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Development of ultra-high performance concrete with locally available materials

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HIGHLIGHTS

- Ultra-high performance concrete using locally available materials was developed.
- Sand gradation, binder content and type, and curing regimens were examined.
- The concrete strength ranged from 114.1 MPa to 155.2 MPa.
- When the binder contains silica fume, using a fine sand does not increase compressive strength.
- Compressive strength of cube specimens were 11 percent greater than cylindrical specimens cast with the same concrete.

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ABSTRACT

Ultra-High Performance Concrete (UHPC) is an advanced type of concrete that can enhance the durability and resilience of concrete structures. The use of local materials is a fundamental step to save materials and energy and reduce the cost of concrete. In this study, the effect of sand gradation, binder type and content, and curing regimes on concrete's compressive strength was examined. Results indicated a 90-day strength of 155 MPa was achieved with a silica fume content of 5% and without heat curing. A curing regime of 2 days at 60 °C followed by 3 days at 90 °C resulted in the highest strength.

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1. Introduction

The development in mineral admixtures (e.g., silica fume and fly ash) and chemical admixtures [e.g., high-range water reducer (HRWR)] leads to the introduction of several types of high-quality concrete. These types of concrete typically include high-strength concrete, high-performance concrete, and fiber-reinforced concrete. The further advancement in concrete technology has resulted in a new type of concrete called Ultra-High Performance Concrete (UHPC). UHPC is a cement-based composite with a compressive strength of 150 MPa and tensile strength of 6.2 MPa [1–3]. The age at which UHPC achieves these strength has not been specified. The benefits of using UHPC in the design of precast, prestressed concrete structures have been confirmed in a number of projects in United States, Germany, Canada, France, and Australia. In the United States, UHPC is mainly used for bridge applications that include precast, prestressed bridge girders, precast waffle panels, and as a jointing material between precast concrete deck panels and girders [4–7].

In 1990s, UHPC was first known as reactive-powder concrete since it contained only very fine materials [8]. A typical UHPC mixture proportion consists of cement, supplementary cementitious materials (e.g., silica fume, fly ash, and slag cement), fine sand, quartz or glass powder, HRWR, steel fiber, and a low water content [1,9,10]. Coarse aggregate is excluded in many UHPC mixture proportion. This exclusion reduces the micro-cracks that are present in the coarse aggregate and in the interfacial transition zone between the paste matrix and coarse aggregate. These micro-cracks can increase the permeability of concrete [11]. In addition, when the

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concrete resists external loads, mechanical cracks tend to occur at the existing micro-cracks and propagate through the paste matrix and coarse aggregate which can lead to failure of the concrete. Therefore, the exclusion of coarse aggregate is necessary to improve the strength and durability of UHPC.

In terms of placement procedures, UHPC can reduce the time and the labor related to placement. UHPC tends to exhibit rheological behaviors similar to self-consolidating concrete. Therefore, the casting efforts are reduced, but additional form preparation is possibly needed [12]. The use of HRWR is one of main contributing factors to the high workability of UHPC while a low water content is necessary to achieve a high compressive strength [2,9,11]. Researchers have found that the water to binder ratio (w/b) of UHPC can be decreased to 0.12 [13]; where binder is the total content of cement and supplementary cementitious materials. However, the required water to cement (w/c) ratio for full hydration of cement is 0.32 [11]. For conventional concrete with a typical w/c ratio of 0.4, the degree of hydration increases from 80% to 100%. For UHPC, the water content is so low that all of the cement particles are not hydrated [14].

UHPC is available as a premix in many markets [5]. The premix requires special attention during mixing, casting, curing and testing. For example, a high-shear mixer is typically necessary for the mixing UHPC and a heat-curing technique can be used to achieve a high compressive strength. Ductal® is a marketed form of UHPC that was developed by the participation of three companies: Lafarge, Rhodia, and Bouygues. Quartz powder with a diameter of 10 μm is used in the UHPC premix as a micro-filler material, and the premix also contains high tensile strength fibers (tensile strength of 2600 MPa) [13,15]. The use of these materials increases the cost of the premix. Commercially available UHPC is about 20 times more expensive than conventional concrete, which is about $100/yd^3. This UHPC price includes the material costs of the proprietary blend and the fiber reinforcement, and the costs associated with the development and delivery of said material [15].

A potential solution to reduce the UHPC cost is to use a sand that has an average diameter of 150–600 μm or a natural sand as a filler material. However, the concrete's compressive strength can decrease when the diameter of the filler material increases. In this study, the authors investigate the effect of using a natural sand on the concrete's compressive strength. The use of a local sand not only reduces the cost of UHPC but also eliminates the time and labor necessary to produce the ultra-fine sand which has an average diameter less than 600 μm. The optimal use of supplementary cementitious materials, typically including silica fume and fly ash, additionally reduces the concrete cost. It is anticipated that UHPC can replace conventional concrete in various structural applications, including precast and cast-in-place concrete applications, due to its improved structural durability and extended service life. Therefore, there is a need to develop UHPC using local materials, which enables engineers to use UHPC when necessary without significant increases in cost.

2. Literature review

A number of studies have developed the mixture proportions and evaluated the mechanical properties of UHPC since 2000s. In the United States, the Federal Highway Administration is one of many organizations that have investigated the development and applications of UHPC [1,13,15,16]. In the literature, there are two major trends in the UHPC research. The first trend focuses on the enhanced UHPC mechanical properties, typically including compressive strength, tensile strength, shear strength, and durability-related properties. These improved properties are achieved by optimizing the UHPC mixture proportion. The second trend concentrates on applications for UHPC and aims at promoting its use in the design and construction of concrete structures. In the current state-of-the-art, UHPC has shown unique advantages for long-span bridge applications [17]. The development of UHPC using local materials can create additional opportunities for the UHPC applications in building and underground structures. In the following paragraphs, the contribution of the constituent materials to the mechanical properties is discussed. This will lead to the development of simplified UHPC mixture proportions as presented in the experimental program.

Table 1 shows a typical mixture proportion of UHPC premix that is available [6,10,13]. A large amount of binder is necessary to produce UHPC with a minimum compressive strength of 150 MPa. For the mixture shown in Table 1, the binder accounts for almost 40% of the total mass of the mixture. Silica fume accounts for 25% of the binder, which could be as high as 30% of the binder according to Ma and Schneider [18]. The use of silica fume is required to achieve a high compressive strength and durability. Silica fume accelerates the pozzolanic reactions that produces additional calcium silicate hydrates (C-S-H) and fills the voids in the paste matrix [11]. However, the improved properties associated with the addition of silica fume do come with a price; in the current market, silica fume is 4–7 times more expensive than Portland cement. Wang et al. [19] stated that a UHPC mixture with a minimum compressive strength of 138 MPa at 28 days and 150 MPa at 56 days can be produced with 10% of the binder replaced by silica fume. Likewise, El-Hadj Kadri et al. [20] concluded that the effect of silica fume on the concrete's compressive strength is minimal when used at a replacement rate greater than 10% of the binder. The concrete mixtures using silica fume at replacement rates of 20% and 30% had lower compressive strength when compared to the mixtures containing 10%. The effect of silica fume and any other pozzolanic materials can depend on the curing conditions. In this study, the authors determine the most effective silica fume content for developing UHPC using the locally available materials, which not only provides an adequate compressive strength but also minimizes the cost of UHPC.

Ground quartz is another filler material that accounts for 8.4% of the total weight of the mixture shown in Table 1. Ground quartz has an average diameter slightly less than the diameter of Portland cement, which enables this material to fill the possible voids between sand, unhydrated cement particles, and the hydration products which creates a denser paste matrix. A denser concrete matrix increases the compressive strength and decreases permeability. However, the use of ground quartz may not be necessary due to a substantial portion of unhydrated Portland cement which fills the voids and produces a dense paste matrix. Velez et al. [21] found that the stiffness of unhydrated cement particles is greater than the other components in the paste matrix. Therefore, the

Table 1
Typical UHPC mixture proportion [6,10,13].

Material	Amount (kg/m^3)	Percentage by weight	Average diameter (μm)
Total Binder (Portland cement and silica fume)	943	37.8	n/a
Portland cement	712	28.5	15
Silica fume	231	9.3	<10
Filler material (ground quartz and fine sand)	1231	49.2	n/a
Ground quartz	211	8.4	10
Fine sand	1020	40.8	150–600
Water	109	4.4	n/a
Superplasticizer	30.7	1.2	n/a
Accelerator	30	1.2	n/a
Steel fibers	156	6.2	200

(Note: n/a = not applicable).

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