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Engineering Performance and Interface Shear Behaviour of Crumb Rubber-Stabilized Clay Subgrade Reinforced with Geogrid

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Abstract

Clayey soils are generally characterized with low strength and high plasticity which may affect the stability of the subgrade in road infrastructure and hence encourage research into sustainable stabilization techniques. The objective of this study was to investigate the possibility of using recycled crumb rubber (CR) mixed with biaxial geogrid reinforcement to enhance the engineering performance and interface shear behaviour of problematic clayey soil. The experiments were performed on biaxial geogrid BX1100, waste crumb rubber, clay subgrade soil, type B subbase granular material and other materials. The subgrade soil of clay has been collected from the airport area of Al-Muthanna region, Baghdad. An extensive programme of laboratory tests was conducted on soil mixtures with 5%, 10% and 15% of crumb rubber (CR) and untreated soil to determine the effect of stabilization with crumb rubber. The protocol consisted of Atterberg limits, modified Proctor compaction, California Bearing Ratio (CBR) and large-scale direct shear testing. The results showed that the engineering properties of the clay soil were improved by using CR. Maximum improvement was observed at 15% CR content where CBR increased by 56.6% and plasticity index decreased by 44% over the untreated soil. In addition, the large-scale direct shear tests showed that the interface shear strength increased with increasing CR content under geogrid reinforcement. The calculated interaction coefficients were greater than unity for all the tested mixtures indicating effective bonding and interlocking between the reinforced soil layers. The results indicate that the synergistic effect of CR and geogrid reinforcement could improve the interface behaviour of the weak clay subgrade soils with sustainable reuse of waste tyre rubber.

Keywords: crumb rubber; clay subgrade soil; geogrid reinforcement; interface shear strength; large-scale direct shear; soil stabilization

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1. Introduction

Recent surveys indicate that the rapid increase in the number of vehicles has resulted in a substantial rise in waste tyre generation. Approximately 1.5 billion tyres are produced worldwide each year, of which about one billion reach the end of their service life annually [1–4]. A large proportion of these discarded tyres are stockpiled or disposed of in landfills, occupying valuable land and posing significant environmental challenges. In some cases, waste tyres are burned without proper recovery or recycling processes [5–7]. This uncontrolled combustion releases toxic emissions, including styrene, benzene derivatives, butadiene, polycyclic aromatic hydrocarbons, carbon monoxide (CO), sulphur dioxide (SO_2), and nitrogen oxides (NO_X), among others [8–10]. Consequently, the improper storage and disposal of waste tyres contribute to air, water, and soil pollution and pose serious risks to public health [11,12].

The incorporation of tyre-derived materials as additives in civil engineering applications has received growing attention in recent years as an economical and environmentally friendly solution for scrap tyre disposal. Furthermore, these materials exhibit unique engineering characteristics for some geotechnical applications. Tyre-derived materials may be used in lightweight fill applications, backfill behind retaining walls, freeway and earthwork construction, drainage materials, leachate treatment media, and thermal insulation layers beneath pavement systems in cold regions [13].

Generally, tyre-derived materials are highly elastic and compressible. Their mechanical properties, particularly their elasticity, resilience, and energy absorption capacity, make them suitable for a wide range of geotechnical and transportation engineering applications, including embankment construction, highway base and sub-base layers, and the reinforcement of pavement subgrade layers [14–16]. In addition to their use as lightweight fill materials, tyre-derived products have also been employed to improve the engineering properties of soils. Such applications require a sound understanding of the strength-related characteristics and limitations associated with these recycled materials [15]. In pavement engineering, the use of locally available or low-cost materials to improve weak subgrades is a well-established strategy for reducing construction costs. However, replacing unsuitable subgrade materials is not always practical or economical. An alternative approach is to enhance the mechanical performance of the existing subgrade through the incorporation of stabilizing additives, thereby reducing the required thickness of the pavement structure while improving its long-term performance [17].

The effectiveness of soil stabilization depends on both the type and proportion of the additive used [18]. Improved subgrade stiffness enables the pavement foundation to sustain higher traffic loads while reducing permanent deformations [19]. Consequently, enhancing both the strength of the subgrade and the quality of the interface between pavement layers contributes to more durable and cost-effective pavement systems.

There has been great interest in the use of waste-derived products for soil stabilization due to the increasing interest in sustainable building techniques. This review presents studies on the effect of crumb rubber (CR) on geotechnical behaviour of soils. Papp et al. [20] reported California Bearing Ratio (CBR) tests on mixtures of shredded tyre chips with cohesionless soils. Their results showed that the addition of tyre chips had an effect on the strength characteristics of the soil, where the percentage of tyre chips was the main factor controlling the reduction in CBR values. A similar trend was observed in resilient modulus results where increasing tyre content consistently reduced the performance levels required for subbase applications. Similarly, Ghazavi and Sakhi [21] studied the effect of the geometry of rectangular tyre shreds on the CBR response of tyre-shred–sand mixtures. They found that the CBR values of the composite material are influenced significantly, not only by the proportion of tyre shreds, but also by their width, aspect ratio and the applied compaction energy.

Rao and Dutta [22] carried out a study to evaluate compressibility and strength properties of sand and tyre mixtures for the suitability of sand-tyre chip mixtures for embankment construction. The results indicated that the compressibility of the sand-tyre mixture was 1% up to 20% within the tolerance range for an embankment 10 m high. The results gave cohesion values between 7 and 17.5 kPa, while the internal friction angle increased from 38 to 40 degrees. Karmokar et al. [23] carried out CBR tests on rubber chips and shreds from scrap tyres. Their findings showed extremely low CBR values of 0.3% to 0.6%, indicating that these materials are generally categorized as poor quality road aggregates. Pando and Garcia [24] in another study reviewed the shear strength behaviour of tyre crumbs with particle sizes between 2 and 13 mm under different confining pressures based on the findings reported by previous researchers. They also noted that, for tyre crumbs with a maximum particle size of 4.5 mm tested at 20% strain and under confining pressures of 25–100 kPa, the effective cohesion ranged from 0 to 11.4 kPa, while the effective friction angle varied between 8.2° and 14.9°.

Akbarimehr et al. [16] investigated the compaction characteristics of clayey soils incorporating rubber wastes. Optimum moisture content (OMC) and maximum dry density (MDD) tests were carried out to compare the performance of powdered rubber and granulated rubber and it was found that powdered rubber performed better. Haq [25] studied the effect of addition of rubber powder and lime on clayey soils. The results of the plasticity index, shear strength, modified soil compaction and triaxial shear tests proved that the addition of 3% rubber powder and 12.5% lime significantly enhanced the cohesion and load-bearing capacity of the soil.

In a recent study, Banyhussan et al. [26] studied the use of waste foundry sand as a stabilizing material for clayey subgrade soils reinforced with geogrid, using large-scale direct shear testing. The results indicated that the addition of waste foundry sand improved the shear strength of the interface between clayey subgrade and granular subbase, which helped to improve the interlayer interaction and the stability of the entire structure. However, the mechanical behaviour of CR is different from waste foundry sand due to its higher deformability and elasticity, which may affect the interaction mechanisms developed at the soil–geogrid interface.

Waste tyre rubber has also received increasing attention because of its excellent energy absorption, vibration damping, and acoustic insulation properties. Recent studies have demonstrated its successful use in sound-insulating building systems, porous materials for road traffic noise mitigation, and vibration and noise control applications in railway infrastructure, highlighting the versatility of recycled tyre-derived materials in sustainable civil engineering [27–30]. These applications contribute to the circular economy by promoting the beneficial reuse of end-of-life tyres while reducing the environmental impacts associated with their disposal. Overall, crumb rubber represents a sustainable recycled material that offers both environmental and engineering benefits for modern construction practices.

The novelty of the present study lies in its integrated approach. Previous studies have primarily focused on the influence of crumb rubber on individual engineering properties of clayey soils without considering the reinforcing effect of geogrids. In contrast, this study provides a comprehensive assessment by combining crumb rubber stabilization with geogrid reinforcement. The experimental programme included a series of standard laboratory tests to evaluate the effects of crumb rubber on the Atterberg limits, density–moisture relationships, and California Bearing Ratio (CBR), together with large-scale direct shear tests performed on both untreated and crumb rubber-modified soils containing 5%, 10%, and 15% crumb rubber. In addition, the shear response at the interface between the clay subgrade and granular subbase layers was investigated both with and without geogrid reinforcement. This integrated experimental approach enables a comprehensive evaluation

of the combined effects of crumb rubber stabilization and geogrid reinforcement on both the engineering properties of the soil and the interface behaviour between pavement layers, which has received limited attention in the existing literature.

2. Material and Experimental Programme

2.1. Materials

2.1.1. Clayey Subgrade Soil

The subgrade soil used in this study was a clayey soil obtained from the same area of the Al-Muthanna Airport. The soil was selected because of its relatively high plasticity (PI = 12.4%) and low bearing capacity (CBR = 5.3%), which are representative of problematic subgrade soils often encountered in pavement engineering applications.

2.1.2. Subbase Material

The granular material of the subbase (SGM) used in this study was collected from the Sabeaa Al-Bour region in Baghdad and classified as a subbase material of type B. The grading results show that the material is in accordance with the requirements of SCRB/R6 (2003) for type B subbase materials and is therefore suitable for pavement subbase applications. The subbase granular material is classified according to AASTO T27.

2.1.3. Crumb Rubber

In this research, recycled rubber with high density was used as styrene-butadiene polymer from heavy truck tyre waste. In accordance with ASTM International ASTM D6270-20 [31], the recycled rubber could be processed in three major forms such as granules, chips and fibres. In this study granulated recycled rubber with size range of 1–5 mm was used. The granulated rubber manufacturing process comprised shredding the discarded tyres to produce particles less than 5 mm.

The authors conducted laboratory analysis to experimentally evaluate the chemical composition of the recycled shredded tyre rubber. The elemental composition was mainly carbon (58%) followed by iron (23.37%), oxygen (8.82%), silicon (6.19%), zinc (1.8%), sulfur (1%), aluminum (0.12%) and magnesium (0.7%). This characterization provides information on the elemental composition of the recycled crumb rubber, which is useful for interpreting its interaction with the clay matrix and its engineering performance. The particle size range chosen was to encourage a more uniform distribution of CR in the clay matrix and enhance the interaction between the soil particles and the rubber inclusions. Figure 1 illustrates the recycled crumb rubber used in this study together with the waste tyres from which it was produced.

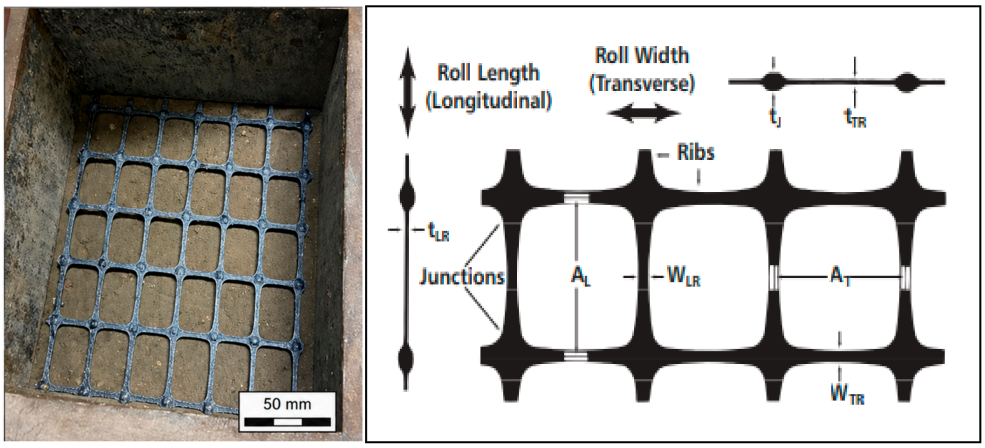


(**a**) (**b**)

Figure 1. (**a**) Crumb rubber produced from recycled tyres and (**b**) waste truck tyres.

2.1.4. Geogrid Reinforcement

In this study, the reinforcement material used was a biaxial geogrid, BX1100 (G1) (Figure 2), manufactured by Tensar International Company (Alpharetta, GA, USA). The main mechanical and physical properties of the G1 geogrid are summarized in Table 1. A geogrid was used to improve the interlocking mechanism to enhance the interface shear resistance between the clayey subgrade and the granular subbase layers under applied loading conditions.



(**a**) (**b**)

Figure 2. Geogrid reinforcement: (**a**) BX1100 biaxial geogrid (with graphical scale) and (**b**) manufacturer's technical specifications.

Table 1. Geometric and physical features of the BX1100 biaxial geogrid (G1).

Physical Characteristic		**Data**	
Type		Biaxial geogrid	
Colour		Black	
Polymer		PP	
Rib shape		Rectangular	
Guide properties	Units	MD	XMD
Rib thickness	mm	0.76	0.76
Opening dimensions	mm	25	33
Tensile strength	kN/m	12.4	19
Tensile strength *	kN/m	8.5	13.4
Tensile strength **	kN/m	4.1	6.6

* For 5% strain; ** for 2% strain; PP = polypropylene; MD = machine direction (longitudinal direction); XMD = cross-machine direction (transverse direction).

2.2. Experimental Program

The liquid limit (LL), plastic limit (PL) and plasticity index (PI) were determined according to ASTM D4318-17e1 [32] procedures. Soil samples were tested for their water content using ASTM International ASTM D2216-19 [33]. A modified Proctor compaction test was performed to determine MDD and OMC. Furthermore, the CBR test was conducted in accordance with ASTM International ASTM D1883-21 [34] for the assessment of the load–penetration relation and CBR values. In addition, large-scale direct shear tests were performed to determine the interface shear properties and load–displacement characteristics of the tested materials.

This study was concerned with the effect of different amounts of recycled CR on the engineering properties of clayey subgrade soils. The physical and mechanical parameters like MDD, OMC, Atterberg limits and CBR values were studied for sixteen specimens. The experiments were conducted with different amounts of CR from 5% to 15%.

In the second stage of the investigation, the soil was partially replaced with CR in the same percentages as in the first stage. Geogrid reinforcement was also introduced, placed between the subbase and clay subgrade layers. Twenty specimens were tested for the evaluation of the interface shear strength. The stability and improvement of soil using CR and geogrid were assessed by comparing the results with untreated soil and soil reinforcement using only geogrid.

3. Large-Scale Direct Shear Testing

3.1. Direct Shear Apparatus (Large-Scale)

A custom-designed large-scale direct shear apparatus was fabricated locally. The device features a two-part box configuration, comprising an upper box measuring 20 × 20 × 10 cm and a lower box measuring 20 × 25 × 10 cm. A deliberate difference in the geometries of the two sections was introduced to ensure a stable and well defined shear plane during testing. The main aim of this device is to study the interaction behaviour at the interface of reinforcement of subbase layers and stabilized subgrade materials. It was designed specifically to simulate, in a controlled laboratory environment, the stress and contact behaviour typical in the field between pavement layers. The complete apparatus and details of the test setup are illustrated in Figures 3 and 4.

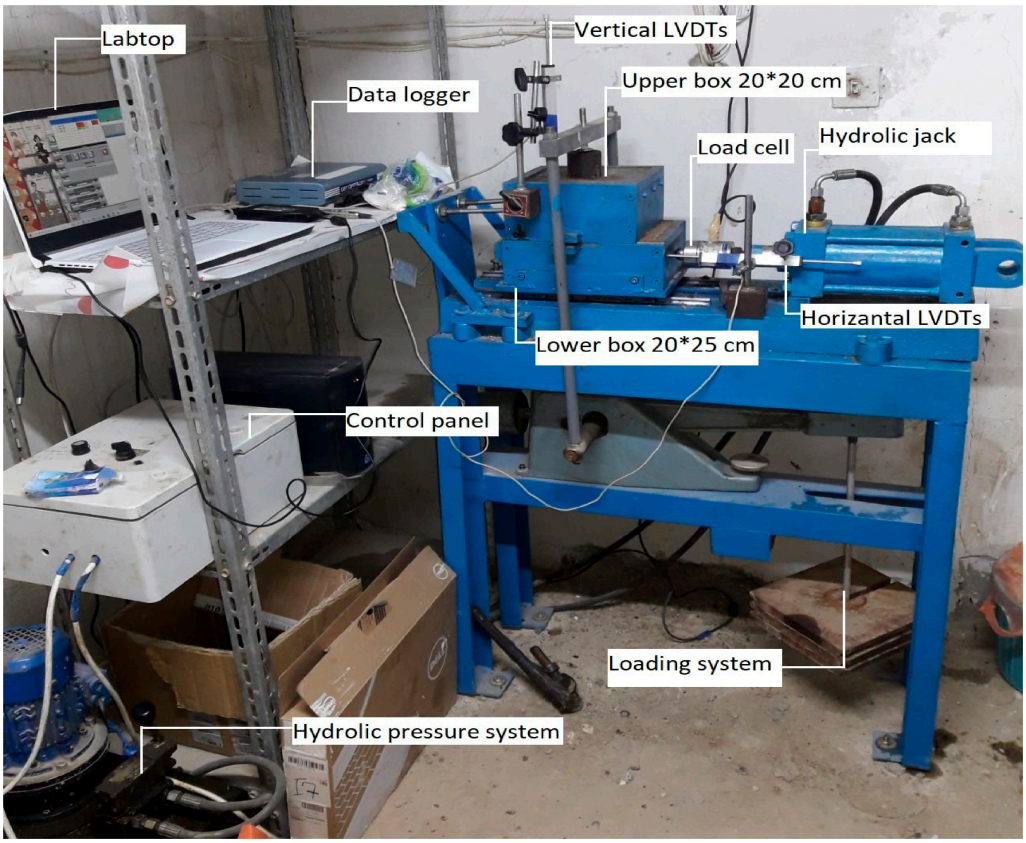


Figure 3. Large-scale direct shear apparatus showing the main components of the experimental setup.

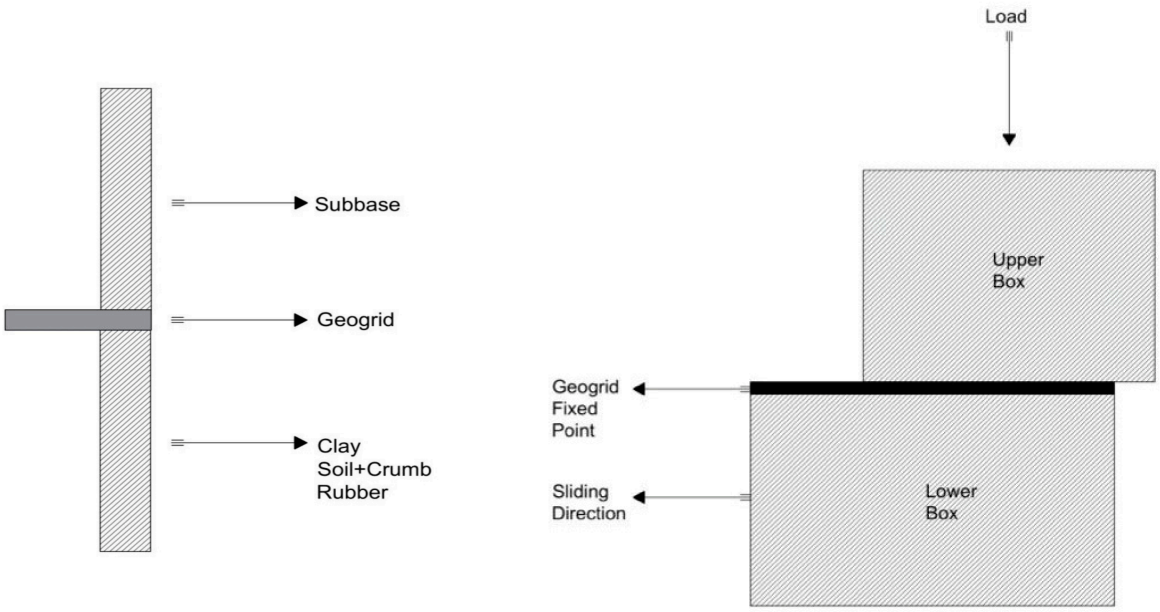


Figure 4. Schematic illustration of the test setup: (**a**) arrangement of the materials within the shear box and (**b**) interface shear surface.

3.2. Test Configuration

The experimental programme is based on the use of a direct shear based on a large-scale device developed according to the procedure of Youwei et al. [35] for the investigation of the interaction behaviour between soil and geosynthetic materials. The system is equipped with lateral load cells with a peak capacity of 50 kN and two LVDTs for precisely measuring horizontal and vertical displacements in a range of ±50 mm. All measurements are registered in a data acquisition system (DAQ) for detailed post-processing and analysis. The shear rate is kept constant at 1 mm/min. This shear rate was selected in accordance with ASTM D5321/D5321M-14 (Section 11.6 in [36]), which recommends a displacement rate of 1 mm/min when excess pore pressures are not anticipated at the interface during testing. The clay specimens were compacted at their optimum moisture content and maximum dry density. Under these testing conditions, the clay remained unsaturated; therefore, excess pore pressures were not anticipated during shearing, and the applied normal stresses were considered representative of the effective stresses acting on the interface.

In each test the geogrid layer is properly installed at the interface between the clayey subgrade and the overlying subbase layer so that both longitudinally oriented and transverse ribs are aligned across the predefined shear plane. Figure 5 shows the position and installation method of the biaxial geogrid inside the box, where the biaxial geogrid is fixed using a metal straightedge at the beginning of the bottom box. As loading progresses, the soil particles interact with the geogrid ribs to mobilize the passive resistance by pushing against the grid structure. This results in an increase in the shear strength of the interface. The setup does not permit the separation of the individual mechanisms, such as the frictional resistance and mechanical interlocking, but provides a complete measure of the overall shear response of the geogrid–soil interface under controlled loading conditions.



(a) (b)

Figure 5. Installation of the BX1100 biaxial geogrid inside the large-scale direct shear box: (**a**) position of the geogrid at the interface and (**b**) fixation method using a metal straightedge.

3.3. Failure Standard

Based on ASTM D3080/D3080M-11 [37], the specimen shall be displaced in the horizontal direction at least 10% of the shear box dimension which is 20 mm in this setup. Youwai et al. [38] proposed that the maximum value at the end of the measurement can be used to evaluate shear stress. In addition, according to ASTM D5321/D5321M-14 [36], the test permits applying horizontal movements up to 75 mm, or other displacement limits that may be specified by the operator depending on the test requirements, with testing typically terminated once the peak shear resistance is reached. Consistent with these standards, the present study defines failure in terms of the peak shear stress observed during testing.

4. Results and Discussions

4.1. Improvement of Clay Subgrade Soil

This study investigated the role of CR as a stabilizing additive for clay subgrade soils. First the liquid limit, plastic limit and plasticity index of the untreated clay were determined and compared with the soil treated with CR. In addition, the maximum dry density and OMC (optimum moisture content) of the natural clay were determined using the modified Proctor test. The soil was mixed with different percentages of CR and California Bearing Ratio (CBR) was tested to measure the improvement in the engineering properties of the clay.

4.1.1. The Properties of Materials Without Stabilizers

The Properties of Clayey Subgrade Soil

The soil sample was compacted in a total capacity mould of 944 cm^3. To determine the optimum moisture content and maximum dry density of the soil sample, the Proctor compaction procedure was followed and compacted in five equal layers with 25 blows from a 4.54 kg hammer dropped from a height of 45.7 cm. The compaction test yielded a maximum dry density (MDD) of 1.84 g/cm^3 and an optimum moisture content (OMC) of 9.8%. The compaction curve of the clay soil is shown in Figure 6.

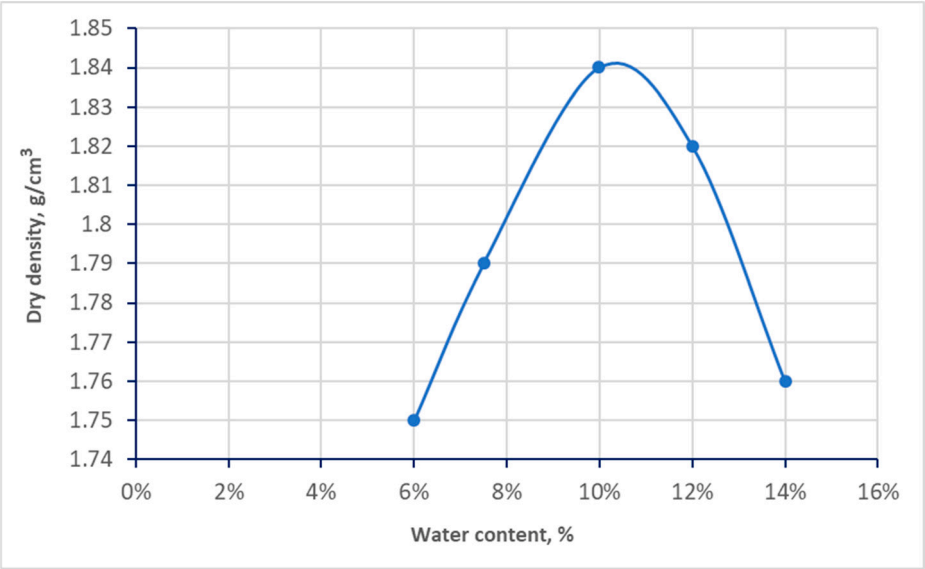


Figure 6. Modified Proctor compaction curve of the clayey subgrade soil.

The measured Atterberg limits were a liquid limit (LL) of 33.2% and a plastic limit (PL) of 20.8%. The grain-size distribution of the clayey subgrade soil is presented in Figure 7.

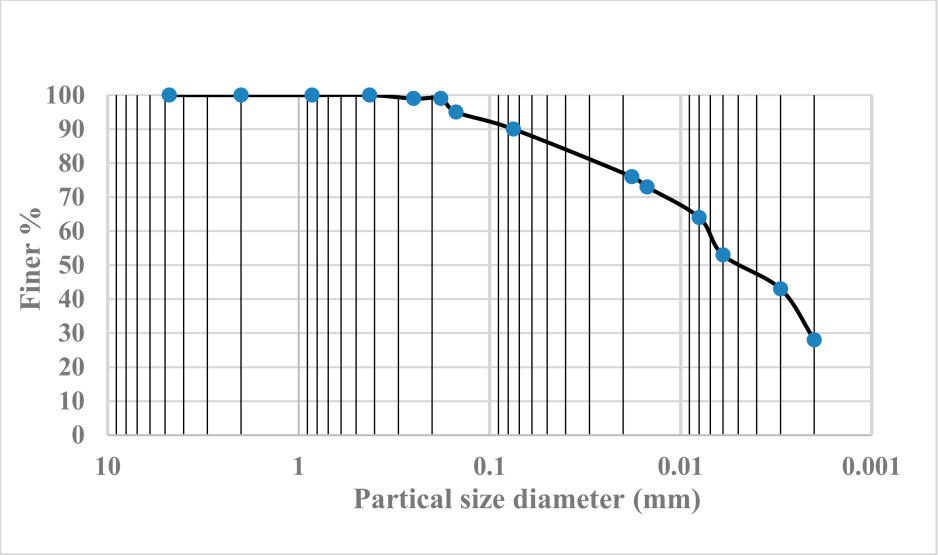


Figure 7. Grain-size distribution of the clayey subgrade soil.

The Properties of Subbase Soil

The selected subbase material has an MDD of 2.24 g/cm^3 and an OMC of 7%. The compaction curve of the subbase soil is shown in Figure 8. The chemical characterization showed that the content of the organic matter, total soluble salts, SO_3, and gypsum were 0.84%, 7.58%, 2.6%, and 5.59%, respectively. The liquid limit was determined as 22.5% and the plastic limit as 17.6%. The grading properties and particle size distribution of the SGM are shown in Table 2.

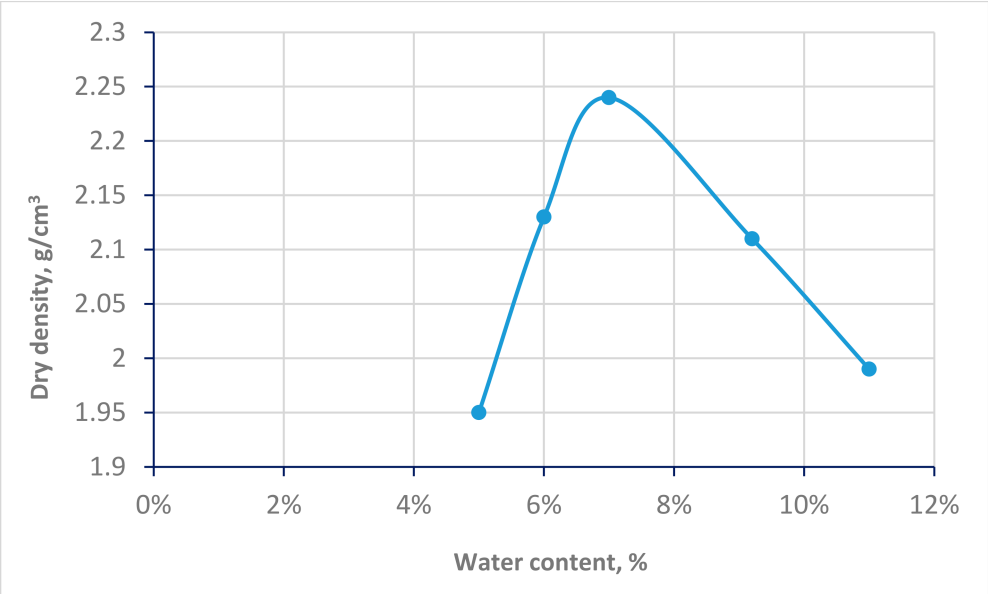


Figure 8. Behaviour of the compaction curve for the subbase soil.

Table 2. Classification of SGM.

Weight Percentage Passing		
Sieve Size (mm)	**Passing (%)**	**Limits of SCRB/R6, 2003**
0.75	100	-
50	100	100
25	88.5	75–95
9.5	74.5	40–75
4.75	51.2	30–60
2.36	41.4	21–47
0.3	27	14–28
0.075	14.3	5–15

4.1.2. Effect of Stabilizers on Atterberg Limits

Atterberg limits tests were performed following the procedures outlined in the ASTM D4318-17 standard [32]. It can be seen from Figure 9 that the plasticity index of the clay specimen decreases consistently with an increase in the CR content. The highest reduction of 44% was achieved at the addition level of 15% of CR. The incorporation of CR, due to its non-cohesive and hydrophobic properties, significantly decreased the soil plasticity by disrupting the clay matrix and reducing the water retention capacity [16]. The obtained results show that the plastic properties of the clay soil are improved with the addition of CR to the clay soil. Such improvements generally lead to better volumetric stability and improved engineering properties to make the stabilized soil more suitable for a wider range of geotechnical applications. The results agree with the results obtained by Akbarimehr et al. [16] and Haq [25] who reported the progressive decrease in the plasticity index with increasing CR content. These findings further indicate that the reduction in soil plasticity achieved through crumb rubber stabilization can provide additional benefits when combined with geogrid reinforcement, as investigated in the present study, by improving the overall performance of the pavement foundation system.

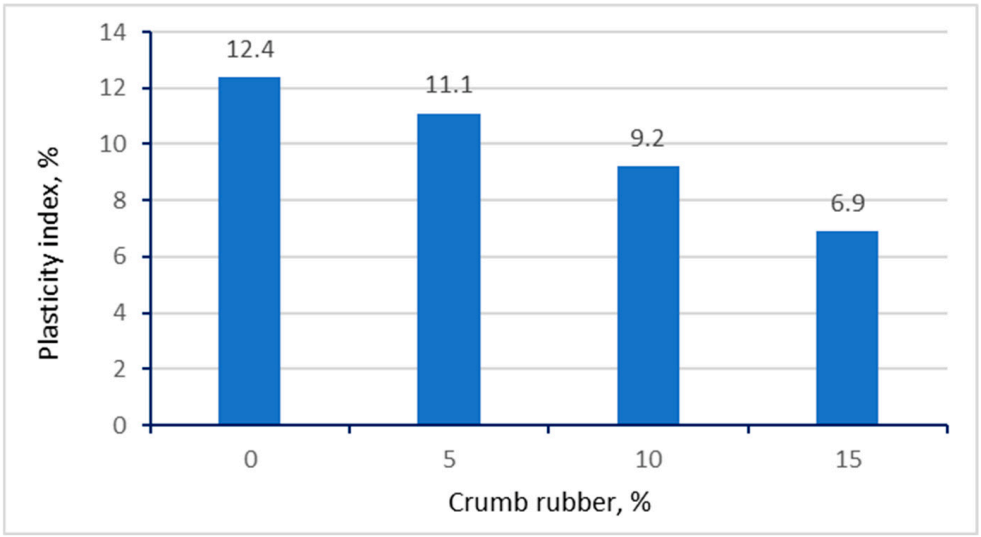


Figure 9. Plasticity index of clay subgrade soil with different CR contents.

4.1.3. Effect of Stabilizers on Compaction Characteristics

Maximum Dry Density

Results of the modified Proctor compaction test measuring the MDD of stabilized clay soil with different percentages of CR are shown in Figure 10. The graph shows the effect of addition of CR on MDD of soil. The reference value corresponds to a density of 1.84 g/cm^3. The highest increase was seen for the addition of CR especially at 15% with a value of 1.98 g/cm^3 which is an increase of 7.6% compared to the reference soil. This behaviour can be explained by the ability of CR to improve the initial compaction due to its interaction with the soil particles.

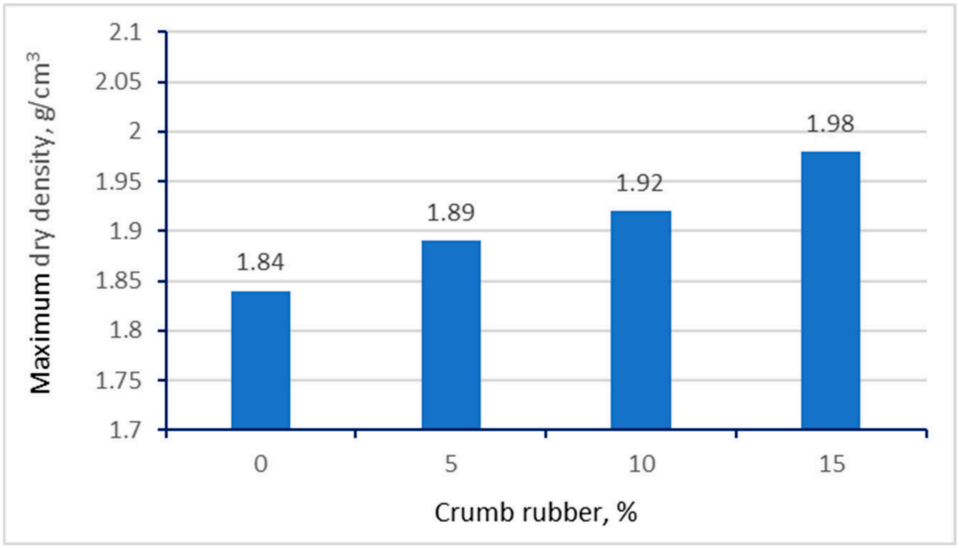


Figure 10. MDD of clay subgrade soil with different CR contents.

The observed increase in MDD and reduction in OMC are consistent with the trends reported by Gaurav and Vyawahare [39], Albert et al. [40], and Dukare et al. [41]. The increase in MDD may be associated with improved particle rearrangement promoted by CR inclusion within the soil matrix, as well as with the interaction between the soil particles and the rubber inclusions [25,40]. In addition, the recycled crumb rubber used in this study contains relatively high proportions of iron and silica, as indicated by the chemical characterization presented in Section 2.1.3. Since these constituents possess higher densities than

the rubber matrix, they may also have contributed to the observed increase in MDD. However, this interpretation remains qualitative because the present experimental programme was not designed to isolate or quantify the individual contribution of these constituents.

Optimum Moisture Content

The results of the modified Proctor compaction test to determine the OMC of stabilized clay soil with different CR contents are shown in Figure 11. The graph illustrates the OMC required to achieve the maximum dry density. The OMC of the reference soil is 9.8%, and it decreases progressively with increasing CR content. For instance, at 15% CR, the OMC decreases to 8.2%, representing a 16% reduction compared to the reference soil. Such behaviour suggests that the addition of CR decreases the water content required to achieve optimum compaction conditions.

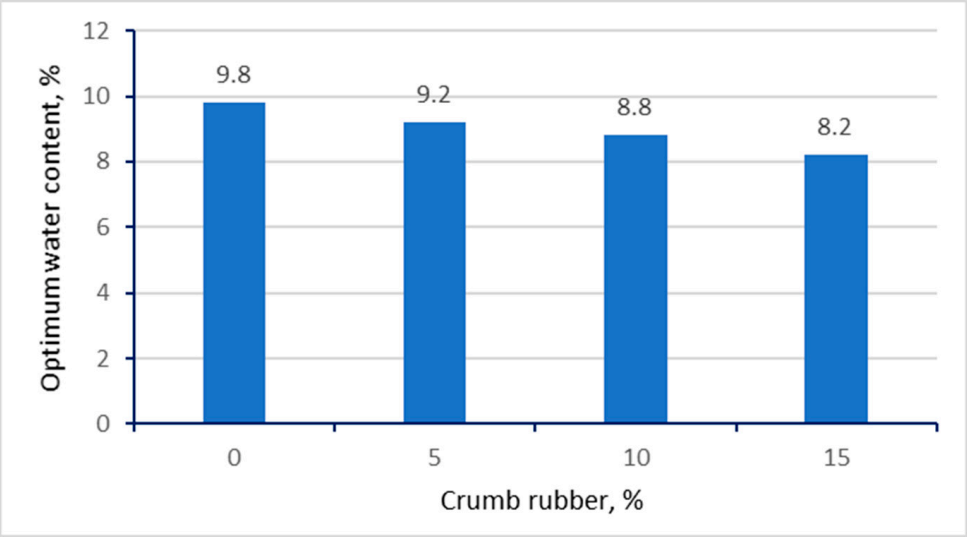


Figure 11. Optimal moisture content of clay subgrade soil with varying CR contents.

These results are consistent with observations in the previous literature. Powdered CR showed better results as reported by Akbarimehr et al. [16], Dukare et al. [41] and Teja et al. [42].

4.1.4. Effect of Stabilizers on CBR Values

Figure 12 evaluates the effect of different proportions of CR on the bearing capacity of the soil, measured by the CBR test. The values obtained are compared with the reference soil without additions, whose CBR is 5.3 [35]. The results showed that the addition of CR to the subgrade clay soil significantly improves the mechanical behaviour of the soil with increases of up to +56.6% compared to the reference soil.

For the clay soil, the best performance was observed for the CR additions reaching a CR content of 15% with a CBR of 8.3 which is 56.6% higher than the one of the reference soil. These results are consistent with previous studies that have emphasized the potential of utilizing sustainable materials as stabilizers to improve the mechanical performance of clay soils. The observed increases in CBR due to partial replacement of soil by sustainable materials have also been reported in previous research. Papp et al. [20], Ghazavi et al. [21], and Karmokar et al. [23] observed the increase in CBR value with the increase in CR content. This improvement might be associated with the better interaction between particles, and the better distribution of stresses within the stabilized soil matrix [43,44]. Compared with previous investigations that mainly evaluated CBR improvements, the present study further

relates the enhanced bearing capacity to the interface shear performance of the reinforced pavement system, providing a more comprehensive assessment of the stabilization strategy.

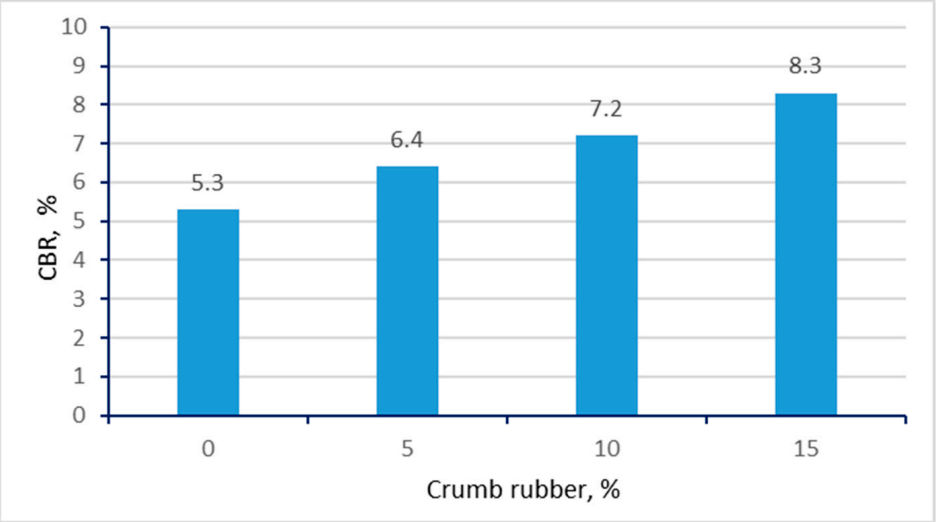
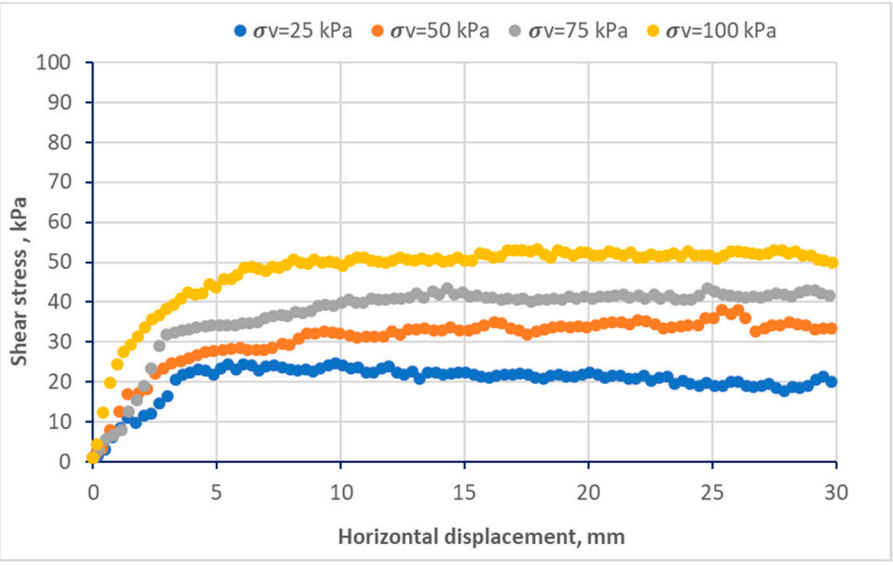


Figure 12. CBR values of clayey subgrade soil with different CR contents.

4.2. Improvement of Interface Shear Strength

A series of large-scale direct shear tests were performed to evaluate the shear strength of the interface for subbase–subgrade soil systems in accordance with ASTM D5321/D5321M-14 [36]. The study investigated the effect of different percentages of CR additive on the shear behaviour. Figure 13 shows the shear stress–horizontal displacement response of clay soil compacted at its OMC and maximum dry density. The performance is investigated for soil mixtures modified with 0%, 5%, 10% and 15% crumb rubber (CR) in unreinforced conditions and with geogrid reinforcement. To evaluate the response of the specimen under different confinement conditions, each specimen was tested under four different confining stresses of 25, 50, 75 and 100 kPa. The corresponding interface shear parameters, namely the adhesion (c_a) and friction angle (φ), were determined from the interface shear strength envelopes obtained under the four applied normal stress levels (25, 50, 75 and 100 kPa) and are presented in Table 3.



(a)

Figure 13. *Cont.*

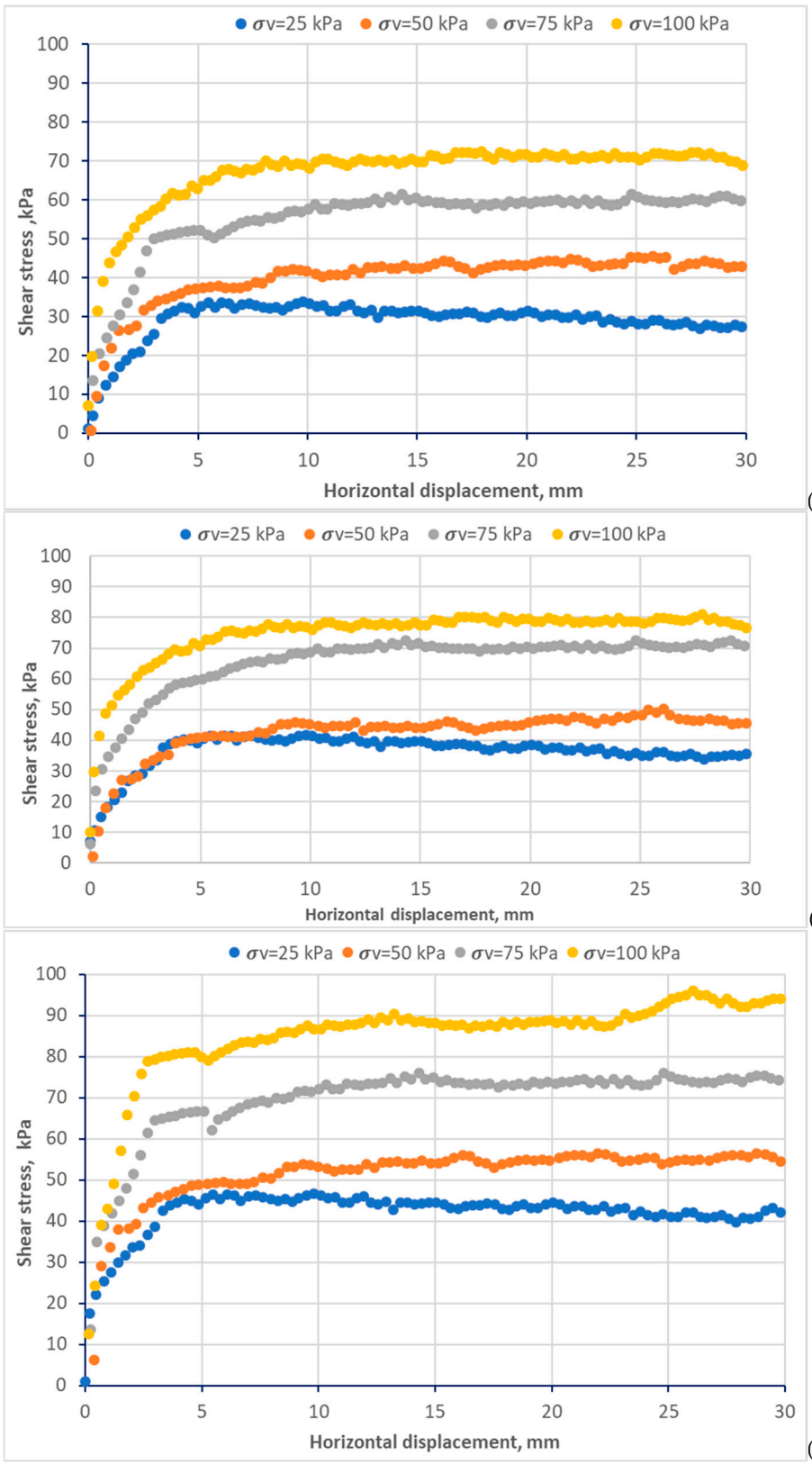


Figure 13. Shear stress–horizontal displacement relationships for the interface between the sub-base material and clay subgrade soil reinforced with a geogrid at different CR contents: (**a**) 0%, (**b**) 5%, (**c**) 10%, and (**d**) 15%.

Table 3. Shear characteristic of clay subgrade soil reinforced with geogrid at various CR contents.

State	CR, %	σ_v, kPa	τ, kPa	c_a, kPa	φ, °
Clay-G1-Subbase	0%	25	25	15	22
		50	35		
		75	45		
		100	55		
	5%	25	32	19	27
		50	44		
		75	57		
		100	70		
	10%	25	39	26	28
		50	53		
		75	66		
		100	79		
	15%	25	40	22	35
		50	57		
		75	74		
		100	92		

The results obtained show that the shear strength values increase with the increase in the total normal stresses. Moreover, the presence of waste CR had a significant effect on the interface shear strength between the subbase layer and the underlying clay subgrade soil, resulting in a significant change in their interaction behaviour. The interface shear strength increased with increasing CR content. The improvement values attained were 27%, 43% and 67% for the CR contents of 5%, 10% and 15%, respectively, under a total normal stress of 100 kPa. Such behaviour is consistent with previous research findings. The inclusion of 20% waste CR resulted in an improvement in the values of cohesion from 7 to 17.5 kPa and also increased the internal frictional angle from 38° to 40° (Rao et al., [22]). Pando and Garcia [24] reported that the cohesion values ranged from 0 to 11.4 kPa and the internal friction angle from 8.2° to 14.9°. Although previous studies have investigated either crumb rubber-modified soils or geogrid-reinforced interfaces separately, the present study evaluates their combined contribution. The results indicate that the simultaneous use of crumb rubber and geogrid reinforcement provides enhanced interface performance, offering additional insight into the interaction mechanisms governing reinforced pavement systems.

This behaviour may be explained by the increased interlocking with an increasing amount of rubber added in the soil. CR has a relatively rough surface texture, which may increase the frictional resistance at the interface between the clay subgrade and the geogrid-reinforced subbase layer. This mechanism may contribute to the increased interface shear resistance observed in the tests.

Figure 14 shows the shear strength versus applied normal stress for clay subgrade soil compacted at its OWC and MDD in reinforced and unreinforced conditions with different CR contents. The reinforcement coefficient was proposed to evaluate the effect of the reinforced geogrid on the interface shear behaviour between the clay subbase and subgrade. This parameter is denoted as the interface coefficient (η) and defined in Equation (1). It is the ratio of the shear strength of the reinforced system (τ-reinforced) to the shear strength of the unreinforced system (τ-unreinforced) for the same normal stress.

$$\eta = \tau_{\text{reinforced}} / \tau_{\text{unreinforced}} \quad (1)$$

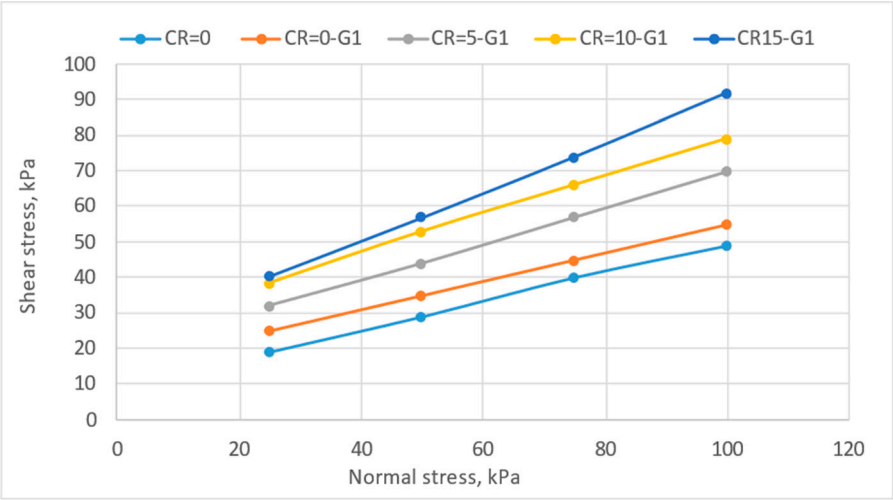


Figure 14. Relationship between shear strength and total normal stress for clay subgrade soil reinforced with geogrid at different CR contents.

Values of the interaction coefficient greater than one ($\eta > 1$) point to an effective contact between the soil and the geogrid material. That is, the interface strength of the reinforcement and soil is greater than the shear strength of the unreinforced soil [45]. When $\eta > 1$, significant bearing resistance is developed because of the interlocking mechanism between the geogrid and surrounding soil particles. On the other hand, η values less than 0.5 may indicate weak interaction between the soil and the geosynthetic reinforcement [45]. The shear interaction coefficient values of the clay-subbase mixtures with different CR contents under the total normal stresses of 25, 50, 75 and 100 kPa are summarized in Table 4. The calculated η values for all the tested mixtures were found to be greater than 1, which indicated a strong interaction between the clay subgrade and subbase materials when reinforced with geogrids at various CR contents.

Table 4. Shear characteristic of clay subgrade soil reinforced with geogrid at various CR contents.

CR, %	η			
	σ_v = 25 kPa	σ_v = 50 kPa	σ_v = 75 kPa	σ_v = 100 kPa
0	1.31	1.20	1.12	1.13
5	1.68	1.51	1.42	1.42
10	1.97	1.82	1.65	1.61
15	2.05	1.96	1.85	1.87

As shown in Table 4, the interaction coefficient (η) increases exponentially with increasing CR content, with a maximum value of 2.05 at 15% CR. At an applied normal stress of 25 kPa, the interaction coefficient increased from 1.31 for the untreated soil to 1.68, 1.97, and 2.05 for CR contents of 5%, 10%, and 15%, respectively, corresponding to increases of approximately 28%, 50%, and 56%. This behaviour shows that the increased CR content improves the interaction of the soil matrix with the geogrid reinforcement, which results in improved bonding and mechanical interlock of the composite system. However, the improvement rate becomes less pronounced with an increase in the CR content, indicating the existence of an effective range for the addition of CR in the investigated percentages. These results are in general agreement with those reported in previous studies [26,46,47]. They pointed out the need to optimize the reinforcement conditions to get a better engineering performance.

Finally, the high-density crumb rubber used in this study, recycled from heavy truck tyres, contains metallic components (steel cords and bead wires) together with silica,

which is commonly used as a reinforcing filler in rubber products. These characteristics may explain the increase in the maximum dry density (MDD) observed with increasing crumb rubber content. In addition, the low water absorption capacity of the recycled crumb rubber contributes to the reduction in the optimum moisture content (OMC) of the soil–rubber mixtures. The observed increase in CBR may be attributed to the improved interaction between the soil particles and the crumb rubber inclusions, together with the relatively high density of the recycled material used in this study. Furthermore, the rough surface texture of the crumb rubber is likely to enhance the frictional resistance at the interface between the clay subgrade and the geogrid-reinforced subbase, promoting greater mechanical interlocking and, consequently, higher interface shear resistance. It should be noted, however, that the large-scale direct shear tests performed in this study provide an overall assessment of the interface behaviour and do not allow the individual resistance mechanisms to be identified or quantified directly. Accordingly, the proposed mechanisms should be regarded as plausible interpretations of the observed experimental behaviour rather than as mechanisms that have been directly demonstrated by the present experimental programme.

5. Conclusions

Most of the prior studies utilized either waste CR or a geogrid individually for stabilization of the clay subgrade soil. This study finds that the use of CR in clayey soils can upgrade their mechanical properties for greater improvement of the clay soil properties, enabling an easier use in road subgrades. The main results are:

- The addition of 15% CR improved the CBR by up to 56.6% as compared to the untreated soil and the PI decreased by up to 44% as compared to the reference soil.
- Increasing the CR content in clayey soil mixtures resulted in a reduction in the OMC required to achieve maximum dry density. This behaviour may be attributed to the hydrophobic nature of CR, which reduces water absorption and consequently lowers the water content required for optimum compaction.
- The total normal stress was found to have a good positive correlation with the interface shear strength. The interface shear strength increased with increasing applied normal stresses.
- The interface shear strength increased by 27%, 43% and 67% for the CR contents of 5%, 10% and 15%, respectively.
- All tested crumb rubber (CR) contents showed η values greater than 1. This indicates effective bonding and interaction between the geogrid-reinforced subbase and the clay subgrade under the investigated conditions.

Although the experimental programme provided consistent trends across all testing methods, the results presented in this study are based on a single specimen for each testing condition. Owing to the scope of the experimental programme and the time- and resource-intensive nature of the large-scale laboratory tests, replicate testing was beyond the scope of the present study. Consequently, statistical indicators such as standard deviations, confidence intervals, and error bars could not be determined. In addition, the large-scale direct shear tests provided an overall assessment of the interface response but did not permit the individual soil–rubber–geogrid interaction mechanisms to be identified or quantified directly. Future studies should therefore include replicate testing, complementary experimental techniques to investigate the individual soil–rubber–geogrid interaction mechanisms, and a broader range of soil types, geogrid products, crumb rubber characteristics, and loading conditions to extend the applicability of the present findings.

The results obtained are based on the use of a biaxial geogrid and the incorporation of granulated recycled rubber with a size range of 1–5 mm at 0%, 5%, 10%, and 15% amounts

in clay subgrade soil that has high plasticity and low bearing characteristics. According to the results of the research, it is recommended to use waste granulated recycled rubber and biaxial geogrid reinforcement together for improving the engineering properties of the clay subgrade soil, as well as to increase the interface shear strength between the stabilized soil and subbase material under four different confining stresses of 25, 50, 75, and 100 kPa. The results suggest that the combined use of these materials is an effective approach for improving the engineering performance of clay subgrade soils and also contributes to the sustainable reuse of waste tyre rubber.

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References

1. Pacheco-Torgal, F.; Ding, Y.; Jalali, S. Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview. *Constr. Build. Mater.* **2012**, *30*, 714–724. [CrossRef]
2. Yadav, J.S.; Tiwari, S.K. Effect of inclusion of crumb rubber on the unconfined compressive strength and wet-dry durability of cement stabilized clayey soil. *J. Build. Mater. Struct.* **2016**, *3*, 68–84. [CrossRef]
3. Azevedo, F.; Pacheco-Torgal, F.; Jesus, C.; de Aguiar, J.B.; Camões, A. Properties and durability of HPC with tyre rubber wastes. *Constr. Build. Mater.* **2012**, *34*, 186–191. [CrossRef]
4. Eiras, J.; Segovia, F.; Borrachero, M.V.; Monzó, J.; Bonilla, M.; Payá, J. Physical and mechanical properties of foamed Portland cement composite containing crumb rubber from worn tires. *Mater. Des.* **2014**, *59*, 550–557. [CrossRef]
5. Yoon, Y.W.; Heo, S.B.; Kim, K.S. Geotechnical performance of waste tires for soil reinforcement from chamber tests. *Geotext. Geomembr.* **2008**, *26*, 100–107. [CrossRef]
6. Mohammed, B.S.; Hossain, K.M.A.; Swee, J.T.E.; Wong, G.; Abdullahi, M. Properties of crumb rubber hollow concrete block. *J. Clean. Prod.* **2012**, *23*, 57–67. [CrossRef]
7. Romero-Flores, M.; Becerra-Lucatero, L.M.; Salmon-Folgueras, R.; Lopez-Salinas, J.L.; Bremer-Bremer, M.H.; Montesinos-Castellanos, A. Thermal performance of scrap tire blocks as roof insulator. *Energy Build.* **2017**, *149*, 384–390. [CrossRef]
8. Zornberg, J.G.; Cabral, A.R.; Viratjandr, C. Behaviour of tire shred-sand mixtures. *Can. Geotech. J.* **2004**, *41*, 227–241. [CrossRef]
9. Liu, L.; Cai, G.; Liu, S. Compression properties and micro-mechanisms of rubber-sand particle mixtures considering grain breakage. *Constr. Build. Mater.* **2018**, *187*, 1061–1072. [CrossRef]
10. Morales, E.; Filiatrault, A.; Aref, A. Seismic floor isolation using recycled tires for essential buildings in developing countries. *Bull. Earthq. Eng.* **2018**, *16*, 6299–6333. [CrossRef]
11. Sheikh, M.N.; Mashiri, M.; Vinod, J.; Tsang, H.-H. Shear and compressibility behavior of sand–tire crumb mixtures. *J. Mater. Civ. Eng.* **2013**, *25*, 1366–1374. [CrossRef]
12. Tafreshi, S.M.; Mehrjardi, G.T.; Dawson, A. Buried pipes in rubber-soil backfilled trenches under cyclic loading. *J. Geotech. Geoenviron. Eng.* **2012**, *138*, 1346–1356. [CrossRef]
13. Edincliler, A. Using waste tire-soil mixtures for embankment construction. In Proceedings of the International Workshop on Scrap Tire Derived Geomaterials: Opportunities and Challenges, Tokyo, Japan, 23–24 March 2007; pp. 319–328.

14. Edincliler, A.; Ayhan, V. Influence of tire fiber inclusions on shear strength of sand. *Geosynth. Int.* **2010**, *17*, 183–192. [CrossRef]
15. Edincliler, A.; Baykal, G.; Dengili, K. Determination of static and dynamic behavior of recycled materials for highways. *Resour. Conserv. Recycl.* **2004**, *42*, 223–237. [CrossRef]
16. Akbarimehr, D.; Eslami, A.; Aflaki, E. Geotechnical behaviour of clay soil mixed with rubber waste. *J. Clean. Prod.* **2020**, *271*, 122632. [CrossRef]
17. Washington Asphalt Pavement Association (WAPA). *Asphalt Pavement Guide*; WAPA: Olympia, WA, USA, 2002.
18. *TM 5-822-14/AFJMAN 32-1019*; Soil Stabilization for Pavements. Departments of the Army and Air Force: Washington, DC, USA, 1994.
19. *EM 1110*; Engineering and Design—Airfield Flexible Pavement Mobilization. Construction Army Corps of Engineers: Washington, DC, USA, 1984; pp. 3–141.
20. Papp, W.; Maher, M.H.; Baker, R.F. Use of shredded tires in the subbase layer of asphalt pavements. In *Testing Soil Mixed with Waste or Recycled Materials*; ASTM STP 1275; ASTM International: West Conshohocken, PA, USA, 1997; pp. 286–298.
21. Ghazavi, M.; Sakhi, M.A. Optimization of aspect ratio of waste tire shreds in sand-shred mixtures using CBR tests. *Geotech. Test. J.* **2005**, *28*, 564–569. [CrossRef]
22. Rao, G.V.; Dutta, R.K. Compressibility and strength behaviour of sand–tyre chip mixtures. *Geotech. Geol. Eng.* **2006**, *24*, 711–724. [CrossRef]
23. Karmokar, A.K.; Takeichi, H.; Kawaida, M.; Yasuhara, K. Evaluation of load bearing capacity of shredded scrap tire geomaterials. In *Scrap Tire Derived Geomaterials—Opportunities and Challenges*; Taylor & Francis: London, UK, 2008; pp. 269–275.
24. Pando, M.; Garcia, M. Tire-derived aggregates as a sustainable backfill or inclusion for retaining walls and bridge abutments. In Proceedings of the 6th Geo3T2 Conference and Expo, Raleigh, NC, USA, 6 April 2011.
25. Haq, M.; Khan, M.A.; Ali, S.; Ali, K.; Yusuf, M.; Kamyab, H.; Irshad, K. Enhancing clayey soil performance with lime and waste rubber tyre powder: Mechanical, microstructural, and statistical analysis. *Environ. Res.* **2024**, *256*, 119217. [CrossRef] [PubMed]
26. Banyhussan, Q.S.; Abdulrazzaq, J.; Hussein, A.A.; Dulaimi, A.; Andrade, J.M.A.; Bernardo, L.F.A. Stabilization of clay subgrade soil by using waste foundry sand with a geogrid. *CivilEng* **2025**, *6*, 26. [CrossRef]
27. Balmori, J.-A.; Casado-Sanz, M.; Machimbarrena, M.; Quirós-Alpera, S.; Mostaza, R.; Acuña, L. The use of waste tyre rubber recycled products in lightweight timber frame systems as acoustic insulation: A comparative analysis of acoustic performance. *Buildings* **2024**, *14*, 35. [CrossRef]
28. Lu, K.; Shang, X.; Yuan, M. Preparation and performance analysis of porous materials for road noise abatement using waste rubber tires. *Appl. Acoust.* **2025**, *228*, 110374. [CrossRef]
29. Qiang, W.; Jing, G.; Connolly, D.P.; Aela, P. The Use of Recycled Rubber in Ballasted Railway Tracks: A Review. *J. Clean. Prod.* **2023**, *420*, 138339. [CrossRef]
30. Zhao, C.; Wang, P.; Yi, Q.; Meng, D. Viability Analysis of Waste Tires as Material for Rail Vibration and Noise Control in Modern Tram Track Systems. *Shock Vib.* **2015**, *2015*, 725808. [CrossRef]
31. *ASTM D6270-20*; Standard Practice for Use of Scrap Tires in Civil Engineering Applications. ASTM International: West Conshohocken, PA, USA, 2020.
32. *ASTM D4318-17e1*; Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International: West Conshohocken, PA, USA, 2017.
33. *ASTM D2216-19*; Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International: West Conshohocken, PA, USA, 2019.
34. *ASTM D1883-21*; Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. ASTM International: West Conshohocken, PA, USA, 2016.
35. Xu, Y.; Williams, D.J.; Serati, M. Investigation of shear strength of interface between road base and geosynthetics using large-scale single-stage and multi-stage direct shear test. *Road Mater. Pavement Des.* **2018**, *21*, 1588–1611. [CrossRef]
36. *ASTM D5321/D5321M-14*; Standard Test Method for Determining the Shear Strength of Soil-Geosynthetic and Geosynthetic-Geosynthetic Interfaces by Direct Shear. ASTM International: West Conshohocken, PA, USA, 2014.
37. *ASTM D3080/D3080M-11*; Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions. ASTM International: West Conshohocken, PA, USA, 2011.
38. Youwai, S.; Bergado, D.T.; Supawiwat, N. Interaction between hexagonal wire reinforcement and rubber tire chips with and without sand mixture. *Geotech. Test. J.* **2004**, *27*, 260–268. [CrossRef]
39. Gaurav, R.M.; Vyawahare, M.R. Enhancing the Bearing Capacity of B.C. Soil by Using Shredded Rubber Tyre. *Int. J. Adv. Innov. Technol.* **2018**, *3*, 1–5.
40. Albert, J.V.; Heydi, K.H.M.; Victor, H.M.; Nelfa, E.A.A.; Aron, J.A.C.; Carlos, E.L.H.; Boris Senin, C.P. Sustainable Stabilization of Clayey Soils: The Influence of Recycled Rubber and Eucalyptus Ash. *Civ. Eng. Archit.* **2025**, *13*, 3093–3106. [CrossRef]
41. Dukare, S.; Barad, P.; Gupta, M. Effect of rubber tyre shred on properties of black cotton soil. In Proceedings of the International Conference on Science and Technology for Sustainable Development, Paris, France, 15–17 July 2026.

42. Teja, S.S.; Siddhartha, P. Stabilization of subgrade soil of highway pavement using waste tyre pieces. *Int. J. Innov. Res. Sci. Eng. Technol.* **2015**, *4*, 3265–3273. [CrossRef]
43. Guerrero-Bustamante, O.; Camargo, R.; Dawd, I.; Duque, J.; Polo-Mendoza, R.; Gálvis, J.; Diaz, J.; Daza, O.; Cucunuba, J.; Acosta, C. Implementation of crumb rubber (CR) in road pavements: A comprehensive literature review. *Infrastructures* **2024**, *9*, 223. [CrossRef]
44. Zimar, Z.; Robert, D.; Giustozzi, F.; Zhou, A.; Setunge, S.; Kodikara, J. Use of industrial wastes for stabilizing expansive clays in pavement applications: Durability and microlevel investigation. *Acta Geotech.* **2024**, *19*, 6259–6287. [CrossRef]
45. Tatlisoz, N.; Edil, T.B.; Benson, C.H. Interaction between reinforcing geosynthetics and soil–tire chip mixtures. *J. Geotech. Geoenviron. Eng.* **1998**, *124*, 1109–1119. [CrossRef]
46. Sahib, B.Q.; Jaafar, A.; Dulaimi, A. Effect of water content and degree of compaction of clay subgrade soil on the interface shear strength using geogrid. *J. Adv. Res. Appl. Sci. Eng. Technol.* **2025**, *52*, 262–280. [CrossRef]
47. Jaafar, A.; Sahib, B.Q.; Ahmed, A. Investigation of the use of glass powder on the interface shear properties of clay subgrade soil. *Geotechnics* **2026**, *6*, 43. [CrossRef]

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