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Adverse effect of the mass substitution of natural aggregates by air-dried recycled concrete aggregates on the self-compacting ability of concrete: evidence and analysis through an example

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ABSTRACT

This paper is part of a study aiming to define the best way to incorporate recycled concrete aggregates (RCA) in the production of self-compacting concrete (SCC), with a view to reduce the excessive use of natural aggregates, which are a non-renewable resource, and to remove the large quantities of concrete waste generated by demolition. RCA differ from natural aggregates essentially by their lower density, higher water absorption capacity and systematic angularity. Here, the effect on self-compacting ability of replacing natural coarse aggregates (NCA) with coarse RCA in a dry state at the time of mixing is assessed. Starting from a reference SCC incorporating rounded NCA only, three replacement rates were studied: 40%, 60% and 100% by weight. The water amount was adjusted so that the standardized 24-h absorption of RCA was satisfied. The key properties of SCC recommended by European specifications and guidelines (EFNARC), i.e. filling ability, passing ability and segregation resistance, were measured in the fresh state, immediately after mixing (t_0). Shear-dependent properties were also quantified by means of rheological measurements at t_0 and $t_0 + 25$ min. Through this study are shown and interpreted the difficulties in achieving the self-compacting ability under certain conditions of use of RCA. The experimental results showed that the self-compacting ability criteria were not satisfied, irrespective of the replacement rate of NCA with RCA. This replacement implied an increase in the rheological properties (yield torque and torque in steady-state flow) of concrete. The increased volume of coarse aggregates together with a constant volume of interstitial paste, and the angular shape and rough surface texture of RCA, are the main causes of the alteration of the flow of concrete. Also, the impairment with time of the flow properties of concrete was noted and is due to the movement of water from the interstitial paste towards dry RCA. Such results were supported by the fact that rheological data on RCA concretes were not in agreement with multi-scale models describing the flow of reference concrete as a suspension of spherical occlusions in a viscoplastic phase. Through this study, it is evidenced what to avoid regarding the technical approach envisaged to the RCA incorporation in SCC.

1. Introduction

The ability of fresh concrete to fill formworks of any shape with low economical and energetic costs is the main reason for the popularity of concrete. Faced with the challenge of building structures more and more complex and the lack of skilled manpower, a new generation of concrete has emerged, i.e. self-compacting concrete (SCC), first in Japan in 1980s (Ozawa et al., 1989) and then around the world. Domone (2006) reported sixty eight case studies developed in Japan, Europe and Americas and raised statistically the properties, constituents and mix proportions suitable for different applications of SCC. Later, while summarizing the story of SCC, Khrapko (2009) acknowledged the efforts of research to be conducted and the promising future of SCC.

Indeed, developed to replace traditional vibrated concrete (VC), SCC has many known advantages, such as lower energy costs and reduced noise thanks to a vibration-free environment. Self-compacting ability means that a fresh concrete will flow under its own weight, whatever the confinement surroundings, and remain homogeneous during the flow (no dynamic segregation) and after placing (no static segregation), as largely reported in literature, see for example (Gibbs and Zhu, 1999) and (Okamura and Ouchi, 2003).

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Such properties are the result of complex interactions among the constituents, which must be taken into consideration during the mix design process. The existence of complex interactions of constituents in SCC is caused by the systematic incorporation of chemical admixtures (superplasticizer and possibly a viscosity agent) and high content of fines (particles less than 100 μm). Diederich et al. (2013) have proposed a diphasic approach to design SCC and considered the physical properties of fine particles (grading size, morphology, surface charges, fineness) via the characterization of their arrangement in suspension (water + chemical admixtures).

As a result of the use of chemical admixtures and high amount of fines, the price per cubic meter is higher for SCC than for VC.

The need for high fines content in SCC is satisfied by the replacement of a part of cement with industrial by-products, such as fly ash (combustion residues of power stations), ground granulated blast furnace slag (by-product of iron and steel-making), fillers (by-product of stone-crushing industry), etc. Incorporation of such supplementary cementitious materials or mineral admixtures can solve solid waste disposal problems and imply significant energy and cost savings in concrete production. Different types of mineral additives have been successfully used to achieve self-compacting ability, namely, limestone filler (Petersson et al., 1996), class F fly-ash (Siddique, 2011) and bagasse ash waste (Sua-iam and Makul, 2013).

Another possibility to further reduce the cost of SCC consists of the use of recycled concrete aggregates (RCA) in the concrete design as a replacement for natural aggregates (NA). RCA are generated from the demolition of concrete elements made of 100% NA. The need to reduce the excessive use of natural aggregates, which are a non-renewable resource, and to remove the large quantities of concrete waste generated by demolition fits perfectly into a concept of sustainable development. This concept is widely developed in the industry of building materials which is in nature a source of pollution, for the design of mineral processing operations (McLellan et al., 2009) as well as for the means to reduce CO_2 footprint in the cement production (Vatopoulos and Tzimas, 2012). Apart from its sociological and economic aspects, sustainable development involves energy saving, protection of the environment, and conservation of non-renewable natural resources, notably in the context of recycled aggregates from old masonry and old concrete (Levy and Helene, 2004), RCA and re-used RCA (Marie and Quiasrawi, 2012). The simultaneous consideration of environmental, social and financial aspects in sustainable development is feasible through the approach of ecological costs accounting (ECA). By this way, Passarini et al. (2014) showed that construction building wastes can be recycled in order to clean sewage and obtain sludges successfully used as organic amendments for soil culture.

Coming back to the context of concrete waste, RCA are most often incorporated in base or sub base of roads or for the construction of embankment rather than in concrete buildings, because they present physical and chemical properties which can be hardly compatible with the specified properties of structural concrete. Even if different properties exist between RCA and NA, RCA still can be incorporated in structural concrete provided that they fulfill certain specifications listed synthetically by Pacheco-Torgal et al. (2013). For instance, remnant quantities of mortar and cement paste from original concrete attached to the NA after the crushing phase confer to RCA less density and higher water absorption, compared to NA. High water absorption of RCA can impair the flow properties of fresh vibrated concrete (VC). Poon et al. (2007) reported that the slump loss is marked during 30 min after mixing when NA is totally replaced with saturated surface-dried RCA. Mefteh et al. (2013) observed the same trend as Poon et al. (2007) but only during the first 15 min after mixing, which evidences the influence of absorption kinetics of RCA on the flow alteration. The results of Poon et al. (2004) and Mefteh et al. (2013) are consistent to show that the alteration of flow (slump loss) is dramatically enhanced when dried RCA are used.

The question arises as to whether the key characteristics defining self-compacting ability, i.e. flowability, passing ability and segregation resistance, specified by EFNARC recommendations (2002), can be compromised if recycled aggregates are used as the only aggregates for the production of SCC. Considering the environmental aspect of the ECA approach reminded by Passarini et al. (2014), the present study is situated in the context of technical feasibility before processing to a fully sustainable position which, ideally, would banalize the incorporation of RCA in SCC.

Limited studies have been conducted on the use of recycled concrete aggregates (RCA) and their effects on the fresh-state properties of SCC. Tu et al. (2005) showed that a 100% w/w replacement of natural aggregates by RCA (hydric state at the time of mixing not specified) was possible in the production of SCC provided that the design was right. However, they also showed that 100% RCA content altered the flow after 1 h due to the higher absorption capacity of RCA. When adding water into RCA-SCC mixtures initially to compensate for the high 24-h water absorption of the fine RCA (0/5 mm) used in air-dried conditions, Kou and Poon (2009) reported that the slump flow and L-box filling ratio increased with the increase in the fine RCA replacement rate by volume (0, 25, 50, 75 and 100%). At the same time, they showed that there was no significant change in the segregation resistance. They explained that part of the additional water could not be absorbed by the fine RCA during the first minutes and the excess of water helped to improve the flow. Grdic et al. (2010) experimented on three types of concrete mixtures where the percentages of substitution of coarse aggregate by RCA were 0%, 50% and 100% by weight. In the process of mixing, the amount of water was adjusted so that equal consistency was achieved in all cases. Even though the hydric state of RCA at the time of mixing was not specified, the results indicated that the flow differed only a slightly and the recycled coarse aggregate could successfully be used for self-compacting concrete. Safiuddin et al. (2011) concluded that overall test results showed that recycled concrete aggregates in air-dry conditions could be used in SCC in replacement of natural aggregates for up to 50% by weight without affecting the key fresh properties such as filling ability, passing ability, and segregation resistance of concrete.

It should be noted that most of the studies presented above were specifically interested in the properties of hardened concrete and only briefly verified that workability criteria for the fresh SCC were satisfied. Complementary information is necessary on the flow and flow evolution with time of fresh SCC incorporating RCA, based on rheological measurements. The underlying phenomena in relation with the hydric state of aggregates are yet to be explored.

This paper is part of a study aiming to define the best way to incorporate RCA for the production of SCC. The adverse joint effects of the substitution by weight of natural coarse aggregates (NCA) by less dense coarse RCA in a dry state at the time of mixing are evidenced on the key fresh properties such as filling ability, passing ability, and segregation resistance. Rheological measurements on fresh mixes together with the characterization of the granular skeleton will enable the evolution of the flow to be explained as a function of the RCA content.

2. Details of the experiment

2.1. Materials used

2.1.1. Cement

Portland cement (OPC) used in this study was produced according to European Standard NF EN 197-1 (2012) and labeled as a