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Full Paper

Effects of Crumb Rubber on the Shear Strength of Sand: An Experimental Study

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Abstract

The application of waste rubber tires for ground improvement helps to improve the environment by recycling and reusing it as admixtures. This research aims to investigate the shear strength parameters of rubber-sand mixtures. By using crumb rubber with a constant size (425μm), the sand is replaced by different percentages (0, 2.5, 5.0, 7.5, and 10%) of crumb rubber by weight. A direct shear box test is used to determine the shear strength parameters of rubber-sand mixtures with two different controlled densities. The samples were loaded with normal stresses of 20, 40 and 80kPa and were sheared at a rate of 1mm/min. Although, this experiment discovered that crumb rubbers improve the shear strength parameters in loose sand, however, a reduction in shear strength parameters was found in dense sand. Moreover, it was observed that the inclusion of crumb rubbers into sand greatly improve the strain energy of both loose and dense sand. Likewise, rubber has a low unit weight which makes it suitable for lightweight backfill materials. The surface properties of rubber should be further studied to understand the contribution of shear strength in the rubber-sand mixture.

Keywords: Density, direct shear box test, lightweight backfill materials, rubber content, shear strength

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Introduction

In every construction development, it is essential to ensure the ground can withstand the load applied by the structure. Ground containing weak soils are common encounters and it does not exhibit high shear strength to support the structure that is being built on. A few options to overcome this geotechnical problem are abandoning the site and searching for a more suitable ground, replacing or mixing weak soil with appropriate material, and finally piling systems that bypass the weak portion of ground. However, in some cases, these solutions are too expensive and not economically sustainable. Hence, ground improvements are introduced to improve the strength and stability of the soil. There are various ground improvement methods being practised in the industry. Common ground improvement methods include deep vibro-compaction, deep soil mix, vertical drain, and soil reinforcement with geotextiles. Despite what methods are used, the main goal is to stabilize and increase the shear strength of the soil.

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With the rise in urbanisation, the use of sand in construction as a backfill material is inevitable. Strength from pure sand is usually limited to a typical friction angle value. Thus, civil and geotechnical engineers have come up with multiple solutions to improve and enhance the performance of sand. In construction, sand is commonly used as a backfill material. However, pure sand does not contain strength that is high enough to meet the requirements of engineers. As waste materials are increasing exponentially, a wise approach to overcome this problem is to reuse waste materials as binder materials for ground improvement. Waste materials such as waste tires can be processed into shreds or crumbs and are extremely useful for civil engineering applications. Multiple studies were carried out in the past to investigate the effect of crumb rubber as a soil stabilizer. The mechanical properties of rubber are lightweight and high tensile strength which makes it suitable for lightweight geo-material [1]. Researchers [6, 7, 9, 12, 13] are still persistent towards delivering the knowledge for more understanding of the shear parameters of the rubber-sand mixture.

This research explores the effects of shear strength in sand using crumb rubbers. Utilising waste tyres as a ground improvement method could be helpful to engineers and the environment. It is essential to investigate the mechanical properties of the rubber-sand mixture as it is beneficial for lightweight fill. Previous researchers tend to investigate the shear strength of cohesive soil mixed with rubber. However, insufficient studies were made to investigate the effect of shear parameters on cohesionless soil and rubber mixture. It is important to have adequate research on the effect of crumb rubbers on all types of soil.

Methodology

Introduction

This research is a laboratory experiment that aims to evaluate the effect of crumb rubbers on the shear strength of sand. A series of direct shear box tests will be conducted at different density state and crumb rubber content. Furthermore, the direct shear box test is favourable for evaluating shear strength parameters in terms of shear stress and friction angle. The sample will be tested in a 60×60mm shear box loaded at three different normal stress. The direct shear box test is conducted accordingly to British Standards [4] and the results obtained are tabulated and analysed using Microsoft Excel. Soil classification is carried out by sieve analysis to characterise the type of sand. A standard approach of using British Standards as guidance in classifying the soils is to maintain the consistency of the experiment.

Research Framework

The complication of this research is the uncertainty of the relationship between crumb rubber content and shear strength parameters on the sand. There are multiple factors affecting the shear strength of sand when crumb rubbers are used as admixtures. This is due to the disparity of mechanical properties between rubbers and sand that causes the complication. For instance, rubber in nature has elastic properties, low specific weight, and high tensile strength [1]. The mechanical properties demonstrated by sand are high stiffness modulus, high specific weight, and brittle in nature. The combination of these two materials is said to improve the shear strength and geotechnical properties of sand. The problem served in this research can be determined by investigating the shear strength of different density state (loose and dense) of sand by adding different percentages of crumb rubber. The independent variable in this

experiment is the different content of crumb rubbers. The sand used is a controlled variable and has been graded as poorly graded sand. In addition, the controlled density of the sand sample serves as the moderating variable. Finally, the shear strength parameters are defined as shear stress and friction angle that act as the dependent variable in this experiment. The addition of crumb rubbers to the mixture is by different percentages of the total weight. Replacing a portion of sand with a certain percentage of crumb rubber ranging from 0-10% with an interval of 2.5% will be able to manipulate the shear strength of sand.
The sand sample was controlled at two different density states (loose and dense) by regulating the level of compaction. At a loose state, the sample was loosely packed and leveled in the shear box. At a dense state, the sand was compacted with 30 blows at three different layers. This is unconventional compared to several similar research since no classification of maximum and minimum density was made. The shear strength is the dependent variable which means it is the effect of the changes of the moderating and independent variables. The parameters of shear strength focused on this experiment are shear stress and friction angle. The relationship between shear stress and friction angle between shear strength is linear. As the friction angle and shear stress increase, the shear strength of the rubber-sand mixture increases. This is because the strength of the sand is completely dependent on the interlocking between sand particles. In conclusion, this experiment is manipulated by the different percentages of crumb rubber (independent variable) to affect the shear strength (dependent variable) at two different conditions of density (moderating variable). A flowchart (Figure 1) can be represented to conclude this research framework.

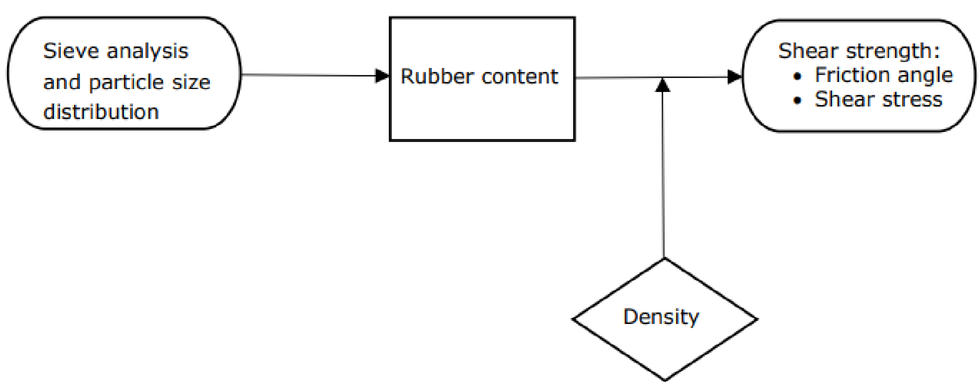

Figure 1. Flowchart of theoretical framework

Materials

Sand

This experiment used poorly graded sand as the controlled variable to determine the shear strength which was added with different rubber content. The sand was prepared and graded using sieve analysis according to [2] (Dry sieve method). A total mass of 5kg sand sample was collected and riffled for three particle size distribution tests to improve the consistency and accuracy of data. The sand was observed to be lightly brown in colour. The data obtained from sieve analysis is used to plot the particle size distribution curve and the properties of particle size (Table 1) are used to grade the sand sample. Figure 2 presents the particle size distribution averaged from three tests. The characteristic of particle shape was graded based on the coefficient of curvature (C_c) and the uniformity coefficient (C_u). The sand is graded based on the particle shape according to [5] clause 4.3. The percentage passing on the 0.5mm sieve falls around 58.6% and is categorised as medium to fine sand according to British Standards. Besides, the maximum particle size does not exceed 2mm.

Table 1. Properties of sand particles

Type of sand	**d_{10} (mm)**	**d_{30} (mm)**	**d_{60} (mm)**	**C_c**	**C_u**
Poorly graded sand	0.12	0.26	0.51	1.12	4.36

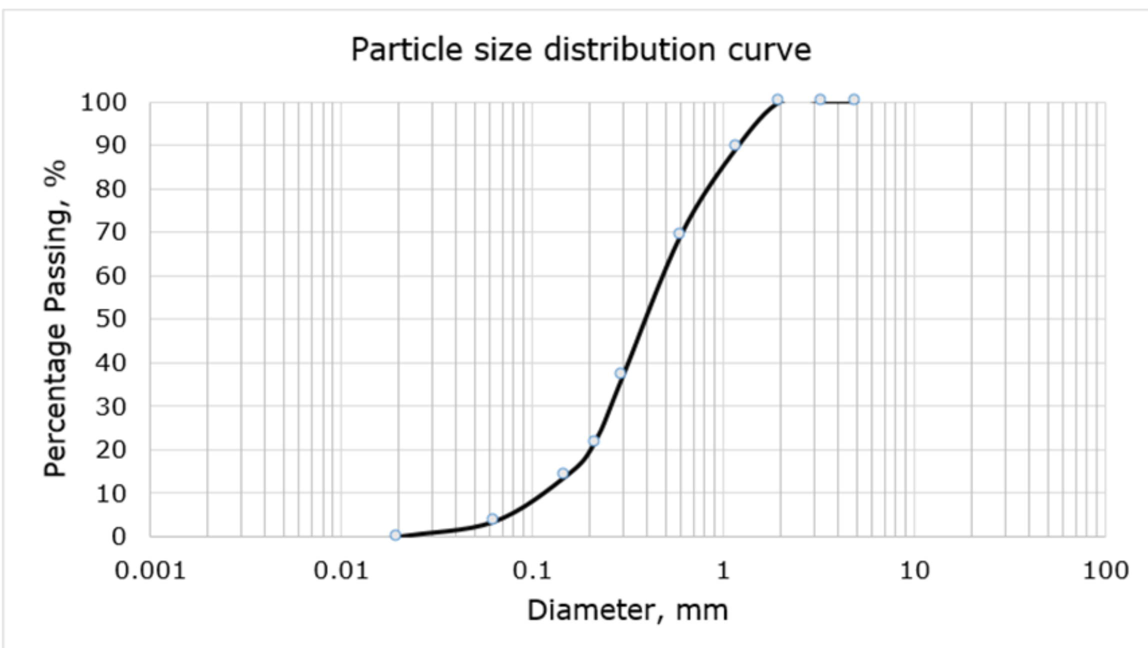

Figure 2. Particle size distribution curve of the sand

Crumb Rubber

The rubber was obtained from waste rubber tyres and the steel wires in the tyre were removed prior to shredding. The crumb rubber size used in this research was sieved and collected at a pan size of 425µm. This size was chosen to avoid the rubber particle size to be random in the rubber-sand matrix. Furthermore, particle size 425µm falls around 50% of the percentage passing in the particle size distribution curve of sand. This allows the crumb rubbers to blend in well to the mixture. From Figure 3, the crumb rubber is observed to have spherical shapes and rough surface properties. Besides, rubber exhibits properties such as low specific weight, durability, and high resistance to shear and tension making it a propitious material for ground improvement [1].

Figure 3. Close up view of crumb rubber

Sample Preparation

The sample used in this experiment was prepared by mixing the poorly graded sand with different percentages of crumb rubber. The crumb rubber content (0, 2.5, 5, 7.5, and 10%) was determined by the weight of the total sample. For example, if the total mass of a sample is 100g, 5% of rubber content would be 5g of crumb rubber mixed with 95g of sand. The % of crumb rubber can be defined as in Equation 1.

$$\%\ of\ crumb\ rubber = \frac{M_R}{M_R + M_s} \times 100\% \qquad \text{Equation 1}$$

M_R = Mass of rubber

M_S = Mass of sand

The sand and crumb rubbers were measured at dry conditions without moisture and separately on an electronic scale balance. After the mass and ratio of the mixture were measured correctly, the crumb rubber is poured into the sand container. The sand and crumb rubbers were mixed accordingly using a spatula until a homogeneous mixture is produced. The mixture was then poured into the shear box container and compacted to the desired controlled density.

The loose sample was prepared by pouring the homogenous rubber-sand mixture rapidly into the 60×60mm shear box. The sample was ensured to be loosely compacted by tamping the surface lightly. The surface was leveled carefully and the thickness of the sample was measured according to the requirement of British Standards.

For dense samples, the rubber-sand mixture was poured into the shear box container in four layers. The respective layers were compacted by a wooden rammer and hammered for 30 counts. The height and mass of the sand were refined to achieve the highest density possible by fulfilling the minimum height requirement (20mm) in a direct shear box test by British Standards. The samples were prepared and grouped into loose and dense states (Table 2).

A total of 30 sets of samples were being prepared and a series of direct shear box tests were carried out to assess the shear strength of the samples. Each specimen was prepared in 3 sets to be sheared through 3 different vertical loads. Overall, the samples were prepared in 0, 2.5, 5, 7.5, and 10% crumb rubber by weight in a loose and dense state. All 30 samples were compacted and the thickness was measured to comply with [4]. Moreover, each test specimen was loaded at a normal stress of 20, 40, and 80kPa to evaluate the friction angle.

Table 2. Summary of test samples prepared

Test specimen	Loose state	Dense state
Sand + 0% rubber	3 sets	3 sets
Sand + 2.5% rubber	3 sets	3 sets
Sand + 5% rubber	3 sets	3 sets
Sand + 7.5% rubber	3 sets	3 sets
Sand + 10% rubber	3 sets	3 sets

Experimental Section

Particle Size Distribution

This soil classification test was carried out by sieve analysis according to [2]. The size of the test sieve that was used in this test is 200mm in diameter and 300g of sand is sieve at a time. The sieve analysis was repeated 3 times to produce more accurate results. The sand was rifled before every repeated test. Figure 4 shows the setup of the sieve analysis using a mechanical shaker. The sand sieved was categorized as medium to fine sand according to [3].

Direct Shear Box Test

The direct shear box (Figure 5) test is commonly used to determine the shear stress, friction angle, and dilatancy behavior of the sand. All tests were executed based on the guidance of [4]. The direct shear test was conducted on a 60×60mm square shear box ELE digital shear machine. For this experiment, the shearing rate was set constant at 1mm/min during the tests. The data was recorded manually using a phone camera to capture the reading of the proving ring and vertical displacement for every interval of 0.25mm horizontal displacement. The ultimate failure of this test was determined to be at 15% of the shear box length which is 9mm of the horizontal displacement. The samples of this experiment were loaded at three different vertical stresses of 20, 40, and 80kPa. The readings were recorded and analyzed by Microsoft Excel to obtain the shear stress and friction angle.

Figure 4. Sieve analysis apparatus

Figure 5. Direct shear box machine

Result and Discussion

Effect of Crumb Rubber Content on Maximum Friction Angle

Figure 6 presents the maximum friction angle of different crumb rubber content under a loose and dense state. The loose samples expressed an improvement in shear strength with the addition of crumb rubber content up to 7.5%. Although the shear strength containing 10% of crumb rubber was observed to be decreasing after 7.5%, the friction angle was yet slightly improved as compared to unreinforced sand. The maximum friction angle was achieved at 7.5% crumb rubber content with a value of 38.0°. For dense samples, the friction angle decreases as the crumb rubber content increases. The highest friction angle value obtained was 43.6° with 0% of crumb rubber content. In contrast, the arrangement of particles caused by the degree of compaction does influence the shear strength of sand containing crumb rubbers. The loosely packed samples exhibit improvement of friction between rubber and sand particles. Under the loose condition, the rough surface texture of rubber is utilised to improve friction between particles. However, for dense samples, the ability to resist shear is lower as the content of crumb rubber increases. The presence of crumb rubber particles under dense conditions reduces the inter-locking properties of sand. From the standpoint of surface properties, crumb rubber particles under dense conditions are being compressed resulting in a reduction in surface area and thus reducing the ability to mobilised friction. In general, a rubber-sand mixture under loose conditions improves the angle of friction between particles by 9.2%. The interaction of rubber and sand particles provided higher inter-locking properties but begins to decrease as the concentration of rubber becomes higher. However, the effectiveness of friction between rubber and sand particles decreases under dense conditions up to 12.8%. Table 3 concludes the percentage difference of maximum friction angle for the loose and dense states.

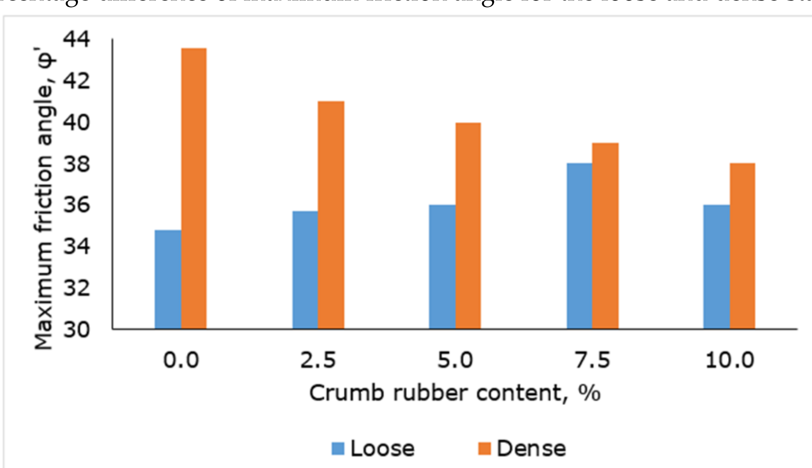

Figure 6. Maximum friction angle against crumb rubber content

Table 3. Maximum friction angle values and percentage difference of various crumb rubber content

Density state	Crumb rubber content, %	Friction angle, φ′	Percentage difference, %
Loose	0.0	34.8°	0.0
	2.5	35.7°	2.6
	5.0	36.0°	3.4
	7.5	38.0°	9.2
	10.0	36.0°	3.4
Dense	0.0	43.6°	0.0
	2.5	41.0°	-6.0
	5.0	40.0°	-8.3
	7.5	39.0°	-10.6
	10.0	38.0°	-12.8

Effect of Crumb Rubber Content on Ultimate Friction Angle

Figure 7 shows the ultimate friction angle value for loose and dense samples. For loose samples, the ultimate friction angle increases as crumb rubber content increases. The ultimate friction angle begins to decline again after exceeding 7.5%. The highest ultimate friction angle value was achieved at 35.5° with 7.5% rubber content. For dense samples, the ultimate friction angle decreases up to 5% of crumb rubber content and gradually increases again after exceeding 5% crumb rubber. The highest ultimate friction angle was achieved by 10% of crumb rubber content with a value of 36.6°. In contrast, a great improvement in ultimate shear strength was observed in the dense sample containing 10% of crumb rubber. This can be explained by the elastic properties of rubber that contributed to the development of ultimate shear strength. In a high concentration of crumb rubber content, the difference in maximum and ultimate friction angle is greatly reduced. Furthermore, the addition of crumb rubber in sand improves the strain energy of sand. In general, crumb rubber successfully stabilized the sand by increasing strain energy and ductility of sand. In loose samples, it is observed that the ultimate friction angle improved up to 9.9%. Meanwhile, the ultimate friction angle is improved by 5.8% in dense samples. Table 4 demonstrates the percentage difference of the ultimate friction angle in a loose and dense state.

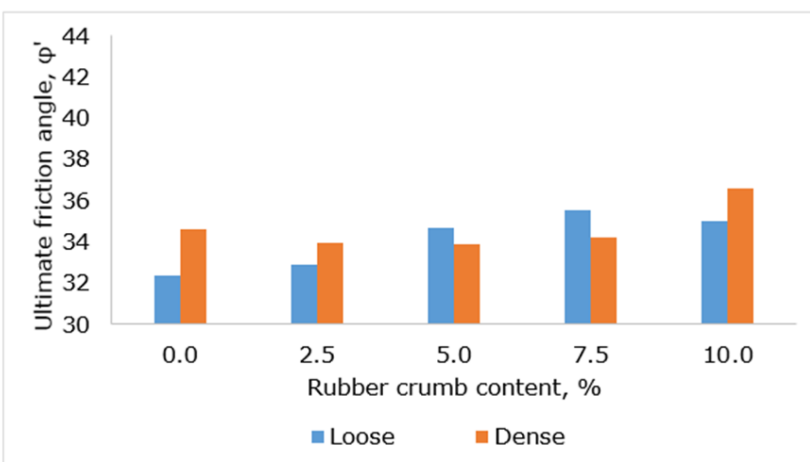

Figure 7. Ultimate friction angle against crumb rubber content

Table 4. Ultimate friction angle value and percentage difference of various crumb rubber content

Density state	Crumb rubber content, %	Friction angle, φ′	Percentage difference, %
Loose	0.0	32.3°	0
	2.5	32.9°	1.9
	5.0	34.7°	7.4
	7.5	35.5°	9.9
	10.0	35.0°	8.4
Dense	0.0	34.6°	0
	2.5	34.0°	-1.7
	5.0	33.9°	-2.0
	7.5	34.2°	-1.2
	10.0	36.6°	5.8

Effect of Crumb Rubber Content on Shear Stress – Loose State

Figure 8 demonstrates the addition of crumb rubbers does increase the shear stress. As crumb rubber content increases, shear stress increases. In addition, the maximum shear stress was observed to be achieved at 7.5% of crumb rubber content. However, at 10% of crumb rubber content, the shear stress begins to decrease. The potential drawback to this is the dominating quantity of rubber in the sample. The reduction of sand particles decreases the efficiency of inter-particle friction [14]. Moreover, the addition of crumb rubbers was seen to improve the residual strength of the sand as discovered by [15]. In contrast, the sample containing 10% crumb rubber content displayed an increase in residual strength between horizontal displacement 5-9mm. This proved that the elastic properties of rubber increase the energy capacity to mobilize the ultimate strength of the rubber-sand mixture. Therefore, samples containing a high concentration of crumb rubber can improve the shear strain of sand. Conclusively, the maximum shear stress of sand in loose conditions can be improved by adding crumb rubber. The optimum rubber content to achieve maximum shear stress is 7.5% and further decreases after exceeding this level. Also, the characteristic of sand has a tendency to be more ductile as crumb rubber increases in the matrix. As observed in Table 5, at low normal stress (20kPa), the shear strength of sand showed significant improvement when added to crumb rubber. The maximum shear strength increased as much as 33.93% with 7.5% crumb rubber content at normal stress 20kPa and further decreased at 10% crumb rubber content. The maximum shear stress occurred at roughly 4mm of horizontal displacement for loose samples. In short, the shear strength of loose sand is improved with the addition of crumb rubbers.

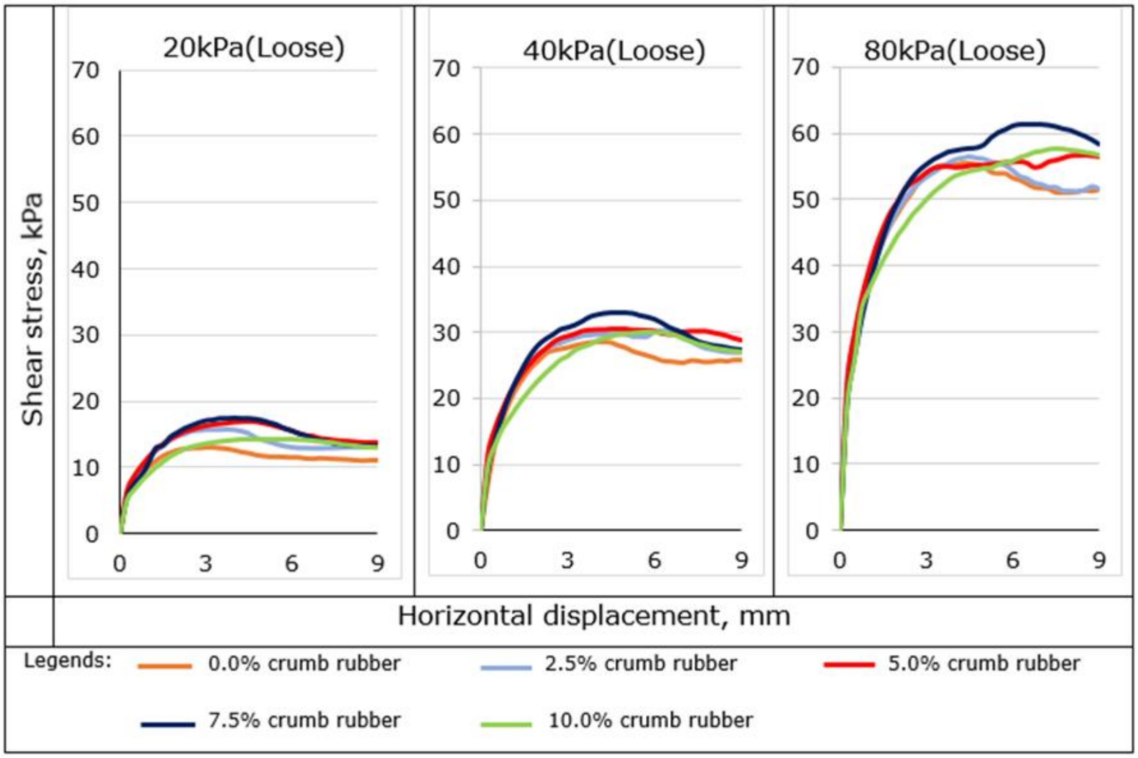

Figure 8. Graph of shear stress against horizontal displacement (20, 40 and 80kPa, loose)

Table 5. Maximum shear stress and percentage difference of various crumb rubber content (loose)

Normal stress (kPa)	Crumb rubber (%)	Horizontal displacement (mm)	Maximum shear stress (kPa)	Percentage difference (%)
20	0.0	3.00	13.13	0.00
	2.5	3.75	15.66	19.23
	5.0	4.50	16.98	29.28
	7.5	4.00	17.59	33.93
	10.0	4.25	14.34	9.18
40	0.0	4.00	28.63	0.00
	2.5	6.25	30.23	5.59
	5.0	4.50	30.50	6.53
	7.5	4.50	32.86	14.77
	10.0	5.75	30.17	5.38
80	0.0	4.25	55.40	0.00
	2.5	4.50	56.44	1.89
	5.0	8.50	56.71	2.38
	7.5	6.25	61.33	10.71
	10.0	7.50	57.59	3.97

Effect of Crumb Rubber Content on Shear Stress – Dense State

The results presented in Figure 9 illustrates the shear stress of sand with different percentage of crumb rubber in a dense state. Pure sand was used as a reference to determine how dense a sample should be due to the addition of crumb rubber tends to lower the maximum density of sand. For a sample containing pure sand, the density achieved was around 1.60Mg/m^3. The addition of crumb rubber in dense samples did not improve the shear strength of the sand. The maximum shear stress decreases as the crumb rubber content increases. This behaviour was expressed similarly by [11] and [14]. It was noted that the size of the crumb rubber particles is too small and spherical in shape. Sand initially contracts and then dilates under dense conditions, thus promoting sand particles to slide over easily. This phenomenon can be illustrated by the analogy of ball bearings. As suggested by Sheikh and his researchers [11], the reduction of shear stress can be minimized by increasing the crumb rubber size. Furthermore, the behaviour of shear stress in sand sample added with 10% of crumb rubber displayed an improvement in residual strength at normal stress 40 and 80kPa. At a high concentration of crumb rubber content, no peak stress was observed and the residual strength is greatly improved. This showed that the addition of crumb rubber in high quantity can increase the strain energy and reduce the brittleness properties of sand. In short, the maximum shear stress of sand decreases as crumb rubber content increases in dense samples. The optimum rubber content is 0% for dense samples to achieve maximum shear stress. Besides, the rubber particles under dense conditions served as a ball-bearing effect for sand particles to 'climb' over each other. Therefore, resulting in weak frictional characteristics in the mixture. However, the strain energy and residual strength were greatly enhanced for both loose and dense sand at a high quantity of crumb rubber content. As shown in Table 6, the maximum shear stress gradually decreases as crumb rubber content increases at 3 different normal stresses. It was observed that the reduction of maximum shear stress significantly decreased after exceeding 2.5% of crumb rubber content. The occurrence of maximum shear stress for dense samples was about 2-3mm when rubber content is low. Similar to the loose samples, as rubber content increases, the time to achieve peak stress has been delayed.

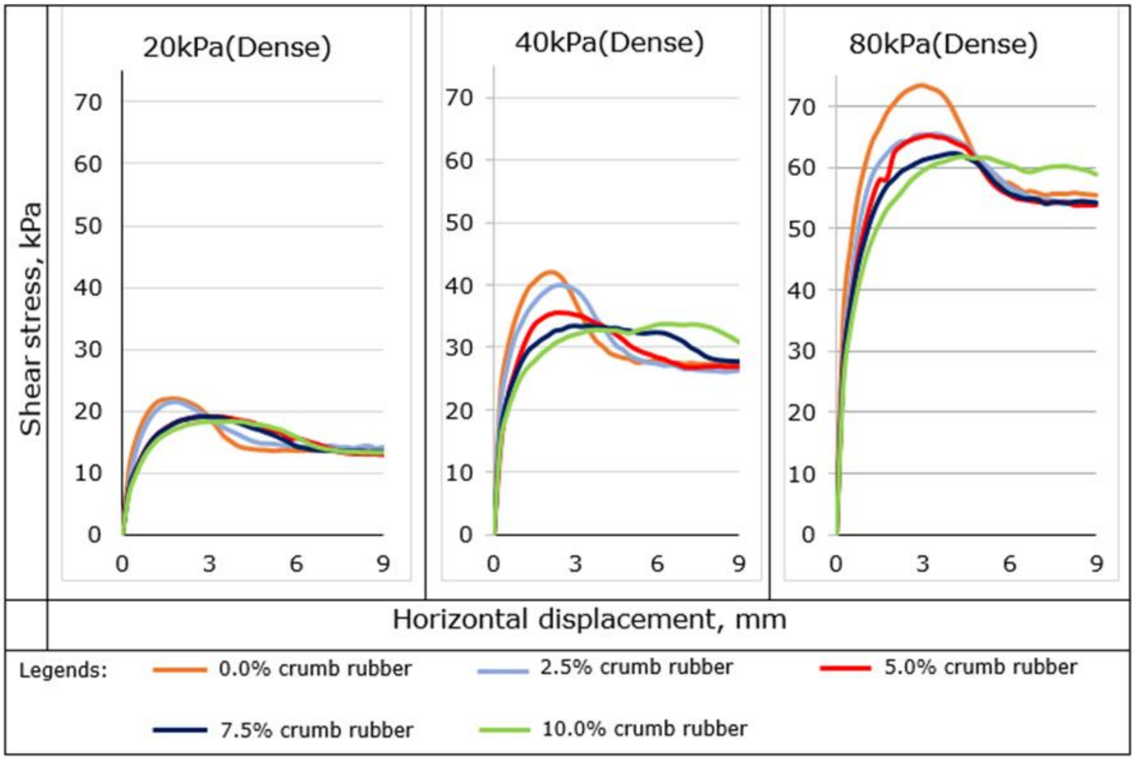

Figure 9. Graph of shear stress against horizontal displacement (20, 40 and 80kPa, dense)

Table 6. Maximum shear stress and percentage difference of various crumb rubber content (dense)

Normal stress (kPa)	Crumb rubber (%)	Horizontal displacement (mm)	Maximum shear stress (kPa)	Percentage difference (%)
20	0.0	1.75	22.09	0.00
	2.5	1.75	21.49	-2.74
	5.0	3.25	19.23	-12.94
	7.5	2.75	19.23	-12.94
	10.0	3.75	18.36	-16.92
40	0.0	2.00	42.10	0.00
	2.5	2.50	39.90	-5.22
	5.0	2.25	35.61	-15.40
	7.5	3.50	33.63	-20.10
	10.0	6.25	33.74	-19.84
80	0.0	3.00	73.31	0.00
	2.5	3.50	65.40	-10.79
	5.0	3.25	65.12	-11.17
	7.5	4.00	62.32	-14.99
	10.0	4.25	61.66	-15.89

Influence of Crumb Rubber Content on the Density

A major factor influencing the shear strength of sand is density. For this experiment, the relationship between the content of crumb rubber and density is presented in Figure 10. It was noted that the density of the samples was decreasing as crumb rubber content increases. The significant drop of density from 7.5% to 10% crumb rubber content in loose state explains the sudden decreased in shear strength which was observed previously. Due to the light unit weight of rubber, the replacement of sand with crumb rubber increases the total volume in the matrix. Consequently, the effort to compact to the previous density was harder since the volume has increased while the mass remained the same.

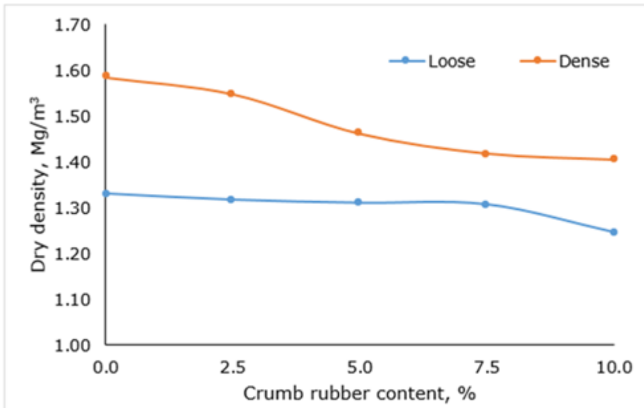

Figure 10. Graph of dry density against crumb rubber content

Influence of Crumb Rubber Content on Volume Change – Loose State

Figure 11 presents the dilatancy behaviour of rubber-sand mixtures under loose state. For loose samples, the maximum dilation is experienced by the sample containing 7.5% of crumb rubber with a height of 0.64mm at normal stress 20kPa. After the crumb rubber content exceed this level, the dilation is greatly reduced indicating a high concentration of crumb rubber inhibiting the sliding of sand particles over each other. Besides, it is observed that as the normal stress increases, the tendency to dilate is reduced. The explanation for this behaviour is due to the rate of dilation is smaller in high confining pressure [10, 14]. At normal stress 80kPa, the contraction is greatest between rubber and sand particles at 10% crumb rubber content. Due to the weak interaction between crumb rubber and sand particles, the arrangement of particles is looser. Furthermore, shearing in a loose state causes particles to experience contraction and densification due to the rearrangement of particles.

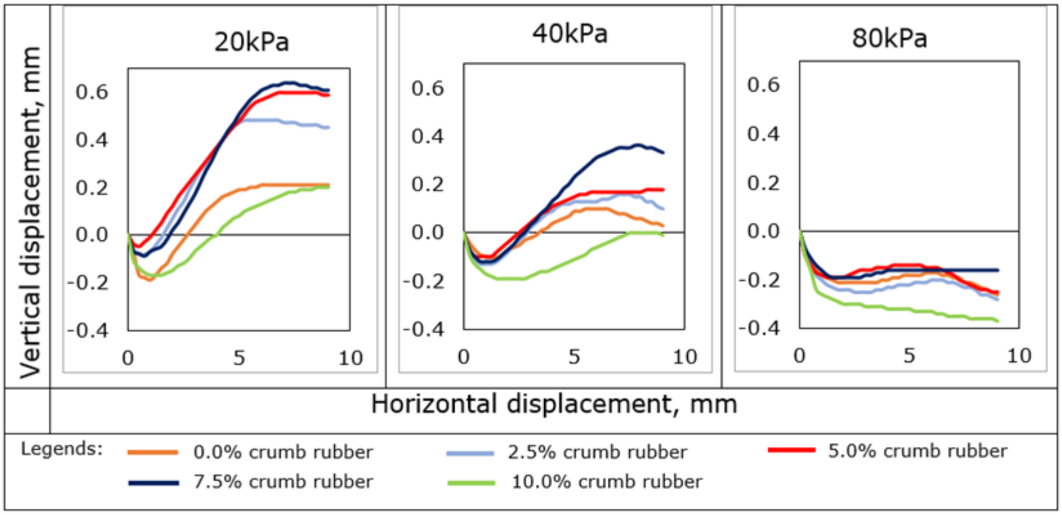

Figure 11. Graph of vertical displacement against horizontal displacement (loose)

Influence of Crumb Rubber Content on Volume Change – Dense State

Figure 12 presents the dilatancy behaviour of rubber-sand mixtures under dense state. For dense samples, it was observed that the sample containing more sand particles tend to experience larger angle of dilation. The sand tends to densify more when crumb rubbers are added into it. It can be explained that the shape and surface properties of sand particles provide higher inter-locking properties compare to crumb rubber [14]. The maximum dilation occurs at normal stress 20kPa containing 2.5% of crumb rubber with an increment height of 1.09mm. Moreover, the tendency for the mixtures to dilate is reduced when the normal stress and crumb rubber content is increased. This similar behaviour was also observed in the loose samples. In dense samples, contraction only occurs in the initial stage of shearing followed by dilation. This explains the rapid rise and drop of shear strength in dense sands.

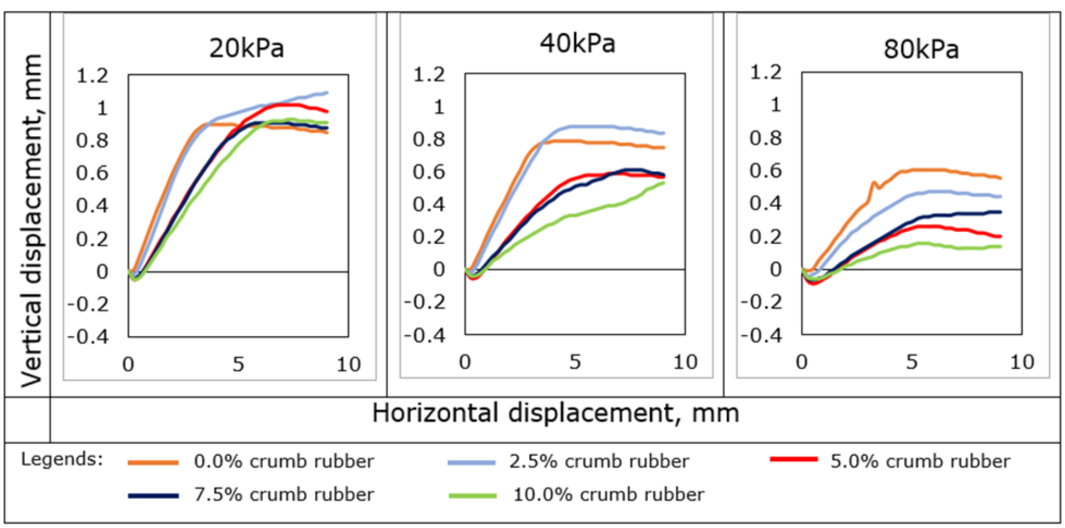

Figure 12. Graph of vertical displacement against horizontal displacement (dense)

Conclusions

The results presented above can be concluded that the addition of crumb rubber enhances the shear strength slightly in loose sand but decreases in dense sand. The optimum rubber content for loose sand is 7.5% to achieve maximum shear strength and 0% for dense sand. However, it was observed that the ultimate shear strength was greatly improved as the rubber content increased in both loose and dense sand. [11] and [15] also highlighted the addition of rubber significantly enhances the strain energy and reduces brittleness in the sand. As such, based on the observation from the results, as the content of crumb rubber increases, the peak behaviour is successfully reduced, and strain-hardening properties are induced [8]. Furthermore, it was noted that crumb rubber has a low bulk density which causes the density of the mixture to decrease as the content of crumb rubber increases making it a suitable lightweight fill material. This indirectly influences the rate of dilation because the tendency to dilate or contract depends on the initial density. As reported by Lee [11], the addition of rubber to sand has more tendency to dilate compared to pure sand which can also be observed in this experiment for a loose state. However, in a dense state, the influence of crumb rubber tends to decrease the behaviour of dilation. From this experiment, it can be noted that the application of crumb rubber alters the behaviour of shear strength in terms of maximum and ultimate strength under different density states. Therefore, careful selection of crumb rubber content and density for design purposes is needed to prevent adverse effects from occurring. Based on the findings of this research, crumb rubber affects the shear strength of sand differently in a loose and dense state. The results were discussed and are concluded as follows:

1. Maximum shear strength of sand improves up to 7.5% of crumb rubber content in a loose state. The addition of crumb rubber in a dense state did not improve the maximum shear strength of sand.
2. Ultimate shear strength improves in both loose and dense states as crumb rubber content increases indicating an increase of strain energy in the mixture.
3. The optimum rubber content for the loose state is 7.5% and 0% for the dense state to achieve maximum shear strength.
4. The bulk density decreases as crumb rubber content increases.
5. Under the loose condition, sand with the addition of crumb rubber tends to dilate more but decreases when crumb rubber content exceeded 7.5%. Under the dense condition, the addition of crumb rubber decreases dilation in the sand.

In conclusion, the usage of crumb rubber as ground improvement admixtures improves the shear strength of loose sand and reduces the shear strength in dense sand. However, there is an advantage to improving the ductility of sand by adding crumb rubbers. For the loose state, shear strength of sand is improved at 7.5% crumb rubber content up to 9.2% and 9.9% for maximum shear strength and ultimate shear strength respectively. For dense state, there is no improvement in maximum shear strength but increases 5.8% for ultimate shear strength at 10% crumb rubber content.

Conflicts of Interest

The authors declare no conflict of interest.

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