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Assessing drying shrinkage and water permeability of reactive powder concrete produced in Hong Kong

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ABSTRACT

Reactive powder concrete (RPC) is coarse aggregate-free which differs from that of the ordinary concrete. Instead, fine powders such as quartz sand and crushed quartz, with particle sizes ranging from 45 to 600 μm are used. In fact, it is rather a mortar than a concrete mixture because of the lack of coarse aggregate. The mechanical property performance of RPC has been investigated by the previous researchers. However, the performance on drying shrinkage and water permeability is of paucity in the literatures. This paper examines the influences of water-to-binder ratio and superplasticizer dosage on the drying shrinkage and water permeability of RPC. Recommendations for reducing drying shrinkage and water permeability of RPC are also discussed.

1. Introduction

Exciting new developments have been recorded in the area of cementitious materials such as the recent innovations in high strength concrete (HSC), high performance concrete (HPC) and ultra-high strength (performance) concrete (UHSC or UHPC). With the development of these concrete technologies, these high-tech materials provide great application potentials to the construction field. Reactive powder concrete (RPC) is coarse aggregate-free concrete, which has limited applications so far recorded in the construction industry. RPC was originally developed by Rhodia, Lafarge and Bouygues, the parent company of VSL, and is a registered trademark under the name of Ductal [1], which reported that the durability properties of RPC were in multiple folds of magnitude better than the current high performance concrete.

The ultra-high performance of RPC provides many advantages compared to the conventional concrete; such as:

(i) superior strengths with very high compressive strength of 200 MPa (approximately four times the strengths of conventional concrete) result in significant reduction in dead load. RPC structures may weigh only one-third or one-half of the corresponding conventional concrete structures. Weight reduction is good in producing more slender transportation structures, reducing overall costs and increasing usable floor space in high-rise buildings [1–3];
(ii) superior ductility and energy absorption (typical values of 300 times greater than that of HPC and is comparable to those of some metals) provide greater structure reliability even under overload conditions or earthquakes [2–4]; the high energy absorption characteristics of RPC may also allow improved post-elastic response of columns, beam-column joints and shear walls [5];
(iii) superior durability which leads to long service life with reduced maintenance. RPC is nearly impermeable, allowing almost no carbonation or penetration of chlorides and sulphates. The enhanced abrasion resistance provides extended life for bridge decks and industrial floors [3]; while the enhanced corrosion resistance provides protection to areas with bad or harsh climate conditions such as concentrated rain and snow, and heavy sandstorms [6];
(iv) elimination of steel reinforcement bars reduces high labour costs and provides greater architectural freedom, allowing nearly limitless structural member shapes and forms for architects and designers [2–4];
(v) reduction of thickness of concrete elements results in material and cost savings [7];
(vi) a significant amount of unhydrated cement in the finished product provides a self-healing potential under cracking conditions [3]; and
(vii) the fineness of the RPC product allows high quality surface finishes [3].

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Though RPC possesses many outstanding properties, they also have certain weaknesses; for example:

(i) cement content as high as 800–1000 kg/m^3 not only affects the production costs, but also has negative effects on the heat of hydration, causing shrinkage problems [7]; and
(ii) RPC is generally costly and cannot replace the conventional concrete in most applications where the conventional mixes can economically meet the performance criteria [3].

This paper aims to achieve the following objectives:

- to investigate factors affecting the drying shrinkage and water permeability behaviour of RPC;
- to examine the influences of water-to-binder ratio and superplasticizer dosage on drying shrinkage and water permeability of RPC; and
- to recommend methods for improving the behaviour of RPC.

2. Theoretical background on shrinkage of concrete

Shrinkage of concrete is caused by loss of water due to evaporation or by chemical change resulted from hydration of cement, as well as by carbonation. In general, shrinkage of concrete is believed to take place in the cement paste matrix. There are many types of shrinkages, in which drying shrinkage, autogenous shrinkage and chemical shrinkage are the most common ones. Although some other types of shrinkage, such as carbonation shrinkage, are also present, they contribute very little to the overall shrinkage and may be neglected [8]. Shrinkage is the major cause of cracking in concrete, so it should be carefully monitored.

2.1. Drying shrinkage

Drying shrinkage of concrete is the reduction in volume caused by the withdrawal of water from hardened concrete stored in unsaturated air to the surroundings [8]. It is also defined as the time-dependent strain measured at constant temperature in an unloaded and unrestrained specimen [9]. Shrinkage presents the greatest value at the member surfaces exposed to drying and decreases towards the interior of the member [9]. If drying conditions are the same at both top and bottom surfaces of the specimen, the total strain would be uniform over the depth of the specimen; however, if drying occurs at a different rate from the top and bottom surfaces, the total strain distribution becomes inclined and warping of the member would result. Drying shrinkage induces tension and results in the formation of cracks, leading to serviceability and durability problems. Factors that affect drying shrinkage of concrete include constituents, porosity, age of concrete, curing temperature, relative humidity, moisture content and types of admixtures used [10,11].

2.2. Autogenous shrinkage

Autogenous shrinkage is the apparent volume (sum of volumes of its different components such as solid, liquid or gaseous phases) reduction of cementitious materials by cement hydration [12,13]. However, it does not include volume change due to loss or ingress of substances, temperature variation, application of an external force and restraint [14]. When there is no additional water beyond that added during mixing is provided, the concrete would begin to dry out even if no moisture is lost to the surroundings. Both water-to-cement ratio and the incorporation of silica fume have significantly effects on the autogenous shrinkage of concrete [15], which is due to the internal consumption of water during hydration, which leads to autogenous shrinkage [11]. The autogenous shrinkage increases with decreasing water to cement ratios and with increasing silica fume content [14–17]. Autogenous shrinkage becomes more significant as the strength of concrete is increased, and it is analogous to drying shrinkage [10]. The major differences between drying shrinkage and autogenous shrinkage are listed in Table 1.

2.3. Chemical shrinkage

Chemical shrinkage is a phenomenon in which the absolute volume (sum of volumes of solid and liquid phases) of hydration products is less than the total volume of unhydrated cement and water before hydration, and the consequence is a decrease in the absolute volume of the hydrated cement paste during its hydration (autogenous shrinkage) [18]. In other words, chemical shrinkage is the driving mechanism of autogenous shrinkage. Chemical shrinkage is caused by hydration which depends on the porosity and on the rigidity of the material. It was confirmed that apparent volume variations coincide with absolute volume variations until the mineral skeleton is sufficiently rigid to restrain these deformations [19,20].

3. Theoretical background on permeability of concrete

Permeability refers to flow of fluids under a pressure differential through a porous medium [21]. It is used for assessing the overall movement of fluids into and through concrete. Owing to the existence of different kinds of pores, some of which contribute to permeability and some do not, it is thus important to distinguish between porosity and permeability.

3.1. Relationship between porosity and permeability

Porosity is a measure of the proportion of the total volume of concrete occupied by pores, and is usually expressed in percent [21]. If the porosity is high and the pores are interconnected, they contribute to the transport of fluids through concrete and thus its permeability is high. As stated from the above, the permeability of concrete is not a simple function of its porosity, but also depends on the size, distribution, shape and continuity of the pores. For example, though cement gel has a porosity of about 28%, its permeability is only 7×10^{-16} m/s, due to the extremely fine texture of hardened cement paste in which the pores and the solid particles are very small and numerous [22].

3.2. Factors affecting permeability of concrete

3.2.1. Progress of hydration

Permeability of cement paste varies with the progress of hydration [21]. With the progress of hydration, the permeability rapidly decreases because the gross volume of gel (including the gel pores) is approximately 2.1 times the volume of unhydrated cement, so that the gel gradually fills some of the original water-filled space. In a mature paste, permeability depends on size, shape, concentration of gel particles and on whether the capillaries have become discontinuous or not [23].

3.2.2. Water-to-cement ratio

The lower the water-to-cement ratio of the cement paste or concrete, the lower is its permeability. For cement paste, a reduction of water-to-cement ratios from 0.7 to 0.3 will lower the coefficient of permeability by 3 orders of magnitude [24]. Similarly, for concrete, a reduction of water-to-cement ratios from 0.75 to 0.26 will substantially decrease the value of the coefficient of permeability up to 4 orders of magnitude [25].