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Mix design of structural lightweight self-compacting concrete incorporating coarse lightweight expanded clay aggregates

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HIGHLIGHTS

- Mix design of structural lightweight self-compacting concrete (LWSCC) was evaluated.
- Lightweight expanded clay aggregates (LECA) were used to produce LWSCC.
- Methodology set by Nepomuceno et al. for self-compacting concrete (SCC) was tested.
- Methodology for SCC mix design successfully produced LWSCC using proper correlations.
- Correlations to support application of the mix design method for LWSCC were presented.

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ABSTRACT

This paper reports an experimental study that aimed to define the parameters for the mix design of structural lightweight self-compacting concrete (LWSCC) incorporating coarse lightweight expanded clay aggregates and natural sand. The starting point was the methodology proposed by Nepomuceno et al. (2014) for normal density self-compacting concrete (SCC). The necessary modifications were evaluated and new correlations obtained to support the definition of the mix design parameters. It was concluded that the coarse aggregates reference curve, as well as the mortar phase flow properties proposed by Nepomuceno et al. (2012) for the SCC, are adequate to produce LWSCC. Correlations to quantify the volume of coarse lightweight aggregates (Vg) are presented. It was shown that Vg depends on the mortar phase proportions, concrete workability properties, concrete compressive strength and concrete oven-dry density. The analysis of dynamic and static segregation shows a satisfactory performance with a uniform distribution of lightweight aggregates.

1. Introduction

In the last decades, the intense research in the area of the materials for structural application has led to the development of concrete with special characteristics, for special applications. This is the case of lightweight self-compacting concretes (LWSCC), which combine the advantage of self-compactability with the advantage resulting from the reduction of density. The reduction of concrete density usually results from the incorporation of lightweight aggregates (LWA), which may have different origins and properties, therefore introducing some additional complexity in the predictability of the behaviour of the concrete in the fresh and hardened state [1,2]. Vakhshouri et al. [2] have reported an analysis of 114 LWSCC mix designs of 21 laboratory researches from 2001 to 2013, giving a framework for researchers and practitioners about mix design, component materials and fresh and hardened state properties. Since then, other recent mix design methods were described in the literature [3,4]. It is a fact, that many academic institutions, admixture, ready mixed, precast and contracting companies have developed their own mix proportioning methods [5].

In this paper an experimental study that aimed to define the parameters for the LWSCC mix design is reported. Such parameters were investigated having in mind the adaptation of the existing methodology proposed by Nepomuceno et al. [6–9] for the mix design of normal density self-compacting concrete (SCC). Nevertheless, it should be emphasized that those parameters are still useful for general application in any method. The methodology proposed by Nepomuceno et al. [6–9] for SCC has been used in

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recent years with success, and there are already some studies attesting its validity to different types of materials [10–12], including recycled coarse aggregates [13,14]. Furthermore, it should be mentioned that some successful attempts have already been made by other authors to test its applicability to concrete with lightweight aggregates [15,16]. However, it is considered that such attempts should be more thorough so as to extend the parameters intervals and develop new correlations to support the mix design. Therefore, those relevant studies will be used in conjunction with the present research to complete the necessary range of information.

The methodology proposed by Nepomuceno et al. [6–9] for the mix design of normal density SCC is based on simple procedures and assumes the SCC as a two phase material, namely the mortar phase and the coarse aggregates. Appropriate mortar phase mix design is considered crucial to obtain SCC mixtures. The mortar phase key parameters includes the volumetric ratio of each powder material (p1, p2,.., pn) in the total volume of powders (Vp), the volumetric ratio of each fine aggregate (s1, s2,.., sn) in the total volume of fine aggregates (Vs), the ratio between the volume of powders and fine aggregates (Vp/Vs), the ratio between the volume of water and powders (Vw/Vp) and finally, the percentage mass ratio between the superplasticizer and the powders (Sp/p%). The maximum coarse aggregate volume fraction of SCC is quantified taking into account the required fresh concrete properties, namely the adequate filling ability, resistance to segregation and the passing ability. The mix design of SCC is completed by the definition of the volumetric ratio of each coarse aggregate (g1, g2,.., gn) in the total volume of coarse aggregates (Vg); the volume of voids in concrete (Vv) and the ratio between the volume of mortar and coarse aggregates (Vm/Vg). The quantification of the referred SCC mix design key parameters is supported by reference grading curves of the fine and coarse aggregates, by pre-existing correlations and by iterative experimental procedures for the adjustment of the mortar phase rheological properties.

In the present research work, the key parameters that support the methodology proposed by Nepomuceno et al. [6–9] for SCC mix design were thoroughly analysed and, consequently, the research activities needed to extend its use to LWSCC mix design were identified. Following this analysis, an extensive experimental program was implemented to define the key parameters that support the referred methodology for mix design of LWSCC. The coarse lightweight aggregates reference curve and the mortars flow properties suitable for LWSCC production were evaluated. The correlations to determine the volume of coarse lightweight aggregates were studied, namely by investigating its dependence on the mortar phase proportions, concrete workability, concrete compressive strength and concrete oven-dry density. The static segregation was evaluated by a non-conventional method.

2. Research needs and methodology

Looking at the step-by-step application sequence of the methodology proposed by Nepomuceno et al. [6–9], it becomes easier to unveil the changes needed to adapt its use to the LWSCC and to formulate the research needs that justified the significance of the present study.

The first step of the methodology consists in the selection and characterization of constituent materials. For normal density SCC, natural aggregates are used. For LWSCC, the introduction of lightweight expanded clay aggregates, which has high porosity, will require a detailed analysis of water absorption. Furthermore, due to lower crush resistance of the LWA, it will be necessary to provide for a strengthened mortar phase, by choosing cement with higher compressive strength class.

The second step consists in the determination of the volumetric ratio of each fine aggregate (s1, s2,.., sn) in the total volume of fine aggregates (Vs) and the volumetric ratio of each coarse aggregate (g1, g2,.., gn) in the total volume of coarse aggregates (Vg). For SCC, those values are determined by using reference grading curves of fine and coarse aggregates. For the present study, it was decided that LWSCC should be of type "*sand-lightweight concrete*" according to ACI 318 [17], i.e., a concrete with natural fine aggregate and coarse lightweight aggregates. Therefore, there is no need for changing the reference grading curve of fine aggregates. Concerning the coarse LWA, due to differences in shape index when compared to natural coarse crushed aggregates, it becomes necessary to verify the applicability of the reference grading curve used for coarse natural aggregates. This will be done by using a procedure similar to the one reported by Nepomuceno et al. [7,8] when investigating the reference grading curve of natural fine and coarse aggregates.

The third step consists in the determination of the volumetric ratio of each powder material (p1, p2,.., pn) in the total volume of powders (Vp). The definition of the powder mixture is determinant for the mortar compressive strength and, consequently, for the concrete compressive strength. Since the concrete compressive strength is affected by the Vp/Vs ratio of the mortar phase, this value should be defined prior to the determination of powder mixture, being recommended a Vp/Vs value of 0.80 if the objective is to maximize the volume of coarse aggregates in SCC. Despite the Vp/Vs ratio can vary between 0.60 and 0.80, it should be noted that mortars having higher Vp/Vs values, which means a larger volume of powders, will lead to SCC with a higher volume of coarse aggregates and a lower volume of mortar for the same workability. On the other hand, lower values of Vp/Vs will result in a SCC with a lower volume of coarse aggregates and a higher volume of mortar. When using binary blends of powders in SCC, the unit percentage of cement replacement by the addition (fad) is quantified by using correlations between fad, W/C ratio and the Vp/vs. The W/C ratio of the concrete is the same as for the mortar phase. Therefore, the W/C ratio is quantified by using an appropriate correlation with the 28-days concrete compressive strength ($f_{cm,28}$).

Since it is expected that the introduction of LWA will affect the correlations between the $f_{cm,28}$ and the W/C ratio, new correlations have to be produced. On the other hand, it is foreseeable that the Vm/Vg ratio can significantly affect the compressive strength of LWSCC as opposed to SCC, where the Vm/Vg ratio exerts a very slight influence when it varies between 2.0 and 2.6. There are still few studies on mathematical models to estimate the compressive strength of LWSCC, so the literature review was extended to conventional lightweight concretes. Some of the parameters susceptible to affect the compressive strength of concrete incorporating LWA were identified in literature review [5,15,18–20], which include: the particle density, the crush resistance of LWA, the shape index of LWA, the volume of LWA, the mortar phase compressive strength and the W/C ratio. Properties of the aggregates, such as particle density, crush resistance and shape index were kept constant, since only one type of LWA was used, so that the influence of these variables was not questioned. Therefore, the main variables include the volume of LWA, the mortar phase compressive strength and the W/C ratio. To obtain these correlations it will be necessary to produce LWSCC mixtures of different compressive strength, combining different W/C ratio, Vp/Vs and Vm/Vg values.

The fourth step consists in the determination of the Vw/Vp and Sp/p% ratios. Those values are determined by an experimental and iterative process that consists of testing mortars with different Vw/Vp and Sp/p% ratios until it complies with the required rheological properties. The mortar rheological properties are measured indirectly by flow capacity and fluidity. The flow capacity is measured