CHAPTER 4

ENGINEERING PROPERTIES OF TIRE CHIPS - AGGREGATES MIXTURES

4.1 General

This chapter discusses the assessment of optimum mix proportions of tire chips and aggregates based on shear strength and index properties (specific gravity and unit weight) for applications in granular piles. The optimum mixing ratio is a function of the mixture's void ratio and shear strength. Tire chips of cubical size 10 mm × 10 mm × 10 mm and aggregates passing through 12.5 mm and retained on 10 mm were used. The aggregates and tire chips were mixed using the volumetric mix proportions (tire chips: aggregates) (%) of 0:100, 25:75, 50:50, 75:25, and 100:0. A series of large direct shear tests were carried out to investigate the strength properties of tire chips - aggregates mixtures. The impact of tire chip content, p_t (%), on the aggregate mixture has been examined regarding shear stress versus shear strain behavior, shear strength parameters, dilation, and shear modulus at normal stresses of 50 kPa, 100 kPa, and 150 kPa. Table 4.1 summarizes the test program, and Fig. 4.1 shows the large direct shear test setup with tire chips and aggregate mixture.

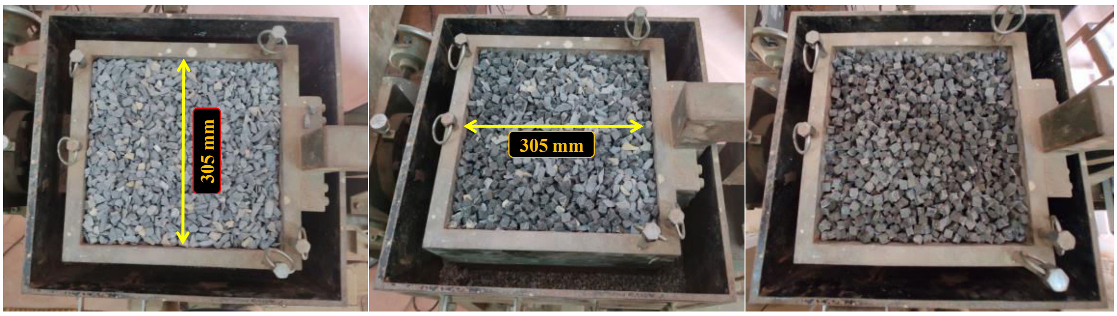
Table 4.1 Summary of the direct shear test program for tire chips and aggregates mixture.

S. No.	Notation used	Normal stress (kPa)	I_D(%)
Mixture 1	(0% TC + 100% AG)	50, 100, 150	70
Mixture 2	(25% TC + 75% AG)	50, 100, 150	70
Mixture 3	(50% TC + 50% AG)	50, 100, 150	70
Mixture 4	(75% TC + 25% AG)	50, 100, 150	70
Mixture 5	(100% TC + 0% AG)	50, 100, 150	70

4.2 Results and Discussion

A total of 15 direct shear tests were performed on the above five mix proportions, as summarized in Table 4.1. The major factors in this investigation are unit weights (γ), shear parameters (c and ϕ), dilatancy angle (ψ), and shear modulus (G) of all mix proportions and its influence on optimum mix proportion. The shear strength parameters of tire chips and aggregate mixture have been determined using a large-size direct shear test of 305 mm × 305 mm × 200 mm. The selection of test conditions, including normal stresses and strain rates representing field conditions, has been investigated. After the mix proportions were compacted to 70% relative density in the shear box, each mixture was subjected to shear loading under three normal stresses of 50 kPa, 100 kPa, and 150 kPa, representing the as-built model ground conditions (Gong et al. 2019; Yoo and Abbas 2020). All experiments were conducted at a strain rate of 1.20 mm/min. The shearing rate was kept low enough to ensure drained conditions. A rapid shear rate was used to simulate a rapid, quasi undrained condition in the field. In this analysis, the strain rate proposed by (Murugesan and Rajagopal 2009) was followed. These recorded data have been used to calculate the shear parameters (c and ϕ) and dilatancy angle (ψ). The shear parameters were determined at the maximum shear stress. If no peak was observed until 10% shear deformation, the stress at 10% shear deformation was used to calculate the shear strength of the mixtures (ASTM D3080. 2012).

(a)



(b) (c) (d)

Fig. 4.1 Large direct shear test setup with (a) shear box with loading plate, (b) shear box with 100% aggregates, (c) shear box with tire chips and aggregates mixture, and (d) shear box with 100% tire chips.

4.2.1 Dry unit weight of the mix proportions

The variation of dry unit weights of all mix proportions with % tire chips content, p_t is shown in Table 4.2 and Fig. 4.2(a). It clearly indicated a reduction in dry unit weight with increased tire chip content. The dry unit weight of the tire chips and aggregate mixture was reduced linearly with increasing tire chip content due to the significantly lower specific gravity of the tire chips' content. From Fig. 4.2(b), the percentage decrease in dry unit weight values was 14.60%, 29.20%, 43.90%, and 57.80% for 25%, 50%, 75%, and 100% tire chips content, respectively. A decrease in the dry unit weight of the mixture is advantageous for lightweight geotechnical applications where lateral earth pressure must be reduced, such as in the design of box culverts, foundations, retaining walls, and embankments (Choobbasti et al. 2015; Sarokolayi et al. 2015).

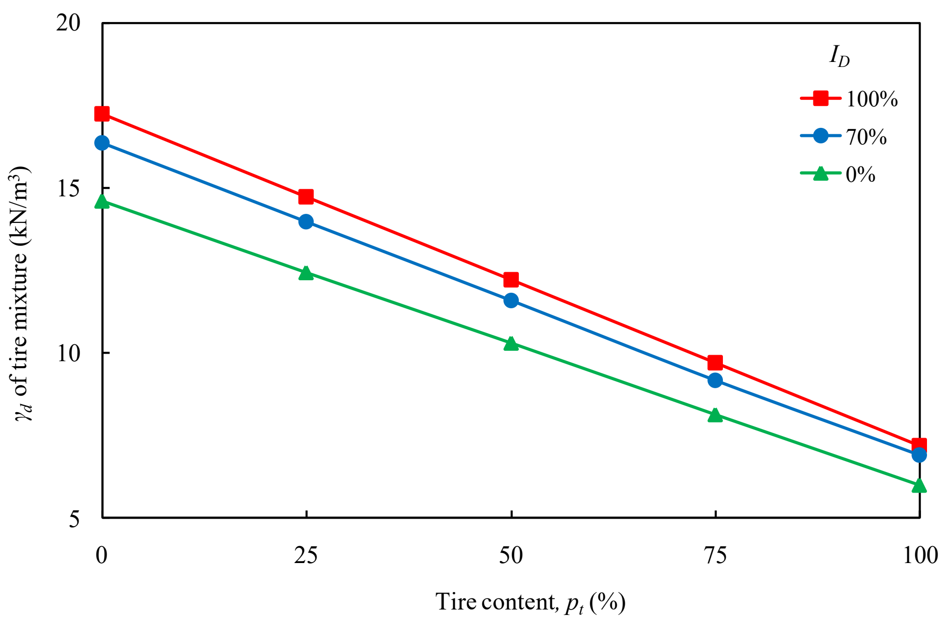


Fig. 4.2(a) Variation of dry unit weights of mixtures with tire chip content.

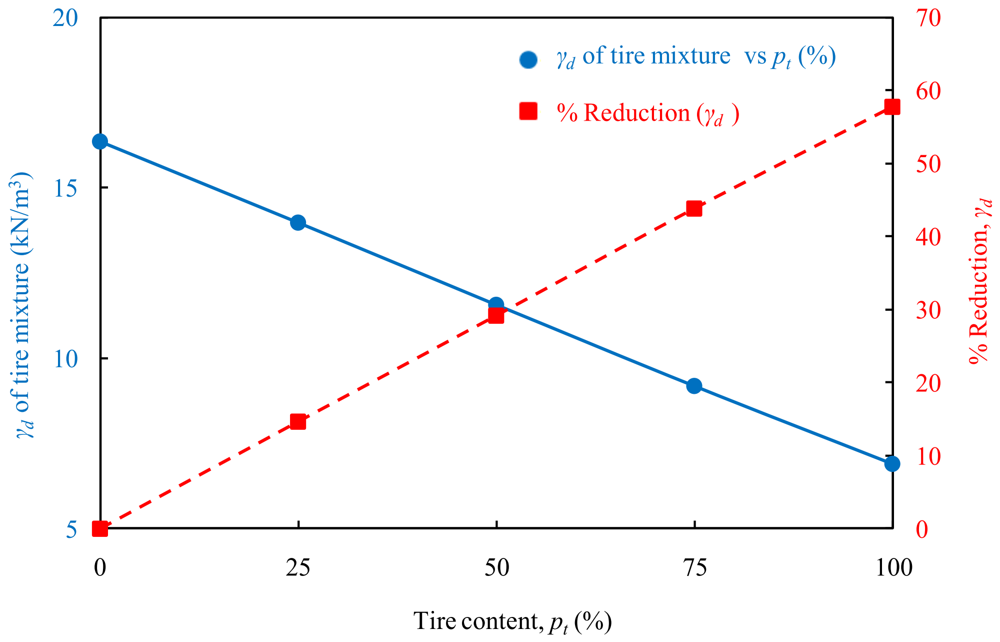


Fig. 4.2(b) Dry unit weight *(γ_d)* and % reduction in γ_d of tire chips - aggregates mixture at 70% I_D.

Table 4.2 Dry unit weights of tire chips - aggregates mixtures.

Mix proportion	$\gamma_{d\ max}$ (kN/m^3)	$\gamma_{d\ min}$ (kN/m^3)	$\gamma_{d\ 70\%ID}$(kN/m^3)
(0% TC + 100% AG)	17.25	14.60	16.36
(25% TC + 75% AG)	14.74	12.45	13.97
(50% TC + 50% AG)	12.23	10.30	11.58
(75% TC + 25% AG)	9.71	8.15	9.18
(100% TC + 0% AG)	7.20	6.00	6.91

4.2.2 Void ratio of the mixtures

The void ratios of the mixtures at any relative density are calculated using Eq. 4.1 with known values of dry unit weights and specific gravity values of tire chips-aggregate mixtures (Bali Reddy et al. 2016).

$$e = \frac{V_v}{V_s} = \frac{V_m - \left(\frac{W_{tc}}{G_{tc}} + \frac{W_{ag}}{G_{ag}}\right)}{\left(\frac{W_{tc}}{G_{tc}} + \frac{W_{ag}}{G_{ag}}\right)} \quad (4.1)$$

where e is the void ratio, V_v is the volume of voids, V_s is the volume of tire chips - aggregates mixture, V_m is the volume of mold, W_{tc} is the weight of tire chips in the mold, W_{ag} is the weight of aggregates in the mold, G_{tc} is specific gravity of tire chips, and G_{ag} is specific gravity of aggregates. The variations of void ratio with the percentage of tire chips content at different relative densities are plotted in Fig.4.3. A decrease in the void ratio of the mixture with an increment of relative density is observed. It clearly indicates that the void ratio of the mixture at dense state, loose state, and at 70% relative density has the same variation of decreasing trend till tire content of 50% followed by an increasing trend beyond tire content of 50%. Some other researchers also reported an identical pattern (Umashankar Balunaini and Sungmin Yoon 2009; Bali Reddy et al. 2016).

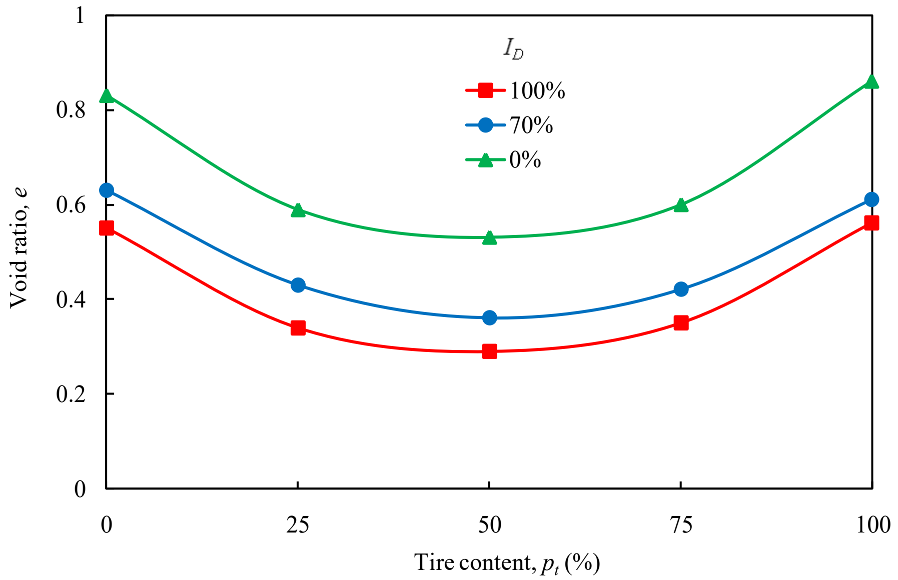


Fig. 4.3 Void ratio of tire chips - aggregates mixture with tire content.

4.2.3 Large direct shear tests

4.2.3.1 Shear stress versus shear strain behavior

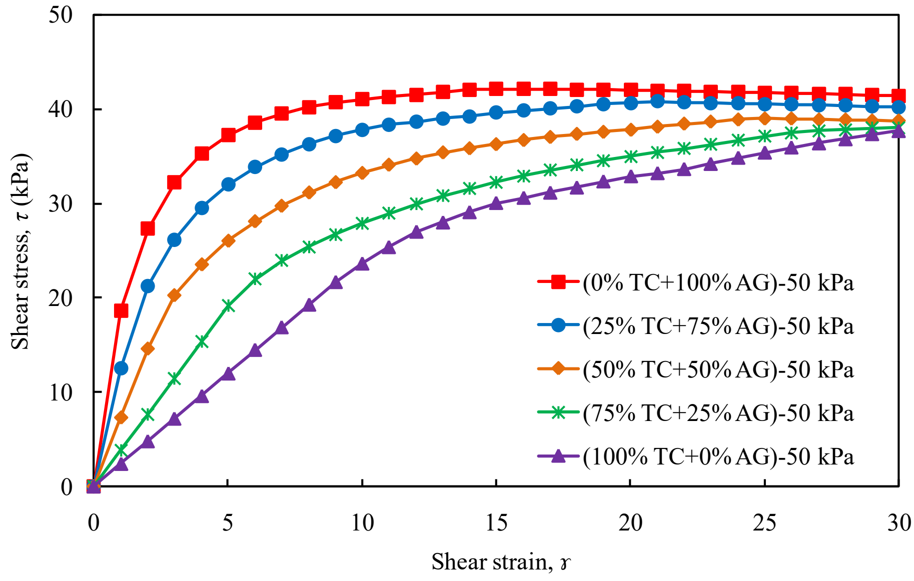


Fig. 4.4 Shear stress versus shear strain for tire chips - aggregates mixtures at 50 kPa.

Fig. 4.4 represents the findings of shear stress variation with shear strain of all five mix proportions at a normal stress of 50 kPa, and the results of shear stress versus shear strain at the other two normal stresses follow the same pattern. From Fig. 4.4, up to 50% tire chip content, the shear stress versus shear strain curve shows a peak shear stress value without any post-peak drop. After reaching the peak shear stress value, the curve becomes flatter, and the shear stress attains a constant value for a shear strain of about 30 mm. Fig. 3.7 shows that 75% of tire chip content by weight is equivalent to 87.8% by volume. Therefore, the shear stress response of mixtures containing 75% and 100% tire chips follows the same pattern until a shear strain of 30 mm due to the dominance of higher tire chip content. It has to be observed that, by gradually increasing the tire chips content in the mixture, a higher shear strain is necessary to facilitate the peak shear stress value. As mentioned earlier, if no peak shear stress was observed up to 10 percent shear strain, shear stress at 10% shear strain is used to calculate the shear strength of the mixtures (ASTM D3080 2012). All the mix proportions exhibited strain hardening behavior and did not fail up to 10 percent shear strain. The shear strain corresponding to the attained maximum shear stress value increased with the increment of tire chip content compared to aggregates alone. This implies that the mixture behavior changes from fragile/brittle to ductile nature with addition of tire chip content. This ductile behavior permits using tire chips - aggregates mixture in resilient structures and structures in seismic isolation.

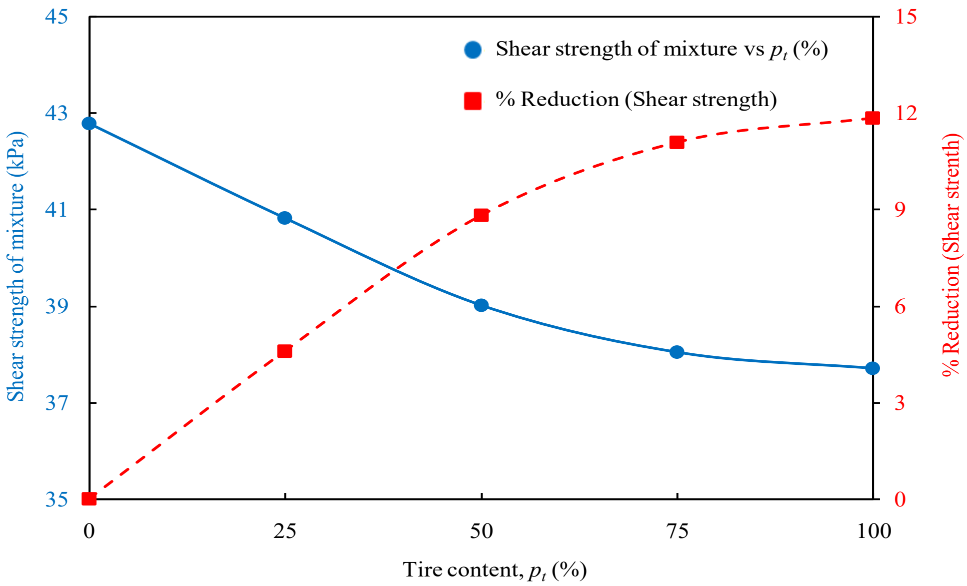


Fig. 4.5 Shear strength of tire chips - aggregates mixtures with tire content (p_t).

Fig. 4.5 illustrates the maximum shear strength values of the mixtures with tire chip content and the reduction in shear strength values with the increment of tire chips at a normal stress of 50 kPa. The percentage reductions in shear strength are 4.60%, 8.80%, 11.10%, and 11.85% for tire chip contents of 25%, 50%, 75%, and 100%, respectively. The percentage reduction is very low for 25% tire chip content due to the domination of aggregates in the mixture. However, the percentage reduction is a fairly considerable value for tire chip contents exceeding 25% due to the domination of tire chips in the mixture on a volume basis.

4.2.3.2 Mohr-Coulomb failure criterion for the mixtures

The Mohr-Coulomb failure criterion determined the cohesion and angle of internal friction of the mixtures utilized in this investigation. As previously mentioned, each mixture was examined at the three typical normal stresses of 50 kPa, 100 kPa, and 150 kPa. The Mohr-Coulomb failure envelope is a linear relationship between equivalent normal stress and the shear stress. The peak shear stress values were considered for tire content up to 50%, and remaining tire content of 75% and 100%, shear stresses at 10% shear strain were considered for the Mohr-Coulomb failure envelope. The slope of the failure envelope represents the angle of internal friction, and the intersection with the Y-axis demonstrates cohesiveness. Eq. 4.2 represents the Mohr-Coulomb failure envelope.

$$\tau = c + \sigma \tan \phi \qquad (4.2)$$

where c is the cohesion intercept, ϕ is the angle of internal friction, σ is the normal stress, and τ is the shear stress at failure. The shear strength parameters from the Mohr-coulomb envelopes for all the mix proportions are shown in Figs. 4.6, 4.7, and 4.8, and the values are presented in Table 4.3.

Table 4.3 Shear strength parameters of tire chips – aggregates mixtures.

Mix proportion	c (kPa)	$\phi°$
(0% TC + 100% AG)	0	40.11
(25% TC + 75% AG)	3.10	37.22
(50% TC + 50% AG)	6.74	33.34
(75% TC + 25% AG)	13.83	26.66
(100% TC + 0% AG)	15.85	23.51

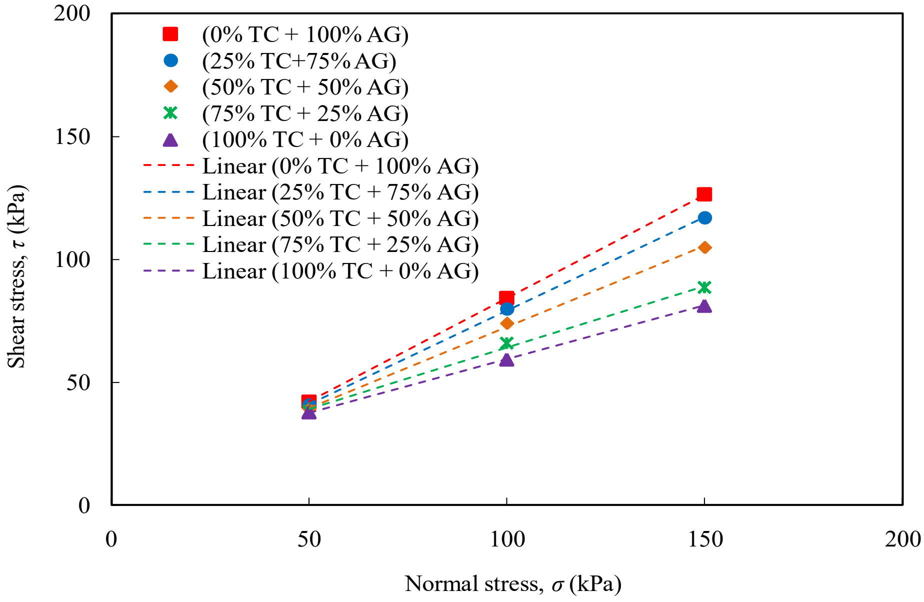


Fig. 4.6 Shear stress (τ) versus normal stress (σ) for all mix proportions.

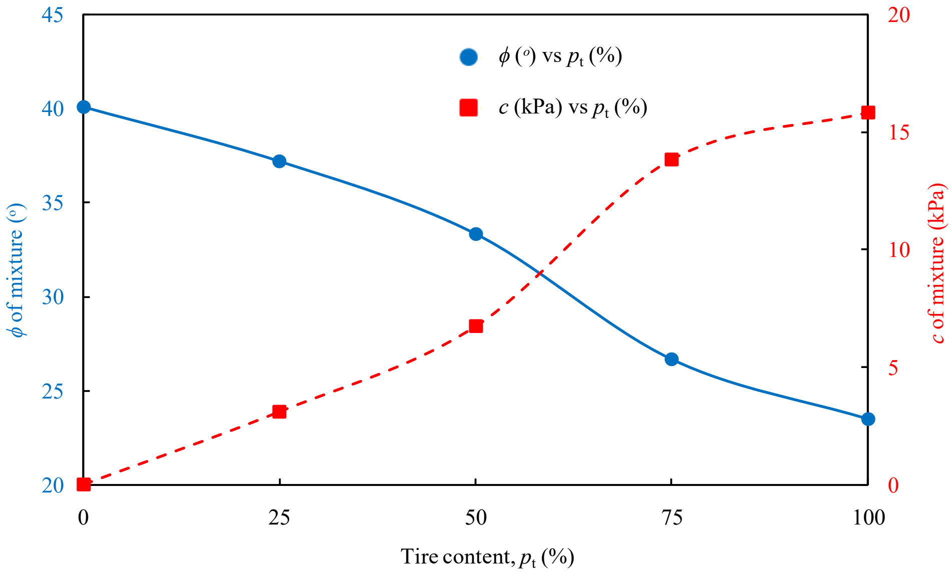
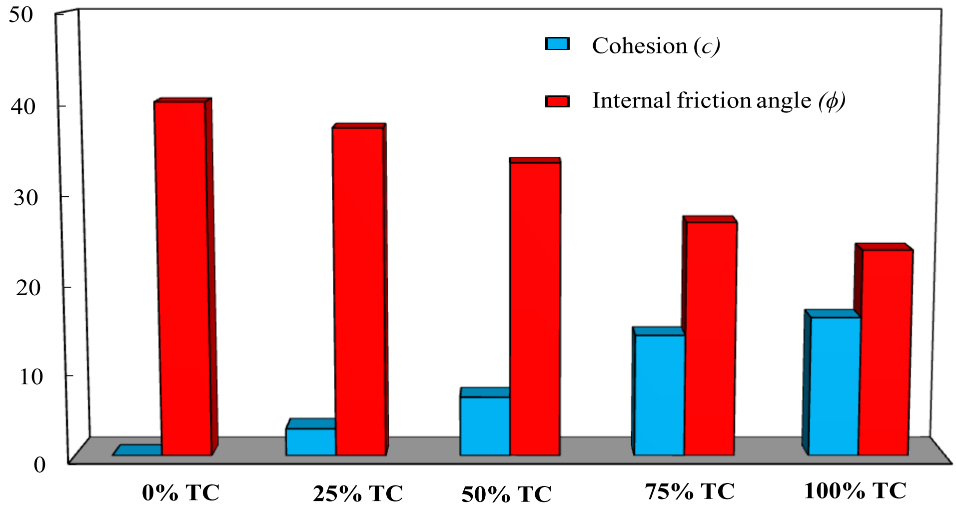


Fig. 4.7 Variation of the shear strength parameters of the tire chips- aggregates mixtures.

From Fig. 4.6, it is observed that the shear stress of all the mixtures increases with increasing normal stress, and the Mohr-Coulomb envelopes of all the mixtures are approximately similar. Figs. 4.7 and 4.8 demonstrate that the variation in cohesion and angle of internal friction is correlated with the increase in tire chip content in the tire chip-aggregate mixtures. It is observed that the angle of internal friction (ϕ) values decreased with an increase in tire chip content, while the cohesion (c) values improved with the increase in tire chip content in the mixtures. The decrease in ϕ values and increase in c values are nominal up to 50% tire chip content, but the rate is very high, from 50% to 100%. From earlier studies (Ahmed 1993; Foose et al. 1996), the potential range of c values and ϕ values obtained for different mix proportions are in the range of 10 to 25 kPa and 20-55^{o}, respectively.



ϕ °	40.11	37.22	33.34	26.66	23.51
c (kPa)	0	3.10	6.74	13.83	15.85

Fig. 4.8 Summarization of the shear parameters of the tire chips- aggregates mixtures.

Fig. 4.9 shows the normalized trends of the angle of internal friction of tire chips - aggregates mixture with respect to (0% TC + 100% AG). The percentage reduction in friction angle from 0% tire chips to 25%, 50%, 75%, and 100% tire chips is 7.2%, 17%, 33.5%, and 42.4%, respectively. Based on the above results, it was found that the percentage reduction in friction angle from 0% tire chips to 25% tire chips was very minimal due to the dominance of aggregates in the mixture.

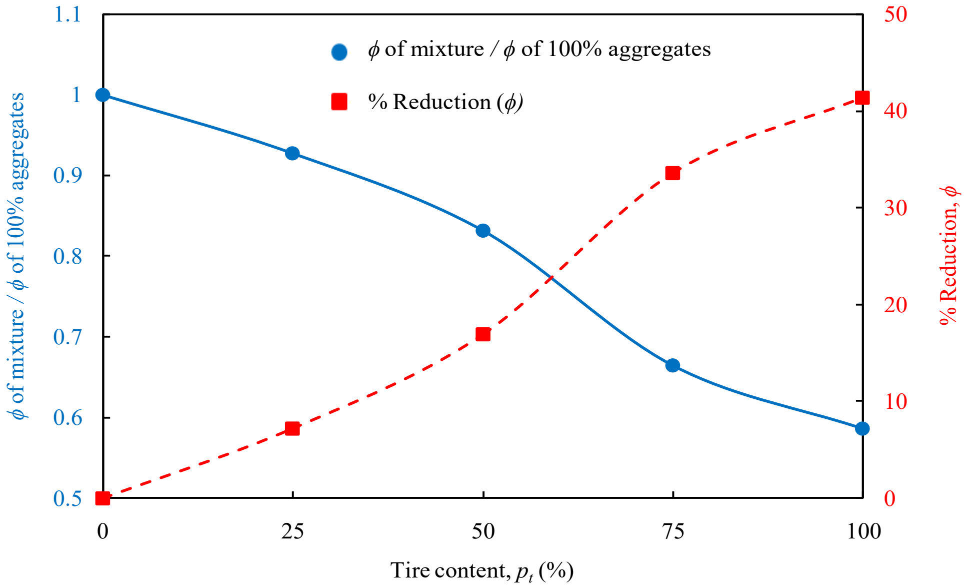


Fig. 4.9 Normalized angle of internal friction trends for tire chips - aggregates mixtures.

4.2.3.3 Vertical deformation versus shear strain behavior

The vertical deformation with shear deformation variation for the tire chips-aggregates mixtures at the normal stress of 50 kPa is shown in Fig. 4.10. From Fig. 4.10, it is evident that all the mix proportions show similar behavior for vertical deformation illustrating initial compression and increasing shear behavior represents dilation. The extent of dilation depends on the normal stress employed and the relative density at which the sample is prepared. It is also observed that, up to 50% tire chips content, initial compression is negligible, and the mixture is mainly dilated upon shearing, and beyond 50% tire chips content, the range of shear deformation in which compression happens became wider.

The main conclusion from Fig. 4.10 is that the dilation of the mixture decreases with increasing the tire chips content. It has to be reported that a higher shear deformation is needed to mobilize constant volume with an increment of the tire chips in the mix proportion. The initial compression is negligible for tire chips and aggregates mixture containing up to 50% tire chip content, and the dilation value is higher. Beyond 50% tire chips content, initial compression increased with considerable dilation value.

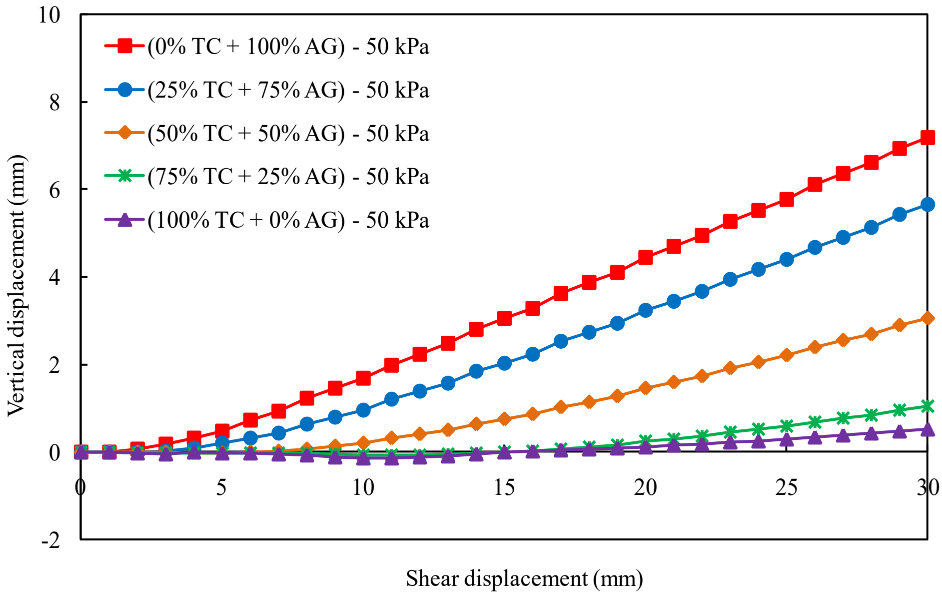


Fig. 4.10 Vertical strain versus shear strain for the aggregate and tire chips mixtures at 50 kPa.

Table 4.4 Dilatancy angles of tire chips – aggregates mixtures.

Mix proportion	ψ °
(0% TC + 100% AG)	13.5
(25% TC + 75% AG)	10.7
(50% TC + 50% AG)	5.8
(75% TC + 25% AG)	2.0
(100% TC + 0% AG)	1.0

The dilation angle (ψ) is defined as the ratio of incremental vertical deformation (∂y) to the incremental shear deformation (∂x) measured during testing as given below:

$$\tan\psi = \sin\psi = \frac{\partial y}{\partial x} \tag{4.3}$$

Dilatancy is a fundamental deformation characteristic of any material under shearing. It distinguishes between the plastic behavior of any material in a shear box and that of metal. It denotes the increase in volume caused by shear force. The dilation angle controls the amount of plastic volumetric strain developed during plastic shearing. The dilatancy angles were determined from Fig. 4.10 using Eq. 4.3, as given in Table 4.4.

4.2.3.4 Shear modulus

Shear modulus is a physical term that describes how a material behaves when sheared. The shear modulus is ascertained by using Eq. 3.4 (Das 2014).

$$G_{50} = \frac{\tau}{\gamma} \tag{4.4}$$

where G_{50} is shear modulus, τ is shear stress, and γ is shear strain. The shear modulus has to be calculated by utilizing Eq. 4.4, considering the behavior of the tire chips and aggregates mixture under shear stress versus shear strain. To analyze the shear modulus of the mixed proportions employed in this investigation, "secant shear modulus (G_{50}), which is 50% of the shear strength (τ) divided by the corresponding shear strain (γ), was used".

Fig. 4.11 shows the variation of secant shear modulus (G_{50}) with different mixed proportions at a normal stress of 50 kPa, 100 kPa, and 150 kPa. It shows that at all normal stresses, the shear modulus of the mixture decreases with the increment of tire chip content. The reason for decrement in shear modulus is that replacing aggregates with a higher quantity of tire chips enables the mixture to be softer, and its shear stiffness is decreased. It also observed that the shear modulus of the mixture at 0% tire content was very high when compared to a mixture with 25% tire chips.

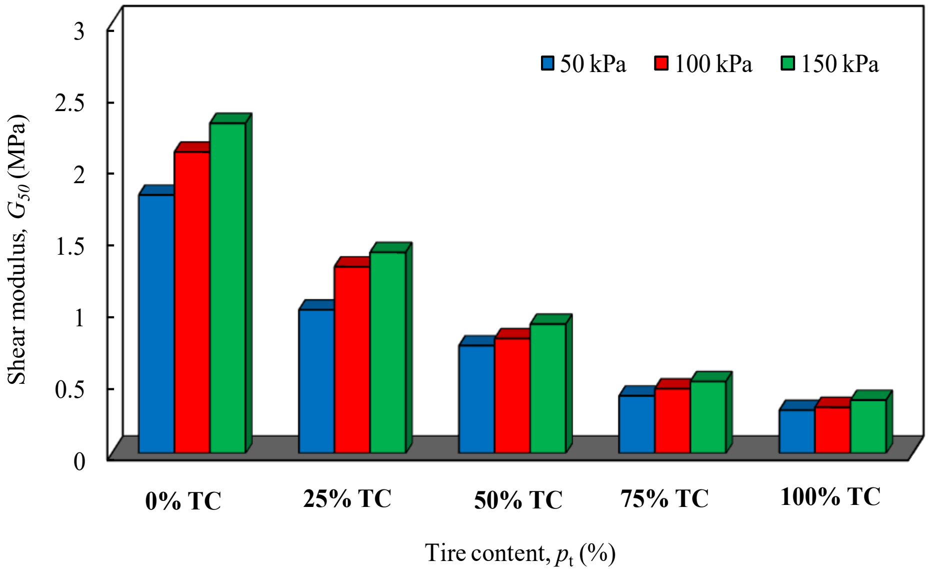


Fig. 4.11 Variation of secant shear modulus with tire content (p_t).

4.3 Optimum mix proportion of tire chips - aggregates mixtures

4.3.1 Effect of shear strength parameters of the mixture on the load-bearing capacity of granular piles

As previously mentioned, numerous researchers have noted an increase in the friction angle of sand-tire combinations; moreover, very limited research has been done on tire chips-aggregate mixtures.

According to (IS 15284 (part 1) 2003), load-bearing capacity based on the bulging of granular pile/stone column,

$$q_u = [\sigma_{ro} + 4c] \times \left(\frac{1+\sin\phi_{gr}}{1-\sin\phi_{gr}}\right) \tag{4.5}$$

According to (Hugher and Withers 1974), the bearing capacity of a granular pile

$$q_u = \left[\sigma_{ro} + c\left(1 + ln_e\left[\frac{E_c}{2c(1+\mu)}\right]\right)\right] \times \left(\frac{1+\sin\phi_{gr}}{1-\sin\phi_{gr}}\right) \tag{4.6}$$

where q_u is the ultimate load-bearing capacity of granular pile, σ_{ro} is the initial effective radial stress, E_c denotes the elastic modulus of the soil, c refers to the undrained shear strength of the surrounding soil, and μ is the Poisson's ratio. The above two equations show that any variations in the angle of internal friction of granular materials used to construct granular piles only affect the value of $\left(\frac{1+\sin\phi_{gr}}{1-\sin\phi_{gr}}\right)$, which stands for the passive coefficient K_p.

The improvement factor is described to determine the optimum mix proportion where the granular pile performs at its best, as discussed by (Shariatmadari et al. 2018).

$$F_{mp} = \frac{q_{u_{mp}}}{q_{u_{ag}}} = \frac{k_{p_{mp}}}{k_{p_{ag}}} \quad (4.7)$$

where F_{mp} is the improvement factor for any mix proportion, $q_{u_{mp}}$ is the ultimate load-carrying capacity of the granular pile with any mix proportion, and $q_{u_{ag}}$ is the ultimate load-carrying capacity of granular piles with 100% aggregates, respectively. $k_{p_{mp}}$ and $k_{p_{ag}}$ are the passive coefficients for a granular pile with any mix proportion and a granular pile with 100% aggregates, respectively.

Table 4.5 Factor of improvement of tire chips – aggregates mixtures.

Mix proportion	$k_{p_{mp}}$	F_{mp}
(0% TC + 100% AG)	4.62	1
(25% TC + 75% AG)	4.06	0.88
(50% TC + 50% AG)	3.44	0.74
(75% TC + 25% AG)	2.63	0.57
(100% TC + 0% AG)	2.33	0.50

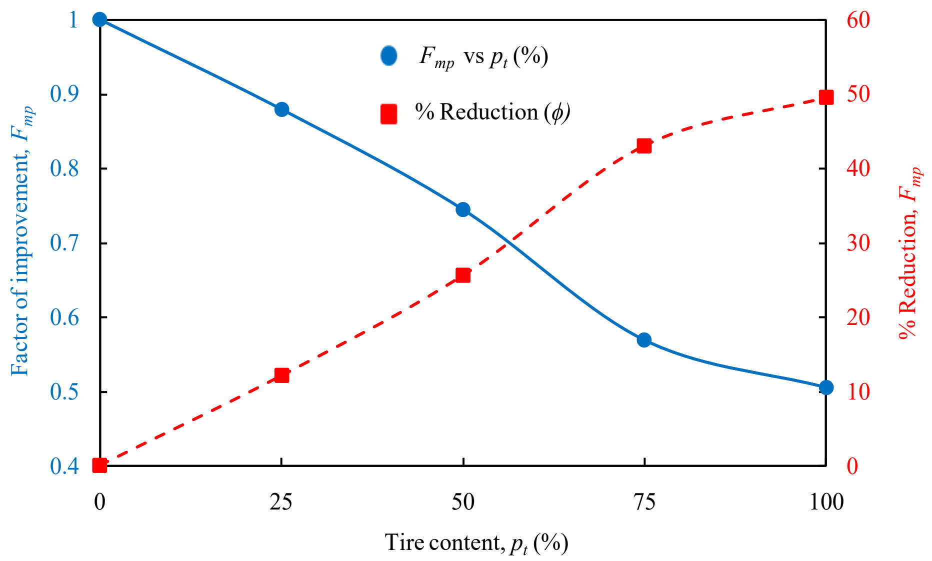


Fig. 4.12 Factor of improvement for different mix proportions.

Fig. 4.12 and Table 4.5 show the improvement factor with the variation of tire chips in mix proportions. The results indicate that the improvement factors for 25%, 50%, 75%, and 100% of tire chip contents are 0.88, 0.74, 0.57, and 0.50 times the 100% aggregate case. So, the loss of improvement for 25% tire chip content was only 12%, which is very low and has a good impact on an environmental point of view.

4.4 Summary

This chapter describes the engineering properties of various tire chips-aggregate mixtures for granular pile applications. Specific gravity, unit weight, and void ratios of all mix proportions were determined. The shear parameters, including cohesion (c), angle of internal friction (ϕ), dilatancy angles (ψ), and shear modulus (G), were obtained through large-size direct shear tests. By observing the variation of index properties and shear parameters of all mix proportions, the optimum mix proportion is determined to be 25% by weight, which is equivalent to 44% by volume. This optimum mix proportion can significantly reduce the demand for large volumes of traditional aggregates in granular pile applications.