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Evaluation of physical and mechanical properties of cement-treated base incorporating crushed waste tires

Keywords: crushed waste tires, recycling, cement-treated base, physical evaluation, mechanical performance

Introduction

Pavements are a crucial component of transportation infrastructure, enabling the efficient and safe movement of people and goods (Mezhoud, Clastres, Houari & Belachia, 2018). However, the conventional construction and maintenance of pavements typically require significant amounts of virgin materials, leading to the depletion of natural resources (Li, Xiao, Zhang & Amirkhanian, 2019). In recent years, there has been a growing need to find efficient and sustainable ways to recycle and reuse waste materials in pavement construction to reduce the environmental impact of these activities (Plati, 2019). The incorporation of recycled materials in pavement construction is gaining attention as a potential solution. Such sustainable pavement practices can help promote resource conservation and reduce the carbon footprint of the transportation infrastructure (Correia, Winter & Puppala, 2016). Several recycled materials have been explored for their use in pavement construction, including reclaimed asphalt pavement and recycled concrete aggregate, which have shown promising results in terms of both

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mechanical performance and environmental benefits (Siddika et al., 2019). In addition, various other recycled materials such as fly ash, bottom ash, recycled asphalt shingles, lignin, waste plastic, crushed brick, recycled glass, glass powder, glass fibers and crumb rubber have also been examined as replacements for conventional pavement materials (Mezhoud, Houari & Boubaker, 2017; Orouji, Zahrai & Najaf, 2021; Medaoud, Mokrani, Mezhoud & Ziane, 2022; Orouji & Najaf, 2023). While much of the research on recycled materials in pavement construction has focused on asphalt layers, the base and subbase layers have greater potential to incorporate sustainable materials due to their greater thickness (Mohanty, Mohapatra & Nayak, 2022). The use of waste tires in pavement construction has received significant attention in recent years due to its potential to mitigate environmental pollution and promote sustainability. The utilization of waste tires in bituminous layers of pavement has been extensively investigated. Zhang, Li, Ding and Li (2019) studied the use of crumb rubber in asphalt pavements and found that it enhanced the rutting resistance and reduced cracking. Similarly, Lu, Qing, Xin, Alamri and Alharthai (2021) investigated the use of crumb rubber in open-graded friction course (OGFC) pavements and reported improved skid resistance and durability. In addition to bituminous layers, waste tires have also been explored as an additive in base layers. Pham, Zhuge, Turatsinze, Toumi and Siddique (2019) investigated the use of waste tire rubber as an additive in cement-stabilized aggregate and found that it improved the mechanical properties and reduced water absorption. Moreover, studies have shown that using waste tire-derived aggregate in the base layer can reduce the overall cost of pavement construction while improving its durability (Saberian, Perera, Zhou, Roychand & Ren, 2021). Despite the promising results reported in the literature, there are still some challenges and limitations associated with the use of waste tires and plastic in pavement construction. One of the major concerns is the lack of standardization in the manufacturing and characterization of waste tire materials. Another challenge is the limited knowledge of the long-term performance and environmental impact of these materials. Therefore, further research is needed to address these challenges and optimize the use of waste tires and plastic in pavement construction. For this reason, this study aims to investigate the potential of incorporating waste tire aggregates in cement-treated base layers for pavement construction. The purpose is to comprehensively evaluate the physical and mechanical properties of CTB mixtures containing crushed waste tires, with a focus on their deformation capability, compressive strength, tensile strength, modulus of elasticity, and shrinkage behavior. Through this investigation we aim to provide valuable insights into the feasibility and benefits of utilizing waste tire aggregates in cement-treated base layers, thereby supporting the advancement of environmentally conscious and economically viable pavement construction practices.

Methodology

To achieve the objectives, the methodology was structured into the following steps: (1) Material selection and characterization: The initial step involved selecting natural aggregates, including crushed sand and gravel, along with recycled rubber derived from non-reusable tires. Subsequently, a thorough characterization of these materials was conducted to assess their mechanical strength, density, and elasticity, and chemical composition. (2) Mix design and preparation: This phase encompassed the meticulous preparation of cement-treated base (CTB) mixtures under controlled conditions. (3) Compaction and Proctor tests: Proctor compaction tests should be executed; the objective is to ascertain the optimal water content and maximum dry density of the CTB mixtures. (4) Mechanical testing: A series of mechanical tests were conducted to evaluate the performance of the CTB mixtures. Compressive strength tests were performed on cubic specimens ($10 \times 10 \times 10$ cm^3) at varying ages (7 and 28 days). Indirect tensile strength tests were carried out on prismatic specimens ($7 \times 7 \times 28$ cm^3) at specified time intervals. Furthermore, the modulus of elasticity was evaluated using cylindrical specimens (10×20 cm^3) after 28 days. (5) Shrinkage analysis: shrinkage behavior was assessed through measurements on prismatic specimens ($7 \times 7 \times 28$ cm^3) utilizing a refractometer and digital comparator. Concurrently, the strain was monitored, and correlations were established. (6) Data analysis and interpretation: In the final step, a thorough analysis of test results was undertaken to elucidate the impact of rubber aggregates on mechanical properties and deformations of the CTB mixtures.

Experimental Procedure

Materials

CPJ-CEMII-42.5A cement was used as the binder in the study. This binder is composed of finely ground clinker and additives, with the main addition of pozzolana. The cement has a density of 3,030 kg·m^{-3} and an average 28-day compressive strength of 45.1 MPa. Table 1 shows the chemical composition of the cement used.

TABLE 1. Chemical compositions of cement

Chemical compositions [%]		Elements [%]	
C3S	55–65	clinker	≥ 74
C2S	10–25	gypse	4–6
C3A	8–12	calcaire	0
C4AF	9–13	pozzolana	≤ 20

Source: own work.

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Two types of aggregates were used in this study: natural aggregates and recycled aggregates. The natural aggregates were sourced from the Mila region in the North of Algeria and consisted of crushed sand (0/3) and crushed gravels (3/8, 8/15, and 15/20 mm) with a measured density of about 2,700 kg·m^{-1}. The rock is of limestone origin, and the characteristics complies with the normative specifications for use as a road subbase material. In this study, one type of recycled aggregate was used, recycled rubber from non-reusable tires (Table 2), which contained textile fibers. These aggregates come in three forms (0/2 sand, 2/4 gravel, and powder with size less than 500 μm). The rubber granulates have a density of 1.12. They were used in their raw state and were supplied by local recycling factory.

TABLE 2. Details of granular fractions of natural and recycled aggregates

Type	Origin/Size		
	natural 0/3 sand		natural 3/20 coarse
Natural aggregates			
	powder 0/2 sand		2/4 rubber gravel
Recycled crushed rubber			

Source: own work.

TABLE 3. Physical characteristics of natural aggregates – type according to NF EN 13242+A1 (Association française de Normalization [AFNOR], 2008)

Parameter	Description/Value
Natural aggregates	
Mechanical strength of aggregates	D
Manufacturing characteristics	III
Manufacturing characteristics	B
Angularity of aggregates and sands	$Ic > 30$
Rubber aggregates	
Tensile strength [MPa]	11.8
Breaking strength [kg·mm^{-2}]	3.1
Elasticity [%]	42
Density [kg·dm^{-3}]	3 043
UV radiation resistance	excellent
Water permeability	0

Source: own work.

CTB samples and testing procedure

Samples of the cement-treated base (CTB) were studied and formulated according to the NF EN 14227-1 standard (AFNOR, 2005). The grain size of the reconstituted mixture must comply with the specification range. To form the median curve, each fraction must have a well-determined weight. Once the control mixture was reconstituted, a granulometric analysis was carried out to confirm the calculation and then to verify that the curve of the analysis fits into the specification range of the NF EN 13285 standard (AFNOR, 2018; Fig. 1).

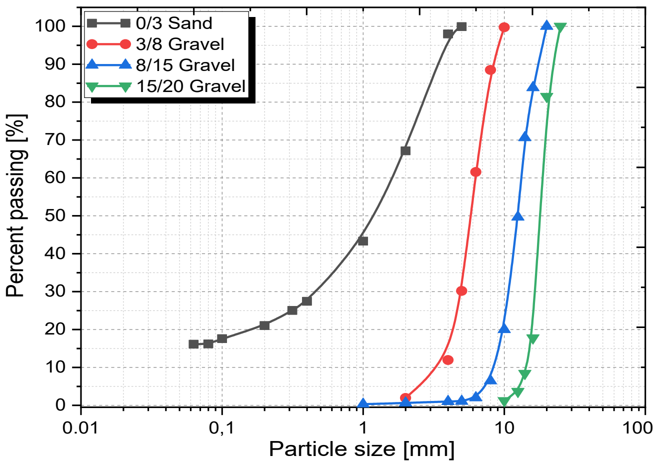

FIGURE 1. Size distribution of natural aggregates according to NF EN 14227 standard (AFNOR, 2005)
Source: own work.

For the experimental plan, three gravels were reconstituted from tire waste (Table 4). The first artificial gravel is reconstituted with 100% tire waste, meaning that three artificial fractions (0/2 and 2/4) are introduced into the calculation of the control normative mixture mass. The replacement concerns the 0/2 and 2/4 fractions of natural aggregates, and the other fractions remain unchanged. In the other reconstituted gravels, only the concerned fraction is replaced: 0/2 only and 2/4 only. However, the mass inclusion percentage is 25% and then 50% of the concerned mass. Because suitability tests showed that 100% inclusion gives very low results, the specimens break during demolding.

Furthermore, to valorize the powder of tire waste, other gravels were reconstituted, but this time this artificial ingredient was incorporated as an addition at 10%, 15%, and 20% compared to the dry weight of the normative mixture of Table 4.

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TABLE 4. Mixes design

Abbreviation	Natural aggregate content (0/20) [%]				Rubber aggregates content [%]		Rubber powder content [%]
	0/2	2/4	4/15	15/20	0/2	2/4	×
CTB-CTRL	×	×	×	×	×	×	×
CTB-RUS-100	0	×	×	×	100	×	×
CTB-RUS-50	50	×	×	×	50	×	×
CTB-RUS-25	75	×	×	×	25	×	×
CTB-RUG-50	×	50	×	×	×	50	×
CTB-RUG-25	×	75	×	×	×	25	×
CTB-RUP-10	×	×	×	×	×	×	10
CTB-RUP-15	×	×	×	×	×	×	15
CTB-RUP-20	×	×	×	×	×	×	20

Source: own work.

The CTB mixtures were manufactured in a laboratory environment at 20°C and 50% relative humidity using a mixer of 150 l capacity. The mixed materials were placed in molds fixed on the vibrating table, vibrated for 1 min after each layer. After 24 h, the specimens were removed and kept in water at 20°C until the testing age. Tests were performed on the CTB mixes in both fresh and hardened states. Fresh concrete tests included modified Proctor compaction tests. The compaction was carried out with a 4.5 kg hammer dropped from a height of 450 mm into a mold with a diameter of 102 mm and a height of 127 mm. Hardened CTB experiments included compressive strength, tensile strength, and modulus of elasticity. Compressive strength tests were conducted on cubic specimens of 10 × 10 × 10 cm³ at the age of 7 and 28 days according to EN 196-1 standard (European Committee for Standardization [CEN], 2016). Indirect tensile strength tests were performed on cylindric specimens of 10–20 cm at the age of 7 and 28 days according to EN 196-1 standard. The modulus of elasticity was tested at the age of 28 days.

Results and discussion

Compaction test results

The Proctor compaction test was carried out according to the NF EN 13286-2 standard (AFNOR 2010) to determine the optimal water content and maximum dry density. The results are reported in Figure 2. The Proctor test results show very close results between mixtures containing rubber and CTB-CTRL. The small observed variability of the maximum dry densities of the different mixtures is directly linked to the percentage of insertion.

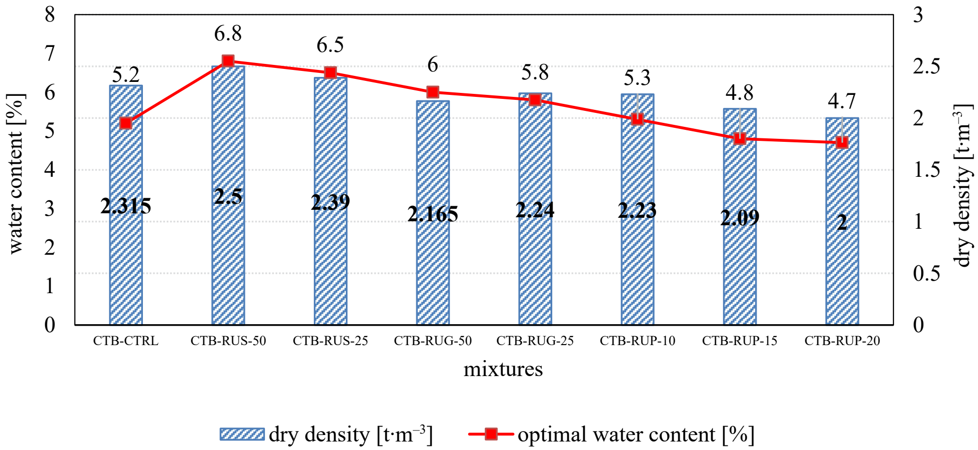

FIGURE 2. Compaction test results
Source: own work.

This observation underscores the inherent advantage of rubber-based aggregates, which have been reported to manifest lower water absorption rates compared to conventional natural aggregates (Prasad, Ravichandran, Annadurai & Rajkumar, 2014).

Compressive test results

Figure 3 shows the variations in compressive strength obtained at 7 and 28 days with respect to the percentage of rubber. For all mixes, they follow the same trend regarding the increase of the percentage of cement. Gradual decrease in compressive strength was noticed as the percentage of rubber increased. The reduction in compressive strength of the mix with 100% of rubber or the case of inclusion of rubber as sand 0/2 were more than the case of inclusion of rubber as gravel 2/4. The results are 50% than the value of the control mix. However, the case of inclusion as gravel or addition of 10% of rubber powder shows appreciable results compared to the control mix. At 7 days, the maximum compressive strength (7 MPa) was obtained for the control mix with 0% rubber and the value 6.18 MPa for the mix with 25% rubber as gravel. Same trend was observed for

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the compressive strength at 28 days, a strength above 11 MPa was obtained in the case of mixes containing 25% of rubber and appreciable strength for mixes containing rubber powder at 10%.

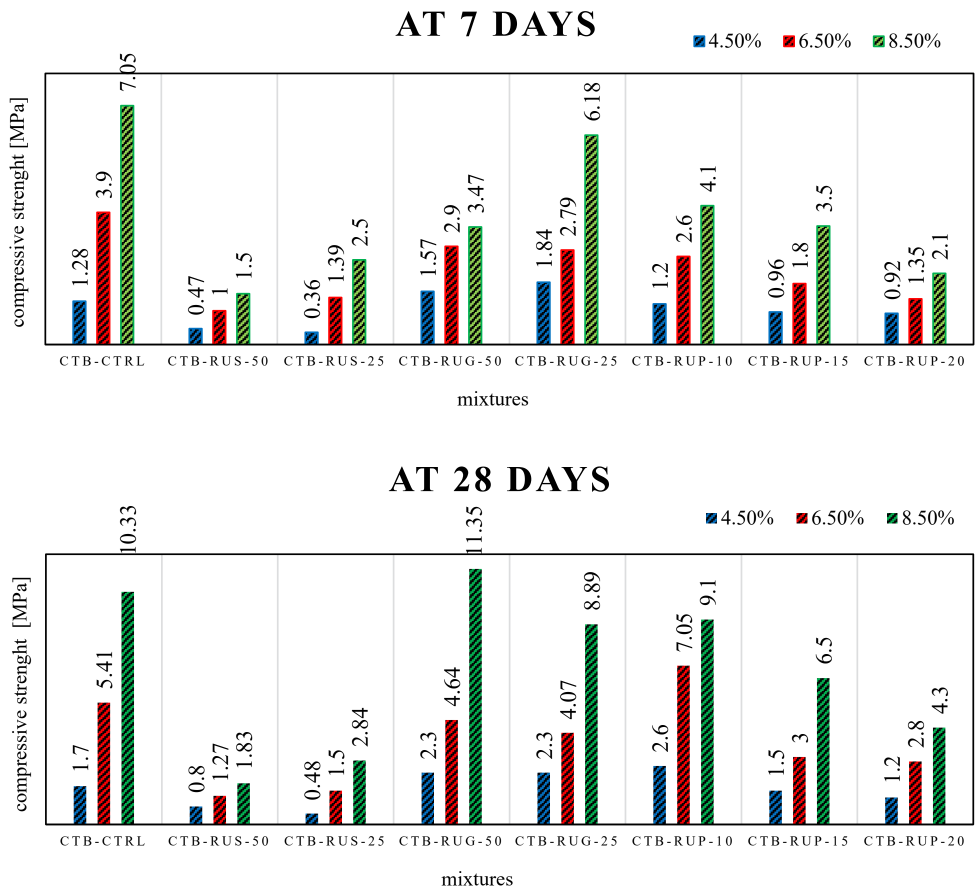

FIGURE 3. Compressive strength at 7 and 28 days for several rate of cement
Source: own work.

The loss in mechanical properties of rubberized concrete was supported by the results obtained by various researchers (Sofi, 2018). The reason for the decrease in compressive and flexural strength of the rubberized concrete is that the aggregate would be surrounded by the cement paste containing rubber particles. This cement paste would be much softer than that without rubber (Ganjian, Khorami & Maghsoudi, 2009).

Indirect tensile test results

Figure 4 presents the test and results of the indirect tensile strength at the laboratory. It can be observed that the mixture including 100% rubber did not yield any results as the specimens break even under minimal stress. The added cement content (8.5%) was unable to achieve the desired bond. It was observed for all mixes that the addition of cement increases the tensile strength. In addition, the results show

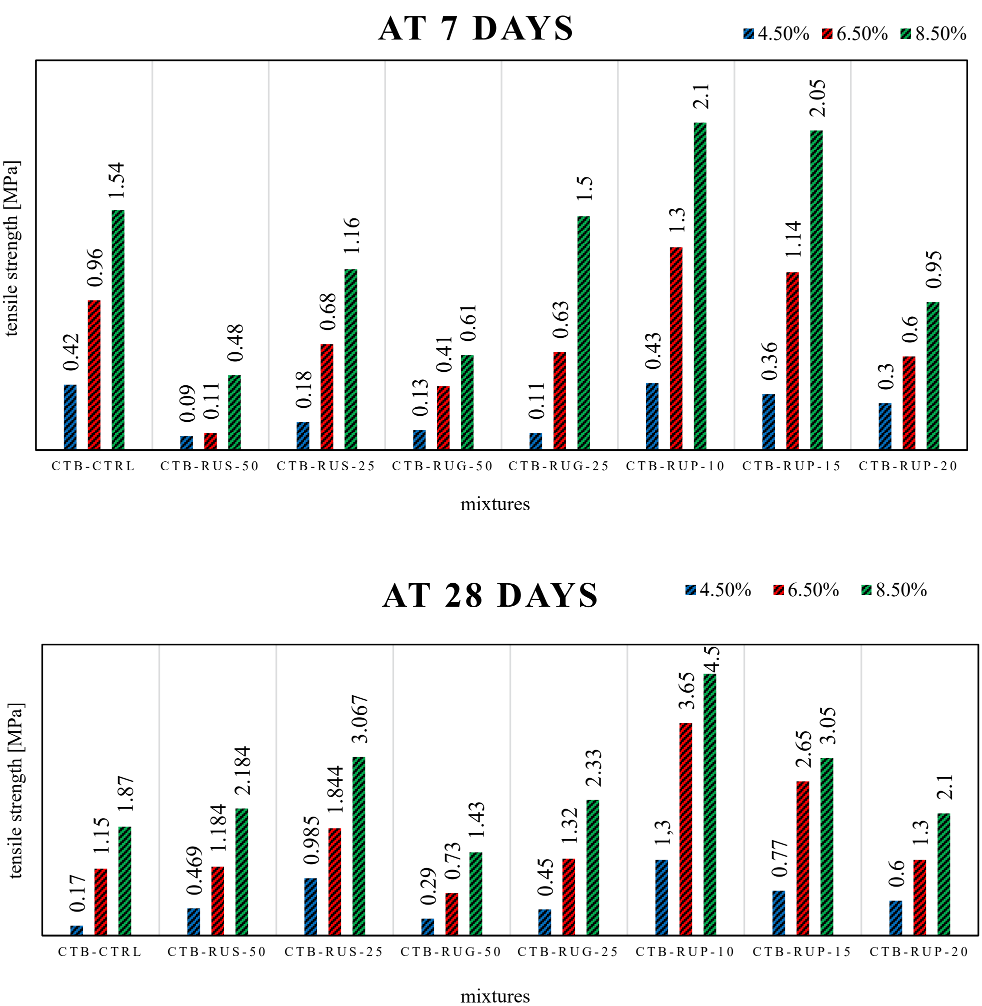

FIGURE 4. Indirect tensile strength at 7 and 28 days for several cement rate
Source: own work.

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that the tensile strengths decrease with the increase of the rubber content, however, the results are acceptable compared to those of the control mixture in case of adding the rubber as gravel. The decrease was 18% in case of adding gravel with 25% and cement rate of 8.50%. The results even surpassed the control mix when using rubber powder additions between 10% and 15%. These results are in conformity with Alam, Mahmood and Khattak (2015).

It was initially hypothesized that the presence of tire rubber, acting as a soft material, would enhance the tensile strength of the concrete and serve as a barrier against crack growth. For this reason, these results confirm this hypothesis and demonstrate that the incorporation of artificial aggregates, whether through substitution or addition, improves the tensile strengths. Thus, it provides further support for the use of these materials in road construction. In summary, although the inclusion of rubber in the concrete was expected to enhance tensile strength, the results demonstrated a reduction in tensile strength. This outcome can be attributed to the weak bonding at the interface between rubber and cement, leading to a micro-crack zone and surface segregation between these two materials.

Modulus of elasticity

Figure 5 presents the test and results of elastic modulus at laboratory. The result concerns the mixtures when the binder percentage is 6.5%.

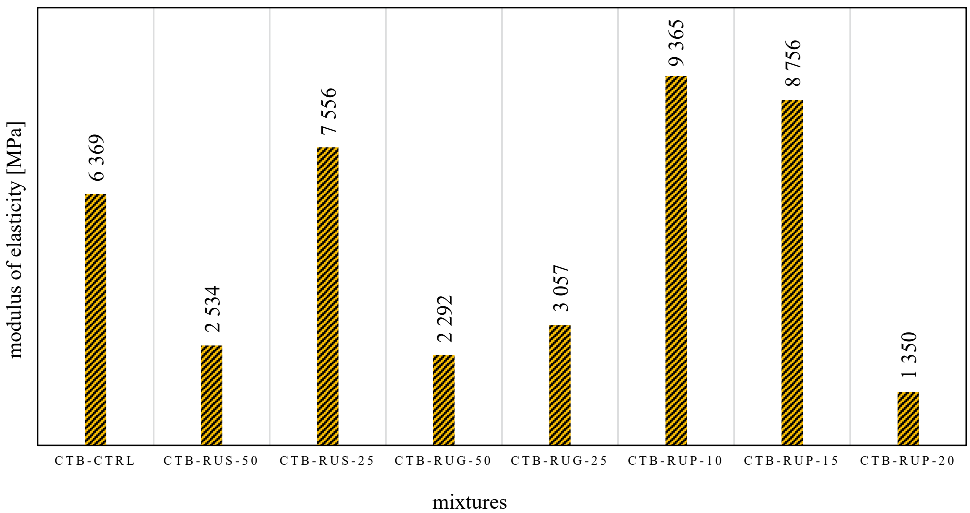

FIGURE 5. Modulus of elasticity at 28 days for cement rate of 6.5%

Source: own work.

It can be observed that increasing the amount of rubber tires in CTB leads to a decrease in the modulus of elasticity. However, in the case of a mixture containing 25% tire rubber sand, a performance superior to that of the control CTB by approximately 20% is exhibited. This observation is evident when tire rubber is added as powder at levels of 10% to 15%, where the results surpass the control CTB by about 47%. This trend is reported by Mohajerani et al. (2020). In addition, when tire rubber is introduced as coarse aggregates, the modulus of elasticity yields lower results. This can be attributed to the fact that the characteristics of coarse aggregates significantly impact the modulus of elasticity. Since concrete can be regarded as a composite material comprising various phases, including coarse or fine aggregates and cement, in which the modulus of elasticity and volumetric ratio in concrete are influenced by the nature of the aggregates. Therefore, if the aggregates have a higher modulus of elasticity than the cement paste, increasing the elastic modulus of aggregates in the concrete mixture will consequently elevate the overall concrete's modulus of elasticity. In simpler terms, the resulting concrete's modulus of elasticity increases when aggregates with higher elastic moduli are employed, particularly when the aggregate volume in the mixture is augmented.

Shrinkage measurement

Shrinkage property, one of durability parameters of CTB, significantly affects their application, especially in mass road structure construction. So far, plenty of investigations have been conducted particularly on the free shrinkage properties of CTB, as a key indicator of the shrinkage phenomena. The results are depicted in Figure 6. The outcomes indicated that the CTB mixtures underwent notable volume fluctuations during the curing of the binder due to water evaporation from capillaries and pores. Across all specimens, the following observations were noted: shrinkage remained below 2%; the control mixture exhibited minimal shrinkage, while mixtures incorporating rubber waste displayed higher shrinkage values. This can be attributed to the additional water content required for achieving optimum compaction during the compaction test and the water absorption capacity of rubber aggregates when compared to natural ones.

However, mixtures incorporating rubber as powder with the percentage of 10% or as sand demonstrated acceptable shrinkage in comparison to the control mixtures. CTB containing rubber gravel exhibit a shrinkage higher about 100% than mixtures containing rubber sand. This observation can be explained by the presence of fine rubber particles in the rubberized concrete, which helped

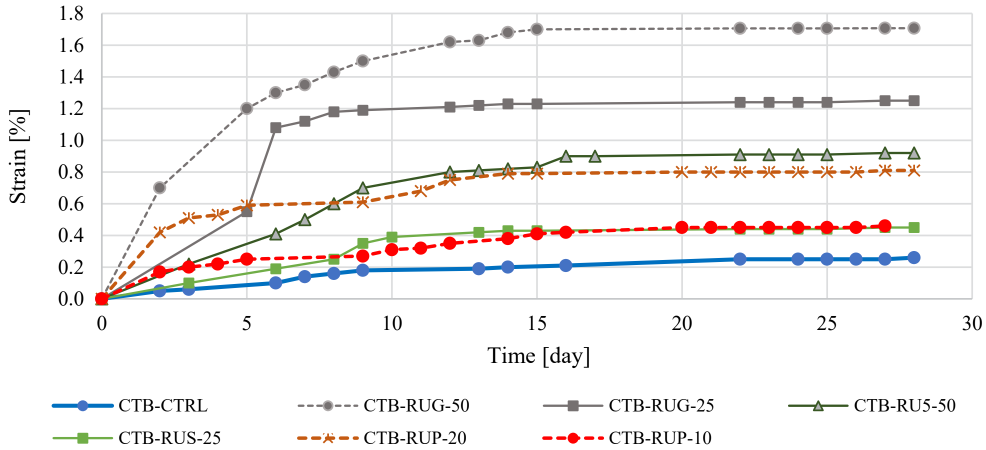

FIGURE 6. Shrinkage measurement results
Source: own work.

maintain the cohesion of constituent particles, preventing crack formation and material separation. Globally, for all specimens, starting from the 15th day onwards, shrinkage became stable.

Conclusions

The following conclusions from this experiment:

1. The compaction test results showed that the mixtures made from waste tires had similar dry densities and water contents to those of the control aggregates, supporting their use in road construction.
2. The compressive strength decreased gradually as the percentage of rubber increased. The substitution of 25% of rubber gravel or the addition of 10% of rubber powder gives acceptable compressive strength. In the tensile strength test, the mixture with 100% rubber did not yield any results, while significant improvement was observed in the tensile strengths of mixtures containing rubber, surpassing even those of the control mixture, especially the case of addition of 10% rubber powder. The addition of cement further increased the tensile strength of all mixtures. The modulus of elasticity decreased when rubber particles were used as replacements for aggregates in hydraulic binder-treated mixtures, while it surpassed the control mix in the case of the addition of 10% to 15% of rubber powder.

3. Shrinkage measurements indicated that the mixtures incorporating rubber waste exhibited higher shrinkage values compared to the control mixture. Incorporating rubber as 10% addition of rubber powder exhibits acceptable shrinkage compared to natural aggregates.

Overall, the results indicate that the addition of 10% of rubber powder exhibits the best performance compared to the natural aggregates.

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Summary

Evaluation of physical and mechanical properties of cement-treated base incorporating crushed waste tires. Pavements play a pivotal role in facilitating safe and efficient transportation. However, conventional pavement construction consumes substantial virgin resources, necessitating a shift towards sustainable alternatives. This study explores the integration of crushed waste tires as partial replacements for sand and gravel in cement-treated base (CTB) layers, aiming to enhance pavement sustainability. The CTB mixtures were meticulously formulated and tested for their physical and mechanical properties. Results revealed that while the presence of waste tire aggregates affected the fresh-state rheology, the cured-state performance remained satisfactory, often exceeding normative requirements. Notably, the addition of 10% rubber powder enhanced the mechanical performance of the CTB mixtures and overall exhibited acceptable shrinkage values. The findings offer insights into designing resilient and sustainable pavement systems by using crushed waste tires, aligning with modern infrastructure demands.