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The influence of expansive agent on the performance of fibre reinforced cement-based composites

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HIGHLIGHTS

- Study of fibre reinforced cement-based composites with CaO-based expansive agent.
- Synergy between brass-coated steel fibres and CaO improving flexural strength.
- Reduced expansion/shrinkage by using fibres and expansive agent.
- Durable UHPC containing CaO-based expansive agent and shrinkage reducing admixture.

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ABSTRACT

In this work several fibre reinforced cement-based composites (FRCCs) as well as ultra high performance concretes (UHPCs) were studied, in which CaO-based expansive agent was added in order to help in reducing the risk of cracking induced by drying shrinkage. Three different kinds of metallic reinforcing fibres were tested: flat (and flexible) steel-alloy fibres, and brass-coated either hooked or straight steel fibres. All the mixtures were characterised at both fresh and hardened state, by measuring fresh consistency, compressive and flexural strength, as well as length changes under drying shrinkage test. Moreover, FRCC microstructure was investigated by means of Mercury Intrusion Porosimetry (MIP) and Scanning Electron Microscope (SEM) observations. The effect on mechanical performance of a thermal pre-treatment at 80 °C for the first 24 h of curing after casting was also evaluated. Results obtained confirmed the effectiveness of CaO addition on material stability under drying shrinkage; moreover, it seems to produce a beneficial effect on flexural strength if used with brass-coated fibres. The reason of this synergy probably lies in the formation of calcium-hydroxy-zincate crystals at the interface between fibres and surrounding cement paste (phenomenon promoted by dezincification of brass in alkaline environment), able to significantly improve the quality of the interface fibre–matrix by increasing adhesion.

1. Introduction

Cement-based materials (i.e. mortars and concretes) are the most widely used construction materials because they offers outstanding economic efficiency compared to other construction materials, as well as remarkable mechanical performances and durability. However, cement-based materials also involves some problems, such as their low strength characteristics (especially in bending) compared to their weight, and their brittleness. Recently, research for the development and practical use of FRCCs, and especially UHPCs, has been actively carried out to solve such problems.

Moreover, concrete has a peculiar characteristic with respect to other construction materials such as steel, wood and fibre reinforced polymer (FRP): concrete shrink due to loss of moisture by cement hydration and water evaporation.

In particular, UHPC is subject to significant plastic shrinkage and autogenous shrinkage as it has very low water/binder ratio (0.2), does not use coarse aggregates, and adopt high fineness admixtures (such as silica fume) [1,2]. In addition, FRCCs such as those studied in this work have low water/binder (0.27–0.30), and does not use aggregates particles greater than 1 mm, and it could be expected for them the same problems of UHPC in terms of shrinkage behaviour.

According to previous research [1–3], UHPC is exposed to a very high risk of shrinkage cracks if restrained by external form and internal reinforcement. Such shrinkage cracks degrade the durable lifetime of the structure and the structural performance.

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Consequently, there is a need to conduct research to provide solutions to reduce shrinkage in order to apply FRCC as well as UHPC to real structures.

A way to reduce concrete cracking could be the use of shrinkage-compensating concrete technology, which is based on the use of special products, such as calcium sulpho-aluminates or calcium oxide, which react with water and produce a restrained expansion in reinforced concrete structures. In particular, the transformation of calcium oxide to calcium hydroxide by reacting with water causes its volume increase of about 90% [4]. This technology has been invented many years ago [5], but its use has been very limited in practice, due to the difficulty in assuring a continuous water curing, absolutely needed in the early ages after setting. Consequently, from a practical point of view, this technology can be adopted only in some special constructions such as concrete floors or slab foundations. However, Collepardi et al. [6] found that there is a synergistic effect in the combined use of SRA and a CaO-based expansive agent in terms of more effective expansion, even in the absence of wet curing. In fact, due to the additional effect of SRA, shrinkage-compensating concrete was used to produce crack-free concrete without wet curing for an outside industrial floor of 800 m^2 in absence of contraction joints [7]. The synergistic effect of expansive and shrinkage reducing admixture was recently studied also by Meddah et al. [8]. They found a reduction up to 50% of autogenous shrinkage and self-tensile stress induced if using a combination of SRA and expansive agent for concrete with a w/b of 0.15, whereas increasing the w/b of concrete up to 0.23 and 0.30 resulted in a drastically reduction or even the completely elimination of both autogenous shrinkage and the internal tensile stress. However, the inclusion of the combination of SRA and expansive agent induced a slight decrease of both the compressive and splitting tensile strengths as well as the modulus of elasticity.

The addition of expansive agent on plain concrete (without fibre reinforcement) proved to be able to increase compressive strength a little, to leave the same flexural strength, and above all to produce initial expansion with consequent reduced final shrinkage at long ages [4,5,9].

Moreover, an interesting application is that of the so-called Chemical Prestressed Reinforced Concrete (CPRC), which is obtained by adding expansive agent to the mix, without fibre reinforcement [10,11]. Sahamitmongkol and Kishi [10,11] found a certain compressive prestress effect due to the external constraint offered by the reinforcement bars to the expanding cement matrix, which was able to increase the flexural behaviour. However, this reinforcement, which was localised (and not diffused), did not allow to fully utilise the prestress effect because it involved only a small portion of material, that was the thin layer located nearby the reinforcement bars. In theory, it would have been much more effective a fibrous reinforcement uniformly distributed throughout all the portion of material undergoing tensile stress when put in bending.

Nevertheless, the study of concrete containing both short fibre reinforcement and expansive agent in the cement mixture has been quite limited until now [3,12–17], and this combination has been mainly investigated with the aim of reducing autogenous shrinkage more than of improving mechanical performance in bending.

Sun et al. [12] showed that the incorporation of expansive agent with proper content made the interfacial strength between shrinkage resisting components (aggregates and fibres) and cement paste improved, especially in the early hydration period. They found improved pore structure of concrete, as well as improved shrinkage resistance and impermeability of concrete.

Toutanji [13] showed that the effect of expansive agent combined with a SRA in the presence of polypropylene fibres has led to a slight decrease of: compressive strength, splitting tensile strength and elastic modulus.

Park et al. [3], found that the expansive agent (mainly based on calcium sulpho-aluminates) combined with SRA did not show any positive effect of UHPC mechanical performance, while it was able to reduce by 80% autogenous shrinkage.

Huang et al. [14] studied a cementitious mixture in order to produce a shotcrete that contains both expansive agent and short steel fibres. They noticed an improvement of 28-day flexural strength without reaching values greater than 7 MPa indeed.

Aiguo et al. [15] studied a cementitious mixture containing magnesium oxide as expansive agent and steel fibres. They noticed some improvement of splitting tensile strength (+38%).

Cao et al. [16] produced a lightened high-strength mixture by using both high-modulus steel fibres and expansive agent in which a certain synergic effect of expansive agent and steel fibre was detected in terms of flexural strength.

He et al. [17] found that, by adding an expansive agent to cement-based materials reinforced by steel bars and/or steel fibres, it can be produced the so-called ‘self-stressing cement’, in which the expansion after cement hydration is so significantly restrained that the steel bars/steel fibres are tensioned, and able to create compressive pre-stresses in cross section, usually in the range 3–6 MPa.

2. Research significance

The first scope of this paper was to verify the positive influence of CaO-based expansive agent on reducing the autogenous shrinkage of both FRCC and UHPC.

In particular, in UHPC also the effectiveness of the combination CaO-based expansive agent and SRA was evaluated. In fact, a problem involving these cement-based composites with low w/b ratio is the likely tendency to crack at early age, due to autogenous and plastic shrinkages. SRA proved to be effective in counteracting concrete cracking [18], but especially in combination with expansive agent it showed synergic effect [6–9,19].

The second scope was to evaluate the influence of CaO-based expansive agent on the flexural strength of FRCC with high volume of metallic fibres (including UHPC). In fact, some papers are reported in the literature in which an improvement of tensile and flexural strengths was found thanks to a certain synergy between expansive agent and steel fibres [14–17]. However, in these papers the mechanism though which this likely synergy is able to develop was not investigated, even if it is presumable it can be the same found in the Chemical Prestressed Reinforced Concrete (CPRC) technology [10–11,17].

The third scope was to evaluate the effectiveness of a 24-h thermal treatment at 80 °C on the values of compressive and flexural strengths.

3. Materials and methods

In this work it was studied the influence of CaO-based expansive agent on the properties of cement-based composites reinforced with three different type of metallic fibres: flexible amorphous metallic fibres (Flex), and brass-coated steel fibres either hooked (Hook) or straight (Straight). Fibres were separately added to FRCC mixtures at a rate of about 1.4% and 1.9% by volume for ‘Hook’ and ‘Flex’ type respectively, while the type ‘Straight’ was used in UHPCs at a rate of 2.4% (the same dosage suggested by Richard and Cheyrezy [20] and adopted in a previous work [21]).

All the mixtures were characterised at both fresh and hardened state, by measuring fresh consistency, compressive and flexural strength, as well as length changes under drying shrinkage test. Moreover, FRCC microstructure was investigated by means of Mercury Intrusion Porosimetry (MIP) and Scanning Electron Microscope (SEM) observations.

3.1. Materials

Commercial Portland-limestone blended cement type CEM I 52.5 R according to the European Standards EN-197/1 [22] was used. The Blaine fineness of cement was 480 m^2/kg and its relative specific gravity was 3.15. Its chemical composition is reported in Table 1.