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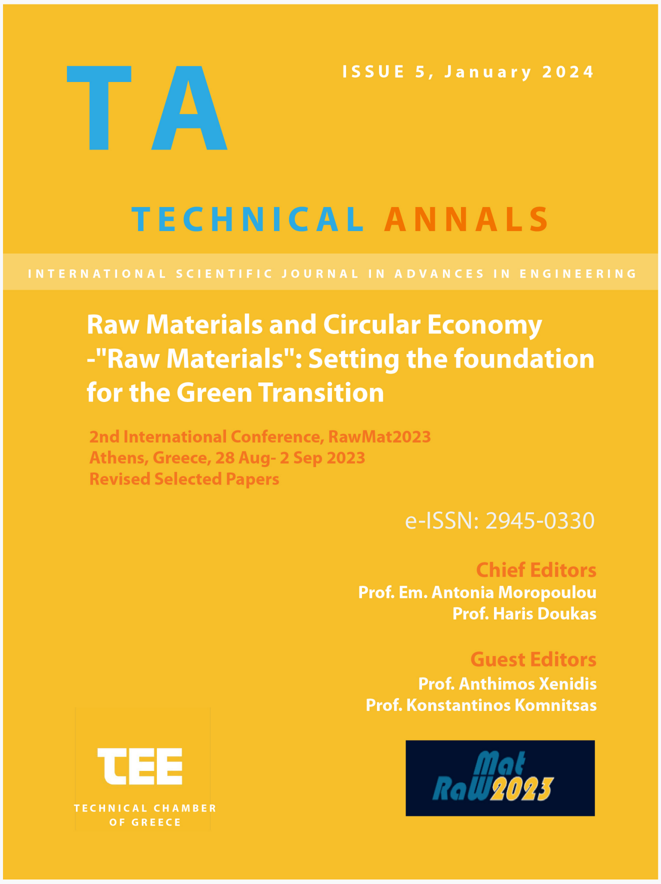

Compressive strength of concrete containing rubber particles from recycled car tires confined with textile reinforced mortar (TRM) jackets

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Compressive strength of concrete containing rubber particles from recycled car tires confined with textile reinforced mortar (TRM) jackets

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Abstract. This study examines the mechanical characteristics of concrete incorporating recycled rubber aggregates as a partial substitute for natural aggregates. The concrete is confined with fibre textile jackets using an inorganic mortar. Systems like this are known as textile reinforced mortars (TRM) or fibre reinforced cementitious mortars (FRCM). The experimental program includes studying the mechanical properties of concrete containing recycled aggregates compared to conventional concrete, through uniaxial compression tests of cylindrical specimens of 100 mm diameter and 200 mm height. Furthermore, the mechanical properties of confined concrete specimens with one or two layers of basalt fibre mesh in a cementitious matrix are examined. The findings underscore a significant reduction in the compressive strength of concrete when substituting natural aggregates with rubber, accompanied by an augmented deformation capacity. The incorporation of an inorganic matrix proves effective in enhancing compressive strength up to 38%, particularly with the addition of more confinement layers. These results collectively suggest the feasibility of employing this environmentally friendly "green" concrete with TRM in applications prioritizing high deformability.

Keywords: Green concrete, confinement, TRM, rubber, recycled tires.

1 Introduction

According to the European Commission, the construction industry contributes to annual gaseous pollutant emissions in the range of 5-12% of the total emissions in the European Union. Remarkably, a reduction of up to 80% can be achieved by incorporating recycling and recovery practices into the production of construction materials [1]. Concrete stands out as a fundamental and extensively utilized material in the construction sector. As efforts intensify to curtail gaseous pollutant emissions associated with concrete production, the utilization of recycled aggregates has garnered significant attention. Recent research has been dedicated to exploring the feasibility and benefits of integrating aggregates sourced from recycled materials into concrete formulations.

This approach aligns with the broader goal of mitigating the environmental impact of the construction industry. In recent years, there has been a notable emphasis on researching the utilization of aggregates derived from recycled rubber, particularly sourced from the recycling of car tires. Within the European Union, the recycling and reuse of car tires have achieved a commendable rate, reaching 91% of tires removed from end-of-life vehicles. This trend highlights a growing interest in sustainable practices and the circular economy, with a specific focus on repurposing materials from discarded automotive components to contribute to more environmentally friendly construction methods [2].

Recent studies have delved into the substitution of natural aggregates with recycled rubber granules [3, 4]. The outcome of this replacement is a considerable decrease in the compressive strength of the concrete, a factor influenced by both the size and the content of recycled rubber aggregates in the concrete mix [5]. Despite the reduction in compressive strength, an observable increase in toughness is noted, stemming from a significant rise in deformations, both axial and lateral [6,7].

Due to the adverse impact of rubber on the compressive strength of concrete, the application of this "green" concrete has been constrained to uses with lower compressive strength requirements, such as in pavement construction [8]. This limitation reflects the ongoing challenge of balancing environmental considerations with the structural performance demands of different construction applications. In an attempt to counteract the adverse effect, the use of composite jackets to confine the concrete has been considered. At present, research has focused on confinement using Fibre-Reinforced Polymers (FRPs) or steel tubes [9-11].

The utilization of FRP confinement for concrete, incorporating rubber granules, has demonstrated notable effectiveness in contrast to traditional concrete practices. This is attributed to the substitution of a portion of natural aggregates with recycled rubber granules, resulting in heightened lateral deformations of the concrete [12, -13]. Simultaneously, the application of FRP enhances the maximum axial deformation capacity. This capacity increases with the increase of FRP layers and rubber content, while concurrently mitigating the adverse impact on compressive strength [14].

Over time, the adoption of Textile Reinforced Mortars (TRM) has surpassed that of FRPs, aiming to address the limitations associated with organic matrices. The inorganic matrix presents an appealing alternative characterized by lower costs, increased resistance to high temperatures, and the capability to be applied to wet surfaces. Furthermore, studies indicate that the effectiveness of TRM confinement is comparable to that of FRP [15]. However, the application of TRM as confinement for concrete containing recycled rubber aggregates remains unexplored as of now.

2 Experimental programme

Initially, the mechanical properties of concrete containing recycled rubber aggregates were examined and compared with those of conventional concrete. For this purpose, cylindrical specimens with a diameter of 100 mm and a height of 200 mm were prepared from a mixture of conventional concrete and a mixture in which part of the natural aggregates has been replaced with recycled rubber at a rate of 42% by volume. A total of eight specimens of each mixture were examined, in three of which the axial strain was measured. Subsequently, six specimens from each mix were reinforced with TRM jackets using a basalt mesh in a cementitious matrix. Three specimens were reinforced using one layer of TRM and three specimens using two layers. All specimens were tested in uniaxial compression.

2.1 Materials

For all the concrete mixtures, Type II Portland cement with a characteristic strength of 42.5 MPa and crushed limestone aggregate (referred to as natural aggregate) with a nominal maximum size of 16 mm were used. For the conventional concrete (CM) mix, crushed limestone aggregates with a maximum diameter of 16 mm divided into 6 gradations were used. The mix design proportions of conventional concrete mixture are provided in Table 1. A small quantity of high range water reducing admixture, based on modified polycarboxylic ether polymers, was used in all mixtures to regulate the workability of the concrete. A ratio of water to cement equal to W/C = 0.4 was used.

Table 1. Mix design of control concrete.

Material		Quantity (kg/m^3)
Cement		365.8
Water		145.2
Limestone Aggregates	8-16 mm	507.9
	4-8 mm	432.7
	2-4 mm	357.5
	1-2 mm	169.3
	0.5-1 mm	169.3
	0-0.5 mm	244.9
Superplasticizer		2

The recycled rubber employed in the study originated from a tire recycling plant in Drama, Greece, where the rubber undergoes separation from other tire materials such as linen and steel. The separated rubber is then processed into granules of diverse grades. Specifically, in the concrete with recycled aggregates (RuC), the natural aggregates with a gradation of 2-8 mm (refer to Figure 1) were completely replaced by recycled rubber of identical diameter, accounting for 100% substitution. It was determined that the overall content of recycled rubber in the mixture constituted 42% of the total volume of aggregates.

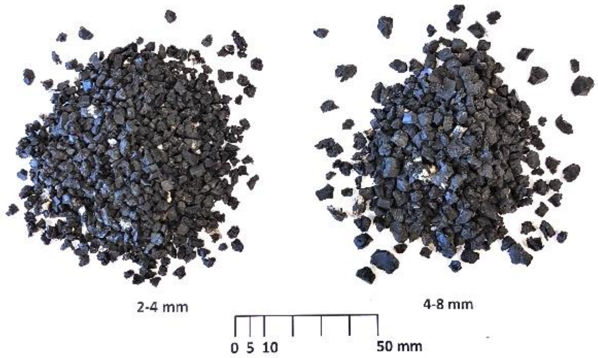

Fig. 1. Rubber particles used as natural aggregate replacement.

A two-way basalt grid (Figure 2a) with a 6 mm pitch, a nominal thickness of 0.039 mm per fibre direction and a weight (with the coating) of 250 g/m^2 was used for TRM confinement. The tensile strength of the textile was 1542 MPa and the modulus of elasticity 89 GPa, according to the manufacturer. The cementitious mortar used contains fine aggregates with a maximum grain diameter of 1.3 mm and polypropylene fibres (Figure 2b). According to measurements made on prismatic samples of the mortar with dimensions of 40x40x160 mm, the 28-day compressive and flexural strengths were found to be 22.6 MPa and 4.0 MPa, respectively.

(a) (b)

Fig. 2. (a) Basalt textile used for confinement (b) Cementitious mortar

The cylindrical concrete specimens (Figure 3) were subjected to uniaxial monotonic compression, while two linear displacement sensors were used on each specimen to measure axial strain. These sensors were positioned vertically at a length of 160 mm, diametrically opposed to each other, as illustrated in Figure 4.

(a) (b) (c)

Fig. 3. (a) Conventional concrete cylinder, (b) rubberised concrete and (c) confined rubberised concrete cylinder using 2 layers of TRM.

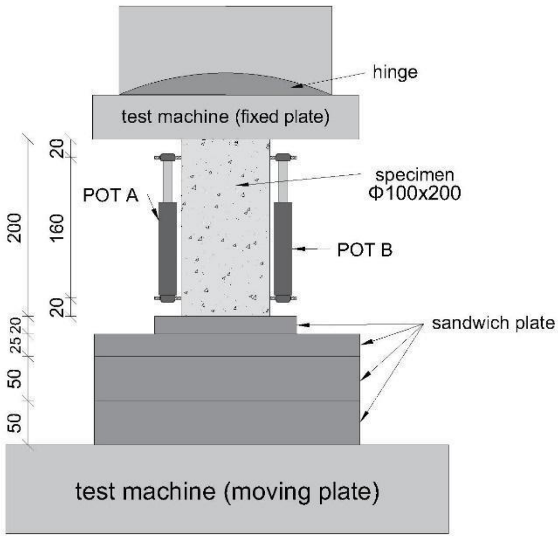

Fig. 4. Experimental Setup (dimensions in mm)

3 Results and discussion

3.1 Compressive Strength

Based on the experimental results, the compressive strength of each specimen is shown in Figure 5. The compressive strength of conventional concrete (CM) was 33.7 MPa for unconfined specimens and increased to 39.0 MPa and 41.0 MPa for confined specimens with 1 and 2 layers respectively. In contrast, the addition of recycled rubber to concrete (RuC) significantly reduced its compressive strength, which was 7.4 MPa for the unconfined specimens, while for the 1- and 2-layer confined specimens it reached 10.0 MPa and 10.2 MPa respectively. This suggests that while TRM confinement does improve strength in rubberized concrete, the improvement is less pronounced than in conventional concrete. Similar findings were reported by Gesoğlu et al. [16], who observed that replacing natural aggregates with recycled rubber resulted in a substantial reduction in compressive strength. In their study, the compressive strength decreased by up to 50% when using a 50% rubber aggregate substitution. However, they noted that the use of external confinement, specifically FRP jackets, helped mitigate the reduction in strength to some extent, aligning with the effects seen in our study with TRM confinement. Furthermore, Siddique and Naik [17] also reported a reduction in compressive strength across different rubberized concrete mixtures. Their research highlighted the importance of the size and content of rubber particles in determining the extent of strength reduction, a factor confirmed by the high rubber content (42%) used in our research.

Moreover, it is observed that in the case of concrete containing recycled rubber, the use of 2 layers of TRM does not result in a significant increase in strength compared to the use of 1 layer. This disparity can be attributed to the elevated content of rubber in the concrete (42%), exerting a significant influence on the mechanical properties of the concrete.

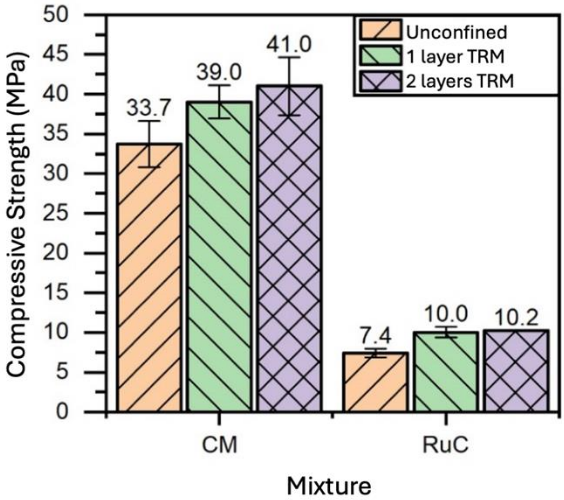

Fig. 5. Concrete compressive strength comparison

3.2 Stress-Strain curves

During the uniaxial compression tests axial strains were recorded using the axial transducers. Using the recoded loads (from the load cell) and deformations typical stress-strain diagrams for both unconfined (Unc - unconfined) and confined (1L - 1 layer, 2L - 2 layers) specimens from the two concrete mixes were drawn. The resulting diagrams are displayed in Figure 6. Failure was conventionally defined as the point where the load dropped by 20% after the maximum value was reached. The conventional failure point is indicated on the curves of Figure 6 with dots.

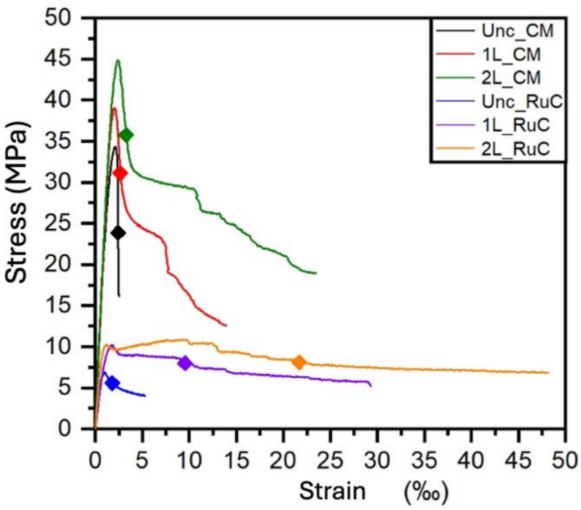

Fig. 6. Stress vs strain curves

It is evident from the stress-strain diagram that in the case of conventional concrete, the confinement increased the compressive strength, but without an appreciable increase in the axial strain up to failure. This occurs due to the premature failure of the TRM jacket at the ends of the specimen, as a result of which the confinement does not have time to fully activate and, by extension, the load drops. In the context of concrete with recycled rubber, TRM confinement demonstrated superior effectiveness, notwithstanding premature failure at the edges. This superiority can be attributed to the substantial swelling of the concrete caused by the rubber, triggering a quicker activation of the confining jacket. Consequently, the confined specimens experienced failure at significant values of maximum axial strain. Furthermore, it was observed that the utilization of 2 layers of TRM further increased the axial strains compared to the use of 1 layer of TRM. Similar findings were reported by Aiello et al [18], who reported that.

The stress-strain behavior of rubberized concrete under confinement in this study demonstrated that TRM was more effective in increasing axial strain in concrete containing recycled rubber than in conventional concrete. Similar behavior has been observed in other studies. More specifically, Güneyisi et al. [19] found that rubberized concrete exhibited increased lateral expansion when confined, leading to earlier activation of confining jackets, a phenomenon particularly notable in concrete with a higher rubber content. Additionally, Xue and Shinozuka [20] noted that as rubber content increased, axial strain also increased. However, they observed diminishing returns in strain improvement beyond a certain rubber content level.

3.3 Toughness

Toughness is defined as the area enclosed by the curve of the stress-strain diagram until failure and expresses the ability of concrete to absorb energy during compression until fracture. This measurement reflects the concrete's capacity to absorb energy throughout the compression process until it eventually fractures. In essence, the greater the area under the stress-strain curve, the higher the toughness of the material, indicating its ability to withstand deformation and absorb energy prior to failure.

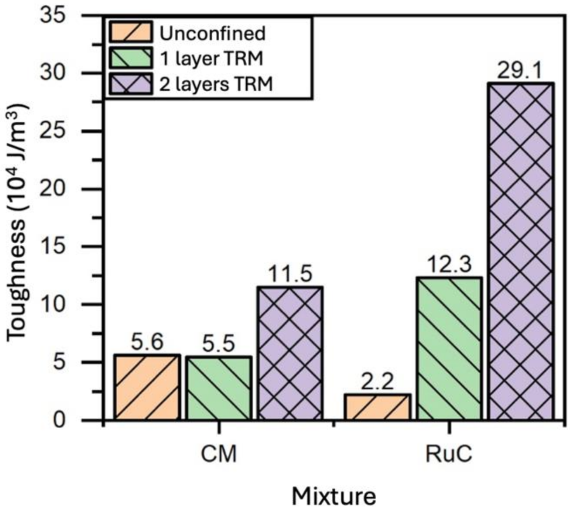

Fig. 7. Comparison between geopolymer and cement-based mortar strength.

As shown in Figure 7, the toughness of unconfined concrete with recycled rubber is lower than that of conventional concrete, as the very low compressive strength significantly affects the energy absorption capacity. However, the use of confinement significantly increases the toughness of the rubberised concrete specimens, especially as the layers increase. Similar findings have been reported in other studies [21,22].

It is evident that the toughness of unconfined rubberized concrete decreases when natural aggregates are replaced with rubber particles, primarily due to the reduced compressive strength and weak bonding between rubber and the cement matrix, which limits the material's energy absorption capacity during axial compression. This observation aligns with findings from other studies, such as those by Güneyisi et al. [18] and Li et al. [21], who also reported a decrease in toughness in rubberized concrete compared to conventional concrete. Although rubberized concrete exhibits higher deformability, it cannot absorb as much energy as conventional concrete due to its lower compressive strength. However, the application of confinement techniques, such as FRP or Textile Reinforced Mortars (TRM), significantly improves the toughness by enhancing both strength and deformability, as observed in this study.

Specifically, as observed in this study, the use of TRM jackets on rubberized concrete specimens results in a notable increase in toughness, particularly with the use of two layers of TRM, which significantly boosts the energy absorption capacity compared to unconfined specimens. This improvement is attributed to the confinement's ability to restrain the lateral expansion of the concrete, delaying failure and enabling higher axial strains. Previous research, such as that by Güneyisi et al. [18] and Razagpur et al. [22], supports these findings, showing that FRP confinement techniques effectively enhance the toughness of rubberized concrete by preventing premature failure and allowing for greater deformation under load. The increase in toughness with confinement, especially with multiple layers, demonstrates the potential of rubberized concrete for applications requiring high deformability and toughness, such as in seismic structural elements.

4 Conclusions

In this study, the impact of incorporating recycled rubber in concretewas examined, along with the effects of using TRM (Textile-Reinforced Mortar) jackets for confinement.

Based on the results, the following conclusions can be drawn:

- The incorporation of recycled rubber as an aggregate in concrete led to a notable decrease in compressive strength.
- The application of TRM jackets increased the deformability and toughness of rubberized concrete.
- Confined concrete containing recycled rubber demonstrated enhanced confinement effectiveness, primarily due to the lateral dilation caused by the rubber particles, which activated the TRM jacket more effectively.

Based on these findings, it is recommended to further explore the use of confined rubberized concrete in applications requiring high deformability, such as seismic-resistant structures. However, optimizing the concrete mix design is crucial to mitigate the reduction in compressive strength. Additionally, care must be taken to optimize the application of TRM jackets to prevent premature failures and to ensure consistent performance.

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