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Influence of type of fibers on the properties of high performance cement-based composites

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HIGHLIGHTS

- Cement-based composites with expansive agent reinforced by several kinds of fibers.
- Synergy between brass- and zinc-coated fibers with CaO improving flexural strength.
- PET fiber degradation due to alkaline hydrolysis promoted by expansive agent.

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ABSTRACT

In this work twenty fiber reinforced cement-based composites (FRCCs) were studied, in which CaO-based expansive agent was used. Five different kinds of fibers were added, three hooked metallic: steel, zinc-coated and brass-coated; two plastic: corrugated polypropylene (PP) and hooked polyethylene terephthalate (PET) fibers. All the twenty mixtures, as well as a reference mixture without fibers, were characterized by recording fresh consistency, compressive and flexural strength, as well as drying shrinkage strains. Results obtained showed an improved flexural strength if high dosage of CaO-based expansive agent is used with either zinc or brass-coated fibers. The reason could be the formation of calcium hydroxide zincate (CHZ) crystals at the interface between fibers and cement paste promoted by alkaline environment. These CHZ crystals were observed by SEM, and they are likely able to enhance the quality of the interface fiber-matrix by increasing adhesion. On the other hand, the use of CaO seemed to accelerate PET fiber degradation due to alkaline hydrolysis leading to reduced FRCC mechanical performance. When used in the presence of either PP fibers or steel hooked fibers, CaO produced insignificant effects on mechanical performance. Finally, drying shrinkage was reduced due to the addition of CaO, whichever the type of fiber used.

1. Introduction

Cementitious materials are the most widely used construction and building materials because of their cheapness, their easy soft casting, their high mechanical performance, especially in compression, as well as satisfactory durability. However, concerning the last point, if they are exposed to dry climate, drying shrinkage can be responsible for cracking formation by compromising durability. The addition of fiber reinforcement to the concrete mixture has been a solution adopted for overcoming this critical aspect, as well as the use of expansive agents, which can produce early expansion leading to reduced shrinkage at later ages [1,2].

In particular, some authors [3,4] studied the effect of expansive agent in steel reinforced concrete, and found that the constraint offered by the steel bars to the expanding cement matrix was able to develop a compressive prestressing effect in the matrix, which was able to increase concrete flexural strength. However, this reinforcing effect could involve only a small portion of material, i.e. the thin layer around the steel reinforcement. In theory, if the same effect could be promoted by homogeneous and randomly dispersed fiber reinforcement, the prestressing effect could include the whole materials, not only a thin layer.

Nevertheless, the simultaneous effect of expansive agent and fiber reinforcement on the properties of cement-based materials was understudied till now, and a limited number of papers can be found in the literature [5–13]. Some authors studied polypropylene fiber reinforced concretes [5], in which the expansive agent addition led to a slight decrease of compressive and splitting tensile strength, as well as elastic modulus. Others showed that the use of expansive agent improved the adherence between cement paste and aggregate/fiber, especially in the early hydration period

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[6]. They found a refined pore structure of concrete as well as lower drying shrinkage and improved waterproofing. Park et al. [7] studied UHPCs prepared with expansive agent based on calcium sulfoaluminates and shrinkage reducing admixture. The addition of expansive agent didn't improve UHPC mechanical performance, while it was able to reduce by 80% autogenous shrinkage. Huang et al. [8] studied special shotcretes prepared with expansive agent and steel fibers. They noticed an improvement of the 28-day flexural strength. Aiguo et al. [9] investigated the effect of MgO-based expansive agent on steel fiber reinforced concrete by recording significant improvement in terms of splitting tensile strength (+38%). Cao et al. [10] studied lightweight concretes reinforced with steel fibers and they showed a certain synergic effect with expansive agent in terms of improved flexural strength.

An interesting study was carried out by He et al. [11], in which they found that the addition of an expansive agent to a fiber reinforced concrete (also reinforced by steel bars), was able to produce a self-stressing effect due to the hindered expansion of the cement paste by both the steel bars and steel fibers used. Such compressive pre-stress was estimated in the range 3–6 MPa.

Corinaldesi et al. [12,13] found that the use of CaO-based expansive agent can enhance flexural strength if used with brass-coated fibers.

2. Research significance

FRCC is a relatively new technology receiving a great deal of attention because of huge potential of application in the field of civil engineering, but not limited to. The main advantage of such technology with respect to the traditional concrete reinforced with steel bars (RC) is related to increased durability, due to reduced cracking (especially crack width), reduced shrinkage, reduced vulnerability to corrosion phenomena.

However, in terms of mechanical performance the addition of fibers generally is not able to enhance flexural peak strength but only to improve (even if at great extent) the post-cracking behavior (with benefits in terms of ductility, toughness, impact resistance [14,15] as well as fatigue strength [16]). For this reason its application in real cases is still limited, because FRCC needs steel reinforcing bars as well, at least those bars dedicated to flexural stress bearing. On the other hand, concerning shear stresses, Sahoo et al. [17] proved that FRC specimens with combined steel and PP fibers (dosage at least equal to 0.5% by volume) reached the same shear strength as RC specimen in the absence of shear stirrups. Nevertheless, the enhancement of the flexural peak strength (as well as of residual stresses) would be a precious achievement for FRCC, allowing either to reduce longitudinal steel bar reinforcement (or even completely eliminate it in certain cases), with savings in terms of reduced manpower, or to reduce section of structural elements (with improved lightening and energy efficiency).

In particular, the purpose of this study was to evaluate the influence of three different dosages of CaO-based expansive agent on the properties of FRCCs prepared with five different types of fibers: three metallic hooked fibers (either bare steel fibers (STEEL) or brass-coated steel fibers (BRASS), or zinc-coated steel fibers (ZINC)) and, two plastic fibers (either polypropylene fibers (PP) or polyethylene terephthalate hooked fibers (PET)).

The attention was focussed on FRCC drying shrinkage and flexural strength, since some published papers [8–13] detected a synergic effect between expansive agent and steel fibers in terms of increased peak flexural/tensile strength. However, the mechanism though which this synergy could develop needs further investigation.

The final ambitious goal of this study is to proportion FRCC mixtures able to achieve very high performance in bending, both in terms of peak strength and post-cracking behavior, close to that obtained by the expensive UHPCs. In these FRCC mixtures, typical ingredients of UHPC [18] such silica fume or micro silica were not used at all, and the cement dosage is quite low (500 kg/m^3). Even in the more recent UHPC mixtures, developed with the aim of improving their ecological impact [19,20], the overall amount of binders (i.e. expensive ingredients) is sensibly higher with respect to the FRCC mixtures studied in this paper.

3. Materials and methods

3.1. Materials

Portland cement, defined as CEM I 52.5 R in EN-197/1 [21] was used. Its relative specific gravity was 3.14 and Blaine fineness was 0.48 m^2/g. Carballosa et al. [22] showed that by using type CEM I cement, higher efficacy of the CaO-based expansive agents can be expected.

Well-graded quartz sand was used as aggregate, extracted from Po River, with particle size up to 1.0 mm.

The five types of fiber used in this study (showed in Fig. 1) were:

- Corrugated polypropylene (PP) fibers (50-mm long, 0.5 mm diameter).
- Hooked polyethylene terephthalate (PET) fibers (40-mm long, 1.2-mm large, 0.2-mm thick).
- Hooked steel (STEEL) fibers (35-mm long, 0.55 mm diameter).
- Hooked galvanized steel (ZINC) fibers (35-mm long, 0.55 mm diameter) and,
- Hooked brass-coated steel (BRASS) fibers (30-mm long, 0.50 mm equivalent diameter).

Some physical and geometrical characteristics of the fiber used are reported in Table 1.

A water-reducing admixture was added, constituted of a carboxylic acrylic ester polymer (27% dry mass in aqueous solution).

Finally, calcium carbonate ($CaCO_3$) as inert filler, and dead-burnt calcium oxide (CaO) as expansive agent were used.

3.2. FRCC mixture proportions

The same cement dosage of 500 kg/m^3, w/c ratio of 0.30, sand/cement ratio of 2.3, as well as polycarboxylate-based superplasticizer dosage (3.5% by weight of cement) were used for all the twenty mixtures. Five different kinds of fibers were added at the same rate of 2.0% by volume. For each kind of fiber four FRCCs were studied by adding CaO-based expansive agent at different dosages: either 0 or 20 or 30 or 40 kg/m^3. Finally, a control mixture (EA) with 40 kg/m^3 of CaO and without fibers was also manufactured.

In four mixtures (Table 2), 18 kg/m^3 of Type 'PP' fibers were added and the related mixtures are called 'PP', 'PP+20EA', 'PP+30EA' and 'PP+40EA' depending on the different amount of the calcium oxide used as an expansive agent.

For other four mixtures (Table 2), 27 kg/m^3 of Type 'PET' fibers were added and the related mixtures are called 'PET', 'PET+20EA', 'PET+30EA' and 'PET+40EA' depending on the different amount of the calcium oxide.

A reference mixture (REF) was prepared without fibers by adding the maximum amount of the calcium oxide equal to 40 kg/m^3 (Table 2), in order to evaluate the effect of the expansive agent addition alone.

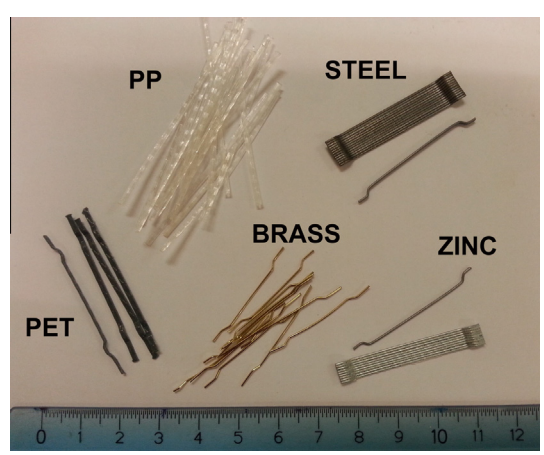

Fig. 1. Fibers used in the study.