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Behaviour of fly ash-lime-gypsum composite mixed with treated tire chips

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Abstract. The present study is carried out to investigate the strength behaviour of the reference mix containing fly ash + 8% lime + 0.9% gypsum mixed with treated tire chips. The dry tire chip was treated with water, sodium hydroxide and carbon tetrachloride. The tire chip content in the reference mix was varied from 5% to 15% and curing period from 7 days to 180 days. The specimens were cured using three different methods of curing (in a dessicator, burlap and water filled container). The results of this study reveal that the stress – strain relationship, strength characteristics, initial tangent modulus, ultimate strength and secant modulus of the reference mix containing dry tire chips is influenced by the tire chip content, curing period, curing method and the treatment provided on the tire chips. These parameters increased with the treatment provided with water, sodium hydroxide, carbon tetra chloride as well as with the increase in curing period in comparison to dry tire chips in the reference mix. A higher increase in these parameters was observed when specimens were cured in water filled container followed by burlap and dessicator respectively. Study further revealed that these parameters decreased with the increase in tire chip content from 5% to 15% and increased with the increase in the confining pressure. The axial strain at failure increased with the treatment provided with water, sodium hydroxide and carbon tetra chloride in comparison to dry tire chips in the reference mix. The results further revealed that axial strain at failure increased with the increase in curing period, change in curing method and increase in confining pressure. Inclusion of 5% dry/treated tire chips in the reference mix increases the axial strain at failure. Beyond a tire chip content of 5%, the axial strain at failure decreased when the content of tire chip was increased to 10% and 15% respectively.

Keywords: tire chip; strength characteristics; curing period; curing method; treatment.

1. Introduction

Waste transformation is the powerful term used in effective solid waste management technique. Under this preview the ultimate goal should be to convert entire waste material produced into useful engineering material. By doing so, the growing concern of solid waste and related disposal problems will be minimized. Further, in an effort to address the ever-increasing waste disposal problem and to conserve our depleting landfill spaces, there has been a growing interest in recent years in for studying the strength behaviour of waste materials for geotechnical application. The present work is

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one such attempt to examine the behaviour of fly ash–lime–gypsum composite mixed with treated tire chips. A series of laboratory unconsolidated undrained (UU) triaxial tests were carried out by varying treated tire chip content, curing method and curing period. The results obtained from these tests are presented and discussed in this paper.

2. Background

Many researchers have undertaken various studies for the strength of tire chips alone or mixed with sand/clayey soil (Humphrey and Sandford 1993, Edil and Bosscher 1994, Foose *et al.* 1996, Wu *et al*. 1997, Lee *et al.* 1999, Ghazavi and Sakhi 2005, Bergado *et al.* 2005, Rao and Dutta 2006, Cetin *et al.* 2006, Dutta and Rao 2009). Beside this there are numerous studies on application of fly ash as bulk fill material are available (Raymond 1958, DiGioia and Nuzzo 1972, Gray and Lin 1972, Joshi *et al.* 1975) which demonstrated the possibility of utilizing huge amount of fly ash in construction of embankments, dykes, and road sub grade. A wide range of soils can be stabilized using fly ash (Chu *et al.* 1955, Goecker *et al.* 1956, Viskochil *et al.* 1957, Vasquez and Alonso 1981, Lo and Wardani 2002). Other uses of fly ash are land reclamation (Kim and Chun 1994), and injection grouting (Joshi *et al*. 1981). Raymon (1961) reported undrained shear strength parameters of fly ash. Sutherland *et al.* (1968) reported that although the strength of cement stabilized ashes is more compared to the corresponding strength of lime stabilized ashes at early stages, the difference is eliminated in three months in most of the cases. Gray and Lin (1972) conducted undrained triaxial test for fly ash specimens cured up to 3-4 years. Gidley and Sack (1984) reported different solidification techniques for waste disposal among which stabilization with lime was one of the promising methods. Poran and Ahtchi-Ali (1989) reported undrained shear strength parameters of solid waste incinerator fly ash stabilized with lime and cement. Huang and Lovell (1990) studied the leaching behavior of bottom ash and its effect on ground water quality. Ghosh *et al.* (2005) demonstrated the use of fly ash as foundation medium reinforced with jute-geotextiles. Ghosh and Subbarao (2007) also reported shear strength characteristics of a low lime class F fly ash modified with lime alone or in combination with gypsum. The results of their studies have revealed that addition of a small percentage of gypsum (0.5 and 1.0%) along with lime (4-10%) enhances the shear strength of modified fly ash even at the short curing periods (7 and 28 days).

The literature presented above clearly indicate that there are number of studies relating to the use of fly ash or tire chips alone or mixed with soil, cement, lime and gypsum or in combination. However studies relating to the strength behaviour of tire chip mixed with reference mix containing fly ash-lime-gypsum have not been reported so far. The present study is thus an attempt to examine the effect of treated tire chip content, curing period and curing method on the stress-strain relationship, strength characteristics, initial tangent modulus, ultimate strength and secant modulus of reference mix containing fly ash-lime-gypsum composite.

3. Materials used and experimental procedure

3.1 Materials used

The fly ash used in this study was collected in dry state from Ropar Thermal Power Station, India. The fly ash had a specific gravity, dry unit weight and optimum moisture content of 2.07, 9.54 kN/m^3 and 20% respectively. The chemical composition of fly ash was: SiO_2 = 56.32%; Al_2O_3 = 30.87%; Fe_2O_3 = 4.94%; CaO = 1.58%; MgO = 0.70; loss on ignition = 4.52. The tire chips were derived from waste tires for the study. The tread rubber was first removed from waste tire and was cut into strip of 10 mm size. Further, chips of approximately 5 mm irregular size were derived as per the technique reported by Rao and Dutta (2006). Taha *et al.* (2008) reported that the size of tire chip significantly affect the compressive strength of rubber concrete. The authors further reported that large size rubber particles in rubber concrete reduce the compressive strength. Many other researchers like Khatib and Bayomy (1999), Segre and Joekes (2000) also used smaller size tire chips in cement paste. Commercially available lime and gypsum were used in this investigation. The chemical composition of lime was SiO_2 = 0.98%; Al_2O_3 = 5.38%; Fe_2O_3 = 0.69%; CaO = 69.50%; MgO = 0.30%; loss on ignition = 22.80%; and others = 0.71%. The chemical composition of gypsum was; CaO = 28.34%; SiO_2 = 5.47%; Al_2O_3 = 2.45%; Fe_2O_3 = 1.93%; MgO = 2.06%; SO_3 = 40.43%. The standard Proctor compaction tests were carried out on fly ash–lime–gypsum mix. The dry unit weight and optimum moisture content of the flyash + 8% lime + (0.4 to 0.9%) gypsum varied from 10.10 to 10.38 kN/m^3 and 26.15% to 26.20% respectively when the content of gypsum was increased from 0.4 to 0.9% in the flyash + 8% lime mix. However, the change in the dry unit weight and optimum moisture content is within the experimental error, hence for all practical purposes Guleria and Dutta (2012) concluded that addition of small percentages of gypsum (less than 1%) to the fly ash + 8% lime mix has no effect on the dry unit weight and optimum moisture content. Based upon the above study, a reference mix of fly ash + 8% lime + 0.9% gypsum was selected for further experimental work.

3.2 Sample preparation and experimental procedure

The fly ash was ground lightly by hand with a pestle to separate the individual particles. A metallic mould having size 38 mm inner diameter and 76 mm long, with additional detachable collars at both ends were used to prepare cylindrical specimens. In order to keep the total volume of the cylindrical specimen as constant, fly ash equivalent to the weight of tire chips was removed and replaced with dry tire chips (designated as C1 tire chips) corresponding to 5%, 10% and 15% of dry weight of fly ash. The quantity of 8% lime and 0.9% gypsum corresponding to reduced dry weight of fly ash was then mixed thoroughly and the required quantity of water (corresponding to optimum moisture content (OMC)) was added to the mix. Further, the dry tire chips will absorb the water when mixed with the wet reference mix and thus decreasing the optimum moisture content and affecting the dry unit weight. Also the dry tire chips contain dust particles on its surface. These dust particles may cause hindrance in bonding of tire chips with fly ash-lime-gypsum matrix.

Various researchers (Raghavan *et al.* 1998, Lee *et al.* 1998, Chung and Hong 1999, Segre and Joekes 2000, Biel and Lee 1996) have reported that the lower bond strength between dry tire chips with cement/concrete matrix results the decrease in the compressive strength of the composite. Thus in order to keep the OMC constant and make the surface of the tire chips free from dust, tire chips in the subsequent series of experiments were dipped in water (designated as C2 tire chips), sodium hydroxide solution (designated as C3 tire chips) and carbon tetra chloride solution (designated as C4 tire chips) for 20 minutes before adding them to the reference mix. The concentration and chemical composition of chemical used for treatment of tire chips are given in Table 1. Further, to facilitate compaction, the quantity of water/solution equivalent to the weight of the absorbed water by the tire

Table 1 Concentration and chemical composition of chemical used for treatment of tire chips

Carbon tetra chloride	Sodium hydroxide	Water
Assay (GLC) = 99% Wt. per ml at 20ºC = 1.590 gm Boiling range (95%) = 76-77ºC N.V.M. - 0.003% max.	Carbonate 2% Chloride 0.01% Sulphate 0.05% Potassium 0.1% Silicate 0.05% Zinc 0.02% N/10 solution	Tap water was used for treatment

Table 2 Curing methods

Curing method	M1: The specimen was placed in an air tight polythene bag which was then placed in a dessicator and was closely tight with a lid for air drying. The dessicator was then placed in the laboratory at room temperature. M2: The specimen was put in burlap for curing. The burlap was kept wet by sprinkling water regularly. M3: The specimen was placed in a container having a provision of inflow and out flow and filled with water.

chips was deducted from the quantity of water corresponding to the optimum moisture content. To ensure uniform compaction, specimen was compressed statically from both ends till the specimen just reached the dimensions of the mould so as avoid the elastic rebound of tire chips. Then the specimen was extracted with the hydraulic jack and was allowed to dry for one day at room temperature. The specimens prepared were cured for 7, 28, 90 and 180 days using three different curing methods (in a dessicator (designated as M1), burlap (designated as M2) and water filled container (designated as M3)). More details of the curing methods are given in Table 2. The unit weight of the reference mix mixed with tire chips was maintained at 9.80 ± 0.58 kN/m^3 for different specimens and unconsolidated undrained triaxial tests were conducted in accordance with BIS 1971 at a deformation rate of 0.04 mm/min. Proving rings of capacity 2 KN and 5 KN were used for testing specimens cured for 7 & 28 days and 90 & 180 days respectively.

4. Results and discussions

4.1 Stress-strain behaviour

The stress-strain behavior of the reference mix with and without 5% C1, C2, C3 and C4 tire chips and cured for 7 days with curing methods M1, M2 and M3 respectively at a confining pressure 49.05 kPa are shown in Figs. 1(a), (b), (c). The curves for reference mix with and without 5% C1, C2, C3 and C4 tire chips cured for 90 days with curing methods M2 and M3 and at a confining pressure of 98.1 kPa and 196.2 kPa respectively are shown in Figs. 1(d), (e), (f), (g), (h) and (i). Study of Figs. 1(a), (b) and (c) reveal that the peak deviator stress of reference mix mixed with C1 tire chips increases when C1 tire chips were replaced with C2, C3 and C4 tire chips in the mix. For example, for 5% inclusion of C1 tire chips in reference mix cured for 7 days with curing method

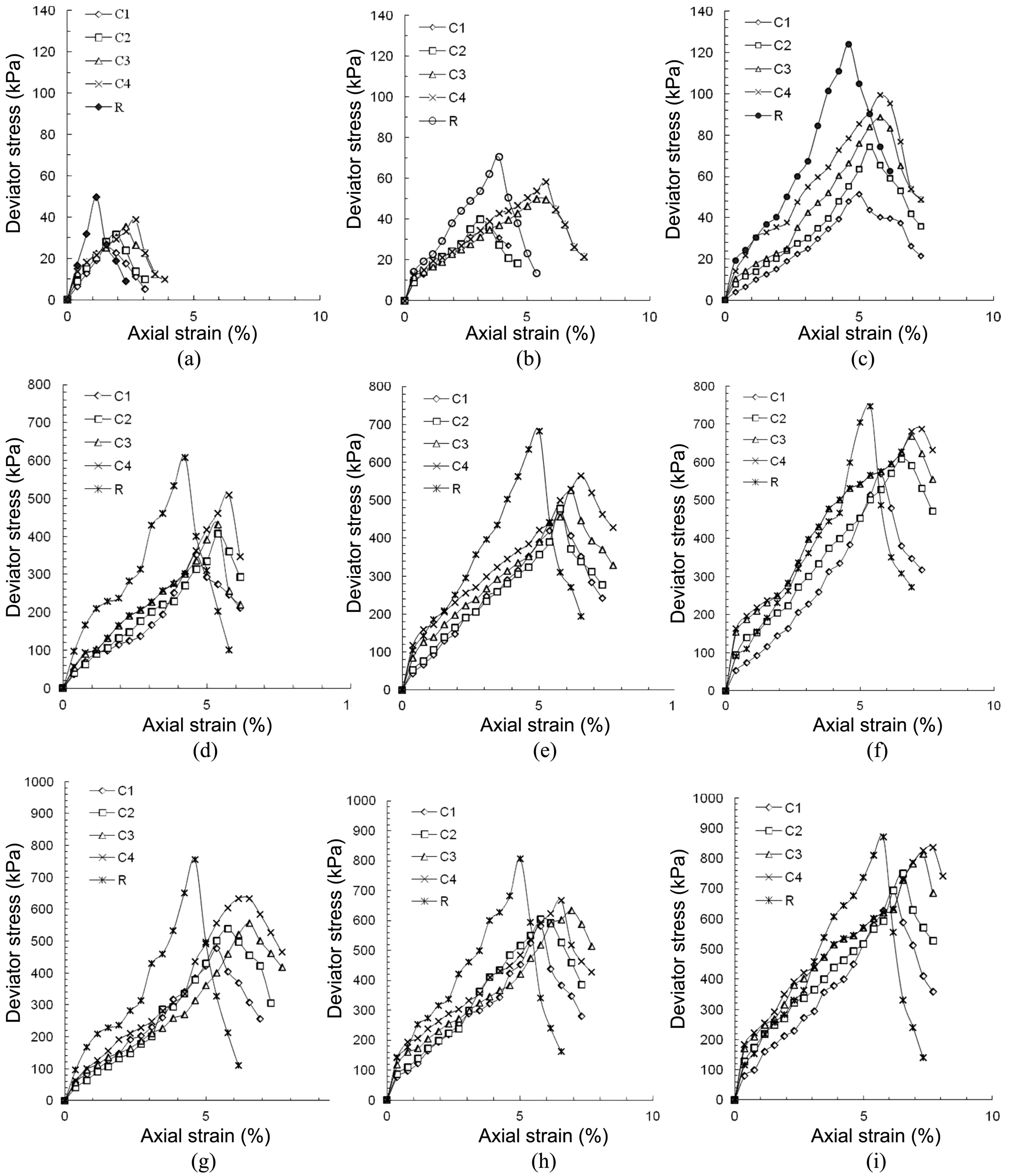

Fig. 1 (a) Stress-strain behavior of reference mix with and without 5% C1, C2, C3 and C4 tire chips at a confining pressure of 49.05 kPa and cured for 7 days with curing method M1. (b) M2. (c) M3. (d) Stress-strain behavior of reference mix with and without 5% C1, C2, C3 and C4 tire chips at a confining pressure of 98.1 kPa and cured for 90 days with curing method M1. (e) M2. (f) M3. (g) Stress-strain behavior of reference mix with and without 5% C1, C2, C3 and C4 tire chips at a confining pressure of 196.2 kPa and cured for 90 days with curing method M1. (h) M2. (i) M3

M1 has shown a peak deviator stress of 25 kPa which increased to 31 kPa, 35 kPa and 39 kPa respectively when C1 tire chips were replaced with C2, C3 and C4 tire chips in the reference mix for the same specimen. Similar behavior was observed for specimens cured for 90 days with M2 and M3 method of curing and at confining pressures of 98.1 kPa and 196.2 kPa respectively as evident from Figs. 1(d), (e), (f), (g), (h) and (i) respectively.

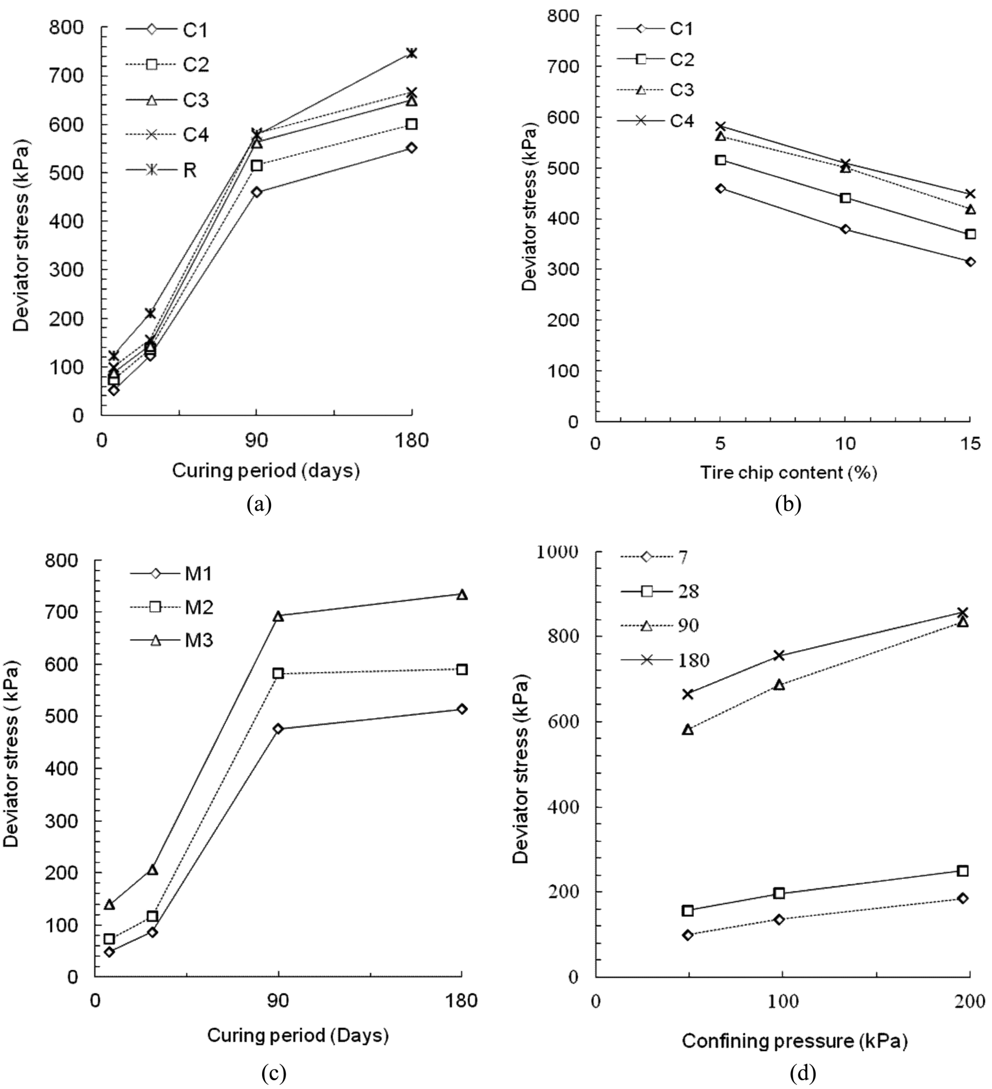

Fig. 2 (a) Variation of peak deviator stress with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M3 method of curing and at a confining pressure of 49.05 kPa, (b) Variation of peak deviator stress with tire chip content for the reference mix mixed with C1, C2, C3 and C4 tire chips and cured with M3 method of curing and at a confining pressure of 49.05 kPa, (c) Variation of peak deviator stress with curing period for the reference mix mixed with 5% C1 tire chips and cured with M1, M2 and M3 methods of curing and at a confining pressure of 196.2 kPa, (d) Variation of peak deviator stress with confining pressures for the reference mix mixed with 5% C4 tire chips and cured for 7, 28, 90 and 180 days with curing method M3

Study of Figs. 1(a), (b) and (c) further reveal that the axial strain at failure increases with the inclusion of tire chips in the reference mix. The increase in axial strain at failure was highest with the inclusion of C4 tire chips followed by C3, C2 and C1 respectively. For example, at a confining pressure of 49.05 kPa, the axial strain at failure of reference mix cured for 7 days with curing method M1 was 1.15% which increased to 1.53%, 1.92%, 2.30% and 2.69% with the inclusion of 5% C1, C2, C3 and C4 tire chips in the reference mix. A similar increase in axial strain at failure was observed with M2 and M3 method of curing as evident from Figs. 1(b) and (c).

Fig. 2(a) shows the variation of peak deviator stress with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M3 method of curing at a confining pressure of 49.05 kPa. Study of Fig. 2(a) reveals that peak deviator stress increases with the increase in curing period. For example, peak deviator stress of reference mix mixed with 5% C1 tire chips at 7 days with curing method M3 was 51 kPa which increased to 74 kPa, 88 kPa and 99 kPa after 28, 90 and 180 days of curing respectively. A similar increase in peak deviator stress was observed with the inclusion of 5% C2, C3 and C4 tire chips in reference mix as evident from Fig. 2(a).

Fig. 3(a) reveals that the axial strain at failure of reference mix mixed with 5% C1, C2, C3 and C4 tire chips increases with the increase in curing period. For example, At a confining pressure of 49.05 kPa, for the reference mix with 5% C1 tire chip content cured for 7 days with curing method M3, the axial strain at failure was 5.0% which increased to 5.38%, 5.76% and 6.15% with the increase in curing period to 28, 90 and 180 days respectively. Similar increase in axial strain at failure with the increase in curing period was observed with the inclusion of 10%/15% C1/C2/C3/C4 tire chips with other curing methods and confining pressures.

Fig. 2(b) shows the variation of peak deviator stress with chip content for the reference mix mixed with C1, C2, C3 and C4 tire chips and cured for 90 days with M3 method of curing and at a confining pressure of 49.05 kPa. A study of Fig. 2(b) reveals that peak deviator stress decreases with the increase in the tire chip content. For example, a peak deviator stress of 460 kPa of the reference mix mixed with 5% C1 tire chips and cured for 90 days with M3 curing method was observed to decrease to 379 kPa and 316 kPa respectively with the inclusion of 10% and 15% C1 tire chips in the reference mix. A similar decrease in peak deviator stress was observed with the inclusion of C2, C3 and C4 tire chips in the reference mix.

The axial strain at failure increases with the inclusion of 5% C1/C2/C3/C4 tire chip content in the reference mix as evident from Figs. 1(a), (b) and (c). For example, at a confining pressure of 49.05 kPa, for the reference mix cured for 7 days with curing method M1, the axial strain at failure of 1.15% increased to 1.53% with the inclusion of 5% C1 tire chips in the reference mix. Similar increase in axial strain at failure was observed with the inclusion of 5% C2/C3/C4 tire chips at all other curing periods, curing methods and confining pressures. Study of Fig. 3(b) reveals that axial strain at failure decreases with the increase in the tire chip content (5% to 15%). For example, at a confining pressure of 49.05 kPa, for the reference mix mixed with 5% C1 tire chips and cured for 7 days with curing method M3, the axial strain at failure of 5.76% decreased to 5.0% and 4.61% with the inclusion of 10% and 15% tire chips respectively in the reference mix. Similar decrease in axial strain at failure was observed with the inclusion of C2/C3/C4 tire chips with all curing methods and at all curing periods & confining pressures.

Fig. 2(c) shows the variation of peak deviator stress for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M1, M2 and M3 methods of curing at a confining pressure of 196.2 kPa. Study of Fig. 2(c) reveals that peak deviator stress of reference mix mixed with 5% C1,

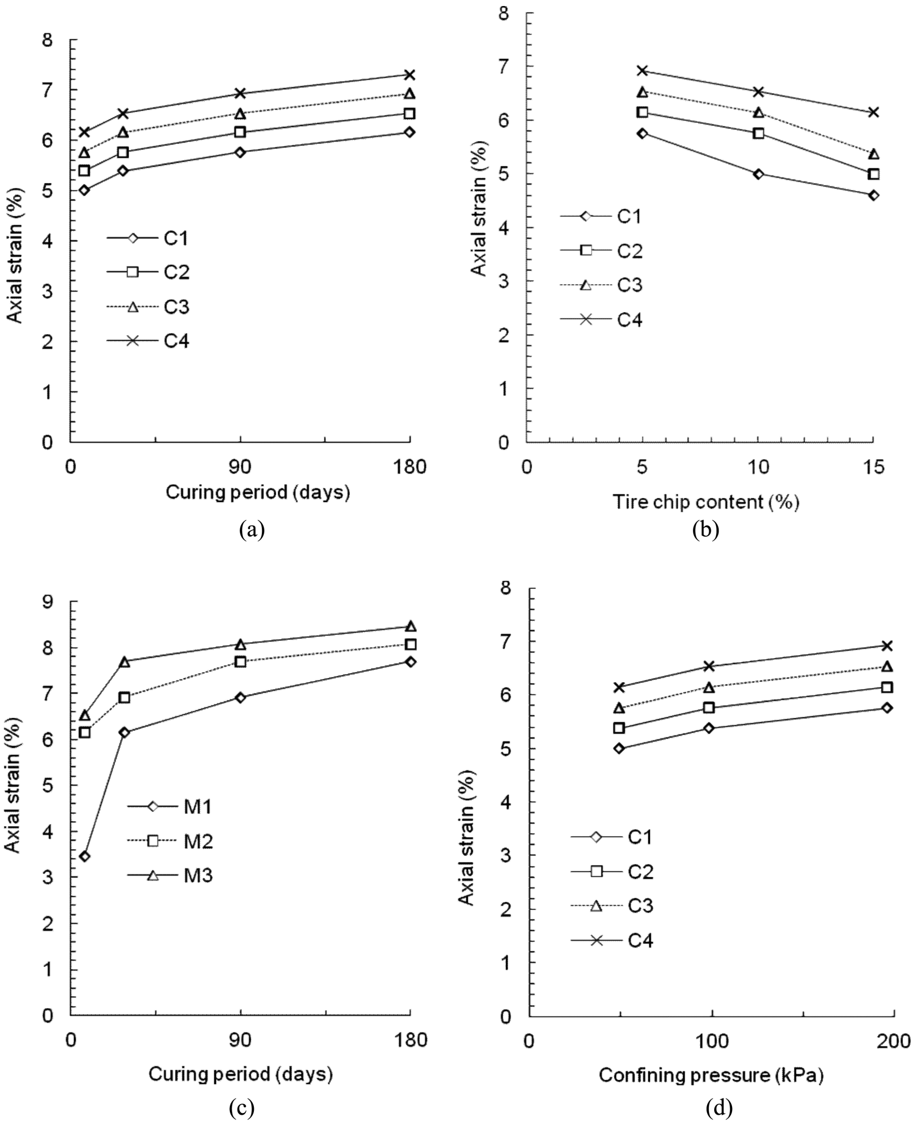

Fig. 3 (a) Variation of axial strain with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M3 method of curing and at a confining pressure of 49.05 kPa, (b) Variation of axial strain with tire chip content for the reference mix mixed with C1, C2, C3 and C4 tire chips and cured for 7 days with M3 method of curing and at a confining pressure of 196.2 kPa, (c) Variation of axial strain with curing period for the reference mix mixed with 5% C3 tire chips and cured with M1, M2 and M3 methods of curing and at a confining pressure of 196.2 kPa, (d) Variation of axial strain with confining pressures for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 7 days with curing method M3

C2, C3 and C4 tire chips increases with the change in the curing method from M1 to M2 and M1 to M3. For example, a peak deviator stress 476 kPa for the reference mix mixed with 5% C1 tire chip and cured for 90 days with curing method M1 increased to 582 kPa and 693 kPa with the change in the curing method to M2 and M3 respectively.

The axial strain at failure was observed to increase with the change in curing method from M1 to M2 and M1 to M3. For example, an axial strain at failure of 3.46% for reference mix with 5% C4 tire chips and cured for 7 days with curing method M3 was observed to increase to 6.15% and 6.53% respectively with the change in the curing method to M2 and M3. A similar trend of increase in the axial strain at failure was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix as evident from the Fig. 3(c).

Fig. 2(d) shows the variation of peak deviator stress with confining pressure for the reference mix mixed with 5% C4 tire chips and cured for 7, 28, 90 and 180 days with curing method M3. Fig. 2(d) reveals that peak deviator stress increases with the increase in the confining pressures. For example, at a confining pressure of 49.05 kPa, a peak deviator stress of 582 kPa for reference mix mixed with 5% C4 tire chips cured for 90 days of curing increased to 687 kPa and 836 kPa with the change in the confining pressures to 98.1 kPa and 196.2 kPa, respectively. A study of the Fig. 2(d) further reveals that increase in the peak deviator stress was significant at a lower confining pressure of 49.05 kPa in comparison to 98.1 kPa and 196.2 kPa respectively.

The axial strain at failure of reference mix with 5% C1, C2, C3 and C4 tire chips increased with the increase in the confining pressures as evident from Fig. 3(d). For example, for the reference mix with 5% C1 tire chips and cured for 7 days with curing method M3, the axial strain at failure of 5.0% increased to 5.38% and 5.76% with the increase in the confining pressure to 98.1 kPa and 196.2 kPa respectively. Similar increase in axial strain at failure was observed with the inclusion of C2, C3 and C4 tire chips as evident from Fig. 3(d).

4.2 Strength characteristics

Typical *p-q* plots were depicted in Figs. 4(a), (b), (c) and (d) for the results obtained from unconsolidated undrained triaxial tests. The strength parameters obtained are tabulated in Tables 3 and 4. Table 3 shows the results of the cohesion obtained from *p-q* plots of the reference mix with and without 5%, 10%, 15% C1, C2, C3 and C4 tire chips cured for 7, 28, 90 and 180 days of curing with curing methods M1, M2 and M3. Study of Table 3 reveals that cohesion of reference mix mixed with C1 tire chips increases when C1 tire chips were replaced with C2, C3 and C4 tire chips in the reference mix. For example, cohesion of 8.80 kPa of reference mix mixed with C1 tire chips and cured for 7 days with M1 curing method increased to 10.40 kPa, 11.46 kPa and 11.95 kPa when the C1 tire chips were replaced with C2, C3 and C4 respectively in the reference mix. Similar increase in the cohesion was also observed with the use of other curing methods as evident from Table 3. Table 3 further reveals that cohesion of the composite increases with change in the curing method. For example, cohesion of 8.80 kPa of reference mix mixed with 5% C1 tire chips and cured for 7 days with M1 curing method was observed to increase to 9.50 kPa when the curing method was changed from M1 to M2. The cohesion of same specimen further increased to 10.73 kPa with the change in curing method to M3. A close examination of Table 3 reveals that the cohesion increases with the increase in curing period. For example, cohesion of 8.80 kPa of reference mix mixed with 5% tire chips and cured for 7 days with M1 method of curing increased to 17.84 kPa, 54.78 kPa and 74.55 kPa after 28, 90 and 180 days respectively. Similar trend of increase in cohesion was observed with the inclusion of C2, C3 and C4 tire chips and with M2 and M3 curing methods. Table 3 further reveals that cohesion decreases with the increase in the tire chip content. For example, cohesion of 8.80 kPa of reference mix mixed with 5% C1 tire chips and cured for 7 days with M1 method of curing decreased to 5.91 kPa and 2.39 kPa with the increase in

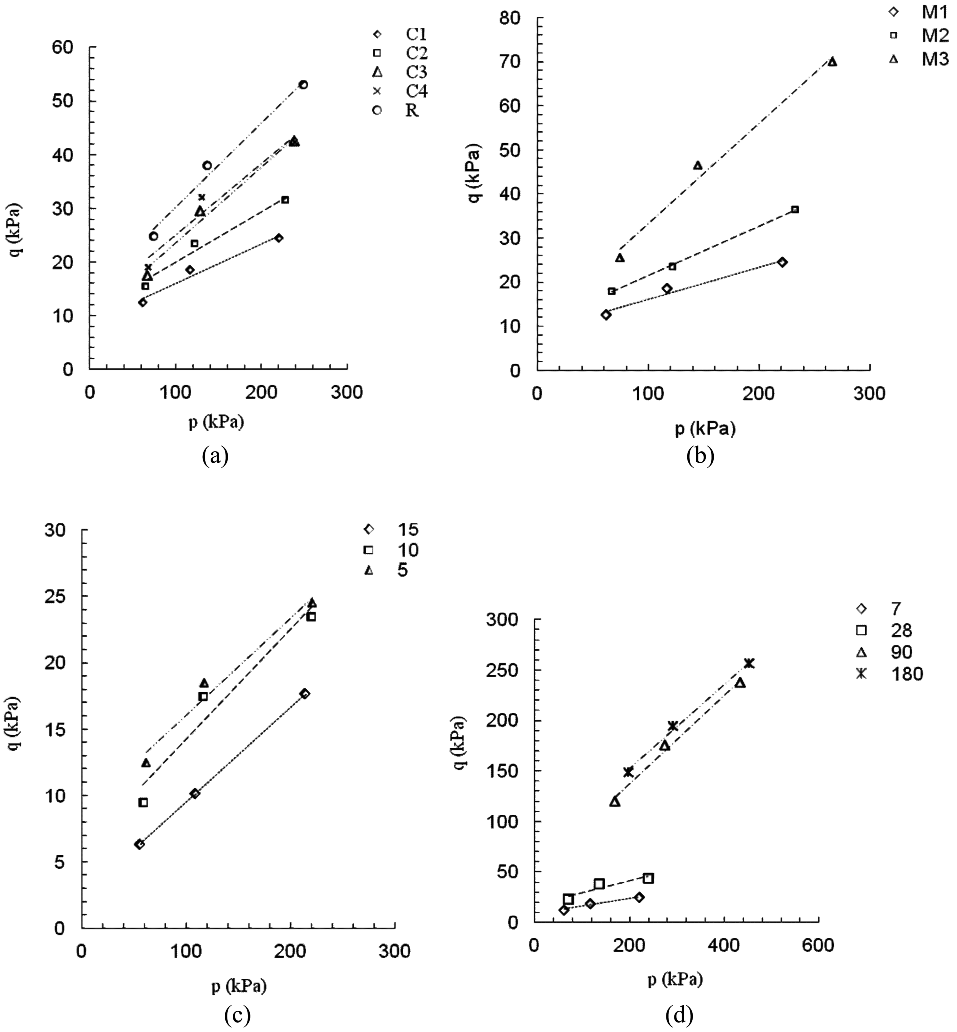

Fig. 4 (a) $p - q$ plots for the reference mix with and without 5% C1, C2, C3 and C4 tire chips and cured for 7 days with curing method M1, (b) $p - q$ plots for the reference mix with and without 5% C1, C2, C3 and C4 tire chips and cured for 7 days with curing method M1, M2 and M3, (c) $p - q$ plots for reference mix mixed with different percentages of C1 tire chips and cured for 7 days with curing method M1, (d) $p - q$ plots for reference mix mixed with 5% C1 tire chips and cured for 7, 28, 90 and 180 days with curing method M1

C1 tire chip content to 10% and 15% respectively. A similar decrease in the cohesion was also observed with the inclusion of C2, C3 and C4 tire chips in reference mix with all curing methods and curing periods as evident from Table 3.

Table 4 shows the variation of friction angle for the reference mix with/without 5%, 10%, 15% C1, C2, C3 and C4 tire chips and cured for 7, 28, 90 and 180 days with M1, M2 and M3 curing methods. A study of Table 4 reveals that the friction angle of reference mix mixed with C1 tire chip increases when C1 tire chips were replaced with 5% C2, C3 and C4 tire chips in the reference mix. For example, friction angle of 4.1° for the reference mix mixed with 5% C1 tire chips and cured for

Table 3 Variation of cohesion (kPa) of the reference mix with and without 5%, 10% and 15% C1, C2, C3 and C4 tire chips and cured for 7, 28, 90 and 180 days of curing with curing methods M1, M2, M3

% Tire chips	Curing period	Cohesion (kPa)														
		M1					M2					M3				
		C1	C2	C3	C4	R	C1	C2	C3	C4	R	C1	C2	C3	C4	R
0	7					14.68					20					39
	28					17.82					38.95					71.79
	90					128.94					152.17					182.63
	180					160.79					175.3					234.76
5	7	8.8	10.4	11.46	11.95		9.50	10.16	13.35	18.44		10.73	18.89	25.47	29.59	
	28	17.84	18.69	21.57	28.53		18.33	25.64	30.14	32.46		39.53	44.53	48.48	50.64	
	90	54.78	65.38	80.84	103.69		90.36	94.27	114.09	134.4		123.84	138.78	148.92	153.9	
	180	74.55	91.16	96.27	121		128.84	133.5	144.64	156.2		166.48	175.57	216.59	229	
10	7	5.91	5.10	8.23	10.21		8.46	9.01	9.60	15.20		9.68	13.25	21.11	25.82	
	28	13.13	14.42	21.16	23.25		13.08	17.85	21.96	26.66		30.85	37.06	40.77	45.34	
	90	37.66	50.35	69.96	102.4		69.03	90.21	104.3	123.5		94.76	118.14	132.25	135	
	180	62.32	63.24	85.3	111.2		103.12	107.91	116	140.3		143.28	171.55	194.6	199	
15	7	2.39	3.70	5.89	7.46		8.23	6.03	7.99	13.50		5.57	10.41	11.72	15.63	
	28	4.28	8.18	14.95	15.01		11.58	14.42	18.16	22.71		21.88	28.64	33.51	41.94	
	90	24.50	42.85	58.86	89.95		53.59	75.91	87.65	114.4		73.55	96.85	111.57	126.1	
	180	59.91	50.94	78	101.5		95.43	103.15	111.4	119		127.46	144.95	121	132	

7 days of with M1 method of curing was observed to increase to 5.45º, 8.1º and 8.5º when the C1 tire chips were replaced with C2, C3 and C4 tire chips respectively. A similar increase in the friction angle was observed with other curing methods as evident from Table 4. A further examination of Table 4 reveals that friction angle increases with change in the curing method. For example, friction angle of 4.1º for the reference mix mixed with 5% C1 tire chips and cured for 7 days with M1 method of curing was observed to increase to 6.43º with the change in the curing method from M1 to M2. The friction angle of the same specimen was further increased to 13.17º with the change in the curing method to M3. Table 4 also reveals that the friction angle increases with the increase in curing period. For example, friction angle 4.1º of the reference mix at 7 days of curing with M1 curing method was observed to increase to 6.60º, 22.1º and 24.6º after 28, 90 and 180 days of curing respectively. A similar trend of increase in friction angle was also observed with the inclusion of C2, C3 and C4 tire chips in reference mix with all curing methods as evident from Table 4.

Study of Table 4 reveals that friction angle of reference mix decreases with the increase in the C1, C2, C3 and C4 tire chip content in the reference mix. For example, friction angle of 12.34º of the reference mix at 7 days of curing with M1 method decreased to 4.1º with the inclusion of 5% C1 tire chips in the reference mix. The values further decreased to 2.76º and 1.5º with the inclusion of 10% and 15% C1 tire chips in the reference mix. A similar trend of decrease in the friction angle was also observed with the inclusion of 10% and 15% C2, C3 and C4 tire chips in the reference mix at all curing periods and with all curing methods.

Table 4 Variation of angle of friction (degree) of the reference mix with and without 5%, 10% and 15% C1, C2, C3 and C4 tire chips and cured for 7, 28, 90 and 180 days of curing with curing methods M1, M2, M3

% Tire chips	Curing period	Angle of friction (degree)														
		M1					M2					M3				
		C1	C2	C3	C4	R	C1	C2	C3	C4	R	C1	C2	C3	C4	R
0	7					12.34					12.94					14.94
	28					17.27					18.18					19.41
	90					27.38					29.53					29.73
	180					29.3					30.6					31.8
5	7	4.1	5.45	8.1	8.5		6.43	9.26	9.96	10.1		11.17	12.06	12.76	13.59	
	28	6.60	9.67	11.36	11.80		9.38	11.71	12	13.47		12.65	13.29	13.06	13.76	
	90	22.1	22.25	23.01	24.1		23.11	24.10	24.89	25.62		25.04	26.91	27.25	27.38	
	180	24.6	25.1	25.91	26.10		27.2	27.5	28.1	28.9		28.1	28.9	29.2	29.7	
10	7	2.76	4.07	5.16	6.25		6.01	9	9.10	9.75		10.01	12.05	12.12	12.35	
	28	6.2	8.6	8.16	10.12		8.9	10.2	11.41	13.23		9.4	12.35	12.51	13.06	
	90	20.8	21.2	21.9	22.8		21.34	22.21	23.2	24.4		22.19	23.1	24.56	26.23	
	180	22.9	23.7	24.1	25.5		24.1	26.61	27.1	27.8		24.8	25.2	28.2	28.7	
15	7	1.5	3.55	4.86	6.14		3.78	5.73	8.39	8.46		8.33	10.77	11.88	12.29	
	28	4.5	7.9	7.91	10		7.7	9.24	10.23	12.41		9.1	11.06	12	13.2	
	90	19.1	20.4	21.4	22.6		20.8	21.64	22.7	23.3		23.1	24.15	25.2	27.4	
	180	22.45	23.1	23.8	25.1		23.2	25.1	26.3	27.1		24.1	24.6	27.3	27.8	

4.3 Hyperbolic stress-strain relationship

The hyperbolic stress-strain relations suggested by Kondner and Zelasko (1963) are given by the Eq. (1).

$$\frac{\varepsilon}{\sigma_1-\sigma_3} = b.\ \varepsilon + a \tag{1}$$

where

σ_1 and σ_3 are the major and minor principal stresses respectively,

ε is the axial strain, and

a and b are hyperbolic parameters which can be determined experimentally.

4.3.1 Initial tangent modulus

Inverse of parameters "a" predicts the initial tangent modulus. Fig. 5(a) shows the variation of initial tangent modulus at a confining pressure of 49.05 kPa for reference mix mixed with 5% C1, C2, C3 and C4 tire chips cured for 7, 28, 90 and 180 days with M3 curing method. Study of Fig. 5(a) reveals that initial tangent modulus of reference mix mixed with C1 tire chips increases when C1 tire chips were replaced with the C2, C3 and C4 tire chips in the reference mix. For example, initial tangent modulus of 10.89 MPa of the reference mix mixed with C1 tire chips cured for 90 days with M3 curing method increased to 14.78 MPa, 18.77 MPa and 18.96 MPa, when C1 tire

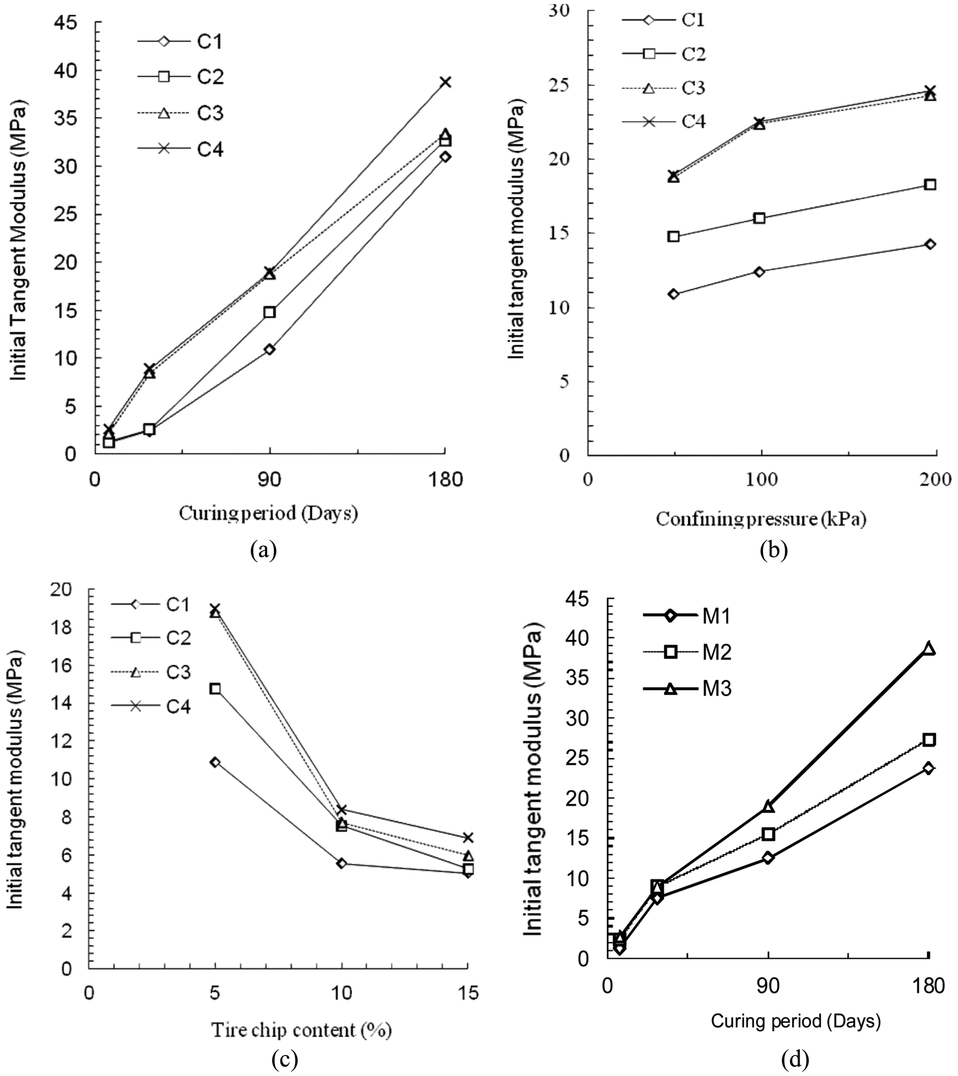

Fig. 5 (a) Variation of initial tangent modulus with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M3 method of curing and at a confining pressure of 49.05 kPa, (b) Variation of initial tangent modulus with confining pressure for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 90 days with curing method M3, (c) Variation of initial tangent modulus with tire chip content for the reference mix and cured for 90 days with curing method M3 and at a confining pressure of 49.05 kPa, (d) Variation of initial tangent modulus with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M1, M2 and M3 methods of curing and at a confining pressure 49.05 kPa

chips were replaced with C2, C3 and C4 respectively. A close examination of Fig. 5(a) reveal that initial tangent modulus of reference mix mixed with C1, C2, C3 and C4 tire chips increases with the increase in the curing period. For example, initial tangent modulus of 1.2 MPa of the reference mix mixed with the 5% C1 tire chips cured for 7 days with M3 method of curing increased to 2.42 MPa, 10.89 MPa and 30.96 MPa, after a curing period of 28, 90 and 180 days. A similar increase in the initial tangent modulus with the increase in curing period was also observed with the inclusion of C2, C3 and C4 tire chips in the reference mix.

Fig. 5(b) shows the variation of initial tangent modulus with confining pressure for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 90 days with M3 method of curing. Study of Fig. 5(b) reveals that initial tangent modulus of reference mix mixed with 5% C1, C2, C3 and C4 increased with the increase in the confining pressure. For example, initial tangent modulus of 18.96 MPa of the reference mix mixed with 5% C4 tire chips, at a confining pressure of 49.05 kPa with M3 method of curing, increased to 22.57 MPa and 23.27 MPa, with an increase in the confining pressure to 98.1 kPa and 196.2 kPa, respectively. A similar increase in initial tangent modulus was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix.

Fig. 5(c) shows the variation of initial tangent modulus with tire chip content of the reference mix mixed with C1, C2, C3 and C4 tire chips and cured for 90 days with M3 method of curing. Study of Fig. 5(c) reveals that initial tangent modulus decreases with the increase in the tire chips content in the reference mix. For example, initial tangent modulus of 18.96 MPa of the reference mix mixed with 5% C4 tire chips and cured for 90 days with M3 method of curing decreased to 8.38 MPa and 6.90 MPa with an increase in the tire chip content to 10% and 15%, respectively. A similar decrease in initial tangent modulus was also observed with the inclusion of C1, C2 and C3 tire chips in the reference mix.

Fig. 5(d) shows the variation of initial tangent modulus of reference mix mixed with 5% C1, C2, C3 and C4 tire chips at a confining pressure of 49.05 kPa with the change in the curing method from M1 to M2 and M1 to M3. For example, initial tangent modulus of the reference mix mixed with 5% C4 tire chips and cured for 90 days with M1 method was 8.53 MPa which increased to 15.48 MPa and 18.96 MPa with the change in the curing method to M2 and M3, respectively. A similar increase in the initial tangent modulus with the change in the curing method from M1 to M2 and M1 to M3 was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix.

4.3.2 Ultimate strength

The inverse of "*b*" as obtained with the use of equation 3 shows the ultimate strength. Fig. 6(a) shows the variation of ultimate strength with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 7, 28, 90 and 180 days with M3 method of curing and at a confining pressure of 196.2 kPa. Study of Fig. 6(a) reveals that the ultimate strength of the reference mix mixed with C1 tire chips increased when C1 tire chips were replaced with C2, C3 and C4 in the reference mix. For example, ultimate strength of 1998 kPa of the reference mix mixed with 5% C1 tire chips and cured for 90 days with curing method M3 increased to 2345 kPa, 2567 kPa and 3325 kPa, when C1 tire chips were replaced with C2, C3 and C4 respectively in the reference mix. A similar increase in the ultimate strength was observed with the inclusion of C2, C3 and C4 tire chips in the reference mix. Fig. 6(a) further reveals that increase in the ultimate strength was highest with the inclusion of C4 tire chips followed by C3, C2 and C1 tire chips in the reference mix. A close examination of Fig. 6(a) further reveals that ultimate strength of reference mix mixed with 5% C1, C2, C3 and C4 tire chips increased with the increase in the curing period. For example, ultimate strength of 2020 kPa of the reference mix mixed with 5% C3 tire chips and cured for 7 days increased to 2330 kPa, 2567 kPa and 2878 kPa, after 28, 90 and 180 days of curing. A similar increase in the ultimate strength was observed with the inclusion of C1, C2 and C4 tire chips in the reference mix.

Fig. 6(b) shows the variation of ultimate strength of reference mix mixed with 5% C4 tire chips at

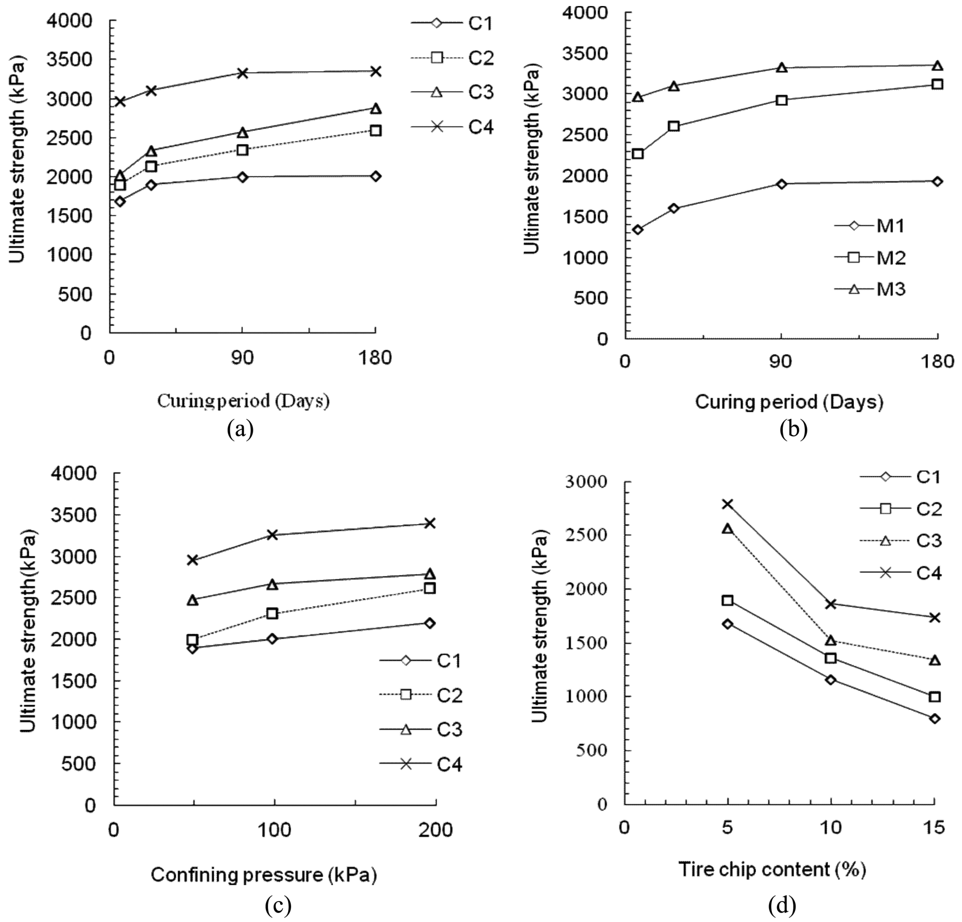

Fig. 6 (a) Variation of ultimate strength with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M3 method of curing and at a confining pressure 196.2 kPa, (b) Variation of ultimate strength with curing period of the reference mix mixed with the 5% C4 tire chips and cured with M1, M2 and M3 methods of curing and at a confining pressure 196.2 kPa, (c) Variation of ultimate strength with confining pressure of the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 90 days with curing method M3, (d) Variation of ultimate strength with tire chip content of the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 28 days with curing method M3

a confining pressure of 196.2 kPa and cured with M1, M2 and M3 methods of curing. Study of Fig. 6(b) reveals that ultimate strength increases with the change in the curing method from M1 to M2 and M1 to M3. For example, ultimate strength of 1934 kPa of the reference mix mixed with 5% C4 tire chips and cured with M1 method increased to 3119 kPa when the curing method was changed from M1 to M2. The ultimate strength of the same specimen further increased to 3353 kPa with the change in curing method to M3.

Fig. 6(c) shows the variation of the ultimate strength with confining pressure for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 90 days with M3 method of curing. A study of Fig. 6(c) reveals that ultimate strength of reference mix mixed with 5% C1, C2, C3 and C4 tire chips increases with the increase in the confining pressure. For example, ultimate strength of 2956 kPa of the reference mix mixed with 5% C4 tire chips and cured for 90 days with M3 method increased to 3256 kPa and 3325 kPa with the increase in confining pressure to 98.1 kPa and 196.2 kPa respectively. A similar increase in the ultimate strength was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix.

Fig. 6(d) reveals that ultimate strength decreases with the increase in the C1, C2, C3 and C4 tire chip content in the reference mix. For example, ultimate strength of 2789 kPa of the reference mix mixed with 5% C4 tire chips and cured for 28 days with curing method M3 decreased to 1863 kPa and 1740 kPa with the inclusion of 10% and 15% C4 tire chips in the reference mix. A similar decrease in ultimate strength was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix.

4.3.3 Secant modulus

Fig. 7(a) shows the variation of secant modulus (at 50% of the peak stress) with curing period of the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M3 method of curing and at confining pressure of 49.05 kPa. A study of Fig. 7(a) reveals that secant modulus of reference mix mixed with C1 tire chips increases when C1 tire chips were replaced with the C2, C3 and C4 tire chips in the reference mix. For example, secant modulus of 8.77 MPa of the reference mix mixed with 5% C1 tire chips and cured for 90 days with M3 method of curing increased to 9.97 MPa, 11.11 MPa and 11.19 MPa, when C1 tire chips were replaced with C2, C3 and C4 respectively. A similar increase in the secant modulus was also observed at 7, 28 and 180 days of the curing as evident from the Fig. 7(a). Fig. 7(a) further reveals that secant modulus increases with the increase in the curing period. For example, secant modulus of 1.77 MPa of the reference mix mixed with 5% C4 tire chips and cured for 7 days with curing method M3 increased to 2.43 MPa, 11.19 MPa and 20.90 MPa after 28, 90 and 180 days of curing. A similar increase in the secant modulus was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix as evident from the Fig. 7(a).

Fig. 7(b) shows the variation of secant modulus with confining pressure for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 7 days with curing method M3. Study of Fig. 7(b) reveals that secant modulus of reference mix mixed with 5% C1, C2, C3 and C4 tire chips increases with the increase in the confining pressure. For example, secant modulus of 1.77 MPa of the reference mix mixed with 5% C4 tire chips increased to 2.18 MPa and 2.72 MPa with the increase in the confining pressure to 98.1 kPa and 196.2 kPa. A similar increase in the secant modulus with the increase in confining pressure was observed with inclusion of C1, C2 and C3 tire chips in the reference mix as evident from Fig. 7(b).

Fig. 7(c) shows the variation of secant modulus with tire chip content for the reference mix mixed with 5%, 10% and 15% C1, C2 and C3 tire chips and cured for 180 days with curing method M3 and at a confining pressure 49.05 kPa. Study of Fig. 7(c) reveals that secant modulus of decreases with the increase in the tire chip content in the reference mix. For example, secant modulus of 20.9 MPa of the reference mix mixed with 5% C4 tire chips and cured for 180 days with curing method M3 decreased to 10.11 MPa and 6 MPa with the inclusion of 10% and 15% C4 tire chips in the reference mix. A similar decrease in the secant modulus as evident from Fig. 7(c) was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix.

Fig. 7(d) shows the variation of secant modulus at confining pressure of 196.2 kPa for the reference mix mixed 5% C4 tire chips and cured for 7, 28, 90 and 180 days with curing methods

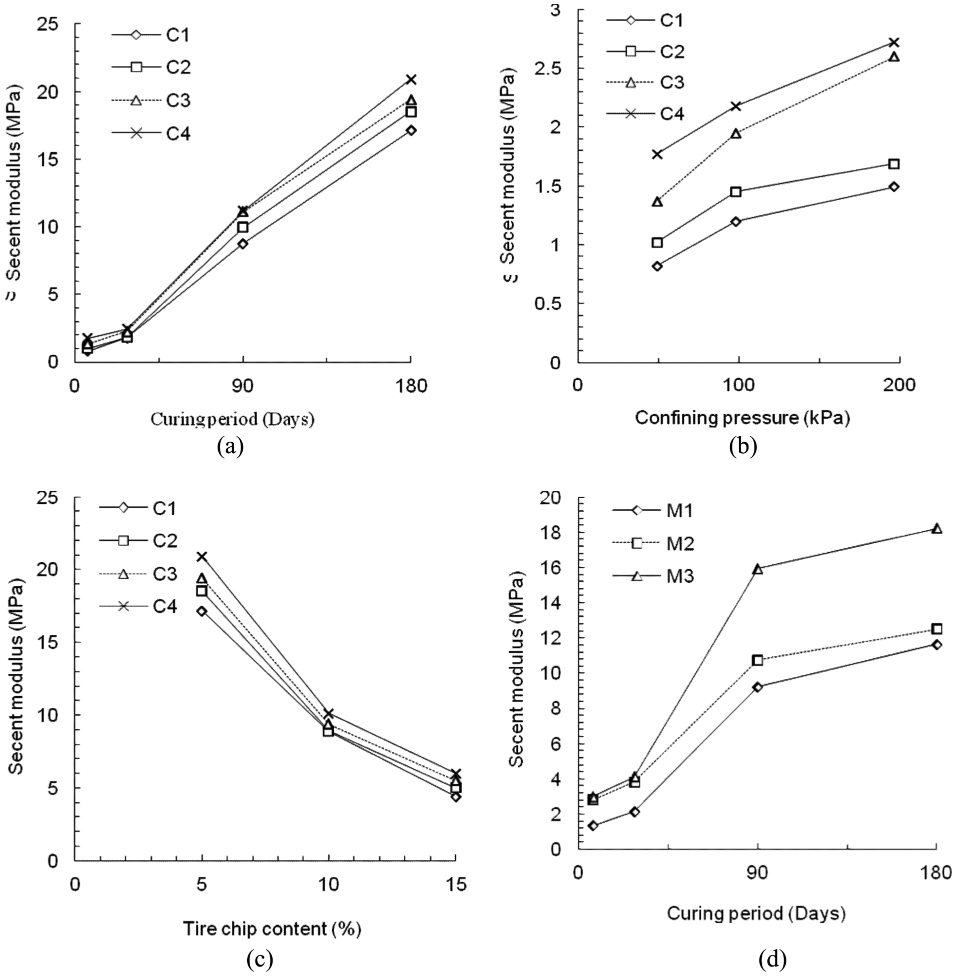

Fig. 7 (a) Variation of secant modulus with curing period for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured with M3 method of curing and at a confining pressure 49.05 kPa, (b) Variation of secant modulus with confining pressure for the reference mix mixed with 5% C1, C2, C3 and C4 tire chips and cured for 7 days with M3 method of curing, (c) Variation of secant modulus with tire chip content for the reference mix mixed with C1, C2, C3 and C4 tire chips and cured for 180 days with curing method M3 and at a confining pressure of 49.05 kPa, (d) Variation of secant modulus with curing period for the reference mix mixed 5% C4 tire chips and cured with M1 to M2 and M3 methods of curing and at a confining pressure of 196.2 kPa

M1, M2 and M3. Study of Fig. 7(d) reveals that secant modulus of reference mix mixed with 5% C4 tire chips increases with the change in the curing method from M1 to M2 and M1 to M3. For example, secant modulus of 9.22 MPa of the reference mix mixed with 5% C4 tire chips and cured for 90 days with M1 method of curing increased to 10.73 MPa and 15.93 MPa with the change in the curing method from M1 to M2 and M1 to M3. A similar increase in the secant modulus was observed with the inclusion of C1, C2 and C3 tire chips in the reference mix as evident from Fig. 7(d).

4.4 Discussion

The results presented in the previous sections reveal that peak deviator stress, cohesion, friction angle, initial tangent modulus, ultimate strength and secant modulus increased with the treatment provided with water, sodium hydroxide and carbon tetra chloride in comparison to dry tire chips in the reference mix. The increase in these parameters of the specimen with C2, C3 and C4 tire chips is attributed to the removal of acidic and carboxyl groups present on the tire chips by dipping them in water, sodium hydroxide and carbon tetrachloride resulting improved adhesion and better bond of tire chip with the reference mix. Eldin and Senouci (1993), Segre and Joekes (2000) and Rostami *et al.* (1993) made similar observation where treatment of tire chips with water, sodium hydroxide and carbon tetra chloride increases the adhesion of tire chips with the concrete/cement paste resulting improvement in strength. Further at all tire chip content, curing periods, confining pressure and with all curing methods, the results shown in Tables 3 to 4 and Figs. 1 to 7 reveal that the increase in these parameters is more for C4 and least for C1. i.e., C4 > C3 > C2 > C1. This is attributed to the fact that C4 tire chips will dissolve all dust and impurities present on its surface resulting higher adhesion and better bond with the reference mix. C3 tire chips will not only remove dust and impurities present on the surface of tire chips but will also react with organic compound (isoprene, styrene, butadiene etc. present in the tire chips) leading to the formation of bubbles at the junction of the reference mix and tire chips. Due to this bubble formation, the improvement in adhesion and bonding will be less in comparison to C4 tire chips. C2 tire chips will perhaps partially remove dust and impurities present on the tire chips leading to less improvement in adhesion and bonding in comparison to C3 tire chips. Further, higher values of these parameters was observed when specimens were cured in water filled container (M3) followed by burlap (M2) and dessicator (M1) respectively. The lesser value of these parameters with curing method M1 was attributed to the fact that loss of moisture in the specimen in plastic bag due to capillary rising deactivates the pozzolanic reaction. Contrary to this, in curing methods M2 and M3, continuous supply of moisture activates the pozzolanic reaction leading to higher value of these parameters. The results have further revealed that these parameters increased with the increase in the curing period and decreased with the increase in tire chip content. The decrease in these parameters with the increase in tire chip content is attributed to the fact that tire chip act like a soft particle within the composite in comparison to hardened reference mix thus develop tensile stresses at the particle surface and the reference mix vicinity. Development of such tensile stresses results in premature cracking under compressive loading and thus causes decrease in these parameters. The results have further revealed that these parameters increase with the increase in confining pressure. Further, the increase in these parameters was significant at lower confining pressure in comparison to higher confining pressure. This may be attributed to more influence of tire chips at lower confining pressure in comparison to higher confining pressure.

The axial strain at failure increased with the inclusion of 5% C1, C2, C3 and C4 tire chips in the reference mix. This is attributed to lower modulus of the tire chips compared to hardened reference mix which results in dissimilar deformation and induce multiple cracking. Due to this multiple cracking, the specimen fails at larger strain. Beyond a tire chip content of 5%, the axial strain at failure decreased when the content of tire chip was increased to 10% and 15% respectively. This is attributed to the fact that tire chips act as voids and thus causes premature cracking at lower strain. Cetin *et al.* (2006) made similar observations where a decrease in the vertical strain with the increase in the tire chip content in cohesive clayey soil was reported when tested using direct shear tests. The results further reveal that the axial strain at failure of the reference mix with C4 tire chips was higher followed by C3, C2 and C1 tire chips in the reference mix in comparison to the reference mix without tire chips. This may be attributed to the fact that the improved bond of tire chips with the reference mix due to different treatment, increase in curing period and change in curing method (M1 to M2 and M1 to M3) delays the widening of crack which results in the increased axial strain at failure of the reference mix. The results reveal that the axial strain at failure of reference mix with C1, C2, C3 and C4 tire chips increased with the increase in the confining pressures. The authors of this paper are of the opinion that the use of this composite material can be more economical in those areas where these waste materials are available in the nearby places. However, further more studies relating to durability has to be carried out before the using this composite material at the actual site condition. Beside this, the analysis regarding the leachability of metal from the composite has to be carried out to ascertain that leaching metals does not cause any harmful impact on the surface/ground water quality.

5. Conclusions

In the present paper, reference mix containing fly ash + 8% Lime + 0.9% Gypsum was mixed with the dry and water, sodium hydroxide and carbon tetra chloride treated tire chips. The tire chip content was varied from 5% to 15% and the specimens were cured for 7 to 180 days by three different curing methods (in a dessicator, burlaps and in water filled container having a provision of inflow and out flow). The unconsolidated undrained triaxial tests were conducted on reference mix mixed with C1, C2, C3 and C4 tire chips by varying the confining pressure 49.05 kPa to 196.2 kPa. On the basis of results of the experimental investigation and the discussions made in the earlier sections, the following conclusions are drawn.

Stress – strain relationship, strength characteristics, initial tangent modulus, ultimate strength and secant modulus of the reference mix containing dry tire chips is influenced by the tire chip content, curing period, curing method and the treatment provided on the tire chips.

The peak deviator stress, cohesion, friction angle, initial tangent modulus, ultimate strength and secant modulus increased with the treatment provided with water, sodium hydroxide and carbon tetra chloride in comparison to dry tire chips in the reference mix.

The peak deviator stress, cohesion and friction angle, initial tangent modulus, ultimate strength and secant modulus increased with the increase in the curing period.

A higher increase in peak deviator stress, cohesion, friction angle, initial tangent modulus, ultimate strength and secant modulus was observed when specimens were cured in water filled container followed by burlap and dessicator respectively.

The peak deviator stress, cohesion and friction angle, initial tangent modulus, ultimate strength and secant modulus decreased with the increase in tire chip content from 5% to 15%.

The peak deviator stress, initial tangent modulus, ultimate strength and secant modulus increased with the increase in the confining pressure and the increase was significant at lower confining pressure in comparison to higher confining pressure.

The axial strain at failure increased with the treatment provided with water, sodium hydroxide and carbon tetra chloride in comparison to dry tire chips in the reference mix.

The axial strain at failure increased with the increase in curing period, change in curing method and increase in confining pressure.

Inclusion of 5% dry/treated tire chips in the reference mix increases the axial strain at failure. Beyond a tire chip content of 5%, the axial strain at failure decreased when the content of tire chip was increased to 10% and 15% respectively.

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