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Research Article

Mechanical Properties of Scrap Tire Crumbs-Clayey Soil Mixtures Determined by Laboratory Tests

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Some laboratory tests, such as Proctor compaction test, direct shear and cyclic direct shear tests, consolidation test, and unconfined compression test, were performed on scrap tire crumbs-clayey soil mixtures to study the mechanical properties of the mixtures. The results show that (1) the maximum dry unit weight and the corresponding optimum moisture content of the mixtures decrease rapidly with the increase of scrap tire crumbs content (C_{STC}), showing good potential for using the mixtures as lightweight fill material; (2) it is not possible to prepare the mixture when C_{STC} exceeds 30% due to the occurrence of cracks in the mixture after removing from a mould; and (3) the shear strength of mixtures approximately increases by 20% when C_{STC} is up to 30%, while the residual strength decreases by 15%, compared with that of pure clayey soil. During shearing, the dilation of the mixtures occurs, particularly under the condition of a high C_{STC} and a low vertical pressure. Besides, the compressive strength and consolidation settlement of the mixtures decrease with C_{STC} increasing. The results indicate that it is possible for scrap tire crumbs used to improve clayey soil, which is suitable to act as a fill material.

1. Introduction

Six hundred million scrap tires were generated in China by 2015, while two hundred million scrap tires still remained in stockpiles [1]. Huge quantities of scrap tires were generated in other countries as well. For example, nearly three hundred million scrap tires were generated in the European Union by 2015 [2]; two hundred million scrap tires were generated in the US [3]; and one hundred and fifty million scrap tires were estimated to be generated per year in India [4]. Land filling or stockpiling of scrap tires is prone to cause environmental problems, such as (a) largely occupied spaces, (b) health hazards (scrap tires will provide a natural breeding place for diseases caused by insects and rodents), and (c) air pollution (stockpiling of scrap tires could pose a major fire risk and then cause air pollution). Therefore, there exists an urgent need to explore new and beneficial ways to recycle or reuse scrap tires.

Scrap tire pieces have been applied in civil engineering, such as using as embankment fill material [5–8], drainage material to collect leachate landfill [9], retaining wall backfill material [10, 11], and bridge abutment fill material [12]. Laboratory testing and field demonstration of the application of sands mixed with scrap tire pieces with various shapes and sizes have shown that the ductility and shear strength of sands could be significantly enhanced [13]. Furthermore, the mixture has lower unit weight and higher compressibility, compared with clean sands [14].

It is concluded that scrap tire pieces with various shapes and sizes can be successfully used for modification of sand. However, it is necessary to study effects of amounts of scrap tire pieces on the mechanical performance for clayey soil. Hasan et al. [15] and Sellaf et al. [16] investigated the mechanical properties of scrap tire chips-cohesive clayey soil mixtures. The results revealed that it is possible to use clayey soil mixed with tire chips as a fill material. Attom et al. [17] found that increasing the content of scrap tire shreds can improve the shear strength and permeability of clayey soil but can cause a decrease in the plasticity index, the expansion pressure, and expansion potential, compared with that of pure

Figure 1: Test materials. (a) Clayey soil. (b) Scrap tire crumbs.

Table 1: Components of clayey soil.

Sand content (%)	3.80
Silt content (%)	20.6
Clay content (%)	75.6
Soil classification	Silty clay

Table 2: Some properties of clayey soil.

Liquid limit (%)	37.2
Plastic limit (%)	17.1
Plastic index (%)	20.1
Nature void ratio	1.13
Specific gravity	2.72
Nature moisture content (%)	45.5

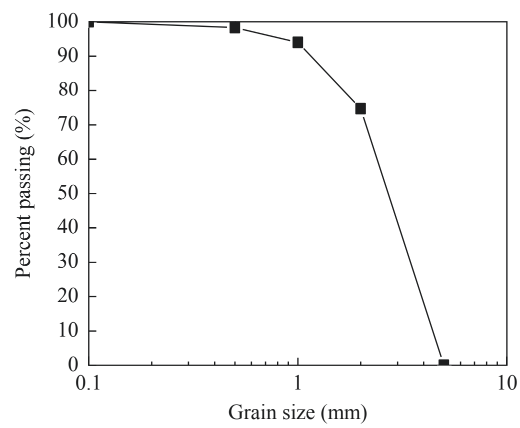

Figure 2: Particle-size distribution of scrap tire crumbs.

clayey soil. Kalkan [18] concluded that the silica fume-scrap tire rubber fiber mixture materials can be used to improve clayey soils.

The mechanical properties of scrap tire crumbs-clayey soil mixtures, such as shear strength, residual shear strength, unconfined compressive strength, and consolidation settlement, were explored by a series of laboratory tests. Three scrap tire crumbs contents (C_{STC}), 10, 20 and 30%, were used in this study. The effects of the C_{STC} on the mechanical properties of the mixtures were discussed.

2. Materials

2.1. Soil Specimens. Figure 1 shows the materials used in the experiments. The components of clayey soil are shown in Table 1. Besides, the engineering parameters of clayey soil were measured according to the Standard for Soil Test Method (GB/T50123) [19]. Such parameters are summarized in Table 2.

2.2. Scrap Tire Crumbs. Scrap tire crumbs were obtained from a local rubber processing factory. It should be noted that the steel and fluff in the scrap tire crumbs have been removed. The scrap tire crumbs vary from 0.5 to 4.5 mm in diameter. The specific gravity of scrap tire crumbs was tested to 1.15 according to ASTM C127 (2007) [20]. The sieve analysis of scrap tire crumbs was determined according to ASTM D422-63 (1998) [21]. The result of the sieve analysis is shown in Figure 2.

3. Experiment Descriptions

3.1. Sample Preparation. Hasan et al. [15] found that the shear strengths increase up to 30% for fine tire chip and 20% for coarse tire chip-cohesive clayey soil mixtures. The diameter of fine tire chips is less 0.425 mm, and the diameter of coarse tire chips is between 2 and 4.75 mm. Moreover, it is not possible to prepare the mixture when C_{STC} exceeds 30% due to the occurrence of cracks in the mixture after removing from a mould. Therefore, the content of scrap tire crumbs used in this study is less than 30%. The scrap tire crumbs content, C_{STC}, is defined as the ratio of weight of scrap tire crumbs to the total dry weight of the mixture [15].

The process of preparing the mixtures includes three steps:

Step 1: the clayey soil was oven-dried at approximately 65°C [19], and then the soil mass was ground to particles of less than 0.05 mm in diameter.

Step 2: the mixtures were compacted at the optimum moisture content to obtain the maximum dry unit

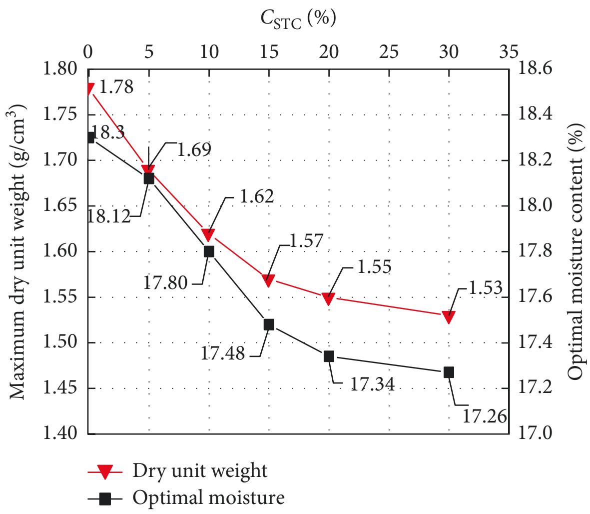

FIGURE 3: Variations of dry unit weight and the corresponding optimal moisture content for mixtures.

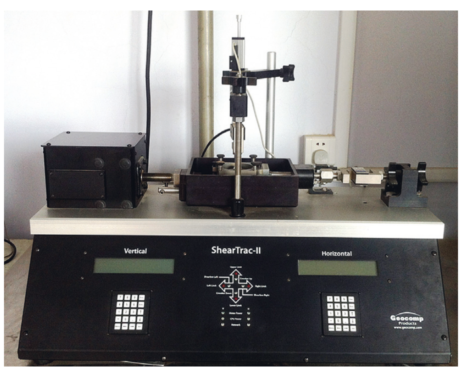

FIGURE 4: Direct/residual shear test apparatus (ShearTrac II).

weight. For the mixtures with various C_{STC}, weights of needed clayey soil, scrap tire crumbs, and water were calculated, respectively. The dry clayey soil particles and dry scrap tire crumbs were mixed uniformly in a laboratory mixer. Water needed was then added in the laboratory mixer until the optimum water content of the mixture is reached.

Step 3: the mixture was compacted in three equal-thickness layers with a hammer that delivers 25 blows to each layer. The hammer has a mass of 2.5 kg and has a drop of 30.5 mm. The mixture specimens were obtained using a standard ring sampler, and the specimens were saturated in a vacuum pump.

To determine the maximum dry unit weight and the corresponding optimum moisture of the mixtures, the Proctor compaction tests were carried out according to ASTM D698-78 (1989) [22]. The variations of maximum dry unit weight and the corresponding optimal moisture content for the mixtures are given in Figure 3. It is shown that the maximum dry unit weight and the corresponding optimum moisture of mixtures are less than that of pure clayey soil and decrease rapidly with C_{STC} increasing. It is similar to that

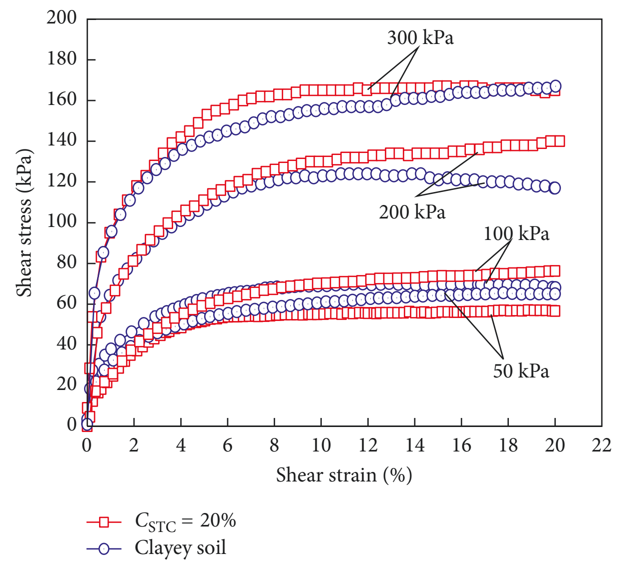

FIGURE 5: Variations of shear stress versus shear strain for mixtures.

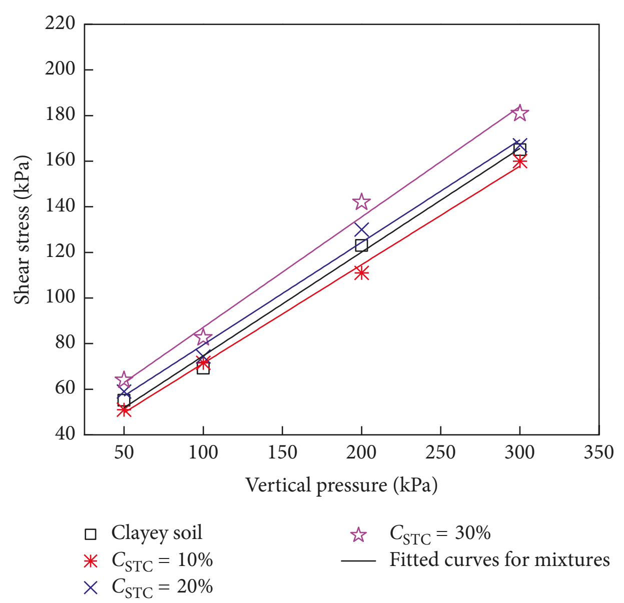

FIGURE 6: Mohr–Coulomb failure envelopes for mixtures.

found by Kalkan [18] and Akbulut et al. [23], who mixed clayey soil with scrap tire rubber fiber. The reason of the reduction in maximum dry unit weight of the mixtures is the low density of scrap tire crumbs [24]. In addition, bibulous rate of the scrap tire crumbs is very low compared with that of the clayey soil, resulting in the decrease of optimum moisture content for the mixtures.

3.2. Test Methods

3.2.1. Direct Shear Tests. Figure 4 shows the direct/residual shear test apparatus (ShearTrac II) used in this study. This apparatus is capable of performing the consolidation and shearing phases of a standard direct shear test and cyclic

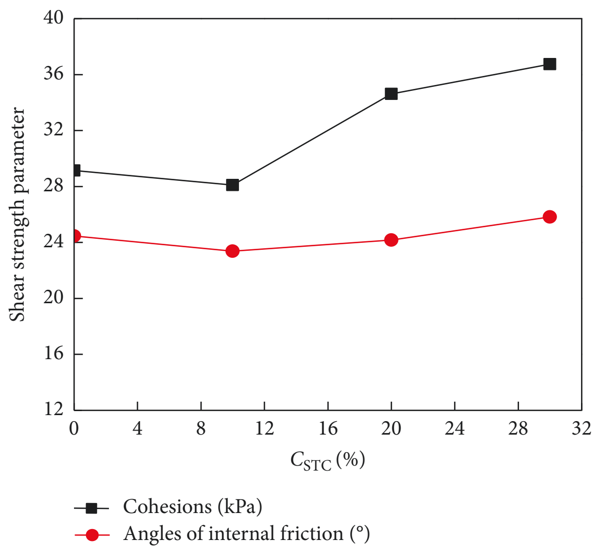

Figure 7: Variations of cohesion and internal friction angle for mixtures.

direct shear tests. Besides, it is capable of performing the consolidation tests under different stress paths. The specimens were 63.5 mm in diameter and 20 mm in height.

The direct shear tests were carried out according to the procedure described by ASTM D3080-98 (2003) [25]. The vertical pressures of 50, 100, 200, and 300 kPa were applied. During shearing, the shear rates were kept 0.1 and 0.8 mm/min. The shear strengths, shear parameters (cohesion and the angle of internal friction), and volume changes of the mixtures were derived from test results.

3.2.2. Cyclic Direct Shear Tests. The cyclic direct shear tests were carried out to elucidate the influence of C_{STC} on the residual shear strength of mixtures with the apparatus shown in Figure 4. The mixtures were placed in the shear box; after about 12 hours (to allow for consolidation), shearing was recommenced at a rate of 0.1 mm/min under the vertical pressure of 50, 100, 200, and 300 kPa, respectively.

3.2.3. Consolidation Tests. One-dimensional consolidation tests for the mixtures using incremental loading were conducted with the apparatus shown in Figure 4. The mixtures were consolidated at 50, 100, 200, and 300 kPa, respectively, and each vertical pressure increment is maintained until excessive pore water pressure completely dissipates.

3.2.4. Unconfined Compression Tests. The mixture specimens are 39.1 mm in diameter and are trimmed to 80 mm height. Compressive strengths of the mixtures with the C_{STC} of 10%, 20%, and 30% were obtained using a strain rate of approximately 3%/min under unconfined compaction conditions.

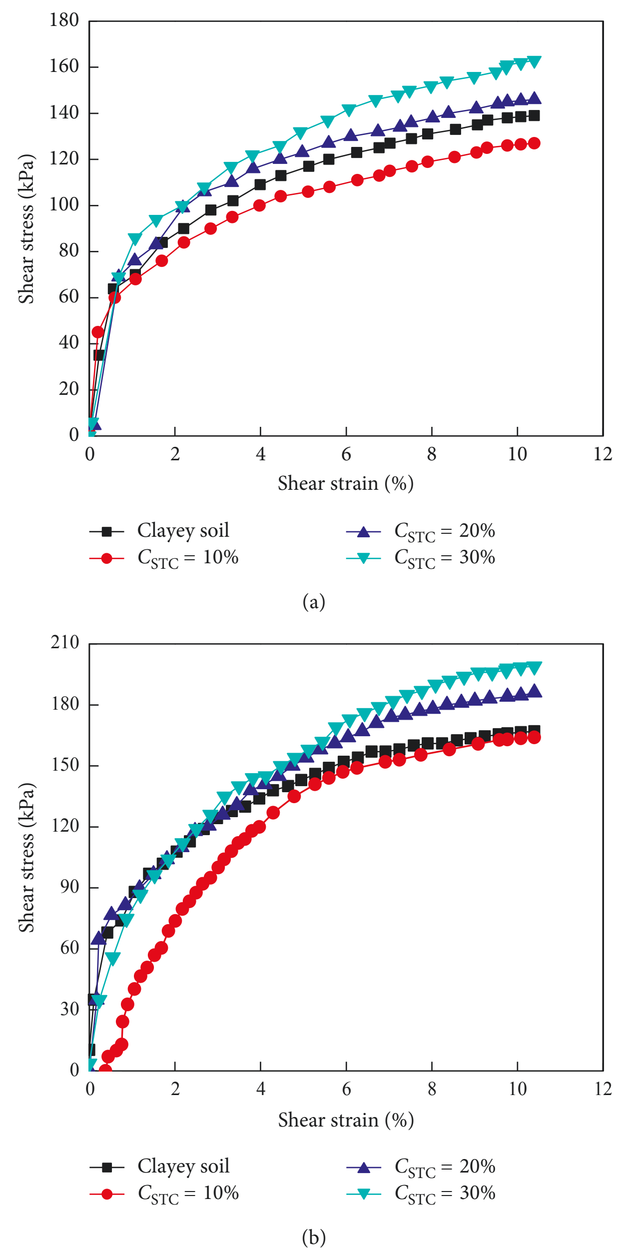

Figure 8: Shear stress-shear strain curves for mixtures under vertical pressure of 200 kPa. (a) Shear rate of 0.8 mm/min. (b) Shear rate of 0.1 mm/min.

4. Results and Discussion

4.1. Direct Shear Behavior of the Mixture

4.1.1. Effects of Vertical Pressure and C_{STC} on Shear Strength. Figures 5–7 compare the results of direct shear tests of pure clayey soil with those of the mixtures. Figure 5 shows some typical curves of the shear stress versus shear strain for the test specimens, where the shear stress has a general tendency to increase with the shear strain increasing. It is similar to the researches by Hasan et al. [15] and Tang et al. [26]. In addition, it should be noted that the shear strength of the mixture is equal to the shear stress at the shear strain of 10% [15].

Table 3: Effects of shear rates on shear strength of mixtures.

C_{STC} (%)	Shear rate (mm/min)	Vertical pressure (kPa)			
		50	100	200	300
0	0.1	56.6	83.5	157	215
	0.8	54.1	71.8	123	160
10	0.1	52.0	81.8	147	207
	0.8	44.0	71.6	115	156
20	0.1	65.0	92.5	166	219
	0.8	60.7	75.3	128	168
30	0.1	68.2	99.3	174	229

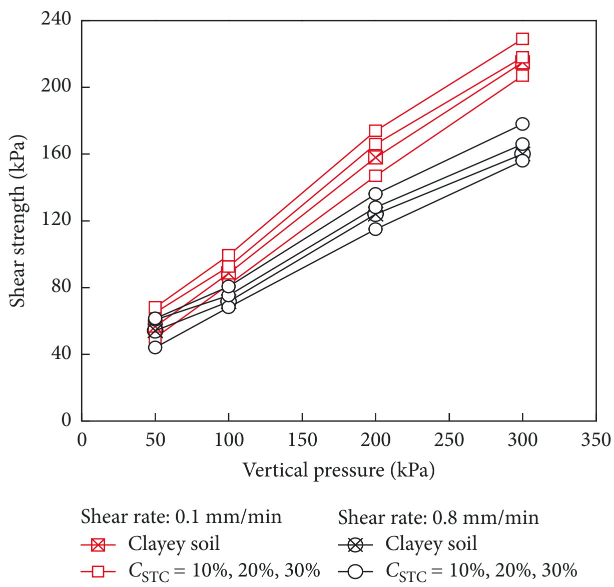

Figure 9: The shear strength of mixtures under different shear rates.

The Mohr–Coulomb failure envelopes and curves of the cohesion and angle of internal friction versus C_{STC} are shown in Figures 6 and 7. In Figure 6, each point represents the shear strength of mixtures under a certain vertical pressure, where the shear strengths of mixtures increase with the increase of vertical pressure. Besides, an approximately linear correlation between the shear strength and vertical stress was found in Figure 6. It is also found that C_{STC} has a strong influence on the shear strength of the mixture. The shear strength approximately enhances by 20% when C_{STC} is up to 30%. However, when C_{STC} is less than 10%, the shear strength of mixtures decreases compared with that of pure clayey soil.

The shear strength parameters of mixtures, such as the cohesion and the angles of internal friction, were determined to further analyze of the effect of C_{STC} on the shear strength of mixtures. The cohesion is calculated to be 29.15, 28.11, 34.61, and 36.74 kPa for pure clayey soil and the mixture with C_{STC} of 10, 20, and 30%, respectively. Moreover, the angle of internal friction is calculated to be 24.46°, 23.38°, 24.18°, and 25.83° for pure clayey soil and the mixture with C_{STC} of 10%, 20%, and 30%, respectively. The relationship between shear strength parameters and C_{STC} is illustrated in Figure 7, showing that C_{STC} has a significant influence on the cohesion of the mixture. However, the angle of internal friction of mixtures does not change significantly with C_{STC} increasing. With the increase of C_{STC}, there is an increase in the friction between clayey soil particles and scrap tire crumbs, as well as the friction between scrap tire crumbs and scrap tire crumbs. However, the value of C_{STC} is small (≤30%) in this study. Furthermore, the dilation of mixtures during shearing will weaken the friction. Therefore, the angle of internal friction does not change significantly with the increase of C_{STC}.

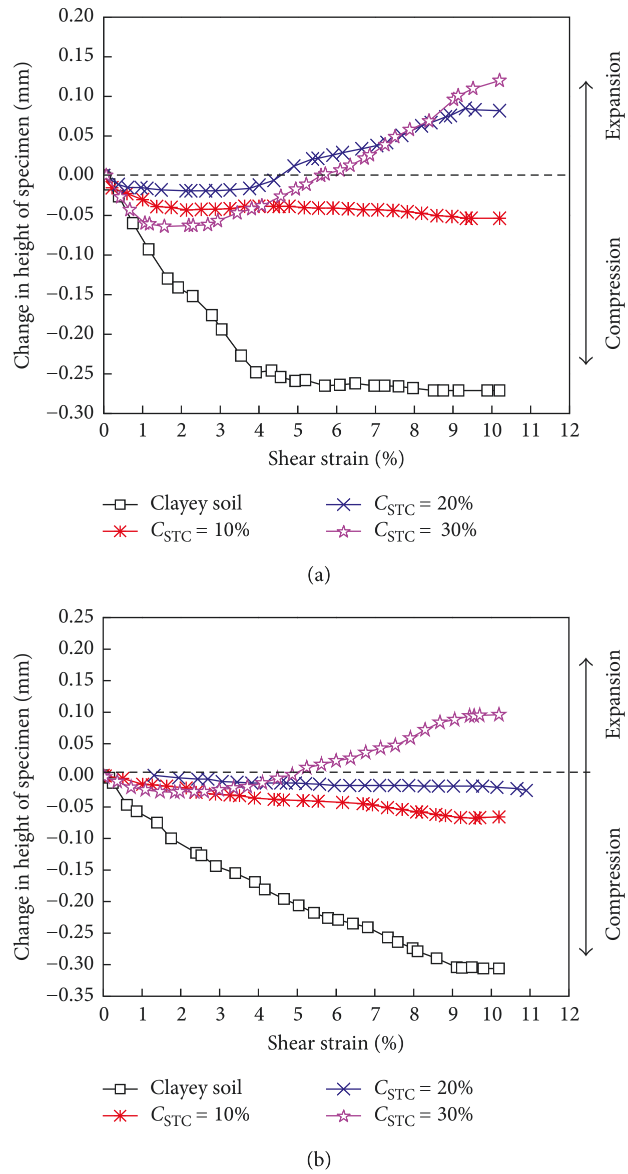

Figure 10: Variations of height of mixtures against shear displacement. (a) Under vertical pressure of 50 kPa. (b) Under vertical pressure of 300 kPa.

4.1.2. Effects of Shear Rate on Shear Strength. Figure 8 shows the variations of shear stress with the increase of shear strain

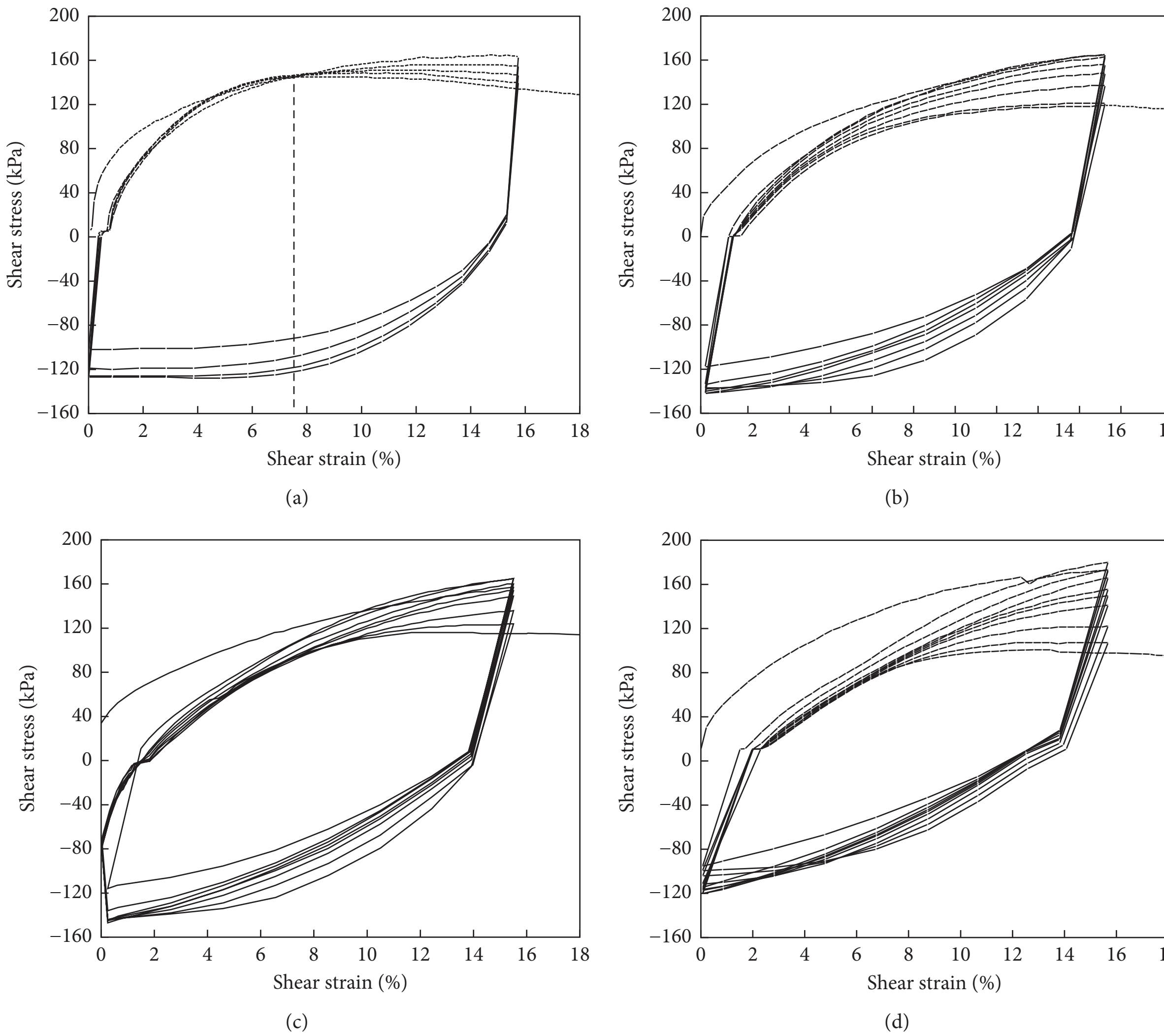

FIGURE 11: Variations of shear stress versus shear strain for mixtures under vertical pressure of 200 kPa. (a) Clayey soil. (b) $C_{STC} = 10\%$. (c) $C_{STC} = 20\%$. (d) $C_{STC} = 30\%$.

for mixtures under vertical pressure of 200 kPa. It indicates that there is no peak shear stress observed in the shear stress-shear strain curves. Therefore, the shear stress at the shear strain of 10% can be used as the shear strength of the mixtures. The shear strengths of mixtures with various C_{STC} are given in Table 3, and the Mohr–Coulomb failure envelops for mixtures are shown in Figure 9. The results show that when the vertical pressure is less than 100 kPa, the shear strength of mixtures does not vary significantly with the decrease of shear rate. However, when the vertical pressure exceeds 100 kPa, the shear strength significantly increases with the shear rate increasing.

4.1.3. Effects of Vertical Pressure and C_{STC} on Volumes of Mixtures. Figure 10 shows the volume changes of the mixtures (in height) versus shear strain for the mixtures and possible specimen volume compression (with a "−" sign) and dilation (with a "+" sign) shown in this figure. It was found that, when the vertical pressure is 50 kPa, the clayey soil and the mixture with C_{STC} of 10% compress during shearing. However, the mixture with C_{STC} of 20% initially compresses and then begins to dilate after the shear strain exceeds 4.5%. Furthermore, with C_{STC} of 30%, the mixture compressed at first and then began to dilate after the shear strain of 5% to 6%. This shearing dilation for scrap tire rubber shreds-soil mixture was also observed by Hasan et al. [15]. However, when the vertical pressure is 300 kPa, during shearing the clayey soil and the mixtures with C_{STC} of 10 and 20% are compressed. It can be concluded that during shearing, the dilation of mixtures occurs, particularly under the condition of a high C_{STC} and a low vertical pressure.

4.2. Evaluation of Cyclic Direct Shear Tests Results. The residual shear strengths of mixtures were obtained from cyclic direct shear tests. In addition, the volume changes of mixtures were measured during cyclic direct shearing. The test results for 48 specimens are presented in Figures 11–13 and Table 4. Figure 11 presents the variations of shear stress

Table 4: The results of repeated direct shear tests for mixtures.

Rubber content (%)	Normal stress (kPa)	Peak strength (kPa)	Residual strength (kPa)	Shear displacement at residual strength (mm)	Moisture content increase ratio (%)
	100	83.5	78.5		
Clayey soil	200	157	135	45~48	1.58
	300	221	202		
	100	71.6	68.7		
10	200	140	125	65~70	1.15
	300	215	180		
	100	88.5	63.5		
20	200	137	116	83~86	1.46
	300	219	175		
	100	95.3	62.6		
30	200	155	109	94~97	1.27
	300	210	170		

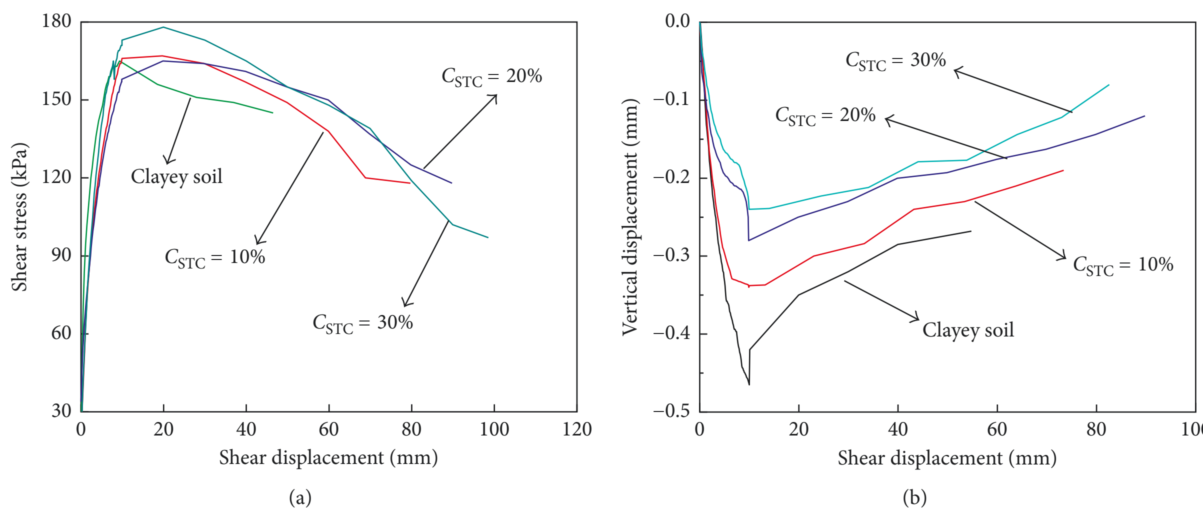

Figure 12: Plots of shear stress and vertical deformation of mixtures against shear displacement for mixtures under vertical pressure of 200 kPa. (a) Shear stress versus shear displacement. (b) Vertical displacement versus shear displacement.

versus shear strain for mixtures under vertical pressure of 200 kPa.

Figure 12(a) presents that the shear stress of mixtures increases initially, after reaching a maximum value, it decreases with the shear displacement increasing, indicating a strain-softening phenomenon for the mixtures. It also can be found that the peak strength of mixtures enhances with the increase of C_{STC}. Conversely, the residual shear strengths of mixtures rapidly decrease with C_{STC} increasing. The residual shear strength of the mixture with C_{STC} of 30% decreases by about 15%, compared with that of pure clayey soil. The reason is that the volume of void in the mixture is larger than that of the pure clayey soil.

Figure 12(b) shows that, during cyclic direct shearing, the vertical displacements decrease initially and then increase with increasing the shear displacement. It can be also observed that the mixtures can effectively limit the vertical deformation under the same shear rate and the same vertical pressure, compared with that of pure clayey soil.

The envelopes of the residual shear strength for the mixtures are shown in Figure 13. The results reveal that the residual shear strengths of mixtures gradually decrease with C_{STC} increasing. However, when the C_{STC} is larger than 20%, the effect of the C_{STC} on the residual strength of the mixture can be neglected.

It can be also concluded from Table 4 that the required shear displacement to obtain the residual shear strength of mixture increases with increasing the C_{STC} value. As the C_{STC} increases from 10 to 30%, the corresponding maximum shear displacements increase by 45.8%, 79.2%, and 102%, respectively, compared with that of pure clayey soil. Furthermore, changes in the moisture contents of the mixtures were measured (Table 4). It is concluded that the moisture content increases by an average of 1.3%, compared with the initial moisture content of the shear surface. The increase of moisture content is caused by the increase of the void ratio of mixture located in shear zone during cyclic shearing.

4.3. Evaluation of Consolidation Tests Results. The estimation of consolidation settlement is one of the most important

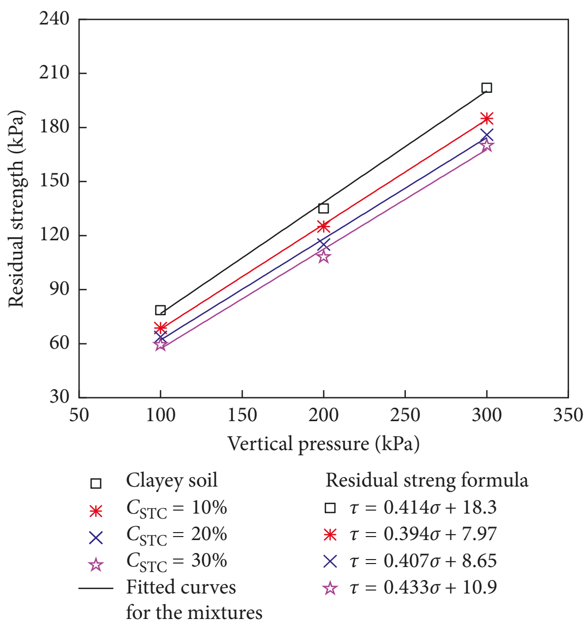

FIGURE 13: Envelopes of the residual shear strength for mixtures.

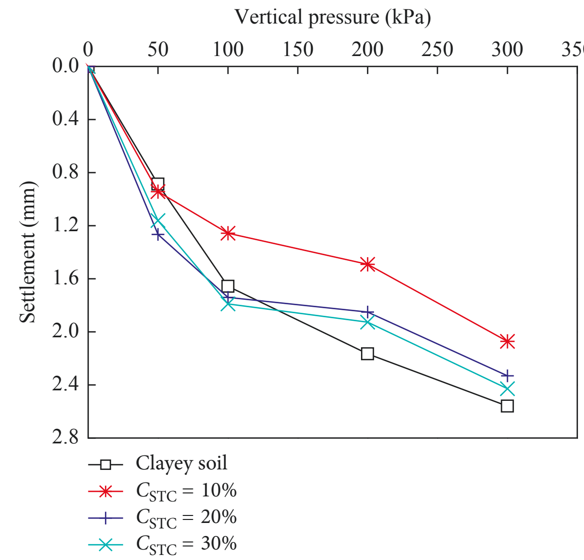

FIGURE 14: Settlement development with vertical pressure for mixtures.

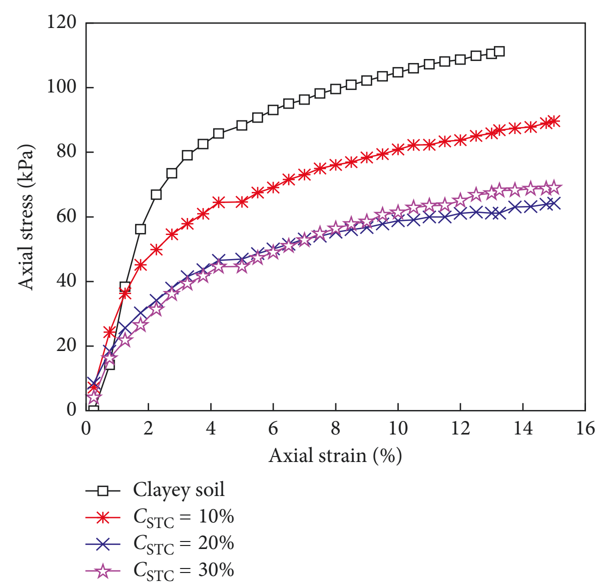

FIGURE 15: The axial stress-strain relationships for mixtures.

procedures in the design of soft ground improvement projects [17]. Figure 14 shows the changes of consolidation settlement for pure clayey soil and the mixtures under various vertical pressures. When the vertical pressure is less than 100 kPa, the consolidation settlement of mixtures does not vary significantly with C_{STC} increasing. However, as the vertical pressure is greater than 100 kPa, the settlements of the mixtures with C_{STC} of 10, 20, and 30% decreased approximately 25%, 12%, and 8%, respectively, compared with that of pure clayey soil. The reason of the reduction in consolidation settlement for mixtures is that, with the increase of C_{STC}, the mixtures tend to be more elastic and resilience.

4.4. Compressive Properties

4.4.1. Effect of C_{STC} on Compressive Strength of Mixtures. For each compression test under the undisturbed, remolded, and compacted conditions using a strain-controlled axial load, the compressive strength of mixtures, which is taken as the load per unit area at 15% axial strain, can be obtained. The variations of axial stress for the mixtures with axial strain increasing are plotted in Figure 15. The results from Figure 15 present that the unconfined compressive strength of these specimens was decreased from 111 to 90 kPa, from 111 to 69 kPa, and from 111 to 66 kPa for pure clayey soil and mixtures with C_{STC} of 10%, 20%, and 30%, respectively. It is pointed out that, when C_{STC} is 20%, there is an approximately 40% decrease in compressive strength of the mixture compared with that of pure clayey soil. However, when C_{STC} exceeds 20%, the effect of C_{STC} on the compressive strength is weak for the mixtures. The decrease in the compressive strength of mixtures with C_{STC} increasing is attributed to the presence of scrap tire crumbs, which causes the increase of contact between scrap tire crumbs, resulting in higher resilience, higher deformation, and less strength.

4.4.2. Effects of C_{STC} on the Failure Modes of Mixtures. The failure modes of pure clayey soil and the mixture with C_{STC} of 10% by unconfined compression tests are presented in Figures 16(a) and 16(b), respectively. Figure 17 shows the failure modes of the mixture with C_{STC} of 20%; this failure mode is similar to that of the mixture with C_{STC} of 30%. As shown in Figures 16(a) and 16(b), the inclined plane failure occurs for pure clay and the mixture with C_{STC} of 10%. Instead, when the C_{STC} exceeds 20%, mixture specimens

(a)

(b)

Figure 16: Inclined plane failure of (a) clayey soil and (b) mixture with C_{STC} of 10%.

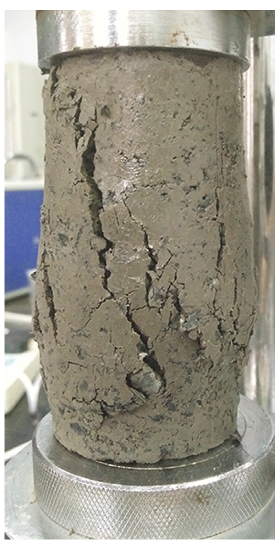

Figure 17: Bulging failure of mixture with C_{STC} of 20%.

exhibit bulging failure. It is concluded that C_{STC} may have influence on the failure modes of the mixtures effectively.

5. Conclusions

A series of laboratory tests were performed on scrap tire crumbs-clayey soil to study the mechanical properties. The following conclusions can be obtained:

(1) Maximum dry unit weight and the corresponding optimum moisture content of the mixtures decrease with increasing the C_{STC} value.

(2) For a given C_{STC}, the direct shear strength of the mixtures increases with the increase in vertical pressure and decreases with the decrease in shear rate. Moreover, the dilation of the mixtures occurs during shearing, particularly under the condition of a high C_{STC} and a low vertical pressure.

(3) Residual shear strength, compressive strength, and consolidation settlement decrease markedly with C_{STC} increasing, while start to decrease slightly when the C_{STC} exceeds 20%.

Scrap tire crumbs-clayey soil mixture has the advantages of higher shear strength, and lower density and settlement compared with that of pure clayey soil. This mixture can be used in many geotechnical applications, such as backfills behind retaining structures and embankments on soft compressible soil.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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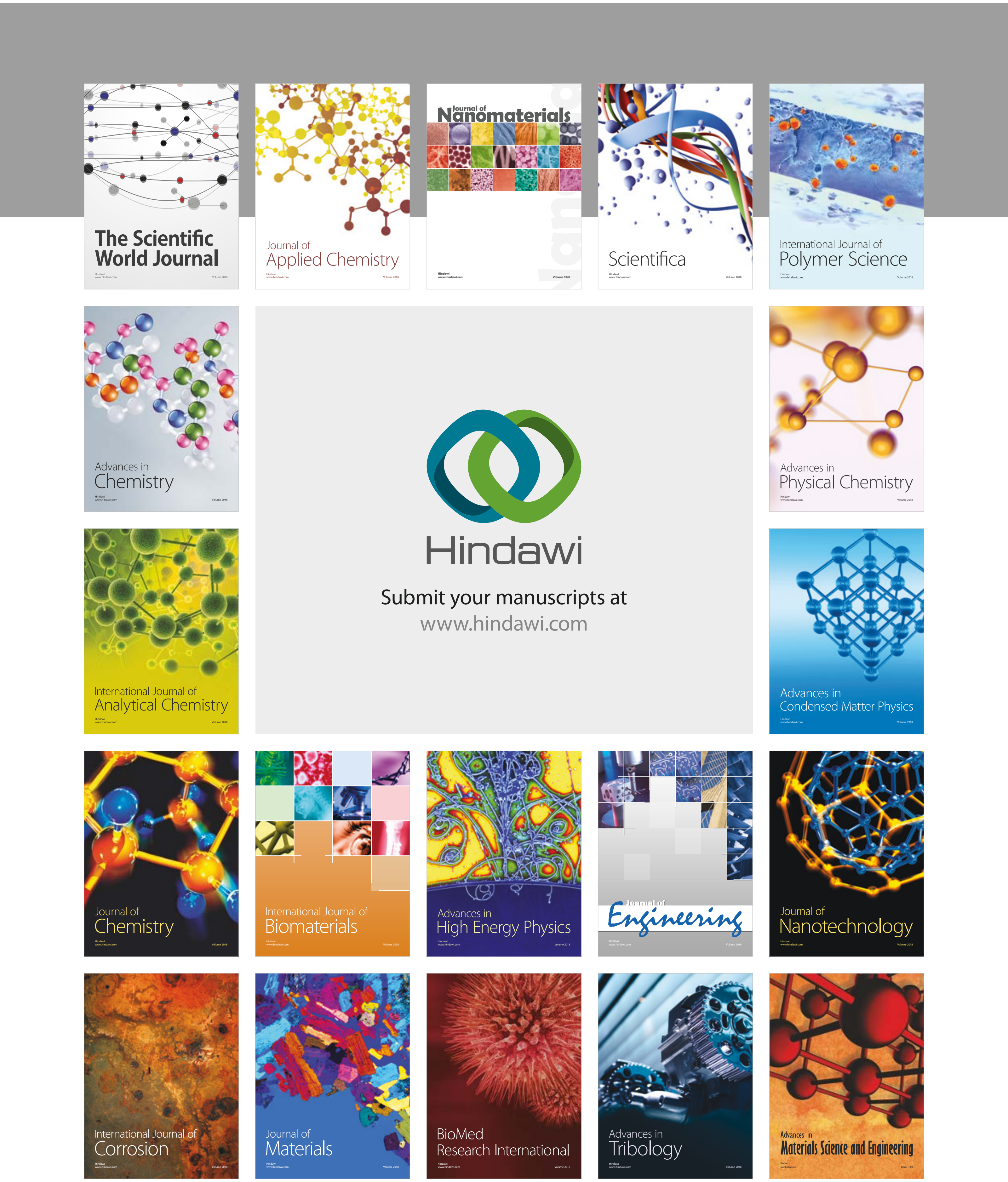
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