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Influence of nanoparticles additions on the bond between steel fibres and the binding paste

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HIGHLIGHTS

- Evaluation the influence of nano-SiO_2, nano-Al_2O_3 and nano-ZnO on fibres-to-binding paste bond.
- Innovative pull-out test designed to record the bond-slip curves of fibres using traditional equipment.
- Adding nanoparticles to the binding paste is more effective than applying on the fibres' coating.
- Nano-Al_2O_3 increases slightly the bond strength and nano-ZnO has a negative effect on the bond strength.

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ABSTRACT

In the last decades, steel fibres have been widely used to reinforce the binding paste of concrete, mainly aiming at preventing/controlling cracking, by significantly increasing the (low) tensile strength and deformation capacity of current concretes. In this scope, the bond between steel fibres and the binding paste is of paramount importance. Following the more recent development of nanoparticles, several studies have been conducted to assess how they can enhance the properties of concrete mixtures.

An experimental program was defined and conducted to analyze the influence of nanoparticles additions in the fibre-to-paste bond strength. A new pull-out test for monitor the fibres' slip versus the applied load was specifically designed in this scope, using current equipment, and thirty-six specimens were tested up to failure. It was concluded that it is more effective to add nanoparticles to the binding paste than to add these as fibres' coating and the fibres' anchorage, namely the hooks at both ends of the fibres, plays a much more significant role on the fibres-to-paste bond strength than the nanoparticles addition.

1. Introduction

When cracks initiate at the binding paste for relatively low stresses/strains, fibres are useful to bridge their borders, creating this way a path for tensile stresses, limiting the propagation of existing cracks and also preventing new ones from opening. For these reasons, steel fibres are used to reinforce cementitious materials, increasing their low tensile strength [1–3]. Besides this benefit and the enhanced control of cracking provided by a better redistribution of stresses within the matrix, the addition of steel fibres also increases its deformation capacity (ductility) and the material's strength regarding to impact loads. Considering all these advantages, steel fibres can be used to replace partially or totally the reinforcement of concrete members, e.g., in industrial floors, prefabricated members, and tunnels' coatings.

The steel fibres-to-paste bond strength strongly influences the mechanical behaviour of fibre reinforced concrete (FRC). The bond strength typically involves three components: *i)* adhesion, understood as a chemical connection; *ii)* mechanical interlock, originated by the texture of the fibre's surface, and/or by a deformed shape along its length or localized at its ends (typically a hook shaped); and *iii)* friction, mobilized by a relative displacement between the fibre and the binding paste, this component is highly dependent on the roughness of the interface surface [4,5].

The toughness mechanism in these composites is related with the effectiveness of the fibres to transmit tensile stresses across the cracks, which is related with the bond between the binding paste and the fibres. To assess the latter, can be performed a pull-out test considering only a single fibre, although having as main drawback the need to consider several identical specimens,

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for statistic reasons, and the need to use special equipment, due to the considerably reduced values of the applied load. For instance, Banthia and Yan [6] conducted this type of test using an equipment capable of measuring loads lower than 250 N. The purpose of this test is monitor the fibre slip as a function of the tensile force applied, aiming at analysing the bond behaviour as well as the influence of fibres' characteristics on the latter, such as geometry, and surface coatings, among others.

In the last years, the application of nanotechnology to several domains also reached the concrete sector allowing to improve its properties, focusing mostly on the possibility of reducing the dosages of both cement and additions, e.g., fly-ash and silica-fume [7,8]. Nanoparticles have reduced size (typical diameters varying between 0.1 and 100 nm), high surface-volume relation, and high reactivity during the cement's hydration process, increasing the density of the binding paste, reducing the concrete porosity, and improving the interfacial transition zone (ITZ) between aggregates and the cement paste [8,9]. These improvements recorded at the micro-scale have a positive impact on the strength and durability of concrete [7,10–14]. According to several authors [13,15], nanoparticles should be added to the mixtures in percentages between 0.5 and 2%.

The nanoparticles of silica (SiO_2), usually named as nano-SiO_2, are one of the most used in this field because they have showed good results in reducing porosity and thus in increasing the matrix density [7,10]. According to several studies [11–14,16–19], it can be stated that nano-SiO_2: (i) accelerates the cement hydration process, (ii) increases the compressive strength and the bond strength of the paste-to-aggregate interface, especially at early ages; (iii) enhances the concrete durability, by reducing the water absorption and the capillary absorption, decreasing the chloride ions penetration and increasing the electrical resistivity of concretes, which is relevant to reduce the corrosion of steel reinforcing bars (rebars). To achieve these results, it is mandatory to ensure a good dispersion of nano-SiO_2 within the cement paste.

Other types of nanoparticles that have also been studied as additions to concrete mixes include: nano-TiO_2, nano-ZnO_2, nano-Fe_2O_3, nano-Al_2O_3, and graphene nanoplatelet (carbon-based nano-material) having been observed that they also enhance the concrete's performance [20–23]. The nano-Al_2O_3 addition showed to increase the density of the paste, the compressive strength and the Young's modulus of concrete [19,24,25]. According to other studies, adding nano-ZnO_2 to concrete mixtures reduces their workability in the fresh state, which is common to all nanomaterials additions, decreases as well as the water absorption in the hardened state, and increases the strength capacity [26]. The addition of 2.5% graphene nanoplatelet significant decreases water penetration depth, chloride diffusion coefficient and chloride migration coefficients in cement mortars [23].

2. Scope and goals

Most studies regarding nanoparticles addition are focused on the concrete behaviour, either in the fresh state or in the hardened state, and in the latter case addressing mainly strength and durability. Considering that adding nanoparticles to the binding paste enhances concrete properties, in some cases by improving the interfacial transition zone (ITZ), it is expected that steel fibres-to-paste bond be also improved. It is worth to investigate this possibility because any improvement on the fibres bond would lead to an increase in both strength and ductility of FRC.

The effects of nanoparticles on the bonding strength have already been studied with steel rebars and the results show that the nanoparticles addition can improve the steel-to-concrete bond, specially, when a less usual nanoparticle, nano-kaolinite clay, is used [27]. Results of another study also indicate that the nanoparticles influence mostly the adhesion component of bond, which is particularly relevant when plain rebars were used [28].

Considering the effects described, it is expected that the bond between steel fibres and the concrete paste be also enhanced with nanoparticles addition. For this reason, and taking into account that the influence of adding nano-SiO_2, nano-Al_2O_3, and nano-ZnO on the bond between steel fibres and the binding paste has not been studied so far, it was decided to conduct the work herein described.

The main goals of the present research are:

- Analyze the effects of using different types of nanoparticles in the bonding strength between steel fibres and the binding paste, particularly, in the adhesion component;
- Evaluate the efficiency of two different approaches of adding nanoparticles to achieve the latter purpose: i) add nanoparticles to the binding paste, and ii) apply nanoparticles as fibres' coating.

In addition, considering the drawbacks already referred to the existing pull-out tests in fibres, the following supplementary objective was also settled:

- Develop a pull-out test to monitor the fibre's slip versus the applied load, with the restrain of using the same equipment used in the conventional rebars' pull-out tests.

3. Experimental program

3.1. Materials and mixtures

To produce the pull-out specimens, cement CEM I 52.5 and three types of nanoparticles, nano-SiO_2, nano-Al_2O_3, and nano-ZnO, produced by *Smart Innovation* company (Fig. 1), were adopted considering two different dosages of binder, namely 750 and 550 kg/m^3.

In total, eight mixtures were designed considering different combinations of cement and nanoparticles (Table 1). The two binder dosages were considered aiming at reaching different concrete strengths. The dosages of nanoparticles, 1% or 2% (in relation to the cement mass), were chosen based on preliminary tests developed by Lourenço et al. [29] and Soldado et al. [30], conducted to maximize the properties of the binding matrix using the minimum amount of constituents. Several mixtures were produced with this goal using different dosages of nanoparticles, ranging from 1 to 4%. Based on these tests, and using as selection criterium the obtained tensile and compressive strengths, it was concluded that 1% of nano-SiO_2 and nano-ZnO was the most favorable dosage since higher percentages did not lead to significantly higher strengths. A similar trend was found when the nano-Al_2O_3 was used and only the effect in the compressive strength analyzed. However, a more substantial impact in the tensile strength was detected when the percentage changed from 1% to 2%, which justified the choice of the latter percentage for this type of nanoparticle. This result is within the range described in other studies [13,15]. The nano-SiO_2 particles have a size of 70–150 nm, whereas both nano-ZnO and nano-Al_2O_3 particles have a size slightly higher, respectively 0.9–5 μm and 3–20 μm. The nano-SiO_2, nano-ZnO, and nano-Al_2O_3 particles, with a density of respectively 2.22, 5.41 and 3.95 kg/dm^3, were provided in solid state (powder) with 99.5% purity and were later dissolved in water before adding them to the concrete mixtures.

Besides cement CEM I 52.5 R, with a density of 3.16 kg/dm^3, and nanoparticles, a 0/1 mm fine sand, with a density of 2.63 kg/dm^3, and a third generation superplasticizer, Glenium SKY 526, were also adopted as binding paste's constituents. To achieve an appropriate workability of the mixtures in the fresh state, small adjustments to the superplasticizer dosage were considered.

Steel fibres Dramix® 5D 65/60 BG with a tensile strength of 2300 MPa, a Young's modulus of 210 GPa, a length of 60 mm, a diameter of 0.9 mm, a shape factor (l/d) of 67, and a hook-end anchorage were adopted. In some tests, one of the hooks at the fibres' end was cut off to measure the adhesion and friction components of bond. In fact, eliminating the mechanical interlock provided by the hook turns possible to analyze both adhesion and friction components.

To measure the effect of nanoparticles on the fibres-to-matrix bond two different approaches were adopted: first, nanoparticles were added to the binding paste and, second, nanoparticles were directly added to the fibres as coating (the fibres were soaked in an adhesive liquid with nanoparticles). In the second case, it was