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Durability properties of lightweight self-consolidating concrete developed with three types of aggregates

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HIGHLIGHTS

- Lightweight self-consolidating concrete (LWSCC) with three types of aggregates.
- Evaluate LWSCC resistance to elevated temperatures and acid attack.
- Evaluate LWSCC resistance against freeze–thaw and salt scaling.
- Confirm potential of proposed LWSCC mixtures for construction applications.

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ABSTRACT

The durability properties of lightweight self-consolidating concrete (LWSCC) using three types of lightweight aggregates: furnace slag (FS), expanded clay (EC), and expanded shale (ES) is presented. LWSCCs exhibited superior fire resistance in terms of residual strength showing formation of no major cracking (only visible hairline cracks)/spalling after exposure to elevated temperatures of up to 900 °C for a duration of 1.5 h. Salt-scaling resistance was also found to be adequate and primarily dependent on the aggregate quality and associated properties. LWSCC mixtures showed enhanced resistance against sulfuric acid attack due to proper formation of the cementitious paste matrix. However, non-air entrained LWSCC mixtures were unable to withstand severe freezing and thawing cycles.

1. Introduction

Using lightweight aggregates (LWA) in concrete has several advantages including lower thermal connectivity as well as maximized heat and sound insulation properties due to air voids. It is also reported that reducing the dead load of a building, by using lightweight concrete, could lead to a considerable decrease in the cross-section of steel-reinforced columns, beams, plates and foundations, thus reducing the need for steel reinforcement and leading to increased cost savings [1–3]. In addition to its many benefits, the unique aggregate-paste matrix which comprises this material requires some additional consideration to ensure long-term durability. lightweight self-consolidating concrete (LWSCC) has been successfully produced in the past to meet and surpass various durability criteria [4].

Lightweight concrete is more resistant to elevated temperatures than normal weight concrete because of its lower thermal conductivity, lower coefficient of thermal expansion, and inherent fire stability of an aggregate already heated to over 1100 °C during production [1]. The lower thermal conductivity of the lightweight concrete allows the concrete reinforcement to be better insulated from high temperatures, thus allowing longer structural stability. Potential air pockets play a large role in the elevated temperature resistance of concrete. It has been found previously that the introduction of synthetic fibers into concrete mixtures may reduce damage at elevated temperatures as the fibers will tend to melt and form a pore system that allow vapor pressure to escape [5]. On that similar concept, the introduction of already porous LWA may be beneficial.

However, some researchers had found that concrete porosity may adversely affect the resistance (specifically LWSCC) to elevated temperatures [6]. Thermal crack patterns have a tendency to follow concrete's weakest zone, the interfacial transition zone (ITZ), whereas cracks tend also to follow a path inside specifically

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porous aggregate [6]. Also, the higher porosity of LWA may lead to a higher moisture content inside the concrete, and thus a buildup of vapor pressure, especially in cases of higher strength/lower permeability concrete, which may lead to spalling [7]. In the case of self-consolidating concrete (SCC) of a decreasing strength, it has been found to experience increased strength loss at higher temperatures compared to a higher strength concrete [8]. As such, achieving the desired paste matrix remains critical in the design of LWSCC.

In other studies, the acid resistance of lightweight mortars made with Pumice have exhibited rather less resistance to acid attack where excessive damage was observed on the outer surface of specimens [9]. However, evidence of higher damage to LWA concrete was also exhibited in the case of sulfuric acid relative to conventional concrete, especially when an air-entraining agent was used [10]. Given the exhibited performance, it remains crucial to investigate this parameter to determine an adequately resistant LWA.

In colder climates, it is also important to understand the freezing and thawing behavior of concretes as well as their resistance to salt-scaling. LWSCC with adequate freezing and thawing resistance has been produced in the past [11]. In fact, enhanced compressive strength (relative to conventional aggregate concrete) was even observed after cycles of freezing and thawing in instances where LWA was introduced into mixtures [12]. Resistance to freezing and thawing in lightweight concrete has been found to improve through various means including the pre-wetting of the lightweight aggregate [13], the use of silica fume and metakaolin [13,14], use of volcanic ash and pumice aggregates [4], as well as the use of water-reducing admixtures to increase paste density and improve durability through controlling the micro-cracking behavior of LWA concrete [15]. The fact remains that the freeze–thaw resistance is still dominantly influenced by the paste properties, specifically adequate air-entrainment as LWA concretes tend to be more sensitive to scaling due to the higher degree of saturation [16].

This paper compares the durability properties of LWSCC mixtures developed with various types of lightweight aggregates by describing experimental results of resistance to elevated temperatures, salt scaling, sulfuric acid attack, and cycles of freezing and thawing.

2. Research significance

Lightweight concrete is widely used due to its better structural and elevated temperature resistance performance. While several researchers studied various factors including fresh, mechanical, and durability performance of self-consolidating normal-weight concrete, there is no adequate research for LWSCC. This research compares the durability properties in terms of resistance to elevated temperatures, salt scaling, sulfuric acid attack, and cycles of freezing and thawing for nine LWSCC mixtures developed with three widely available lightweight aggregates types namely, furnace slag (FS), expanded clay (EC) and expanded shale (ES). As a result, the authors believe that this specific study dealing with the long-term durability performance of LWSCC will contribute to the enhancement of existing knowledge and will be very useful to the construction industry.

3. Experimental investigation

3.1. Materials

General Use (GU) Portland cement (equivalent to ASTM Type I), Class F fly ash (FA) and silica fume (SF) were used. The physical and chemical properties of cement, FA, and SF are presented in Table 1. FA and SF were incorporated into the mixtures at a fixed percentage (by mass of total binder) at 12.5% and 7.5%, respectively.

Three types of aggregates were used to develop the LWSCC mixtures: screened air-cooled blast furnace slag from an Ontario, Canada source, expanded clay from Erwinville, Louisiana, USA, and expanded shale from Denver, Colorado, USA. These lightweight aggregates had maximum nominal sizes of 4.75 mm and 10 mm, used as fine and coarse aggregates, respectively (Fig. 1). Table 2 presents specifications for coarse and fine lightweight aggregate gradation according to ASTM C330, as well as the gradations and physical properties of fine and coarse lightweight aggregates of FS, EC, and ES.

Table 3 presents the chemical properties of lightweight furnace slag, expanded clay and expanded shale. SF was used to develop a sticky mixture, holding the coarse aggregate in place and preventing aggregates from floating over the surface, hence enhancing the segregation resistance. A polycarboxylate ether type High Range Water Reducing Admixture (HRWRA) with a specific gravity of 1.05 and total solid content of 26% was used as Superplasticizer (SP).

3.2. Mix design methodology and mixture proportion

Regarding the concrete mix design, the standard mixture proportions of LWSCC were determined through preliminary experimentation. LWSCC mixtures should satisfy flowability, segregation resistance, L-box ratio, and filling ability in its fresh state. Accordingly, three LWSCC mixtures made with three different lightweight aggregates, furnace slag, expanded clay and expanded shale (total nine mixes) aimed to satisfy EFNARC [17] classes for SCC (1–3) were investigated for fresh and hardened properties. The typical fresh properties of SCC as per EFNARC are presented in Table 4.

The mix proportions of FS-LWSCC, EC-LWSCC and ES-LWSCC mixtures were formulated to yield three classes of LWSCC mixtures with the following fresh properties/classes:

LWSCC-1: Casting by a pump injection system (e.g. tunnel linings).

LWSCC-2: Suitable for many normal applications (e.g. walls, columns).

LWSCC-3: Suitable for vertical applications in very congested structures, structures with complex shapes, or for filling under formwork.

3.3. Batching procedure, casting, and curing of test specimens

All concrete mixtures were prepared in 125 L batches in a fixed horizontal industrial pan mixer. Due to the high water absorption capacity of the lightweight aggregates, the aggregates were pre-soaked for a minimum of 72 h. The saturated surface dry

Table 1
Chemical and physical properties of cement, fly ash and silica fume.

Chemical composition	Cement	Fly ash	Silica fume
SiO_2 (%)	19.6	46.7	95.21
Al_2O_3 (%)	4.9	22.8	0.21
Fe_2O_3 (%)	3.1	15.5	0.13
CaO (%)	61.4	5.8	0.23
MgO (%)	3	–	–
SO_3 (%)	3.6	0.5	0.33
Alkalis as Na_2O (%)	0.7	0.7	0.85
LOI (%)	2.3	2.2	1.97
Blaine (cm^2/g)	3870	3060	21000
+45 μm (%)	3.00	17	2.85
Density (g/cm^3)	3.15	2.48	2.20