

Behavior of Clay-Tire Mixtures Subjected to Undrained Monotonic Loading

H. Soltani-Jigheh, V. Marefat, A. Ersizad

Abstract. Soil - tire mixtures have been recently used as construction materials in civil engineering projects. In this research, a number of undrained triaxial tests were carried out on the compacted clay-tire mixtures and their behaviors were compared with behavior of pure clays. The results of the tests indicate that adding more than about 20%-30% tire to the low plasticity clay doesn't reduce the shear strength in comparison with the associated values of pure clay. In the mixtures made of high plasticity clay, the shear strength decreases by increasing tire content. Moreover, friction angle and cohesion values vary with increasing tire-chips, which is completely dependent on the clay plasticity. The results also demonstrated that, for the mixtures of low plasticity clay, maximum excess pore water pressure occurs in the specimens with tire content of about 10%-20%. For the mixtures consist of high plasticity clay, at low consolidation stress, the pore water pressure decreases slightly with an increase in tire content. At high consolidation stress, excess pore water pressure induced within these mixtures increases slightly with an increase in tire-chips content. Adding tire-chips to the clay also lead to increase deformability of mixtures considerably.

Keywords: clay-tire-chip mixtures, triaxial test, shear strength, pore water pressure.

1. Introduction

A large volume of waste tires is being generated every year and results in major environmental hazards worldwide. Rubber Manufacturer's Association (2013) estimates that about 296.7 million tires (5170.5 thousand tons) were generated in the USA in 2009 and the total percent of tires consumed in end-use markets reached approximately 84.9%. It also estimates that about 12.6% of scrap tires have been disposed in the land at the end of 2009.

It has also been reported that about 20 million tires were produced in Iran 2005 and about 10 million scrap tires were added to the existing stockpile annually. Therefore, in the last decade, considerable research and development has been carried out for the use of tire crumbs in asphaltic pavement layers in Iran (Iran Transportation Research Institute, 2006) and it is also essential to find beneficial ways of recycling and/or reusing tires.

According to Humphrey (1999), using scrap tires in civil engineering projects are advantageous because of their low density, high durability, and high thermal insulation and in many cases least cost compared to other fill materials. These materials are used for reinforcing soft soil in road and embankment construction (Bosscher *et al.*, 1997; Heimdah & Druscher, 1999; Velazco *et al.*, 2000; Zornberg & LaRocque, 2005), as lightweight fill materials (Bosscher *et al.*, 1997; Tatlisoz *et al.*, 1998; Lee *et al.*, 1999; Edil & Bosscher, 1994), as an additive material to asphalt (Foote *et al.*, 1996; Tuncan *et al.*, 1998), as a source for creating

heat (Lee *et al.*, 1999), and as landfill barrier materials (Al Tabbaa & Aravinthan, 1998; Al Tabbaa *et al.*, 1997; Baykal & Alpatly, 1995).

Bosscher *et al.* (1993) reported that an embankment constructed with sand-tire shreds operated satisfactorily even when subjected to heavy loads. They also found that the long-term settlement of such embankment could be alleviated if a soil cap with a thickness of 1 m overlies the sand-shred mixtures. Bosscher *et al.* (1997) performed large-scale models of tire-chips embankments and showed that tire chip-soil mixtures exhibit a significant initial plastic compression under load.

Lee *et al.* (1999) carried out triaxial tests on pure tire-chips and tire-chips mixed with sand. Youwai & Bergado (2004) carried out drained triaxial compression tests on shredded tire-sand mixtures with different amount of tire-chips. They found that with an increase in sand content, the strength and unit weight of mixtures increase and deformation due to isotropic compression decreases. Rate of reduction in deformation was significant when the sand in the mixture was more than 30%.

Former studies have mainly concentrated on determining engineering properties of tire-chips alone and/or various mixtures of tire-chips with sand as a lightweight fill material for embankment construction (Lee *et al.*, 1999; Edil & Bosscher, 1994; Foote *et al.*, 1996; Garga & Zargarbashi, 2002; Zornberg *et al.*, 2004; Venkatappa & Dutta, 2006; Vafaeian & Mehran-Nia, 2006; Ghazavi & Sakhi, 2005).

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Some investigators have recently been studied the behavior of clay - tire mixtures. Cetin *et al.* (2006) added two types of tire-chips to clay and indicated that the shear strength increases up to 30% for fine and 20% for coarse tire-chip mixtures. Moreover, with the increase tire-chips up to 40% cohesion of samples increases, while the angle of internal friction decreases. For the tire-chips more than 40%, the cohesion decreases, whereas the angle of internal friction grows up. They also demonstrate that under lower normal pressures percent of tire-chips do not have considerable effect on the vertical strains or volume change during shear. However, under higher normal pressures, originally high negative vertical strains for the clayey soil alone decrease considerably for the fine tire-chip mixtures or become slightly above zero or positive for the coarse tire-chips mixtures up to 50%. They concluded that the dry densities of clay-tire chip mixtures are lower than that of pure clayey soil.

Özkul & Baykal (2007) investigated the influence of rubber fiber inclusion on the shear behavior of low plasticity clay by performing a series of triaxial compression tests under confining stresses ranging from 50 kPa to 300 kPa. They pointed that the contribution of rubber fibers to the strength of clay mixtures decreases with increasing levels of confining stress. A limit confining pressure also exists beyond which the presence of rubber fibers tend to degrade the strength of the clay.

When confining stresses are below this limit value the peak drained strength of the composite specimens is higher, occurs at greater strains, and has higher post peak strength in comparison with the associated values of unreinforced clay. During undrained loading, composite specimens again have higher peak strengths but show faster strength development compared to samples of clay alone. In addition, they showed that the deformation behavior of the clay is significantly changed.

Overview of the previous studies reveals that the effects of tire-chips content and clay characteristics on the behavior of clay - tire mixtures have not clearly been investigated (Cetin *et al.*, 2006; Özkul & Baykal, 2007). In addition, the studies on behavior of these mixtures under undrained loading condition are incomplete. With this intend, a number of undrained triaxial tests are carried out on the compacted specimens made of clay-tire chips mixtures. Then, the obtained results are compared with the associated behavior of pure clay and an analysis is performed in terms of tire-chips content and clay plasticity. It should be noted that the materials presented in this article is a part of a comprehensive study on clay-tire mixtures and the effect of tire-chips size on the behavior of these mixtures published previously by Marefat & Soltani-Jigheh (2011).

2. Materials and Methods

2.1. Materials and sample preparation

Samples were prepared by mixing cohesive clayey soils with 10, 20 and 30% tire-chips, free of steel belts, by

weight. The tire-chips used in the mixtures were obtained from a local waste tire manufacturing plant which grinds them for reusing. The size of tire-chips were between 4.75 mm (No. 4 sieve) and 1/4" sieve, with an average size of 5.53 mm and specific gravity of 0.988.

Major part of clayey soil used in the mixtures was locally obtained from the Azarshahr clay deposits in East-Azarbaijan state. This cohesive soil has index properties of $LL = 33\%$, $PI = 12\%$, and $G_s = 2.698$ and denoted with AC. To investigate the effect of clay plasticity on the characteristics of clay-tire mixtures, an artificial clay was prepared by mixing 80% AC clay with 20% commercial bentonite. This clay is characterized by ACB and has index properties of $LL = 61\%$, $PI = 33\%$, and $G_s = 2.64$ (Table 1). According to Unified Soil Classification System (USCS), AC and ACB clays were categorized as CL and CH, respectively (ASTM, 2008a). Mineral component and index properties of these clays are also listed in Table 1. Grading curves of tire-chips and clayey soils are depicted in Fig. 1 and also some grading specifications of these materials are listed in Table 2.

In order to model samples closely the prototype conditions, standard Proctor compaction tests were performed on the clayey soils and mixtures to determine compaction characteristics (ASTM, 2008b). The resulting compaction curves provide information on maximum dry unit weight (γ_{dmax}) and optimum water content (w_{opt}). Names of tested samples as well as some of their specifications are listed in Table 3. In the name of specimens, R3 shows the tire-chips

Table 1 - Mineral components and index properties of clayey soils.

Clay type	AC	ACB
Minerals		
Calcite (%)	59	26
Quartz (%)	17	21
Feldspar (%)	12	14
Clay minerals (%)	11*	37**
Other mineral	1	2
Consistency indices		
Liquid limit (%)	33	61
Plastic limit (%)	21	28
Plasticity index	12	33
Specific gravity	2.698	2.64
USCS classification	CL	CH

*This value indicates total percentage of clay minerals by weight, which mainly consists of Kaolinite, Illite, Chlorite and Montmorillonite, respectively.

**This value indicates total percentage of clay minerals by weight, which mainly consists of Montmorillonite, Kaolinite and Illite, respectively.

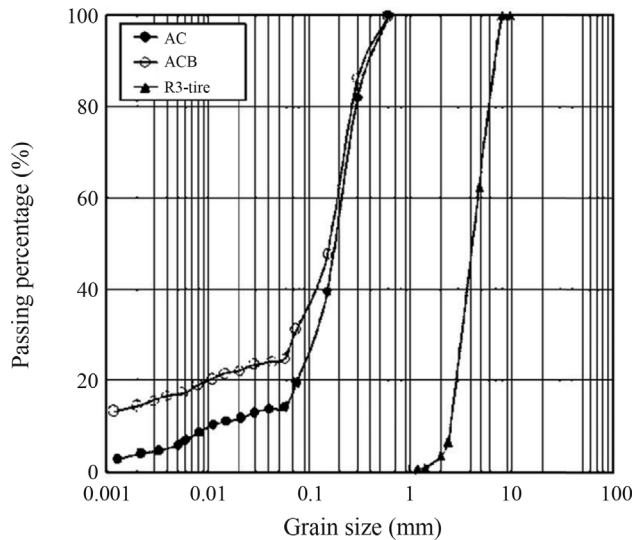


Figure 1 - Particle size distribution of used materials.

Table 2 - Some properties of used materials.

Material	AC	ACB	R3-tire
D ₁₀	0.01	-	2.5
D ₃₀	0.14	0.07	3.4
D ₆₀	0.19	0.21	4.6
C _u	19	> 25	1.84
C _c	10.31	-	1.005

in the mixtures and AC and ACB stand for the type of clay matrix. The numbers denote the clay percent in weight; *e.g.*, the specimen made of 80% AC clay and 20% R3 tire-chips was named as R3-AC80.

Soil specimens were then compacted in 50 mm diameter and 100 mm height steel mold with density of $0.95\gamma_{dmax}$ at 1% of the optimum moistures. In order to obtain a uniform mixture, water was sprayed onto the surface of the materials and then mixed and placed in sealed plastic bags and stored overnight in a controlled humidity room.

Due to the presence of tire-chips, it was impossible to cut or trim compacted composite soil without causing considerable disruption. Hence, the specimens had to be compacted into a mold that was suitably sized for triaxial testing. A special splitting type cylindrical mold of 50 mm diameter and 100 mm height was used.

2.2. Shear Testing

After extruding the specimens from the mold, they were set up in triaxial cell. The triaxial apparatus had an automatic data acquisition and logging system was used during all stages of testing to periodically record cell pressure, back pressure, pore water pressure, load and deformation of tested specimens. A manually volume change was con-

nected to the backpressure line for obtaining the volume change of specimens.

Standard consolidated undrained (CU) triaxial testing procedures were followed (ASTM, 2008c). To saturate the specimens, distilled water was transmitted through them and then incremental backpressure saturation with a pressure differential of 30 kPa was applied. The backpressure was raised to a maximum of 375 kPa and B value was calculated for each increment. Saturation of the specimens took approximately 4-7 days to complete until reaching at least B-value of 0.97. The specimens were consolidated under three different effective consolidation stresses of 100, 200, and 300 kPa. Shearing was applied to the specimens with deformation rates of 0.05 mm/min until reaching up to 18% strain and simultaneously shear-induced pore water pressure was measured.

3. Typical Test Results

Considering the large number of the tests, it is not possible to present all of their immediate results; hence, only typical results are introduced. However, all of the immediate results are compiled, analyzed, and presented in the following sections. The results of the tests on ACB100 and R3-AC80 specimens are typically presented in Figs. 2 and 3. These figures show variations of deviatoric stress *vs.* axial strain (ϵ_a), excess pore water pressure (Δu) *vs.* ϵ_a , and deviatoric stress ($q' = \sigma'_1 - \sigma'_3$) *vs.* mean normal effective stress ($p' = (\sigma'_1 + 2\sigma'_3)/3$).

4. Analysis of Results

4.1. Stress-strain behavior

A comparison of the stress-strain behavior of clay-tire mixtures with different amounts of ω_R was complied. Typical results of these comparisons for different R3-AC and R3-ACB specimens under $\sigma'_3 = 300$ kPa are presented in Figs. 4 and 5, respectively. In general, it can be observed that at low level of strains, the unamended clays is stronger than the clay-tire chip mixtures (Figs. 4a and 5a). In contrast, in high level of strains the trend is different; some mixtures are stronger than the pure clay and some others are weaker than the pure clays. In general, the effect of tire-chips on the stress-strain curves is not considerable.

4.2. Shear strength

To study the effect of tire content on the shear strength of clayey soils, the variations of shear strength of specimens has been plotted in terms of tire-chips content (Fig. 6). As illustrated in this figure, the effect of tire-chips on the shear strength of clays depends on the clay plasticity. The shear strength of AC clay-tire mixtures reduces as the tire content (ω_R) increases (in comparison with the associated values of unamended clay) until reaching a minimum value at a given tire content. After this given value, by increasing tire content in the specimens the shear strength

risks up. This given value for ω_R is about 10%-20% dependent on the value of σ'_c . The shear strengths of specimens amended with 30% tire approximately equal to associated values of unamended clay. In contrast, for ACB clay-tire

mixtures, the shear strength reduces slightly as the tire content increases.

From Fig. 6, it can be realized that the shear strength of mixtures of high plasticity clay decreases with increas-

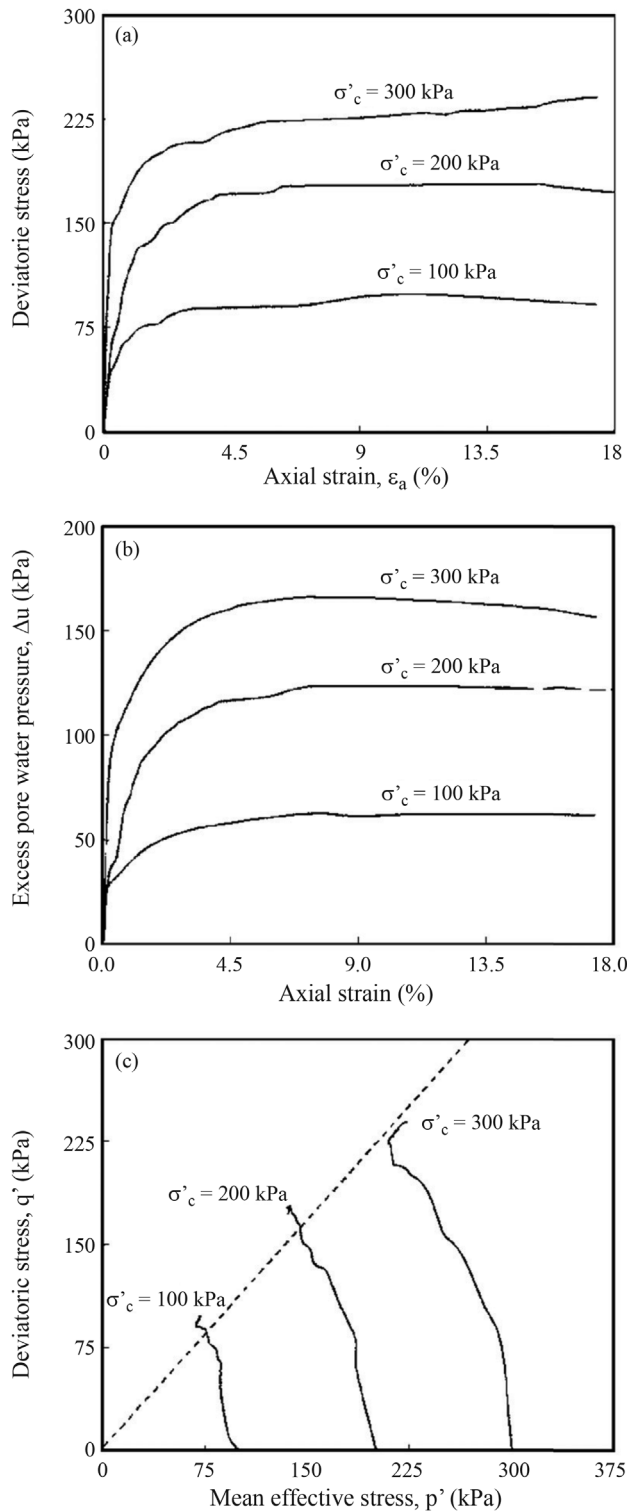


Figure 2 - Results of the tests on ACB100 specimen: a) stress-strain plots, b) Δu vs. ϵ_a , and c) stress paths on q' - p' space.

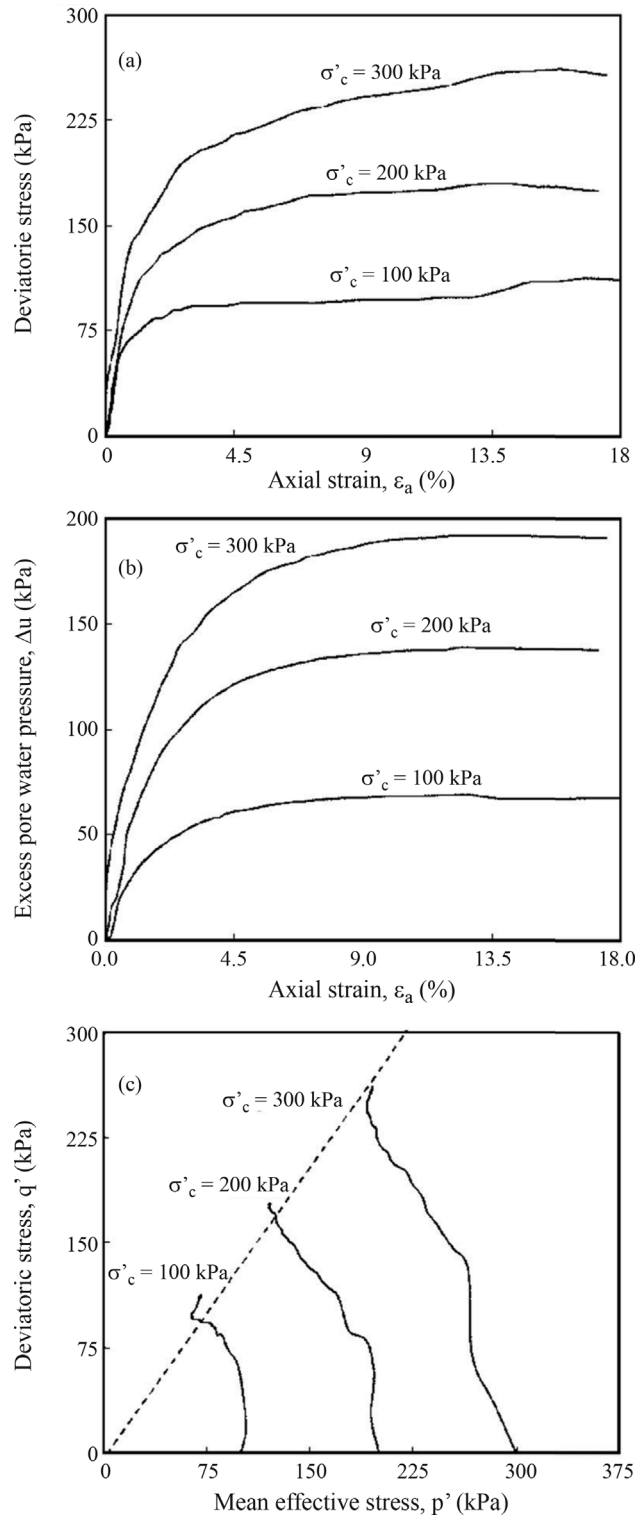


Figure 3 - Results of the tests on R3-AC80 specimen: a) stress-strain plots, b) Δu vs. ϵ_a , and c) stress paths on q' - p' space.

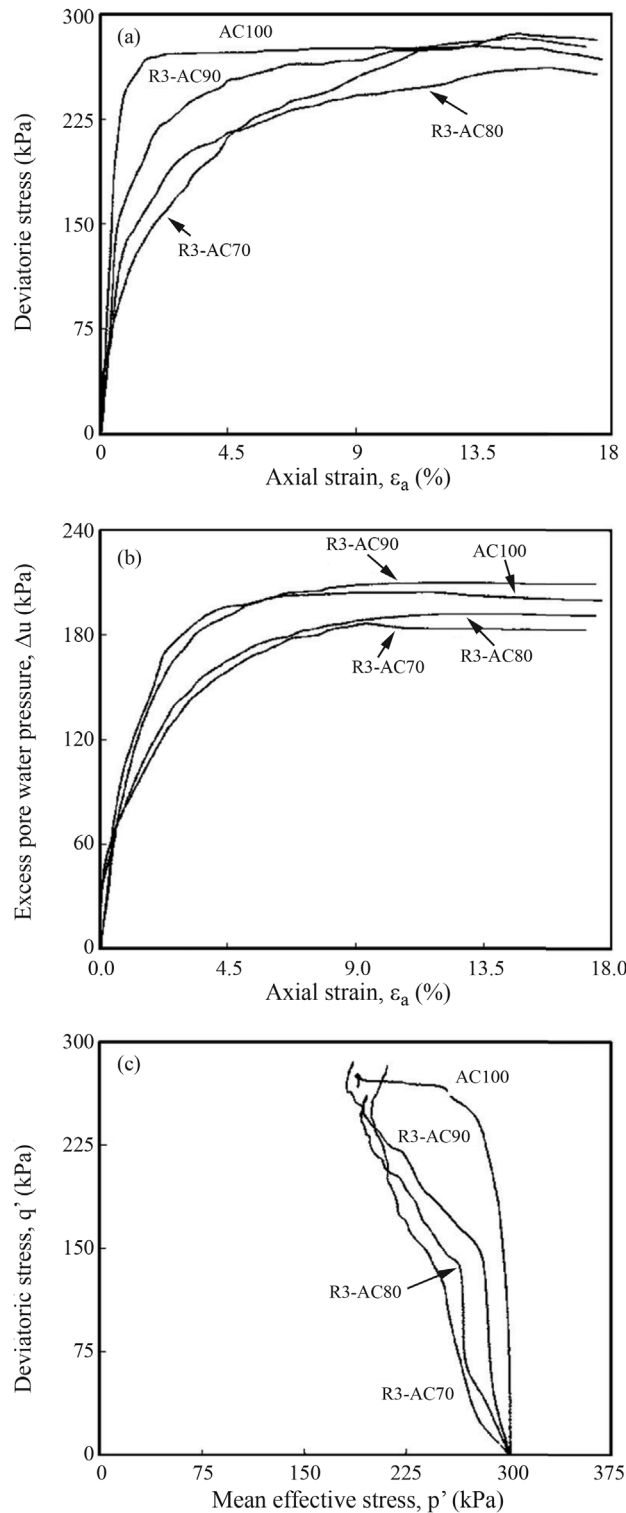


Figure 4 - Behavior of R3-AC specimens under $\sigma'_c = 300$ kPa: a) stress-strain plots, b) Δu vs. ϵ_a , and c) stress paths on q' - p' space.

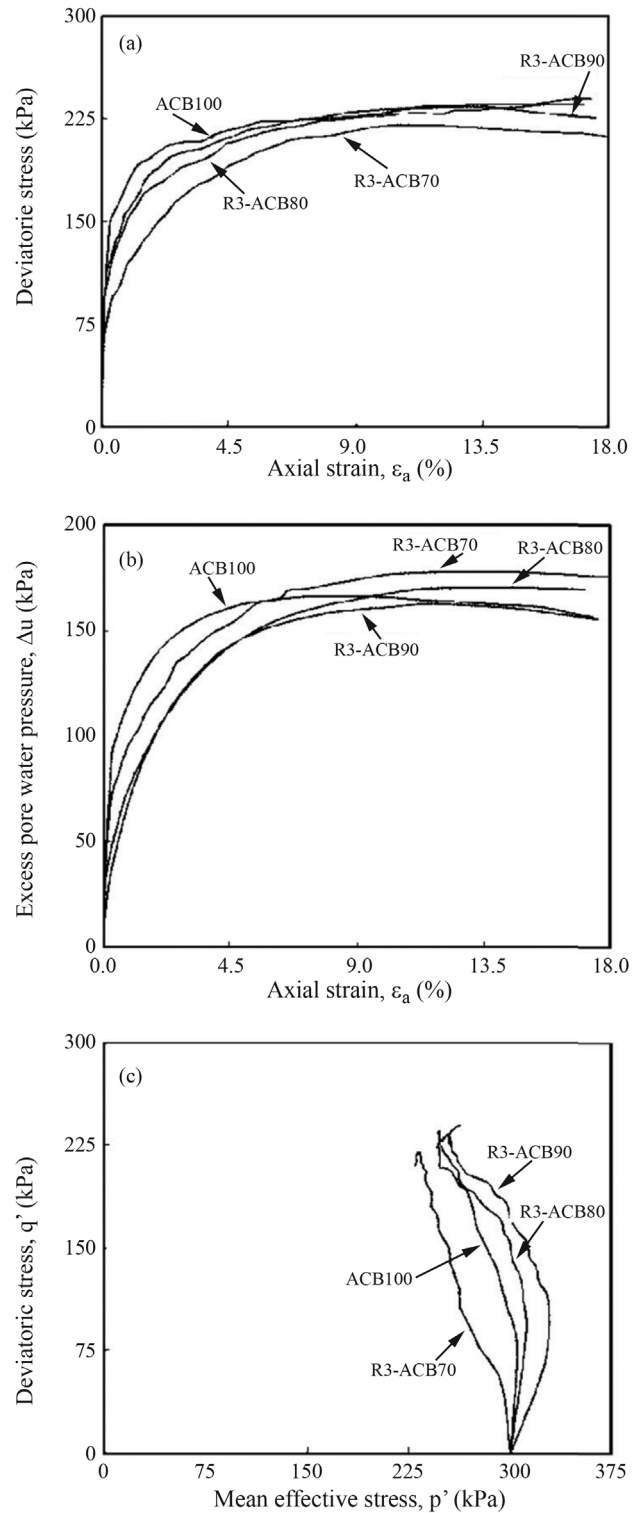


Figure 5 - Behavior of R3-ACB specimens under $\sigma'_c = 300$ kPa: a) stress-strain plots, b) Δu vs. ϵ_a , and c) stress paths on q' - p' space.

ing the tire content. While for the specimens made of low plasticity clay, it is abated to a given value of ω_R , and then the trend is altered conversely.

In addition, to investigate the effect of tire-chips on the values of shear strength parameters, the values of internal friction angle (ϕ') and cohesion (c') evaluated in terms

of tire contents, as depicted in Fig. 7. It can be found that the changing ϕ' and c' values with ω_R are completely vice versa in the mixtures of AC and ACB clays.

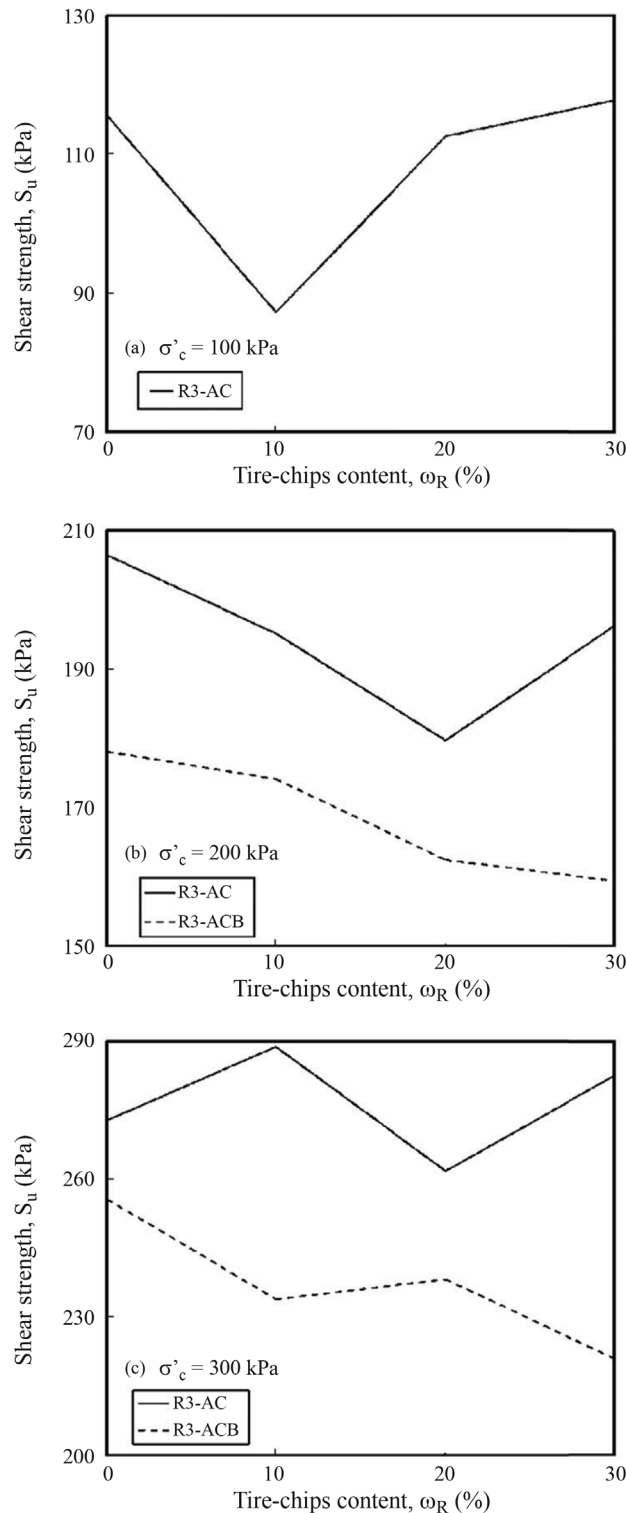


Figure 6 - Effect of tire-chips on the shear strength of specimens under σ'_c of: a) 100 kPa, b) 200 kPa, and c) 300 kPa.

As illustrated in Fig. 7b, the friction angle of R3-AC90 specimen is higher than that of other specimens of R3-AC. The ϕ' values of R3-AC80 and R3-AC70 specimens are lower than the associated value of AC100 specimen. Unlike, for the mixtures of ACB clay, the minimum value of ϕ' obtained for the specimen with $\omega_R = 10\%$, and beyond this ω_R , the values of ϕ' increase with increasing tire content. The ϕ' values of R3-ACB80 and R3-ACB70 specimens are greater than the associated value of unamended clay.

Figure 7b shows that changing cohesion parameter with tire content is strictly in contrast with the trends of ϕ' in associated mixtures. The values of c' are the least and the most respectively for the mixed specimens of AC and ACB clays consist of 10% tire-chips. Thereafter, adding tire-chips to the clays causes the cohesion increases and decreases, respectively. Similar trend for ϕ' and c' was reported by Cetin *et al.* (2006) for mixtures comprising low plasticity clay.

To interpret the effect of tire-chips on the shear strength parameters, it can be said that AC clay includes

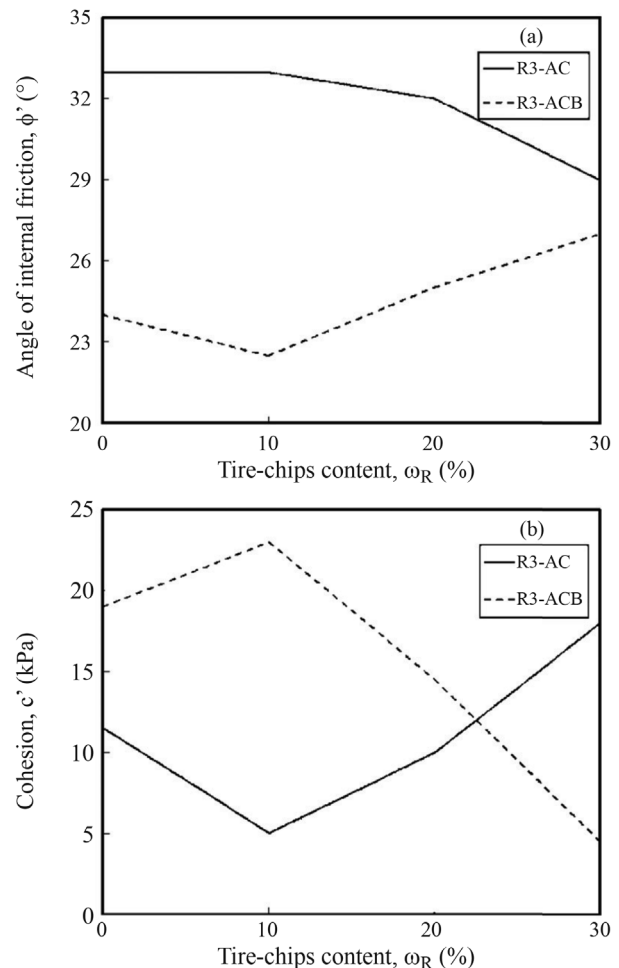


Figure 7 - Variations of a) friction angle, and b) cohesion, vs. tire content.

low content of cohesive clay minerals and its shear strength is mostly based on the friction between particles and cohesion between soil particles plays small role. One may be concluded that the non-clay minerals of soil are stiffer than additive tire-chips; in other words, the total hardness of AC clay is higher than tire-chips. Thereupon, inclusion of tire-chips reduces the friction angle; because tire-chips induce space between frictional particles or change contact structure to floating structure. The compaction may also induce cohesion between tire-chips and soil particles, which is higher than the cohesion between soil particles in low plasticity clay. Therefore, inclusion of tire chips heightens the cohesion values in AC mixtures.

Reversely, in high plasticity ACB clay, content of clay minerals is high, in general the soil is softer, and also its shear strength is mostly based on the cohesion between soil particles. When the tire-chips are added to the clay, the attractive force between clay minerals reduces which is lead to reduction in cohesion. Moreover, the tire-chips are stiffer than the predominant minerals of ACB clay, which cause to increase the friction angle of mixtures.

Comparison of failure envelopes of samples (see Fig. 8 and Table 3) shows that slope of the envelopes (M) does not affected significantly by inclusion of tire-chips to the clay.

4.3. Deformability

Secant deformation modulus (E_{50}) is an index of specimen deformability. Therefore, the values of E_{50} for the specimens obtained from the associated stress-strain curves (Table 4) and variations of them plotted in terms of tire-chips content as indicated in Fig. 9. This figure shows that, irrespective of clay matrix, the values of secant deformation modulus decreases with increasing tire-chips content; in other words, the deformability of specimens rises as ω_R increases. The rate of reduction is considerable for the

Table 3 - List of specimens with some specifications.

Specimen designation	Clay (%)	Tire, ω_R (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	M
AC100	100	0	16.35	19.50	1.104
R3-AC90	90	10	15.20	19.54	1.190
R3-AC80	80	20	14.40	18.00	1.148
R3-AC70	70	30	13.80	16.25	1.158
ACB100	100	0	14.78	21.75	1.000
R3-ACB90	90	10	13.63	18.51	0.940
R3-ACB80	80	20	13.42	19.25	0.944
R3-ACB70	70	30	13.10	20.25	0.948

higher values of σ'_c and it is about 70%-80% for $\sigma'_c = 300$ kPa.

4.4. Excess pore water pressure (EPWP or Δu)

Comparison of Figs. 4a and 5a shows that shear-induced pore water pressure of unamended clays at low level of strains are higher than the similar values of mixed specimens, but at high level of strains the trend is changed. Maximum values of EPWP (Δu_{max}) of the specimens vs. tire-chips content are presented in Fig. 10. This figure explains that the effect of tire-chips on Δu_{max} depends on the type of clay. For the mixtures of AC clay, Δu_{max} rises at first with increasing tire content up to 10%-20%, dependent on the values of confining stress and, afterward, it begins to reduce. For the mixtures made of ACB clay, inclusion of tire-chips to the clay lead to decrease pore water pressure slightly at $\sigma'_c = 200$ kPa. But at consolidation stress of 300 kPa, maximum EPWP increases with an increase in tire-chips content. However, the effect of tire-chips on the excess pore water pressure is not most considerable and it is about 8%-15%.

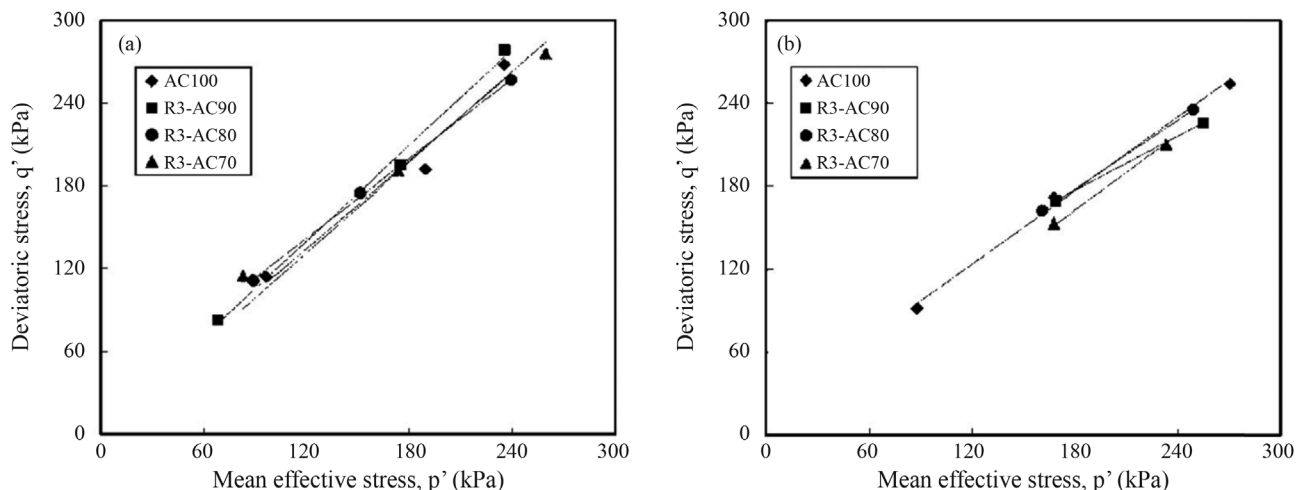


Figure 8 - Failure envelopes of specimens comprising: a) AC clay, and b) ACB clay.

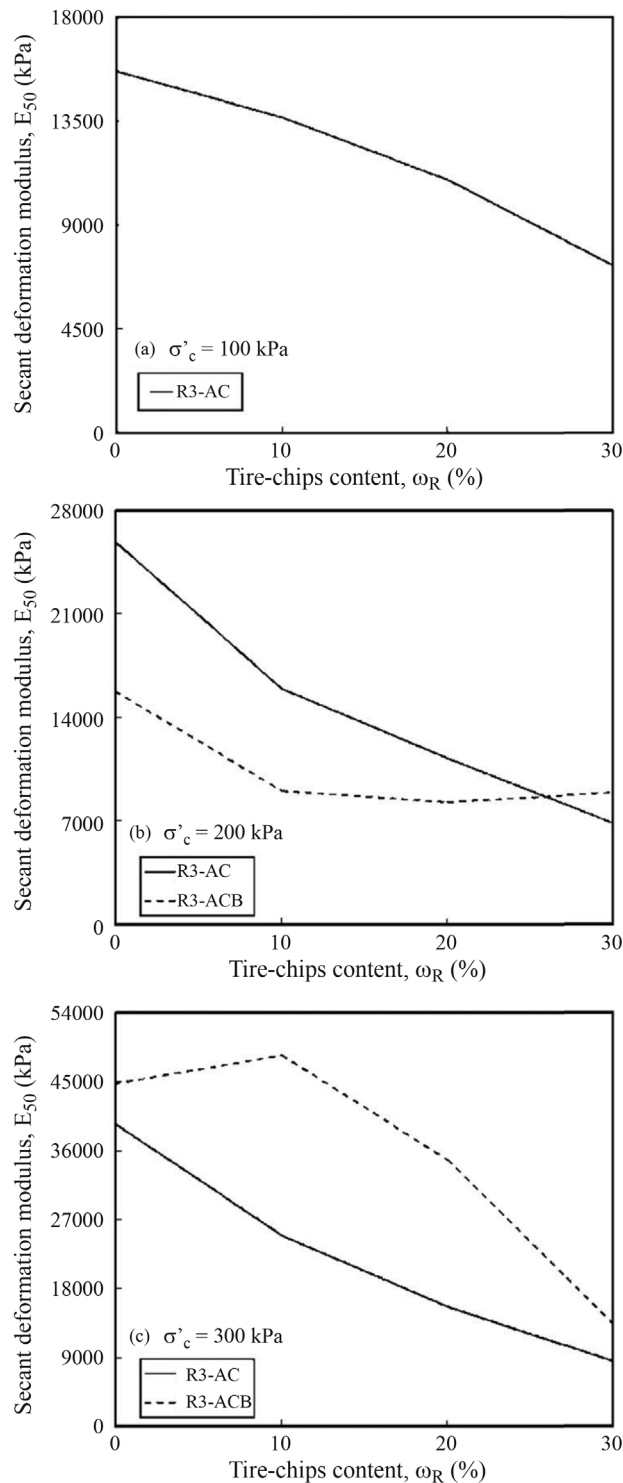


Figure 9 - Secant deformation modulus vs. tire chips content for: a) AC, and b) ACB, clay mixtures.

4.5. Stress paths

Study the stress paths indicates that at low level of strains the behavior of all the AC clay mixed specimens are contractive, but at large level of strains the behavior of

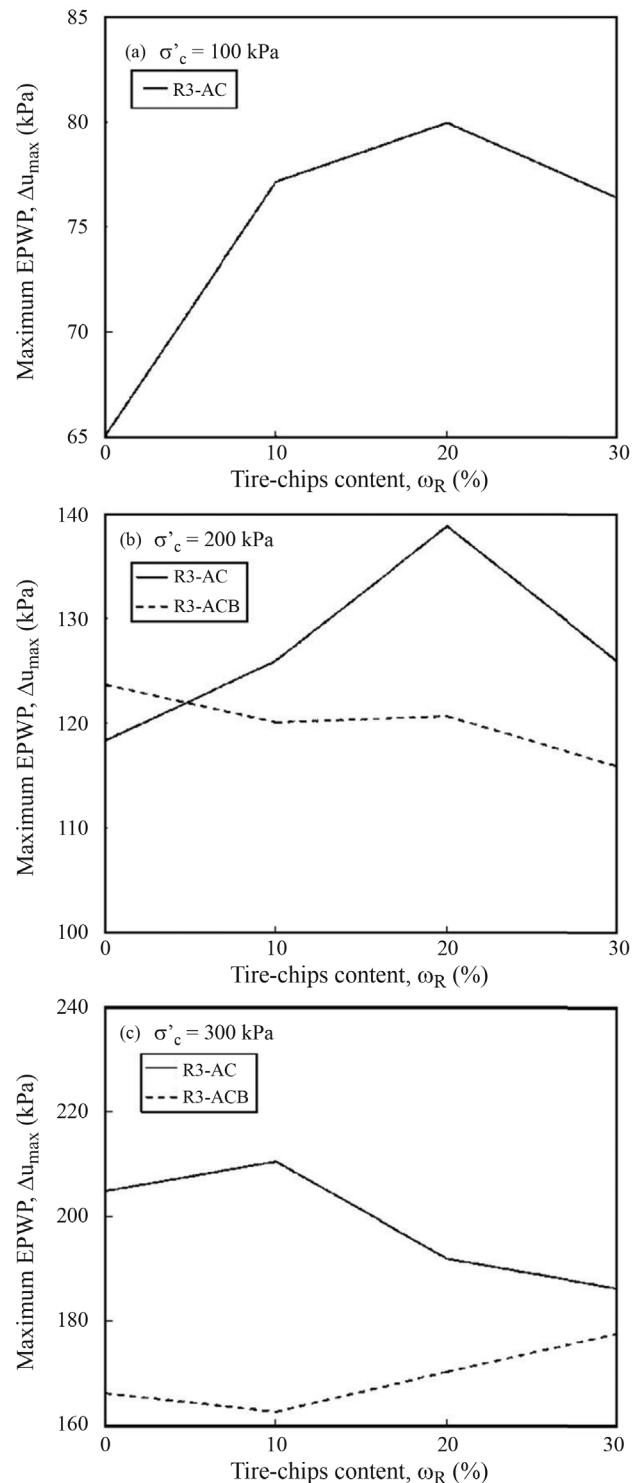


Figure 10 - Effect of tire-chips content on Δu_{max} values at σ'_c : a) 100 kPa, b) 200 kPa, and c) 300 kPa.

R3-AC80 and R3-AC70 specimens changes from contractive to dilative one. The results explain that the ACB100 and R3-ACB90 specimens have dilative behavior and with increasing ω_R from 10% to 30% the behaviors change from dilative to contractive one.

Table 4 - Values of E_{50} for all of the tested specimens.

Specimen designation	Tire, ω_R (%)	E_{50} (kN/m ²)		
		$\sigma'_c = 100$ kPa	$\sigma'_c = 200$ kPa	$\sigma'_c = 300$ kPa
AC100	0	15635	25887	39503
R3-AC90	10	13678	15950	24954
R3-AC80	20	10961	11235	15649
R3-AC70	30	7261	6840	8386
ACB100	0	-	15745	44780
R3-ACB90	10	-	8997	48495
R3-ACB80	20	-	8265	34756
R3-ACB70	30	-	8911	13218

It can be concluded that adding the tire-chips to the clay changes the tendency of specimens during shearing. The change in tendency depends on the plasticity of clay matrix. Specimens made of low plasticity clay tend to contract during shearing, while adding tire-chips causes they exhibit dilative behavior. In contrast, specimens consisting of high plasticity clay represent relatively dilative behavior, whereas the mixtures of this clay with higher values of tire-chips tend to contract.

5. Conclusions

In the present study, a number of undrained triaxial tests were carried out on the compacted clay-tire mixtures and their behaviors were compared with the behavior of the unamended clay. The compaction tests showed that the units weights of mixed specimens are about 11%-17% lower than those of unamended clays. The majority of this decrease is due to the lower specific gravity of tire-chips.

The results of triaxial tests indicated that adding more than 20-30% tire-chips to the low plasticity clay don't reduce the shear strength in comparison with the associated values of unamended clays. While, in the mixtures made of high plasticity clay, as tire content increases the shear strength of specimen decreases. In addition, the friction angle and cohesion parameters are obviously dependent on the tire chips content and clay plasticity. However, tire-chips in the range of 10% to 30% don't influence the shear strength much more, but it has considerable effect on the deformation modulus.

Also the results showed that when tire-chips added to the low plasticity clay, maximum excess pore water pressure occurs at tire content about 10%-20%. For the mixtures made of high plasticity clay, the pore water pressure under low consolidation stress decreases slightly as the tire content decreases, while, it is increased with tire-chips content at high consolidation stress.

Finally, it can be concluded that possible usage of clay-tire mixtures as light construction material exists in the earth structures, without considerable reduction in shear

strength. Hereby, it can be managed the waste tire materials and embedded them within the ground.

Acknowledgments

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List of Symbols

- E_{50} = Secant deformation modulus
 LL = Liquid limit
 M = Slope of failure line
 PI = Plasticity index
 p' = Mean effective stress ($= (\sigma'_1 + 2\sigma'_3)/2$)
 w = Water content
 w_g = Granular material content
 Δu_g = Shear-induced excess pore water pressure
 Δu_{max} = Maximum shear-induced excess pore water pressure
 γ_d = Dry density
 σ'_c = Effective consolidation stress
 q' = Deviatoric stress ($= \sigma_1 - \sigma_3$)