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Effects of nano-silica treatment on the flexural post cracking behaviour of polypropylene macro-synthetic fibre reinforced concrete

Pietro Di Maida[a], Corrado Sciancalepore[b], Enrico Radi[a,*], Federica Bondioli[c]

[a] Dipartimento di Scienze e Metodi Dell'Ingegneria, Università di Modena e Reggio Emilia, Italy
[b] INSTM, National Interuniversity Consortium of Materials Science and Technology, Florence, Italy
[c] Dipartimento di Ingegneria Industriale, Università di Parma, Italy

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A B S T R A C T

The effects of a surface nano-silica treatment, carried out with the sol gel method, on the post-cracking behaviour of polypropylene macro-synthetic fibre reinforced concrete are experimentally investigated here for the first time. The present study extends previous experimental and analytical investigations on the corresponding improvement of the bonding properties of a single synthetic macro fibre, performed by means of pull-out test. Scanning electron microscopy is adopted here to explore the changes in the morphological characteristics of polypropylene macro synthetic fibres, before and after mixing in the concrete matrix. A comparative analysis, carried out with three-point bending tests on notched beam specimens, is used to evaluate the effects of the nano-silica treatment on the concrete post cracking behaviour. Increase in concrete toughness and residual post-cracking strength is recorded due to improved adhesion between fibres and the concrete matrix and to the consequent increase in the frictional shear stress generated during the fibre pull-out, especially for large crack opening. As shown by the SEM images, the nano-treatment favours the bonding of the concrete hydration products to the surface of the treated fibres, thus ensuring strengthening of the interface transition zone. In addition, the links between the nano-silica coating and the concrete hydration products improve the frictional shear stress and thus the overall energy absorption, as denoted by the increase of the residual strength during the post-cracking phase.

1. Introduction

Concrete is one of the most widespread materials used for buildings and constructions because of its many benefits in terms of high performance, economic purposes and versatility. As well known, plain concrete exhibits a high compressive strength. However, it suffers a limited tensile strength that makes it classifiable as brittle material. To overcome this limit, concrete is usually reinforced with materials that provide ductility and tensile strength after first cracking. The most common application is certainly reinforced concrete (RC) with steel bars or webs, which today is massively used in most civil engineering structures. Fibre reinforced concrete (FRC) with short fibres of various materials (steel, glass, polymeric, natural, carbon etc.) has developed over the last 50 years as an alternative solution to plain concrete or RC. If compared to plain concrete, FRC shows greater toughness, that is the capacity of energy absorption during the fracture process, and higher post cracking tensile strength. Assessment of FRC properties required an intensive study in terms of experimentation and modelling until it was introduced into the Model Code 2010 [1], which is currently the most authoritative and updated FRC design guideline. Steel fibres are the most commonly used for FRC, even if they exhibit some problems due to corrosion in alkaline or chemically aggressive environments and to their electromagnetic properties [2]. For these reasons and for others of economic nature, there has been an increasing interest in synthetic fibres of various types of materials (polypropylene, polyethylene, polyvinyl chloride, polyethylene terephthalate, etc.) in recent years. In particular, polypropylene (PP) fibres display high stability in the chemical concrete environment without the critical features of steel fibres [3]. Two class of synthetic fibres are usually employed for FRC: micro-synthetic fibres (micron order diameters), which are used for contrasting micro cracking of cement composites resulting from plastic shrinkage [4], and macro-synthetic fibres (mm order diameters), which have comparable dimensions with steel fibres and can equally improve concrete toughness and tensile strength [5]. For their properties, the macro-synthetic fibres have increased their commercial attractiveness over the years, be-

* Corresponding author.
E-mail address: eradi@unimore.it (E. Radi).

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ing used in many civil engineering applications such as concrete pavements (used for industrial floors, roads, harbour piers), tunnels shotcrete (fibre reinforced sprayed concrete) and precast industry [6–11]. Despite the increased use of macro-synthetic fibres, they also display some peculiar weakness mainly related to the low elastic modulus, if it is compared to that of steel fibres [12], high deformability in time (creep) [13,14] and poor adhesion to the cement matrix due to the chemical inertia of PP and polymeric materials in general [15]. In order to mitigate the low adhesion of PP fibres to the cement matrix, several mechanical measures have been implemented such as giving a favourable shape to the fibres (crimped, undulated, fibrillated, embossed, etc.) that increase the grip [16,17]. Two other methods have been used to improve the fibre surface characteristics: the first one, of physical nature, aims to increase the surface micro roughness [18] and the second one, of chemical nature, tends to increase the functionality of the surface by improving the bonding with the hydration products of the cement matrix [19]. The proper working mechanism of FRC requires the progressive pull-out of fibres from the matrix without breaking during the post cracking process. During this process, each fibre experiences progression of debonding, then followed by frictional slippage between fibre and matrix. In this way, energy dissipation is promoted so that FRC becomes able to display ductile behaviour [20]. The pullout of the macro synthetic fibres is mainly related to the properties of the Interface Transition Zone (ITZ), that is the crossing zone between the fibre and the matrix. Due to its chemical-physical characteristics, the ITZ is identified as the weak zone where the local rupture of the fibre-matrix link occurs [21]. As reported in some experimental works [22], the mechanical properties of fibrous reinforced cementitious composites can be improved by increasing the local strength and micro hardness of the ITZ. This purpose can be achieved by reducing the porosity of the ITZ, by adding nano-fillers or polymers to the concrete mixture [23,24] or by performing chemical treatments on the outer surface of the fibre [25] that increase the functionality and the specific contact surface area, in order to produce an anchoring effect. The influence of various treatments on the fibres adhesion were mainly studied and validated by pull-out tests on single-fibre. However, the strengthening effects observed in the pull-out response of a single treated fibre may only partially extend to the macroscopic flexural behaviour of macro synthetic fibre reinforced concrete (MSFRC) [26] depending on fibre dosage and other random factors, such as the fibres distribution and orientation [27–29], which may reduce the overall effects of the advantages observed in the pull-out of a single treated fibre.

The present investigation provides the first experimental data available in literature on the post-cracking flexural behaviour of MSFRC whose fibres are treated with nano-silica, thus extending previous experimental and theoretical studies on the efficiency of nano-silica treatment on single fibre pull-out [30,31]. The effectiveness of the treatment has been evaluated in terms of toughness and post cracking residual strength of MSFRC beam specimen. In order to improve the interactions between the synthetic fibres and cementitious matrix, the superficial functionalization of PP fibres was achieved by a base-catalysed sol-gel treatment. Sol-gel reactions promote the growth of colloidal particles and their subsequent network formation through the hydrolysis and condensation reactions of inorganic alkoxide monomers. Tetraethoxysilane (TEOS) was used here as metal alkoxide. Under base-catalysed conditions, TEOS allows to obtain highly branched clusters due to the longer time that monomers need to aggregate in a most thermodynamically stable arrangement [32,33]. Adhesion of the so obtained silica nanoparticles on the PP fibre surface was evaluated by scanning electron microscopy and the resulting enhancement in the interfacial strength between treated fibres and cementitious matrix was characterized by mechanical three point bending tests.

Table 1
Reference concrete mix proportions.

Portland cement	350 kg/m^3
Water	150 l/m^3
Fine aggregate (0–2 mm)	742 kg/m^3
Coarse aggregate (2–16 mm)	1058 kg/m^3
Water/cement ratio	0.43

Table 2
Cement characteristics.

Time	Cement compressive strength
2 days	10 MPa (>100 kg/cm^2)
28 days	32.5 MPa (>325 kg/cm^2)

Table 3
Characteristics of the aggregates.

Sieve size (mm) ISO 3310-1/2	Passing (%)
31.5	100.0
22.4	100.0
20	100.0
16	99.8
14	96.6
12.5	93.5
11.2	90.1
10	87.2
8	82.0
6.3	76.9
5.6	74.7
4	63.4
2	41.2
1	26.1
0.5	17.2
0.25	9.6
0.125	2.8
0.063	0.6
Bottom	0.0
Water abs.	1.2–1.9
31.5	100.0

Table 4
Results of compressive tests.

Specimen	Compressive strength (MPa)	R_{cm} (MPa)	SD (MPa)
R_{c1}	30.67	30.50	0.20
R_{c2}	30.25		
R_{c3}	30.56		

2. Materials and methods

2.1. Reference concrete

Mix proportions for the reference concrete are reported in Table 1. The used cement was Portland Cement type CEM II/B–LL 32.5R according EN 197-1 with mechanical characteristics as reported in Table 2. The used water/cement ratio was 0.43. Crushed gravel with maximum size of 16 mm and controlled granulometric distribution, reported in Table 3, was used for coarse aggregate and river sand was used as fine aggregate. In order to classify the strength class of the reference concrete, compression tests were performed on three cubic specimen 150 × 150 × 150 mm^3 according to UNI EN 12390-1:2002. The concrete was poured in cubic moulds and compacted properly so as not to have any voids. After 24 h, the moulds were removed and test specimens were ripened to season. After 28 days of curing the specimens were tested in a compressive Metrocom testing machine (3000 kN of capacity) to get the concrete cubic strength R_c reported in Table 4.