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Strength Characteristics of Clay-Rubber Waste Mixtures in UU Triaxial Tests

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Received: 5 July 2019; Accepted: 8 August 2019; Published: 10 August 2019

Abstract: This paper presents results of undrained and unconsolidated (UU) triaxial tests related to the influence of tire waste addition on strength characteristics of red clay from Patoka in Southern Poland. Angle of internal friction and cohesion values were estimated for 30 specimens prepared from pure red clay (RC), its mixtures with two different fractions of shredded rubber in 5%, 10%, and 25% mass proportions as well as for pure powder (P) and granulate (G). It has been observed that the addition of granulate contributes more to the increase in the angle of friction than the addition of powder ($\Delta\Phi_{uu}$ = +1% (G-5) / +16% (G-10) / +31% (G-25), $\Delta\Phi_{uu}$ = +1% (P-5) / +10% (P-10) / +19% (P-25)). On the other hand, rubber additions reduce cohesion in mixtures, and the effect is enhanced with increases in their grain size and percentage composition (Δc_{uu} = −31% (G-5) / −63% (G-10) / −87% (G-25), Δc_{uu} = −67% (P-5) / −58% (P-10) / −58% (P-25)). It has been noticed that a change of parameters Φ_{uu} and c_{uu} causes a decline of shear stresses at increasing granulate content. There is an inverse relationship for powder. At the same time, it has been shown that the failure strain, hence a change in red clay-rubber (RCR) mixtures plasticity, is related to the level of confining stress σ_3 and the type of rubber waste. Results of tests and their comparison with results of other researchers show that each time it is necessary to experimentally verify a given soil with specific rubber waste.

Keywords: tire waste; clay; civil engineering construction; UU triaxial test; shear strength of mixtures

1. Introduction

The contemporary world grapples with many problems, including the disposal of a huge number of waste car tires (referred to as 'end-of-life tires' (ELT)) and the need to strengthen or to reuse weak fine-grained soils, in particular expansive clays. Scrap tires create breeding grounds for disease carrying vermin (tires hold water, which becomes stagnant and attracts the insects), in case of (self)ignition the tires emit black, thick and toxic smoke, which is very difficult to fight. Expansive soils cause serious damage and distortion to light buildings (especially to wooden constructions), highway pavements, and underground networks. Rogers et al. [1] state that according to estimates, shrinking and swelling soils cause about $2.3 billion of damage annually in the United States alone which, to put things in perspective, is more than twice the annual cost of damage from floods, hurricanes, tornadoes, and earthquakes combined [2].

The practice of dumping tires anywhere or stockpiling them on huge dump sites results not only in the environmental pollution but causes also significant fire and life hazards. Methods of various rubber types waste management (not only tires) are regulated by appropriate laws and regulations, which require tests to be performed on new applications, e.g., in civil engineering works (reported by the World Business Council for Sustainable Development (WBCSD) [3]). Primarily their use as backfills for road and railway embankments or as retaining wall backfills (e.g., [4–9]) or adding them to asphalt mixtures (e.g., [10,11]) or as buildings protection against earthquakes (e.g., [12]). It is true that the excess of waste, including rubber, results directly from human activities. On the other hand, the existence of weak soils is a natural factor that causes a lot of difficulties in founding buildings. Also, their reuse after appropriate modification of their properties is not an easy job. This is caused, among other things, by the fact that the testing methodology dedicated to such soils is specific and frequently complicated [13,14]. Soils, which feature plastic consistency, or those which show volume changes (swelling or shrinking) due to moisture content, change and are considered weak cohesive soils. The subsoil built of such soils features a low strength and is susceptible to significant and uneven settlement [15]. One of the methods for improving weak cohesive soils usability consists of reducing the weight of embankments built on them, and in the case of expansive soils, reducing their swelling. To this end, rubber waste originating from car tires can be used in each of these cases.

The basic aim of the presented paper—being the determination of rubber waste in the form of 0–1 mm powder and 1–5 mm granulate influence on strength parameters of swelling red clay—results from those premises. UU triaxial tests (unconsolidated and undrained shearing) were performed for this issue, considering such a case as the most unfavorable in the situation of quick loading. The influence of the aforementioned waste on swelling parameters was presented by Kowalska and Jastrzębska [16]. They drew attention to three important aspects. First of all, not every research method (e.g., free-swell after Head or the swelling index from the Casagrande apparatus) is suitable for soil—rubber mixtures. Secondly, after the initial compaction of the mixture in Proctor's apparatus it should be taken into account the fact that the rubber relaxes, which is difficult to quantify. Thirdly, certainly, the rubber waste reduces the swelling pressure of expansive soils, but the determination of the optimal rubber size and shape and its content in the mix still requires further research.

2. Literature Review

The majority of research carried out on waste is directed primarily towards checking their influence on a change of the optimum moisture content in soils [17,18], on the mechanical behavior of soils [19–23], on the reduction of Atterberg's limits and plasticity index of fine-grained soils [21,24–26], and on the reduction of natural soils swelling [16,27–30]. If the first two groups of issues apply to all soils, then the next two are strictly related to cohesive (frequently expansive) soils. At the same time, most papers definitely focus on non-cohesive soils. The few referring to cohesive soils, and related to their shear strength, are based primarily on direct shear tests or on unconfined compression tests. Triaxial tests are performed relatively less often, and if they are, then they are only done so with consolidation and are drained (CD—consolidated drained tests) or undrained (CU—consolidated undrained tests) during shearing. The author is aware of only one paper where the researchers carried out UU triaxial tests [31].

The above observation is confirmed inter alia by an extensive review by Yadav and Tiwari [32], devoted entirely to the ELT inclusion in fine-grained soils. At the same time, having analyzed the available literature, the following conclusions come to the fore, which frequently function within a given soils group: non-cohesive or cohesive. First of all, irrespective of the soil type, after adding it to rubber waste, its unit weight goes down, making the structure lighter. Moreover, after adding shredded rubber to non-cohesive soils, a noticeable decline of the angle of internal friction value is observed by approximately 22%, according to CD triaxial tests [26] or even by approximately 30% according to tests in a direct shear apparatus [6]. It is accompanied by an increase in the apparent cohesion of the mixture, where so-called threshold values are observed (according to Bałachowski and Gotteland [33] this is approximately 50% of rubber waste content in the mixture, and according to Kowalska and Chmielewski [6] this is approximately 30%). After exceeding them, the cohesion starts showing downward trends after its initial increase. Then, such a proportion between the strength parameter values and the content of the rubber additive is sought that finally the mixture would reach the highest strength.

In the case of mixing cohesive soils with rubber waste, it is not possible to generalize those mixtures' behavior due to the diversity of the mechanical properties of this group of soils. For example, when analyzing deformation parameters, Carraro et al. [20] in triaxial tests with internal measurement of strains and bender elements observed a small increase in the Poisson's ratio and a decrease in the stiffness modulus in the case of expansive soils with 6.7 mm granulate. The author is not aware of other reports of similar scope, with the exception of a few other papers published by researchers gathered around Carraro, including Dunham-Friel and Carraro [34].

In turn, Ramirez et al. [18], also in CD triaxial tests, have shown a significant impact of confining stress value on the shear strength of clay with granulate mixture. The strengthening of material was highest for the confining stress of 100 kPa at 10% addition of granulate, while for 400 kPa, the shear strength slightly diminished, whereas different behaviors are observed in direct shear tests. Cetin et al. [21] showed an increase in cohesion with the addition of rubber to 40%, and then its decrease when the addition of rubber was greater than 40%. In turn, Balasooriya et al. [19] observed a decrease in cohesion with the addition of rubber to 1.7%, and then its increase (with a rubber addition greater than 1.7%). Also, the value of the angle of internal friction behaves non-linearly, where its changes are fairly irregular [19,21]. Only Tafti and Emadi [35] observed a steady increase of the internal friction angle. However, it should be noted that they only studied clayey soils with a small content of tire fibers (maximum 3%).

All those discrepancies observed in the soil-rubber mixtures behavior result from three basic reasons: soil type, type of rubber waste used (size/shape; e.g., [28,29,36,37]), and its percentage (weight or volume) content. According to European Committee for Standardization Workshop Agreement CEN CWA 14243:2002 [38], the following types of rubber waste are distinguished: powder (P) <1 mm and fine powder (F) <0.5 mm, granulate (G) 1–10 mm, chips (C) 10–50 mm, shreds (S) 50–300 mm, tire cuts (X) >300 mm, and buffings (B) 1–40 mm. American Society for Testing and Materials ASTM D 6270-08:2014 [39] suggests another division, with different size ranges: granulated rubber, ground rubber, powdered rubber, rough shreds, tire chips, tire-derived aggregate, and tire shreds, but the author will use the breakdown consistent with CEN CWA 14243:2002 [38]. Referring to the percentage content of rubber waste, most frequently, the rubber content in the mixture ranges from 5% to 50%, although additions of 60%–80% or 0.5%–5% are also encountered. Most often, in the case of small reported rubber contents, additionally cement, fly ash, bottom ash, silica fume, and biomass silica are used [32,40–42]. Certain authors also take into account in the mixtures the fact of random or intentional distribution of rubber additive in the mixture. For example, Bałachowski and Gotteland observed a five-time decrease in the strength of the mixture with chips placed randomly compared against the mixture with horizontally arranged chips [33].

The few examples presented prove various soil responses in the field of their physical and mechanical properties changes after adding rubber waste originating from tires to them and justify the need to undertake further research in this direction.

3. Materials and Methods

3.1. Fine-Grained Soil

A cohesive soil originating from Triassic deposits in Patoka near Częstochowa, Southern Poland, was used in tests. Because of its characteristic reddish-brown color caused by the presence of iron compounds, it was referred to as red clay (RC). On the basis of areometric [16], and with the use of laser analyzer tests [43], the soil was classified as clay with silt (siCl) in accordance with PN-EN ISO 14688-2:2006 [44]. According to classification consistent with the Unified Soil Classification System (USCS) [45], the soil subjected to the tests is clay with high plasticity (CH). According to Stempkowska's X-ray diffraction [43], this soil is the expansive soil. Its basic parameters are presented in Tables 1 and 2.

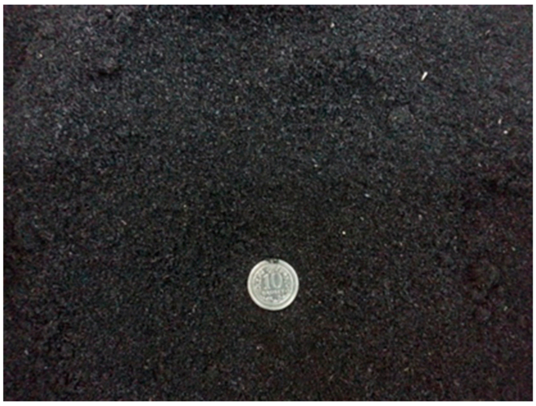
3.2. Rubber Waste

In this research, two sizes of tire waste were used: powder (P) 0.1–1.0 mm (Figure 1a) and granulate (G) 1–5 mm (Figure 1b). Both rubber additives originated from two different local shredding companies and contained negligible amounts of textile parts. The values of coefficient of uniformity and coefficient of curvature were obtained based on grain size curves (effective diameters according to [16,43] are presented in Table 2) and indicate rubber materials with uniform granulation (C_u = 3.5 and C_c = 1.2, and C_u = 2.1 and C_c = 0.8, respectively). Specific gravity of rubber was approximately ρ_s = 1.15 g/cm^3, which falls within the range of values given by, for example, Akbulut, Arasan, and Kalkan [46], and Kalkan [27]. The basic parameters of tire waste are presented in Table 2.

Table 1. Basic geotechnical properties of red clay (siCl/CH) [16,43].

Properties	Value	Standard Designation
Specific gravity, G_s (g/cm^3)	2.77	PKN-CEN ISO/TS 17892-3 [47]
Consistency limits:		
Plastic limit, PL (%)	25	PKN-CEN ISO/TS 17892-12 [48]
Liquid limit-cone penetrometer method, LL (%)	65	PN EN ISO 17892-3 [49]
Liquid limit-Casagrande method, LL (%)	75	PKN-CEN ISO/TS 17892-12 [48]
Swelling properties:		
Swelling pressure, σ_{sp} (kPa)	97	PN-EN ISO 17892-5 [50]
Free-swell, FS (%)	31.50	Head [51]
Grain-size distribution:		ASTM D422 [52]
Gravel (>2000 µm), (%)	0	
Sand (75–2000 µm), (%)	0	
Silt (2–75 µm), (%)	71	
Clay (<2 µm), (%)	29	PKN CEN ISO/TS 17892-4 [53]
Mineralogy:		
Quartz, (%)	41.8	
Kaolinite, (%)	31.5	
Illite, (%)	19.5	
Siderite, (%)	5.6	
Goethite, (%)	2.0	
EC7 soil classification	siCL	PN-EN ISO 14688-2 [44]
USCS soil classification	CH	ASTM D2487-11 [45]
Compaction characteristics:		PN EN 13286-2 [54]
Optimum moisture content (OMC), w_{opt} (%)	18.0	
Maximum dry density, ρ_{dmax} (g/cm^3)	1.75	

siCL—clay with silt or silty clay; CH—clay with high plasticity; EC7—Eurocode 7; USCS—Unified Soil Classification System.



(**a**)

(**b**)

Figure 1. Rubber waste: (**a**) powder (P) 0–1 mm, (**b**) granulate (G) 1–5 mm.

Table 2. Physical properties of the red clay (siCl/CH), powder (P) and granulate (G), based on the grain-size distribution curves [16,43].

Effective Diameter/Properties	Red Clay	Powder	Granulate
d_{10}, (mm)	0.0008	0.165	1.12
d_{30}, (mm)	0.002	0.34	1.45
d_{50}, (mm)	0.0045	0.5	2.0
d_{60}, (mm)	0.008	0.58	2.35
d_{90}, (mm)	0.02	0.85	4.0
Coefficient of uniformity, C_u	100	3.5	2.1
Coefficient of curvature, C_c	0.063	1.2	0.8

3.3. *Red Clay-Rubber (RCR) Mixtures*

For test purposes, specimens were prepared, being either pure clay (clay—100%) or pure rubber waste (P—100% or G—100%), or such a mixture of clay with rubber waste, that the mass of powder or granulate was appropriately 5%, 10%, or 25% of total mass. In future studies, it is planned to make a mixture of soil and rubber in volume proportions, not in weight. This takes better account of the significant difference in density between rubber and soil. The clay, initially of natural moisture content $w_n \approx 30\%$, was dried at 105 °C and then ground in a ball mill. Next, the clay only or clay mixed with rubber (both at room temperature and in air-dry condition) were flooded with distilled water, so as to obtain a mixture of moisture content of approximately $w = w_{opt} = 18\%$ (mass of water against the total of dry soil and rubber mass). Attention should be drawn to the fact that because of the small water absorption capacity of rubber tires (maximum 4%), most of the water in the mixture fell to clay. This means, in reality, that in specimens with higher rubber amounts the moisture content of clay itself was appropriately higher (18.2%, 19.2%, and 23.0%). This fact is a significant limitation in the interpretation of results in this study and their comparison with the data of other researchers. The author is aware that for each mixture the optimum moisture content should be separately determined, which is planned in future studies.

Finally, 6 different mixtures were prepared (Table 3), which were marked according to the code adopted in an extensive project by Kowalska et al. [55]:

RC-P-5 (95% red clay with 5% addition of powder 0–1 mm),
RC-P-10 (90% red clay with 10% addition of powder 0–1 mm),
RC-P-25 (75% red clay with 25% addition of powder 0–1 mm),
RC-G-5 (95% red clay with 5% addition of granulate 1–5 mm),
RC-G-10 (90% red clay with 10% addition of granulate 1–5 mm),
RC-G-25 (75% red clay with 25% addition of granulate 1–5 mm),
and additionally:
RC (100% red clay),
P (100% powder 0–1 mm),
G (100% granulate 1–5 mm).

For example: specimen of RC-G-10 symbol consisted of 90% of red clay and 10% of granulate.

Material prepared this way was laid in three layers in the large Proctor mold (2200 cm^3). Each layer was compacted with 55 impacts with the standard Proctor energy of 0.59 J/cm^3 following recommendations of Polish Standard PN EN 13286-2 [54]. Finally, for the obtained specimens, the obtained density values were $\rho = 0.56–1.85\ g/cm^3$ (Table 3).

4. Test Procedure

The basic objective of studies carried out by Wolner and Ksel [56] in cooperation with Jastrzębska consisted of the determination of rubber additive influence on strength parameters of red clay (angle of internal friction Φ_{uu} and cohesion c_{uu}). To avoid the impact of swelling, a decision was made to perform UU triaxial tests (unconsolidated undrained) in accordance with the European Standard PKN-CEN ISO/TS 17892-8:2009 [57]. For the same reason, specimens were not saturated with deaerated water prior to shearing, contrary to Tajdini et al. [31] whose samples of non-swelling kaolin were saturated before the tests (first by the injection of CO_2, then by deaerated water flushing). Thanks to limiting the swelling of samples in UU triaxial tests in this study and the use of non-swelling material in Tajdini et al.'s tests [31], the author decided to compare the results mostly to Tajdini et al.'s data [31]. Because of the specific nature of the studied materials (pure red clay, clay with addition of rubber powder or granulate, pure powder or granulate), three various forms of specimens formed for triaxial tests were applied, each of them was d = 38 mm in diameter and h = 80 mm high. A minimum of 3 specimens were prepared for each type of material, except for pure clay, their number was 6 (in total 30 specimens).

4.1. Preparation of Proper Specimens from Clay and from a Clay-Rubber Waste Mixture

The forming of proper specimens from clay and from a mixture of clay with rubber waste for triaxial tests proceeded in two ways. Pure clay specimens were cut directly using a string cutter from a block prepared in a Proctor apparatus. In the case of mixture, a large sample was prepared in the Proctor apparatus at the beginning. Later, the cylindrical forms were pressed into Proctor's mold (Figure 2). Finally, the specimens were pushed out from these forms, and then mounted in a triaxial apparatus.

Figure 2. Preparation of specimens from the Red Clay-Rubber (RCR) mixture.

4.2. Preparation of Proper Specimens from Pure Rubber Powder or Granulate

The forming of proper specimens from rubber waste was performed in accordance with the procedure dedicated to non-cohesive soils. Knowing the volume of the mold, in which specimens are prepared, the necessary mass of waste was calculated to obtain the required maximum density in accordance with Table 3. Then, the measured rubber material was poured through a funnel in three layers to the mold lined with a membrane and placed in the triaxial apparatus (Figure 3). Each layer was compacted by a hand rammer.

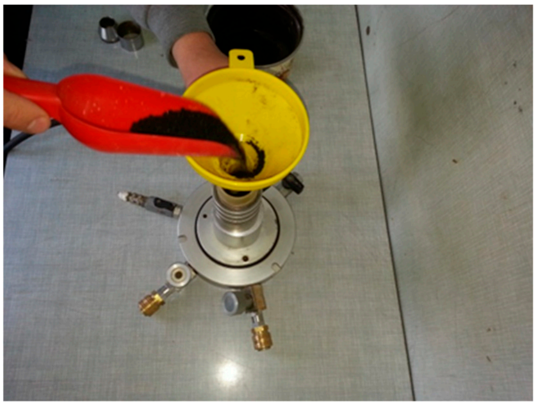


Figure 3. Preparation of specimens from the pure powder or granulate.

4.3. Tests Conditions

A constant loading rate (strain controlled) equal to v_s = 7.2 mm/h was applied in UU triaxial tests. A change of specimen height and the value of shear force were recorded during shearing. Each series of tests was carried out at confining stresses equal to σ_3 = 50 kPa, 100 kPa, and 200 kPa. Because of the tests and specimen type (unsaturated and unconsolidated), the effective stresses were not considered at the results interpretation.

5. Results and Discussion

The influence of the rubber addition on red clay was already observed at the stage of specimens for proper tests preparation in a Proctor apparatus. The obtained values of density ρ = 0.56–1.85 g/cm^3 (Table 3) clearly prove that the addition of powder or granulate reduces the density of pure red clay by approximately 2.2% and 3.8% (for P-5 and G-5, respectively). For P-10 and G-10 this is a reduction by 6.0% and 7.6%, while in the case of 25% rubber addition, the declines are 14.1% (P-25), and 16.8% (G-25). The given values show that the higher the grain size of rubber waste, the higher the decrease of density, which results from a low specific gravity of rubber itself and from reduced compaction efficiency due to the elasticity of rubber particles. This relationship is confirmed by most researchers, e.g., Yadav and Tiwari [58].

Table 3. Results of strength parameters Φ_{uu} and c_{uu} and of density ρ determination for studied materials obtained for moisture content w = 18%.

Material	Rubber Content (%)	Internal Angle of Friction Φ_{uu} (^{0})	Ratio of Improvement in Angle of Friction	Cohesion c_{uu} (kPa)	Ratio of Reduction in Cohesion	Density for w = 18% (g/cm^3)
RC	0	21.03	-	167.45	-	1.85
RC-P-5	5	21.21	1.0	55.66	0.33	1.81
RC-P-10	10	23.12	1.1	69.60	0.42	1.74
RC-P-25	25	24.93	1.19	69.71	0.42	1.59
P	100	27.50	-	1.72	-	0.56
RC-G-5	5	21.17	1.0	114.88	0.69	1.78
RC-G-10	10	24.37	1.16	62.00	0.37	1.71
RC-G-25	25	27.63	1.31	21.51	0.13	1.54
G	100	28.74	-	6.06	-	0.61

Results of UU triaxial tests are presented in the form of angle of internal friction Φ_{uu} or cohesion c_{uu} changes depending on the powder or granulate content (Figures 4 and 5) and in the form of shear characteristics in Figure 6.

In addition, Figure 7 shows the plots of the shear stress against the confining stress for the (RC) and the (RCR) mixtures (this study), and for the clay and clay-crumb mixtures (Tajdini et al.'s tests [31]). In turn, Figure 8 shows the variation of deviator stress at failure with rubber waste content for this study and Tajdini et al.'s tests [31]. The results interpretation is supplemented with Figure 9, which shows the variation of the failure strain $\varepsilon_{1,f}$ with confining stress (this study and Tajdini et al.'s tests [31]).

5.1. The Effect of Rubber Waste on the Shear Strength Parameters

The analysis of results shows a clear influence of rubber additives on the strength properties of soil-rubber mixtures. The results of all tests are specified in Table 3. It has been noticed that the addition of 5% of powder or granulate practically does not affect the value of Φ_{uu} (change of approximately 1%). At a further increase in the rubber waste content in the mixture, the angle of internal friction Φ_{uu} also grows. Higher increments are observed when rubber granulate has been added to clay, so for contents: (P-10)—$\Delta\Phi_{uu}$ = +10%, (G-10)—$\Delta\Phi_{uu}$ = +16%, (P-25)—$\Delta\Phi_{uu}$ = +19%, (G-25)—$\Delta\Phi_{uu}$ = +31% (Figure 4).

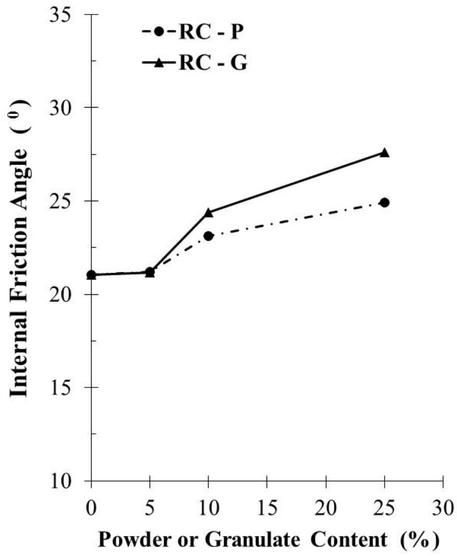


Figure 4. Variation of the angle of internal friction with the rubber waste content.

By analyzing the obtained values of cohesion c_{uu}, it has been found that rubber additives cause its decisive decline in mixture, the higher it is, the bigger their grain size and percentage composition (Figure 5). This fact can be explained by the decreasing domination of electromagnetic force between clay particles, which results in the separation of soil particles due to the increasing content of rubber waste. The following relationships have been observed in presented studies. For contents: 10% and 25% of powder—Δc_{uu} = −58%, 10% granulate—Δc_{uu} = −63%, 25% granulate—Δc_{uu} = −87%. Although the disturbance of general trend in the mixture containing 5% powder content seems problematic, for which the cohesion decrease is higher than for the other mixtures with powder (Δc_{uu} = −67% > −58%), contrary to 5% of granulate, where Δc_{uu} = −32% < −63% < −87%. This requires the performance of the next tests to confirm or reject a similar relationship.

It is worth drawing attention to the fact that results of presented tests can be compared with only one paper, in which authors also were carrying out UU triaxial tests on specimens of kaolinite clay and kaolinite clay-crumb rubber mixtures [31]. In both cases, for rubber waste there are similar values of angle of internal friction −27.5° for powder and 28.7° for granulate (in this study) and 19°–26° for crumb [31] as well as cohesion—1.7 kPa for powder and 6 kPa for granulate (in this study) and 1–5 kPa for crumb [24]. Tajdini et al. [31], in mixtures with kaolin, were using crumb-type waste in two size ranges: 2–5 mm (marked by symbol G30) and 1–3 mm (marked by symbol G80) and with three weight contents: 5%, 10%, and 15%. In the study by Tajdini et al. [31], an increase in the angle of friction was observed up to 10% of G30 and G80 content, and then its decline for 15% content of rubber waste. A decline of cohesion occurred for each rubber waste content (Figure 5). In terms of quality, the presented Tajdini et al. [31] results are mostly consistent with this study's results. An increase in the angle of friction in presented tests is the exception.

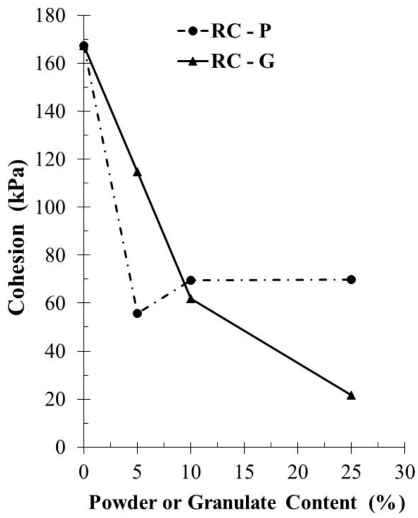
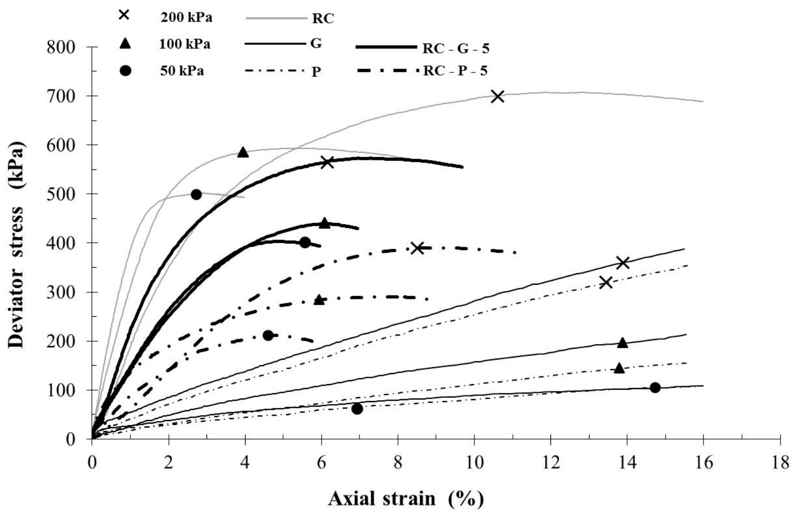


Figure 5. Variation of the cohesion with the rubber waste content.

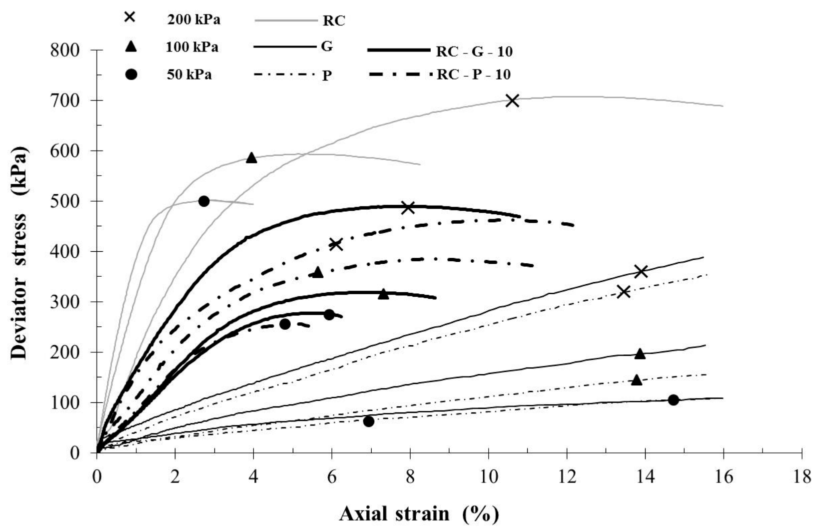
5.2. Analysis of Shear Strength Test Results

The analysis of soil-rubber mixtures behavior should not be limited only to the discussion of changes observed for strength parameters, i.e. cohesion and angle of internal friction. It should be expanded with the information on the development of shear stresses, stress deviator, as well as of failure strains. The shear characteristics presented in Figure 6 directly show the influence of rubber addition on the strength of tested mixtures.



(a)

Figure 6. *Cont.*



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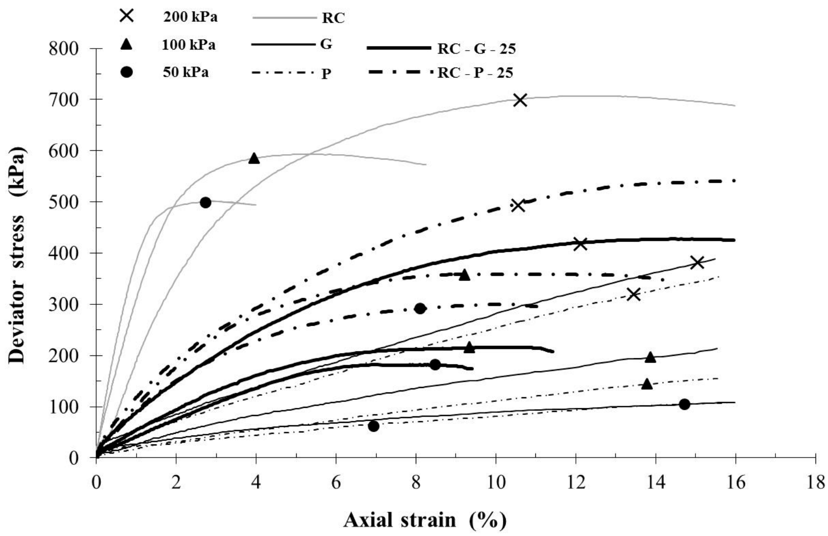

(**c**)

Figure 6. Deviator stress versus axial strain for pure red clay, powder and granulate, and for RCR mixtures, under confining pressure 50, 100, and 200 kPa: (**a**) 5% addition of (P) or (G), (**b**) 10% addition of (P) or (G), and (**c**) 25% addition of (P) or (G).

The effect of strengthening was not observed in any cases. Most likely, it is related to the method of specimen preparation, which were compacted in a Proctor apparatus at the optimum moisture content. The shown decline of density proves partial loosening of the mixtures structure as against pure (RC), hence at the same time, there was a general decrease of the shear strength. In addition, as can be seen in Figure 6, the maximum failure stress was achieved at a different axial strain. For the tested red clay and all mixtures, with increasing confining pressure, the higher deformations were obtained for the maximum deviator stress. This can be explained by the fact that for higher confining pressure the swelling effect is clearly reduced. Soltani et al. [28,29] also wrote about a reduction of the swelling pressure mainly in the context of the rubber size and shape in the evident favor of a coarser rubber sizes and more elongated form. In this study for the same confining pressure, the axial failure was greater for all mixtures with rubber than for pure clay. At the same time, the maximum stress at failure was higher for pure clay than for soil-rubber mixtures (no strengthening effect after adding rubber powder or granulate). However, Soltani et al. [28,29] do not recommend the addition of rubber at more than 20%, because then a decrease in the mixture strength is observed. The reduction in strengthening may improve the small addition of polymers (0.2 g/l) to the soil-rubber mixtures [30] or adding only 10% of the rubber to the expansive soil so as to obtain a favorable relationship between reinforcement and swelling reduction [37].

At the same time, Tajdini et al. [31] have shown strengthening of clay-crumb mixtures against pure clay, where for both types of materials in UU tests the specimens were damaged at lower shear stresses than in CD tests. The presented studies have not shown strengthening of (RCR) mixtures (Figures 7 and 8).

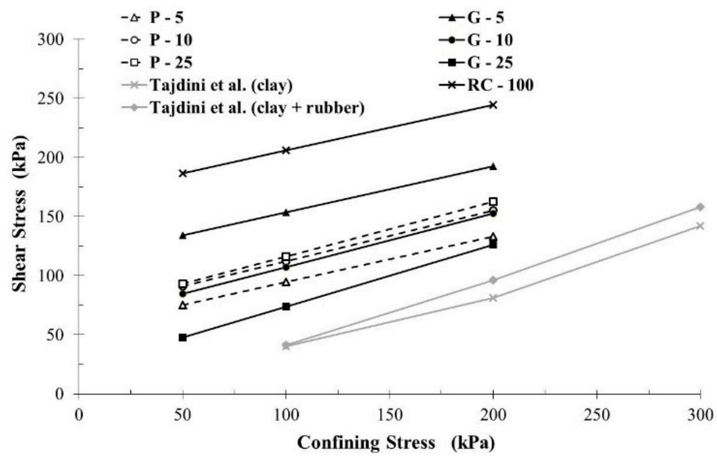

Figure 7. Shear stress versus confining stress for (RCR) mixtures and for the clay and clay-crumb mixtures (based on this study and Tajdini et al.'s tests [31]).

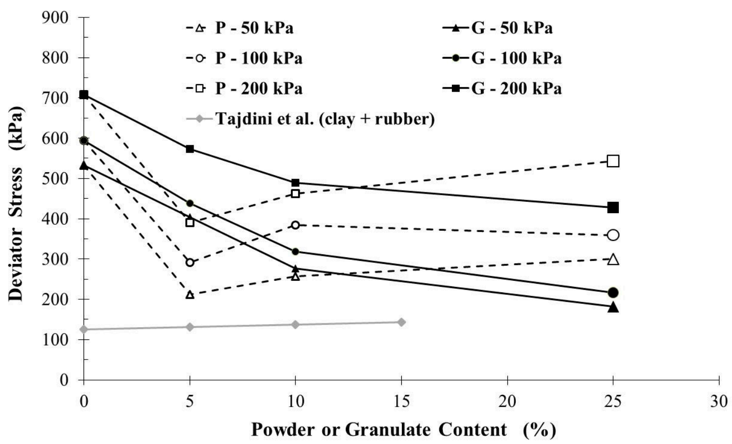

Figure 8. Deviator stress at failure versus rubber waste content for (RCR) mixtures and for the clay and clay-crumb mixtures (based on this study and Tajdini et al.'s tests [31]).

Instead, a clear relationship was noticed with respect to the percentage content of specific rubber waste. The level of failure stresses was going down with the increasing granulate content. In the case of powder, the relationship was inverse: shear stresses were higher for a greater powder content (P-25). The report from Tajdini et al.'s [24] study did not comprise the information on changes of failure shear stress in terms of G30 or G80 content. Obviously, although the conditions of this study were close to those of Tajdini et al. [24], they were not identical. Basic differences included: another soil type, no saturation with water before presented tests, another type of rubber waste, higher decrease of cohesion in (RCR) mixtures, and perhaps a different mineralogical composition of soils (Tajdini et al. [31] did not provide the mineralogical composition of kaolinite clay). That, among other things, is why not all reported changes are identical.

5.3. The Effect of Rubber Waste on Deformability

Figure 9 presents the rubber waste influence on the plasticity of red clay. According to the author, Tajdini et al. [31] were incorrectly referring to this property as ductility. The ductility is a term assigned to such materials as steel or concrete, or in particular cases also to rocks. In recent years, some researchers have applied this term not only referring to cement stabilized soils, but also to soil-rubber waste mixtures, although in their case it is still simply plasticity and the author will be using this term.

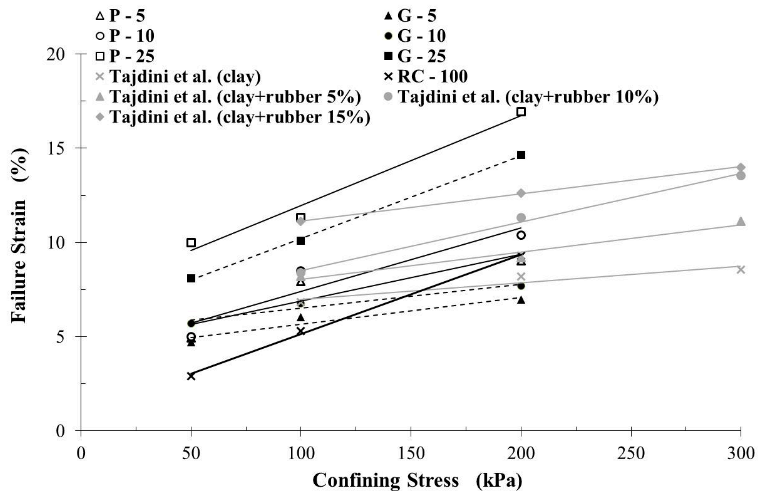

Figure 9. Strain at failure versus confining stress for (RCR) mixtures and for the clay and clay-crumb mixtures (based on this study and Tajdini et al.'s tests [31]).

Figure 9 clearly shows that for higher values of confining stress (50 kPa and 100 kPa), the failure strain $\varepsilon_{1,f}$ increases with increasing the powder and granulate content. For example, for σ_3 = 50 kPa: (P-5)—$\Delta\varepsilon_{1,f}$ = 70%, (P-25)—$\Delta\varepsilon_{1,f}$ = 240%, (G-5)—$\Delta\varepsilon_{1,f}$ = 60%, (G-25)—$\Delta\varepsilon_{1,f}$ = 180%. This indicates an increase in plasticity, the higher it is the smaller the rubber waste particles are. With further growth of confining stress (200 kPa), the situation changes and lower (P) and (G) contents (5% and 10%) in (RCR) mixtures do not result in the failure strain increase against red clay. Only for the 25% content of rubber waste do the mixtures' plasticity continue to grow, so for σ_3 = 200 kPa: (P-25)—$\Delta\varepsilon_{1,f}$ = 82%, (G-25)—$\Delta\varepsilon_{1,f}$ = 57%. In turn, in tests on kaolinite clay with crumb, Tajdini et al. [31] have shown a permanent increase in the failure strain with increasing the crumb rubber particles and its content in mixtures. However, Soltani et al. [37] found that the effect of rubber size/shape mainly translated into higher ductility, lower stiffness (represented by E_{50}—the secant modulus at 50% of the peak strength), and higher energy adsorption capacity, E_u, rather than peak strength, R_c, improvements. For two rubber types (crumbs and buffings content was R_c = 5%, 10%, 20%, and 30% at weight in the mixture of 85% kaolinite with 15% bentonite), the peak strength values in unconfined compression tests were dependent on the rubber content, peaking at R_c = 5%–10% then decreasing at higher rubber inclusions (R_c = 20%–30%). When it comes to the Eu variations, the most optimal cases are for the samples reinforced with 5% crumbs (mixtures E_u increases by 30% in relation to the natural soil E_u) and with 10% buffings (mixtures E_u increases by 57% in relation to the natural soil E_u). On the other hand, the soil reinforcement by adding the rubber causes the reduction in its stiffness (a monotonically decreasing trend with an increasing of rubber content). In relation to the natural soil, the inclusion of 5%–30% crumbs or buffings resulted in E_{50} decreasing by 22%–63% and by 31%–50%, respectively. The effects of rubber on the composite's stiffness are clearly visible and very important in the engineering design.

The discussed behaviors are explained by the fact that the growth of rubber content in the mixture (or growth of its grain size) results in the increase in the rubber effect, i.e., the capability to absorb the deformation energy. It is well known that rubber particles are more elastic than the soil. Thereby, soil-rubber waste mixtures can feature a higher plasticity than the soil itself. In the author's opinion, however, certain threshold values of confining stress can exist, after exceeding which, the influence of rubber on plasticity of the mixtures substantially decreases. Soltani et al. [37] and Zhang et al. [59] take into account the mechanical interlocking of soil particles and rubbers [37] (or jute fibers [59]) and the frictional resistance generated at the soil-rubber [37] (or jute fibers [59]) interface. At present, this issue is intensively studied by many researchers.

Based on results of tests reported in the Yadav and Tiwari [32] review, it is clearly visible that the values of the angle of internal friction and of cohesion for mixtures originating from fine-grained soil and rubber waste show various trends: they can only fall or grow, initially decline and then increase, or vice versa. At the same time, some authors were reporting growing, and others, decreasing cohesion. There is a similar situation with the effect of strengthening, which was confirmed or not. Such behavior proves that there is no clear answer to the question of how the rubber waste addition affects the soil.

Undoubtedly, the behavior of such mixture depends on the type of soil itself and on the type of rubber waste, as well as on the testing method used, which can reflect the actual conditions of the soil-rubber mixtures use. This fact proves that it is necessary to perform appropriate tests each time.

6. Conclusions

Red clay with the optimum moisture content of w_{opt} = 18% originating from the Patoka deposit is a soil featuring good strength parameters and a high swelling pressure. The addition to it of rubber waste in the form of 0–1 mm powder or 1–5 mm granulate results in specific consequences in the form of:

(1) A general decrease in the shear strength by a much higher reduction of cohesion than increase in the angle of internal friction;
(2) Various effects of shear strength decline due to the content (5%, 10%, or 15%) and the size of rubber waste particles (powder 0–1 mm or granulate 1–5 mm);
(3) Reduction of the soil-rubber mixtures density;
(4) Increase in the soil-rubber mixtures plasticity for certain ranges of confining stress;
(5) Reduction of the swelling pressure and other swelling parameters [16].

Because of that, the next possibilities of such mixtures' application appear, for example, as a material used to backfill engineering structures such as embankments or bridge abutments, founded on weak soils, for which it is very important to limit their deformations. It is worth paying attention to the fact that the above conclusions are based on tests reproducing the most unfavorable case of fast loading of the subsoil. The performance of a series of consolidated and undrained with measurement of water pressure triaxial tests (CU + u) is planned next.

Funding: This research received no external funding.

Acknowledgments: The Author would like to express her gratitude to the representatives of the tire shredding companies ORZEŁ S.A. and ATB TRUCK S.A., who delivered the rubber powder and granulate for this study free of charge. Also, the author would like to thank the students Michał Ksel and Tomasz Wolner for their valuable involvement in the performance of experimental research.

Conflicts of Interest: The author declares no conflict of interest.

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