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Technical note

Abrasion resistance of ultra high performance concrete incorporating coarser aggregate

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HIGHLIGHTS

- UHPC shows excellent abrasion resistance compared with HPC.
- Abrasion resistance of UHPC was decreased by using coarser aggregates.
- Exposure of steel fiber might became surface corrosion spots.

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ABSTRACT

This experimental study was conducted to evaluate the abrasion resistance of ultra high performance concrete (UHPC) that incorporated pre-selected coarser aggregates. The aggregates were selected based on their properties and local availability. In addition, coal bottom ash powder was also used with coarser aggregates as a replacement for silica powder. The examination was made according to the ASTM C 944 test method and the results were determined and presented as mass loss and depth of abrasion. All the results from the tests reveal the excellent abrasion resistance of UHPC; however, when compared to each other, the UHPC with coarser aggregates shows a lower abrasion resistance than the UHPC with no coarser aggregates.

1. Introduction

In the last few decades, the enhancement of concrete properties has led to the development of ultra high performance concrete (UHPC), which shows advanced mechanical and durability properties. Although different researchers or societies have defined UHPC using several criteria, most works in the literature have defined it as a cementitious composite material that has a compressive strength greater than 150 MPa, internal fiber reinforcement, selected aggregates based on particle packing theories, and low water-cement ratio (less than 0.25) with a high dosage of superplasticizer [1–3]. With little or no sacrifice of mechanical properties, pre-selected coarser aggregates having the particle size ranged from 1 to 9 mm have been implemented along with finer one ranged from 0.15 to 5.2 mm in certain studies leading to cost reduction [4,5] and improvement of shrinkage properties [6]. The development of UHPC has mainly been focused on the mechanical and structural properties; however, the durability properties are strongly related to the mechanical properties [7]. Due to the superior strength and durability of UHPC over the ordinary concrete, the application of UHPC can reduce the required quantity of concrete for structures as well as the maintenance cost [8].

Among many factors that affect the durability of concrete, one type of commonly occurring concrete deterioration, which causes surface deterioration or progressive mass loss from the concrete surface, is abrasion or wearing. It mostly occurs on pavements, industrial floors, and surfaces that are exposed to rubbing, skidding, sliding, and friction forces [8–10]. The definition of ASTM for abrasion is “wear due to hard particles or hard protuberances forced against and moving along a solid surface” [11]. The American Concrete Institute (ACI) [12] defines abrasion resistance as the “ability of a surface to resist being worn away by rubbing and friction”.

Previous studies have indicated that the abrasion resistance of concrete is related to several factors like compressive strength, tensile strength, quality of aggregates, concrete type, the use of supplementary cementitious materials, curing condition, and surface finishing. The replacement of a certain amount of cement by supplementary cementitious materials, i.e., fly ash, silica fume,

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and granulated blast furnace slag, leads to a pore refining effect and creates a denser interfacial transition zone. Due to this, improvements of compressive strength and abrasion resistance are observed [9,13,14]. According to the study of Sonebi and Khayat [15], incorporation of granite aggregate leads to improvement of the abrasion resistance of high-strength concrete. In the study of Graybeal and Tanesi [7], the effects of curing types and surface treatment methods on the abrasion resistance of UHPC were evaluated, while concrete samples having different strength and mix proportions were not evaluated.

In this experimental study, the effect of coarser fine aggregates on the abrasion resistance of UHPC is evaluated. Two types of rock aggregates, i.e., dolomite and basalt, was chosen for the UHPC considering strength of particles and local availability. Note that the rock aggregates having high uniaxial compressive strength (UCS) showed high abrasion resistance in general [16,17]. Dolomite is a sedimentary carbonate rock composed of calcium magnesium carbonate. It has been reported that the UCS of dolomite was within the ranges from 100 MPa to 240 MPa [18,19]. Basalt is a quartz-based volcanic rock having 150–250 MPa of UCS which may differed by their mineral composition and porosity [20,21]. Additionally, coal bottom ash powder was also used with coarser aggregates as a replacement for silica powder. The abrasion examination is conducted using ASTM C-944 [22], the standard test method for abrasion resistance of concrete or mortar surfaces using the rotating-cutter method. For the purpose of comparison, high strength and normal strength concretes are prepared and examined for abrasion. Compressive and uniaxial tensile strength tests of the prepared UHPC are also performed.

2. Experimental program

2.1. Materials and mix proportions

The experimental program implemented in this study utilized six types of mixture. Four of them were UHPC mixtures that were designed based on particle packing theory. The other two types were a normal and high-strength concrete designed according to ACI standards [23,24]. For the UHPC mixtures, two types of carefully selected locally available dolomite and basalt coarser aggregates with a maximum particle size of 5.2 mm were included. The size information for the coarser aggregates used for UHPC is presented in Table 1. Furthermore, the ground bottom ash powder having the mean particles size of 5.88 μm and specific gravity of 2.47 of was also used with coarser aggregates as a replacement for silica powder. In all UHPC mixtures, a brass coated smooth steel fiber with 19.5 mm length, 0.2 mm diameter and a minimum tensile strength of 2.45 GPa were used. All the applied material properties and mix proportions for UHPC are identical to Ref. [5]. For the normal and high-strength concrete, natural river sand as fine aggregates and crushed coarse aggregates with a maximum size of 19 mm were used. The mix proportions, and the compressive and tensile strength results of the mixtures, are presented in Table 2.

Each UHPC series name is designated according to filler (S for silica powder and C for coal bottom ash powder), coarser aggregates (N for no coarser aggregates, D for dolomite and B for basalt), and 1.5 for fiber volume fraction. For instance, SB1.5 represents a mixture with silica powder used as filler, basalt used as coarser aggregates and a 1.5 volume fraction of steel fibers. The designations for normal-strength and high-strength concrete are NSC and HSC, respectively.

2.2. Experimental details

All the mixtures described in Table 2 were mixed in a similar manner using a laboratory planetary mixer. In order to minimize the agglomeration of particles, silica fume and silica sands were first dry mixed together for about 5 min, and then cement and fillers (silica powder or coal bottom ash powder) were added and dry mixing was continued for an additional 5 min. After the fine particles seemed to have an equal distribution, water and a superplasticizer were gradually added to the dry mixture while the mixer was spinning. Once the mixture started to show adequate consistency, steel fibers and coarser aggregates were added to the mixer and it was allowed to mix until a uniform distribution was achieved. In the cases of normal- and high-strength concrete, all solid materials were dry mixed for 3–5 min; then, water and superplasticizer were added and materials were mixed for 2 min more. For the UHPC mixtures, compressive and uniaxial tensile strength and abrasion tests were executed; however, for the normal and high strength concrete, only compressive and abrasion resistance tests were executed. The UHPC mixture was poured into 150 × 60 mm cylindrical molds for abrasion tests, 50 mm cubic molds for compressive tests, and JSCE molds for tension tests; then, the surfaces were polished properly. The normal and high-strength concrete mixtures were poured into 150 × 150 × 60 mm rectangular molds and 100 × 200 cylindrical molds for abrasion and compressive strength tests, respectively. In order to prevent moisture loss, the casted specimens were covered with plastic sheets and stored at room temperature for 24 h. After 24 h, the specimens were cured in a 23 °C water tank.

Assessment of the abrasion resistance of concrete is difficult because the damaging action depends on the exact cause of the wear [10]. In this study, the examination was carried out using ASTM C-944. This test method has been successfully used in the quality control of highway and bridge concrete subject to traffic. This test method is also used to simulate the abrasive effect of foot traffic, light-to-medium tire-wheeled traffic, forklifts, heavy tire-wheeled traffic, automobiles with chains, heavy steel-wheeled traffic or studded tires, etc. This method produces a much more rapid abrasive effect than the other respective ASTM test methods [11]. Before the test, the specimens were water cured for 28 days and dried at room temperature for several days. This method is intended to measure the mass loss and abraded depth when the specimens are subjected to scraping and skidding forces by a dressing wheel. The rotating cutter, constructed with 22 dressing wheels with diameters of 37.5 mm (1.5 in.) and 24 washers with diameters of 25.4–31.75 mm (1–1.25 in.), were mounted on a drill press that was capable of holding and rotating the abrading rotating cutter at a speed of 200 rpm while exerting a constant load. According to the recommendation of ASTM C-944 and due to the expected high abrasion resistance of UHPC, a double loading condition (197 ± 2 N or 20 kg) was used throughout the testing. A total 40–80 min abrasion period was applied and measurements for mass and depth were taken at intervals of 10 min to the nearest

Table 1
Particle size of aggregates in UHPC (reproduced from Ref. [5]).

Parameters	Sand I	Sand II	Dolomite I	Dolomite II	Basalt
Aggregate fractions (mm)	0.01–0.65	0.03–1.1	0.15–2.2	1.3–5.0	0.45–5.2
Median size (mm)	0.15	0.53	1.23	2.91	3.38
Specific gravity	2.65		2.75		2.0