Analytical Model for the Compressive Strength of Confined Concrete with Textile Reinforced Mortar

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Abstract. This paper proposed an analytical model to predict the confined concrete compressive strength with textile reinforced mortar (TRM). Based on 341 compression tests, different parameters have been analyzed to clarify their influence on the compressive strength of concrete column confined with TRM. The various existing models for compressed concrete columns confined by TRM have been assessed. Then, a simplified model for concrete elements wrapped with TRM are developed and verified through a best-fit analysis of the experimental database. It found that the proposed model showed good agreement with experimental results.

Keywords: textile reinforced mortar, TRM, confinement, concrete, axial compression.

1. Introduction

Using the jackets externally bonded to the concrete surface is the most popular solution for strengthening existing reinforced concrete (RC) structures. In the last 20 years, the fiber-reinforced polymers (FRP) are widely used in the rehabilitation of RC structures. This technique allows attaining large improvements in terms of deformation capacity and concrete strength. However, some drawbacks were found as the inapplicability on wet surfaces, the incompatibility of epoxy resins and substrate materials, the high costs of epoxy resin. To alleviate these problems, the textile reinforced mortar (TRM) system was developed recently [1, 2]. TRM is a cement-based composite material which consists of high strength fibers in form of textiles combined with inorganic matrices, such as cement-based mortars. A significant research effort has been made towards the exploitation of the TRM for strengthening or retrofitting of concrete structures. It found that TRM helps to increase the ultimate flexural, shear and torsion capacity of RC members. TRM also increases their stiffness, reductions in crack widths and deflections. In the literature, TRM composites can be found with different names, with the most common being the TRC (Textile Reinforced Concrete), FRCM (Fabric Reinforced Cementitious Matrix) or FRM (Fiber Reinforced Mortar). Different design guidelines for the repair and strengthening externally of structures with TRM have been published such as the ACI 549.4R-13 [3], RILEM TC-250 [4], CNR-DT 215/2018 [5] and RILEM TC 234-DUC [6].

TRM has been also used in column confinement applications utilizing plain concrete cylinders and RC columns [7, 8]. When the elements are subjected to axial compression, the TRM jackets provides passive confinement stresses. Several experimental investigations demonstrated the effectiveness of using TRM as concrete confinement systems, mainly based on non-reinforced elements. It was found that the compressive strength of the tested samples has been influenced by a wide range of variables, including concrete strength, fiber type, wrapping configurations, cross-section shape or slenderness. Up to date, some analytical models have been proposed for TRM confined concrete by fitting analysis with available experimental study. However, these models were developed based on limited data with their specific confining TRM systems. In consequences, an accurate model to predict the axial strength of confined concrete column has not been provided yet. They are ineffective in prediction the compressive strength of all types of TRM confined concrete.

The objective of this paper is to introduce an analytical model for predicting the compressive strength of confined concrete by TRM. An updated database of 341 compression tests performed on plain concrete specimens wrapped by TRM was collected and analyzed in first part of this paper. In the second part, some existing models for compressed concrete columns confined by TRM have been assessed. Then, an analytical model for concrete elements wrapped with TRM are developed and verified through a best-fit analysis of the experimental database. Finally, the database is used to compare the performance of the proposed models to formulations available in the literature.

2. Analysis of experimental databases

2.1. Databases

In this section, different publications related to confinement of concrete specimens using TRM composites are summarized (Table 1). A total of 341 databases were found and used to analyses the behavior of TRM confined concrete. The points correspond to specimens that had been wrapped with TRM composite that was continuous along the specimen length. It was noted that the values correspond exclusively to specimens tested under concentric compression and monotonic loading. The databases include the geometric details of the specimen (diameter D, height H, the corner radius r_c), area of the textile by unit width A_f, angle of inclination of fiber θ, number of fiber layers n, fiber equivalent thickness t_f, mechanical properties of the fibers (E_f - fiber elastic modulus of the bare fibers, f_u - fiber tensile strength, ε_{fu} - ultimate fiber strain), and the compressive strength of the unconfined specimen f_{c0}).

Table 1. Experimental databases [7, 9–28]

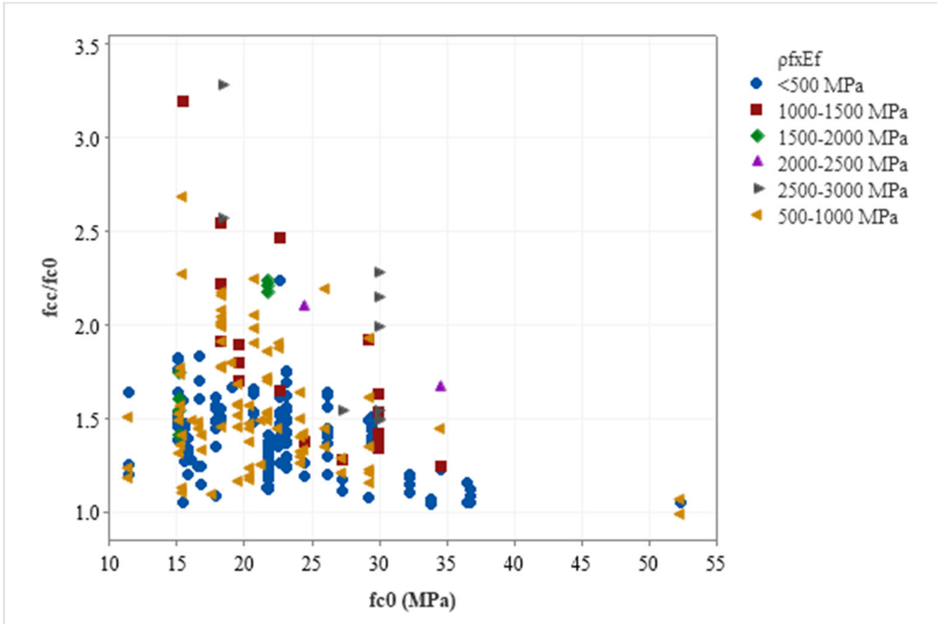
Parameters	Min	Max
D / H	0,3	0,75
f_{c0} (MPa)	11,4	52,39
f_u (MPa)	586	5800
E_f (GPa)	52	330
$\rho_f = 4nt_f / D$	0,00023	0,32
$\rho = 2r_c / D$	0	1
A_f (mm^2/m)	1,7	563
θ^0	30^0	90^0

2.2. Main parameters

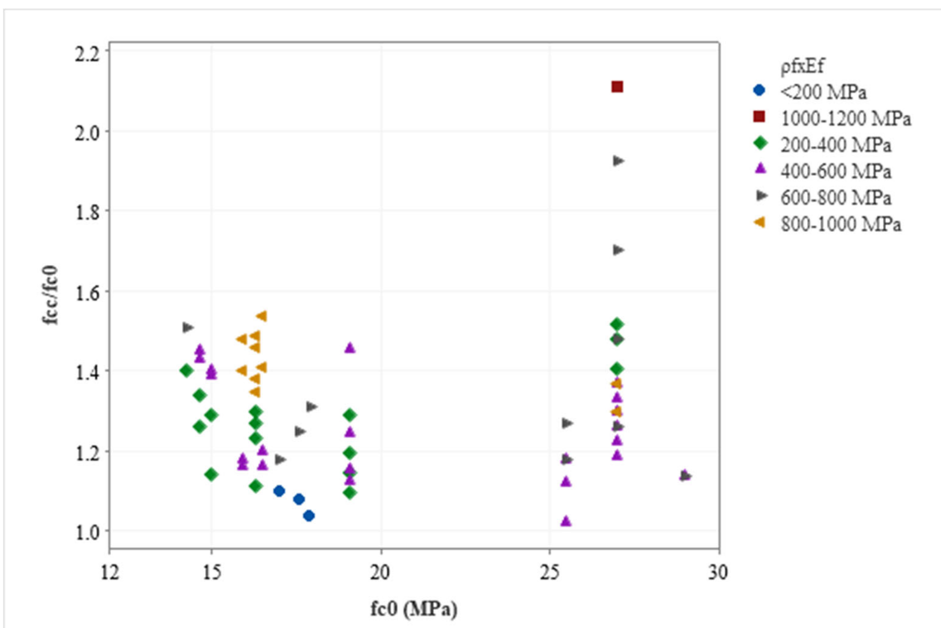
Based on the collected databases, the influence of main parameters on the compressive strength of concrete column confined with TRM is analyzed. The gain in axial strength provided by the ratio f_{cc} / f_{c0}, where f_{cc} and f_{c0} are the compressive strengths of the confined and unconfined specimen, respectively.

2.2.1. Properties of unconfined concrete

The variation of f_{cc} / f_{c0} as a function of f_{c0} is presented in Figure 2. As can be seen, this relationship is quite different between cylindrical and rectangular section of specimens. For cylindrical concrete elements, the ratio f_{cc} / f_{c0} increase appears more substantial for concretes with lower compressive strength.



(a)



(b)

Figure 1. Variation of f_{cc} / f_{c0} with f_{c0}: (a) cylindrical specimens, (b) prismatic specimens

2.2.2. Properties of TRM

The variation of f_{cc} / f_{c0} with $\rho_f \times E_f$ for cylindrical and prismatic specimens is shown in Figure 2. The results show that the capacity of axial compression increases with higher value of $\rho_f \times E_f$.

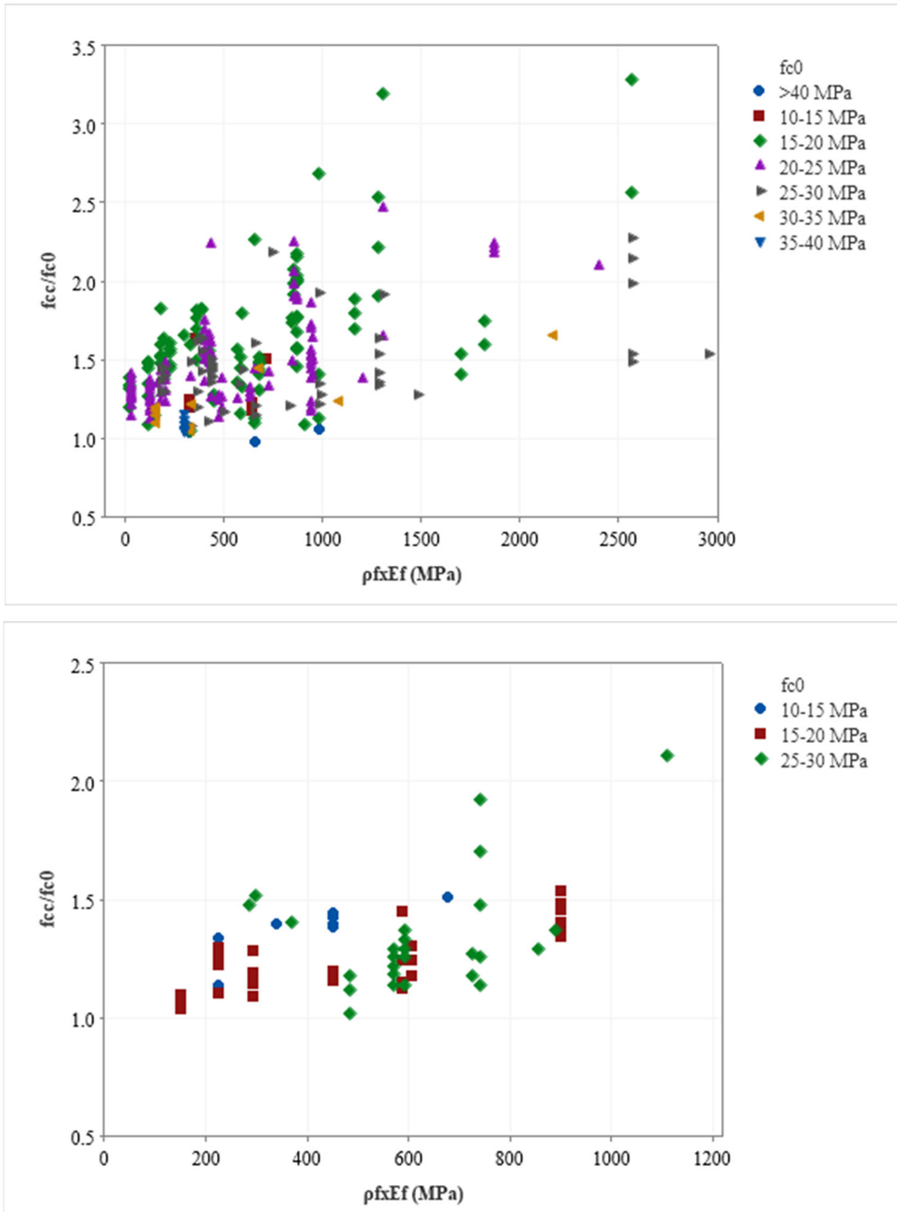


Figure 2. Variation of f_{cc} / f_{c0} with $\rho_f \times E_f$: (a) cylindrical specimens, (b) prismatic specimens

2.2.3. Cross section shape of specimen

The parameter ρ stands the influence of geometry of specimens to compressive strength of confined concrete with TRM. This parameter depends on the corner radius of cross section r_c, where $\rho = 2r_c / D$. It is clear in Figure 3 that the maximum value of f_{cc} / f_{c0} corresponds the value $\rho = 1$ (circular section).

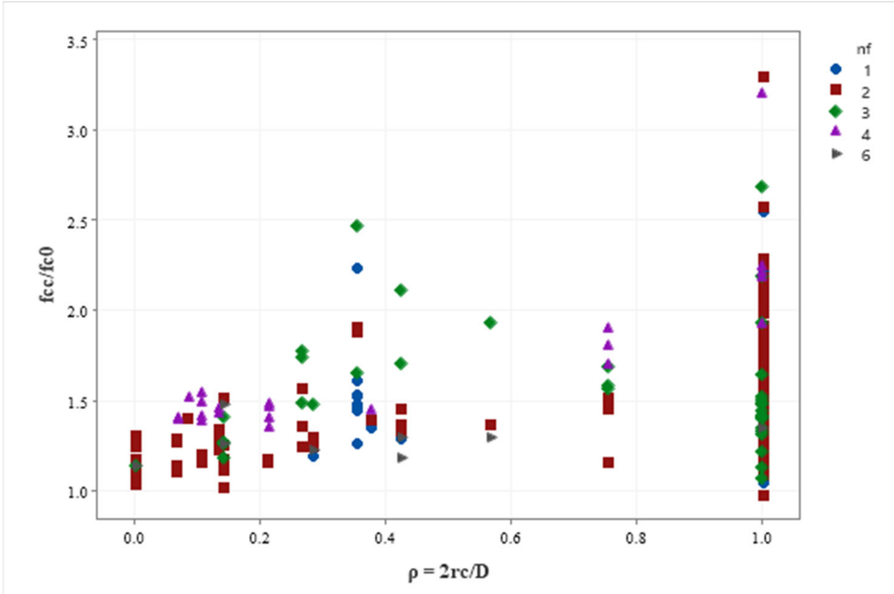


Figure 3. Variation of f_{cc} / f_{c0} with ρ

3. Model for compressed concrete column confined by TRM

3.1. Existing models

Recently, several formulations have been developed to predict the compressive strength of concrete elements confined with TRM. For all models, the axial strength f_{cc} is expressed as a function of the strength f_{c0} of unconfined concrete, and to the lateral confining pressure f_{lu} (Table 2). These models were proposed by calibrating with a limited number of tested specimens, except the Ombres's model [29] which was built based on a database containing the results of 152 specimens.

Table 2. Existing models

Model	Formula
Triantafillou [14]	$\frac{f_{cc}}{f_{c0}} = 1 + 1.9\left(\frac{f_{lu}}{f_{c0}}\right)^{1.27}$
Ombres [29]	$\frac{f_{cc}}{f_{co}} = 1 + 0.913\left(\frac{f_{lu}}{f_{co}}\right)^{0.5}$
De Caso [25]	$\frac{f_{cc}}{f_{c0}} = 1 + 2.87\left(\frac{f_{lu}}{f_{c0}}\right)^{0.775}$
Colajanni [11]	$\frac{f_{cc}}{f_{co}} = 2,254\sqrt{1 + 7,94\frac{f_{lu}}{f_{co}}} - 2\frac{f_{lu}}{f_{co}} - 1,254$

It is mentioned that the values of the confining lateral pressure f_{lu} is defined as:

$$f_{lu} = \frac{1}{2} k_e k_\theta \rho_f E_f \varepsilon_{fu} \quad (1)$$

In this formula, k_θ is the coefficient accounting for the fiber inclination.

$$k_{\theta} = \frac{1}{(1+3\tan\theta)} \quad (2)$$

The strain efficiency factor k_e of the TRM composite defined as the ratio between the ultimate hoop strain in the TRM jacket ε_{fl} and the ultimate strain found from fiber coupon tensile tests ε_{fu}. However, it was noted that the hoop strains are quite difficult measured experimentally. Most of above models did provide the value of k_e as constant. Except the model of Ombres where k_e is presented as a function of ρ_f, E_f and f_{c0} (Table 3).

Table 3. The strain efficiency factor

Model	Strain efficiency factor k_e
Triantafillou [14]	$k_e = 0.3$
Ombres [29]	$k_e = 0,25\left[\left(\frac{\rho_f E_f}{f_{co}}\right)^{0.3} - 1\right]$
De Caso [25]	$k_e = 0.22$
Colajanni [11]	$k_e = 1$

3.2. Proposed model

As mentioned above, the Ombres's model provided the function of k_e based on 152 cylindric specimens. Besides, the effect of cross section of specimens didn't include in the model developed by Ombres. In the following model, this effect will be added with the novel function of k_e.

The confining lateral pressure f_{lu} must be determined by:

$$f_{lu} = \frac{1}{2} k_e k_{\theta} k_{\rho} \rho_f E_f \varepsilon_{fu} \quad (3)$$

In the proposed model, the effect of cross section is added in Eq (3) by the coefficient k_{ρ}:

$$k_{\rho} = 1 - \frac{b_n^2 + h_n^2}{3bh} \quad (4)$$

where $b_n = b - 2r_c$; $h_n = h - 2r_c$. b, h are respectively the width and height of the specimen section.

The main parameters affecting strain efficiency factor k_e are $\rho_f E_f$ and f_{c0}. k_e increases with $\rho_f E_f$ but decreases for high ρ_f values when f_{c0} increases. The ratio $\rho_f E_f / f_{co}$ allows us to satisfy both conditions; consequently, k_e can be defined as a relationship of this ratio.

From updated 341 databases (cylindric and rectangular section), a fit analysis of the k_e function has been carried out, introducing the nondimensional parameter $\rho_f E_f / f_{co}$ by minimizing the average percent error (APE):

$$APE = \frac{1}{n} \sum_{i=1}^{n} \frac{\left(k_{e(\text{model})} - k_{e(\text{experiment})}\right)}{k_{e(\text{experiment})}} \quad (5)$$

where n is the number of experimental specimens, The following function of k_e is obtained:

$$k_e = 0{,}19\left[\ln\left(\frac{\rho_f E_f}{f_{c0}}\right) - 1\right] \tag{6}$$

It was shown in Table 2 that the typical expression of confined concrete column compressive strength is presented by $\frac{f_{cc}}{f_{c0}} = 1 + a\left(\frac{f_{lu}}{f_{c0}}\right)^b$ where a and b are empirical constant. To determine the unknowns a and b, a fit analysis was also investigated using the mean square error (MSE) method:

$$MSE = \frac{\sum_{i=1}^{n}\left(k_{e(proposed)} - k_{e(\text{experiment})}\right)^2}{n} \tag{7}$$

Applying the k_e function in Eq (6) and considering 341 updated experimental results, the values of the coefficients a and b that minimize Eq (7) were 0,984 and 0,295, respectively.

The proposed model is finally obtained in the following form:

$$\frac{f_{cc}}{f_{c0}} = 1 + 0{,}984\left(\frac{f_{lu}}{f_{c0}}\right)^{0{,}295} \tag{8}$$

Comparing to the existing model, the proposed provided the highest calibrations with MSE=0,071 (Table 4).

Table 4. Comparison between different models

Model	MSE
Triantafillou [14]	0,45
Ombres [29]	0,106
De Caso [25]	0,88
Colajanni [11]	0,63
Proposed model	0,071

4. Conclusion

This paper presented a study on the compressive strength of the concrete externally confined with TRM systems. 341 experimental databases on plain concrete confined column have been collected and analyzed. The experimental data was used to investigate the influence of different parameters on the compressive strength of concrete column confined with TRM. Some existing models for compressed concrete columns confined by TRM also have been assessed. Through a best-fit analysis of the experimental database, an analytical model for concrete column wrapped with TRM are proposed where the effect of cross section and the strain efficiency factor have been included. Comparing to the existing formulas, the proposed model provided the highest calibrations with test data. Further experimental database is needed to better estimate the reliability of the model.

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