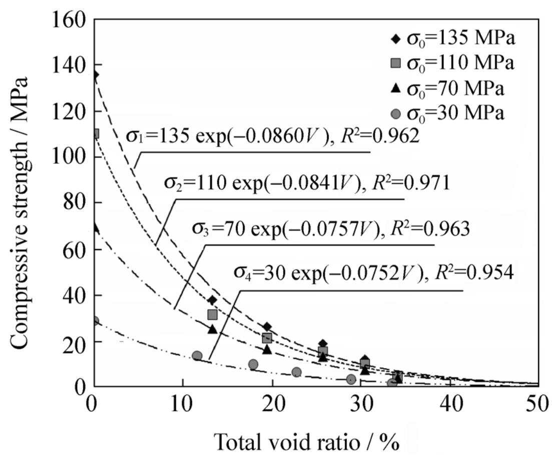

Fig. 2. Compressive strengths of paste and porous concrete *vs.* void ratios (series I).

From Eq. (1), the relationship between compressive strength and total void ratio of porous concrete with No. 6 aggregate can be expressed by a general formula.

$$\sigma=\sigma_0\exp(-0.080V) \tag{7}$$

The graphs of the calculated results were plotted with the experimental results shown in Fig. 3 indicated the applicability of Eq. (7).

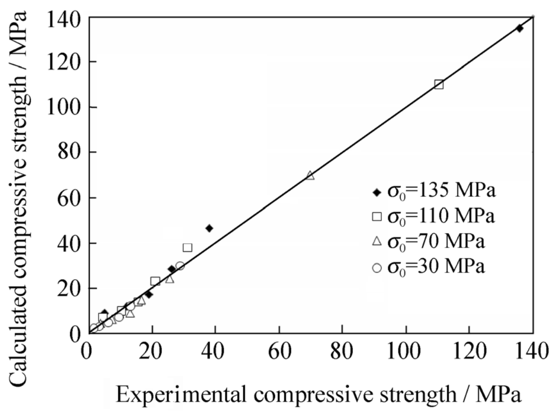

Fig. 3. Experimental compressive strength and calculated compressive strength from Eq. (7) (series I).

3.2. Influence of aggregate size

The results of compressive strength and total void ratio are shown in Fig. 4. Again, the strength of the paste with a flow value of 190±10 mm was used as the strength at zero void of porous concrete. A similar trend of results of the relation between compressive strength and void ratio is obtained. The graphs of the 3 aggregates are clearly different. The graph relating compressive strength and void ratio shifts downward with the reduction in aggregate size. The graph of the largest aggregate (No. 5) lies on the top. The graph of the medium size aggregate (No. 6) is slightly lower and that of the smallest aggregate (No. 7) is the lowest. For example at a void ratio of 20%, the strength of porous concrete with large aggregate (No. 5) is approximately 29.0 MPa whereas that of the smaller No. 6 and No. 7 aggregates are only about 25.0 and 17.0 MPa respectively. The larger total surface area of the small aggregate required a larger amount of paste to cover the aggregate in comparison to the larger aggregate. The paste covering the large aggregate was, therefore, thicker than that covering the smaller aggregate. Under the sufficient compaction and surface vibration, the paste at the contact of two large aggregate particles forms a thicker and stronger paste as shown in Fig. 5. The strength of porous concrete with the larger aggregate is, therefore, higher than that with the smaller aggregate.

The strength and void equations for porous concretes with aggregate Nos. 5, 6 and 7 are found to be:

$$\sigma_5=129\exp(-0.0738V),\ R^2=0.957 \quad (8)$$

$$\sigma_6=129\exp(-0.0862V),\ R^2=0.960 \quad (9)$$

$$\sigma_7=129\exp(-0.1090V),\ R^2=0.964 \quad (10)$$

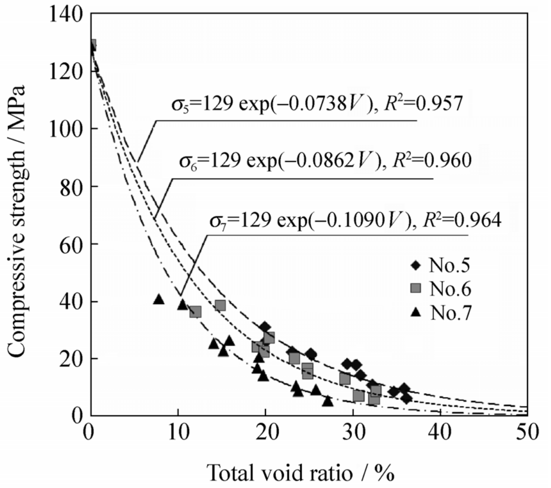

Fig. 4. Compressive strengths of paste and concrete *vs.* void ratios with different aggregate sizes (series 2).

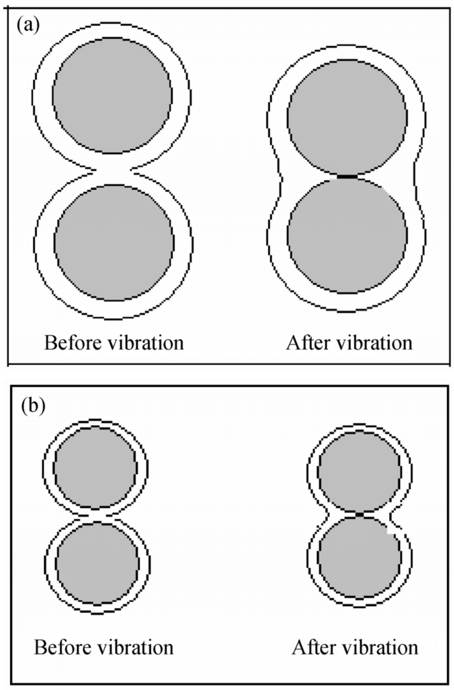

Fig. 5. Schematic diagram of paste at the contact of two aggregates before and after vibration: (a) large aggregate with thick paste; (b) small aggregate with thin paste.

The values of strength reduction parameter B were from 0.0738 to 0.1090 and were dependent on the aggregate size. The most logical factor representing the aggregate size and its distribution was the fineness modulus. The parameter B can be taken as a function of fineness modulus (FM) of aggregate as shown in Fig. 6. From linear fitting of the B values, the empirical equation relating B and FM is obtained as:

$$B=0.1962-0.0174\ \text{FM},\ R^2=0.997 \quad (11)$$

The general equations for strength and void ratio with respect to binder strength and aggregate size could therefore be written as:

$$\sigma=\sigma_0\exp[-(0.1962-0.0174\ \text{FM})V] \quad (12)$$

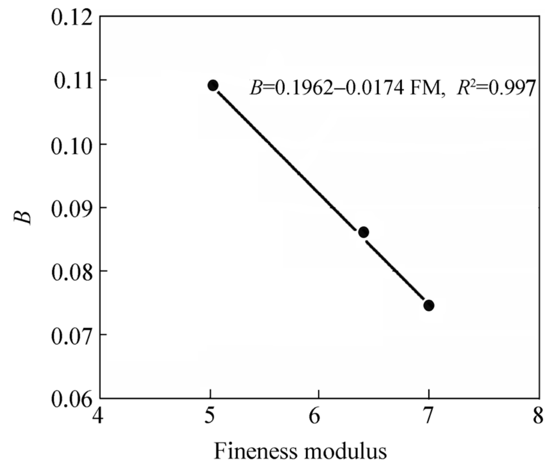

Fig. 6. Strength reduction parameter *B* *vs.* fineness modulus of aggregate.

3.3. Verification of the equations

To verify the correctness of the equations, the calculated data were compared with the obtained experimental test data. As shown in Fig. 7, the results from Eq. (12) are excellent. The usefulness of the general equation relating strength and void ratio of porous concrete using the FM values is thus confirmed.

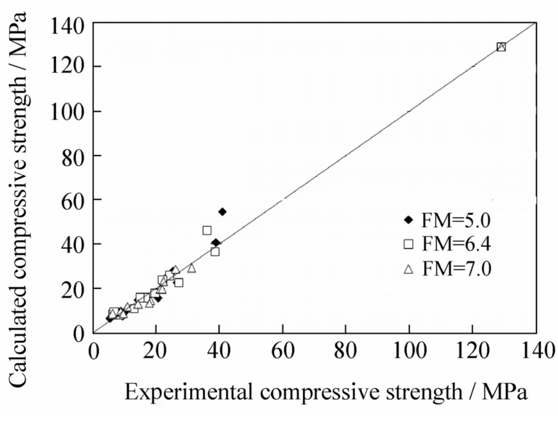

Fig. 7. Experimental compressive strength *vs.* calculated compressive strength from Eq. (12).

4. Conclusions

(1) The results confirm that the compressive strength of porous concrete reduces with an increase in void ratio. The equation relating strength and void ratio in the general form of $\sigma=\sigma_0\exp(-BV)$ is applicable.

(2) For different binders with one aggregate size, the results show that the B value is independent of the binder strength. For No. 6 aggregate with binder

strengths ranging from 30.0-135.0 MPa, the *B* values are approximately 0.080.

(3) With regards to aggregate size, the rate of reduction in compressive strength with an increase in void ratio of porous concrete containing small aggregate is higher than that with large aggregate.

(5) The values of strength reduction parameter *B* are dependent on aggregate size and can be estimated using fineness modulus. Comparing the data from the test and those from the equations indicates that the developed general equation for porous concrete is useful in relating the compressive strength and void ratio of porous concrete.

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