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Mechanical performance of rubberised concrete confined with textile reinforced mortar jackets

Ioanna Skyrianou[1], Christos G. Papakonstantinou[2], Lampros N. Koutas[3]

[1] *PhD candidate*, Concrete Technology and RC Structures Lab, Dept. of Civil Engineering, University of Thessaly, Greece, *iskyrianou@civ.uth.gr*

[2] *Assistant Professor*, Concrete Technology and RC Structures Lab, Dept. of Civil Engineering, University of Thessaly, Greece, *cpapak@uth.gr*

[3] *Assistant Professor*, Concrete Technology and RC Structures Lab, Dept. of Civil Engineering, University of Thessaly, Greece, *koutas@uth.gr*

Abstract

Reuse of waste tyre rubber particles as a sustainable replacement for mineral aggregates in concrete has been an object of research for several years. The severe impact of rubber particles in concrete's mechanical performance (substantial reduction of its compressive strength), has led researchers in examining the confinement via externally bonded composites as a possible solution to mitigate the negative impact and further enhance the concrete's characteristics. This study aims to evaluate the mechanical performance of rubberised concrete confined with textile-reinforced mortar (TRM) jackets subjected to monotonic concentric compression. For this purpose, five trial concrete mixes were examined, in four of which rubber particles replaced fine natural aggregates by volume, with a replacement ratio of 25 %, 50 %, 75 % and 100 %. Overall, 70 cylindrical specimens from all mixes were tested (diameter 100 mm, height 200 mm). From each mix 8 specimens were unconfined, 3 were confined with 1 TRM layer and 3 confined with 2 TRM layers. The results showed that the compressive strength of rubberised concrete decreased up to 78.1 % for the highest replacement ratio. Confinement increased the compressive strength up to 35.5 % for 1 TRM layer and 49.6 % for 2 TRM layers, respectively. The residual strength also increased with an increasing rubber content. However, it was found that incorporating rubber in concrete increased its axial residual strength effectively only when 2 layers of confinement were applied. The findings of this study indicate promising potential for using confined rubberised concrete, particularly in applications where high deformability of elements is crucial (e.g. in seismic-prone areas).

Key words: concrete, rubberised concrete, waste tyre rubber, textile-reinforced mortar, TRM, FRCM

1 Introduction

Although EU directives have been implemented for the disposal, recycling and reuse of waste [1], less than 18 % of end-of-life tyres are still disposed in landfills. Their disposal is a serious threat for both the environment and public health, while their recycling can save up to 58.4 % in terms of CO_2 emissions [2]. In order to find an effective way to reuse waste tyres, promote sustainability and reduce the high environmental footprint of the concrete industry, the use of recycled rubber particles as an alternative to mineral aggregates in concrete was proposed.

The research in the field of rubberised concrete began in the early 1990s [3,4] and is still ongoing. The substantial reduction of the compressive strength and the increase of the axial deformation capacity are the main changes when incorporating rubber particles in concrete [3-6]. This has led researchers in examining the confinement via externally bonded composites as a means of eliminating the negative impact in compressive strength. Studies which examined confinement with fibre-reinforced polymer (FRP) jackets showed that confinement enhanced the initial low compressive strength and further increased the axial deformation and energy absorption capacities of rubberised concrete [7-10]. However, to the best of the author's knowledge, no other alternative composite materials have been studied as a means of rubberised concrete confinement.

The introduction of the so-called textile-reinforced mortar (TRM) as a feasible alternative to fiber-reinforced polymer (FRP) has gained ground lately. Properties of the inorganic matrix such as (a) high performance in elevated temperatures, (b) good adhesion with the concrete substrate, (c) application in wet surfaces and (d) low cost, lead to the progressive replacement of organic binders previously used in FRPs [11]. The aforementioned properties and the comparable effectiveness to FRP confinement [12] led to the selection of TRM confinement for this study.

The main purpose of this study was to assess the mechanical performance of rubberised concrete confined with a cement-based composite material. This includes a comparative evaluation of the content of rubber particles in concrete and the number of confinement layers. This study aims to develop a sustainable option that can be used in structural applications in seismic-prone areas.

2 Experimental program

In this study, five concrete trial mixes were examined, in four of which fine natural aggregates (2 - 8 mm) were replaced by rubber particles by volume with a replacement ratio of 25 %, 50 %, 75 % and 100 %. In total, 70 concrete cylinders with diameter 100 mm and length 200 mm from all the mixes were subjected to monotonic concentric compression to assess their mechanical performance. From each mix 8 unconfined specimens, 3 confined with 1 TRM-layer and 3 confined with 2 TRM-layers were tested. A list of the specimens is presented in Table 1.

Table 1. Details of specimens tested

Mix notation	Replacement ratio	Number of specimens		
		Unconfined	Confined with 1 TRM Layer	Confined with 2 TRM Layers
CM	0 %	8	3	3
R25	25 %	8	3	3
R50	50 %	8	3	3
R75	75 %	8	3	3
R100	100 %	8	3	3

2.1 Mix design

The control mix (CM), which did not contain rubber particles, was designed according to the Greek Concrete Technology Code provisions [13]. Natural aggregates from crushed limestone up to nominal size of 16 mm were used for this study and were sieved in 6 courses. Rubberised concrete mixes had two of the fine natural aggregate courses (2-4 mm and 4-8 mm) replaced by volume with rubber particles of the same size with replacement ratios of 25 % (mix R25), 50 % (mix R50), 75 % (mix R75) and 100 % (mix R100). Rubber particles were obtained by a local tyre recycling plant with state-of-the-art facilities. The density of rubber particles was 1/3 of the natural aggregates as measured in the lab. Superplasticiser was also used to improve workability of fresh concrete. Water to cement ratio (w/c) was 0.397 for all mixes. Thus, the rubberised concrete mixes were not optimised and were based on the ordinary concrete mix (CM). Quantities of each mix are presented in Table 2.

Table 2. Quantities per mix [kg/m^3]

Material		CM	R25	R50	R75	R100
Natural Aggregates	8-16 mm	507.96	507.96	507.96	507.96	507.96
	4-8 mm	432.70	324.52	216.35	108.17	-
	2-4 mm	357.52	268.14	178.76	89.38	-
	1-2 mm	169.32	169.32	169.32	169.32	169.32
	0.5-1 mm	169.32	169.32	169.32	169.32	169.32
	0-0.5 mm	244.58	244.58	244.58	244.58	244.58
Rubber	4-8 mm	-	36.06	72.12	108.17	144.23
	2-4 mm	-	29.79	59.59	89.38	119.17
Water		145.24	145.24	145.24	145.24	145.24
Cement		365.83	365.83	365.83	365.83	365.83
Superplasticiser		1.99	1.99	1.99	1.99	1.99

2.2 TRM confinement

A two-directional coated basalt-fibre textile with a 6 mm square mesh was used for the TRM jackets (Fig. 1a). The textile had a weight of 250 g/m^2, a tensile strength of 1542 MPa and a modulus of elasticity of 89 GPa according to the manufacturer's datasheets. The cementitious mortar used as matrix had water to binder ratio of 0.23. The dry binder contained fine aggregates and micro fibres made of polypropylene. The strength of the mortar was measured through flexural and compressive tests on three 40 x 40 x 160 mm mortar prisms. The prisms were first subjected to three-point bending to obtain the flexural strength. The fractured parts were then used for the compressive tests. The average values of the compressive and flexural strength were 22.6 MPa and 1.79 MPa, respectively.

Specimens from each mix were cast in cylindrical plastic moulds and after demoulding (the next day) they were left to cure in air in ambient environment inside the lab. The specimens were cured for at least 14 days before jacketing. For the jacketing the following procedure was followed: (a) a first layer of mortar was applied on clean and dampened concrete surface, (b) the textile was pressed in the mortar and wrapped around the cylinder in either one or two layers, including an overlapping zone equal to 1/3 of the specimen's circumference (Fig. 1b), (c) additional mortar was applied in-between layers and a final mortar layer was applied to completely cover the textile, (d) extra confinement was provided near the edges of the cylinders (20 mm-wide basalt textile strips) to prevent local concrete crushing due to stress concentrations. As a part of the curing process of the jackets, the specimens were immersed in water for one minute for two consecutive days after the confinement was hardened. Then the specimens were left to cure in air for at least 28 days before testing.

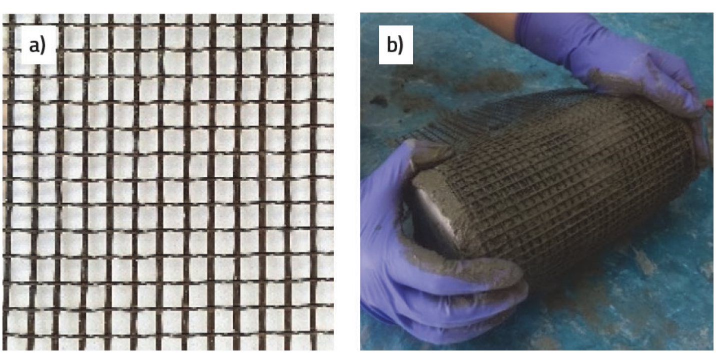

Figure 1. Picture of (a) basalt textile used and (b) application of TRM jacket

Figure 2. Picture of the test setup

2.3 Test setup and instrumentation

All cylinders were capped with gypsum mortar prior to testing. To record the axial deformation of the specimens, two potentiometers were placed along the cylinder's axis under a gauge length varied from 15.7 mm to 16.8 mm. They were attached to threaded rods which were fixed in the concrete core of the cylinders (Fig.2). The axial deformation of the specimen was measured as the average of the two readings divided by the gauge length. All specimens were subjected in monotonic concentric compression using a 3000 kN-capacity hydraulic compression machine at a displacement rate of 15 μm/s.

3 Results and discussion

3.1 Fresh properties and density

The fresh properties of the concrete mixes as well as the density of hardened concrete are presented in Table 3. To evaluate the workability of fresh concrete, the slump of each mix was measured according to ASTM C143 / C143M-20 [14]. The results indicated that increasing the content of rubber particles slightly improved the workability. However, earlier research [5, 6] has shown the opposite, as rubber particles increase the friction of fresh concrete due to their texture; they comprise a rougher surface compared to natural aggregates. This significant divergence in results is possibly attributed to the extensive use of superplasticiser and good distribution of total aggregates in this study, which improved workability of the mixes.
Air content of fresh concrete was also determined for each mix according to ASTM C231 / C231M-17a [15]. The results indicated a slight increase of the air content for higher replacement ratios, which was also confirmed visually as the surface of rubberised concrete specimens were porous. This increase is due to bad interface adhesion between the cement paste and rubber particles which are hydrophobic resulting in large voids in the cement paste.
As expected, the replacement of natural aggregates by rubber particles decreased the density of concrete. This property makes rubberised concrete an ideal candidate for applications where reduced dead loads are required.

Table 3. Fresh properties and density of all the mixes

Mix notation	**Slump** [mm]	**Air content** [%	**Density** [kg/m^3]
CM	150	2.8	2512
R25	155	2.2	2354
R50	165	2.4	2206
R75	160	3.9	2134
R100	n.a.*	n.a.*	1957
*Measurements not available.			

3.2 Compressive strength and modulus of elasticity

The compressive strength results of all specimens are summarised in Table 4. It is evident that the incorporation of rubber particles in concrete decreased its compressive strength from 44 % for the mix with the lowest displacement ratio (R25) up to 78 % for the mix with the highest replacement ratio (R100). The decrease trend was the same for both confined and unconfined specimens and was higher for replacement ratio up to 50 %. The reduction in the compressive strength is a result of the tensile stresses developed in the cement paste due to the dilation of rubber particles. Also, the poor adhesion between rubber particles and cement paste result in a weak interfacial transition zone. These factors lead to the development of premature cracking and consequently in lower compressive strength. The above findings agree with past studies [3-6].

Furthermore, confinement increased the compressive strength from 16 % for CM up to 35.5 % for R100 when 1 TRM layer was applied and from 21.6 % for CM up to 49.6 % for R100 when 2 TRM layers were applied. The effectiveness of the confinement was higher for the mix with higher rubber content (R100) due to excessive lateral dilation caused by rubber particles, which in turn resulted in higher hoop stresses in the TRM jackets. However, confinement with 2 TRM layers was slightly more effective compared to 1 TRM layer in increasing the concrete compressive strength. This was mainly attributed to the premature failure of the specimens with 2 TRM layers; specimens failed near their two edges where the extra provided confinement proved to be inadequate.

The modulus of elasticity (E) was calculated with linear regression analysis from the deformation data obtained from the potentiometers in the linear elastic part (from 5 to 30 % of the peak load). The results indicated a significant reduction in stiffness as the rubber content increased. This can be attributed to the lower stiffness of rubber particles compared to that of natural aggregates.

Table 4. Main test results

Mix notation	**E** [GPa]*	**Compressive strength** [MPa]		
		Unconfined**	**Confined with 1 TRM Layer***	**Confined with 2 TRM Layers***
CM	32.33 (2.97)	33.70 (2.91)	39.01 (2.07)	41.00 (3.63)
R25	22.79 (1.77)	18.86 (1.97)	24.79 (1.32)	24.99 (1.18)
R50	16.34 (1.64)	11.25 (1.38)	15.18 (1.06)	14.05 (2.25)
R75	13.90 (2.99)	9.30 (0.47)	12.41 (0.13)	12.30 (0.52)
R100	10.80 (3.02)	7.39 (0.52)	10.01 (0.66)	11.06 (0.97)

* Mean value from 3 specimens (standard deviation in parenthesis).
**Mean value from 8 specimens (standard deviation in parenthesis).

3.3 Axial stress-strain response

During testing both axial deformation of the specimens and displacement of the testing machine were recorded. However, due to excessive lateral deformations post-peak in the majority of the specimens and in some cases concentration of damage near the anchor points of the sensors, the measurements from the potentiometers were considered as not useful after the first elastic part. Hence, to allow easy comparisons, it was decided by the authors to present the stress-strain curves with the strain values being derived from the testing machine's displacements divided by the height of the cylinders (Fig. 3). It is noted that the magnitude of the presented axial strains cannot be considered as realistic or representative for the material and are only presented here for comparison purposes.

The comparative assessment of the curves showed evident reduction of compressive strength and stiffness when rubber particles were incorporated in concrete. The residual strength increased with an increasing rubber content, resulting in a flattened second part of the curve. At the peak when the rubber content increased, the axial deformation was reduced by 18 % for mix R25 up to 50 % for mix R100. However, the residual strength of rubberised concrete specimens increased considerably after the reduction of the compressive strength was more than 20 %.

Confinement with TRM jackets enhanced the compressive strength of rubberised concrete and the residual strength in all mixes. The response of confined specimens was similar for either 1 or 2 confinement layers. First part of the curve was linear up to peak load as expected. The second part of the curve indicated a drop of strength until the activation of TRM jackets, especially in lower rubber contents. When the rubber content increased, the activation of the jackets was accelerated resulting in less abrupt drop in strength. The delay in activation of TRM jackets was probably caused by imperfect application of the textiles; the coating of the textiles made application of closed jackets difficult due to the added stiffness. This response is contrary to the bilinear curves reported in FRP jacketing [7, 9].

Confinement with 1 TRM layer increased the displacement in all mixes. Specifically, at the peak and at 20 % drop of peak load an increase was observed by 3 % and 10 % for mix CM and up to 48 % and 172 % for mix R100, respectively. This trend was further enhanced when 2 TRM layers were applied, resulting in an increase for mix R100 by 50 % and 341.5 % of the displacement at the peak and at 20 % drop of peak load, respectively. Although confinement increased the residual strength for specimens of the same mix, the same behaviour was not observed when comparing rubberised concrete specimens with those of the control mix. At 20 % drop of the peak load, the displacement was higher for the rubberised concrete mixes only when 2 layers of confinement were applied and for 1 layer of confinement only in mix R100. This is possibly due to the late activation of the TRM confinement which failed to sustain the compressive strength post-peak. It also suggests that in order to overcome the considerable loss in compressive strength and take advantage of the higher residual strength of rubberised concrete, optimisation of both the mix and jackets are needed.

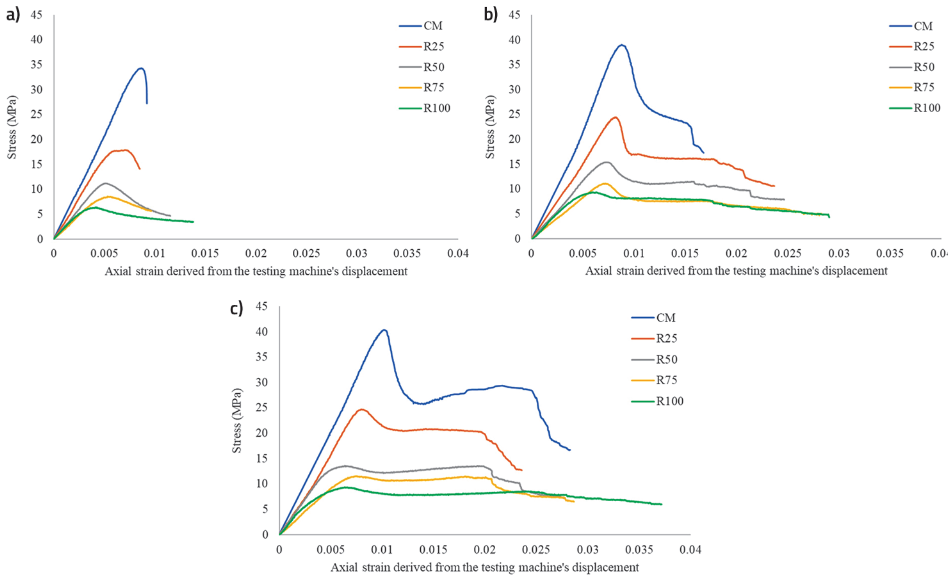

Figure 3. Stress-strain curves of specimens: a) unconfined, b) confined with 1 TRM layer, c) confined with 2 TRM layers

3.4 Failure modes

All unconfined rubberised concrete specimens failed gradually with the development of small vertical cracks, in contrast to the unconfined control specimens (mix CM) which failed abruptly. The increase of rubber content led to thinner cracks, which were mostly concentrated near the edges of the cylinders. This is possibly attributed to concentration of rubber particles in one of the two edges due to floating when concrete was still fresh, thus resulting in a weak concrete zone. Significant lateral dilation was observed in rubberised concrete specimens, that was more pronounced in mixes with higher rubber content. Characteristic failure modes of unconfined specimens from three different mixes are presented in Fig. 4.

Confined specimens failed due to progressive rupture of the textile fibres. Failure initiated near the edges and in most specimens near the end of the overlap zone and propagated towards the middle, thus indicating that the extra confinement at the end zones was inadequate. Significant lateral dilation was also observed in confined specimens and was more pronounced for 2 layers of TRM confinement. Characteristic failure modes of confined specimens are presented in Fig. 5.

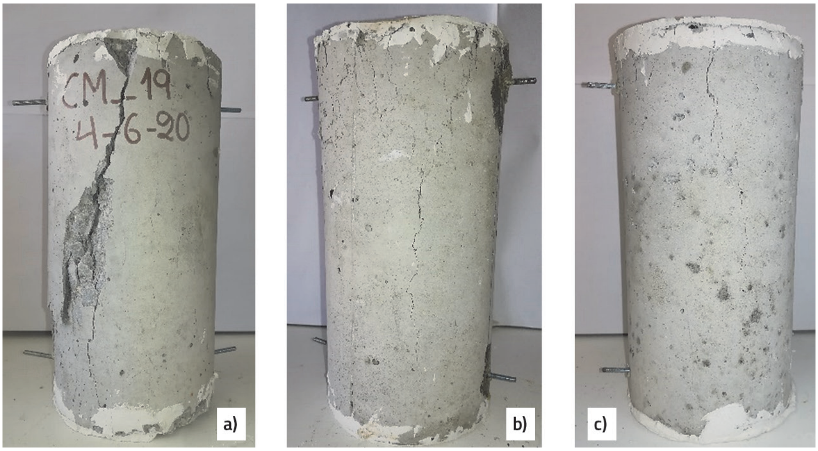

Figure 4. Failure modes of unconfined specimens (a) CM, (b) R50, (c) R75

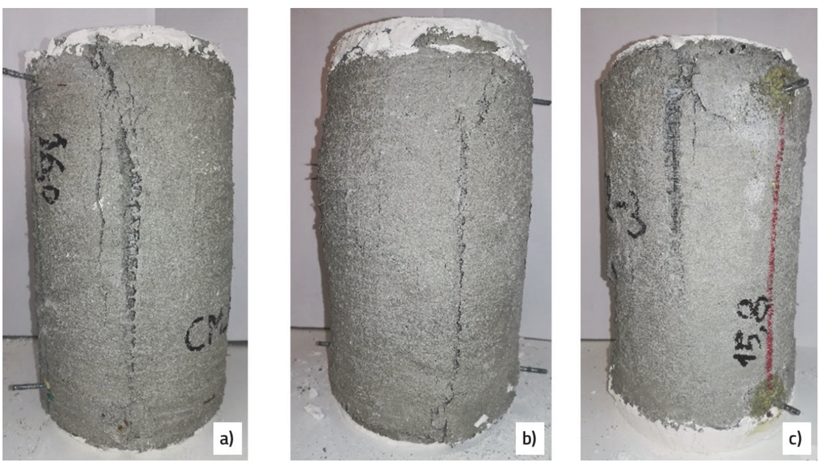

Figure 5. Failure modes of confined specimens (a) CM_1L, (b) R100_1L, (c) R75_2L

4 Conclusions

Based on the results presented in this study, the following conclusions were drawn:

- Implementation of rubber particles increased air content and reduced density of hardened concrete.
- Higher content of rubber particles in concrete decreased the compressive strength and stiffness and increased the residual strength.
- Higher rubber content resulted in notable lateral dilation and gradual failure.
- Confinement with TRM jackets improved the mechanical properties of rubberised concrete.

- Confinement was more effective for higher rubber content due to enhanced lateral dilation of concrete core and faster activation of TRM jackets.
- Confinement with 2 layers of TRM jackets was more effective for enhancing the residual strength of rubberised concrete.
- The results of this study confirm potential utilisation of confined rubberised concrete in structural applications when high deformability is required, especially for applications in seismic-prone areas. However, due to limited data, future research should include optimisation of the concrete mix and the TRM jacketing in order to minimise the reduction of compressive strength, as well as cyclic tests on rubberised concrete members confined with TRM jackets as a means of improving local ductility at the plastic hinge regions.

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