Construction and Building Materials 147 (2017) 803–814

Contents lists available at ScienceDirect

Construction and Building Materials

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

Evaluation of high-performance concrete with recycled aggregates: Use of densified silica fume as cement replacement

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HIGHLIGHTS

- High-performance concrete (HPC) with fine (FRA) and coarse (CRA) recycled aggregates.
- Use of densified silica fume as cement replacement.
- The mechanical and durability performance have been analyzed.
- The total incorporation of FRA and CRA in the production of HPC is deemed possible.
- The silica fume densification process has shown to be "irreversible".

ARTICLE INFO

Article history:
Received 22 November 2016
Received in revised form 19 April 2017
Accepted 1 May 2017
Available online 8 May 2017

Keywords:
High-performance concrete
Recycled aggregates
Silica fume
Mechanical performance
Durability performance

ABSTRACT

This paper intends to evaluate the real influence of a commercial densified silica fume (SF) and of recycled concrete aggregates (RA) on the behaviour of high-performance concrete (HPC). For that purpose, three families of concrete with 0%, 5% and 10% silica fume (SF) of the binder's mass were produced. In addition to the commercial silica fume, fly ash (FA) and superplasticizer (SP) were also incorporated in the concrete mixes. Each type of concrete comprises a reference concrete (RC) and three recycled aggregates concrete (RAC) mixes with replacement percentages (in volume) of fine natural aggregates (FNA) with fine recycled aggregates (FRA) and of coarse natural aggregates (CNA) with coarse recycled aggregates (CRA) of 50/50, 0/100 and 100/100, respectively. Considering the mechanical performance and durability of the concrete mixes, results show that it is possible to incorporate significant amounts of FRA and CRA. Regarding the silica fume, the densification process used in its manufacture seems to lead to the formation of agglomerates that change the real particle size of the SF, originating a loss of performance of the concrete made with them.

1. Introduction

The concept of high-performance concrete (HPC) has evolved with time and is nowadays very widespread. In its origin was the term high-strength concrete (HSC) that was not able to completely/precisely translate the characteristics of some mixes, namely when durability requirements were also specified, sometimes prevailing over strength requirements.

Therefore, in the work carried out by Mehta and Aïtcin [1], the designation HPC was proposed to designate concrete that had three different characteristics: high workability, high strength and high durability. Also, the main difference between HPC and HSC was defined as being the high durability of high-performance concrete.

In terms of constituents, one of the main differences between HPC/HSC and conventional concrete is the frequent use of supplementary cementing materials, namely silica fume (SF). In general, SF is not used in conventional mixes due to its high cost.

Abbreviations: FNA, fine natural aggregates; FRA, fine recycled aggregates; CNA, coarse natural aggregates; CRA, coarse recycled aggregates; NA, natural aggregates; RA, recycled aggregates; RAC, recycled aggregates concrete; HPC, high-performance concrete; RC, reference concrete; FA, fly ash; XRD, X-ray Diffraction; BFS, blast furnace slag; EDS, electron dispersive spectroscopy; ITZ, interfacial transition zone; SEM, scanning electron microscopy; SCM, supplementary cementing materials; nS, nanosilica; SF, silica fume; SP, superplasticizer; UPV, ultrasonic pulse velocity.

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.007
0950-0618/

Silica fume is a material that is substantially more expensive than cement but can increase the mechanical performance and durability of concrete. In many countries 1 kg of SF can cost as much as 10 kg of Portland cement [2].

SF is a by-product of the silicon and ferrosilicon alloy production. Silicon is a by-product in the reduction of high-purity quartz with coal, in electric arc furnaces. The main component of silica fume is SiO_2, in percentages higher than 90%. SF has spherical particles with average diameters typically between 0.03 μm and 0.1 μm, approximately 100 times smaller than cement particles. Its specific surface is circa 20,000 m^2/kg, 10 to 20 times higher than that of other pozzolanic materials [3]. Due to its characteristics, silica fume is an extremely reactive pozzolanic material. However, its extreme fineness and low density is also responsible for difficulties in the transport, handling and storage of this material. In order to overcome these disadvantages, suppliers started to commercialize silica fume in powder form, with small agglomerates of individual particles (densified silica fume), or in liquid form, even though the latter has become unavailable in many countries.

In this context, it is important to understand the characteristics and influence of densified silica fume on concrete properties. Most published research on this subject refers to non-processed SF particles or does not mention the form of SF used based on the assumption that it is not an important aspect [4].

Although the densification process is seen as reversible (even in technical sheets), the research carried out by St. John [5] concluded that, even after ultrasonic dispersion treatments, significant proportions of densified silica fume showed dimensions between 10 μm and 100 μm and agglomerates of higher size (between 100 μm and 1000 μm) were still present. Concerning the use of SF on cementitious materials, there are also studies that point to a high degree of agglomeration [6–11].

According to Yajun and Cahyadi [9], this agglomeration can reduce the effectiveness of silica fume on concrete and mortars because the densified particles have a larger diameter, a smaller specific surface area and a lower pozzolanic reactivity than the individual SF particles. For instance, Bonen and Diamond [12] observed that the pozzolanic reaction can only take place from the agglomerate surface. Through SEM images using backscattered electrons, the abovementioned authors found unreacted cores on some densified silica fume particles, for 1 year old cement pastes.

Also, according to Yajun and Cahyadi [9], the agglomeration of SF particles cannot be easily broken up owing to high interparticle forces, for example, forces due to electrostatic charging and Van der Waal's forces. Therefore, the complete dispersion of densified SF particles (for values in the order of 0.1 μm) appears to be highly improbable to occur through the conventional mixing process of cementitious materials. The actions involved during concrete mixing that contribute to the disaggregation of SF agglomerates can still be reduced by the presence of sand grains around them, cushioning them against impact. In the case of mortars, this becomes even more evident [8].

Considering what was referred, the explanation for the existence of numerous studies in which silica fume is considered highly effective and others in which their effectiveness is reduced can reside in the particle size of SF and not in its chemical composition (typically high SiO_2 content).

Regarding the incorporation of recycled concrete aggregates (RA) on concrete, much fewer research works were found focusing on high-performance concrete than on conventional concrete. Recycled concrete aggregates consist of natural aggregates with approximately 30% adhered mortar [13]. The latter gives RA a rough surface with many pores and micro-cracks [14,15]. For these reasons, RA are characterized by lower density, higher water absorption and lower mechanical strength than those of natural aggregates [16,17]. Recycled aggregates are also very heterogeneous and porous, and may contain a large number of impurities. Heterogeneity affects the characteristics of the RA harming the quality of concrete made with them.

The aforementioned characteristics can lead to a reduction of the amount of effective water for the hydration process and, thus, originate a weaker interfacial transition zone (ITZ) between the recycled aggregate and the cement paste [18].

The quality control of concrete made with RA can be made in different ways: water and cement amount [19]; curing conditions [20]; use of additions [21] and admixtures [22,23]. The origin, moisture content and the crushing process of the RA are also aspects to consider [24–26]. The RA used in concrete can be further treated, in order to improve its properties [15,27].

In terms of the influence of silica fume incorporation on recycled aggregates concrete (RAC), it was found that its effectiveness is also variable. González-Fonteboa and Martínez-Abella [28] analyzed the impact of the addition of this material on concrete with recycled aggregates from construction and demolition waste. The RAC were produced with a higher cement amount (6.2%) than that of the reference concrete (RC) and considering a single substitution rate (50% by volume) of natural coarse aggregate with recycled coarse aggregate. The silica fume was considered as an additional material (both in RC and in RAC), representing 8% of the weight of cement. Results showed that, at 28 days, the compressive cylinder strength of RC and of RAC without SF were similar (approximately 36 MPa) and that silica fume addition only led to a strength increase of about 3 MPa in both types of concrete. Similarly, slight differences were observed in tensile strength and modulus of elasticity with SF incorporation. Furthermore, concrete with SF exhibited higher water absorption (5–10%). In the research conducted by Corinaldesi and Moriconi [29] mixes containing recycled aggregates only (fine and coarse) from construction and demolition waste were used, with and without silica fume. In the mixes with SF, this material represented 15% of the cement weight. Results showed that, due to SF addition, the compressive strength of the RAC (on cubes) increased from 29 MPa to 42 MPa at 28 days. For younger ages, silica fume also contributed significantly. On the other hand, on the work carried out by Çakır and Sofyanlı [30], SF was introduced as a cement substitute in proportions of 0%, 5% and 10%. The specimens were produced by replacing natural aggregates with recycled aggregates. Two size fractions of RA (4/12 mm and 8/22 mm) were used and twelve types of concrete were produced. The results showed that the compressive strength at early ages decreased with increasing silica fume content. However, at 28 and 90 days the strength of all mixes incorporating 5% and 10% SF increased when compared to the reference mix (without silica fume).

Therefore, this paper aims at studying the effects of replacing natural aggregates with recycled ones and of the use of a densified silica fume on the behaviour of high-performance concrete. Its objective is to warn on the potential consequences from the use of some certified commercial silica fumes where there is no reference to the dispersion difficulties or to the actual size of their particles. At the same time, it intends to show that it is feasible to introduce RA in HPC, provided that some requirements related to the quality of recycled aggregates and their addition to concrete are guaranteed.

2. Experimental program

2.1. Materials

Table 1 shows the materials used in the composition of the concrete mixes. The recycled concrete aggregates come from *precast*