Journal of Cleaner Production 175 (2018) 324–332

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Efficient self-compacting concrete with low cement consumption

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ARTICLE INFO

Article history:

Keywords:
Eco-efficient
Self-compacting concretes
Supplementary cementitious materials
Metakaolin
Fly ash

ABSTRACT

Self-compacting concretes (SCCs) must have high fluidity, cohesion and should not segregate. These characteristics of fresh concrete increase the cost of production, particularly for lower projected strengths. In this work, a low Portland cement composition of SCC, with added metakaolin and fly ash (binary and ternary blended cements) was studied to evaluate its rheological and mechanical properties. Materials suitable for the mixture of the SCC were selected, characterized and the maximum packing density of the aggregates was determined. A SCC with a low compressive strength of 28.6 MPa and a cement consumption index of 10.2 kg m^{-3}. MPa^{-1} was produced; these values are among the lowest obtained for this type of concrete. An index of 7.8 kg m^{-3}. MPa^{-1} has been obtained for SCCs with higher compressive strength (67 MPa). Having defined a dosage strength of 25 MPa, a composition of 1:7.45 (cement:aggregates ratio) was obtained, with cement consumption of 222 kg/m^3 (+49.4 kg fly ash and metakaolin) and a cement consumption index (binder index) of 10.8 kg m^{-3}. MPa^{-1}. The results show that it is feasible to produce low strength SCC, with the necessary fluidity and reduced binder consumption, when mineral additions of metakaolin and fly ash are used. This makes SCC more efficient, with important reductions in costs and environmental impact.

1. Introduction

Self-compacting concrete (SCC) initially appeared in the early 1980's, following pioneering research in Japan, Italy and Germany, which led to the development of concrete mixtures that possess both high fluidity and high cohesion (Mehta and Monteiro, 2006). The characteristics of fresh concrete differentiate SCC from conventional concrete. SCC must have high fluidity and mixture stability, thus providing three key characteristics: flow or the ability to fill spaces, the ability to pass restrictions and the ability to resist segregation. This type of concrete is an evolution of conventional Portland cement concrete and its use results in high quality and durability in the execution of structures, consequently contributing to the sustainability of the constructive systems that are built with it.

However, to maintain SCC fluidity without the occurrence of segregation, large amounts of fines and binder are used to guarantee the quality of the final material or structure. In addition, given the current scenario of an industrial activity guided by the reduction of greenhouse gases, the production of more efficient concretes, with relatively “reduced” cement consumption, becomes important for the advancement of SCCs. Since SCCs are produced using highly efficient superplasticizing additives and large amounts of fines, required for mixture stability, the final product presents strengths higher than 40–50 MPa that are sometimes not a requirement of the project. Therefore, the production of SCCs using small amounts of cement and fines should result in concretes with lower strength values that could be used on a larger scale, as well as reducing the environmental and economic impacts, thus contributing to the efficiency of the structural concrete used by the building industry.

Supplementary cementitious materials (SCMs), including fly ash, ground granulated blast furnace slag, silica fume, calcined clays and natural pozzolans, are commonly used in concrete mixtures as a replacement of a portion of clinker in cement or as a replacement of a portion of cement in concrete. This practice is favorable to the industry, generally resulting in concrete with lower costs, a lower environmental impact, higher long-term strength, and improved long-term durability (Juenger and Siddique, 2015). The practice of using SCMs is increasing, with the world average percentage of

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https://doi.org/10.1016/j.jclepro.2017.12.084

clinker in cement having decreased from 85% in 2003 to 77% in 2010, and projected to further decrease to 71% in the future (Schneider et al., 2011).

In addition, SCMs contribute to the flow characteristics and cohesion required of SCCs (Cassagnabère et al., 2009; Sahmaran et al., 2009, Long et al., 2017). In this work, a concrete dosage study was conducted that evaluated: the effect of the composition study (using granular packing and concentration of additives); and the effect of mineral additions of metakaolin, fly ash, and metakaolin + fly ash. Mechanical performance requirements and binder consumption were also assessed.

In this work, compositions of self-compacting concrete with mineral additions were studied in order to reduce the clinker consumption, but maintaining the efficiency rates between 5 and 10 kg m^{-3}. MPa^{-1}, considering a 25 MPa compressive strength (conventional indices of efficiency, Damineli et al., 2010). The lowest cement consumption indexes reported in SCC research are approximately 8 kg m^{-3}. MPa^{-1} (Zhao et al., 2015), but for a high strength of 56 MPa, and 13 kg m^{-3}. MPa^{-1} (Long et al., 2017) for strength of 25 MPa. Granular packing, the maximum efficiency of additives (considering the saturation level) and the effect of metakaolin and its synergy with fly ash were the variables under study. The results showed that producing SCC with reduced strength (between 20 and 30 MPa) and low Portland cement consumption (approx. 220 kg of cement, 25 kg of metakaolin and 25 kg of fly ash), for a projected compressive strength of 25 MPa, is feasible.

2. Experimental procedure

The methodology adopted in this study to define a composition of SCC was structured in three distinct stages. The first step consisted of the selection of the appropriate materials used in a formulation of SCC, in their characterization and obtaining the maximum packing of granular aggregates to produce the SCC. Next, the fluidity of the cement paste (mixture of cement and water) and mortar (mixture of cement, water and sand) was investigated by the mini-slump test to determine superplasticizer saturation. Finally, the effect of fly ash and metakaolin mineral additions to the SCC (mixture of cement, water, sand and gravel) was investigated by evaluating the properties of the SCC in the fresh state (slump test and L-box test) and hardened state (compressive strength, elastic modulus and cement consumption).

2.1. Test methods

2.1.1. Determination of granular aggregate packing

Initially the granular packing density of the fine and coarse aggregates was determined (Table 1). In sequence, the maximum granular packing of the aggregates was determined for three mixtures, A, B and C (Table 2), beginning with the coarse aggregate and ending with the finest.

In mixture A, a granular packing of between gravel 4.75–16 mm and gravel 2.4–9.5 mm (ASTM C136, 2016) was chosen, the aggregates were mixed and the dry packed bulk density of each composition was determined. The quantity of aggregates was varied by 10% (mass) among the compositions to obtain the mixture with the highest density. In mixture B, the granular packing was determined between that of mixture A (gravel 4.75–16 mm + gravel 2.4–9.5 mm) and coarse sand (0–4.75 mm), repeating the previous procedure to obtain the mixture with the highest density. Finally, in mixture C, the granular packing was determined between that of mixture B (gravel 4.75–16 mm + gravel 2.4–9.5 mm + coarse sand) and fine sand (0–0.3 mm), following the same procedure, until the mixture with the highest density was obtained.

Table 1
Density dry unit weight of aggregates.

Aggregate	Packing density (kg/m^3)
Gravel: 4.75–16 mm	1742
Gravel: 2.4–9.5 mm	1656
Coarse sand: 0–4.75 mm	1764
Fine sand: 0–0.3 mm	1716

2.1.2. Determination of superplasticizer saturation

The superplasticizer (SP) was used to increase the workability of fresh concrete and therefore it was necessary to determine the optimum ratio between SP/workability. The fluidity test for cement paste and mortar was performed to determine the level of SP saturation in relation to its workability by measuring the diameter of the spreading of both cement paste and mortar. A mini-cone was used to perform the test (EN 1015-3, 2007). The initial cement paste and mortar (w/c) relationships were defined as 0.55, 0.45 and 0.35. An intermediate 1:4.5 ratio was used to compose the mortars. In the fluidity test, spreading was taken as the mean values of two orthogonal diameter values. For cement pastes with w/c ratios 0.35, 0.45 and 0.55, the variation in the amount of superplasticizer was 0.5% compared with the mass of cement. For mortars with w/c ratio of 0.35, the variation in the amount of superplasticizer was 1.0% compared with the mass of cement. For mortars with w/c ratio of 0.45, the variation was 0.5% and for mortars with w/c ratio of 0.55, the variation was 0.25%.

2.1.3. SCC mixture design

Four compositions were defined for SCC mixtures (Table 3), as a function of the type of mineral substitution: REF, the SCC reference mixture, without mineral substitution; MK, SCC with part of the cement replaced by metakaolin; FA, SCC with part of the cement replaced by fly ash; and MK + FA, SCC with part of the cement replaced by metakaolin and the addition of fly ash.

2.1.4. Determination of SCC properties in the fresh state

The concrete was characterized in the fresh state according to European federation technical standards (EFNARC, 2002). To perform the slump flow test, an Abrams cone was used on a metal plate 85 cm in diameter. For the L-box test, a wooden box was used.

2.1.5. Determination of SCC properties in the hardened state

After determining the fresh state properties of the concrete samples, nine samples (diameter 10 cm, height 20 cm) for each composition were shaped to determine the hardened state properties of the SCC. The average compressive strength of the SCC was determined according to ASTM C-1231, 2010 specifications at 7 days (3 samples for each composition) and 28 days (3 samples for each composition). The concrete elastic tangent modulus was determined according to NBR 8522 (2008 - determined at 30% of the compressive strength, and, equivalent to ASTM C 469, determined at 40% of the compressive strength) at 28 days (3 samples for each composition).

2.2. Materials

Tap water was used for all concrete compositions. A polycarboxylate polymer-based superplasticizer was used as an additive to reduce water content. Fine and coarse sand were used as fine aggregates and gravels (2.4–9.5 mm and 4.75–16 mm) as coarse aggregates. The particle size distribution of aggregates are shown in Table 4 (ASTM C136, 2016).

Portland cement type CP V-ARI RS (similar to ASTM type III) was