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Concrete Confinement with Textile-Reinforced Mortar Jackets

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The application of textile-reinforced mortars (TRMs) as a means of increasing the axial capacity of concrete through confinement is investigated experimentally in this study. TRM may be thought of as an alternative to fiber-reinforced polymers (FRPs), addressing many of the problems associated with application of the latter without compromising performance by a significant degree. Based on the response of confined cylinders and short rectangular columns, it is concluded that textile-mortar jacketing provides a substantial gain in compressive strength and deformability; this gain is higher as the number of confining layers increases and depends on the tensile strength of the mortar. Compared with their resin-impregnated counterparts, mortar-impregnated textiles may result in reduced effectiveness. This reduction was more pronounced in cylindrical specimens but rather insignificant in rectangular ones. Favorable confinement characteristics on rectangular columns were also obtained by using helically applied unbonded strips with end anchorages—an interesting concept that deserves further investigation. Modeling of concrete confined with jackets other than resin-impregnated ones is presented by the authors as a rather straightforward procedure through the proper introduction of experimentally derived jacket effectiveness coefficients. From the results obtained in this study, it is believed that TRM jacketing is an extremely promising solution for the confinement of reinforced concrete.

Keywords: confinement; jackets; mortar.

INTRODUCTION AND BACKGROUND

The need for upgrading existing structures has been tremendous in the past couple of decades, both in nonseismic areas due to deterioration and/or the introduction of more stringent design requirements, and in seismic areas, where structures designed according to old seismic codes have to meet performance levels required by current seismic design standards. One of the most common upgrading techniques for reinforced concrete structures involves the use of jackets, which are aimed at increasing the confinement action in either the potential plastic hinge regions or over the entire member.

Among all jacketing techniques, the use of fiber-reinforced polymers (FRPs) has gained increasing popularity in the civil engineering community due to the favorable properties possessed by these materials; namely, extremely high strength-to-weight ratio, corrosion resistance, ease and speed of application, and minimal change in the geometry.[1,2] Despite all these advantages, the FRP strengthening technique has a few drawbacks, which are attributed to the organic resins used to bind or impregnate the fibers. These drawbacks may be summarized as follows: 1) poor behavior of epoxy resins at temperatures above the glass transition temperature, a fact that often calls for special and expensive fire protection measures; 2) relatively high cost of epoxy resins; 3) hazards for the manual worker, even though modern epoxies gradually become less hazardous due to smaller solvent contents; 4) application of FRP on wet surfaces or low temperatures is not possible; 5) lack of vapor permeability, which may cause damage to the concrete structure; 6) incompatibility of epoxy resins and substrate materials; and 7) difficulty conducting post-earthquake assessment of the damage suffered by the reinforced concrete behind (undamaged) FRP jackets.

One possible solution to the aforementioned problems would be the replacement of organic with inorganic binders, for example, cement-based mortars, leading to the replacement of FRP with fiber-reinforced mortars (FRMs). These materials have a relatively long-term record in structural engineering, especially in the development of thin section products,[3] but they have problems too: as a consequence of the granularity of the mortar, penetration and impregnation of fiber sheets is very difficult to achieve. Also, unlike resins, mortars cannot wet individual fibers. It is this property of epoxies—namely, the ability to penetrate and wet the fibers—that results in excellent bond and tight interaction between fibers and matrix. Hence, epoxy-impregnated continuous fiber sheets are used in a very efficient way. Despite the aforementioned bond-related problems, the use of composites with inorganic matrixes (FRMs) in the field of structural upgrading has not escaped the attention of the research community. The performance of carbon fiber sheets with an inorganic matrix made of aluminosilicate powder and a water-based activator has been evaluated by Kurtz and Balaguru[4] and Garon, Balaguru, and Toutanji.[5] These materials were used as externally bonded flexural strengthening reinforcement of concrete beams[4] or plain concrete prisms[5] and resulted in comparable performance with epoxy-impregnated sheets in terms of strength and stiffness, with some reduction in ductility. The fatigue performance of concrete beams strengthened in flexure with carbon fiber sheets bonded with the same inorganic matrix was evaluated in Reference 6 and was found satisfactory. Large-scale tests conducted by Weiberg[7] on concrete beams strengthened in flexure or shear with externally bonded carbon sheets in a polymer-modified cementitious matrix have demonstrated that the technique is promising, albeit less effective than epoxy-based systems. The only study identified by the authors on the use of inorganic matrix composites for confinement is that in Wu and Teng,[8] where unidirectional carbon sheets bonded with a cementitious binder were employed to confine small (100 x 200 mm)

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cylinders. Confined specimens in this study exhibited high strength and sufficient deformability, comparable to that of companion specimens wrapped with epoxy-impregnated carbon sheets.

Bond conditions in cementitious composites could be improved and fiber-matrix interactions could be made tighter when continuous fiber sheets are replaced by textiles. These materials comprise fabric meshes made of long woven, knitted, or even unwoven fiber rovings in at least two (typically orthogonal) directions. The density, that is, the quantity and the spacing, of rovings in each direction can be controlled independently, thus affecting the mechanical characteristics of the textile and the degree of penetration of the mortar matrix through the mesh. Although research on the use of textile meshes as reinforcement of cementitious products commenced in the early 1980s,[9,10] developments in this field progressed rather slowly until the late 1990s. During the past 5 years or so, however, the research community has increasingly focused on the use of textiles as reinforcement of cement-based products, primarily in new constructions.[11-20] Studies on the use of textiles in the upgrading of concrete structures have been very limited and focused on flexural or shear strengthening of beams and on aspects of bond between concrete and cement-based textile composites.[21-23] These studies have concluded that properly designed textiles combined with inorganic binders have a good potential as strengthening materials of reinforced concrete members. In the present study, the authors go one step further by making use of textiles in combination with inorganic (cement-based) binders, that is, textile-reinforced mortars (TRMs), in the field of concrete confinement for strength and ductility.

RESEARCH SIGNIFICANCE

Jacketing of reinforced concrete members in existing structures is an increasingly attractive strengthening and/or retrofit option both in nonseismic and seismically-prone areas. Among all jacketing techniques, the use of FRP has gained increasing popularity due to the favorable properties possessed by these materials. However, certain problems associated with epoxy resins, namely, poor behavior at high temperatures, high costs, hazards for workers, incompatibility with substrates, inapplicability on wet surfaces and difficulty to conduct post-earthquake assessment behind FRP jackets, are still to be addressed. A solution of great potential would be the replacement of epoxies with inorganic binders, but the impregnation of continuous fiber sheets with mortars is very difficult to achieve, resulting in rather poor bond between the fibers and matrix. Bond conditions could be improved when textiles are used instead of fiber sheets, a concept leading to the use of TRM jacketing as an alternative to FRP jacketing. It is this concept that the authors explore and study experimentally in this paper.

EXPERIMENTAL PROGRAM

Experimental method

The main objective of the experimental program was to provide a better understanding on the effectiveness of various jacketing schemes based on the use of textiles made of continuous fibers (carbon) in combination with inorganic matrix materials (cement-based mortars). The investigation was carried out on: 1) cylindrical specimens with a diameter of 150 mm and a height of 300 mm (Series A and B); 2) short column-type specimens with a rectangular cross section of 250 x 250 mm and a height of 700 mm (Series C). The four corners of all rectangular prisms were rounded at a radius equal to 15 mm. All specimens were unreinforced, as the jacket-reinforcement interactions (for example, prevention of reinforcing bar pull-out at lap splices or delay of reinforcing bar buckling) were outside the scope of the present study.

Three parameters were considered in the investigation with cylindrical specimens, namely, the use of inorganic mortar versus resin-based matrix material for the textile reinforcement, the strength of the inorganic mortar (two different mortars were used) and the number of textile layers (two or three layers). The choice of these parameters aimed at: 1) comparing inorganic mortars versus epoxy resins as matrix materials in confining jackets; 2) investigating the effect of mortar strength on the effectiveness of inorganic mortars as matrix materials; and 3) investigating the role of the number of layers on the effectiveness of jacketing with textiles.

All confining systems in the case of cylindrical specimens were applied with a single textile sheet wrapped around each cylinder until the desired number of layers was achieved. The bonding agent was either epoxy resin or inorganic mortar, applied to the concrete surface, between all layers and on top of the last layer (Fig. 1).

The testing on rectangular prisms was aimed at investigating the following three parameters: inorganic mortar versus resin-based matrix for the textile reinforcement, number of textile layers (two or four), and effectiveness of bonded versus unbonded confining systems. Jacketing of all rectangular columns was provided using a new concept, which involved the formation of each layer through the use of a single strip. The strip was wrapped around the column in a spiral configuration, starting from one end (column top) and stopping at the other (column bottom) (Fig. 2(a)). Each successive strip was wrapped in the direction opposite to that of the previous one (Fig. 2(b)). The strips were attached on the concrete either through full bond (that is, with resin or mortar, as in the case of cylinders) or at the ends only, using a simple method that involved wrapping and epoxy-bonding of another strip, applied laterally in two layers at each end (top and bottom) of the column (Fig. 2(c)).

Test specimens and materials

Three series of concrete specimens (A, B, and C) were cast using the same ready-mixed concrete in each one of them (but different from series to series). Series A included five different designs: the control specimens (without wrapping), specimens wrapped with two or three layers of textile

Table 1—Strength and deformability of concrete cylinders and prisms

Specimen notation	Compressive strength f_{cc}, MPa		Ultimate strain ε_{cc}, %		f_{cc}/f_{co}	$\varepsilon_{ccu}/\varepsilon_{co}$	$f_{cc}/f_{cc,R}$	$\varepsilon_{ccu}/\varepsilon_{ccu,R}$
	Mean	SD*	Mean	SD*				
Series A								
A_C	15.24	0.43	0.20†	0.01	1.00	1.00	N/A	N/A
A_MI2	20.77	0.48	0.96	0.40	1.36	4.80	N/A	N/A
A_MII2	23.88	0.79	1.08	0.06	1.57	5.40	N/A	N/A
A_MI3	26.50	0.55	1.13	0.02	1.74	5.65	N/A	N/A
A_MII3	27.00	2.59	1.22	0.06	1.77	6.10	N/A	N/A
Series B								
B_C	21.81	0.20	0.20†	0.02	1.00	1.00	N/A	N/A
B_R2	33.47	2.16	1.67	0.36	1.53	8.35	1.00	1.00
B_MII2	27.36	1.37	0.98	0.05	1.25	4.90	0.82	0.59
B_R3	41.94	1.38	2.55	0.14	1.92	12.75	1.00	1.00
B_MII3	32.44	1.41	1.08	0.05	1.49	5.40	0.77	0.42
Series C								
C_C	14.25	1.06	0.20†	0.02	1.00	1.00	N/A	N/A
C_R2	18.41	1.70	1.24	0.30	1.29	6.20	1.00	1.00
C_MII2	20.00	0.74	1.18	0.08	1.40	5.90	1.09	0.95
C_A2	19.86	0.91	0.79	0.03	1.39	3.95	1.08	0.64
C_R4	20.97	0.59	2.03	0.18	1.47	10.15	1.00	1.00
C_MII4	21.56	0.16	1.76	0.06	1.51	8.80	1.03	0.87
C_A4	20.64	0.66	1.76	0.52	1.45	8.80	0.98	0.87

*Standard deviation.

†Ultimate strain of control specimens is assumed equal to ε_{co} = 0.2%, which agrees well with mean value (0.22%) recorded at peak stress.

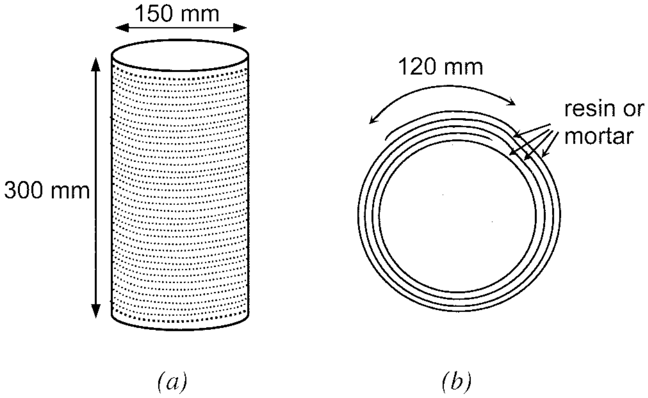


Fig. 1—(a) Concrete cylinders with FRP or TRM jackets; and (b) cross section.

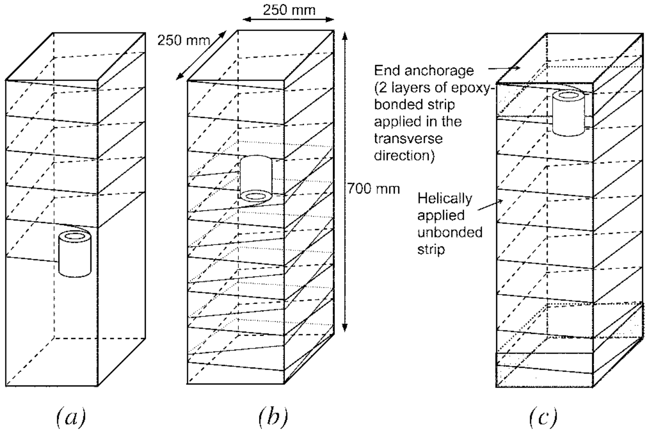


Fig. 2—(a) Column wrapping using helically applied textile material; (b) application of second layer; and (c) helically applied unbonded strips with end anchorages.

bonded with a relatively low-quality mortar (Mortar I), and specimens wrapped with two or three layers of textile bonded with a better quality mortar (Mortar II). These specimens were used to assess the effectiveness of jackets with different mortar strengths for two different jacket thicknesses (number of layers). Specimens in Series A are given the notation A_XN, where X denotes the type of jacket (C for the unjacketed [control] specimens, MI for specimens with mortar Type I jackets, and MII for specimens with mortar Type II jackets) and N denotes the number of layers.

Series B included another five different designs: the control specimens, specimens wrapped with two or three layers of textile bonded with epoxy resin, and their counterparts bonded with mortar Type II. Moreover, the concrete strength was a bit higher in Series B than in Series A due to different batching. These specimens were used to assess the effectiveness of mortar-based versus resin-based jackets, for two different jacket thicknesses (number of layers). The notation of specimens in Series B is B_XN, where X and N are defined as above (R is used to denote epoxy resin, and MII is used to denote mortar Type II).

Finally, Series C included seven different designs of short rectangular column-type specimens: the control column, columns wrapped with two or four layers of textile bonded with an epoxy resin, their counterparts wrapped with two or four layers of textile bonded with mortar Type II, and two more columns with two or four layers of unbonded textile (that is, not impregnated with resin or mortar) anchored at the column ends using transverse wrapping (as in Fig. 2(c)). The notation of columns in Series C is C_XN, where, as above, N is the number of layers and X denotes the type of jacket (C for unjacketed, R for resin-based jackets, MII for Mortar II jackets, and A for jackets made of unbonded strips with end anchorage). All types of specimens are summarized in the first column of Table 1.

Three specimens for the case of cylinders (Series A and B) and two specimens for the case of rectangular short columns (Series C) were considered sufficient for reasonable repeatability. As a result, a total of 44 tests were performed.

Casting of the specimens was made with concrete in stiff steel moulds. Each series was made of concrete from the same batch. The cement:sand:gravel proportions in the concrete mixtures were roughly 1:2:3 by weight and the water-cement ratio (*w/c*) varied between 0.62 to 0.68 (but was constant for each series). All specimens were capped with a special self-leveling high-strength mortar. For the specimens receiving jacketing, a commercial textile with equal quantity of high-strength carbon tows in two orthogonal directions was used (Fig. 3(a)). The fiber rovings in each direction were simply placed one on top of the other and connected through a secondary polypropylene grid (refer to Fig. 3(b) for the carbon roving architecture). Each fiber roving was 4 mm wide and the clear spacing between rovings was 6 mm. The weight of carbon fibers in the textile was 168 g/m^2, and the nominal thickness of each layer (based on the equivalent smeared distribution of fibers) was 0.047 mm. The guaranteed tensile strength of the carbon

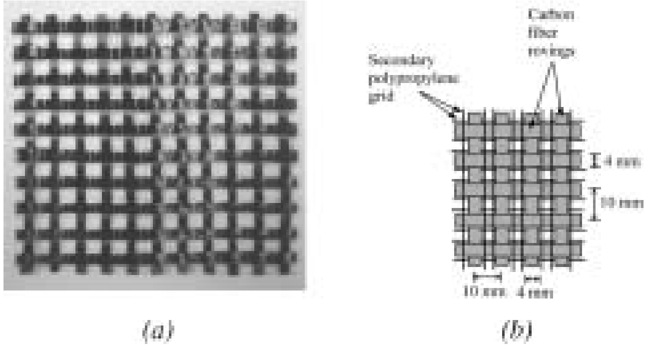


Fig. 3—(a) Photograph and (b) architecture of bidirectional textile used in this study.

fibers (as well as of the textile, when the nominal thickness is used) in each direction was taken from data sheets of the producer equal to 3350 MPa. The elastic modulus of carbon fibers was 225 GPa. For the specimens receiving adhesive bonding, a commercial structural adhesive (two-part epoxy resin with a mixing ratio 4:1 by weight) was used with a tensile strength of 30 MPa and an elastic modulus of 3.8 GPa (cured 7 days at 23 °C). The adhesive was pasty with a viscosity such that complete wetting of the fibers in the textile was possible by using a plastic roller.

For the specimens receiving Mortar I as a binding material, a commercial low-cost, inorganic dry binder (suitable for plastering) was used. This binder contained fine cement and a low fraction of polymers. Mortar II was produced using another commercial inorganic dry binder consisting of cement and polymers at a ratio 10:1 by weight. The water-binder ratios (*w*/*b*) in Mortars I and II were 3.4:1 and 3:1 by weight, respectively, resulting in plastic consistency and good workability. The main difference between Mortar I and Mortar II, besides the *w*/*b*, was the fraction of polymers, which was lower in Mortar I.

Application of the mortars was made in approximately 2 mm-thick layers with a smooth metal trowel. After application of the first mortar layer on the (dampened) concrete surface, the textile was applied and pressed slightly into the mortar, which protruded through all the perforations between fiber rovings. The next mortar layer covered the textile completely and the operation was repeated until all textile layers were applied and covered by the mortar. Of crucial importance in this method, as in the case of epoxy resins, was the application of each mortar layer while the previous one was still in a fresh state. Typical photographs of the application method of textile strips combined with mortar binder to provide jacketing in the rectangular short-column specimens used in this study are shown in Fig. 4.

Testing procedure

The strength of Mortars I and II used in this study was obtained through flexural and compression testing, according to EN 1015-11,[24] using a servohydraulic MTS testing machine. Flexural testing was carried out in 40 x 40 x 160 mm hardened mortar prisms at an age of 7 and 28 days. The prisms were prepared in steel molds with three identical compartments so that three specimens were available for testing each type of mortar at one particular age. Thus, a total of 12 prisms were prepared and cured in the laboratory until testing, in conditions identical to those for the jackets used for confinement (except for the first 2 days, where the prisms were inside the molds). The prisms were subjected to three-point bending at a span of 100 mm (Fig. 5(a)) with a constant loading rate equal to 5 N/s. The load versus crosshead displacement response recorded during each test indicated linear-elastic behavior until fracture, which was due to the development of a single crack at midspan; as a result, each prism fractured into two parts. The peak load was recorded and used for the calculation of flexural strength. Compression testing was carried out on each of the fractured parts (Fig. 5(b)) using two 40 x 40 mm bearing steel platens on top and bottom of each specimen,[24] which were carefully aligned so that the load was applied to the whole width of the faces in contact with the platens.

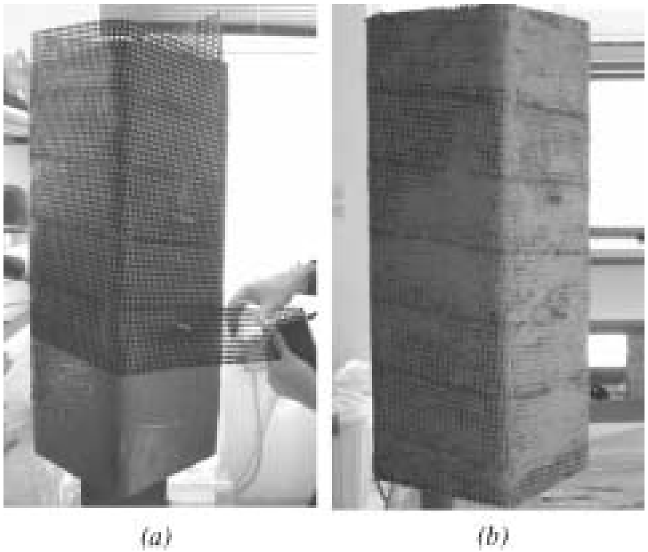


Fig. 4—Application of textile strips: (a) helical wrapping of first layer on epoxy-covered concrete; and (b) impregnation of textile strip with inorganic mortar prior to application for next mortar layer.

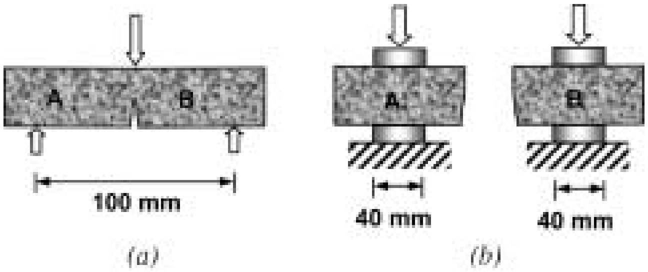
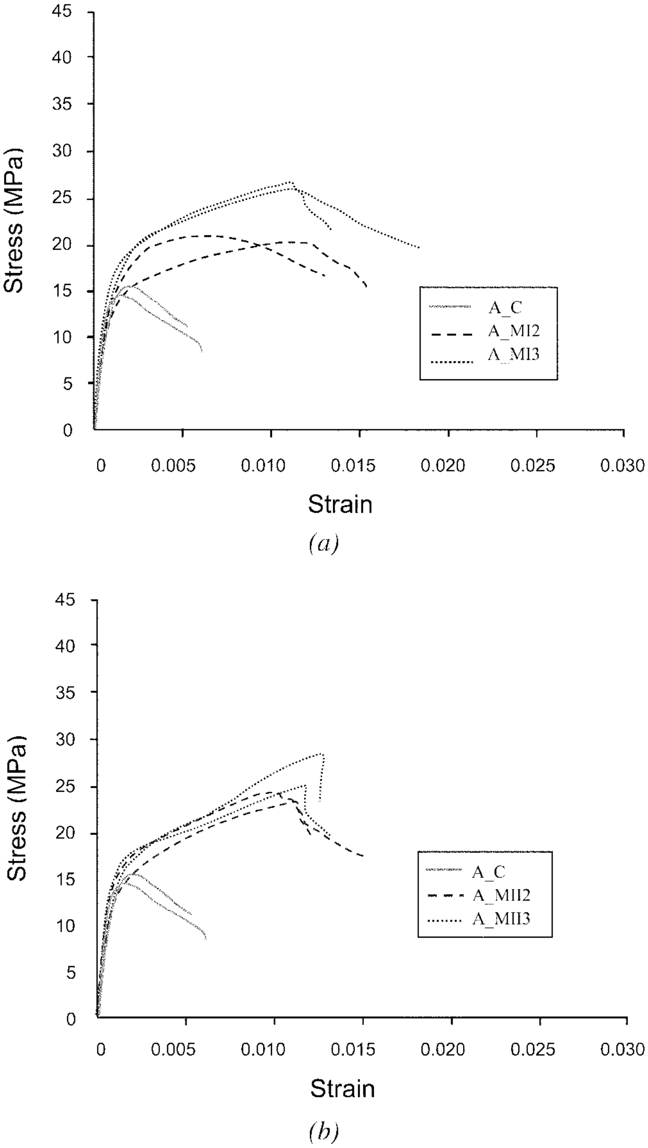


Fig. 5—(a) Flexural and (b) compressive testing of mortar specimens.

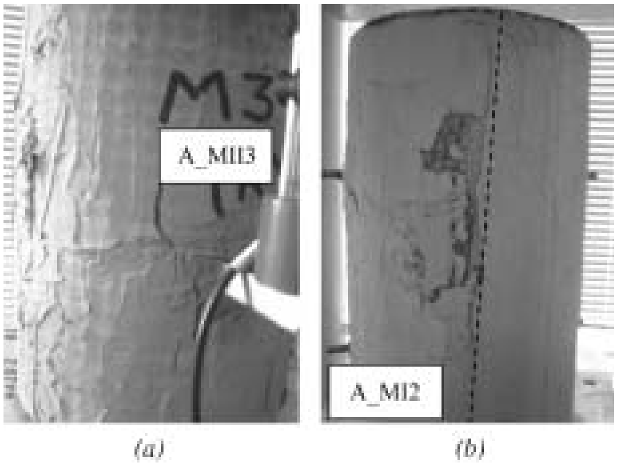
The response of concrete cylinders and short column-type specimens in uniaxial compression was obtained through monotonically applied loading at a rate of 0.01 mm/s in displacement control, using a 4000 kN compression testing machine. Loads were measured from a load cell and displacements were obtained using external linear variable differential transducers (LVDTs) mounted on two opposite sides, at a gauge length of 130 mm for the cylinders and 180 mm for the rectangular columns, in the middle part of each specimen. From the applied load and average displacement measurements, the stress-strain curves were obtained for each test.



(a)

(b)

Fig. 6—Stress-strain curves for specimens in Series A: (a) control and specimens with two or three layers of textile-Mortar I jackets; and (b) control and specimens with two or three layers of textile-Mortar II jackets.



(a) (b)

Fig. 7—(a) Initiation of tensile fracture in specimen with textile-Mortar II jacket; and (b) initiation of debonding at termination of textile sheet.

Table 2—Flexural and compressive strength of mortars

	Flexural strength, MPa		Compressive strength, MPa	
Mortar	Mean	Standard deviation	Mean	Standard deviation
Mortar I				
7 days	2.68	0.57	7.59	0.75
28 days	3.28	0.63	8.56	0.87
Mortar II				
7 days	3.02	0.61	27.45	1.65
28 days	4.24	0.78	30.61	1.83

RESULTS AND DISCUSSION

Strength of inorganic mortars

The average flexural and compressive strength values at 7 and 28 days for Mortars I and II are given in Table 2. Compared with Mortar I at 28 days, Mortar II gave a 30% higher flexural strength and a much higher (nearly 3.5 times) compressive strength.

Series A—Cylindrical specimens (Mortar I versus Mortar II)

Typical stress-strain plots recorded for cylinders with jackets made of textile and two different types of inorganic binders (Mortar I and Mortar II) are given in Fig. 6, along with results for control specimens. Peak stress (confined concrete strength) values f_{cc} and ultimate strains ε_{ccu} are given in Table 1 (mean and standard deviation). With one exception, all σ-ε plots for concrete with textile confinement are characterized by an ascending branch, which nearly coincides with that for unconfined concrete, followed by a second one, close to linear, that drops rather suddenly at a point where the jacket either fractured due to hoop stresses (Fig. 7(a), jacket with Mortar II) or started debonding from the end of the lap (Fig. 7(b), jacket with Mortar I). This notable difference in the failure mechanisms is attributed to the different mortar strengths. It is believed that the property determining which of the two failure mechanisms will be activated first is the interlaminar shear strength of the textile-mortar composite, which is proportional to the tensile (that is, the flexural) strength of mortar. Note that the relatively small difference in flexural strengths between the two mortars is in agreement with the marginally higher effectiveness of jackets with Mortar II compared to those with Mortar I. The term "effectiveness" is quantified herein by the ratios of confined to unconfined strength and ultimate strain. Whereas in unconfined specimens, the ultimate strain is taken equal to 0.002; in confined specimens, it is defined either at the point where the slope of the σ-ε curve drops suddenly or at the point where the stress drops by 20% of the maximum value.

In specimens with two layers of textile-mortar jackets, the gain in compressive strength was 36 and 57% for Mortars I and II, respectively. These numbers are found by dividing the difference between confined and unconfined strength by the unconfined strength, for example $(20.77 - 15.24)/15.24 = 0.36$ = 36% for Specimen A_MI2. The corresponding values in specimens with three layers were 74 and 77%. Gains in ultimate strains were much higher with effectiveness factors (defined previously as the ratio of confined to unconfined ultimate strain) of approximately 5 or 6. Overall, it may be concluded that textile-mortar confining jackets provide substantial gain in compressive strength and deformability. This gain is higher as the number of confining layers increases and depends on the tensile strength of the mortar.

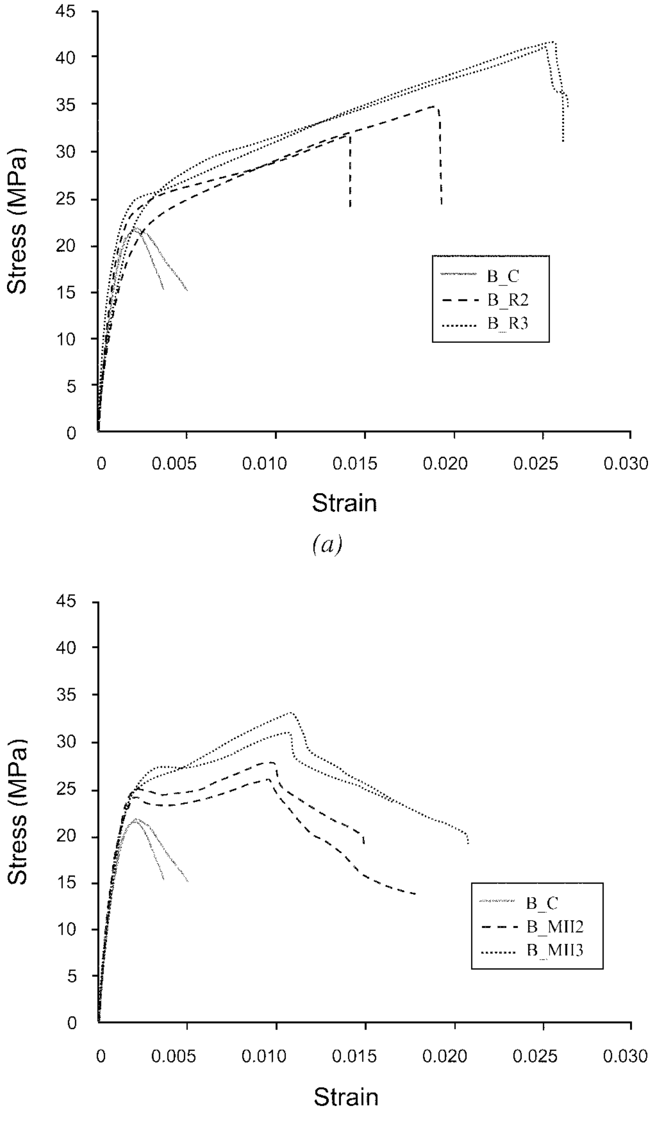
Series B—Cylindrical specimens (mortar versus resin)

Typical stress-strain plots for cylinders with jackets made of textile/epoxy resin (Specimens B_R2, B_R3) or textile/mortar Type II (B_MII2, B_MII3) are given in Fig. 8, along with results for control specimens; peak stresses f_{cc} and ultimate strains ε_{ccu} are given in Table 1. Specimens with resin-impregnated textiles gave a nearly bilinear response with a transition curve and failed due to tensile fracture of the jackets in the hoop direction. In these specimens, the strength increased by 53 or 92% and the ultimate strain increased by a factor that exceeded 8 or 12, when the jacket was made of two or three layers, respectively, compared with the control (unjacketed) specimens.

Similar to specimens with textile-mortar (Type II) jackets in Series A, the σ-ε plots for concrete with textile confinement (B_MII2 and B_MII3) are characterized by an ascending branch, which nearly coincides with that for unconfined concrete, followed by a second one, close to linear, which drops rather suddenly at a point where the jacket fractured due to hoop stresses. A point of difference is that the σ-ε curve has a first local maximum, at strain $\varepsilon_{co} = 0.002$ where unconfined concrete failed, followed by a small descending branch that picked up rather quickly and became ascending until final fracture of the jacket occurred. This distinct behavior was observed only in specimens with two confining layers (and in one specimen with three confining layers), in agreement with similar observations on concrete confined with FRP jackets of low stiffness.[25] Compared with the control specimens, in those with two-layered textile-mortar jackets, the strength increased by 25% and the ultimate strain by a factor of 4.9. In specimens with three-layered textile-mortar jackets, the improvement in mechanical properties was even better: the strength increased by 49% and the ultimate strain increased by a factor of 5.4. It should be noted that these numbers are lower than those recorded when the same jackets (two or three layers of Mortar II) were used in specimens of Series A, where concrete was of lower strength, confirming that the effectiveness of textile-mortar jackets increases as the unconfined concrete strength decreases; the same conclusion applies to classical FRP jacketing.

A comparison of the effectiveness of mortar versus resin in textile jackets can be made by dividing the effectiveness of mortar-based jackets to that of resin-based jackets. The average value of this ratio, given in the last two columns of Table 1, is approximately 0.8 and 0.5 for strength and ultimate strain, respectively, and appears to decrease only marginally as the number of confining layers increases from two to three (from 0.82 to 0.77 for strength and from 0.59 to 0.42 for strain). The higher effectiveness of FRP versus TRM jackets is attributed to the higher strength and deformability of the resin matrix compared with the mortar; this allows for better stress redistribution in the fibers and hence higher strength and deformability of the composite.

Another interesting observation is that, contrary to FRP jackets, textile-mortar jackets do not fail abruptly. This is explained by the fact that the fracture in the hoop direction initiates from a limited number of fiber bundles (when the stress reaches their tensile capacity) and then propagates rather slowly in the neighboring bundles, resulting in a failure mechanism which may be characterized as more "ductile" (compared with FRP jacketing). This fact is also reflected in the σ-ε curves, where the point of maximum stress (and the associated ultimate strain) is followed by a descending branch that keeps a nearly constant slope for a large range of strain.



(a)

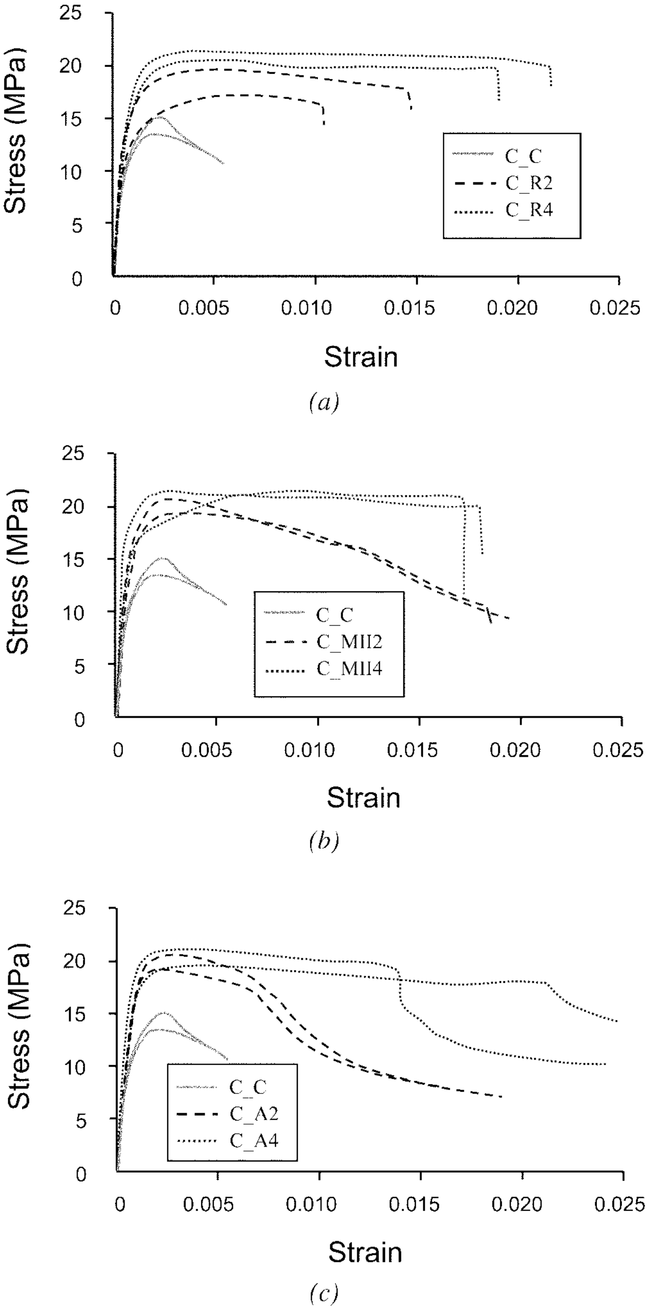
(b)

Fig. 8—Stress-strain curves for specimens in Series B: (a) control and specimens with two or three layers of resin-impregnated textile jackets; and (b) control and specimens with two or three layers of mortar-impregnated textile jackets.

Overall, it may be concluded that textile-mortar confining jackets: 1) provide substantial gain in compressive strength and deformability, and 2) are characterized by reduced effectiveness, when compared with FRP jackets. The reduction in effectiveness is quite small in terms of strength and more notable in terms of ultimate strain.

Series C—Rectangular columns (mortar versus resin versus end anchorage)

All stress-strain plots for short column-type specimens are given in Fig. 9(a), (b), and (c) for specimens confined with two or four layers of textile impregnated with resin (C_R2 and C_R4), textile impregnated with mortar (C_MII2 and C_MII4), and textile strips with end anchorage (C_A2 and C_A4), respectively. For the sake of convenient comparison, each figure also provides the σ-ε curves of the control (unconfined) specimens. Peak stresses, ultimate strains



(a)

(b)

(c)

Fig. 9—Stress-strain curves for specimens in Series C: Control and specimens with two or four layers: (a) of resin-impregnated textile jackets; (b) of mortar-impregnated textile jackets; and (c) made of unbonded strips with end anchorage.

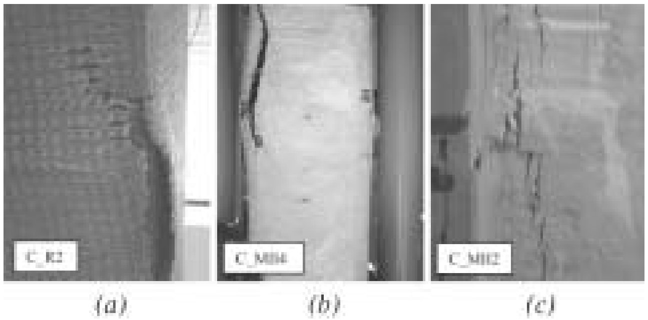


Fig. 10—Tensile fracture of textile jackets at corners of rectangular columns: (a) sudden fracture of resin-impregnated textile; (b) sudden fracture of four-layer mortar-impregnated textile jacket; and (c) gradual fracture of two-layer mortar-impregnated textile.

(defined either at the point where the slope of the σ-ε curve drops suddenly or at the point where the stress drops by 20% of the maximum value) and effectiveness ratios are given in Table 1.

Columns with resin-impregnated textile jackets exhibited a nearly bilinear response (Fig. 9(a)) until tensile fracture of the jackets occurred at the corners (Fig. 10(a)). The strength increased by 29 or 47% and the ultimate strain increased by a factor which exceeded 6 or 10, when the jacket was made of two or four layers, respectively (compared with the control specimens).

The behavior of columns confined with mortar-impregnated jackets was quite similar (Fig. 10(b)). The strength increased by 40 or 51% and the ultimate strain increased by a factor a little less than 6 or 9, when the jacket was made of two or four layers, respectively. Specimens with four confining layers failed in a way very similar to the ones with resin-impregnated textile jackets (Fig. 10(b)), whereas in those with two layers failure was gradual, starting from a few fiber bundles and propagating slowly in the neighboring fibers (Fig. 10(c)); as a result, the σ-ε curves of these specimens do not contain a sudden drop, a characteristic of excessive fiber fracture in a rather large portion of the jacket height. This difference in the behavior may be attributed to the fact that stresses in a thick jacket are better redistributed through the matrix, so that a larger portion of fibers is stressed heavily prior to fracture; hence fracture involves a larger portion of the jacket in the four-layer jackets compared with the two-layer ones and the response is more brittle.

With regard to relative effectiveness, mortar-impregnated textile jackets were found equally good as their resin-impregnated counterparts (in fact, they were superior by 3 to 9%, which may be attributed to statistical error) in strength terms and marginally inferior (by 5 to 13%) in ultimate strain terms. As discussed previously, this was not the case in cylindrical specimens (Series B) where FRP jacketing was more effective compared with mortar-based jacketing. This difference may be attributed to the fact that: 1) both FRP and mortar-based jackets are overstressed at the corners of rectangular columns due to stress concentrations, which cause fracture of the fibers at stresses well below those corresponding to uniaxial tensile stressing of the composites (FRP or TRM); and 2) the effectiveness of jacket confinement in rectangular cross sections is rather low, making the role of the jacket material less important in the development of confining stresses.

Surprisingly, spirally confined columns with unbonded strips anchored at the ends only, behaved nearly as good as those confined with fully-bonded mortar-impregnated or resin-impregnated jackets, especially in the case of four layers (Fig. 9(c)). The strength increased by 39 or 45% and the ultimate strain increased by a factor a little less than 4 or 9, when the jacket was made of two or four layers, respectively. Failure in these specimens developed away from the anchorages and was characterized by a gradual fracture of fiber bundles, as in the case of columns with fully-bonded mortar-impregnated textile jackets. With regard to relative effectiveness, spirally applied unbonded strips with end anchorages were found equally good to their resin-impregnated counterparts in strength terms and inferior by 36 to 13% (depending on the number of layers) in ultimate strain terms. When effectiveness of unbonded jacketing is compared with that of mortar-impregnated jacketing, the results are nearly identical in the case of four layers and slightly inferior in terms of ultimate strain in the case of two layers.

Overall, it may be concluded that mortar-impregnated textile jackets are quite effective in confining columns of rectangular cross sections for strength and axial deformability. When the effectiveness is compared with that of epoxy-bonded jackets, it is found nearly equal in strength terms and slightly inferior in ultimate strain terms. The same conclusion applies in the case of spirally applied unbonded strips with end anchorages, except if the number of layers is quite low, which may adversely affect the deformability.

SIMPLE CONFINEMENT MODEL

A typical approach toward modeling confinement is to assume that the confined strength f_{cc} and ultimate strain ε_{ccu} depend on the confining stress at failure, $\sigma_{\ell u}$, as follows[26-28]

$$\frac{f_{cc}}{f_{co}} = 1 + k_1\left(\frac{\sigma_{\ell u}}{f_{co}}\right)^m \tag{1}$$

$$\varepsilon_{ccu} = \varepsilon_{co} + k_2\left(\frac{\sigma_{\ell u}}{f_{co}}\right)^n \tag{2}$$

where k_1, k_2, m, and n are empirical constants. The reduced effectiveness provided by jackets other than resin-impregnated ones (textile reinforced mortar jackets or unbonded strips anchored at the ends, as used in this study) may be taken into account by splitting k_1 and k_2 in two terms as follows

$$k_1 = \alpha k_{1,R} \tag{3}$$

$$k_2 = \beta k_{2,R} \tag{4}$$

where $k_{1,R}$ and $k_{2,R}$ are the values of k_1 and k_2, respectively, if jackets are made with resin-impregnated fibers, and α and β are effectiveness coefficients, which depend on the specific jacketing system (for example, α_M, β_M for mortar-based jackets and α_A, β_A for unbonded jackets anchored at the ends) and can be derived experimentally.

The confining stress σ_ℓ is, in general, nonuniform, especially near the corners of rectangular cross sections. As an average for σ_ℓ in a cross section with dimensions b and h, one may write (Fig. 11(a) to (c))

$$\sigma_\ell = \frac{\sigma_{\ell,h} + \sigma_{\ell,b}}{2} = \frac{1}{2}k_e\left(\frac{2t_j}{h}E_j\varepsilon_j + \frac{2t_j}{b}E_j\varepsilon_j\right) \tag{5}$$

$$= k_e\frac{(b+h)}{bh}t_jE_j\varepsilon_j$$

where E_j and ε_j is the elastic modulus and strain, respectively, of the jacket in the lateral direction, t_j is the jacket thickness, and k_e is an effectiveness coefficient that, for continuous jackets with fibers in the direction perpendicular to the member axis, is defined as the ratio of effectively confined area (A_e in Fig. 11(d)) to the total cross-sectional area A_g as follows[1]

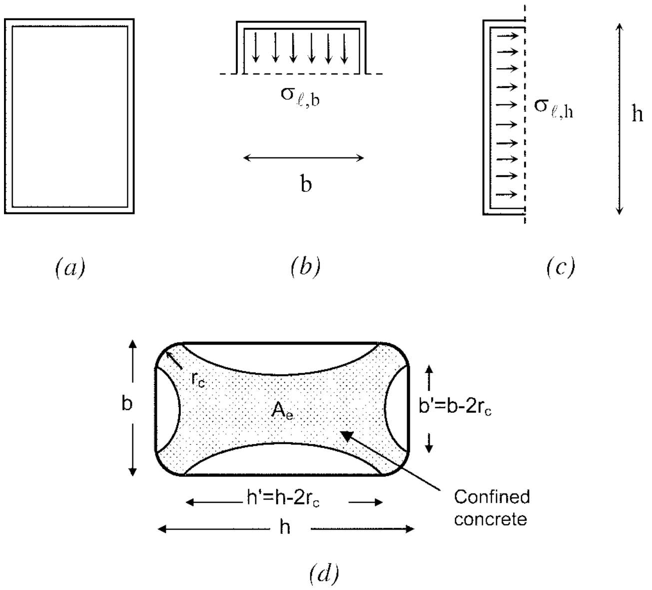


Fig. 11—(a) to (c) Approximate average confining stresses; and (d) effectively confined area in columns with rectangular cross section.

$$k_e = 1 - \frac{b'^2 + h'^2}{3A_g} \tag{6}$$

Hence, the confining stress at failure $\sigma_{\ell u}$ is given by Eq. (5) with $E_j\varepsilon_j$ replaced by f_{je}, the effective jacket strength in the lateral direction

$$\sigma_{\ell u} = k_e\frac{(b+h)}{bh}t_jf_{je} \tag{7}$$

APPLICATION OF MODEL

The literature on the precise form of concrete confinement models for concrete is vast.[25-27] Some of these models, especially the older ones, are based on the assumption that the relationship between confined strength and ultimate strain and their unconfined counterparts is linear, that is, m and n are both equal to 1. In other models, especially in some of the most recent ones, m and n are taken less than, but still close to, 1. Whereas the main advantage of the former approach is simplicity, the disadvantage is that linear relationships between f_{cc}-$\sigma_{\ell u}$ and ε_{ccu}-$\sigma_{\ell u}$ tend to overpredict both the confined strength and the confined ultimate strain for high confining stresses. As our objective in this paper is not to elaborate on confinement models for concrete, but rather to demonstrate the procedure described in the previous section regarding the use of the effectiveness coefficients α and β for the two alternative (to epoxy-bonded) jacketing systems, we also make, for the sake of simplicity, the assumption of linearity. In other words, we consider m and n equal to 1, but the approach presented herein, however, is applicable without difficulty for any set of values for m and n.

The application of Eq. (1), (2), and (7) to the data obtained for rectangular specimens (Series C) and the cylinders in Series B (Series A is excluded, because mortar-based jackets

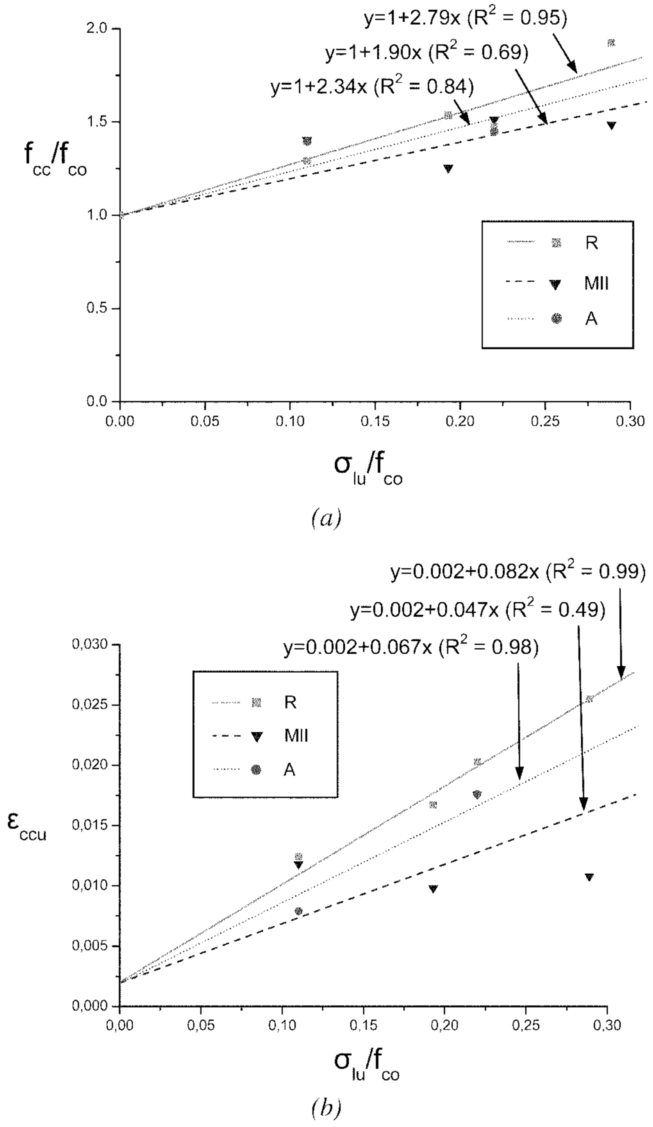


Fig. 12—(a) Normalized compressive strength; and (b) ultimate compressive strain in terms of lateral confinement (R: resin-based jacket; MII: textile with Mortar II; and A: unbonded strips with end anchorage).

cannot be compared with their resin counterparts) results in the plots of f_{cc}/f_{co} and ε_{ccu} versus $\sigma_{\ell u}/f_{co}$ given in Fig. 12(a) and (b), respectively. The best linear fit equations to these data yield $k_{1,R} = 2.79$ ($R^2 = 0.95$), $\alpha_M = 0.68$ ($R^2 = 0.69$), $\alpha_A = 0.84$ ($R^2 = 0.84$), $k_{2,R} = 0.082$ ($R^2 = 0.99$), $\beta_M = 0.57$ ($R^2 = 0.49$) and $\beta_A = 0.82$ ($R^2 = 0.98$), which may be used along with the confinement model. The aforementioned values state that according to the simplified model presented previously, the effectiveness of TRM jackets is roughly 70% in terms of strength and 55 to 60% in terms of ultimate strain; the corresponding values for unbonded jackets anchored at their ends are roughly 85% for strength and 80% for ultimate strain. Of course, these values should be considered as indicative, as the test data used for calibration are relatively limited. However, the method presented for obtaining these effectiveness coefficients is quite general.

CONCLUSIONS

Based on the response of confined cylinders, it is concluded that: 1) textile-mortar confining jackets provide substantial gain in compressive strength and deformability. This gain is higher as the number of confining layers increases and depends on the tensile strength of the mortar, which determines whether failure of the jacket will occur due to fiber fracture or debonding; 2) compared with their resin-impregnated counterparts, mortar-impregnated textiles may result in reduced effectiveness, in the order of approximately 80% for strength and 50% for ultimate strain, for the specific mortar used in this study. It is believed that these numbers depend very much on the type of mortar and could be increased with proper modification of mortar constituent materials, a task not addressed in this study; and 3) failure of mortar-impregnated textile jackets is less abrupt compared with that of their resin-impregnated counterparts, due to the slowly progressing fracture of individual fiber bundles.

From the response of rectangular columns, it is concluded that mortar-impregnated textile jackets are quite effective in confining columns of rectangular cross sections for strength and axial deformability. In comparison with their epoxy-based counterparts, mortar-impregnated textile jackets gave approximately the same effectiveness in strength terms and a slightly inferior one in ultimate strain terms. The same conclusion applies in the case of spirally applied unbonded strips with end anchorages, except if the number of layers is quite low, which may adversely affect the deformability. This concept of spirally applied unbonded jacketing appears to be quite interesting and certainly deserves further investigation.

Modeling of concrete confined with jackets other than resin-impregnated ones becomes a rather straightforward procedure through the introduction of experimentally derived jacket effectiveness coefficients, a concept developed in this study to compare the confining action of mortar-based jackets or spirally applied unbonded jackets to their resin-based counterparts.

From the results obtained in this study, the authors believe that TRM jacketing is an extremely promising solution for the confinement of reinforced concrete. Naturally, further investigation is needed (part of it is already underway) toward the optimization of mortar properties and the understanding of various other aspects, including long-term performance, response under cyclic loading, and jacket-steel reinforcement interactions.

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NOTATION

A_e = effectively confined area
A_g = gross section area
b = cross section width
E_j = elastic modulus of jacket in lateral direction
f_{cc} = compressive strength of confined concrete
$f_{cc,R}$ = compressive strength of concrete confined with resin-based composites
f_{co} = compressive strength of unconfined concrete
f_{je} = effective strength of jacket in lateral direction
h = cross section height
k_1, k_2 = empirical constants
$k_{1,R}$, $k_{2,R}$ = empirical constants for resin-impregnated jackets
k_e = confinement effectiveness coefficient
m = empirical constant
n = empirical constant
r_c = radius at corners of rectangular sections
t_j = thickness of jacket

α, β = jacket effectiveness coefficients
α_A, β_A = effectiveness coefficients for jackets made of unbonded strips with end anchorage
α_M, β_M = effectiveness coefficients for mortar-impregnated jackets
ε_{ccu} = ultimate strain of confined concrete
$\varepsilon_{ccu,R}$ = ultimate strain of concrete confined with resin-based composites
ε_{co} = strain at failure of unconfined concrete
ε_j = jacket strain in lateral direction
σ_ℓ = lateral stress due to jacketing
$\sigma_{\ell,b}$ = lateral stress perpendicular to side b
$\sigma_{\ell,h}$ = lateral stress perpendicular to side h
$\sigma_{\ell u}$ = ultimate lateral stress due to jacketing

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