Research Article

A Comparative Study of Void Distribution Pattern on the Strength Development between OPC-Based and Geopolymer Concrete

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The correlation between the void structure, as a representative of bleeding behaviour, and the strength of concrete is investigated in the current article. Early age cracking, due to dry shrinkage, can negatively influence the durability of pavement structures. Also, dry shrinkage of concrete is directly proportional to the bleeding rate. Thus, modifying the bleeding rate reduces the early cracking that happens in hardened concrete. Geopolymer concrete is presented as a suitable material for the replacement of Ordinary Portland Cement (OPC). Geopolymers have shown superior bleeding behaviour to that of OPC concrete and can be substituted for paving by means of increasing the durability. This research has used section image analysis and rebound hammer techniques to create a relationship between the void structure and the strength of concrete. Mixtures are prepared by 10% substitution of the iron-making slag to study the effects of slag on the bleeding rate. Also, the influence of water-to-binder ratio on the void structure and strength development is studied. The results indicate that the void volume has an indirect correlation to the strength development of normal concrete, while the addition of slag makes it reverse. Geopolymer concrete shows less bleeding than OPC concrete, making it a suitable alternative for pavement. It is also concluded that the replacement of slag in concrete enhances the bleeding rate and durability.

1. Introduction

Bleeding in concrete is a phenomenon that describes water movement to the surface in a plastic state concrete [1–3]. In other words, it is a form of settlement that forces water to the surface as aggregates in the concrete begin to settle. Bleeding occurs in all concrete to some extent, but it is only observed when the rate of bleeding exceeds the rate of evaporation. This rate can be influenced by the type, shape, and content of concrete constituents [2, 4, 5]. It will end when movement of water is blocked by some solid or due to the growth of hydration. However, excessive bleeding in freshly placed concrete results in weakening of surface layer, reduction of the bond between concrete and steel, and, finally, plastic settlement crack [6–8]. Bleeding makes more trouble on slabs and large areas, such as pavement, because of having large surface areas, and it causes a weakening of the top surface, making it less durable. Any attempt to remove water

from the surface may cause a delay in finishing, and it is not economical for large-scale projects.

Ground granulated blast furnace slag (GGBS) has been used as a partial restoration in Ordinary Portland cement (OPC) for many years in different countries [9–14]. Many of the merits and demerits have been understood and published. However, when it comes to bleeding, only limited data are available. The inclusion of GGBS as a partial replacement to OPC and its effect on the bleeding are investigated in the study by Wainwright and Ait-Aider [11]. Concrete mixtures were prepared with the varying amount of cement and replaced slag. The ASTM C232 standard test method to assess bleeding in concrete was carried out. This test examines the relative quantity of water bleed from the freshly mixed concrete. The result showed that an increase in the cement content from 250 to 350 kg/m³ causes a reduction in bleeding by 50% and 60%. Other investigation suggested that cement with narrow size distribution require

more water for workability. Thus, particle size distribution can be an attributing factor to bleeding in concrete. Furthermore, it is reported that an incline in the GGBS inclusion leads to an increase in the bleeding rate.

Geopolymer concrete presented reduced carbon dioxide footprint and embodied energy, providing engineer feasible sustainable alternative [15–17]. Portland cement is a significant contributor to emissions by contributing 76.4% of CO₂ equivalent. In contrast, geopolymer concrete showed 80% less emission, making it a sustainable alternative [18]. Apart from that, many other properties can make geopolymer a feasible alternative, such as durability. Durability is the key characteristic, which should be considered while opting for sustainable alternative [19–21]. Geopolymer concrete is not “labcrete” and has been used in a number of projects in Australia and all around the globe. Australia has taken a major step by revising their specifications for “General concrete paving.” VicRoads (Road regulation in the state of Victoria) also accepted Portland cement concrete and geopolymer concrete as an equivalent product [22]. In pavement construction, James Aldred noticed that geopolymer concrete showed no sign of bleed water on the surface compared with OPC concrete [23]. However, limited research is available on bleeding in fly ash-based geopolymer concrete. Therefore, a comparative study between OPC-based and geopolymer concrete can be worthy.

Moreover, the loss of water from the surface during the drying process leads to a reduction in volume. It is called drying shrinkage. The higher water-to-cement ratio also affects because a higher volume of water in concrete causes bleeding on the surface. It results in an increase in shrinkage. The drying shrinkage is the main reason for early age cracking of the concrete pavement. Consequently, minimising the bleeding rate can help in declining the drying shrinkage of the pavement.

As mentioned before, there are certain methods to measure the bleeding rate of fresh concrete [1, 24–26]. Nonetheless, there are limited approaches to determine the bleeding of hardened concrete. The proposed model of bleeding in the current work is defined as solid particles settle down, and then, the water turns upward. This upward displacement of water may occur through vertical channels or uniformly. As a result of such process, voids may form within the concrete section. The voids and their size are directly correlated to the rate of bleeding. Hence, with a thorough and constant vibration, the void observation of the concrete section provides information about the movement of water throughout the concrete slab. This theory forms the main idea of the current study. It is suggested to measure the void profile of the concrete section and make a correlation between the changes in the void variation and the strength development.

2. Materials and Methods

2.1. Materials. Fly ash used in this study is an Australian Gladstone fly ash, which fulfills the requirements of AS3582.1. Fineness and quantity play significant roles in the characteristics of the final product. The particle size

distribution (PSD) of the utilised fly ash is as that of reported in Figure 1(a). The OPC used in this study for making traditional concrete specimen is general purpose cement type GP. GGBS from Building Products Supplies, PSD as reported in Figure 1(b), is partially replaced with the fly ash and OPC in the mixtures (see Table 1). The particle size distribution of the OPC is illustrated in Figure 1(c).

Sodium hydroxide pellets from Sigma Aldrich are employed in order to prepare sodium hydroxide solution 8 Molar. D grade sodium silicate solution (29.4% SiO₂ and 14.7% Na₂O) supplied by PQ Australia is utilised to make an activator with Na₂SiO₃/NaOH equal to 2. Fine aggregate (sand) and coarse aggregate are used in the preparation of concrete samples. Aggregates used are as per the specifications of AS 2758. The size range of the coarse aggregate is between 9.5 mm and 37.5 mm. The average size used in this research is 20 mm. The grading of fine aggregate also affects workability of geopolymer concrete. Thus, grading of fine aggregate is mentioned in Table 2.

2.2. Mixture Proportions. Six mixtures are designed in order to assess the effects of water-to-binder ratio, and the percentage of replaced slag on the void structure of the OPC-based concrete as well as the relative compressive strength profile of the sections. Table 1 provides the information of mixture proportions that are developed in these experiments. The specimens OS and GS, respectively, are the OPC-based concrete and geopolymer concrete with 10% of substituted slag. O1 and G1 samples have the water-to-binder ratio (w/b) of 0.4, whereas O2 and G2 have w/b = 0.45.

2.3. Sample Preparation and Testing. A specific size of moulds (500 mm × 500 mm × 100 mm) as per the requirement of the experiments are designed and used in the current work. The moulds are cast in one part followed by a 30-second uniform vibration. The vibrating conditions are kept constant through the whole experiments. The specimens are cured in laboratory temperature and humidity for 7 days before cutting and examination. The prepared slabs are then cut in perpendicular directions as shown in Figure 2. The cross sections of the concrete samples are then coated with paint and polished using a rotary sandpaper machine for about 120 seconds. For the image analysing process, images are then taken from each section and analysed with image analyser in order to obtain the voids' distribution and area. Consequently, the voids are categorised as large ($D > 2$ mm), medium ($1 \text{ mm} < D < 2$ mm), and small ($D < 1$ mm), where D is the diameter of the void. Then, the voids are counted, and the void volume fraction (VVF) is measured based on the area that the voids occupied in a plane. For each sample, the average value of eight measurements is reported. The rebound (Schmidt) hammer test is also conducted on the prepared specimens according to ASTM C805 standard. For the data analysis process, each section is divided into three equal horizontal area of interest, which is labelled as top section, middle section, and bottom section. At the same time, concrete cylinders are cast, and the compressive strength testing of the whole mixture is

FIGURE 1: Particle size distribution of (a) fly ash, (b) GGBS, and (c) OPC.

TABLE 1: Mixture proportions.

Materials	Samples designation					
	O1	O2	G1	G2	OS	GS
Cement (kg/m^3)	400	400	0	0	360	0
Sand (kg/m^3)	600	600	600	600	600	600
Aggregate (kg/m^3)	1200	1200	1200	1200	1200	1200
Fly ash (kg/m^3)	0	0	400	400	0	360
GGBS (kg/m^3)	0	0	0	0	40	40
Water (kg/m^3)	160	180	160	180	160	160

TABLE 2: Grading of fine aggregate.

Test sieve size	Retained (%)	Cumulative passing (%)	Specification passing (%)
4.75 mm	0.4	99.6	90–100
2.36 mm	4.6	95.0	85–97
1.18 mm	7.9	87.1	70–95
600 μm	13.2	74.0	45–80
300 μm	36.4	37.6	25–47
150 μm	34.4	3.2	0–15
75 μm	2.9	0.3	0–5
Pan	0.3	0.0	0

FIGURE 2: Sample cutting schematic.

also examined according to the ASTM C39 after 7 days as well.

3. Results and Discussion

The counting results of the void analysis are indicated in Figure 3. It is obviously noted that in samples O1, O2, G1, and G2, the void distribution patterns are analogous. The number of the large voids in the top section is the greatest. Although small voids have the lowest contribution in the top section, it is, however, opposite in the bottom section of the same samples, where the small voids have the largest contribution. One stated that the amount of bleeding is proportional to the content of porosity [27]; hence, assuming the direct correlation between the content of water and the void size distribution, when the number of large voids is higher than the number of small voids, the content of water is greater. It implies that the water can freely move from the bottom toward the top in these specimens causing bleeding. This correlation is confirmed by comparing samples O1 and O2 in which the number of voids in all sections increases from O1 to O2 with a growth in the w/b factor. As it is known, the higher the w/b, the more the bleeding [28, 29].

Moreover, comparing O1 and O2 with G1 and G2 indicates the differences in the void structure and bleeding behaviour of the geopolymers and OPC-based concrete. As clearly seen, the number of voids in the whole section of geopolymer specimens with w/b = 0.45 is less than those in the traditional concrete with w/b = 0.4. Hence, geopolymers have less bleeding than OPC concrete as approved during laboratory exercises and VVF analysis (read the next paragraph). The addition of GGBS to concrete specimens results in significant changes in the bleeding behaviour and void structure too. Not only is a decline in the number of voids observed due to the replacement of

GGBS but also small diameter takes the lead in the distribution of voids. It implies that the replacement of GGBS in the mixtures decreases the bleeding rate. The observation is opposing the previous claim about the addition of GGBS to the concrete mixture and its effects on the bleeding in the study by Wainwright and Ait-Aider [11]. This contrary statement may be attributed to the PSD differentiation in the utilised materials. As a matter of fact, materials with the lower mean particle size absorbs and hold more water (see Figure 1). In the current research, the mean particle size of the utilised OPC is almost 60 times greater than the GGBS ($0.42 \mu\text{m}$ for GGBS and $25.0 \mu\text{m}$ for OPC), which cause a decline in the bleeding rate.

Figure 4 illustrates the changes that take place in the VVF and the compressive strength of the concrete specimens throughout the section. The charts investigate the correlation between the void structure and compressive strength of concrete sections. First and foremost, the VVF of geopolymer concrete is less than OPC concrete, almost 1.76% for G1 and 2.55% for G2 compared with 2.37% for O1 and 2.92% for O2. It confirms our previous claim that geopolymer, even with 0.5 more w/b, has lower bleeding than OPC and hence less dry shrinkage cracking. The first reason for such a characteristic could be the PSD of fly ash, which is much less than OPC and hence absorbs more water and does not let it moves up. Second, the gel pores that form as a result of geopolymerisation seem to be more capable of holding the capillary water within the structure. It is, also, noted that the compressive strength of concrete, regardless of the type, has an opposite trend to the VVF. Therefore, the less VVF, the stronger. Although 0.5 growth in the w/b makes the total VVF increases from 2.37% for sample O1 to 2.92% for sample O2, the VVF rises from bottom to the top in both specimens. The same scenario is observed in the geopolymer concrete (G1 and G2 specimens) where the VVF is almost doubled from bottom to the top sections. Hence, in normal OPC-based and geopolymer concrete (without GGBS), the strength declines in the thickness toward the surface.

Nonetheless, the substitution of 10% GGBS in the mixtures shifts the trends oppositely. The VVFs decline from 0.74% in the bottom to 0.71% in the top and from 0.56% in the bottom to 0.49% in the top of OS and GS specimens, respectively. It leads to not only an increase in the strength of sections from bottom to the top but also 9–10% reduction in VVF due to the addition of GGBS. Thus, the substitution of GGBS in the concrete mixtures positively influences the strength by declining the bleeding rate. Additionally, having concrete that is stronger in the top section might enhance the friction properties of the material when used as pavement. Figure 5 indicates the compressive strength of the concrete cylinders. As illustrated in this figure, the changes that take place in the compressive strength of the concrete mixtures are analogous to that of section analysis. The cylindrical compressive strength ranges between 18 MPa and 31 MPa. The rebound hammer examination results are within 3.3–53.3% approximation of the cylindrical compressive strength. This can be concluded by a comparison between Figures 4 and 5.

FIGURE 3: Void analysis results of the concrete specimens.

FIGURE 4: Continued.

FIGURE 4: Void volume fraction vs. strength.

FIGURE 5: Compressive strength of the concrete cylinders.

4. Conclusions

The relationship between the void distribution pattern and strength development of OPC and geopolymer concrete is studied in this work. The void structure of concrete section is assumed as an indication of bleeding behaviour. An image analysis method is adapted to estimate the void volume fraction of concrete samples, and the rebound hammer technique identifies the strength development throughout the sections. At first glance, the achieved results indicate that there is a strong direct correlation between the void distribution patterns and strength development of concrete specimens in the absence of GGBS. However, the presence of slag in the mixtures modifies the scenario inversely. 10% of

slag replacement also decrease the VVF by up to 10% and may help to reduce the dry shrinkage cracking. Furthermore, geopolymer concrete shows superior void distribution than OPC concrete and hence better performance in bleeding behaviour. It makes geopolymers appropriate alternative materials for pavement. The VVF increases by water-to-binder ratio; this increase is less obvious in the geopolymer concrete though. According to the compressive strength examination of the specimens, the prepared mixtures are all suitable materials for pavement, while geopolymer concrete shows superior in durability characteristics.

Data Availability

The compressive strength and void analysis data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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