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Article

Mechanical Behavior of Sand Mixed with Rubber Aggregates

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Abstract: The main objective of this study is to compare the mechanical behavior of two sands (Hostun or Dune sands) mixed with crushed rubber obtained from used tires. However, it is essential to ensure that his geotechnical application do not result in long-term negative impacts on the environment. The chemical properties of these two sands are given by energy dispersive analysis X-ray fluorescence spectrometry. The mineral composition of these two sands is performed by X-ray diffractometry. The morphological characteristics of the sand grains are given by the analysis of the images of the two sands given by the scanning electron microscope. This study is based on 120 direct shear tests performed on sand-rubber aggregate mixtures. The results show that the rubber content of the aggregates has a significant effect on the shear strength of sand-rubber mixtures in both cases of sand. In fact, the shear strength of the sand-rubber mixture increases with increasing crushed rubber up to 20% for different normal stresses. The analysis of the test results also shows the effect of the angular shape of the sand grains on the interparticle friction. The contribution of the structure effect in the mobilized friction is analyzed by comparing the shear test results of Hostun and dune sand mixtures.

Keywords: shear strength behavior; sand-rubber mixtures; grain sand shape; friction angle; dilatancy

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1. Introduction

The storage of used tires is already a major threat to our environment. Faced with this problem, various academic research studies propose to study the feasibility of reusing this waste via reliable and viable solutions in the long term. Few studies suggest the reuse of waste tires in the form of crumb for applications in the protection of civil infrastructure which are part of one of the possible recycling strategies. The method consists of mixing used tire powder into the soil (generally sands and silts) thus allowing the absorption of vibrations during seismic events. Indeed, the reuse of rubbers from end-of-life tires in the sand mixture can address growing environmental concerns while providing solutions to geotechnical problems associated with low ground shear strength.

Based on the studies of Edil and Bosscher, Foose et al. and Ghazavi and Sakhi [1–3]; the shear strength of sand was not improved by the addition of the granulated rubber. However, this resistance increased with the addition of shreds or chips from used tires to the sand. Table 1 shows the classification of crushed rubbers according to ASTM D 6270 [4].

Table 1. Dimensions of crushed rubbers according to ASTM D 6270 [4].

Rubber Aggregate Classes	Dimensions
Crumbs	Less than 425 μm
Aggregates	425 μm to 12 mm
Shavings	12 mm to 50 mm
Derived aggregate	12 mm to 305 mm
Shreds	50 mm to 305 mm
Large particles	Between 50 mm \times 50 mm \times 50 mm and 762 mm \times 50 mm \times 100 mm

Bali Reddy et al. [5] showed that shear strength increases with increasing rubber shred content up to 30–40% by weight and then decreases. Kim and Santamarina [6] studied the effect of the volume proportion of aggregates ($D_{50} = 3.5\text{mm}$) on the stiffness of the mixtures. They found that the sand controls the behavior of the mixture if the content by volume of the rubber aggregates is less than 30% and, for a proportion by volume of rubber which is greater than or equal to 60%, the rubber forms the backbone and thus controls the behavior of the mixture.

Other previous studies carried out in several laboratories have shown that increasing the rubber content in sand decreases the shear strength of the mixture [7–15]. Several studies [7–10] showed that the shear strength and the friction angle increase with the rubber content of tires (thinner size) up to 20%, but beyond this value the last two decrease. Ghazavi et al. [11] showed that the shear strength increased up to an optimum of 30% by volume of granulated rubber. Tiwari et al. [12] showed that the shear strength increased up to an optimum of 25% by volume and weight of rubber aggregates, respectively, and then it decreases beyond 25%. Anbazhagan et al. [13] showed that the shear strength increased up until mixtures with 20% by volume of granulated rubber (Diameter less than 9 mm), then no increase was observed. Although the shear strength decreases above 20%, it still remains higher than that of pure sand. The friction angle first increases with increasing rubber content and then decreases, while the cohesion of sand always increases with increasing rubber content. Negadi and Arab [14] showed that the shear strength and the friction angle of sand-rubber aggregates mixtures with an average relative density of the order of 55% and 95% increase with the increase in the rubber content up to 30%, then decrease beyond this value. Recently, studies by Balaban et al. [15] showed that the strength increases up to a crushed rubber content of 20% and then it decreases.

According to the work of Enquan and Qiong [16], the shear strength and the friction angle increases with the rubber content. For other experimental condition, Aksoy et al. [17] show that the friction angle increases with the rubber content up to 5% and then it decreases. Rouhanifar et al. [18] show that the shear strength of the sand-rubber mixture depends on the rubber content and the ratio between the diameter of rubber aggregates and that of sand grains. They concluded that the latter with $D_r/D_s \geq 1$ is higher than that of mixtures where $D_r/D_s < 1$ which allows us to say that the size of the rubber particles does not play a significant role. Concerning, the angle of internal friction of the mixtures, it increases with the addition of 20% of the rubber and decreases beyond. The results of the research work mentioned are summarized in Table 2.

It is also important to note that, among other rubber properties, such as the elasticity modulus has a significant impact on the mechanical behavior of sand-rubber mixtures [17]. The study of this parameter is not considered here but will be the subject of future research.

Table 2. Summary table of previous work on sand reinforcement by adding crushed rubbers.

Authors	Physical Characteristics of Sands	Physical Characteristics of Rubber	Test Conditions	Results of Experimental Tests
[1],		$D_{GR} = 20\text{--}80$ mm $\rho_{s(Rubber)} = 1.22$	4, 8.8, 15 and 25% by weight $\sigma_n = 20, 40$ and 75 kPa	The shear strength increases with increasing rubber content.
[2]	$\rho_{s(Sand)} = 2.63$	$D_{GR} = 5$ cm and 15 cm $\rho_{s(Rubber)} = 1.21$ (5 cm) $\rho_{s(Rubber)} = 1.27$ (15 cm)	10, 20, 30% by volume. $\sigma_n = 2, 6.2, 25.5$ and 41 kPa	The shear strength increases with increasing rubber content. Friction angle increases with increasing rubber content.
[3]	$\rho_{s(Sand)} = 2.63$	$D_{GR} = 2, 3$ and 4 cm $\rho_{s(Rubber)} = 1.3$	15, 30 and 50% by volume $\sigma_n = 9.8, 39.2$ and 98.1 kPa	The shear strength increases with increasing rubber content. Friction angle increases with increasing rubber content.
[5]	$\rho_{s(Sand)} = 2.62$	$D_{GR} = 20 \times 10$ mm $\rho_{s(Rubber)} = 1.08$	10 à 70% by weight $\sigma_n = 25, 75$ and 125 kPa	The shear strength increases with the rubber content up to 30% and then it decreases. The friction angle increases with the rubber content up to 30% and then it decreases
[7]	$\rho_{s(Sand)} = 2.67$;	$\rho_{s(caoutchouc)} = 1.15$	15, 30, 45, 60% by volume $\sigma_n = 100, 200, 300$ and 400 kPa ;	The shear strength increases with increasing rubber content. The friction angle increases with increasing rubber content.
[8]	$\rho_{s(Sand)} = 2.68$	$D_{GR(max)} = 2$ mm $\rho_{s(Rubber)} = 1.14$	10, 30, 50 and 100% by weight $\sigma_n = 50, 100$ and 200 kPa	The shear strength decreases with increasing rubber content. The friction angle decreases with increasing rubber content.
[9]	$\rho_{s(coarse\ Sand)} = 2.68$ $\rho_{s(fine\ Sand)} = 2.60$	Rubbercrumbs	5, 10, 20 and 50% by weight $\sigma_n = 28, 42, 68$ kPa	The shear strength decreases with increasing rubber content. The friction angle decreases with increasing rubber content.
[10]	$\rho_{s(Sand)} = 2.74$	$D_{GR} = 1\text{--}4$ mm $\rho_{s(Rubber)} = 1.16$	10, 20, 30, 40, 50% by weight $\sigma_n = 29, 56$ and 110 kPa $Dr = 70\%$	The shear strength increases with the rubber content up to 20% and then it decreases. The friction angle increases with the rubber content up to 20% and then it decreases
[11]	$\rho_{s(Sand)} = 2.67$	$D_{GR} = 1\text{--}10$ mm $\rho_{s(Rubber)} = 1.20$	15, 25, 30, 35 and 100% by volume $\sigma_n = 30, 60$ and 90 kPa	The shear strength increases with the rubber content up to 30% and then it decreases. The friction angle increases with the rubber content up to 30% and then it decreases
[12]	$\rho_{s(Sand)} = 2.66$	$D_{GR} = 0.8\text{--}2$ mm $\rho_{s(Rubber)} = 1.13$	25, 50 and 75% by weight $\sigma_n = 20, 50$ and 100 kPa	The shear strength increases with the rubber content up to 25% and then it decreases. The friction angle increases with the

				rubber content up to 25% and then it decreases.
[13]	<p>Sable A: $D_{max} = 4.75$ mm</p> <p>Sable B: $D_{max} = 2$ mm $\rho_{s(Sand A)} = 2.65$ $\rho_{s(Sand B)} = 2.64$</p>	<p>Group 1: $D_{GR} = 1-2$ mm</p> <p>Group 2: $D_{GR} = 2-4.75$ mm</p> <p>Group 3: $D_{GR} = 4.75-5.6$ mm</p> <p>Group 4: $D_{GR} = 5.6-8$ mm</p> <p>Group 5: $D_{GR} = 8-9.5$ mm</p> <p>Group 6: $D_{GR} = 9.5-12.5$ mm</p> <p>Group 7: $D_{GR} = 12.5-20$ mm</p> <p>$\rho_{s(Group 1)} = 1.11$ $\rho_{s(Group 2)} = 1.13$ $\rho_{s(Group 3)} = 1.14$ $\rho_{s(Group 4)} = 1.14$ $\rho_{s(Group 5)} = 1.16$ $\rho_{s(Group 6)} = 1.17$ $\rho_{s(Group 7)} = 1.16$</p>	<p>10, 15, 20, 25, 30 and 35% by volume.</p> <p>$\sigma_n = 16, 32$ and 80 kPa.</p>	<p>The shear strength increases with the rubber content up to 20% and then it decreases for groups 1, 2, 3 and 4.</p> <p>The shear strength increases with the rubber content up to 30% and then it decreases for groups 5, 6 and 7.</p>
[14]	$\rho_{s(Sand)} = 2.665$	<p>$D_{GR} = 1-5$ mm</p> <p>$\rho_{s(Rubber)} = 1.085$</p>	<p>5, 10, 15, 20 and 30% by weight.</p> <p>$\sigma_n = 100$ kPa.</p>	<p>$Dr = 55\%$: The friction angle increases with the rubber content up to 15% and then it decreases.</p> <p>$Dr = 95\%$: The friction angle increases with the rubber content up to 10% and then it decreases.</p>
[15]	$\rho_{s(Sand)} = 2.9$	<p>$D_{GR} = 1-6$ mm</p> <p>$\rho_{s(Rubber)} = 1.15$</p>	<p>10, 20 and 30% by weight.</p> <p>$\sigma_n = 9.81, 19.62, 40.81$ and 58.86 kPa</p>	<p>The shear strength increases with the rubber content up to 20% and then it decreases for stresses ranging from 19.62; 40.81 and 58.86 kPa.</p> <p>For a low stress of 9.81 kPa, the optimum is 10%. The friction angle increases with the rubber content of 20%</p>
[16]	<p>$D_{max} = 5$ mm</p> <p>$\rho_{s(Sand)} = 2.68$</p>	<p>$D_{GR} = 1-5$ mm</p> <p>$\rho_{s(Rubber)} = 1.21$</p>	<p>5, 10 and 15% by weight.</p> <p>$\sigma_n = 100, 200, 300$ and 400 kPa</p> <p>$Dr = 50\%$</p>	<p>The shear strength increases with the rubber content.</p> <p>The friction angle increases with the rubber content</p>
[17]	<p>$D_{max} = 9.5$ mm</p> <p>$\rho_{s(Sand)} = 2.74$</p>	<p>$D_{GR} = 0.075-2.5$ mm</p> <p>$\rho_{s(Rubber)} = 1.153 / 1.198$</p>	<p>2.5, 5, 7.5 and 10% by weight</p> <p>0.556, 1.1111 and 1.667 kg/cm²</p>	<p>The friction angle increases with the rubber content up to 5% and then it decreases</p>
[18]	<p>$D_{max} = 1.25$ mm</p> <p>$\rho_{s(Sand)} = 2.65$</p>	<p>$D_{GR} = 0.075-0.3$ mm</p> <p>$D_{GR} = 0.3-1.25$ mm</p> <p>$D_{GR} = 1.2-5$ mm</p> <p>$\rho_{s(Rubber)} = 1.04$</p>	<p>5, 10, 15, 20, 25, 30, 40 and 50% by volume</p> <p>$\sigma_n = 50, 100$ and</p>	<p>The shear strength increases with the rubber content up to 20% and then it decreases.</p> <p>The friction angle increases with the</p>

150 kPa $D_r = 30\%$	rubber content up to 20% and then it decreases for $D_{GR}/D_{sand} < 1$. The friction angle for $D_{GR}/D_{sand} < 1$ is less than when the ratio $D_{GR}/D_{sand} > 1$
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Environment Impact

The mixed of rubber aggregates to the sand for geotechnical engineering applications is of great value for the mechanical properties of soils. However, it must be ensured that the rubber granulate do not have a negative environmental impact (soil and groundwater contamination). Indeed, the decomposition of tire rubber give lot of chemical elements such as aluminum, zinc, chromium, iron, lead, manganese, sulfur, black carbon and pigments [19,20]. Many researchers have shown that leaching from rubber occurs as a function of the environment PH and harmful metals are released more under acidic PH conditions [21–23]. Other research has shown that the degradation of tire rubber is related to two main factors: the first one is the action of bacteria that feed on the petroleum products in the rubber and the second one is the exposure of the rubber to the ultraviolet rays.

Concerning the effect of temperature on the mechanical behavior of rubber, Humphrey [24] showed that the oxidation of the metal filaments present in the tires is the main cause of the exothermic reaction. It is also noted that Yoon et al. [25] carried out a monitoring of temperature measurements for one year, in a construction of an embankment based on a sand-rubber mixture, in order to check the development of exothermic reactions. This work concluded that no internal heat generation was detected whatever the weather conditions.

According to the art state discussed above, tire aggregates associated with soils are far from being hazardous to the environment. Indeed, decomposition of these aggregates cannot occur because the action of microbes is inhibited by the presence of zinc oxides in the rubber [26] while exposure to ultraviolet light is completely avoided because the aggregates are buried in the subsoil [27,28].

In all problems of soil stability, it is necessary to know its shear strength. This resistance is very complex because it depends on several parameters including the grains shape, saturation and others.

The objective of this work is to study the mechanical behavior of two types of sands (Hostun and Dune sands) mixed with rubber aggregates at different content ranging from 0 to 30%. The two sands have a grain different morphology: angular grains for Hostun sand and sub-rounded for the Dune sand. Shear tests are performed on 120 samples to study the effect of the angular and sub-rounded character of the grains on the mechanical behavior of the sand-aggregate mixtures.

2. Materials and Methods

2.1. Materials

The materials used in this work are Hostun sand, Dune sand and rubber aggregates from used tires, their characteristics are summarized below.

2.1.1. Hostun Sand

The sand used in the present study considered a reference material in many laboratories in France. The physical and chemical characteristics of this sand were determined in our laboratory (Tables 3 and 4). The sand belongs to the category of fine sands with a uniform and well graded grain size. The sand has an average grain size $D_{50} = 0.32$ mm; the void ratio can vary between $e_{min} = 0.752$ and $e_{max} = 1.006$ and the specific density of the grains is $\rho_s = 2.625$ g/cm³ determined by the pycnometer method NF P94-054 [29] and NF P94-512-3 [30]. The grain size curve of this sand was obtained based on NF P94-056 [31].

Figure 1 shows the grain size distribution of the sand. Figure 2a–c shows a microscopic view (SEM) of the Hostun sand under study.

Table 3. Physical characteristics of used Hostun and Dune sands and granulated rubber.

Materials Under Study	Hostun Sand	Dune Sand	Granulated Rubber 2 mm < DGR < 5 mm
D_{10} (mm)	0.22	0.125	2.55
D_{30} (mm)	0.28	0.22	2.95
D_{50} (mm)	0.32	0.24	3.35
D_{60} (mm)	0.34	0.25	3.55
C_u (/)	1.55	2.00	1.39
C_c (/)	1.05	1.55	0.96
ρ_s (g/cm ³)	2.625	2.982	1.129
ρ_{dmax} (g/cm ³)	1.498	1.97	0.59
ρ_{dmin} (g/cm ³)	1.309	1.76	0.53
e_{max} (/)	1.006	0.697	1.112
e_{min} (/)	0.752	0.514	0.908

Table 4. Chemical characteristics of Hostun and Dune sands by X-ray fluorescence spectrometry.

Chemical Composition (%)	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
Hostun sand	73.73	0.01	0.80	0	0.01	0	0.11	0.19	0.13	0.01
Dune sand	21.71	8.54	4.09	30.97	0.25	3.45	29.33	0.63	0.56	0.50

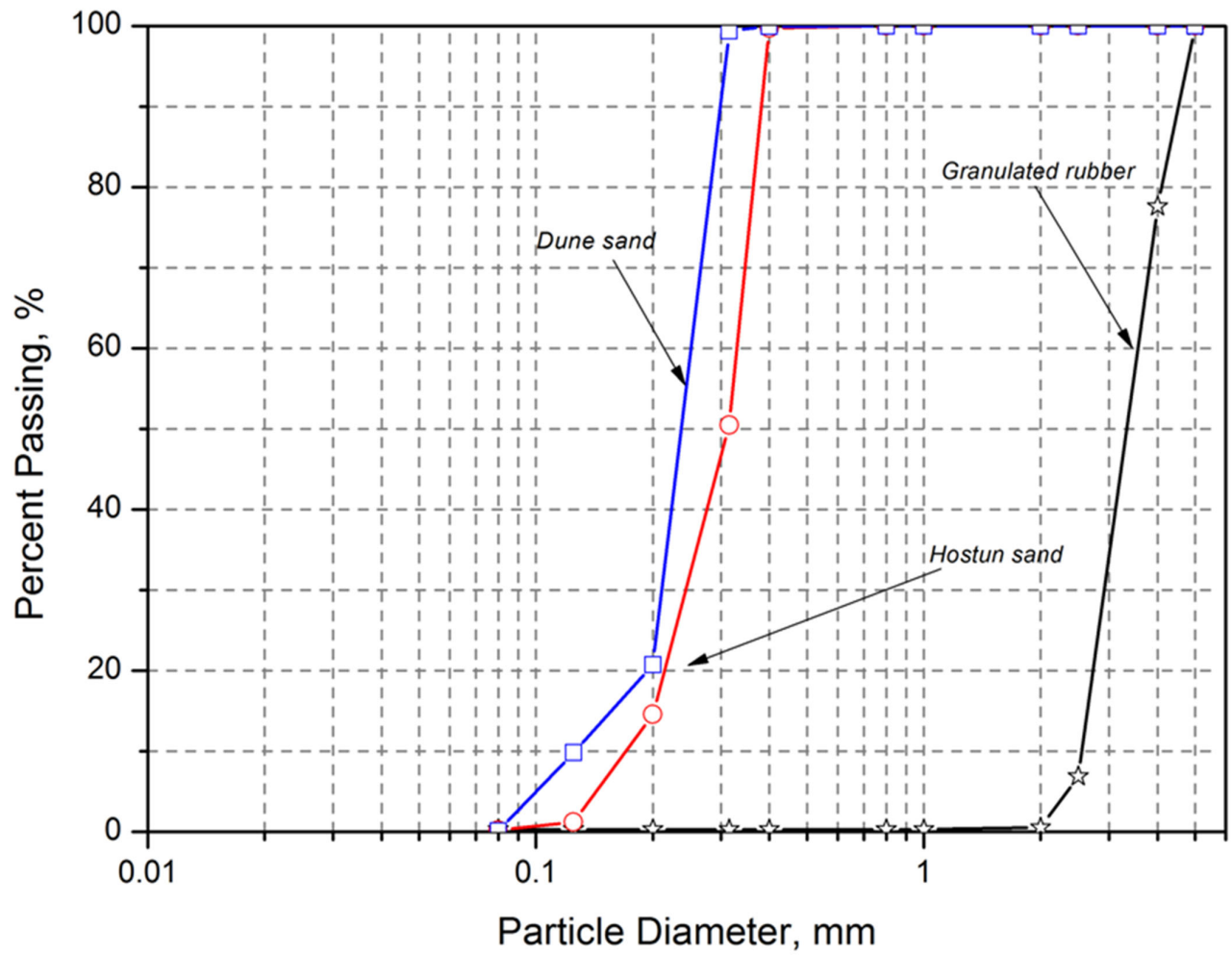


Figure 1. Particle size distribution of testing materials.

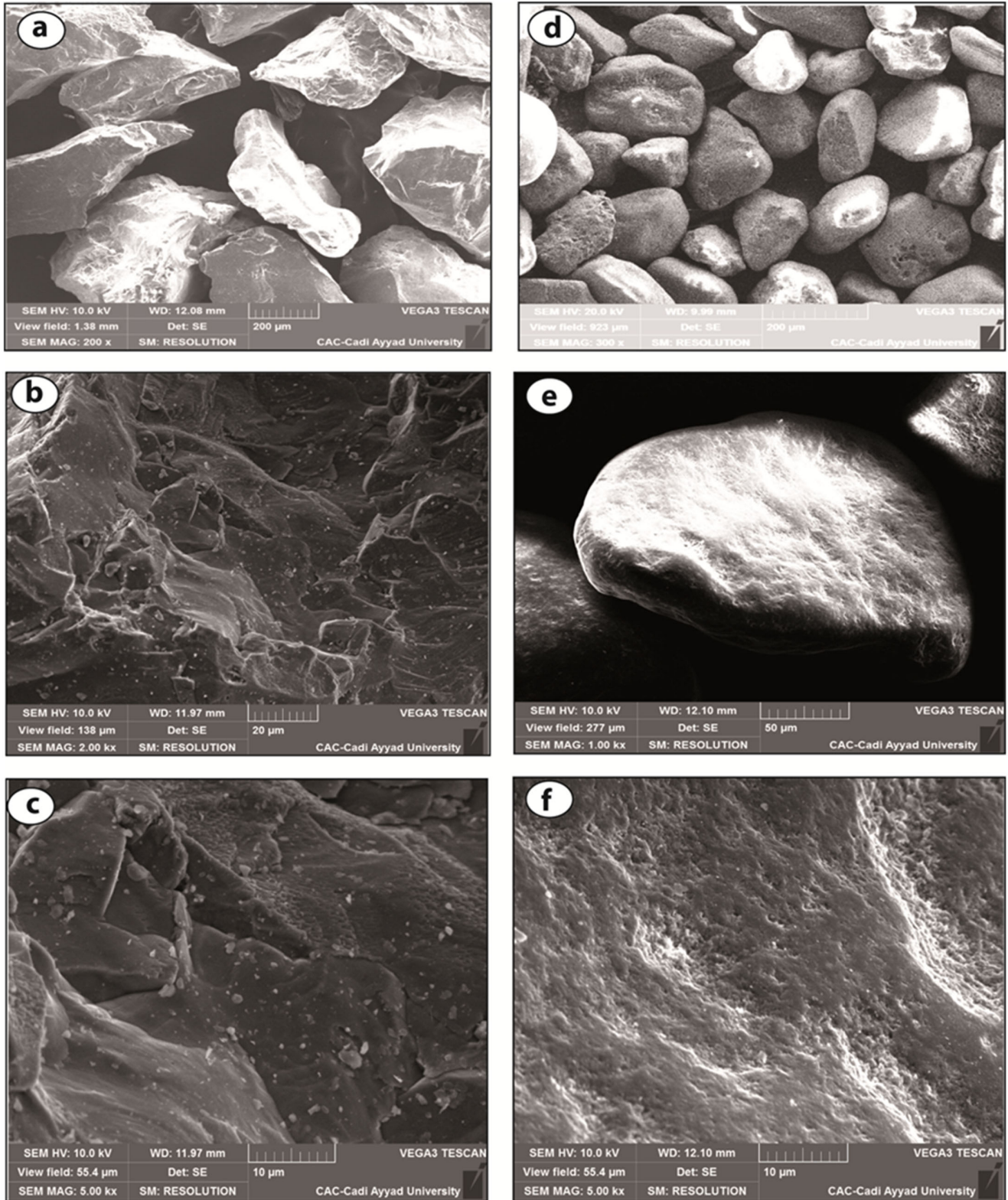


Figure 2. SEM Microscopic view of the Hostun sand (a–c), Dune sand (d–f) at different scale.

2.1.2. Dune Sand

The sand comes from the consolidated dunes of the Middle Quaternary at Sidi Ahmed Essayeh (province of Essaouira region of Marrakech-Tensift-Al Haouz in Morocco)

(Figure 3). The physical and chemical characteristics of this sand were determined in our laboratory (Tables 3 and 4). The sand belongs to the category of fine sands with a uniform and well graded grain size. The sand has an average grain size $D_{50} = 0.24$ mm; the void ratio can vary between $e_{min} = 0.514$ and $e_{max} = 0.697$ and the specific density of the grains is $\rho_s = 2.982$ g/cm³ determined by the pycnometer method NF P94-054 [29] and NF P94-512-3 [30]. The granulometric analysis carried out according to NF P94-056 [31]. The grain size curve of this sand is shown in Figure 1. Figure 2d–f) shows a microscopic view (SEM) of the dune sand under study.

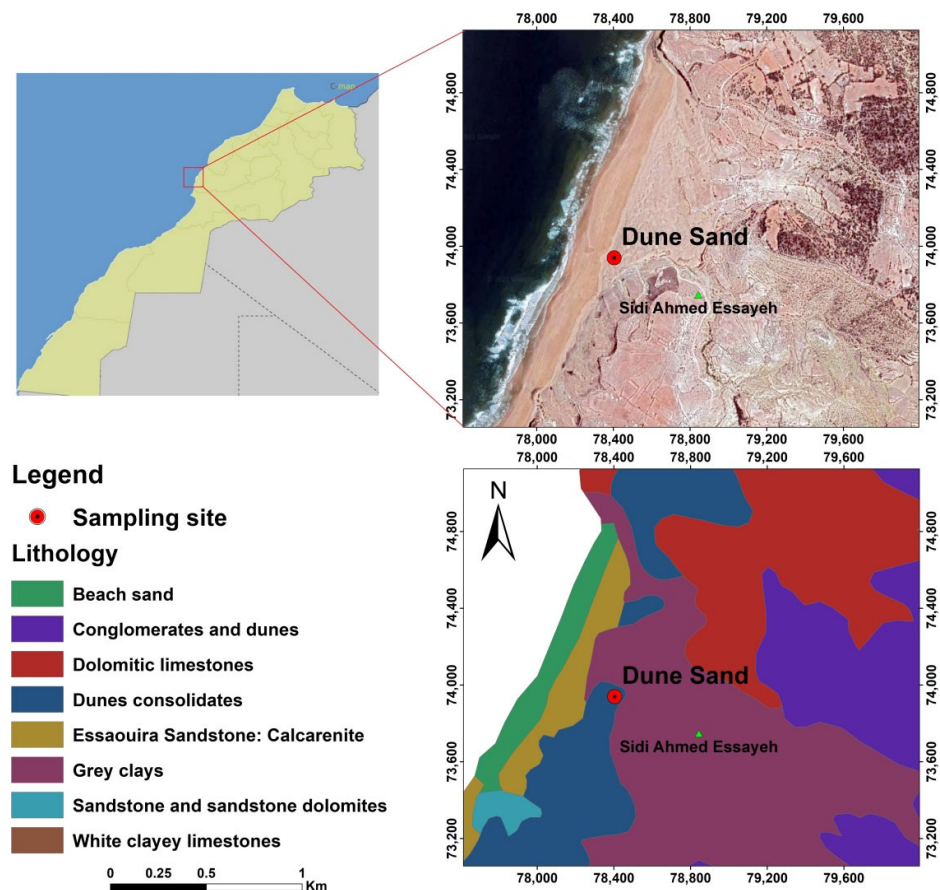


Figure 3. Localization Map of Dune sand site.

2.1.3. Aggregate Rubber

The physical characterization of aggregate rubber samples having different diameters varying from 2 to 5mm with an average diameter $D_{50} = 3.35$ mm requires the determination of various parameters such as: the water content, the specific density of the solid grains, the maximum density ρ_{dmax} (or minimum void index) and the minimum density ρ_{dmin} (or maximum void index). To determine the water content of the “aggregate rubber” sample, the drying method in an oven was used, according to the experimental standard NF P94-050 [32]. The result obtained for the tested sample showed that the water content is around 0.5%. In addition, the determination of the specific density of the solid grains is carried out using the pycnometer method NF P94-054 [29] and NF P94-512-3 [30]. The result obtained for the sample tested showed that the specific density of the solid grains is 1.129 g/cm³. The determination of the minimum density ρ_{dmin} and maximum density ρ_{dmax} of the soils was carried out in accordance with standard NF P 94-059 [33].

The test consists in implementing materials to be studied in a mold successively in a loose state (ρ_{dmin}) and in a dense state (ρ_{dmax}). The void ratio is calculated by the following Equations (1) and (2):

$$e_{max} = \frac{\rho_s}{\rho_{dmin}} - 1 \quad (1)$$

$$e_{min} = \frac{\rho_s}{\rho_{dmax}} - 1 \quad (2)$$

The granulometric analysis carried out according to NF P94-056 [31]. The particle size distribution curve of aggregate rubber is shown on Figure 1. Figure 4 shows picture of the rubber aggregates used and which are differentiated by their geometric characteristics.

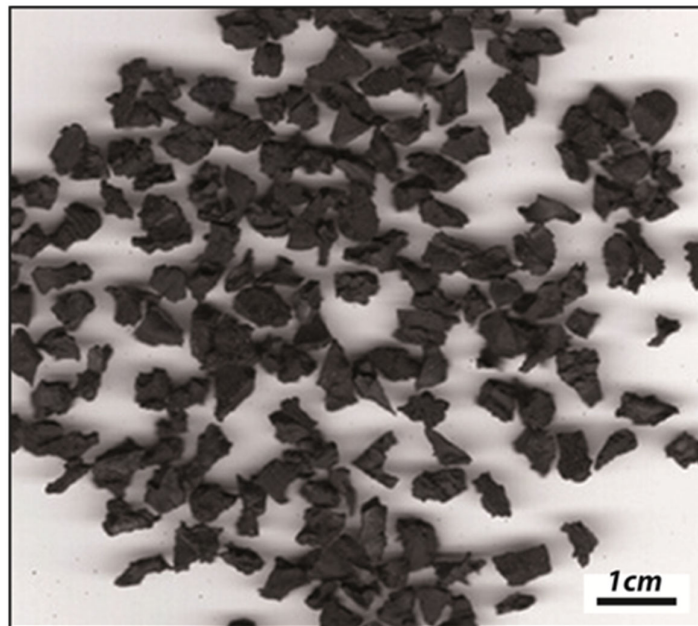


Figure 4. Picture rubber aggregates with $2 \text{ mm} < DGR < 5 \text{ mm}$.

For these two sands tested in this study, the results obtained by X-ray fluorescence spectrometry (Epsilon 4 Benchtop XRF-EDS. It is an energy dispersive spectrometer with a 4000 to 50.000 KV X-ray generator and an Ag (silver) anode) showed that the most dominant chemical elements for Hostun sand is SiO_2 and for the Dune sand is SiO_2 , Fe_2O_3 and CaO . The mineral composition of these two sands is determined by X-Ray Diffractometer (Rigaku-Smart Lab diffractometer). Figure 5 shows that the Hostun sand is composed of Quartz mineral while the Dune sand is composed of Quartz, Calcite, Dolomite and Feldspath K+ Plagioclases minerals (Figure 6). The scanning electron microscope (Vega3 Tescan) shows that Hostun sand is a highly angular particles (Figure 2a–c), while Dune sand is composed of subrounded to rounded particles (Figure 2d–f). Both sands are uniformly graded as can be seen from the particle size distribution curves given in Figure 1. The morphological aspect and shape characteristics of the rubber aggregates are shown in the Figure 4. The physical properties and chemical characteristics of materials used are summarizes in the Tables 3 and 4.

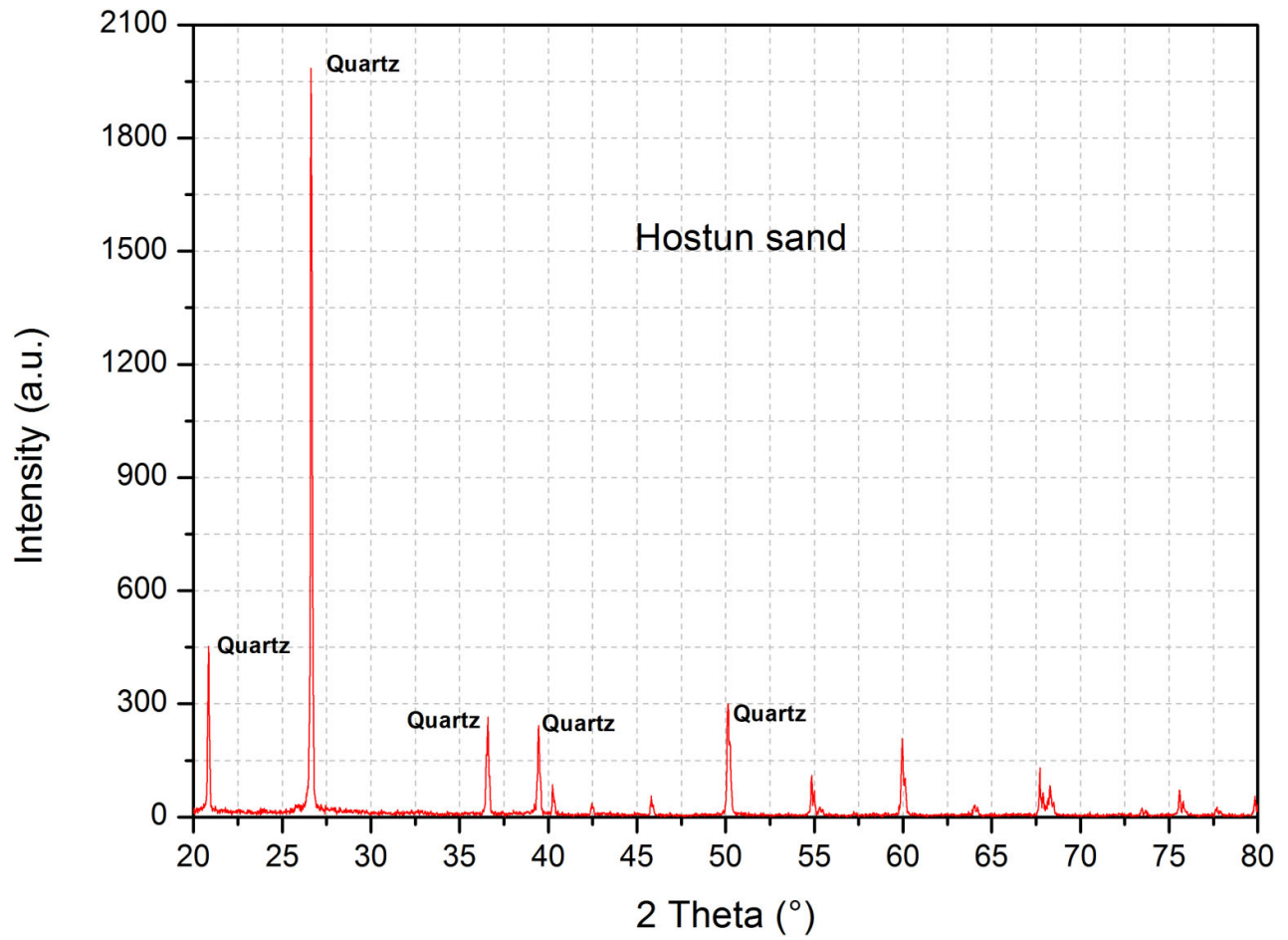


Figure 5. The X-ray diffractometer of Hostun sand used.

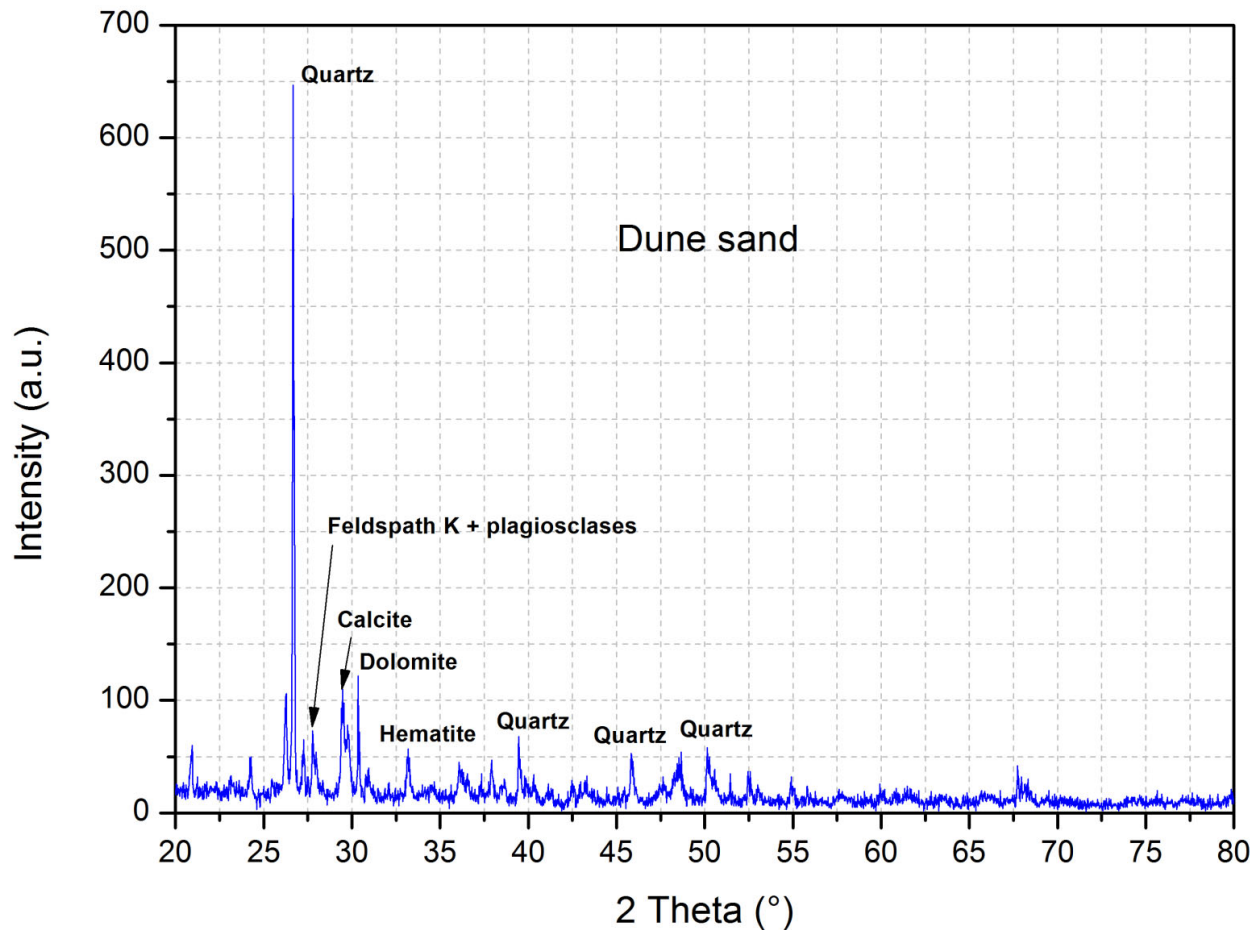


Figure 6. The X-ray diffractometer of Dune sand used.

2.2. Methods

Standard Direct Shear Test and Sample Preparation

In this study, a shear box was used to perform all standard direct shear tests on samples containing sand/rubber mixtures according to NFP94-071-1 [34]. The rectilinear shear tests carried out with the box allow the determination of the effective shear resistance parameters of soils. The test method is to place the sand-rubber mixture (Hostun sand and Dune sand) in a dry state in the mold of the direct shearing apparatus having a square section of side 60 mm and height of 30 mm, and then put it under normal stresses of 100, 200 and 400 kPa. The horizontal boxes containing the mixture are then separated and a displacement at a constant strain rate of 1 mm/min is imposed on one of the two half-boxes. The vertical and horizontal displacements as well as the generated shear force are measured during the shearing of the sample. The shear box is equipped with force and displacement sensors. The precision of the servocontrol allows a measurement of the shear load on the sample up to 5000 N with an accuracy of around 50 N. Regarding horizontal and vertical displacements are measured with a 25 mm sensor for the first and 10 mm for the second with a measurement accuracy of around 0.01 mm. The influence of the crushed Rubber Content (RC), vertical normal stress of 100, 200 and 400 kPa on the shear strength of the dry sand-rubber mixture was studied. Laboratory sample preparation was performed based on maximum and minimum void ratio sand relative density (D_r). The mass of the mixture (m_s) to be placed in the direct shear cell is evaluated as a function of the desired relative density by Equation (4) (the initial volume of the sample is known), the density state of the sample being defined by the relative density D_r :

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \quad (3)$$

$$m_s = \frac{V_T \times \rho_s}{1 + e_{max}(1 - D_r) + D_r \times e_{min}} \quad (4)$$

where: ρ_s is the specific density of solid grains, e_{min} and e_{max} are, respectively, the minimum and maximum void ratios, V_T is the volume of the sample, D_r is the desired relative density.

One of the factors that can influence the experimental results is segregation. To avoid it, necessary precautions were taken when filling the mold of the shear box. We pour the quantity of the mixture (m_s) in three layers in the shear box with a funnel; and continuing to mix the material until it's filled. Then normal stresses are applied and the samples are sheared. The experimental program included direct shear tests which were carried out for sand with different percentages of crushed rubber ranging from 0% to 30% by weight to study the influence of the presence of rubber aggregates on the shear strength of sands (Table 5).

Table 5. Designations for the different mixtures; Hostun or Dune sand-Rubber.

Designations	Sand-Rubber
RC0	100% Sand + 0% Rubber
RC10	90% Sand + 10% Rubber
RC20	80% Sand + 20% Rubber
RC30	70% Sand + 30% Rubber

3. Results and Discussion

3.1. Effect of Aggregate Rubber Content on Shear Strength of Sand

Figures 7 and 8 represent an example of material response as a function of relative horizontal strain for the different procedures, namely Hostun sand-Rubber and Dune sand-Rubber. These direct shear tests were performed for different aggregate rubber contents ranging from 0% to 30% under an applied normal stress of 100 kPa. It is found that the presence of aggregate rubber significantly affects the shear stress where a maximum shear stress is observed for both sands. The shear stress of the sand-rubber mixtures in both cases still tends to increase slightly up to 20% crushed rubber content. The mixtures exhibit a typical behavior of a medium dense sand ($D_r = 55\%$), with no drop-in strength after maximum for the Hostun sand, but for the Dune sand there is a remarkable drop-in strength. It clearly shows that the presence of additional crushed rubber in both sands leads to an improvement in the strength of the sand. Therefore, it can be concluded that the addition of aggregate rubber can significantly improve the shear strength of the mixtures. The increase in the shear strength of the mixtures with the increase in the aggregate rubber content can be attributed to the redistribution of the samples. Thus, the grains of sand are pushed towards the grains of rubber which deform and increase the contact surface between the particles of sand and the grains of rubber. An additional aggregate rubber 30% content increased the shear strength of pure sands, but it decreased compared to 20%. This is because in the shear zone the rubber grains surround the sand grains and tends to roll and slide over them to create more voids. While higher normal stresses cause shrinkage rather than swelling and therefore the mixture becomes more and more compact.

It is also showing that for Dune sand mixed with aggregate rubber, after the initial shear at low horizontal strain, less significant dilation occur as the mobilized shear stress approaches its maximum value. In contrast, for Hostun sand mixed with rubber aggregates, when the horizontal deformation is less than 0.25%, the shear stress increases quickly. Additional shear induces a significant expansion but a relatively small change in

shear stress, resulting in a “plateau” on the stress-horizontal strain curves. As a comparison between Hostun sand and Dune sand, it is observed that Hostun sand/rubber mixture requires larger horizontal deformations to mobilize the maximum shear strength than Dune sand of the same relative density, but the post-maximum strain softening after is gentler than that of Dune sand-rubber mixture.

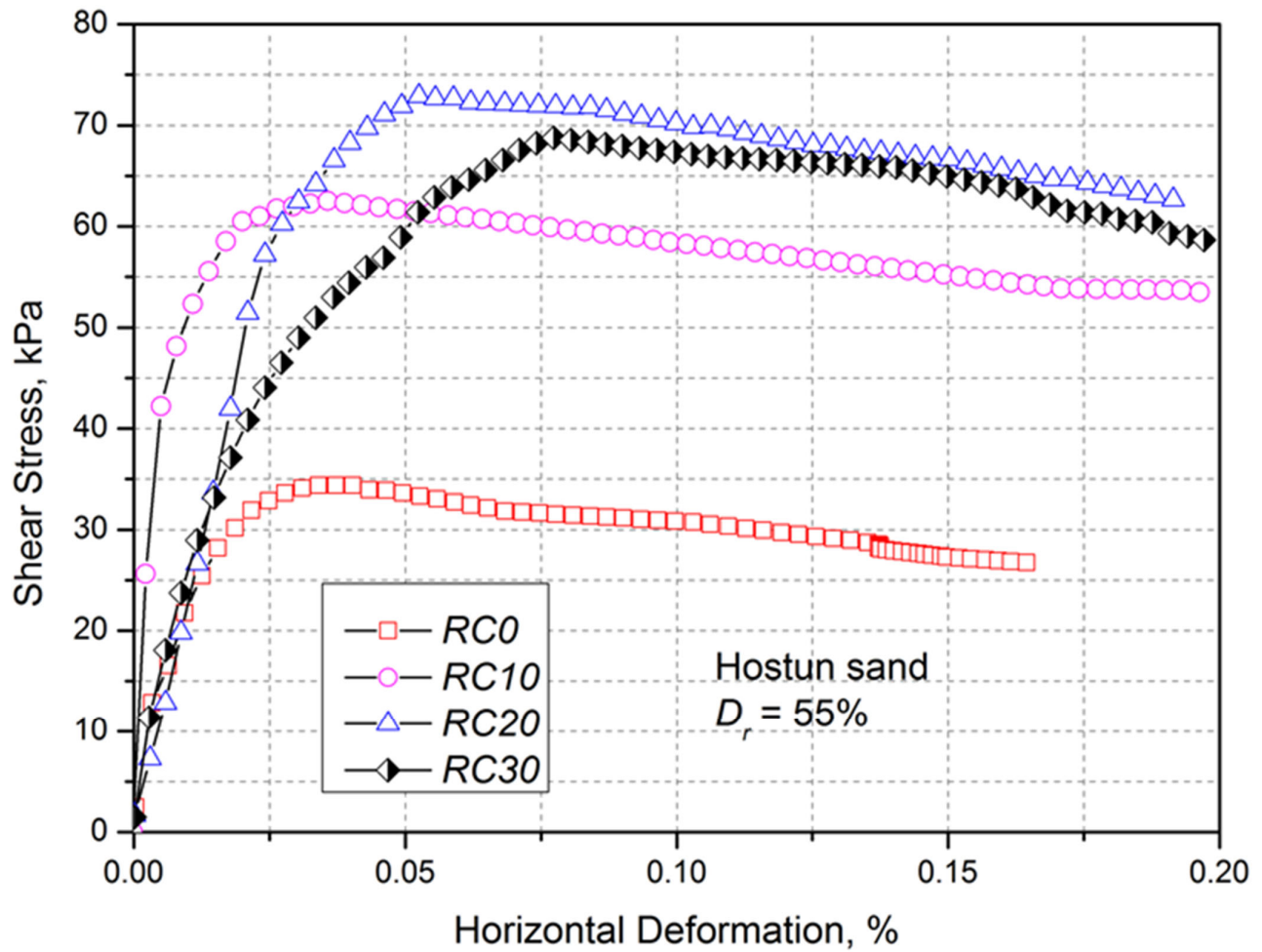


Figure 7. Shear stress variation curves for different rubber contents under a normal stress of 100 kPa.

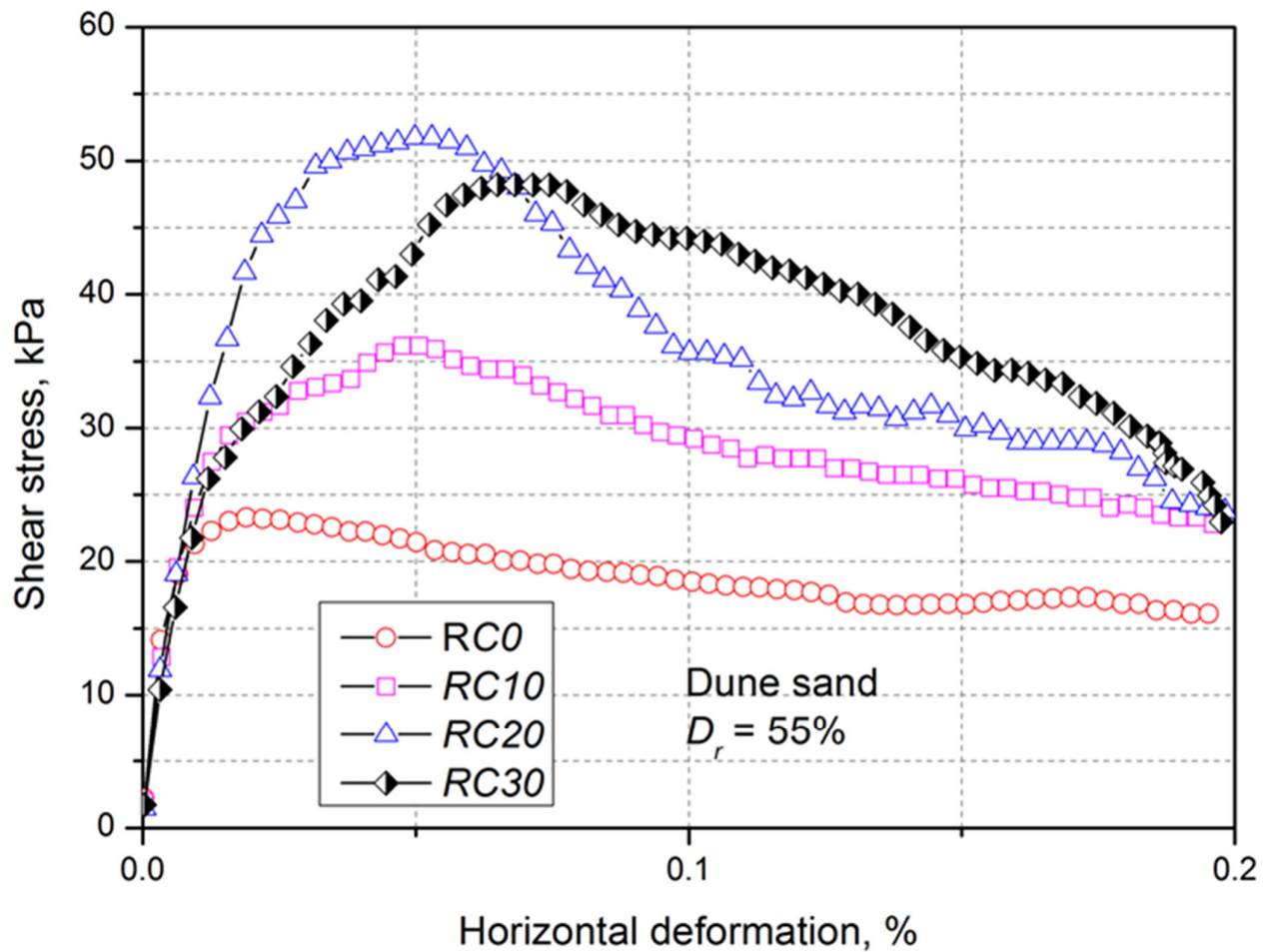


Figure 8. Shear stress variation curves for different rubber contents under a normal stress of 100 kPa.

Regarding vertical deformation as a function of the horizontal deformation (Figures 9 and 10), it is noted that the dilatant character of the mixtures increases with the increase in the rubber content. All lightly compacted sand-rubber mixtures expand under the effect of shear stress. It is also noted that, for pure sand and the 10% aggregate rubber mixture, the expansion phase appears from low horizontal deformation, while for samples with rubber content of 20% to 30% the dilatancy is delayed and appears from a relatively high horizontal strain. This result is in accordance with the results obtained for the sands which showed that the presence of rubbers amplifies the dilatant character of the sand-rubber mixture.

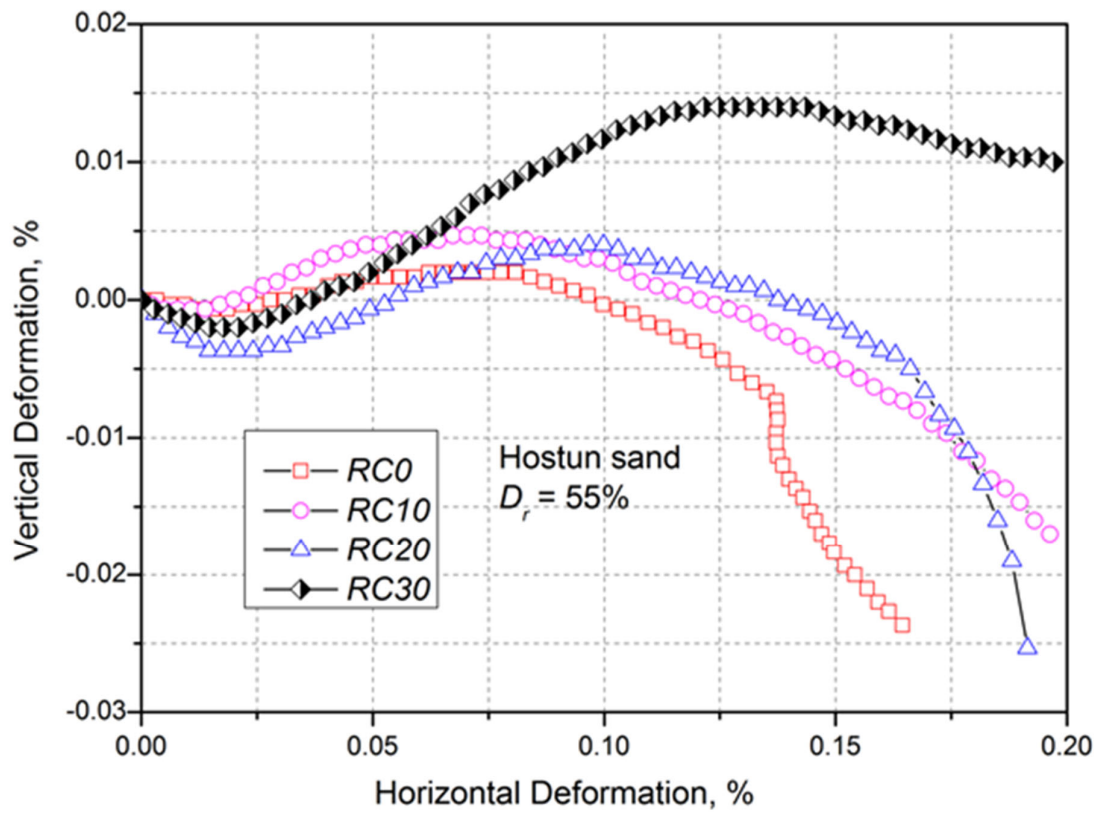


Figure 9. Vertical deformation as a function of the horizontal deformation for different rubber contents under a normal stress of 100 kPa.

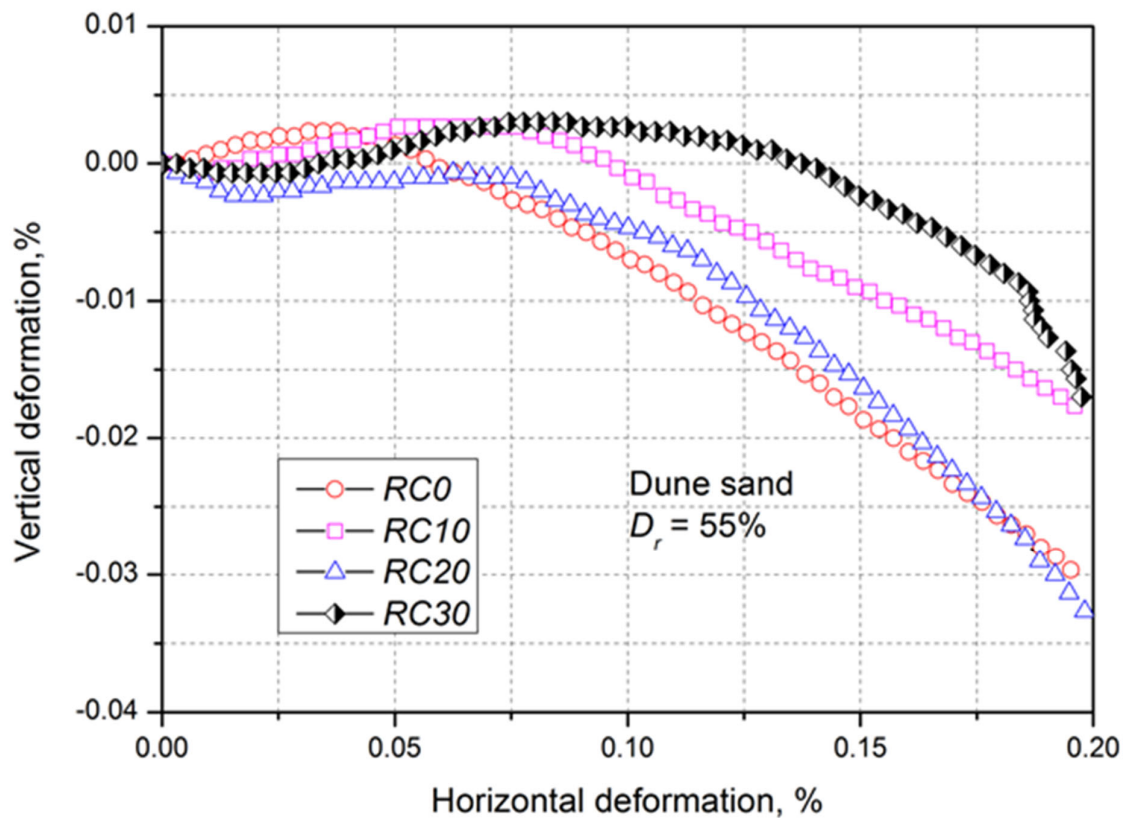


Figure 10. Vertical deformation as a function of the horizontal deformation for different rubber contents under a normal stress of 100 kPa.

3.2. Effect of Normal Stress on Shear Strength of Sand

The dilation of the mixtures increases with increasing rubber content. All lightly compacted sand/rubber mixtures expand under the effect of shear stress. Direct shear tests were carried out on different percentages of rubbers between zero (pure sand) and 30% for three normal stresses (100, 200 and 400 kPa). It is noted that the shear strength of the unreinforced sand and of the sand/rubber mixtures increases considerably with the increase of the normal stress and this shear strength of the mixture becomes greater under higher normal stress (Figure 11). This increase is due to the modification of the microstructure of the mixtures which will generate an improvement in the contacts between the particles, namely the friction angle as already mentioned by Kim and Santamarina [6].

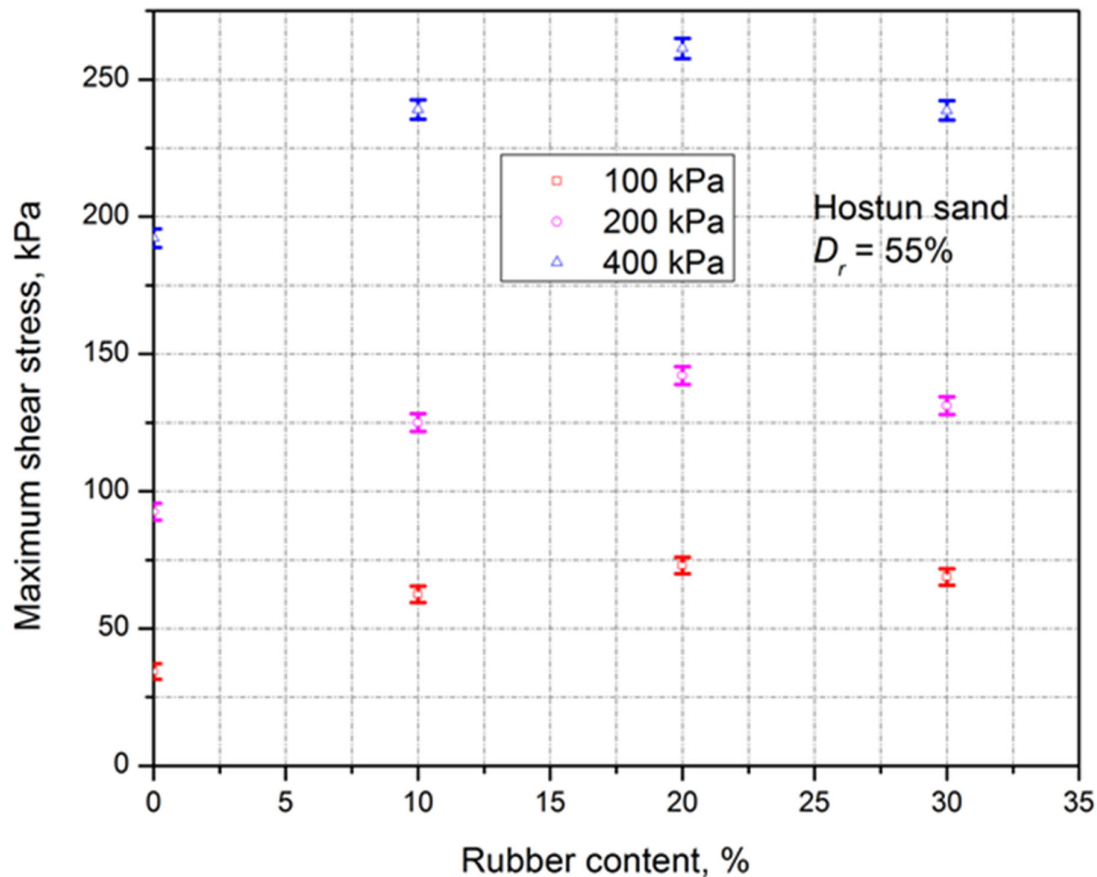


Figure 11. Maximum shear stress in terms of rubber content for Hostun sand.

3.3. Effect of Rubber Content on Maximum Shear Strength of Sand

Figure 12 shows the variation of the maximum shear stress as a function of the rubber content of the crushed tires ranging from 0 to 30%. It's clear that the maximum shear strength of these two sands increased significantly with the addition of rubber content. Indeed, with a rubber content of 20%, the shear strength of Hostun sand and Dune sand has increased from 34.39 ± 2.89 kPa to 72.92 ± 3.02 kPa and from 23.28 ± 2.86 kPa to 51.72 ± 2.95 kPa, respectively, under normal stress of 100 kPa. Beyond this value, the maximum shear strength for these two sands decreased for a rubber content of 30% but it always remains superior to that of pure sand. In fact, the shear strength Hostun sand and Dune sand increased from 34.39 ± 2.89 kPa to 68.75 ± 3.01 kPa and from 23.28 ± 2.86 kPa to $48,194 \pm 2.94$ kPa, respectively, for a rubber content of 30% under a stress of 100 kPa. The shear strength of these two sands is totally dependent on the friction between the particles. The presence of the aggregate rubber material affects the friction between the sand and rubber particles. The increase in maximum shear strength associated with 20% is related to the filling of the voids between the sand particles by the rubber aggregates, which will subsequently prevent the sand particles from moving or sliding easily during the direct shear test; and therefore, sand/aggregate rubber mixtures exhibit higher strength values. Note that the 20% aggregate rubber content is likely to be the optimum content. However, the decrease in maximum shear strength which has occurred in sand when the rubber content is greater than equal to 30% is attributed to the fact that the rubber material can be deformed significantly under the applied normal stress. In addition, the particles in the high rubber content mixtures can move and slide easily during the shear test; and therefore, the blends exhibit lower values of shear

strength. This variation in maximum shear strength as a function of the rubber content of the tires can be explained by the variation of the void ratio of the sand/rubber mixtures as a function of the rubber content.

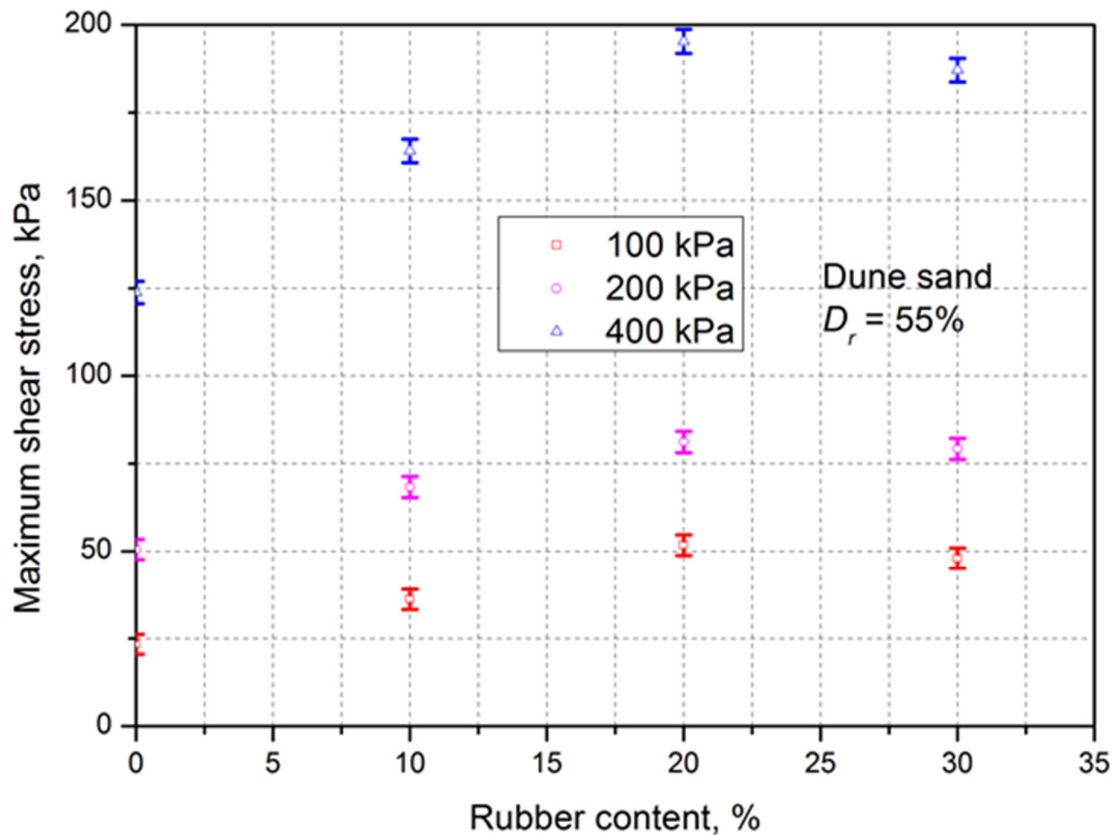


Figure 12. Maximum shear stress in terms of rubber content for dune sand.

Figure 13 shows the variation of the friction angle as a function of the rubber content for a medium relative density ($D_r = 55\%$). It is observed that the addition of aggregate rubber up to 20% can increase the initial friction angle of Hostun sand from $27.57^\circ \pm 1.02^\circ$ to $31.94^\circ \pm 0.62^\circ$ and Dune sand from $18.75^\circ \pm 1.02^\circ$ to $26.18^\circ \pm 0.83^\circ$. However, for a content of 30% aggregate rubber which is added to sand decreases the friction angle from $27.57^\circ \pm 1.02^\circ$ to $29.36^\circ \pm 0.65^\circ$ for Hostun sand and from $18.75^\circ \pm 1.02^\circ$ to $25.38^\circ \pm 0.85^\circ$ for Dune sand. This is explained since in the shear zone by rubber particles surrounding the sand grains and creating more voids. Therefore, the rubber grains mainly control the friction between the particles. These results agree with the results obtained in previous work, in particular that of Tiwari et al. [12]. This difference in the friction angle of Hostun sand and Dune sand mixed with aggregate rubber may also be attributed to the effect of particle shape of the sand. Since the angularity of particles causes more antiparticle locking that restrains relative sliding and rotation between particles. A greater shear stress is required for Hostun sand than for Dune sand to break the interlocking owing to particle angularity before relative particle movement associated with dilation can take place, which also implies that the mobilized shear strength is a combination of dilation and interparticle locking. It should be noted that dilation tends to degrade inter-particle locking; the “plateau” on the stress-strains curves is the consequence of coupled effects of dilation and the degradation of interlocking.

More specifically, the interlocking is degraded with increasing horizontal strain, which reduces the shear strength of the sand. On the other hand, the mobilized expan-

sion tends to enhance the strength of the material. Therefore, the coupling of dilation and interlocking degradation shear strength with continued shear.

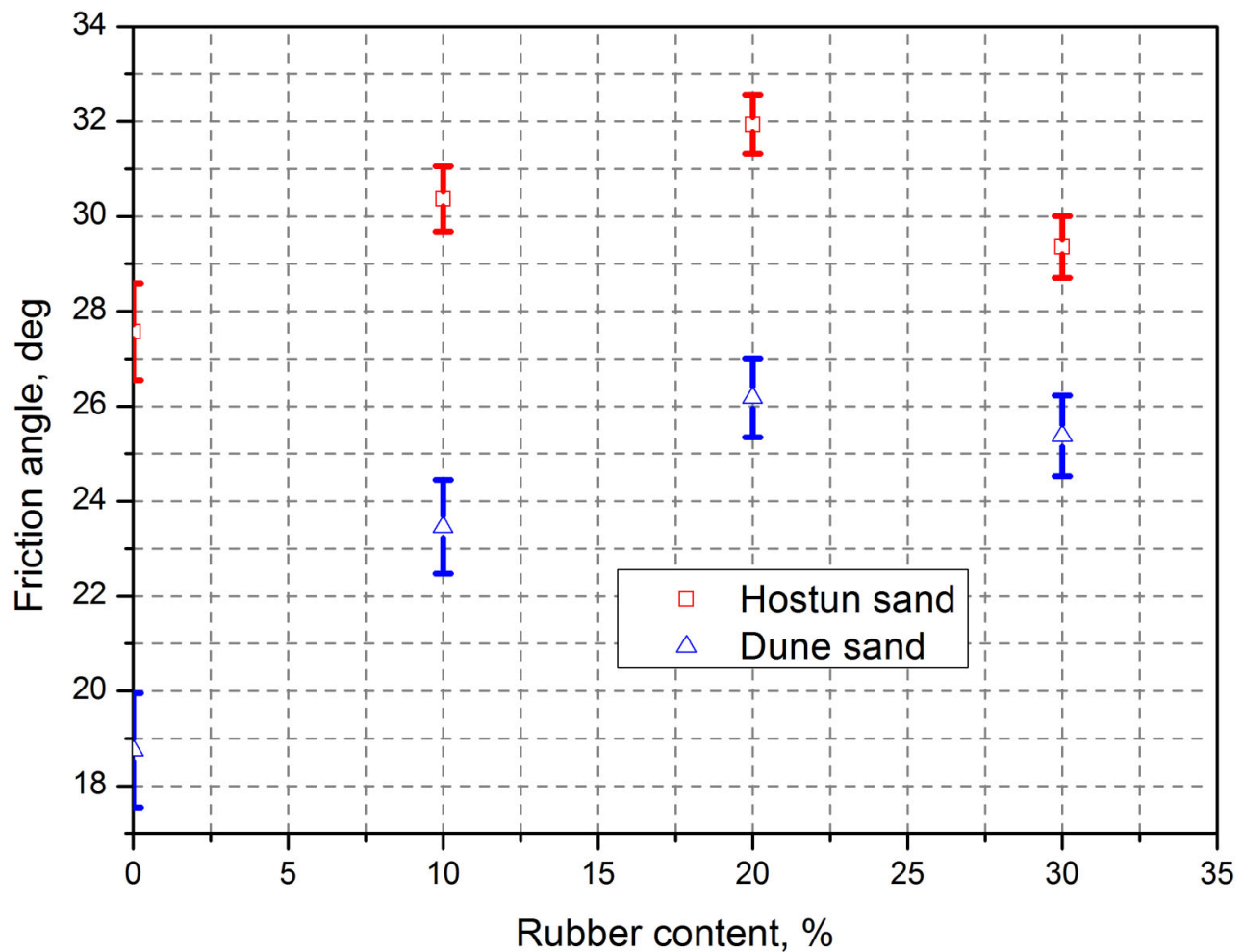


Figure 13. Friction angle in terms of rubber content for different types of sand.

All the results obtained show the value of reusing used tires in civil engineering applications. Used tires were mainly used for non-structural applications (road embankments, embankment stabilization, retaining walls, bridge abutment walls, vibration isolation layer etc.). The mixture of aggregate rubber from used tires and sand is not only an alternative way of recycling tires and an economical way to protect the environment, but also helps to solve the geotechnical problems associated with a low resistance to ground shear.

4. Conclusions

This study investigated the influence of aggregate rubber content and sand particle shape on the shear strength and dilatancy characteristics of granular materials mixed with aggregate rubber. Based on the results of the experimental data, the following conclusions were obtained:

- The increase in the aggregate rubber content from 0 to 20% induces an increase in the maximum shear strength of both sands and then it decreases beyond 20% rubber content.
- The shear strength of the mixture increases with increasing normal stress.

- The presence of rubbers amplifies the dilatant character of the sand-rubber mixture.
- The friction angles obtained by the Hostun sand-rubber mixture are higher than those of the Dune sand-rubber mixture. This is explained on the one hand, by the increase in surface roughness of the grains sand inducing an increase in friction and on the other hand, by the redistribution of grains during shearing and a dilatation whose mobilization requires an additional effort increasing the mobilized friction angle.

It should be noted that this study only tested two sands composed of particles of different shapes. Further tests on materials with the same mineralogy, surface texture, at different temperatures and water contents should be performed to better understand the influence of inter-particle blocking and to become closer to the real conditions of installations and uses of the behavior of sand mixed with aggregate rubber.

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