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The influence of the addition of crumb tire rubber on the shear strength parameters of colliery spoil

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Abstract. The article presents the results of research on the influence of a crumb rubber additive on the mechanical properties of a colliery spoils composite. The analysis covered compaction parameters (optimum moisture content, maximum dry density of solid particles) and shear strength parameters (angle of internal friction, cohesion) for composites containing 5%, 10%, and 20% crumb rubber. Compaction parameters were determined using the Proctor apparatus at a compaction energy of 0.59 J·cm^{-3}. Shear strength parameters were measured in a direct shear apparatus on samples with a cross-sectional dimension of 12 × 12 cm and a height of 2.9 cm. Soil samples were sheared with and without water saturation at a rate of 0.1 mm·min^{-1} until 15% horizontal deformation was achieved. The results indicate that the addition of crumb rubber decreases the maximum dry density of solid particles and increases the optimum moisture content, thereby impairing the material's compactibility. For shear strength, complex relationships were observed: a small addition of crumb rubber (5–10%) improves cohesion by up to 30%, while a higher content (20%) significantly reduces it, along with the angle of internal friction. Water saturation of the samples further decreases the strength parameters, particularly with large crumb rubber additions. The optimal crumb rubber addition ranged from 5 to 10%, yielding the best values of the angle of internal friction and cohesion. The research results highlight the high potential for using colliery spoils composites with crumb rubber in earthworks, provided that the component proportions are appropriately selected.

Keywords: colliery spoils, crumb rubber, composites, compaction, shear strength, circular economy

1. INTRODUCTION

Industrial waste accounts for a significant proportion of total waste in many countries. Its nature and environmental impact depend on the structure of the economy and the dominant industrial sectors. There are a growing amount of waste and a need to transition from a linear to a circular economy in order to reduce negative environmental impacts [1–4]. In Poland, industrial waste accounts for nearly 90% of the total waste mass [5], while the European average is 49%. Its sources are primarily mining, energy, construction, and industrial processing, but also services and trade [6]. The problem in Poland is systemic in nature and results from both technological and legal conditions [7–8]. Research by Gacek [9] shows that the amount of industrial waste in Poland between 2010 and 2020 was strongly linked to technological and structural changes in the economy. The mining and energy sectors generate the largest burden, accounting for more than half of all waste [10]. Dziawgo [11] points out that Poland is struggling to meet EU targets for reducing landfill use and increasing waste recycling.

The largest share of industrial waste is accounted for by waste related to the mining industry, approximately 60%. Colliery spoils poses both an environmental threat and a potential source of raw materials. Safe management in a circular economy requires a combination of a strict regulatory framework, monitoring, advanced technologies, and the development of safe applications. An interdisciplinary approach (environmental chemistry, engineering, toxicology, economics) is essential for sustainable solutions. Increasingly, research focuses on using ash and other coal-related waste in construction, for producing sorption materials, and for recovering valuable elements, including critical metals [12–13].

Coal mining generates large amounts of colliery spoils, which are stored in piles [14]. Colliery spoils can be classified according to storage time and the degree of thermal transformation of the coal waste [15–16]. After mechanical processing, they are used for soil fine-graining and for producing lower-quality aggregates. After crushing and sorting, burnt shale can be used to construct the upper layers of embankments [17].

Rubber waste can originate from both industry and households. The most common and problematic type is used car tires. Tires are very durable, and their decomposition in the environment can take up to several hundred years, making proper management essential [18–19]. Recycled rubber is used as a component of composite materials. Research is underway on technologies for producing composite materials with crumb rubber additions [20]. The aim is to increase the reliability and safety of structures exposed to long-term vibration from machinery. At the same time, efforts focus on using composite surfaces as sound-absorbing elements. Incorporating recycled materials positively impacts the management of environmentally harmful waste, while offering economic benefits [21]. Particles from used tires serve as substitutes for non-renewable mineral aggregates in flexible rubber-cement composites [22–24]. The properties of polymer-stabilized carbonaceous composites based on slag and rubber powder have also been investigated [25].

The use of geomaterials derived from waste tires in geotechnical engineering is gaining increasing interest, as it prevents waste generation and contributes to conserving natural resources, advancing sustainable development. Geomaterials and their mixtures with soils are applied in road embankments, retaining walls, landfills, and other uses as lightweight fill, backfill, compressible inclusions, vibration dampers, and drainage material [26]. Crumb rubber exhibits favorable mechanical properties: it increases the friction angle of mixtures, improves shear resistance, and stabilizes soil under dynamic conditions. Its presence also increases mixture porosity, promoting better water drainage and reducing excess pore pressure. This material is highly durable, non-biodegradable, water-resistant, and maintains stable properties over time.

Composites combining colliery spoils and rubber waste exhibit unique mechanical properties arising from the synergy of materials with differing stiffness and deformation resistance [27]. Research indicates that their shear strength depends on component proportions: higher colliery spoils content increases strength, while rubber additions improve elasticity. Optimizing such composites requires balancing colliery spoils content (for load-bearing capacity) with rubber (for crack resistance).

An important aspect is the environmental dimension. Using crumb rubber enables waste tire management while providing an economically viable alternative to traditional lightweight aggregates.

Although the literature lacks references to composites made solely from colliery spoils and rubber waste, studies exist on versions reinforced with fly ash and stabilized with cement binders. Walotek et al. note that composites based only on colliery spoils and rubber waste have limited mechanical strength and low structural stability. Adding fly ash significantly improves properties by increasing density and reducing porosity. Cement stabilization further enhances the composite, improving resistance to weathering and extending durability [28–29].

The aim of this study was to determine the effect of crumb rubber addition (5%, 10%, and 20%) on the compactability and shear strength of colliery spoils composites, considering compaction and water content.

2. MATERIAL AND METHODS

The studies used colliery spoils with a grain size of less than 10 mm, taken from the HALDEX S.A. landfill in Sosnowiec. HALDEX is engaged in the recovery and technological processing of colliery spoils originating from hard coal mines, coal processing plants, and post-mining heaps. The crumb rubber granulate with a grain size between 2 and 4 mm came from the shredding of car tires.

The composites used in the research were prepared by adding crumb rubber in amounts of 5%, 10%, and 20% relative to the dry mass of the colliery spoils skeleton (Fig. 1). It was assumed that each subsequent crumb rubber addition would be twice as large as the previous one.

Fig. 1. Comparison of the colliery spoils sample with the applied crumb rubber additive

Crumb rubber shreds from automotive tires constitute a lightweight, flexible material used in geotechnics to improve the properties of soil subgrade. They take the form of irregular fragments of clean rubber, usually free of steel and textile reinforcements, with sizes ranging from several to several dozen millimeters [30]. These irregular, elastic shreds have a lower density than mineral grains, which results in a reduction of the bulk unit weight of the mixture; due to their elasticity, they also influence its deformability and vibration damping, which is particularly beneficial in structures exposed to cyclic loading.

The grain size distribution was determined using a combined method, with sieve analysis for grains larger than 0.063 mm and areometric analysis for particles smaller than 0.063 mm. The specific density of the skeleton was determined using a measuring flask in distilled water. The compaction parameters (optimum moisture content and maximum volumetric density of the skeleton) were determined in a Proctor apparatus in a 2,2 dm^3 cylinder at a standard compaction energy of 0,59 $J{\cdot}cm^{-3}$.

The determination of shear strength parameters was carried out in a direct shear apparatus (Fig. 2) [31]. Samples with cross-sectional dimensions of 120 × 120mm and a height of 29 mm were formed directly in the apparatus box at optimal moisture content until a compaction index of CI = 0.90 and 1.00 was obtained. The samples were consolidated for 60 minutes at normal stresses of 100, 200, 300, and 400 kPa. The tests were carried out under conditions without and with water saturation of the samples by flooding them to the height of the shear surface. The water saturation process was carried out during the consolidation of the samples and during their shearing, and it was not possible to control the degree of saturation of the composites. Therefore, tests were carried out at shear rates of 0,1 mm·min^{-1} to achieve 15% horizontal displacement. The values of the angle of internal friction and cohesion were calculated using the least squares method.

Fig. 2. General view of the AB2A direct shear apparatus and shear box (photo: R. Wojtaszek)

The obtained test results were subjected to statistical analysis. Based on the comparative matrix of values for each research series, their mutual similarities or degrees of agreement were determined. The color green indicates high agreement between the series (values close to or equal to 1), while red signifies low similarity or significant differences between the compared data sets. The calculations were performed using the Pingouin library [34].

3. RESULTS

3.1. Grain size distribution

Based on its grain size distribution, colliery spoils were classified by geotechnical describing as multi-fractional fine gravel with sand (saFGr). The gravel fraction dominated in the soil, accounting for over 51%, while the sand fraction accounted for 27%, the silt fraction for over 15%, and the clay fraction for 6% (Fig. 3).

The composite of coal seam shale and crumb rubber was classified as multi-fractional fine gravel with sand (saFGr), regardless of the amount of crumb rubber added. The composite was dominated by the gravel fraction, which accounted for 47 to 62%, the sand fraction accounted for 38 to 27%, the silt fraction accounted for 11 to 9%, and the clay fraction accounted for 4 to 2% with an increase in the addition of crumb rubber from 5 to 20%. Rubber crumb was classified as fine gravel (FGr) with a dominant gravel fraction of 92% and a sand fraction of 8%.

The specific density of colliery spoils ranged from 2.58 to 2.68 g·cm^{-3} (Table 1).

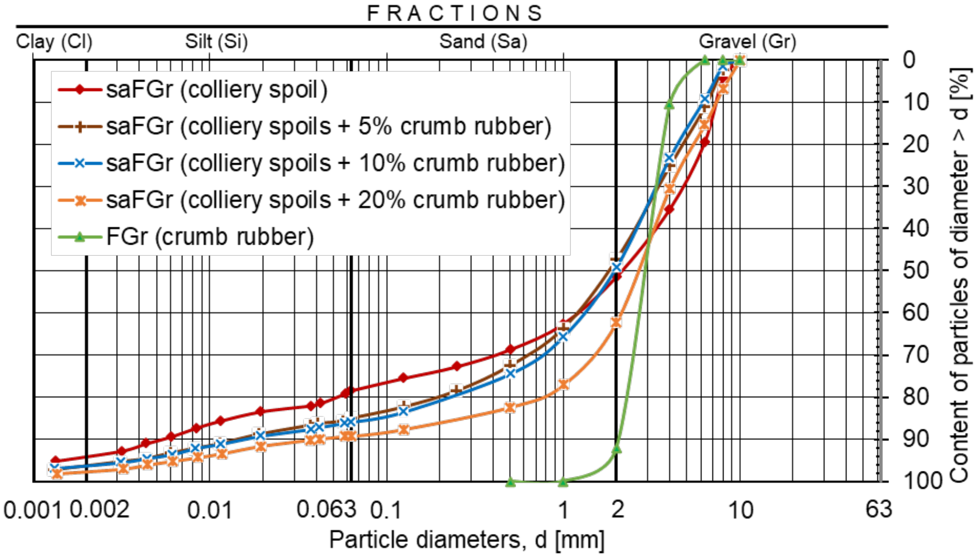


Fig. 3. Grain size curve of the tested materials

Table 1. Grain size distribution and compaction parameters of the tested materials

Parameter	colliery spoils	composite (colliery spoils + crumb rubber)			crumb rubber
Crumb rubber addition [%]	0	5	10	20	100
Fraction content [%]: – gravel, Gr: 63÷2 mm – sand, Sa: 2÷0.063 mm – silt, Si: 0.063÷0.002 mm – clay, Cl: < 0.002 mm	 51.37 27.06 15.47 6.10	 47.34 37.71 11.31 3.64	 49.11 36.77 10.87 3.25	 62.23 27.00 8.52 2.25	 92.03 7.97 - -
Equivalent diameters [mm]. – d_{10} – d_{30} – d_{60}	 0.0052 0.4 3.4	 0.015 0.64 2.6	 0.016 0.75 2.6	 0.035 1.6 3.3	 2.05 2.5 3.1
Coefficient of uniformity, $C_U = \frac{d_{60}}{d_{10}}$ $[-]$	653.9	173.3	162.5	94.3	1.5
Coefficient of curvature, $C_C = \frac{(d_{30})^2}{d_{10} \cdot d_{60}}$ $[-]$	9.1	10.5	13.5	22.2	1.0
Name of soil acc. to PN–EN ISO 14688-2:2006 [32]	saFGr	saclFGr/ saFGr	saFGr	saFGr	FGr
Density of solid particles [g·cm^{-3}]	2.68	-	-	-	1.0-1.1[1)]
Optimum moisture content [%]	11.37	12.20	11.70	12.80	7.0
Maximum dry density of solid particles [g·cm^{-3}]	1.848	1.75	1.68	1.56	0.685
[1)] from [33]					

3.2. Compactability parameters

The tested materials are characterized by different compaction parameters (Table 1). Colliery spoils had the highest maximum dry density of solid particles at the lowest optimum moisture content among the tested materials.

The addition of crumb rubber to coal shale to form composites has a clear impact on compaction parameters. With an increase in crumb rubber addition from 0% to 20%, the maximum dry density systematically decreased from 1.848 g·cm⁻³ (colliery spoils) to 1.75 g·cm⁻³ (5% crumb rubber addition), 1.68 g·cm⁻³ (10% crumb rubber addition), and 1.56 g·cm⁻³ (20% crumb rubber addition) (Fig. 4). This phenomenon was predictable, as crumb rubber has a significantly lower maximum dry density than colliery spoils (Table 1), and its addition reduces the overall maximum dry density of the composite. Crumb rubber is also more elastic than colliery spoils, which can cause loosening of the composite structure, resulting in a lower maximum dry density.

In the case of crumb rubber, maximum dry density of solid particles was the lowest, at 0.685 g/cm³.

The optimum moisture content was characterized by irregular changes. Initially, it increased from 11.4% (colliery spoils) to 12.2% (5% crumb rubber), then decreased slightly to 11.7% (10% crumb rubber), and finally reached the highest value among the composites for 20% crumb rubber addition, amounting to 12.8%. The lowest optimum moisture content of 7% was obtained for crumb rubber. This can be interpreted as an increase in water demand for optimal particle compaction as the content of the lighter rubber fraction increases. In general, the optimum moisture content in the composite tests tended to increase with increasing crumb rubber addition, which could be due to the characteristics of crumb rubber . As a porous and elastic material, crumb rubber can absorb water into its structure (Fig. 5). In contrast to the other materials, crumb rubber exhibited a low maximum dry density of solid particles of solid particles and a relatively low water requirement to achieve maximum compaction.

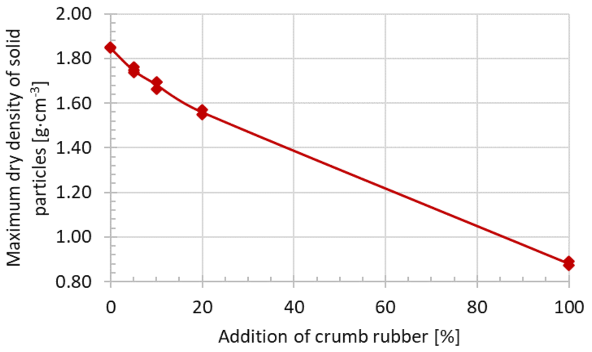


Fig. 4. The dependence of the maximum dry density of solid particles on of the tested materials on the crumb rubber addition

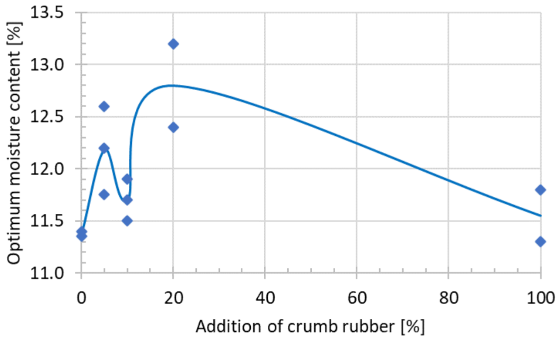


Fig. 5. The dependence of the optimum moisture content of the tested materials on the addition of crumb rubber

An increase in the amount of crumb rubber added to composites reduces the maximum dry density of solid particles and increases the optimum moisture content, thus impairing the compaction properties of the material. In engineering practice, this may be important when designing soil mixtures with added waste materials.

3.3. Shear strength parameters

The addition of crumb rubber exerted a distinct influence on the shear strength parameters of the tested materials (Table 2). A consistent decreasing trend in the angle of internal friction was observed with increasing crumb rubber content (Figs. 6 and 7). Colliery spoils exhibited the highest angle of internal friction values, whereas the inclusion of crumb rubber reduced this parameter by approximately 25–30%. An exception occurred at a 5% crumb rubber addition, for which - under high compaction (CI = 1.00) and unsaturated conditions - a local increase in the internal friction angle was recorded. This effect may be attributed to a favourable structural filling mechanism.

Cohesion displayed an opposite behaviour. At low crumb rubber additive (5–10%), a pronounced increase in cohesion was obtained, reaching 20–30% relative to colliery spoils. For example, at CI = 0.90 under unsaturated conditions, cohesion increased from 33.7 kPa to 44.7 kPa (a 33% absolute increase), while at IS = 1.00 under saturated conditions it rose from 31.5 kPa to 41.1 kPa (a 31% absolute increase). This enhancement may result from improved interparticle bonding facilitated by the presence of elastic rubber particles. However, at a 20% crumb rubber additive, cohesion decreased substantially to approximately 11–26 kPa, and for pure crumb rubber to only from 9 kPa to 11 kPa. This represents a reduction of over 60% relative to colliery spoils and reflects the loss of a mineral skeleton and the mechanical dominance of the compliant rubber phase, which markedly reduces shear resistance.

Increasing the compaction index from CI = 0.90 to CI = 1.00 generally improved the internal friction angle by approximately from 2° to 8°, with the most pronounced increases observed at low crumb rubber contents (e.g., from 7° to 8° for a 5% addition of crumb rubber). Under saturated conditions, this effect diminished, and for colliery spoils became slightly negative, indicating that water reduces the influence of compaction on friction, likely through a reduction of capillary forces. As for cohesion, under unsaturated conditions higher compaction typically decreased cohesion (e.g., by 13.3 kPa for a 5% addition of crumb rubber), presumably due to pore reduction and shifts in the shearing mechanism. Conversely, under saturated conditions, small additions of crumb rubber produced increases in cohesion (e.g., by 13.3 kPa for 5% addition of crumb rubber), suggesting a beneficial influence of water in the presence of elastic particles.

Water saturation of the samples during shearing caused changes in the shear strength parameters depending on compaction. At a compaction index of CI = 0.90, saturation slightly increased the internal friction angle (by 0.4° to 1.7°), but at the same time significantly decreased cohesion (by 10 to 15 kPa), which is typical for soils with higher porosity. In

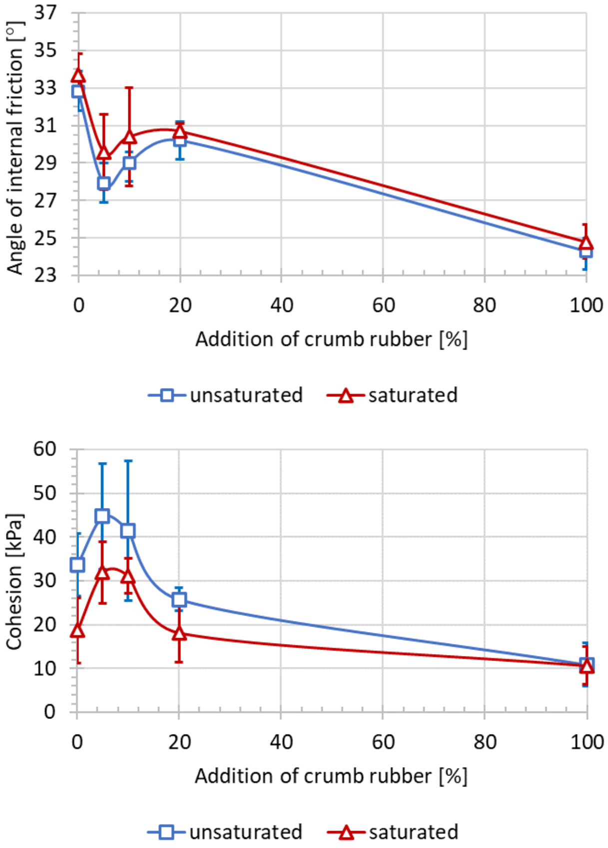


Fig. 6. Dependence of shear strength parameters on crumb rubber additive at a compaction index of CI = 0.90

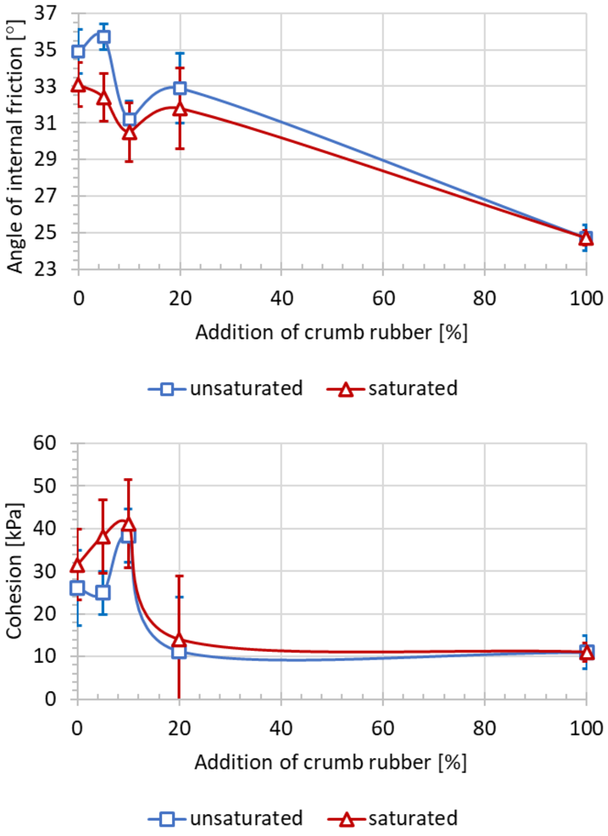


Fig. 7. Dependence of shear strength parameters on crumb rubber additive at a compaction index of CI = 1.00

tests conducted at CI = 1.00 under saturated conditions, a decrease in the internal friction angle was obtained (by 0.1° to 3.3°), which may have been caused by the reduction of frictional resistance between grains by water. For 5% and 10% crumb rubber additions, an increase in cohesion was recorded (e.g., by 13.3 kPa for 5% addition of crumb rubber), but at a 20% content this effect disappeared, which may indicate a certain "viscous" effect in the presence of both water and rubber.

The composite, defined as a mixture of colliery spoils with an addition of crumb rubber, exhibits highly distinctive behaviour compared with the "pure" colliery spoils and the crumb rubber itself. The conducted analysis demonstrated that the mechanical properties of the composites were strongly dependent on the percentage content of crumb rubber, the compaction level, and the shearing conditions, i.e., whether the samples were tested under unsaturated or saturated conditions.

With regard to the angle of internal friction, the composite showed a nonlinear response to increasing crumb rubber content. At a compaction index CI = 0.90 and under unsaturated conditions, the addition of crumb rubber resulted in a pronounced reduction in the angle of internal friction at a 5% crumb rubber addition, its value decreased by approximately 15% relative to colliery spoils. At a 10% crumb rubber addition, a slight increase was observed, whereas at 20% crumb rubber addition the value remained comparable to that of colliery spoils. Conversely, at a compaction index CI = 1.00, the 5% crumb rubber addition produced the opposite effect, yielding the highest angle of internal friction. This improvement may be attributed to enhanced structural filling and reduced void content. However, further increases in crumb rubber additive reduced the angle of internal friction, and at 20% crumb rubber addition combined with water saturation, the values became markedly lower.

Cohesion exhibited much more dynamic behaviour. At small crumb rubber additions (5 and 10%), the composite achieved maximum cohesion values – an increase of approximately from 20 to 30% relative to colliery spoils – indicating a beneficial influence of the elastic rubber particles on interparticle bonding. This effect was particularly prominent under saturated conditions and high compaction, suggesting that water in the presence of crumb rubber may act as an additional adhesive agent. However, at a 20% addition of crumb rubber, cohesion declined sharply, and for pure crumb rubber it reached the lowest values, which reflects the loss of a mineral skeleton and the mechanical dominance of the compliant rubber phase.

Crumb rubber as a stand-alone material exhibited the lowest values of both the angle of internal friction and cohesion, making it a material with very limited capability to sustain shear stresses.

Table 2. Summary of shear strength parameters of tested materials

Type of material	Crumb rubber additive [%]	Angle of internal friction, φ [°]				Cohesion, c [kPa]			
		Compaction index							
		0.90		1.00		0.90		1.00	
		Shear conditions							
		without	with	without	with	without	with	without	with
		water saturation							
Colliery spoils	0	32.8 *(1.1)*	33.7 *(1.1)*	34.9 *(1.2)*	33.1 *(1.2)*	33.7 *(7.2)*	18.7 *(7.5)*	26.1 *(8.8)*	31.5 *(8.3)*
Composite (colliery spoils + crumb rubber)	5	27.9 *(2.0)*	29.6 *(1.1)*	35.7 *(0.7)*	32.4 *(1.3)*	44.7 *(12.0)*	31.9 *(7.1)*	24.9 *(5.0)*	38.2 *(8.6)*
	10	29.0 *(2.6)*	30.4 *(0.6)*	31.2 *(1.0)*	30.5 *(1.6)*	41.4 *(16.0)*	31.2 *(4.0)*	38.3 *(6.2)*	41.1 *(10.4)*
	20	30.2 *(0.4)*	30.7 *(1.0)*	32.9 *(1.9)*	31.8 *(2.2)*	25.8 *(2.6)*	18.2 *(6.7)*	11.3 *(12.6)*	14.0 *(14.8)*
Crumb rubber	100	24.3 *(0.9)*	24.8 *(0.7)*	24.7 *(0.7)*	24.7 *(0.4)*	10.9 *(5.0)*	10.7 *(4.3)*	11.0 *(3.9)*	9.8 *(2.1)*

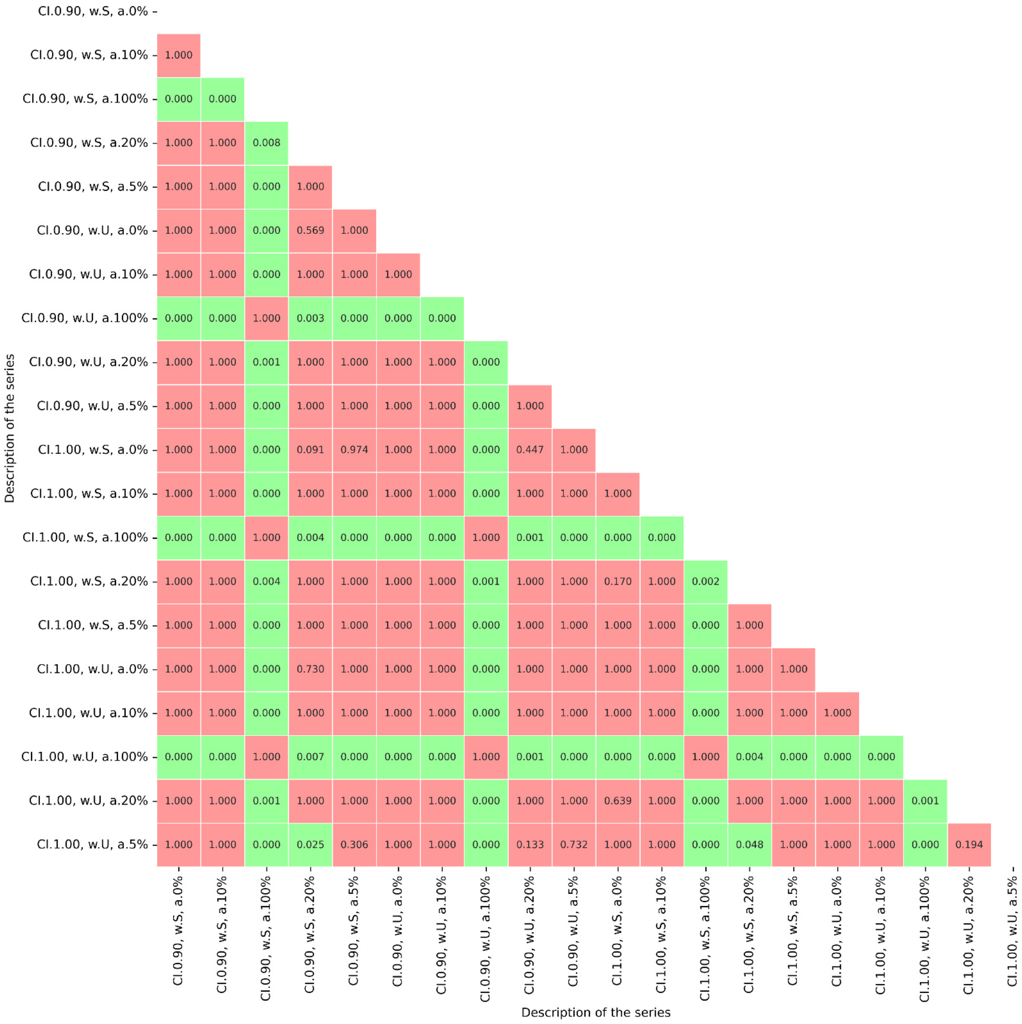
The corresponding mean standard deviation values are reported in parentheses.

3.4. Statistical analysis

In Figure 8, an analysis is presented of the influence of compaction ("CI"), crumb rubber additive content ("a"), and water saturation state ("w") on the shear strength parameters of the tested materials. Analyzing the matrix, it can be observed that compaction, defined by the compaction index at levels of CI = 0.90 and 1.00, in most cases does not generate statistically significant differences, provided that the remaining parameters remain similar. This means that increasing the compaction with a constant amount of crumb rubber and under the same water conditions does not change the characteristics of the samples in a way that would differentiate them in post-hoc tests. A similar stability is observed in the case of crumb rubber addition in the range from 0% to 20%. Red fields dominate in this area and suggest that within these intervals, the material behaves in a predictable and consistent manner, and a slight increase in the amount of crumb rubber does not cause sudden changes in its physical or mechanical properties. A significant change was observed in the studies for higher crumb rubber contents. Green fields indicate that samples consisting entirely of crumb rubber constitute a completely different material, regardless of whether they were tested under unsaturated (w.U) or saturated (w.S) water conditions. The influence of water saturation is also interesting at higher compaction and with a greater amount of crumb rubber. In some cases, especially at CI = 0.90 and under saturated conditions, individual statistically significant differences ($p < 0.05$) can be identified even at lower crumb rubber contents, which may indicate the moment at which the interaction between water and the porous structure of the crumb rubber begins to dominate over the mineral skeleton of the sample. It can be stated that while increasing compaction and crumb rubber addition yields stable results, increasing moisture due to water saturation changes the statistical response of the tested system.

Based on the distribution of p-values, it can be concluded that the most stable structure in terms of resistance to increased moisture content was found in samples with a lower compaction index (CI = 0.90) and crumb rubber addition up to 10%. This suggests that at lower compaction and relatively small crumb rubber content, the composite structure probably has sufficiently high porosity such that the introduction of water does not drastically change its mechanical properties. In this range of results, the composite exhibits high repeatability, which from an engineering perspective indicates low sensitivity to, for example, variable environmental conditions. Conversely, at a compaction index of CI = 1.00, p-values of, for example, 0.306 or 0.194 indicate that at higher compaction, the influence of water saturation was more noticeable, although still not exceeding the significance threshold of 0.05. The least stable composite was the one with 20% crumb rubber addition, where statistically significant differences between test results were found when transitioning between different saturation and compaction states.

The statistical analysis carried out on the basis of variable data concerning the tests of shear strength parameters made it possible to determine the trends of their changes for the tested composites (Table 3). It was found that the addition of crumb rubber in the amount of 5–10% increased cohesion, but a greater amount caused a rapid decrease. The angle of internal friction decreased with the increasing share of crumb rubber, except for a local increase at a 5% addition. High compaction promotes the maintenance of favorable values of the angle of friction, while water saturation of the samples combined with a small amount of crumb rubber further enhanced cohesion, although at the cost of a slight reduction in the angle of internal friction [34].



Description of the series	CI.0.90, w.S, a.0%	CI.0.90, w.S, a.10%	CI.0.90, w.S, a.100%	CI.0.90, w.S, a.20%	CI.0.90, w.S, a.5%	CI.0.90, w.U, a.0%	CI.0.90, w.U, a.10%	CI.0.90, w.U, a.100%	CI.0.90, w.U, a.20%	CI.0.90, w.U, a.5%	CI.1.00, w.S, a.0%	CI.1.00, w.S, a.10%	CI.1.00, w.S, a.100%	CI.1.00, w.S, a.20%	CI.1.00, w.S, a.5%	CI.1.00, w.U, a.0%	CI.1.00, w.U, a.10%	CI.1.00, w.U, a.100%	CI.1.00, w.U, a.20%	CI.1.00, w.U, a.5%
CI.0.90, w.S, a.0%																				
CI.0.90, w.S, a.10%	1.000																			
CI.0.90, w.S, a.100%	0.000	0.000																		
CI.0.90, w.S, a.20%	1.000	1.000	0.008																	
CI.0.90, w.S, a.5%	1.000	1.000	0.000	1.000																
CI.0.90, w.U, a.0%	1.000	1.000	0.000	0.569	1.000															
CI.0.90, w.U, a.10%	1.000	1.000	0.000	1.000	1.000	1.000														
CI.0.90, w.U, a.100%	0.000	0.000	1.000	0.003	0.000	0.000	0.000													
CI.0.90, w.U, a.20%	1.000	1.000	0.001	1.000	1.000	1.000	1.000	0.000												
CI.0.90, w.U, a.5%	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000											
CI.1.00, w.S, a.0%	1.000	1.000	0.000	0.091	0.974	1.000	1.000	0.000	0.447	1.000										
CI.1.00, w.S, a.10%	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000									
CI.1.00, w.S, a.100%	0.000	0.000	1.000	0.004	0.000	0.000	0.000	1.000	0.001	0.000	0.000	0.000								
CI.1.00, w.S, a.20%	1.000	1.000	0.004	1.000	1.000	1.000	1.000	0.001	1.000	1.000	0.170	1.000	0.002							
CI.1.00, w.S, a.5%	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000						
CI.1.00, w.U, a.0%	1.000	1.000	0.000	0.730	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000					
CI.1.00, w.U, a.10%	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000				
CI.1.00, w.U, a.100%	0.000	0.000	1.000	0.007	0.000	0.000	0.000	1.000	0.001	0.000	0.000	0.000	1.000	0.004	0.000	0.000	0.000			
CI.1.00, w.U, a.20%	1.000	1.000	0.001	1.000	1.000	1.000	1.000	0.000	1.000	1.000	0.639	1.000	0.000	1.000	1.000	1.000	1.000	0.001		
CI.1.00, w.U, a.5%	1.000	1.000	0.000	0.025	0.306	1.000	1.000	0.000	0.133	0.732	1.000	1.000	0.000	0.048	1.000	1.000	1.000	0.000	0.194	

Fig. 8. Matrix of pairwise post-hoc comparisons, notation: CI – compation index, w.U. – without water saturation (unsaturated), w.S – with saturation (saturated), a – value of crumb rubber addition

Table 3. Trends in shear strength parameters of tested materials

Type of material	Trend of changes for:		Water saturation sensitivity	Practical recommendation
	angle of internal friction	cohesion		
Colliery spoils	Stable (from 32° to 35°)	High (from 26 kPa to 34 kPa)	Low – slight decrease	Good for variable moisture content conditions
Composite with 5% crumb rubber additive	Moderate increase at higher compaction index (CI = 1.00)	Very high (up to 44.7 kPa)	Medium –cohesion decrease	Optimal additive for cohesion improvement
Composite with 10% crumb rubber additive	Stable (from 29° to 31°)	High (from 31 kPa to 41 kPa)	Medium – cohesion decrease	Good compromise between angle of internal friction and cohesion
Composite with 20% crumb rubber additive	Slight increase	Low (from 11 kPa to 25 kPa)	High – significant decrease in cohesion	Not recommended – crumb rubber destabilizes the composite structure
Crumb rubber	Lowest (about 24°)	Very low (about 10 kPa)	Low – low parameters regardless of water saturation	Do not use standalone – no load capacity

4. CONCLUSIONS

The addition of crumb rubber to the tested composites had a clear influence on the shear strength parameters; however, its impact was complex and depended on the amount added, the compaction index, and the water conditions. In the case of the angle of internal friction, a general decreasing trend was observed with increasing crumb rubber content. The value of the angle of internal friction for crumb rubber was significantly lower than for colliery spoils. In contrast, cohesion at low crumb rubber contents showed a clear increase. However, with greater amounts of crumb rubber, cohesion decreased, and crumb rubber itself exhibited the lowest values.

An increase in the compaction index from CI = 0.90 to 1.00 generally caused an increase in the angle of internal friction, particularly under unsaturated conditions. Under saturated conditions, this effect was weaker, and in the case of colliery spoils, it was even negative. For cohesion, a significant influence of water saturation was found. Under unsaturated conditions, higher compaction reduced cohesion, whereas under saturated conditions with a small amount of crumb rubber, an increase in cohesion was obtained, suggesting a beneficial interaction between water and the elastic particles. The effect of water saturation depended on the compaction level. At lower compaction, water saturation slightly increased the angle of internal friction but significantly reduced cohesion, which is typical for soils with higher porosity. At higher compaction, water saturation decreased the angle of internal friction, while for small additions of crumb rubber, it increased cohesion, indicating a certain adhesive effect in the presence of rubber.

In summary, the optimal range of crumb rubber addition was between 5% and 10%, as within this interval the maximum cohesion was achieved at an acceptable value of the angle of internal friction. Greater additions of crumb rubber caused a deterioration of the shear strength parameters, which limits the applicability of such composites in structures requiring high bearing capacity. High compaction, on the other hand, supported maintaining favorable values of both the angle of internal friction and cohesion.

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