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Tensile and in-plane shear behaviour of textile reinforced concrete: Analysis of a new multiscale reinforcement

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HIGHLIGHTS

- In tension, the TRC efficiency ratios are higher in stiffness than in strength.
- A new in-plane shear test was designed for the characterisation of TRCs.
- TRC with aramid fibres had a far better in-plane shear behaviour than with glass.
- A new type of multiscale reinforcement was tested in this study.
- The new multiscale reinforcement clearly improves the mechanical behaviour of TRC.

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ABSTRACT

In-plane shear strain can significantly influence the behaviour of various TRC structures. Because there is no in-plane shear test for TRC characterisation, a new test has been proposed to broaden the spectrum of TRC applications. The results indicate that a TRC with para-aramid fibres has a far better ratio between shear and tensile strength compared to a TRC with alkali-resistant glass.

Furthermore, a new type of reinforcement, coupled to conventional grids, was tested in this study. In terms of tensile and shear loading, this multiscale reinforcement clearly improves the mechanical behaviour of TRC at the microscopic, mesoscopic, and macroscopic scales.

1. Introduction

The study of textile reinforced concrete (TRC) composites has progressed since the mid-1990s [1]. Researchers have become increasingly interested in TRC composites because of their wide range of rheological, mechanical, chemical and aesthetic characteristics. This interest is also related to the diversity of TRC applications, primarily for light work [2–4] and potentially for structural work [3,5–10].

For structural applications, TRC is primarily used under tensile solicitation (e.g., integrated formwork elements [8] and repair and/or strengthening of reinforced concrete structures [6,7,11–13]). This trend explains the interest in the flexion [1] and tension characteristics of the TRC [3,14–17]. The tensile test and the methodology developed in [17] to utilise its results have been used in this study to advance towards a refined and systematic exploitation of the stress–strain behaviour of the TRC. On this basis, a detailed analysis of the influence of the reinforcement ratio was conducted, resulting notably in the definition of efficiency ratios.

However, in-plane shear strain can influence the behaviour of certain TRC structures and even lead to their failure [10]. Thus, to broaden the spectrum of TRC applications, an exploratory study was conducted to characterise the in-plane shear behaviour of TRC composites. Because the in-plane shear test for TRC characterisation is not found in literature, a new test has been designed based on the picture frame test used for textile characterisation [18–20]. Using this test, the effect of the nature and orientation of the weft yarn in the TRC on its behaviour is studied. Finally,

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an innovative type of reinforcement, designed to improve the performance of TRC, was tested in direct tension and in-plane shear. This new reinforcement, called a 'strengthening net', is intended to be coupled to conventional reinforcement grids.

2. Materials and methods

2.1. Materials

The specimen fabrication method, which is thoroughly described in a previous article [17], was used. TRC plates are hand-made using a contact moulding process. To limit the differential shrinkage of the mortar, a plastic film is placed on the surface. The plates are tested 28 days after moulding.

2.1.1. Matrix

A single-component mortar consisting of a hydraulic binder, a thixotropic synthetic resin, quartz fillers and synthetic micro-fibres are used (EMACO R315 from BASF). This thixotropic mortar has a plastic consistency suitable for direct contact moulding to concrete structures. The main characteristics of the mortar are summarised in Table 1.

2.1.2. Reinforcement

- Main grids

The main grids in the TRC are warp-knitted fabrics with a mesh size of 3 × 5 mm (5 mm between weft rovings). The warp yarns are similar in both fabrics: 2200 Tex high-strength polyester (PET). The only variable in these fabrics is the configuration of the weft yarns (Fig. 1, Table 2). It is well known that AR-glass fibres have a significantly lower transverse shear strength compared to that of para-aramid fibres. This distinctive feature is associated with the cracking behaviour of the cement matrix and can be detrimental to the in-plane shear strength of the TRC. To investigate this hypothesis, a comparison is performed between these two materials in tension and in-plane shear. The para-aramid "Technora$^{®}$" is selected because it exhibits a fair performance in terms of durability when embedded in a cement matrix [21].

- Strengthening nets

The strengthening nets must be placed on both sides of the main grids (strengthening nets and main grids have to be alternated in a symmetrical stack). The yarns in the strengthening nets have a significantly smaller section and ultimate load compared to that of the yarns in the main grids (cf. Tables 2 and 3, Figs. 1 and 2). The strengthening nets should act similarly to the short fibres dispersed in the fibre cement composites (and hence improve the mechanical characteristics of the matrix). Moreover, unlike short fibres, strengthening nets do not reduce the maximum main grid ratio that can be embedded into the matrix. In fact, the addition of short fibres reduces the workability of the mortar. Therefore, it leads to a significant increase in the thickness of the composite (at a constant main grid ratio). By contrast, the addition of strengthening nets in the TRC does not increase its thickness (because of the insignificant diameter of the yarns).

Two different mesh types were developed and tested: a filet net constructed of para-aramid multifilament yarns ('PA', Table 3, Fig. 2a, 2 yarns per direction) and a pillar inlay net constructed of stainless steel monofilament yarns ('SS', Fig. 2b, 2 yarns in 1 direction and 1 yarn in each other directions).

2.2. Testing methods

2.2.1. Direct tensile test

- Test methods

The static tensile characteristics of the TRC are established with a validated test [17] (Fig. 3). Two extensometers are bonded to the middle of each side of the specimen. The homogenised stress is obtained by dividing the tensile force by the cross section of the TRC specimen. The mean strain is calculated by dividing the mean displacement (the arithmetic mean of the 2 displacements measured on the specimen faces) by the length of the LVDT measurement zone (200 mm).

Table 1
Characteristics of the mortar (EMACO R315).

Maximum granularity (EN 12192-1) (mm)	1.25
Compressive strength (28 days) (EN 12190) (MPa)	42
Flexural strength (28 days) (EN 196–1) (MPa)	8
Elasticity modulus (GPa)	17.6

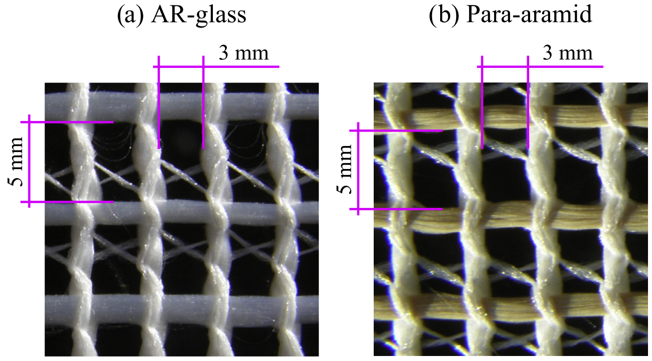

Fig. 1. Illustration of main grids.

- Series of experiments

Two series of tensile tests were conducted. The first series of tests addressed the influence of the main grid ratio for 2 configurations of yarns (PA2 and ARG, Tables 2 and 4). It should be noted that no more than 2 or 3 main grid layers can be embedded into the matrix for a TRC thicknesses of 5 or 10 mm, respectively. Because of the low stress–strain curve dispersion observed for this type of composite [17], 2 specimens per TRC layout were considered to be sufficient.

In the second series of tests, 2 types of composites were studied:

- The TRC was reinforced with both strengthening nets and main grids (PA1) and stacked in the following order: 1 strengthening layer, 1 main grid, 1 strengthening layer, 1 main grid, 1 strengthening layer, 1 main grid, 1 strengthening layer (T/PA1/PA and T/PA1/SS, Table 4). At a constant main grid ratio, the addition of strengthening nets in the TRC does not increase the composite thickness because of the insignificant diameter of their yarns.
- The TRC was exclusively reinforced with strengthening nets (T/SS/4 and T/SS/17). As specified in Table 4, T/SS/4 and T/SS/17 have 4 and 17 layers of strengthening nets (SS) embedded in the matrix, respectively (no main grid).

To accurately determine the influence of the strengthening nets, the crack pattern of the TRC was measured using a plane photogrammetry measurement system and related software [22,17].

Throughout this report, only weft yarns (AR-glass and para-aramid) are considered in the calculation of the main grid ratio of the TRC (volume ratio). These weft yarns and the principal orientation of the stainless steel pillar inlay nets were positioned in the tensile direction of the TRC specimens. Because aramid filet nets are bidirectional, orthogonal and balanced, it was decided to position them at an angle of 45° to the tensile direction to take advantage of the 4 yarn reinforcement directions (45° angle between each). The names of the tensile test specimens all begin with the letter 'T'.

2.2.2. In-plane shear test

- Test methods

A picture frame test (used for textile characterisation [18–20]) makes it possible to impose a pure in-plane shear kinematic to the specimen (Fig. 4). This test was transposed to the TRC composites. This process involved gluing (sandblasting + epoxy glue) aluminium end plates (100 mm deep) to the TRC plate edges (Figs. 5 and 6), which allowed satisfactory loading. End plates that are intended to be in direct contact with the frame must form a perfectly plane surface. An opening is made between these end plates to avoid blocking their movements (Fig. 6). The specimen is screwed onto the articulated frame with 12 screws through precisely drilled end plates. The articulated aluminium frame is designed (Fig. 5) to be non-deformable relative to the specimen. Using a compression machine, a displacement rate of 1 mm/min is set on one diagonal of the frame (*Y* axis, Figs. 4 and 5), thus generating a tensile displacement rate of 1 mm/min along the second diagonal (*X* axis, Fig. 4). To obtain a representative measurement of the response of the TRC, a linear variable displacement transducer (LVDT) with a measurement zone of 160 mm is positioned centrally and horizontally (*X* axis, Fig. 6, photograph on the right). The LVDT covers a sufficient number of cracks to be representative. The average strain is calculated by dividing the measured displacement by the length of the LVDT measurement zone (160 mm).

- Series of experiments

Two series of experiments were conducted with the shear test. The first experiment addressed the influence of the orientation of the main grids for 2 configurations of yarns (PA1 and ARG, Tables 2 and 5). The weft yarns were oriented either