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Effect of key mixture parameters on flow and mechanical properties of reactive powder concrete

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HIGHLIGHTS

- The effect of key mixture parameters on mechanical properties of RPC evaluated statistically.
- The modulus of rupture and modulus of elasticity of RPC correlated to its compressive strength.
- Information presented in the paper can be used to produce optimum mixtures of RPC.

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ABSTRACT

The main objective of the study presented in this paper was to examine the effect of key factors, which affect the performance of reactive powder concrete (RPC) mixtures. Firstly, an optimum sand grading was selected based on the maximum compressive strength and acceptable flow of a typical RPC mixture keeping the proportions of its ingredients constant. Then, keeping the sand grading and fiber content constant at their optimum levels, a total of 27 mixtures of RPC were selected for study by considering three levels of the three key factors namely water-to-binder ratio, cement content and silica fume content, according to a 3^3 factorial experiment design. The dosage of superplasticizer for each mixture was optimized to keep the flow in the desirable range of 180–220 mm. The performance of the selected mixtures of RPC was evaluated in terms of compressive strength, modulus of rupture and modulus of elasticity. Statistical analysis of the experimental data indicated the significant effect of sand grading, water-to-binder ratio, cement content and silica fume content on flowability and mechanical properties of RPC. The regression equations were obtained for mechanical properties of RPC mixtures in terms of the key mixture parameters, which can be utilized to optimize the proportions of RPC mixtures within the ranges of the mixture variables considered in this study.

1. Introduction

It has been a challenging task to produce a very high performance concrete due to the lack of good quality coarse aggregates in many parts of the world. In a conventional mixture of concrete, the coarse aggregate particles weaker than the surrounding mortar are crushed before mortar phase besides the presence of transition zone between the coarse aggregate and mortar matrix, which is often the source of micro cracks in concrete reducing the strength and durability [1,2]. Recently, advances in concrete technology have been reported in literature leading to the development of the reactive powder concrete (RPC), also known as ultra-high performance concrete (UHPC), is relatively new generation of concrete produced as a ultra-dense mixture of water, Portland cement, silica fume, fine quartz sand, quartz powder, superplasticizer and steel fibers. The RPC mixtures are optimized at the nano and micro-scale to provide superior mechanical and durability properties compared to conventional and high performance concretes. The quality requirement of RPC are achieved through: limiting the water-to-cementitious materials ratio to less than 0.20, optimizing particle packing, eliminating coarse aggregate, and implementing special curing regimes. Short fibers are added to enhance the material's tensile and flexural strength, ductility, and toughness [2].

The RPC mixtures are designed to have flow in the desirable range of 180 ± 220 mm. The performance of the hardened RPC is evaluated in terms of mechanical properties such as compressive strength, modulus of elasticity, flexural tensile strength, and fracture toughness. From the literature survey [3–15], the ranges of mechanical properties of RPC at the age of 28 days are found as follows: compressive strength – 130–260 MPa; flexural tensile strength – 30–60 MPa; split-tensile strength – 6–8 MPa; modulus

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of elasticity – 40–70 GPa; and fracture energy – 20–40 kJ/m^2. The requirements of the constituent materials and their proportions for producing RPC mixtures are summarized in the following paragraphs.

From the point of view of chemical composition, cements with low C_3A content (for reducing the water demand) give better results [3]. Use of cements with a high fineness should be avoided due to its high water demand. The best cement in terms of rheological characteristics and mechanical performance is high silica-modulus cement. However, this type of cement has the disadvantage of a very slow setting rate, preventing its certain applications. Conventional quick-setting high performance cement offers very similar mechanical performance, despite a higher water demand.

Silica fume is one of the main constituents of RPC. Silica fume in RPC has the three main functions, which greatly improve the properties of RPC. These are as follows: filling the voids in the next larger granular class, namely cement; enhancing lubrication of the mixture due to the perfect sphericity of the basic particles; and production of secondary hydrates by the pozzolanic reaction with the $Ca(OH)_2$ from primary hydration of cement [3,16]. In typical Portland cement based concrete, 18% silica fume, by weight of the cementitious materials, is enough for total consumption of $Ca(OH)_2$ released from cement hydration [17]. However, considering the filler effect the optimal share of the silica fume may increases up to 30% of cement [3]. Therefore, the silica fume content in RPC is normally kept in the range of 25–30% of the cementitious material. Typically, the silica fume/cement ratio used for RPC is 0.25. This ratio corresponds to optimum filling performance and it is close to the dosage required for complete consumption of the lime resulting from total hydration of cement. However, cement hydration is incomplete in an RPC, and the available quantity of silica fume is more than that required by the pozzolanic reaction. Utilization of fly ash (FA) and ground granulated blast furnace slag (GGBFS) as an alternative to silica fume in RPC has been reported in the literature [4,11].

For enhancing the homogeneity of RPC, coarse aggregate is replaced by fine quartz sand. The maximum size of sand is recommended to be 600 μm for use in RPC [3]. Sand constitutes the largest portion of RPC with about 41% by weight of RPC. To obtain a highly homogeneous matrix as well as minimum void, RPC contains finely graded sand between 150 μm and 600 μm. Sand particle sizes below 150 μm are avoided for preventing interference with the largest cement particles (80–100 μm). Sand with a mean particle size of about 250 μm is preferred.

Crushed crystalline quartz powder in the size range of 10–15 μm is used as filler in RPC. Since quartz powder is a reactive material, it acts as an excellent paste-aggregate interface filler [3]. For cases where heat-treatment is employed, quartz powder demonstrates even higher reactivity. Maximum reactivity during heat-treatment is obtained for a mean particle size of between 5 and 25 μm. The mean particle size of the crushed quartz used for an RPC is l0 μm, and is therefore in the same granular class as the cement [3].

Since RPC uses a small water/binder ratio, superplasticizer is needed to achieve its required flowability. High performance superplasticizers having either polycarboxylate, Naphthalene Sulfonate or Melamine Sulfonate (MS) enable in producing dense and highly homogeneous RPC mixtures, which can be poured without segregation. The most efficient superplasticizers are polyacrylate-based dispersing agents, but it exhibits a retarding characteristic, which can pose a problem for practical applications.

RPC without fibers is also strong but very brittle, consequently fibers are included to increase the tensile capacity and improve its ductility. Studies using different fiber materials, contents, sizes, and shapes have been conducted by various researchers [18]. Dimensionally, the largest constituent in the mix are the steel fibers. Given the relative sizes of the sand and the fibers, the steel fibers are able to reinforce the concrete matrix on a micro level [8]. The addition of steel fibers helps in preventing the propagation of micro-cracks and macro-cracks and thereby limits crack width and permeability. Because of its size relative to the other constituents, it reinforces the concrete on the micro level and eliminates the need for secondary reinforcement in prestressed bridge girders [19]. An optimum dosage of 6.2% (by weight of RPC) of steel fibers is recommended by Ductal® [20].

Sobolev [21] has presented the following approach for optimizing RPC mixture using the rheological and strength models. First, the optimal silica fume (SF) content and superplasticizer (SP) dosage are selected according to the strength model of modified mortars: for optimal performance, SF content is specified within 10–15% and SP dosage is set to be 10% of SF. Second, the aggregates are optimized to fit a specific grading curve. Then water to cement ratio is selected using the strength model. The parameters considered in the design of mixture of RPC are mainly, water to binder ratio, cement content, micro silica to cement ratio, total cementitious material content, total fine aggregate content, and fiber content. From literature survey [3–15], the ranges for these parameters are found to be as follows. Water to total binder ratio: 0.15–0.24 (by weight); cement content: 800–1100 kg/m^3; silica fume content: 150–300 kg/m^3; silica fume to cement ratio: 0.15–0.35 (by weight); cement and micro-silica (i.e., binder or cementitious materials) content: 950–1400 kg/m^3; sand and quartz content: 1000–1400 kg/m^3; steel fiber content: 190–250 kg/m^3; and steel fiber to total binder ratio: 0.15–0.30 (by weight).

From the literature review presented above, it can be noted that a series of the mixtures of RPC can be produced with different combinations of the levels of the key factors within their ranges of variation. This exercise would help in determining optimum proportioning of the constituents of RPC based on the minimum unit cost of RPC satisfying the flowability and mechanical properties. In the present study, an attempt was made first to select the optimum sand grading and then selecting a total number of 27 mixtures of RPC considering three levels of water/binder ratio, cement content and silica fume content according to a 3^3 factorial experiment design. For all 27 mixtures, optimum dosages of superplasticizer were determined based on the required flowability followed by evaluation of their performance in terms of mechanical properties. Statistical analysis of the experimental data was carried out to examine the significance of each factor and finally correlation equations were obtained which could be utilized for optimizing the mixture proportioning.

2. Experimental program

2.1. Materials

2.1.1. Cement and silica fume

Type I cement (ordinary Portland cement) conforming to ASTM C150 [22] with a specific gravity of 3.15 and chemical composition, as shown in Table 1, was used in all the mixtures of RPC. The chemical composition of the silica fume used is also shown in Table 1.

2.1.2. Fine dune sand

Fine dune sand obtained from the deserts of Saudi Arabia, with water absorption of 0.5% and specific gravity of 2.53, was used as aggregate. The natural grading of sand, used in all the mixtures, is shown in Table 2.

2.1.3. Superplasticizer and steel fibers

A liquid superplasticizer (commercial name: Glenium 51) was used to obtain the desired flow. Glenium 51 is a polycarboxylic ether (PCE) based superplasticizer, which does not contain chlorides and complies with ASTM C494 [23] Types A and F. The specific gravity of Glenium 51 was 1.095% with 65% water content by weight. Varying dosage of this superplasticizer was used to obtain a flow of 200 ± 20 mm for all the mixtures. Steel fibers of 0.22 mm diameter and 13 mm length with tensile strength greater than 2850 MPa were used in all the mixtures.