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Textile-reinforced mortar (TRM) versus fibre-reinforced polymers (FRP) in flexural strengthening of RC beams

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HIGHLIGHTS

- TRM was compared to FRP in flexural strengthening of RC beams.
- TRM was almost as effective as FRP when debonding governed the failure.
- Effectiveness of TRM versus FRP was improved by increasing the number of layers.
- Epoxy coated textiles resulted in increased efficiency of TRM system.
- TRM debonding stress was predicted using a formula developed for FRP systems.

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ABSTRACT

This paper compares the flexural performance of reinforced concrete (RC) beams strengthened with textile-reinforced mortar (TRM) and fibre-reinforced polymers (FRP). The investigated parameters included the strengthening material, namely TRM or FRP; the number of TRM/FRP layers; the textile surface condition (coated and uncoated); the textile fibre material (carbon, coated basalt or glass fibres); and the end-anchorage system of the external reinforcement. Thirteen RC beams were fabricated, strengthened and tested in four-point bending. One beam served as control specimen, seven beams strengthened with TRM, and five with FRP. It was mainly found that: (a) TRM was generally inferior to FRP in enhancing the flexural capacity of RC beams, with the effectiveness ratio between the two systems varying from 0.46 to 0.80, depending on the parameters examined, (b) by tripling the number of TRM layers (from one to three), the TRM versus FRP effectiveness ratio was almost doubled, (c) providing coating to the dry textile enhanced the TRM effectiveness and altered the failure mode; (d) different textile materials, having approximately same axial stiffness, resulted in different flexural capacity increases; and (e) providing end-anchorage had a limited effect on the performance of TRM-retrofitted beams. Finally, a simple formula proposed by *fib* Model Code 2010 for FRP reinforcement was used to predict the mean debonding stress developed in the TRM reinforcement. It was found that this formula is in a good agreement with the average stress calculated based on the experimental results when failure was similar to FRP-strengthened beams.

1. Introduction and background

Over the last decades, the issue of upgrading and structural strengthening the existing reinforced concrete (RC) infrastructure has become of great importance. This is due to deterioration of these structures as a result of ageing, environmental conditions, lack of maintenance, and the need to meet the current design codes requirements (i.e. Eurocodes). Over the last two decades, the use fibre-reinforced polymers (FRP) for retrofitting concrete structures, has gain popularity among other conventional strengthening systems (such as steel/RC jacketing). However, some drawbacks have been observed with the use of FRPs, which are mainly associated to the use of epoxy resins. These drawbacks include high cost, inability to apply on wet surfaces or at low ambient temperature, low

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permeability to water vapour, and poor behaviour at high temperatures.

To overcome these drawbacks, a new alternative cement-based composite material, known as textile-reinforced mortar (TRM), has been suggested for external strengthening of structures [1,2]. A TRM is a composite comprises high-strength fibres made of carbon, basalt or glass in form of textiles embedded into inorganic materials such as cement-based mortars. The textiles typically consist of fibre rovings woven or stitched at least in two orthogonal directions, thus creating an open-mesh geometry. TRM composite is also identified with other acronyms such as TRC [3], and FRCM [4]. Several advantages of TRM are associated with the use of cement-based mortars including: resistance to high temperatures [5,6], low cost, ability to be applied in an environment of low temperatures or on a wet surface, permeability to water vapour, and compatibility with concrete substrates.

In the last few years, a significant number of studies have been directed towards investigating possible exploitation of TRM in several cases of retrofitting RC structural elements. Bond between TRM and concrete substrate has been investigated in many studies [7–14]. TRM jacketing has also been applied as a mean of external strengthening of RC structures in the following cases: confinement of RC columns (i.e. [1]), shear retrofitting of RC elements [2,15–19], confinement of RC columns subjected to seismic load (e.g. [20–24]), reinforcing of infilled RC frames subjected to seismic load [25], flexural strengthening of one-way (e.g. [26–28]) and two-way [29] RC slabs. The results indicated that TRM is a promising alternative to FRP in retrofitting structures. Examples of real applications of TRM worldwide in the construction field can be found in [30].

Research on the flexural performance of RC beams strengthened with TRM has been reported in [31–37]. Parameters investigated in these studies, were; the textile-fibre materials, for example, carbon-fibre textiles in [31,33,37], polyparaphenylene benzobisoxazole (PBO)-fibre textiles in [32–34,37], and basalt-fibre textile [35]; the number of layers [32–37]; the strengthening configuration [33]; the compressive strength of concrete [36]; and the type of textile-fibre materials [37]. The main conclusions of these studies were: (a) application of TRM to RC beams considerably improved their flexural capacity [31–37]; (b) increasing the number of TRM layers had twofold effect: increased the flexural capacity and altered the failure mode [32,37].

The comparison between TRM and FRP strengthening system in enhancing the flexural capacity of RC beams has been only reported in a few number of studies. In the study of Triantafillou and Papanicolaou, 2005 [31] it was found, on the basis of only two specimens, that TRM was 30% less effective than FRP, with the observed failure mode being different (rupture of fibres for the FRP-strengthened beam and interlaminar debonding for the TRM-strengthened beam). Elsanadedy et al., 2013 [35] reported that, the performance of TRM strengthening system in enhancing the flexural capacity of RC beams was slightly less than that for FRP system. But TRM system is more efficient in increasing the deformation capacity. This conclusion was made based on the comparison between two tested beams only; one beam strengthened with five layers of TRM in form of U-shaped jacket made of basalt-fibre textile and another retrofitted with one layer of basalt FRP.

Based on the above, it is clear that more research is needed to cover the subject of the effectiveness of TRM versus FRP in flexural strengthening of RC beams. The aim of this paper is to compare the effectiveness of the two strengthening systems in enhancing the flexural capacity of RC beams. Parameters considered were: the number of strengthening layers (1, 3, 5, and 7), the textile surface condition (coated or uncoated), the textile-fibre material (carbon, coated basalt or glass fibres), and the strengthening configuration (end-anchorage).

2. Experimental programme

2.1. Test specimens and investigated parameters

The objective of the present study was to evaluate the performance of TRM versus FRP in increasing the flexural capacity of RC beams. For this purpose, thirteen half-scale beams of rectangular section with dimensions of 101 mm width and 202 mm depth were fabricated, strengthened and tested under 4-point flexure. The length of the beams was 1675 mm (Fig. 1a), whereas the clear flexural and shear span were 1500 mm and 580 mm, respectively (Fig. 1b).

All beams were intentionally designed with a low amount of longitudinal reinforcement ratio (ρ_s = 0.56%) in order to simulate flexural-deficient beams. The internal steel reinforcement comprised two 8 mm-diameter deformed bars in tension and two 12 mm deformed bars positioned in compression (Fig. 1). The transversal reinforcement comprised 8 mm-diameter steel stirrups at a distance of 80 mm along the two shear spans of the beams, (expect for the constant moment zone), resulting - by design – to a shear resistance seven times higher than the shear force corresponding to the predicted flexural capacity of the unstrengthened beam. In all beams, the concrete cover was same and equal to 15 mm.

The investigated parameters were: (a) the reinforcement material (TRM vs FRP), (b) the number of TRM/FRP layers (one, three, five, and seven), (c) the material of the textile-fibres (carbon, glass and basalt), (d) the coating of the textile (coated carbon-fibre versus dry carbon-fibre textile), and (e) the end-anchorage of the externally bonded composite layers (U-jacketing). Table 1, with the support of Fig. 2, provide a description of the tested specimens. The notation of the strengthened specimens is BN_F, where B represents the type of binder (R for epoxy resin, and M for cement mortar), N refers to the number of TRM or FRP layers and F denotes the type of textile fibres (C for dry carbon fibres, CCo for coated carbon fibres, BCo for coated basalt fibres and G for glass fibres). For the specimens retrofitted with U-jackets at their ends, an additional suffix (EA, standing for end-anchorage) is added to the notation. The description of the specimens follows:

- CON: unstrengthened beam which served as control specimen.
- R1_C and M1_C: beams strengthened with 1 dry carbon FRP and TRM layer, respectively.
- M1_ CCo: beam strengthened with 1 coated carbon TRM layer.
- R3_C and M3_C: beams strengthened with 3 dry carbon FRP and TRM layers, respectively.
- M5_C: beam strengthened with 5 dry carbon TRM layers.
- R7_BCo and M7_BCo: beams strengthened with 7 coated basalt FRP and TRM layers, respectively.
- R7_G and M7_G: beams strengthened with 7 dry glass FRP and TRM layers, respectively.
- R3_C_EA and M3_C_EA: 3 dry carbon FRP and TRM layers strengthened beam, anchored at their ends with two dry carbon FRP and TRM layers, respectively.

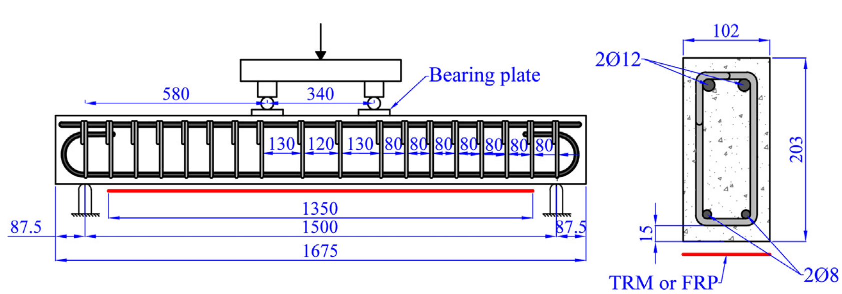

Fig. 1. Details of test beams (dimensions in mm).