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ANALYSIS OF DIFFERENT TYPES OF CEMENTITIOUS-BASED COMPOSITES USED AS SHEAR STRENGTHENING SYSTEM FOR REINFORCED CONCRETE BEAMS

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ABSTRACT

The global tendency to apply sustainable criteria in most of the productive fields and the limited durability and the pathologies that reinforced concrete elements suffer are aspects that explain the increasing necessity of strengthening this type of structures.

The evolution of strengthening techniques has consisted in the development of new technologies that ease the application of the solution and minimise the time structures are out of service. In this way, using composite materials in construction has represented a revolution in the strengthening of structures.

The textile-reinforced mortar (TRM) is a composite material that combines textiles, made of high strength tensile fibres, with cementitious matrix. A remarkable feature of this solution is that it does not require organic resins for its manufacturing and application, unlike the techniques as fibre-reinforced polymer (FRP).

The present work has consisted in the analysis of the mechanical and structural behaviour of reinforced concrete beams strengthened against shear stresses using different types of TRM. To fulfil this aim, an experimental campaign has been carried out. Nine reinforced concrete beams have been subjected to experimental tests, eight of them shear strengthened with four different combinations of textiles and mortars.

Using the experimental data, an analytical study has compared the ultimate capacity of the reinforcements with the predictions obtained from three analytical models included in design standards of FRP and TRM.

The results show that the strengthening system is able to increase an average of 33.7% the shear capacity of reinforced concrete beams. On the other hand, the results of analytical studies indicate that models adapted from FRP standards might show a better prediction capacity than the obtained with the code specifically developed for TRM reinforcements, which has performed significantly conservative.

1. INTRODUCTION

Textile-reinforced mortar (TRM) is a strengthening technique solution for reinforced concrete (RC) elements. It was studied for the first time ten years ago due to the increasing necessity of strengthen this type of structures. The TRM was developed as an evolution of fibre-reinforced polymers (FRP) and its main characteristic is that this reinforcement does not contain organic polymers avoiding the drawbacks associated with their use [1]. It consists of a fabric as a tensile withstanding material, where the fibres are grouped in tows and arranged as a mesh, which is embedded in a cementitious matrix. Mortar plays two roles as a matrix and as an adhesive to the existing structural surface.

The shear strengthening has a special concern because a lack of shear capacity in RC beams might cause a brittle failure of the structure. In this way, the first investigation on RC shear strengthened with TRM was carried out by Triantafillou and Papanicolaou [2], where they studied the structural response of RC elements reinforced with carbon textiles and cementitious matrices and compared it with FRP reinforced ones. Similarly, Blanksvärd et al. [3] analysed the behaviour of different fabrics of carbon fibres combined with various types of mortars and resins and Al-Salloum et al. [4] compared the behaviour of beam-column joints reinforced with FRP and TRM and subjected to cyclic loads. Focusing on glass meshes, Brückner et al. found the relationship between the number of layers of textiles and the increase in the shear capacity of structural elements [5] and between the bonding performance of TRM and the mesh anchorage lengths [6]. On the other hand, Al-Salloum et al. [7] investigated the performance of basalt textiles for TRM and analysed the influence of the number of layers and the orientation of fabrics on the shear capacity of reinforced beams. Recently, studies carried out by Escrig et al. [8] compared the performance of different types of TRM as shear strengthening of RC beams, analysing aspects such as the bonding behaviour and the increment in flexural toughness provided by these materials.

In 2013, the first design guide for external TRM reinforcements (ACI 549.4R-13 [9]) was published. Among other recommendations, this guide proposes an analytical model for the calculation of the TRM shear contribution on RC beams. Previously, other authors proposed analytical models [2,3,10] based on reference FRP standards: fib-Bulletin 14 [11] and ACI 440.2R-08 [12].

The work presented in this paper consists of a comparative analysis of the mechanical behaviour of RC beams strengthened in shear with different types of TRM. To achieve this goal an experimental program was carried out, in which 9 RC full-scale beams were tested using four different TRM materials for shear strengthening. Furthermore, this paper includes a critical study about the applicability of various existing analytical models: TRM shear strengthening from ACI code [9] and models from FRP adapted to a cement matrix [11,12].

2. MATERIALS

2.1 Reinforced concrete beams

The experimental campaign consisted in testing 9 RC beams with a lack of shear reinforcement in a length of 500 mm in both endings. Beams had a length of 1.70 m and a cross-section of 300 mm x 300 mm. The steel reinforcement consisted of three longitudinal bars of Ø16 mm installed on the top and the bottom sides and five transverse stirrups of Ø8 mm, three of them placed at the centre zone of the beams and the other two at the beginning and at the end. All reinforcement bars were B500S. Three different batches of concrete were used.

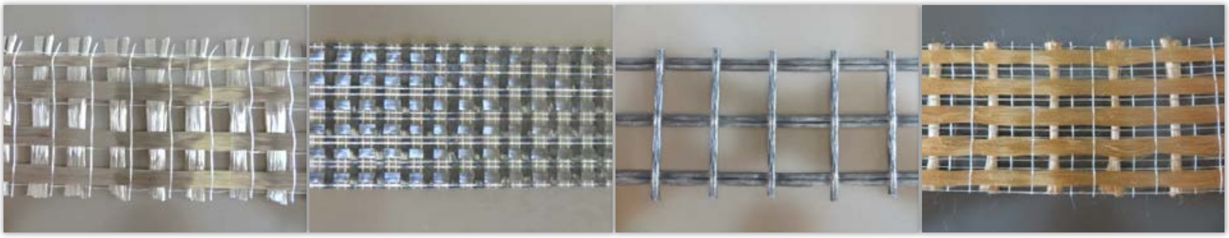
Table 1. Mechanical properties of the concrete and steel bars

Concrete			***Steel***		
Cast batch	***f_{cm} [MPa]***	***E_c [GPa]***	***f_y [MPa]***	***f_u [MPa]***	***E_s [GPa]***
Batch-1	34.07	32.92	517.20	633.63	198.48
Batch-2	33.78	32.83			
Batch-3	40.85	34.82			

The mechanical properties of the concrete and steel (Table 1) were obtained according to European standards. All specimens were cured in ambient conditions for more than 30 days.

2.2 Textile-reinforced mortar

Textiles consisting of mesh basalt fibres (designated as B), mesh carbon fibres (C), mesh glass fibres (G) and mesh Poliparafenil-benzobisoxazole - PBO fibres (P) were used (Figure 1). Mechanical and geometrical properties of the fibres and textiles provided by the manufacturers are summarized in Table 2.



(a) (b) (c) (d)

Figure 1. Textiles used: (a) basalt, (b) carbon, (c) glass and (d) PBO.

Table 2. Properties of the fibres and textiles

Type of fibre			***Basalt***	***Carbon***	***Glass***	***PBO***
Designation			B	C	G	P
Fibres	Fibre orientation [a]		Bi	Bi	Bi	Uni
	Ultimate tensile strength	f_{fib} *(MPa)*	2990	2610	2610	5800
	Young modulus	E_{fib} *(GPa)*	95	90	90	270
	Ultimate strain	ε_{fib} *(%)*	3.15	2.90	2.90	2.15
Textiles	Weight	w *(g/m²)*	200	225	225	88
	Wide of tow [b]	w_m *(mm)*	5	3	3	5
	Distance between tows [b]	s_m *(mm)*	15	25	25	10
	Equivalent thickness [b]	t_{tex} *(mm)*	0.053	0.042	0.042	0.0455

[a] Bi=Bidirectional; Uni=Unidirectional.

[b] In the unidirectional case, the properties given are in the principal direction of the reinforcement.

On the other hand, four types of mortar were used as a matrix of the different combinations of TRM:

- Hydraulic mortar modified with polymeric additions (designated as R3). This is a mortar designed for structural repairing.
- Hydraulic puzzolanic mortar (designated as XM25) with additives. This mortar is perfectly compatible with masonry structures.
- Bicomponent mortar (designated as PHDM) with high strength cement and glass fibres. It is a material specially designed for being applied on masonry.
- Hydraulic mortar (designated as XM750) with high bonding capacity, fibres and special additives. It is a mortar designed for application in concrete structure repairing.

Eight of the nine beams were strengthened with four combinations of textiles and mortars previously to test (Table 3). All applied combinations follow the V-AB-C nomenclature, where A stands for the type of textile, B indicates the type of mortar, and C is the test number.

The beams were shear strengthened by the U-shaped jacket system. To simulate a real strengthening case where cost is an important factor, only the zone with a lack of shear stirrups was reinforced with TRM that included a single layer of fabric.

Table 3. TRM combinations used as shear reinforcement of RC beams

Specimen	***Textile***	***Matrix***	***Concrete batch***
V-CONTROL	-	-	Batch-3
V-BR3-01	Basalt (B)	R3	Batch-2
V-BR3-02	Basalt (B)	R3	Batch-2
V-CXM25-01	Carbon (C)	XM25	Batch-2
V-CXM25-02	Carbon (C)	XM25	Batch-1
V-GPHDM-01	Glass (G)	PHDM	Batch-2
V-GPHDM-02	Glass (G)	PHDM	Batch-1
V-PXM750-01	PBO (P)	XM750	Batch-1
V-PXM750-02	PBO (P)	XM750	Batch-1

3. EXPERIMENTAL CAMPAIGN

3.1 Test set-up

The specimens were tested under three-points flexural tests with a free span between supports of 1.50 m. The section where the load was applied was shifted 50 mm from the centre of the beams to avoid the short shear span effect, at least in one-half of the geometry. The tests were carried out using a hydraulic actuator with a maximum capacity of 500 kN. The load was applied under displacement control at 1 mm/min and the vertical displacement of each beam was measured in load application section by two potentiometers placed symmetrically in both sides of the beam. All data were recorded at a frequency of 50 Hz using a data acquisition system.

3.2 Results

All the beams developed a shear failure. However, three different crack patterns were observed (Figure 2):

- Crack pattern A: the main crack propagating from the load application section towards the bottom of the beam without crossing the TRM strengthened area.
- Crack pattern B: the main crack propagating from the load application section towards the support, avoiding the stirrup reinforcement. After failure, the main crack propagated diagonally towards the support.
- Crack pattern C: the main crack propagating from the load application section towards the support by crossing both the shear reinforcement stirrup and the TRM strengthened area.

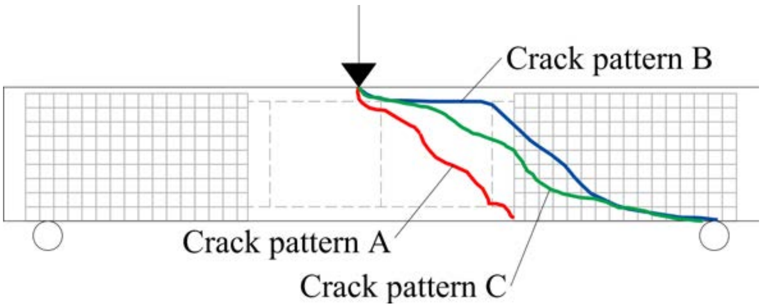


Figure 2. Crack patterns of tested beams.

Table 4 summarises the results obtained in the experimental campaign. This table contains the crack pattern developed for each beam, the ultimate load (F_u), the vertical displacement of the loaded section at the ultimate load (δ_u), the ultimate shear resistance developed in the longest shear span ($V_{u,exp}$) and the geometric angle between the main crack and the longitudinal axis of the beam (θ), which was determined through graphical methods. With the aim of comparing the experiment results of all specimens, in the last column of Table 4 the normalized ultimate shear force (μ_u) according to (1) is included:

$$\mu_u = \frac{d\,\frac{F_u}{L}}{V_c} \qquad (1)$$

where d is the smallest shear span (700 mm), F_u is the ultimate load, L is the distance between supports and V_c is the shear contribution of the concrete without the presence of shear steel reinforcement, which was calculated according to the standard Eurocode2 [13].

Table 4. Summary of the experimental results

Specimen	*Crack pattern*	F_u *(kN)*	δ_u *(mm)*	$V_{u,exp}$ *(kN)*	θ *(°)*	μ_u *()*
V-CONTROL	B	161.59	3.97	75.41	41	0.97
V-BR3-01	A	211.02	8.28	98.48	44	1.34
V-BR3-02 (1)	C	130.04	36.76	60.69	21	0.83
V-CXM25-01	B	220.42	7.44	102.86	38	1.40
V-CXM25-02	B	173.15	5.82	80.81	56	1.10
V-GPHDM-01 (1)	C	104.76	7.05	48.89	33	0.67
V-GPHDM-02	A	219.04	8.62	102.22	46	1.39
V-PXM750-01	A	215.95	20.72	100.77	42	1.37
V-PXM750-02	A	231.66	35.91	108.11	40	1.47

(1) Specimens that did not increase the load bearing capacity with respect to the control beam.

Figure 3 shows the experimental curves of the normalized shear force (μ) versus the vertical displacement of the load application section (δ_F).

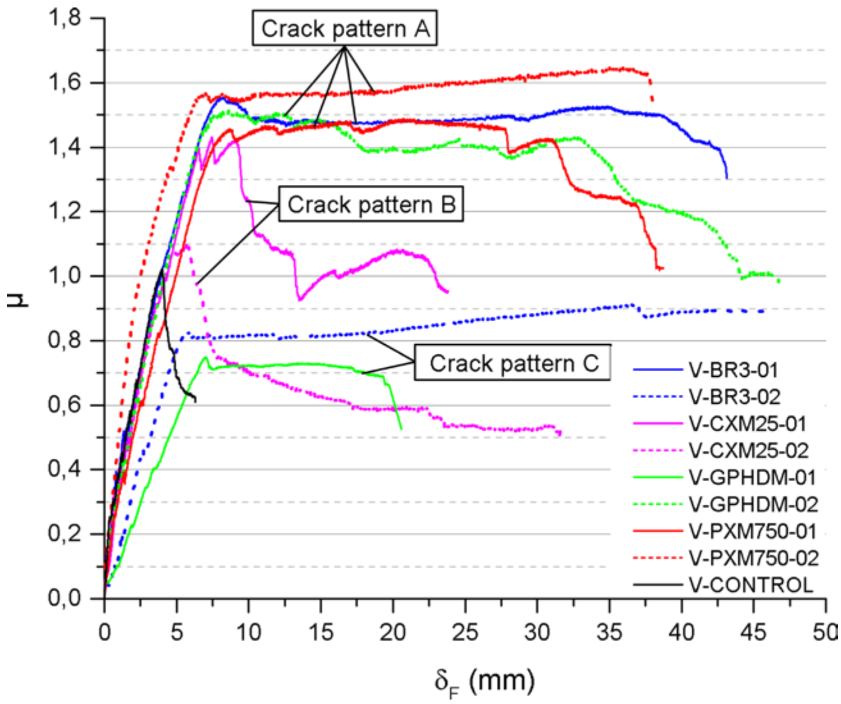


Figure 3. Normalized shear force vs. vertical displacement of the load application section.

It can be observed in Table 4 and Figure 3 that the strengthened beams which developed the crack pattern C were unable to reach the normalized ultimate shear force of the control beam. At low state of load, the deflections of these strengthened beams was significantly higher than the others. Thus, it suggests specimens V-BR3-02 and V-GPHDM-01 presented a lack of flexural stiffness due to an inappropriate curing of the concrete. For this reason, these beams are not take into account in the following discussion and the analytical study.

3.3 Comparison and discussion

First of all, it can be observed in Figure 3 that all of the specimens that developed the crack pattern A reached the flexural yielding avoiding the sudden failure after completing the linear-elastic response. Furthermore, these specimens increased the shear ultimate capacity of the concrete structure by an average of over 36%. Particularly, the beam V-PXM750-02 developed the greatest shear capacity increase (over 43%).

Although the ultimate tensile strength of basalt and glass fibres is significantly lower than the PBO fibres, the shear strengthened beams with BR3 and GPHDM developed similar mechanical response to the beams strengthened with PXM750. This suggests that factors such as textile-matrix and matrix-substrate adhesion have a high influence to the shear strengthening of RC structures with TRM.

V-CXM25 specimens developed the same crack pattern as the control beam (Table 4 and Figure 3). Although the beams strengthened with carbon textiles were not able to develop a nonlinear behaviour before sudden failure, these specimens reached a higher ultimate shear force (between 7% and 36%) than the unreinforced sample. According to Bernat et al. [14], the scatter of this results may be due to a deficient adherence between the textile and the mortar, which can affect the strengthening capacity of the specimens.

4. ANALYTICAL STUDY

In the analytical section, three different models for the contribution of the external reinforcement to the ultimate shear resistance of RC beams were studied. Two of these models are proposed in FRP standards (fib-Bulletin 14 [11] and ACI 440.2R-08 [12]) and the other model was obtained from the TRM design guide (ACI 549.4R-13 [9]). The predictions of these models were compared with the obtained experimental results.

4.1 Studied codes

All of the studied codes propose the contribution to the shear resistance of the external reinforcement as an independent parameter of the ultimate shear resistance of RC beams. In the case of fib-Bulletin 14 [11], the shear contribution provided by FRP ($V_{f,fib14}$) is calculated considering an effective strain in the principal direction of reinforcement $\varepsilon_{f,e}$. This effective strain is, in general, lower than the ultimate strain of FRP ε_{fu} and adopts different expressions depending on the failure mode, the type of the FRP fibre and the reinforcement wrapping configuration.

Regarding the model proposed by ACI 440.2R-08 [12], the contribution of FRP reinforcement to the shear ultimate resistance ($V_{f,ACI440}$) is calculated similarly to fib-Bulletin 14 [11]. In this case, the effective strain depends on the reinforcement-wrapping configuration and it is obtained considering a bond-dependent coefficient for shear (κ_v).

Finally, the formulation included in ACI 549.4R-13 [9] is the only of the studied ones that estimates the shear contribution provided by TRM ($V_{f,ACI549}$). In this case, the model considers a design tensile strain of TRM (ε_{fv}) that equals to the ultimate tensile strain of TRM ($\varepsilon_{fu,TRM}$), limiting this value to 0.004. This limitation is not taken into account in the present study. In contrast with the previous two models, this code poses an analytic development using the mechanical properties of TRM. These properties were taken from studies of characterisation of the TRM (Larrinaga [15]), the design guide ACI 549.4R-13 [9] or provided by the manufacturer (Table 5).

Table 5. Mechanical properties of TRM strengthening composite materials

		BR3 [a]	***CXM25*** [b]	***GPHDM*** [c]	***PXM750*** [b]
Cracked TRM Young's modulus	E_f *[GPa]*	48	80	90	128
Ultimate strain	ε_{fu} *[%]*	1.65	1.00	1.19	1.76

[a] Larrinaga, 2011 [15], [b] ACI 549.4R-13, 2013 [9], [c] Provided by the manufacturer.

4.2 Particularities of the analysis

With the aim of adapting the formulae proposed by fib-Bulletin 14 [11] and ACI 440.2R-08 [12] to calculate the shear contribution provided by TRM reinforcement, the following facts are considered:

- In both cases, the expressions of effective strain $\varepsilon_{f,e}$ derived from U-shaped jacket wrapping configuration are used.
- In the case of fib-Bulletin 14 [11], the expression of effective strain $\varepsilon_{f,e}$ for CFRP (carbon fibre-reinforced polymer) reinforcement is used, taking into account a failure mode based on the reinforcement fracture and discarding the included expression used for peeling-off failures.
- An equivalent uniform distribution of textile fibres along the reinforcement width is considered.
- Mechanical properties of fibres (E_{fib} and ε_{fib}) provided by the manufacturers are considered (Table 2).

The experimental shear contributions of the studied TRM reinforcements ($V_{f,exp}$) have been obtained by subtracting the concrete shear resistance obtained according to the standard Eurocode 2 [13] ($V_{c,EC2}$) from the ultimate shear resistance developed by RC beams strengthened with a particular type of TRM ($V_{u,exp}$) (Table 4). In the case of the existing two samples with the same TRM reinforcement, the ultimate shear resistance developed by RC beams are the average between them.

4.3 Results and comparison

Figure 4 shows the different contributions of TRM to the shear resistance of the studied models and the experimental results obtained. As can be observed, a general trend is that the shear resistance contributions of TRM obtained using the fib-Bulletin 14 [11] formulation overestimate the experimental results. On the other hand, the results obtained according to ACI 549.4R-13 [9] underestimate the experimental values in all cases.

Regarding the individual analysis of the different types of TRM, in the case of basalt textile reinforcement (Figure 4a), the obtained value using fib-Bulletin 14 [11] exceeds 195% of the experimental results. In contrast, the results obtained with this TRM reinforcement according to ACI 440.2R-08 [12] and ACI 549.4R-13 [9] showed conservative. This trend is similar in the case of glass textile reinforcement (Figure 4c).

Figure 4b shows the results obtained with carbon textiles TRM. Herein, the value obtained with ACI 549.4R-13 [9] is considerably lower than the obtained with ACI 440.2R-08 [12], which indicates a much better performance according to the experimental results.

Finally, it is important to outline that the TRM experimental results of the PBO textile reinforcement (Figure 4d) are those that best meet the analytical predictions according to the ACI models.

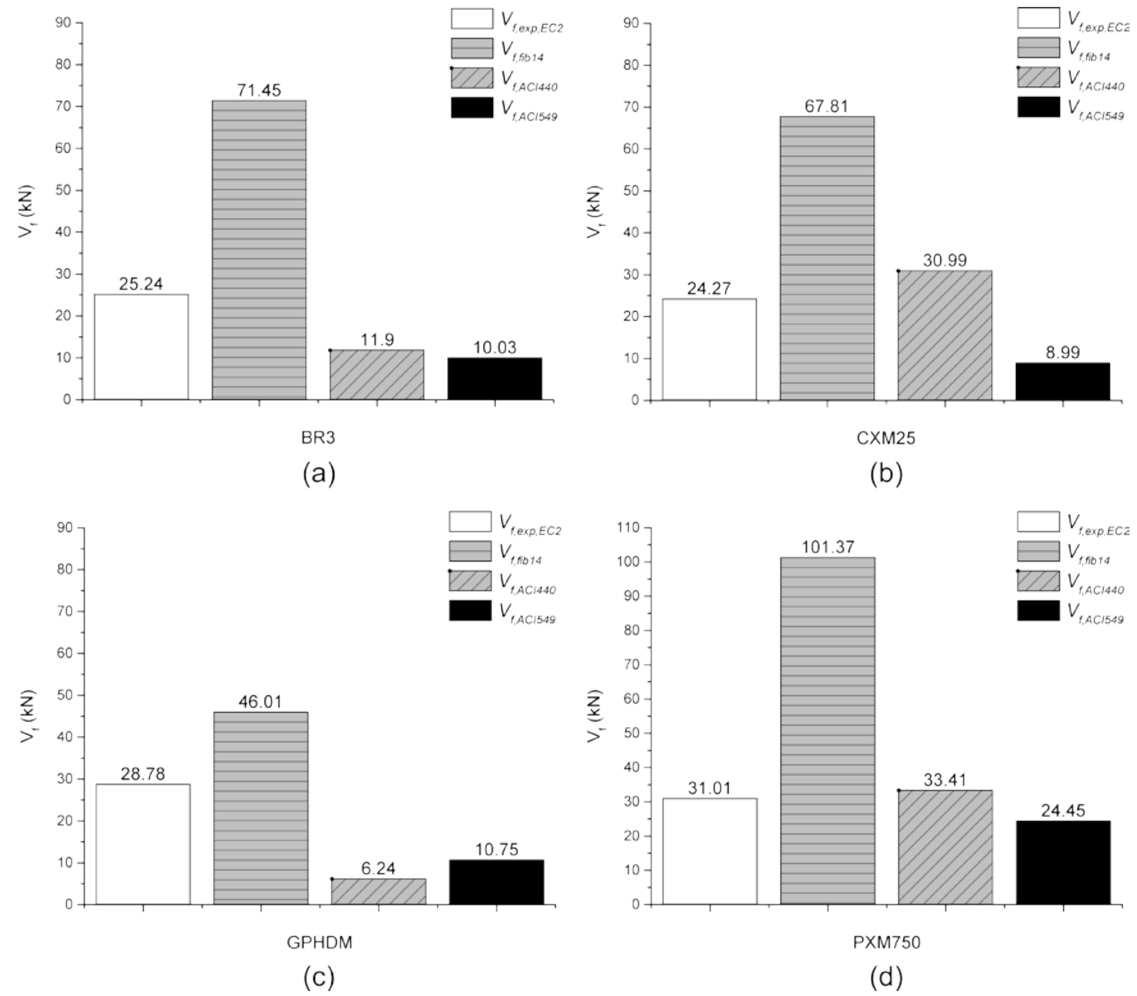


Figure 4. Experimental and analytical shear resistance contributions of the TRM reinforcements: (a) BR3, (b) CXM25, (c) GPHDM and (d) PXM750.

5. CONCLUSIONS

The present research studies the mechanical response of RC beams shear strengthened with four types of TRM. In all the cases the external reinforcements allowed a significant increase in the ultimate shear resistance of the RC beams, reaching an average load-bearing rise of 36%. Moreover, the ductile post-yield behaviour observed in some of the specimens represented a noticeable improvement in comparison with the brittle failure of the unstrengthened beam.

Analytic approaches with standards based on the FRP technology (fib-Bulletin 14 [11] and ACI 440.2R-08 [12]) and TRM strengthening system (ACI 549.4R-13 [9]) were carried out. It is noted that while the predictions using fib-Bulletin 14 [11] highly overestimate the experimental results, the contributions to the shear resistance provided by TRM using ACI 549.4R-13 [9] formulae show a conservative tendency. Although ACI 440.2R-08 [12] is a code for the design of RC beams externally strengthened with FRP, it reached the best accuracy at predicting the contribution of the TRM to the shear resistance, specially for CXM25 and PXM750 reinforcements.

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