

Porosity of Self-Compacting Concrete (SCC) incorporating high volume fly ash

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Abstract. Degradation of concrete could be triggered by the presence of aggressive agents from the environment into the body of concrete. The penetration of these agents is influenced by the pore characteristics of the concrete. Incorporating a pozzolanic material such as fly ash could modify the pore characteristic of the concrete. This research aims to investigate the influence of incorporating fly ash at high volume level on the porosity of Self-Compacting Concrete (SCC). Laboratory investigations were carried out following the ASTM C642 for measuring density and volume of permeable pores (voids) of the SCC with varying fly ash contents (50-70% by weight of total binder). In addition, a measurement of permeable voids by saturation method was carried out to obtain an additional volume of voids that could not be measured by the immersion and boiling method of ASTM C642. The results show that the influence of fly ash content on the porosity appears to be dependent on age of SCC. At age less than 56 d, fly ash tends to cause an increase of voids but at 90 d of age it reduces the pores. The additional pores that can be penetrated by vacuum saturation method counts about 50% of the total voids.

1. Introduction

Self-compacting concrete (SCC) is a type of concrete with special fresh properties i.e. it flows under its own weight and passes any obstacles on its way to fill every spaces within the formwork. With these properties, there is no need of vibration to obtain uniform and dense concrete in the construction of SCC. On the other hand, vibration is necessary in the production of conventional concrete to force the solid particles in freshly mixed become in a closer arrangement. Otherwise, any entrapped air will settle within concrete to form large voids resulting in a very porous concrete. Interconnected voids also facilitates an ingress of aggressive agents from the environment surrounding concrete.

Penetration of aggressive agents into the body of concrete and the chemical reactions that follow may disrupt the integrity of concrete. To increase the resistance of concrete against aggressive agents, it is important to reduce the rate of ionic transport from the environment into the concrete. This ionic transport may be driven by one or combination of the following mechanisms: pressure-induced water flow, water absorption, water vapour diffusion, wick action, ion diffusion, gas diffusion and pressure-induced gas flow [1]. Whatever the driving force is, lower porosity and finer pores with more tortuous pores structure will promote a better durability than concrete with the opposite properties. For this reason, porosity may be used as one of the durability indicators [2].



The porosity of concrete is controlled by the pores size in the interfacial transition zone (ITZ) between aggregates and paste. This is because the porosity of this zone is higher compared to the bulk paste as shown from the image analysis of microstructure [3]. It is also revealed that there are non-homogeneous distribution of pores in the ITZ and bulk paste. The pore volume is higher toward aggregate. It is also interesting to note that the pore volume beneath aggregate is higher compared to that at the top and the side of aggregate. The pore volume in the ITZ is influenced by packing density of the solid ingredients, water to cement ratio (w/c), binder composition, type of filler, etc. All these parameters are represented in the composition and proportion of materials for making concrete.

SCC has been investigated to show a finer and more tortuous pores structure than conventional concrete [4]. The different in the pores characteristic between the two concretes is originated in the proportion of the ingredients. In SCC, one of the key factors to achieve moderate viscosity is its proportion where finer components tend to be higher while the coarser components are lower compared to those of conventional concrete. With a higher finer proportion, they will be a higher surface area of the solid particles to hold free water in the mix. Moreover, the free water is not disrupted in the absence of compacting process. Thus, there is a lower tendency of bleeding and of water accumulating around aggregates and leads to lower pores in the ITZ [3, 4]. On a contrary, free water in conventional concrete is in a motion during vibration and this may provoke bleeding as well as bleeding channels. Therefore, an interconnected network of large pores is developed. In addition, part of the free water is also accumulated around coarse particles on its way to move upward and creates large pores in the ITZ. A closer arrangement of coarse aggregates in conventional concrete due to higher amount of coarse aggregates content will further introduce a closer network of large capillary pores from one ITZ to the adjacent ITZ.

Most of SCC utilises fillers or pozzolanic materials to increase its finer components. Otherwise, the mix will consist of large amount of cement to meet a moderate viscosity. The introduction of fillers and pozzolanic materials will certainly affect the porosity and microstructure of SCC. Silva and Brito [5] point out that the predominant factor influencing the porosity of SCC with the substitution of cement by limestone filler, fly ash or combination of limestone filler and fly ash is the w/c. In a mix with higher amount of cement substitution, w/c ratio is increased resulting in a higher porosity. However, for SCC with fly ash substitution, finer pores is obtained and therefore, lower capillary absorption is noted in comparison to SCC with limestone filler substitution. The pozzolanic reactivity of fly ash also provokes additional pores refinements as indicated by the lower capillary absorption at later age. The beneficial effect of incorporating fillers or pozzolanic materials to reduce water absorption is achieved if the w/b (water/binder ratio) is kept similar. A higher addition of fillers or pozzolanic materials into SCC mix results in a lower water absorption [6]. This may be associated with the enhance of particle distribution, reduction of inter-particle friction and greater packing density.

Concrete with the same amount of total pores may show different ability to facilitate ionic transport. It is the size of the pores which could determine the behaviour. The pores in the concrete can appear as macro-pores, capillary pores and gel pores. The pores in the size of 0.01-1 μ m along with the macro-pores have a real effect on the ionic transport properties. For ionic transport by capillary suction as measured by water absorption, the water can only access the pores in the size of about 0.5 μ m. For finer pores, water pressure is needed to penetrate these finer pores [4]. This research aims to investigate porosity of SCC incorporating various contents of fly ash at high volume level. The porosity is determined on the basis of volume of accessible pores by water absorption and water pressure. The parameters to be investigated include density and volume of permeable pores (voids).

2. Experimental

2.1. Materials and their properties

The composition of materials and their proportion for producing SCC is presented in Table 1. The coarse aggregates were selected to limit their maximum size of 10 mm. The bulk specific gravity of

coarse and fine aggregates were found to be comparable i.e. 2.51 and 2.50, respectively, when they were tested according to ASTM C128. Both coarse and fine aggregates had also been tested to determine their gradation following ASTM C136 and the results conformed to the requirement of gradation as specified by ASTM C33. The aggregates were free from any deleterious substances as specified by ASTM C33. The cement used for making the concrete was Portland Composite Cement (PCC) obtained from PT Indocement. While fly ash was supplied from Cilacap Power Plant. The chemical composition of fly ash is given in Table 2. The total composition of SiO_2 , Al_2O_3 and Fe_2O_3 is more than 70% (Class F according to ASTM C618). However, the CaO content is moderate (13.32%). Considering the amount of CaO, the fly ash is categorised as Class CI according to CSA A3001.

After all the solid ingredients were mixed with the liquid ingredients and obtain a uniform mixture of fresh concrete, this mixture was tested to determine the flowability, fillingability and passingability using flow table, J-Ring, Box-Type and V-funnel test. Table 3 indicates the fresh properties of all SCC used in this research.

Table 1. Composition of SCC

| ID | fly ash (kg) | cement (kg) | coarse aggregate (kg) | fine aggregate (kg) | water (kg) | superplasticizer (kg) |
|-----|--------------|-------------|-----------------------|---------------------|------------|-----------------------|
| 50% | 384.30 | 384.30 | 709.8 | 595.35 | 231 | 7.686 |
| 55% | 422.73 | 345.87 | 709.8 | 595.35 | 231 | 7.686 |
| 60% | 461.16 | 307.44 | 709.8 | 595.35 | 231 | 7.686 |
| 65% | 499.59 | 269.01 | 709.8 | 595.35 | 231 | 7.686 |
| 70% | 538.02 | 230.58 | 709.8 | 595.35 | 231 | 7.686 |

Table 2. Chemical composition of fly ash and their relative amount (%)

| SiO_2 | Al_2O_3 | Fe_2O_3 | TiO_2 | CaO | MgO | K_2O | Na_2O | P_2O_5 | SO_3 | MnO ₂ |
|----------------|-------------------------|-------------------------|----------------|-------|------|----------------------|-----------------------|------------------------|---------------|------------------|
| 45.27 | 20.07 | 10.59 | 0.82 | 13.32 | 2.83 | 1.59 | 0.98 | 0.41 | 1 | 0.07 |

Table 3. Fresh properties of SCC

| Test Method | Parameter | 50% | 55% | 60% | 65% | 70% |
|-------------|----------------|---------|---------|---------|---------|---------|
| Flow Table | diameter (mm) | 655 | 675 | 720 | 730 | 790 |
| J-Ring | diameter (mm) | 570 | 590 | 675 | 670 | 700 |
| Box-type | h_2/h_1 (mm) | 340/340 | 340/340 | 340/305 | 340/340 | 340/330 |
| V-funnel | time (sec) | 13.72 | 20.77 | 12.36 | 11.50 | 12.43 |

2.2. Testing of density and voids in hardened SCC

ASTM C642 was adopted in this research to determine the density and voids in hardened SCC. The specimen was cylinder of 70 mm diameter and 100 mm height. A total of 16 cylinders were prepared from each type of SCC mixture. Testing of specimens were carried out at the age of 7, 28, 56 and 90 day. The density and void of each SCC mixture were determined as an average of measurements on 4 cylinder specimens. The testing procedure for measuring density and voids in hardened SCC is summarized as follows: First, the specimens were dried in an oven at a temperature of 110 °C for 24 h. The oven-dry specimens were weighted to obtain their respective mass (A). Second, the specimens were then immersed in water for a period of 48 h. After taken from the water, the specimens were wrapped with a dry towel to remove any moistures on the surface of specimens. The saturated surface dry (SSD) mass of specimens after immersion were determined (B). Third, the SSD specimens were then put in a suitable receptacle, covered with tap water and boiled for 5 h. The boiled specimens were allowed to cool by natural loss of heat for a period of not less than 14 h to a final temperature of 20-

25°C. Subsequently, any moistures on the surface of specimens were removed and then the SSD mass of specimens after boiling were determined (C). Finally, the specimens were immersed and weighted in water to determine their apparent mass (D). The density and voids of the hardened SCC could be calculated using the following equations:

$$BD = \frac{A}{(C-D)} \quad (1)$$

$$Vo_1 = \frac{(C-A)}{(C-D)} 100\% \quad (2)$$

where BD is bulk density density; Vo_1 is volume of permeable pore space (voids).

2.3. Testing of voids in hardened SCC by vacuum saturation

This research adopted RILEM recommendation [7] for measuring the voids in hardened concrete by vacuum saturation method. Cube specimens with a size of 50x50x50 mm were used to determine the voids of hardened SCC. A total of 12 cubes were prepared to represent each type of SCC mixture. The measurements of voids were carried out at the age of 7, 28, 56 and 90 day. To determine voids of hardened SCC, an average value of measurements on 3 specimens was used. The procedure of testing could be summarized as follows: First, specimens were stored in oven at a temperature of 110 for 24 h. The mass of the oven-dried specimens were determined (W_o). Second, the specimens were then put into a desiccator which was connected to a hose of vacuum pump and to a hose of water tank. The vacuum pump was turned on to evacuate moistures within the specimens with a pressure of -1 bar for 24 h while the hose of water tank was closed (disconnected). The hose of vacuum pump was then closed (disconnected) and the dessicator was filled with tap water when hose of water tank was opened. The water would penetrate into the evacuated pores of specimens with the aids of atmospheric pressure. The specimens were left while immersed in such condition for 24 h. After which the specimens were weighted in water to determine their mass in water after immersion (W_w). The next step was to take the specimens and wrap with a dry towel to remove moistures on the surface. The SSD mass of the specimens were then weighted (W_a). The total voids (Vo_2) could be calculated using the following equation:

$$Vo_2 = \frac{W_a - W_w}{(W_a - W_o)} 100\% \quad (4)$$

3. Results and discussion

3.1. Density and voids in hardened SCC measured by ASTM C642

The bulk density of hardened SCC is presented in Fig. 1 (a). All SCC show an increase of density with time. Initially the bulk density of SCC is vary in accordance with a variation of fly ash content. The density is in the range of 2100-2200 kg/m³ when it is measured at 7 d. It is likely that at early age, SCC with a lower inclusion of fly ash content will give a greater bulk density. However, at later age the bulk density of all SCC is nearly similar at about 2300 kg/m³ after 90 d of age. The comparable value of bulk density at later age is linked with the rate of the increase in density. As shown in the figure, the increase of bulk density with time in SCC containing higher fly ash is greater than that of SCC with lower fly ash content. The increase in the density is associated with the pores refinement due to progress of cement hydration and pozzolanic reaction of fly ash.

The voids of SCC measured on the basis of water which can enter the permeable pores by capillary suction is presented in Fig. 1 (b). All SCC show a consistent behaviour where the voids drop with time. This trend is coherent with the corresponding trend of bulk density where density is increased with time. The reduction of voids which leads to a denser hardened SCC with time is associated with the continuous hydration and pozzolanic reaction which takes place at later age. These two reactions give a similar product i.e. calcium silicate hydrates which refine the pores of hardened SCC.

It is also noticed that the decline in the percentage of voids is more significant in SCC with high (above 60%) fly ash content. The highest reduction of voids is observed on SCC with 60% fly ash

content. Initially the voids in this SCC count about 15.3% at 7 d, but the value drops to 2.1% at 90 d. The significant reduction of voids in hardened SCC with high fly ash content may be explained as follows. At low fly ash content, higher cement is available for hydration; more hydration products would fill the inter particles space and so a denser hardened SCC is obtained at early age [8]. However, at later age pozzolanic reaction will takes place since at this age there are sufficient calcium hydroxide, which is one of the main products of cement hydration, to be consumed by fly ash for the pozzolanic reaction. The product of pozzolanic reaction i.e. calcium silicate hydrate will fill an empty pores which are not occupied by the previous hydration products. Consequently, there is a continuation of pores refinement at later age and the pores refinement would be more effective when the original pores is coarser as in SCC with high fly ash content. Thus, even though initially the pores in SCC with high fly ash content is greater, but in a longer time pozzolanic reaction together with continuous hydration will cause a refinement of pores at a faster rate.

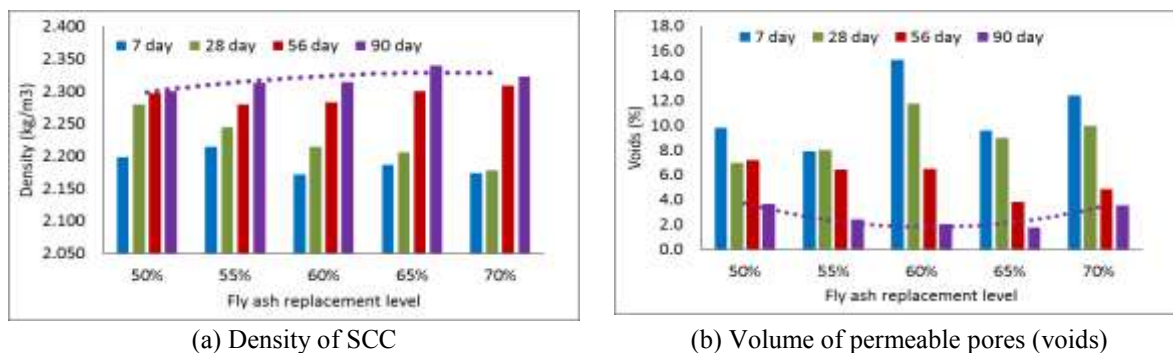


Figure. 1. Density and voids in hardened SCC determined according to ASTM C642

Fig. 1 (b) also indicates that the effect of fly ash on the formation of voids in hardened SCC depends on age. At early ages, fly ash tends to increase the presence of voids within hardened SCC. However, from 56 d and afterward the influence of fly ash seems to decrease voids. At 90 d of age, there is an optimum amount of fly ash content which provide a minimum voids in hardened SCC as shown in the curve of Fig. 1 (b). There are several factors that may explain the influence of fly ash content on the formation of voids in hardened SCC. First, is the particle packing density factor. It is thought that the finer size of fly ash would be beneficial to fill the inter particles of solid ingredients. A denser inter particles packing is expected in the presence of fly ash. However, there is always an optimal amount of combination that the voids are minimized. Excessive fly ash content could dilate the inter particles space leading to higher porosity at the start of the hardening process [8-10]. The particle packing density factor may be considered as the origin of the inter particles space of mixture before the concrete hardened. Therefore, the effect is foremost at early age. Comparison of the voids of all SCC at early age, it seems that fly ash content of 55% gives the best particle packing density. Second, is cement content. As previously mentioned a higher cement content provokes a higher hydration products which occupy the inter particles space. Hence, a lower voids is expected on SCC with high cement (or low fly ash) content at early age. Third, is the pozzolanic reaction between fly ash and calcium hydroxide that takes place at later age. The reaction together with the continuous hydration cause a refinement of pores at later age [10]. To sum up, the voids at early age is predominantly affected by particle packing density and rate of cement hydration factor while at later age the major factor is refinement of pores by continuous hydration and pozzolanic reaction.

3.2. Voids in hardened SCC measured by RILEM Method

The voids within the hardened SCC are formed in various sizes. Cappillary suction during water absorption test of ASTM C642 method can only draw water into capillary pores with a minimum size of 0.5µm. For finer pores, a hydraulic pressure is necessary [4]. RILEM Method provides an atmospheric pressure to aid the water to penetrate into the finer pores. As a result, the voids measured

using this method is higher compared to those measured by ASTM C642. Fig. 2 clearly confirms this phenomenon. At early age, the difference of the total voids content measured by RILEM and ASTM C642 is high. However, the difference in the total voids is getting lower with time. For example, at 7 d of age the voids in hardened SCC with 70% fly ash is 22.1% and 12.3% when measured by RILEM and ASTM C642, respectively. The corresponding voids in this concrete reduce to, respectively, 7.4% and 3.6% at 90 d of age. This range of total voids difference actually represents about 50% of the voids. The difference in the voids content measured by the two methods may be considered as the amount of the finer pores that can not be penetrated by capillary suction only.

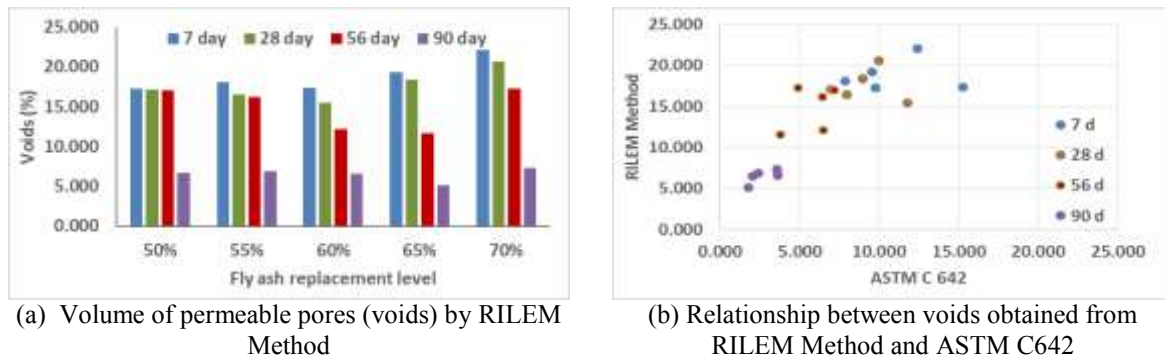


Figure 2. Voids in hardened SCC measured by RILEM Method

It is interesting to note that at 50-55% of fly ash replacement level, the voids in the hardened SCC are barely drop until 56 d of age (see Fig. 2 (a)) even though the voids measured by ASTM C642 show a reduction of voids (see Fig. 1 (b)). This finding indicates that the refinement of pores in this concrete may only occur at the inter particles space while fine capillary pores remain unchanged.

4. Conclusions

The volume of permeable pores (voids) in hardened SCC decreases with time. The trend is coherent with the increase of density with time. The decline in the total voids is more significantly observed in SCC with at least 60% of fly ash content. The influence of fly ash content on the porosity appears to be dependent on age of SCC. At age less than 56 d, fly ash tends to cause an increase of voids but at 90 d of age it reduces the pores. The voids observed via vacuum saturation method is higher than those of immersion and boiling method. The finer pores that can be penetrated by vacuum saturation method counts about 50% of the total voids.

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