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Application of statistical models in proportioning lightweight self-consolidating concrete with expanded clay aggregates

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HIGHLIGHTS

- Developed statistical models for proportioning of expanded clay aggregate LWSCCs.
- Evaluated the influence of mix design parameters on the properties of LWSCCs.
- Mix design parameters are optimized for satisfactory LWSCC properties.
- Robust LWSCC mixtures satisfying EFNARC criteria are proposed.
- Proposed models are useful tools for designing LWSCCs for practical applications.

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ABSTRACT

A response surface method based experimental study was carried out to model the influence of key parameters on the properties of Lightweight Self-Consolidating Concrete (LWSCC) mixtures developed with expanded clay (EC) aggregates. Three key mix design parameters were selected to derive mathematical models for evaluating fresh and hardened properties. Water to binder ratio of 0.30–0.40, high range water reducing admixture (HRWRA) of 0.3–1.2% (by total content of binder) and total binder content of 410–550 kg/m^3 were used for the design of and testing of twenty LWSCC mixtures. Slump flow diameter, V-funnel flow time, J-ring flow diameter, J-ring height difference, L-box ratio, filling capacity, sieve segregation, fresh/28-day air/oven dry unit weights and 7- and 28-day compressive strengths were evaluated to analyze influence of mix design parameters and develop the models. Utilizing the developed models, three optimum expanded clay LWSCC (EC-LWSCC) mixtures with high statistical desirability were formulated and tested. It was possible to produce robust EC-LWSCC mixtures that satisfy the European EFNARC criteria for Self-Consolidating Concrete (SCC). The proposed mix design models are proved to be useful tools for understanding the interactions among mixture parameters that affect important characteristics of EC-LWSCCs. This understanding might simplify the mix design process and the required testing, as the model identifies the relative significance of each parameter, provides important information required to optimize mix design and consequently minimizes the effort needed to optimize LWSCC mixtures, and ensures balance among parameters affecting fresh and hardened properties. Examples highlighting the usefulness of the models are presented using isoresponse surfaces to demonstrate single and coupled effects of mixture parameters on measured properties. LWSCCs with EC lightweight aggregates can reduce the construction pollution, increase the design solutions, extend the service life of the structure and hence, promote sustainability in construction industry.

1. Introduction

Self-Consolidating Concrete (SCC) is capable of filling up the formwork and encapsulate reinforcement by its self-weight without the need for additional compaction or external vibration. In addition it has excellent segregation resistance and high flowability and passing ability at fresh state. There are many other advantages of using SCC which include: reduction in the labor cost, better compaction and finish-ability in confined and restricted areas where compaction is difficult, and faster construction completion [1]. Due to these advantages, in recent years, SCC has been extensively used in many structural applications [1]. Lightweight

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aggregate concrete (LWC) has also been used successfully for the structural purposes for many years [2].

Lightweight SCC (LWSCC) combines the favorable properties of LWC and SCC. Using lightweight aggregates (such as expanded clay/shale, pumice, and blast furnace) in concrete has several advantages including increased strength-to-weight ratio, reduced modulus of elasticity, improved thermal and sound insulation and fire resistance properties [2]. Potential use of structural LWC involves situations when it is desirable to reduce a structure's dead load particularly in earthquake zones [2,3]. In addition, substantially lighter LWC (compared to normal weight concrete) can also save on transportation, formwork and concrete placement related costs [2,3]. These LWC advantages can be greatly utilized by incorporating lightweight aggregates in SCC mix design. Provided that the strength, mechanical and durability characteristics are comparable to normal weight SCC, LWSCC can be prompted as a new generation of high performance concrete in construction.

Although numerous investigations have been made on SCC and LWC, to the authors' best knowledge little research has been conducted on the design procedures and statistical modeling of LWSCC [4–7]. Choi et al. [8] designed the mix proportion for LWSCC by adopting a modified method proposed by Su and Miao [9]. The slump flow, V-funnel and U-box tests were then used to evaluate the workability of LWSCC. Similarly, Shi and Wu [10] used the slump flow, V-funnel, and L-box tests, and the visual observation method to study the properties of LWSCC.

Hwang and Hung [11] evaluated the performance of LWSCC mixtures containing sintered bottom ash, for varying water to cement ratio (w/c) and cement paste content. Thirteen mixes were designed with the densified mixture design algorithm method (DMDA). The main goal of this method was to obtain high strength along with a high flowing concrete. The approach taken during this investigation was to use fly ash to fill voids of aggregate instead of replacing part of the cement as in traditional mix design methods. Thus, fly ash physically filled the voids, densified the mixture and acted chemically as a pozzolanic material to strengthen the microstructure. Müller and Haist [12] proposed three mix proportions for LWSCC and assessed their self-compacting properties by the slump flow, J-ring, V-funnel, and L-box tests. No significant difference in the mix proportion design was found compared with SCC except for the aggregate used. Wu et al. [13] investigated workability of LWSCC and its mix proportion design using expanded shale aggregates at fixed fine and coarse aggregate contents using the volumetric method. The study demonstrated that fixed aggregate contents can be used effectively in volumetric method to design LWSCC mixtures. An increase in the paste content of the mix increased the flow velocity but reduced resistance to segregation.

Lachemi et al. [14] developed three different classes of LWSCC mixtures with two different types of lightweight aggregates (blast furnace slag and expanded shale aggregates). The influence of the type of concrete (LWSCC vs. normal weight SCC), and the type of lightweight aggregates on the steel–concrete bond strength and failure modes were also studied. Kim et al. [15] studied the characteristics of SCC using two types of lightweight coarse aggregates with different densities, mostly semi-lightweight (2000–2300 kg/m^3). Nine mixes were evaluated in terms of flowability, segregation resistance and filling capacity of fresh concrete. The mechanical properties of hardened LWSCC, such as compressive strength, splitting tensile strength, elastic modulus and density were assessed.

Due to the increasing interest in LWSCC construction in recent years, a comprehensive research program was developed by the authors to contribute to the existing knowledge. While design procedures and statistical modeling for self-consolidating normal-weight concrete have been published [16–19], lacks in adequate research studies warrants investigations on LWSCC technology. Authors research based on statistical experimental design approach to identify primary mix design parameters and their coupled effects on relevant properties of expanded clay (EC) lightweight SCC (EC-LWSCC) is a timely initiative. The knowledge of influence of mixture variables on fresh state and hardened characteristics (which is the objectives of the current study) is essential for successful development of EC-LWSCCs.

This paper presents the outcomes of the research conducted in three phases and explains the relationships between mix design parameters/factors affecting EC-LWSCC important characteristics. In addition, the paper presents development and validation of statistical models for the design of EC-LWSCC mixtures with desired fresh and hardened properties. The statistical models developed in this study will simplify the test protocol needed to optimize EC-LWSCCs and can serve as a tool for practical production. In addition, simplification of the optimization process of EC-LWSCC mixtures also led to a balance between mix design parameters affecting workability and hardened properties. The recommendations of this research will be useful for engineers, designers and manufacturers involving in the development, production and use of EC-LWSCCs.

2. Research program

This research was conducted in three phases. The Phase I focused on the experimental study of the fresh and hardened properties of mathematically derived EC-LWSCC mixes. Twenty concrete mixtures were designed. Three key mix design parameters namely water (w) to binder (b) ratio (w/b) (0.30–0.40), dosage of high range water reducing admixtures (HRWRA) (0.3–1.2% by total content of binder) and total binder content (b) (410–550 kg/m^3) were selected to derive mathematical models for the design of EC-LWSCC mixtures. The tested EC-LWSCC properties were, slump flow, V-funnel flow time, J-ring flow diameter/height difference, L-box ratio, filling capacity, segregation resistance, unit weight and compressive strength.

Phase II focused on the model development. Based on the test results, the influences of various parameters (w/b, HRWRA% and binder content) on EC-LWSCC fresh and hardened properties were analyzed. The relative significance of these primary mixture design parameters and their coupled effects on relevant properties of EC-LWSCCs were established. Afterward, statistical models were developed for prediction of these properties.

In Phase III, the developed statistical models were used to derive optimized industrial class EC-LWSCCs. EC-LWSCC mixtures were mathematically optimized to satisfy three classes of EFNARC industrial classifications and their performance was experimentally validated through fresh and hardened properties. In addition, the relationship between theoretical and experimental results was further investigated, where validation of the statistical models were performed.

3. Investigation in Phase I

3.1. Materials

ASTM Type I cement, 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 mixture at a fixed percentage by mass of total binder at 12.5% and 7.5%, respectively. Nominal sizes of 4.75 mm and 12 mm lightweight expanded clay were used as fine and coarse aggregates, respectively. Table 1 presents the chemical properties of expanded clay aggregates, and Table 2 presents their grading and physical properties.

The proposed EC-LWSCC mixtures contained no viscosity-modifying admixture (VMA). The use of VMA can ensure good flowability with lower paste volume. However, many successful LWSCC mixtures were developed without the use of VMA [14,15,20]. The silica fume is used to enhance the fresh properties as it helps to improve the cohesiveness and homogeneity of the LWSCCs; holding the lightweight