Relationship between Porosity & Compressive Strength of Concrete with Variable W/C Ratio

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ABSTRACT

This research used a comprehensive experimental program. The objective of this research was to quantify and investigate the correlation between effective porosity and compressive strength of concrete developed during the curing process. Compressive strength and porosity of concrete were tested at ages of 1, 3, 7, 14, 28, and 56 days, respectively and concrete cylinder samples were prepared with different water to cement *(w/c)* ratio of 0.40, 0.55 and 0.70. The hardening concrete's compressive strength was increased with curing time, while effective porosity measurements was in opposite pattern. The relationship between effective porosity and compressive strength of concrete has been as an empirical correlation. The time-dependent measurements are beneficial in better understanding in term of hardening concrete's pore structure development.

Keywords: Hardening concrete, Compressive strength, Effective porosity and Water to cement ratio

1. INTRODUCTION

Hydration progressively fills the pore space in the concrete during the curing process. Existing continuous pathways can become blocked when pore space is filled with enough cement reaction products [1]. Porosity also plays a role in the relationship between concrete's mechanical properties, such as the compressive strength-modulus of elasticity relationship [2]. This is not to say that no attempt has been made to establish quantitative relationships between concrete compressive strength and porosity, but rather that such attempts have been sporadic, as in [3] and [4].

The compressive strength of concrete is a well-known measure of its consistency, and it may have a strong relationship with concrete porosity, which is an inherent property of cement paste [5], so the latter can be used in routine concrete quality control. The microstructure of the cement matrix (i.e., pore shape, porosity, and pore size distribution), ion concentration, and mobility in the pore solution [7] all influence the compressive strength of cement paste as the *w/c* ratio decreases [6].

However, there have been few studies that consider the time-dependent changes in compressive strength and effective porosity in relation to other properties of a hardening concrete. An experimental program was set up and carried out on a large number of concrete samples in order to investigate the correlation between the compressive strength and effective porosity of concrete formed during the curing phase in this paper.

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1.1 THEORY OF CONCRETE MICROSTRUCTURES

Coarse and fine aggregate particles are trapped in a matrix of hardened cement paste in hardened concrete. Approximately 25 percent of the concrete amount (space originally filled with water in excess of that required for hydration of the cement), Calcium silicate hydrate (CSH) gel, Calcium hydroxide (CH), Calcium sulphoaluminate Cements (CSA), and capillary pore space make up the hardened paste.

The CSH gel is porous in and of itself, with an intrinsic porosity of about 28 % [1]. The microstructure of concrete paste is depicted in Figure 1, and Table 1 provides a summary of concrete pore forms and their corresponding sizes. The solid part of the hydrated cement gel is represented as tiny black spheres by Power and Helmuth [8]. The gel pores are the interstitial spaces between the spheres. A "C" represents the capillary pores.

During the mixing and compaction of fresh concrete, air voids are invariably trapped or entrained. Entrapped air voids ranging in size from 1 to 10 mm can account for 1 to 3 % of the volume in concrete. The distance between entrained air voids is normally between 50 and 200 µm. Concrete with entrapped and entrained air voids may have a negative impact on its strength and impermeability [6]. Capillary pores may be large capillaries (macro - pores) with diameters ranging from 100 to 10,000 nm and medium capillaries (large meso-pores) with diameters ranging from 10 to 100 nanometers.

Table 1 shows the large meso-pores in well-hydrated, low *w/c* ratio pastes can be as small as 10 to 50 nm; in high-water cement ratio pastes, capillary voids can be as wide as 3 to 5 nm in the early stages of hydration. Gel pores are too small for hydration items to fill in the concrete paste microstructure. The gel pores range in size from less than 0.5 nm to 2.5 nm. Small isolated capillaries (small meso-pores) with diameters ranging from 2.5 to 10 nm, micro-pores with diameters ranging from 0.5 to 2.5 nm, and interlayer spaces of less than 0.5 nm are the three types of gel pores.

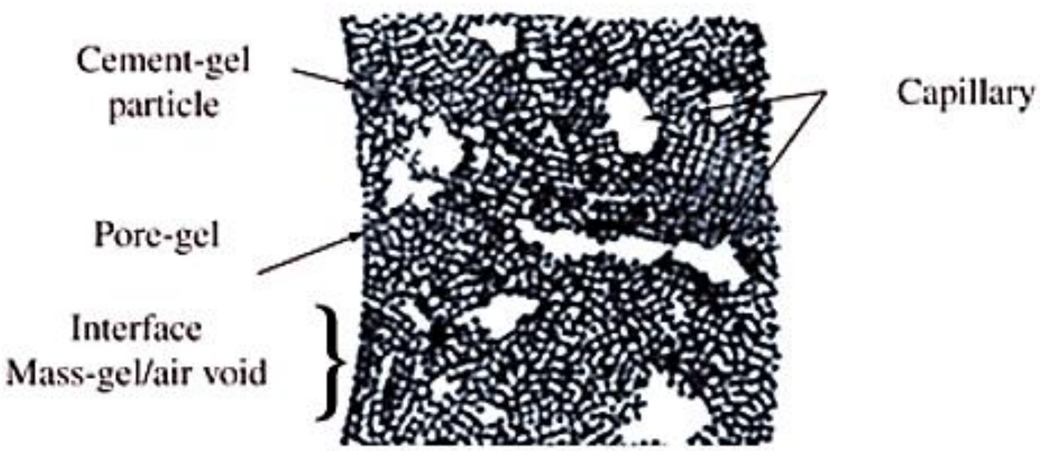

Figure 1. Concrete paste microstructure [8].

2. MATERIALS AND METHODS

2.1 Materials

Portland cement, stone (crushed limestone, 20 mm maximum size), sand, and water were used in this study. Sieve analysis was used to determine the size distributions of all-in aggregates, mixed sand and stone, from which a grading limit was established. The grading limits of all-in aggregates confirm that the grading distribution is appropriate, resulting in appropriate workability and durability. Under saturated surface dry conditions, coarse aggregates had 0.50 percent absorption and fine aggregates had 0.70 percent absorption, with specific gravity of 2.68 and 2.64, respectively.

To quarter the samples, the method started with weighing approximately 90 kg of samples, spreading them out, and thoroughly mixing them into a conical heap. Quartering was done once more. For the handling of excess samples, a bin was replaced. The particle size gradation of a sample of the well graded aggregate was reasonably uniformly distributed from the finest to the coarsest.

Table 1. Classification of pore size in concrete and cement paste [6].

Designation	Diameter	Description
Entrapped air voids Entrained air bubbles	10 - 1 mm 200 - 50 µm	1 to 3 % of concrete volume
Capillary pores	10,000 - 100 nm	Large capillaries (Macro - pores)
	100 - 10 nm	Medium capillaries (Large meso - pores)
Gel pores	10 - 2.5 nm	Small isolated capillaries (Small meso - pores)
	2.5 - 0.5 nm	Micro - pores
	$\leq$ 0.5 nm	Interlayer spaces

Table 2. Mixture proportions (kg/m^3).

Mix No.	Cement	Sand	Stone	Water to cement ratio
1	500	650	990	0.40
2	360	790	990	0.55
3	280	870	990	0.70

Table 3. Test specimens.

Test methods	Size (mm)	Type	Samples
Compressive strength ASTM C39 - 14 [10]	100 x 200	Cylinder	120
Porosity ASTM C642 - 97 [11]	100 x 100 x 100	Cube	90

2.2 Mixture proportions

The concrete samples were mixed at 0.40, 0.55, and 0.70 *w/c* ratios, respectively. ACI 211.1 - 2000 [9] is used for the mix design of control and blended mixes. Table 2 also shows the different amounts for various combinations. Concrete compressive strength was evaluated at ages of 1, 3, 7, 14, 28, and 56 days, respectively.

2.3 Method of casting and curing

For laboratory experiments, the specifications vary depending on the intent of the tests, and each test variable needs three test specimens made from one batch of concrete. Table 3 shows the procedure for preparing examining specimens.

The freshly mixed concrete was poured into the molds in three layers, with each layer tamped 25 times. The strokes are evenly spaced around the cross-sectional area. A vibrator table is used after mixing to ensure proper compaction. Until processing, the test specimen is caped to make the top surface of the specimen smooth and plain.

2.4 Test methods

In terms of compressive strength testing: Figure 2 shows the compressive strength testing configuration, which follows ASTM C39 - 14 [10]. Five samples were checked in order to achieve an accurate calculation for each curing period. Compression testing will be carried out at a rate within the range 12 - 24 N/(m^2·min) in a suitable testing machine and the rate of failure noted as follow:

$$f_c' = \frac{P}{0.25\,\pi d^2} \qquad (1)$$

where: f_c' (MPa) = compressive strength
P (kN) = maximum load
d (m) = diameter of cylinder

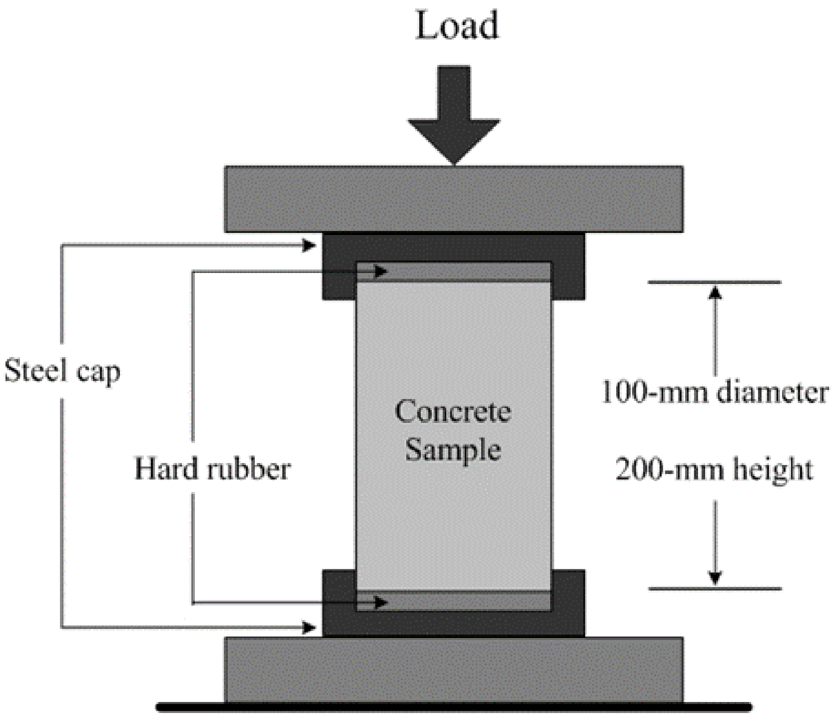

Figure 2. Compressive strength test of concrete.

Porosity testing was conducted on concrete cube samples 100 x 100 x 100 mm. in accordance with ASTM C 642 - 97 [11]. The following are the steps in the research procedure:

Phase 1: The portion volume not less than 350 cm^3 and normal weight concrete, approximately 800 g.

Phase 2: Setup temperature 100 to 110°C and drying the samples in an oven for at least 24 hours. At the temperature of 20 to 25°C, the specimens allowed to cool in dry air an after being removed from the oven. M1 denotes the mass, which is weighted.

Phase 3: Immerse the specimen in water at a temperature of about 21°C for at least 48 hours. Determine the mass after drying the specimen by extracting surface moisture with a towel. M2 represents the final surface-dry mass after immersion.

Phase 4: Boil the specimen for 5 hours in a suitable receptacle, covered with tap water. The final temperature of 20 to 25°C allowed it to cool by natural heat loss for at least 14 hours. Remove any surface moisture with a towel and calculate the specimen's mass, which is denoted by M3.

Phase 5: After boiling and immersion, suspend the specimen by a wire and assess the apparent mass in water.

M4 is the designation for this mass. The following calculations can be done.

$$g_1 = \frac{M_1}{(M_3 - M_4)} \times \rho_w \quad (2a)$$

$$g_2 = \frac{M_1}{(M_1 - M_4)} \times \rho_w \quad (2b)$$

$$\phi_e = V_v = [(g_2 - g_1) / g_2] \times 100 \quad (2c)$$

where: g_1 (t/m^3) = bulk density;
g_2 (t/m^3) = apparent density;
ρ_w (kg/m^3) = density of water;
ϕ_e (%) = effective porosity;
V_v (%) = volume of permeable voids.

3. RESULTS AND DISCUSSION

Compressive strength: When forming concrete, the *w/c* ratio is usually used to regulate the compressive strength. The compressive test results of concrete mixes with variations of *w/c* ratio were presented in Figures 3, after 56 days of mixing groups. During the curing cycle of 1, 3, 7, 14, 28 and 56 days, samples were poured and checked.

The graph of strength versus *w/c* ratio are approximately in the shape of hyperbola [12 and 13]. The findings revealed that the compressive strength of concrete mixes increased with curing time and *w/c* ratio [14]. Any reduction in the *w/c* ratio could boost compressive power.

Effective porosity of concrete: The factors responsible for the strength of the hydrated cement paste and the effect of increasing *w/c* ratio on porosity at a given degree of cement hydration. Figure 4 depicts the variation in effective porosity as a function of curing time. An increasing effective porosity with increase in the *w/c* ratio. However, the porosity of concrete decreases with more time.

The pore space in the concrete progressively fills as the hydration continues. Existing continuous pathways can become blocked when a pore is sufficiently filled with cement reaction products. The more pores that are blocked, the less water can percolate through the concrete. The amount of air voids in concrete is determined by the *w/c* ratio. When this occurs, the concrete's compressive strength deteriorates.

Compressive strength versus effective porosity: The strength and porosity relationship is applicable to very wide range of materials. Figures 5 show the relationships between effective porosity and concrete compressive strength over time for w/c ratios ranging from 0.40 to 0.70. Since the water in the gel pores is tightly bound to the inner surface of the cement paste, it is not conductive, while the water in the capillary pore water is more or less free and mobile. The following are the relationships of changes in compressive strength and porosity over time, as well as the associations between compressive strength and porosity, either individually for each w/c ratio (0.40, 0.55, and 0.70) or for all w/c ratios lumped together, as shown in equation (3) with a strong correlation coefficient (R2 > 0.94):

$$f_c' = 324.78\,\phi_e^{-1.283} \quad (3)$$

From the equation (3), the empirical correlation between porosity and strength, within the range of the latter between 3 to 13 percent. The results of this study are in the same direction as Rossler and Odler ,1985 [15] with a value between 5 and 28 percent. There are other elements that affect the relationship between strength and porosity, such as water to cement ratio and aggregate properties. However, the total porosity on strength must be considered.

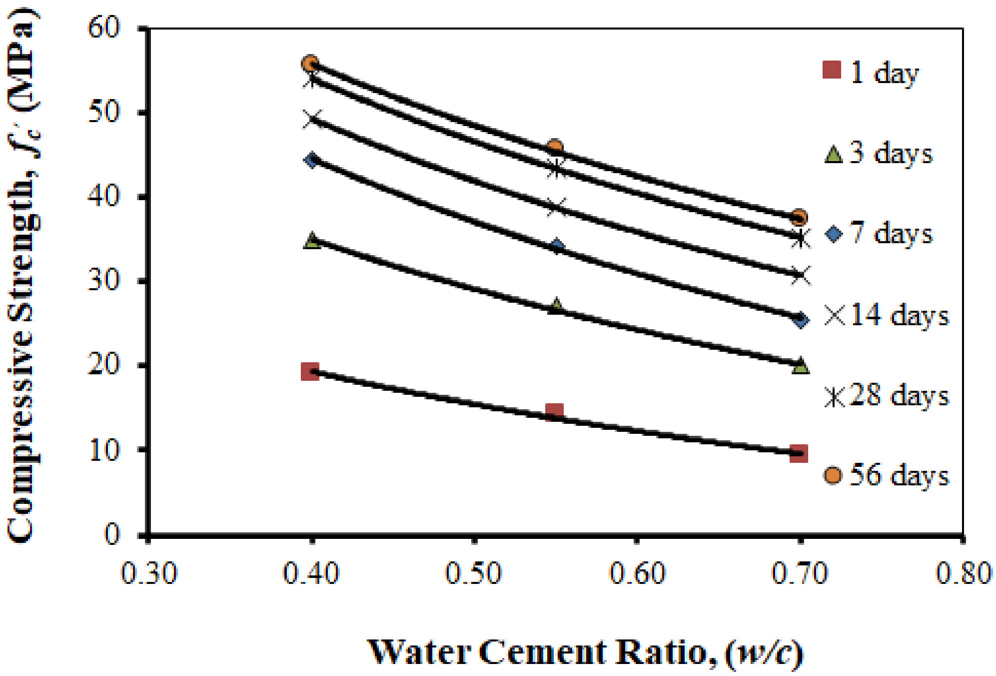

Figure 3. Compressive strength versus w/c ratio.

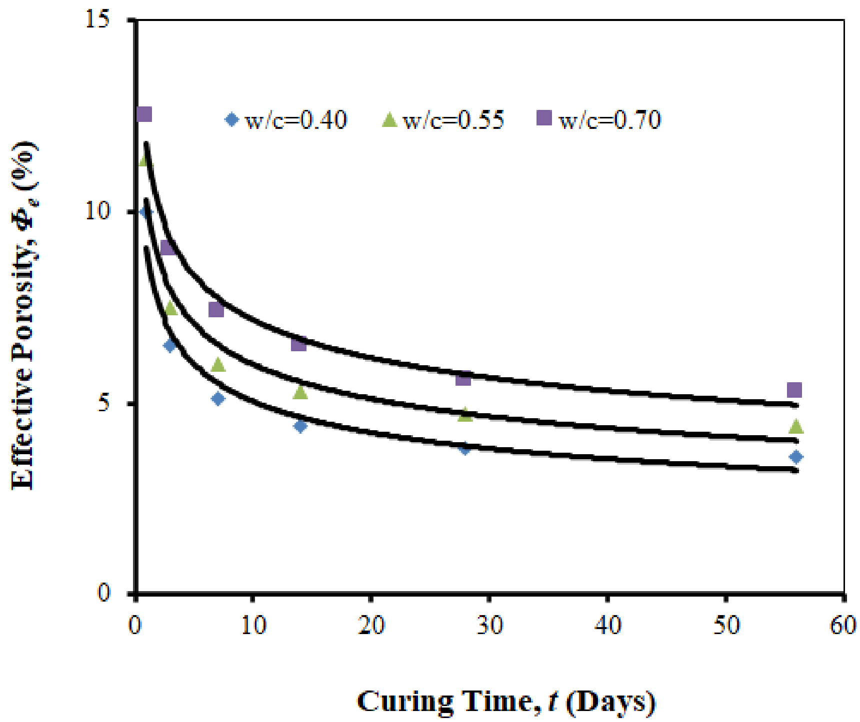

Figure 4. The change in effective porosity with the curing time.

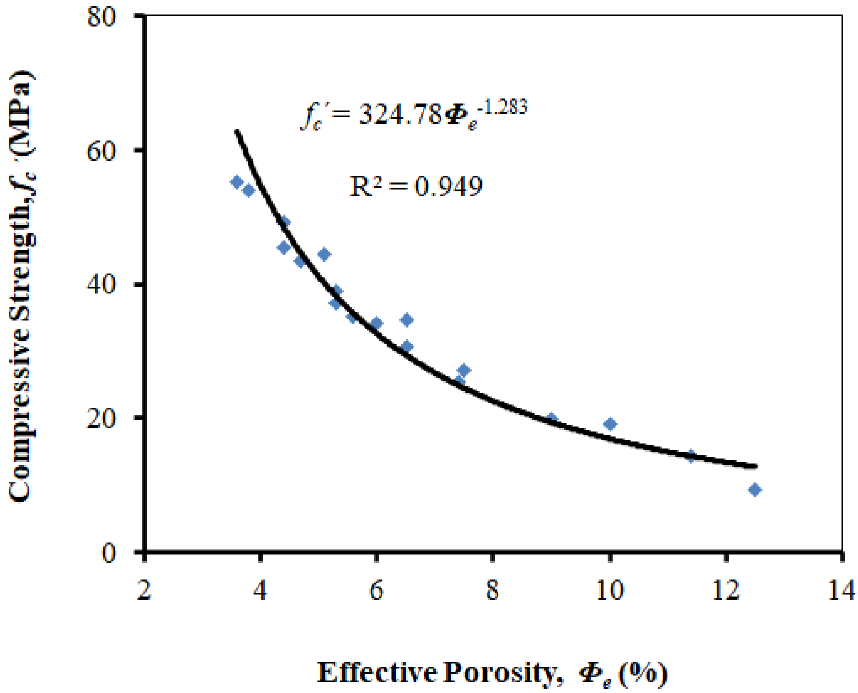

Figure 5. Compressive strength versus effective porosity.

The *w/c* ratio is low. Since their use necessitates the batching, shipping, and placement of significantly less concrete to accommodate the loads acting in a specific system, they are much more sustainable than standard *w/c* ratio concrete.

4. CONCLUSIONS

In conclusion, a significant number of samples were made from three concrete mixes with *w/c* ratios of 0.40, 0.55, and 0.70, respectively, denoted as A, B, and C. For a 56 - day curing period, the compressive strength and porosity of a hardened concrete were measured. The hardening concrete's compressive strength was found to increase with curing time, while effective porosity measurements showed the opposite pattern.

The association with concrete compressive strength, can be used to predict concrete porosity effectively. This does not mean that no efforts have been made for the development of quantitative relationships between effective porosity and strength but rather that these efforts have been sporadic and the results have less than satisfactory.

5. ACKNOWLEDGMENTS

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