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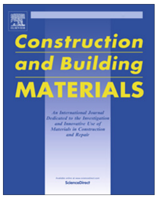

Fresh and mechanical behavior of a self-compacting concrete with additions of nano-silica, silica fume and ternary mixtures

J. Bernal [a,*], E. Reyes [b], J. Massana [c], N. León [b], E. Sánchez [c]

[a] *Escuela de Ingeniería Mazatlán, Universidad Autónoma de Sinaloa, Mexico*
[b] *Dpto. Ingeniería Civil: Construcción, Universidad Politécnica de Madrid, Spain*
[c] *Dpto. de Ingeniería Agroforestal, Universidad Politécnica de Madrid, Spain*

HIGHLIGHTS

- The use of nSi reduces the workability of SCC due to its high water demand.
- The greater the quantity of nSi the greater is the demand of superplasticizer additive.
- The use of mSi and nSi increased the compressive strength of the SCC.
- The greater compressive strength value was obtained by ternary mixture made with 2.5% of mSi and 2.5% of nSi.
- The main part of the hydration of the cement in mixtures with nSi occurs before seven days.

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ABSTRACT

Self-compacting concrete (SCC) has experienced significant development in the light of results obtained from numerous studies due to a series of advantages that it offers. The use of mineral admixtures at microscale and recently at nanoscale has permitted high-performance SCC to be obtained. Over the past few years, micro silica (mSi) and nano silica (nSi) have been the most used admixtures in continuing research into the areas of civil and agricultural engineering. This paper examines the behavior of 10 mixtures of SCC prepared with binary and ternary dosages through use of Portland cement (CEM I 52.5 R), mSi and nSi. As a reference, a SCC was designed which used no mineral admixtures, with the rest of the dosages using different percentages of mSi and nSi. Three were made with 2.5%, 5% and 7.5% of nSi; three more with 2.5%, 5% and 7.5% of mSi, and the remaining three by using both admixtures (ternary mixtures) mSi and nSi, with percentages of 2.5%/2.5%, 5%/2.5% and 2.5%/5%. The properties studied are rheological (flow test, funnel test and box test), mechanical (compressive strength, tensile strength and modulus of elasticity), and microstructural (hydration composites). According to the results obtained, all the concretes meet the requirements to be classified as SCCs by monitoring the quantity of superplasticizer additive according to the type and quantity of mineral admixture used. The higher compressive strength value was obtained by the ternary mixture with 2.5%/2.5% of mSi and nSi both at 28 and 90 days. Ternary mixtures of 2.5%/5% and 5%/2.5% reach values similar to those obtained by the mixture with 7.5% of nSi. Based on these results, it is possible to say that the compressive strength depends on the particle size and the amount of the admixture, and the particle-size distribution of the resulting mixture. This allows the advantage of obtaining considerably high compressive strength by using lower amounts both of nSi and of mSi and, therefore, of SP.

1. Introduction

Since Okamura developed self-compacting concrete (SCC) at the University of Tokyo in the mid-1990s [1–5]. the material has experienced a significant degree of development in the light of results obtained from numerous studies and continues to be examined in research due to a series of advantages that it offers [6–16]. The properties of SCC in fresh state permit it to be placed into every corner of a formwork, allowing correct filling of highly congested reinforcement areas and without segregation and exudation, purely by means of its own weight and without the need of vibrating compaction [17,18]. In addition, SCC allows the final cost of the structural element to be reduced and production methods

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[*] Corresponding author.
E-mail address: jmbernalc@uas.edu.mx (J. Bernal).

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improved, at the same time as achieving good mechanical properties, durability and uniformity of the hardened material. Such advantages promote use of SCC in several projects, highlighting its utilization in the prefabrication industry given that costs of production and maintenance of equipment are lower. In order to obtain an adequate flowability in fresh state, the use of a high amount of cement, special admixtures and superplasticizer is often required, as the water/cement ratio is low. Furthermore, SCC requires special care as regards the regularity and dosage of aggregates to assure the correct fresh characteristics. It is generally obtained by limiting the coarse aggregate content (that has a particularly intense energy consumption). It should also be noted that the aggregate content is smaller than in conventional concrete.

Generally, to obtain a high-performance SCC, it is necessary to use mineral admixtures at microscale and, recently, at nanoscale. The oxides of silica, titanium, alumina and iron are the most recently used admixtures at a nanoscale in published research. The type of admixtures employed depends on the properties required in the concrete. Over the past years, nano silica (nSi) has been the most used admixture in continuing research into the areas of civil and agricultural engineering [10,13,19–21]. Most of the results showed that nSi produces changes at a microstructural level, activating a pozzolanic reaction [22]. The nSi reacts with calcium hydroxide, producing a larger amount of calcium silicate hydrate (CSH) gel that densifies the material, reducing its permeability and controlling the leaching of the Ca^{2+} that is among the most frequent causes of degradation of the concrete [23]. The silica particle size used in the dosage of concrete produces significant changes in the number and average size of portlandite crystal [24]. These microstructural changes are associated with the macrostructural properties of mortars and concretes, such as compressive strength, modulus of elasticity, tensile strength and durability properties, among others [9,13,20,25–29]. With regard to the mechanical properties of the mixtures prepared with nSi, several works show an increase of the compressive strength directly related with the amount of nSi [13,30–33] Cement paste prepared with a content of nSi between 0.2% and 10%, with respect to the weight of the cement, showed an increase of 65% in its compressive strength in comparison with the mortar without nSi [32]. In the case of concrete, the improvement of compressive strength is remarkable when nSi is used as admixture. It is important to mention that some authors have obtained better results with the use of 2% of nSi as an admixture than with a 10% of micro silica (mSi). [10,34–36].

In the SCC, the use of nSi led to a decrease of fluidity due to the high specific surface of nSi, which means a larger water demand [37]. This was addressed with the use of superplasticizer additives. There are several published papers which compare the influence of mSi and nSi in mixtures with the same composition, studying parameters such as compressive strength, modulus of elasticity, and permeability, among others [28,38,39]. However, there is a lack of works that study ternary mixtures with the use of nSi, mSi and cement.

This paper examines the behavior of several mixtures of SCC prepared with binary and ternary dosages by using mSi and nSi. The properties studied are rheological (flow test, funnel test and box test) and mechanical (compressive strength, tensile strength and modulus of elasticity). The authors evaluated the behavior of all SCCs and determined the dosages with the best performance to be used during the preparation of the concrete both in situ and in the prefabrication industry. It is worth noting that the greater compressive strength value was obtained by ternary mixture with mSi and nSi at both 28 and 90 days. The improvement in compressive strength depends not only on the particle size and the amount of the admixture but also on the particle-size distribution of the resulting mixture, with the best result being obtained with ternary mixtures by using lower amounts both of nSi and of mSi and, therefore, of SP.

2. Materials and method

In this study, the cement used was a CEM I 52.5 R (termed PC), in accordance with UNE-EN 197-1:2011 [40]. Table 1 presents the chemical composition and physical properties of cementitious materials. The mineral admixtures used were mSi and nSi. The mSi used was Elkem Microsilica® MS 940 U, with it being composed of nonporous amorphous spheres of SiO_2 with a submicron size and small agglomerates, with a specific surface area of 15–30 m^2/g and particle size of 0.15 μm (approximately). A dispersion of nSi in water was used, under the trade name of Levasil® 200/40%, with 40% of solids by weight, specific surface area of 200 m^2/g and a particle size of 15 nm (approximately) (see Table 1). Even when some of the spheres are found in an individual way, the majority tend to form agglomerates of primary particles with a size range between 0.1 and 1 micra. The additives employed were the following: Sika® ViscoCrete-5720 (termed SP) based on polycarboxylate polymers and Sika® Stabilizer 4R (termed MV) which permits the viscosity of concrete to be monitored. The fine aggregate used was siliceous sand (termed A) with a size of less than 4 mm, coarse aggregate (termed G) with a size between 6 mm and 12 mm and limestone filler (termed FC) with a maximum size of 63 μm, in accordance with UNE 12620:2003 + A1:2009 [41].

All the SCCs were made by using a water-to-cementitious material ratio (w/cm) of 0.36 and 450 kg of cement since the objective was to make high-performance SCCs. Table 2 shows the 10 dosages designed. The admixtures of mSi and nSi were used in different percentages as regards cement weight. It is important to mention that admixtures (mSi and nSi) were not used as a cement replacement but as an additional cementitious material. Regarding the SCC dosages, the following should be noted: three of them were made with 2.5%, 5% and 7.5% of nSi, which were identified as [nSi]-2.5; [nSi]-5; [nSi]-7.5, respectively; three more were made with 2.5%, 5% and 7.5% of mSi, which were identified as [mSi]-2.5; [mSi]-5; [mSi]-7.5; and the remaining three were made by using both admixtures (ternary mixtures) mSi and nSi, with percentages of 2.5%/2.5%, 5%/2.5% and 2.5%/5%, respectively, identified as [nmSi]-2.5/2.5; [nmSi]-5/2.5; [nmSi]-2.5/5. In order to obtain reference values to compare the results, a SCC was designed (HAC) which did not use any mineral admixture (with the CEM I 52.5 R being the sole cementitious material).

Several standard tests were carried out in fresh state to evaluate the self-compacting properties of the mixtures, in accordance with European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC) (2005) [50] and with the Spanish Stan-

Table 1
Properties of Portland cement (PC) and mineral admixtures (mSi and nSi).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Loss to fire (%)	Density (g/cm^3)	Specific surface area (m^2/g)
PC	19.20	6.07	1.70	63.41	2.56	3.38	0.2	0.33	2.09	3.5	0.42
nSi	99.90	–	–	–	–	–	–	–	0.10	1.29	200
mSi	94	–	–	–	–	–	–	–	–	0.7	30