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Research Paper

Assessment of geotechnical properties of uncemented/cemented clayey soil incorporated with waste crumb rubber

J.S. Yadav, S.K. Tiwari*

Civil Engineering Department, Malaviya National Institute of Technology Jaipur, 302017, India

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ABSTRACT

Discarded waste tires are becoming a serious threat to health, environment, and ecological systems worldwide if it is not disposed of properly. Every year 1000 million of waste tires are discarded. This number may grow up to 1200 million by the year 2030. On the other hand, construction of civil engineering structures such as buildings, dams, highways, etc. are at high risk of differential settlement, especially in the case of weak or soft clay, which is due to its low shear strength and high compressibility. The paper aims to assess geotechnical properties of uncemented/cemented clayey soil incorporated with waste crumb rubber. Compaction parameters, unconfined compressive strength, split tensile strength, toughness index, CBR values and swelling pressure of rubberized uncemented/cemented clayey soil (3%, and 6% cement and different percentage of crumb rubber) have been obtained. After rigorous extensive study, it has been concluded that unconfined compressive strength and split tensile strength of rubberized cemented clayey soil decreases with the increase of the percentage of crumb rubber whereas the axial, and diametral strain are found to be increased with the addition of crumb rubber up to 5% after that it starts to decrease. The CBR values, swelling pressure, and toughness index of uncemented/cemented clayey soil was significantly affected by incorporation of crumb rubber. SEM studies have also been incorporated in this investigation.

1 Introduction

The rapid urbanization and industrialization has created an aggravating situation for the suitable construction sites especially in metropolitan cities area across the globe. It enforced the utilization of places containing highly problematic soils (clayey soils) for development activities. The clayey soils are considered unsuitable for construction activities due to its low resistance to deformation under wet conditions, poor drainage, high swelling, and shrinkage properties [1]. These problems associated with the sites containing clayey soil enforced the pre-requisites treatment of the soil. Many successful

* *Corresponding author. Tel.: +91-9461595625.*
E-mail address: jitendershine@gmail.com

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engineering endeavours have been made in last two decades on the stabilization of these arguable soils by mechanical, chemical stabilization or by using natural and artificial fibres.

On the other hand, one of the prime disadvantages of rapid urbanization and industrialization is the increase in the generation of an enormous quantity of municipal and industrial wastes. Discarded vehicle tires have a vital share in the solid waste and have turned into a major and bigger challenge worldwide. About 1.5 billions of tires are manufactured globally per year. It is estimated that about 1000 million tires reach the end of their serviceable lives every year. This figure may increase up to 1200 million by the year 2030. Approximately 50% of these waste tires are discarded to landfills or garbage, without any treatment. In the Indian scenario, about 112 million discarded tires are produced every year after retreading it twice [2].

The conventional practice of disposal of waste tires such as landfills; stockpiles and fuel have been regarded as a major threat to health, environment and ecological systems. The disposal of waste tires as landfills provides the space for breeding of rodents and problems with heaving of the ground. Stockpiling of tires resulted in health and environmental problems because it provides potential sites for the breeding of mosquitoes, pests and is at high risk of ignition. The burning of tires as a fuel causes the liberation of poisonous gasses in the environment and raises the temperature of the surrounding, which is very dangerous to the living thing in the area nearby. The government of many countries has restricted the use of discarded tires as a fuel because of the hazardous impact of it on health and ecosystems. Therefore, there is urgent exigency to utilize or dispose this waste by some scientific and economically viable method, having minimum impact on the health and environment.

It is estimated that only 4% of the discarded tires are used in the civil engineering's applications such as concrete, asphalt pavement, waterproofing system and membrane liner, etc [3]. The geotechnical fraternity has tried to utilize this hazardous waste as a soil amendment of soil. Due to the lightweight of rubber tires, its inclusion in soil could be highly advantageous. The incorporation of discarded rubber tires could not only mitigate the ill effects associated with the utilization of clayey soil for construction activities, but also open a new venue for the disposal of this hazardous waste. The lightweight geomaterials made up of soil-rubber mixtures could be used as filling materials for road construction purposes. The lighter materials minimize foundation requirements, reduce land cutting for mountainous areas, prevent settlements and shorten construction times. In the case of retaining walls, lighter backfill would reduce the lateral earth pressure thus reducing the structural requirements of the wall including the foundations.

2 Literature review

Geotechnical properties of clayey soils such as consistency limit's, compaction parameters, strength, permeability, swelling potential, swelling pressure, consolidation characteristics, etc are affected by the incorporation of waste rubber tires. The values of liquid limit and plastic limit of clayey soil have been observed to decrease with increase in shredded tyre waste [4, 5]. The reduction in Atterberg's limits is attributable to decrease in clay content. However, Srivastava et al. [5] reported increase in shrinkage limit and decrease in shrinkage ratio with an increase in the percentage of tyre waste incorporated with clayey soil. Sarvade and Shet [6] also observed a decrease in the liquid limit, plastic limit and an increase in shrinkage limit with the addition of crumb rubber in the problematic clayey soil.

The compaction parameters of the rubberized clayey soil are affected by the content and type of the waste tire. The maximum dry density (MDD) of clayey soil has been observed to decrease with increase in waste rubber tire content [4-11]. Al-Tabbaa and Aravinthan [8] and Singh and Vinot [12] reported that the optimum moisture content (OMC) of the clayey soil roughly remains the same with the inclusion of waste shredded tires and tire chips. Contrary to this, a decrease in OMC with an increase in waste rubber content in clayey soil was reported in other studies [4]. Lekan and Ojo [13] reported that MDD of soil stabilized with tyre ash systematically decrease whereas the OMC increases with an increase in tyre ash content. The decrease in the MDD was attributed to the low specific gravity of tyre ash and porosity of tyre ash was ascribed the reason behind the increase in the OMC. Cabalar et al. [11] reported that a reduction in the maximum dry unit weight of lime stabilized clay on inclusion of tyre buffing whereas increase in the lime content higher the OMC of the mixtures citing two possible reasons (i) high water absorption capacity of lime particles and (ii) water used for hydration process. Srivastava et al. [5] reported a lower MDD of the black cotton soil incorporated with coarser size (4.75 mm- 2.00 mm) shredded tyre waste as compared to MDD of black cotton soil incorporated with finer size (2.00 mm- 0.075 mm) shredded tyre waste. Further, Kalkan [14] carried out an investigation on rubber fiber-clayey soil with the inclusion of silica fume. It has been shown that the voids of the mixture were filled by silica fume, which resulted in the decrease in MDD and the change of the gradation resulted in the increase in OMC.

Systematic reduction in the unconfined compressive strength of the clayey soil has been observed with increase in waste rubber tire content [6, 8, 11, 19]. Cokca and Yilmaz [15] reported about 35 times reductions in unconfined compressive strength of fly ash as rubber content increases from 0 to 10% and bentonite decreases from 10 to 0%. Cetin et al. [8] reported an improvement in the shear strength by incorporation of 30% fine tyre chips (<0.425mm) and 20% coarse tyre chips (4.75- 2.00mm) in clay. Akbulut et al. [16] observed an increment in the unconfined compressive strength of the clayey soil with the inclusion of 2% rubber tire fibers of 10mm length. Kalkan [14] had made the similar observation for clayey soil modified with rubber fiber and silica fume. According to Srivastava et al. [5] the undrained cohesion values of the black cotton soil decrease with the addition of finer size shredded tyre waste as compared to coarse size shredded tyre waste. The addition of 5% coarse size shredded tyre waste in the black cotton soil improves the undrained cohesion value by approximately 60%, and further inclusion of waste tyres reduces the undrained cohesion of black cotton soil. Contrary to this, Wang and Song [17] reported that the unconfined compressive strength of rubberized cemented clayey soil had not been affected by the size of crumb rubber. Hambirao and Rakaraddi [18] and Otoko and Pedro [19] suggested the optimum dose of 5% shredded tires in the cemented clayey soil. Further incorporation of shredded tire reduces the unconfined compressive strength of clayey soil.

The inclusion of waste rubber tire affects the California Bearing Ratio (CBR) value of the clayey soil. Hambirao and Rakaraddi [18] and Otoko and Pedro [19] reported more than 5% additions of shredded rubber tyre chips and fibers in the cemented clayey soil reduce the CBR value. CBR values of rubberized cemented clayey soil having the optimum dose of 5% were found more than the non-rubberized cemented clayey soil. Cabalar et al. [11] carried out an experimental investigation on the CBR value of clay stabilized with tyre buffing and lime. The addition of tyre buffing markedly reduces the CBR value of clay and lime stabilized clay. Subramanian and Jeyapriya [20] observed 6% improvement in the CBR value of clay by the addition of 7.5% waste tyre pieces (ranged between 20-25mm).

Very few studies have been reported in the literature on the swelling potential and swelling pressure of clay- tire mixtures. Cokca and Yilmaz [15] observed decrease in the swelling pressure of fly ash-bentonite-rubber mixture with an increase in the rubber content and decrease in bentonite content. Kalkan [14] had made the similar observation for clayey soil modified with rubber fibers and silica fume. The creation of drainage path for the dissipation of pore pressure and restraining of swelling pressure generated during the application of load on the sample by the rubber fibers was identified as the reason behind this. Srivastava et al. [5] reported a lower swelling pressure of black cotton soil with coarse size shredded tyre waste as compared to swelling pressure of black cotton soil with fine size shredded tyre waste.

Many experimental studies have been cited in the literature on the utilization of waste rubber tires for improving the geotechnical properties of clayey soil. Very few studies have been reported in the literature on the uncemented/cemented clayey soil incorporated with crumb rubber. Hence, there is a need for rigorous research work to evaluate properties of clayey soil incorporating crumb rubber (with and without cement).

In this context, compaction parameters, unconfined compressive strength, split tensile strength, toughness index, California Bearing Ratio and swelling pressure are evaluated for clayey soil by varying cement content (0%, 3% and 6%) and crumb rubber content (0%, 2.5%, 5.0%, 7.5% and 10.0%) respectively. Microstructural studies of rubberized uncement/cemented clayey soil have also been carried out using scanning electron microscope. The proposed composite could be used for construction of roads having low traffic intensity, lightweight backfill behind retaining wall, etc.

3 Material used and Experimental procedure

The soil used in the investigation was procured from Kanota, Rajasthan India. It was collected from a depth of 1 m from the ground surface. It had a liquid limit, plastic limit, specific gravity, dry unit weight and optimum moisture content of 34.2%, 24.8%, 2.69, 16.35 kN/m^3, and 20.89% respectively. The soil was classified as CI (clay with medium plasticity) according to IS 1498-1970 [21]. Commercially available OPC-43 grade cement of Binani Cement Company was used in the investigation. Fig.1 shows the crumb rubber ranged from 0.8-2mm, having the specific gravity, effective size, coefficient of uniformity and curvature of 1.13, 0.80, 1.48 and 1.40 respectively. Grain size distribution of crumb rubber is illustrated in Fig. 2. Four different crumb rubber contents (2.5%, 5%, 7.5%, and 10% by the dry weight of clayey soil) and two different cement contents (3% and 6% by the dry weight of clayey soil) were adopted in the investigation. The general expression for the total dry weight (W) of clay-crumb rubber-cement mixture is

$$W = W_S + W_R + W_C \tag{1}$$

where W_S, W_R, and W_C is the weight of soil, crumb rubber, and cement respectively. The details of various combinations on which modified proctor tests, unconfined compressive strength, split tensile strength, CBR and swelling pressure tests were carried out are presented in Table 1.

Table 1- Details of clay-crumb rubber-cement mixtures for tests conducted

$W = W_S + W_R + W_C$	Variation of Ws	Variation of W_R	Variation of W_C
	(% by total dry weight)		
Combination 1	100, 97.5, 95, 92, 90	0, 2.5, 5, 7.5, 10	0
Combination 2	97, 94.5, 92, 89.5, 87	0, 2.5, 5, 7.5, 10	3
Combination 3	94, 91.5, 89, 86.5, 84	0, 2.5, 5, 7.5, 10	6

Fig. 1- Crumb rubber used in the study

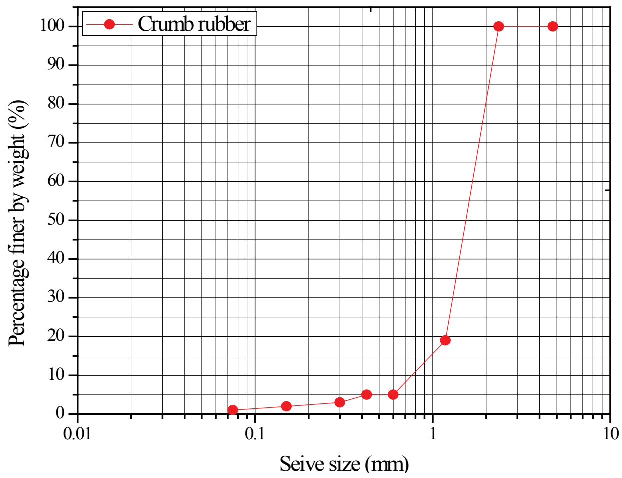

Fig. 2- Grain size distribution of crumb rubber

Initially, dry mix of crumb rubber and oven-dry clayey soil was prepared in a laboratory mixer and stored in plastic bags for future use. The required quantity of cement was added at the time of preparation of specimens and mixed thoroughly. Then the desired amount of water was added in the mixture as per the optimum moisture content. After mixing varying quantities of crumb rubber and cement, a series of tests were performed according to the standard procedure laid down in various ASTM codes. The modified proctor tests were conducted (Fig. 3(a)) in conformity with ASTM D 1557-12 [22]. The compaction parameters (maximum dry unit weight and optimum moisture content) of the various mixtures were determined. The results of the tests are very helpful from an application perspective as fill material behind the retaining wall, sub base of pavements and embankment constructions. The unconfined compression strength (UCS) tests were carried out on the cylindrical specimens of size 38.1mm diameters and 76.2mm length at the strain rate of 1 mm/minute as per ASTM D 2166-06 [23] as shown in Fig. 3(b). The static compaction method was used for the preparation of the specimen at their respective maximum dry unit weight and optimum moisture content. The specimens were wrapped in a thin plastic film and cured for 7, 14, and 28 days in the humidity-controlled chamber at the temperature of 25 C^0 and 96% humidity respectively. The UCS is an indicator of the structural stability of the soil. Split tensile strength (STS) tests were performed according to ASTM C 496-96 [24] on the specimens of the same dimension prepared in the same manner as for UCS test. Two curved shapes, 76.2mm long and 10mm wide metal strips of thickness 5mm were used for maintaining the uniform bearing pressure on the specimens as illustrated in Fig. 3(c). The California Bearing Ratio (CBR) tests were performed on the mixture of crumb rubber-cement-clayey soil as per ASTM D 1883-99 [25] as demonstrated in Fig. 3(d). The feasibility of the mixes as the subgrade for the road having low traffic intensity is evaluated by this test. The swelling pressure test was conducted in conformity with ASTM D 4546-08 [26] for the various mixtures. Specimens of 60mm diameter and 20mm height were prepared and cured for 28 days. A constant volume method was used for evaluating the swelling pressure as shown in Fig. 3(e). The scanning electron microscope (SEM) analysis was carried on the specimen of size 1cm x 1cm x 1cm in Nova Nano FE-SEM 450 to establish the change in the structure of clayey soil with the addition of cement and crumb rubber.

Fig. 3-Specimen under (a) modified compaction test; (b) unconfined compressive strength test; (c) split tensile strenght test; (d) California bearing ratio test; (e) Swelling pressure test

4 Results and discussions

4.1 Effect of cement and crumb rubber on the compaction parameters

Fig. 4 shows the effect of cement and rubber content on the compaction parameters such as maximum dry unit weight and optimum moisture content obtained from modified proctor tests. It is observed that with the inclusion of cement, maximum dry unit weight decreases and optimum moisture content increases. The base exchange aggregation and flocculation phenomenon, which leads to increase the void ratio, is the possible reason behind the decrease in the maximum dry unit weight. Increase in optimum moisture content is attributed to the development of heat of hydration and water held within the flocs. On the other hand, both maximum dry unit weight and optimum moisture content of clayey soil is decreased with increasing percentage of crumb rubber. For example, the max. dry unit weight of the mix containing 3% cement and 2.5% rubber and mix containing 3% rubber and 10% rubber is 15.84 kN/m^3 and 14.827 kN/m^3, respectively. Similarly, the maximum dry unit weight of mix containing 6% cement and 2.5% rubber and mix containing 6% rubber and 10% rubber is 15.65 kN/m^3 and 14.67 kN/m^3, respectively. A reduction of 10.20% and 11.62% in the maximum dry unit weight is observed with the inclusion of 10% rubber in the clayey soil stabilized with 3% and 6% cement content as compared to clay alone. Decrease in compaction parameters is ascribed to the loss of compaction efficiency (elastic response of rubber during compaction), low specific gravity and low water absorption capacity of crumb rubber [4][27]. Conventional fill materials (soil or sand) have unit weight ranging from 16 to 21 kN/m^3. A comparison of unit weights between composite obtained using cement-stabilized clay containing rubber and clayey soils revealed that the lightweight feature would be, advantageous for sites containing cohesive soils with high unit weight in particular, when the weight of fill needs to be lowered.

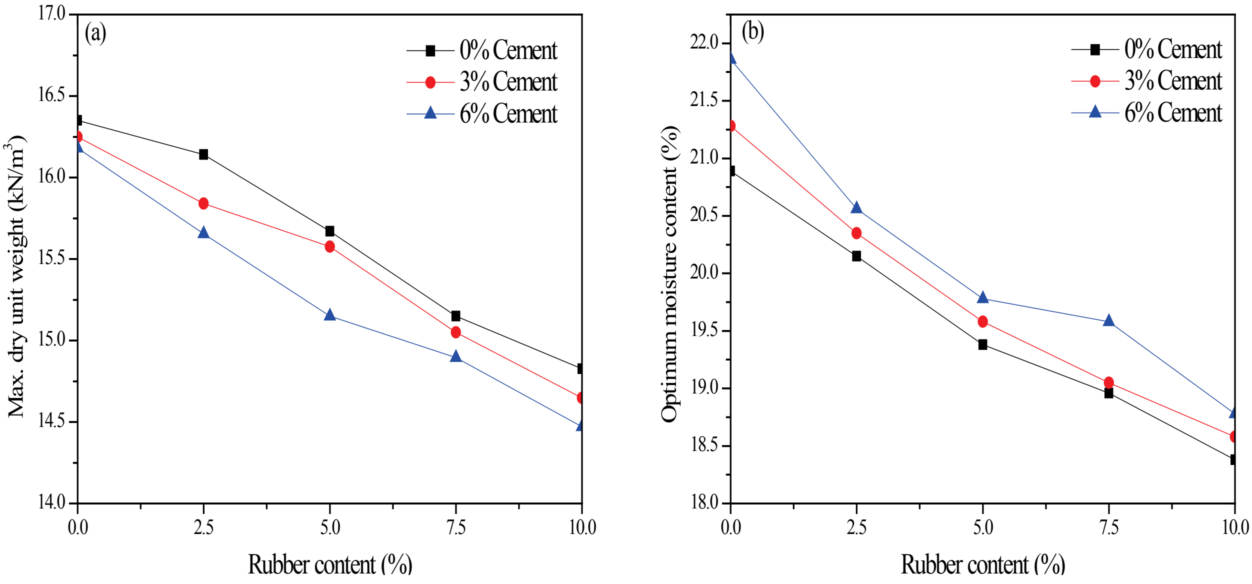

Fig. 4- Effect of cement and rubber content on the (a) maximum dry unit weight; (b) optimum moisture content

4.2 Effect of cement and crumb rubber on the UCS

Fig. 5 illustrates the effect of cement and crumb rubber on the UCS values of the clayey soil. As the cement content increases, the UCS value of clayey soil increases. The UCS value of 28 cured, clayey soil samples stabilized with 3% and 6% cement increased from 60.62 kPa to 222.05 kPa and 407.91 kPa respectively, which is 3.66 and 6.72 times more than clayey soil. The formation of hydration products such as calcium silicate hydrate gel enhances the bond strength, which ultimately results in increasing the UCS value but makes the composite brittle.

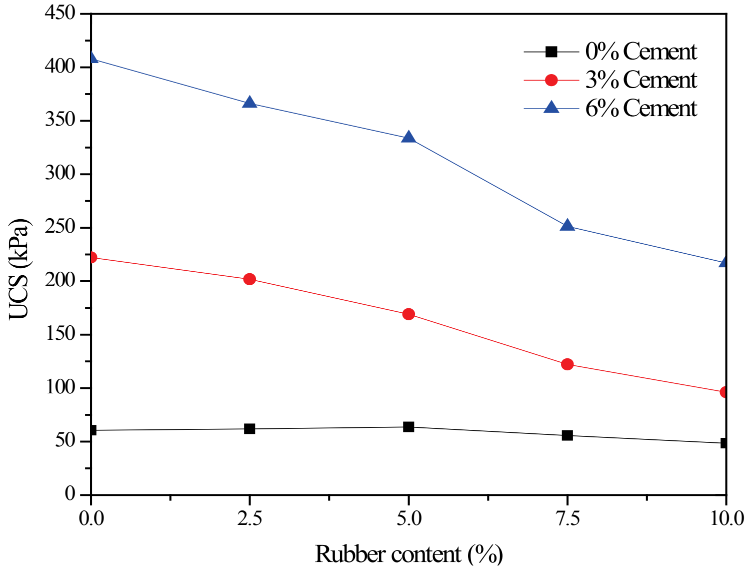

Fig. 5- Effect of cement and rubber content on the UCS of the 28 days cured specimens.

UCS value of uncemented clayey soil increases slightly from 60.62 kPa to 63.71 kPa with the inclusion of 5% crumb rubber. After that, it decreases vigorously with the addition of 7.5% and 10% rubber content. The reason for this decline can be attributed to the increase in rubber particle-to-particle interaction. When crumb rubber is added to the cemented clayey soil samples, the UCS is decreased with the increase in percentage of rubber content from 0% to 10%. It is found that UCS values decrease from 201.89 kPa to 96.22 kPa and 366.13 kPa to 217.11 kPa for specimens containing 3% and 6% cement and 2.5% and 10% rubber content respectively. The reduction in UCS value is due to (i) non-polar nature of crumb rubber, which have tendency to entrap air during mixing resulted into formation of voids within the specimens; (ii) negligible load carrying capacity of crumb rubber in comparison to cemented clay resulted into non-uniform rate of deformability under compressive load [17] . These results are contrary to the work carried out by Otoko and Perdo [19] on cemented clayey soil incorporated with waste rubber fibres.

Table 2 and Table 3 give the summary of UCS and axial strain at the failure of the specimens cured for 7, 14 and 28 days. UCS value increases with curing period and cement content but decreases with increase in rubber content. The increase in the UCS values may be attributed to the relative increase in cement per grain contact point and the formation of secondary cementitious products. The increase in the relative volume occupied by crumb rubber and dominance of interaction between rubber-to-rubber particles over the rubber particles to hydration products and clay seem to be the possible reasons for the decrease in the UCS value as rubber content increases.

It is observed from Table 3 that the axial strain of the composite is increased with the increasing the percentage of crumb rubber up to 5%. After that, it decreases as rubber content increases from 7.5% to 10%. Table 3 further reveals that the axial strain increases with the increasing of the curing period.

Table 2- Variation of UCS (kPa) of the specimens cured for 7, 14, and 28 days

Cement content	**3%**					**6%**				
Crumb rubber content	**0%**	**2.5%**	**5.0%**	**7.5%**	**10.0%**	**0%**	**2.5%**	**5%**	**7.5%**	**10.0%**
Curing period (days)										
7	175.08	164.40	131.07	99.97	70.70	374.44	279.54	248.40	195.06	173.08
14	204.97	184.07	146.84	114.80	81.58	397.45	342.26	321.30	228.13	198.85
28	222.05	201.89	168.96	122.14	96.22	405.09	366.13	333.85	251.36	217.11

Table 3- Variation of axial strain (%) at failure of the specimens cured for 7, 14, and 28 days

Cement content	**3%**					**6%**				
Crumb rubber content	**0%**	**2.5%**	**5.0%**	**7.5%**	**10.0%**	**0%**	**2.5%**	**5%**	**7.5%**	**10.0%**
Curing period (days)										
7	2.63	2.63	4.61	3.95	3.29	4.61	4.61	4.61	4.61	3.95
14	2.63	3.29	5.26	4.61	3.95	4.61	4.61	5.26	5.26	4.61
28	3.29	3.29	5.92	4.61	3.95	5.26	5.26	5.92	5.26	4.61

4.3 Effect of cement and crumb rubber on the STS

Fig. 6 shows the effect of cement and crumb rubber on the STS value of clayey soil. It follows the similar trend as in UCS test. The results of STS tests are summarized in Table 4 and 5. STS value of 28 cured, cemented clayey soil sample containing 3% and 6% cement increased from 14.99 kPa to 80.28 kPa and 141.67 kPa respectively, which is 5.35 and 9.45 times more than clayey soil.

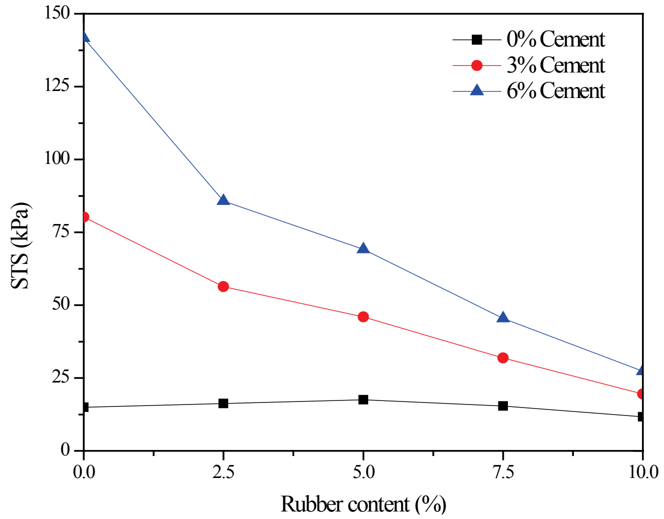

Fig. 6- Effect of rubber content on the STS of the 28 days cured specimens

The diametral strain of the cemented clayey soil is increased from 7.97% to 10.50% with the increasing cement content increases from 3% to 6%. This is an indication that cementation of clayey soil is more efficient under tension in comparison to compression. The reduction in diametral strain in tension is on the same guidelines as of axial strain in compression but the rate of reduction in diametral strain is more. The reduction of diametral strain at the time of failure can be attributed to the sliding of the rubber particle, which is not restricted by the interfacial mechanical interaction between rubber and cemented clay particles [27].

Table 4- Variation of STS (kPa) of the specimens cured for 7, 14, and 28 days

Cement content	**3%**					**6%**				
Crumb rubber content	**0%**	**2.5%**	**5.0%**	**7.5%**	**10.0%**	**0%**	**2.5%**	**5%**	**7.5%**	**10.0%**
Curing period (days)										
7	63.11	41.89	31.45	22.04	14.22	84.48	54.53	48.97	30.29	19.19
14	71.25	49.90	39.89	28.5	18.44	126.09	72.70	58.78	40.39	25.81
28	80.28	56.372	45.99	31.86	19.49	141.67	85.70	69.13	45.44	27.29

Table 5- Variation diametral strain (%) at failure of the specimens cured for 7, 14, and 28 days.

Cement content	**3%**					**6%**				
Crumb rubber content	**0%**	**2.5%**	**5.0%**	**7.5%**	**10.0%**	**0%**	**2.5%**	**5%**	**7.5%**	**10.0%**
Curing period (days)										
7	5.25	3.94	3.94	2.62	2.62	7.97	5.25	6.66	5.25	2.62
14	6.66	3.94	5.25	2.62	2.62	9.29	6.66	7.97	5.25	3.94
28	7.97	5.25	5.25	3.94	3.94	10.50	7.97	7.97	6.66	3.94

4.4 Effect of cement and rubber content on the Toughness Index

The toughness index (TI) is a measure of stress-strain energy to complete failure of the material. It exhibits the behaviour of the material in the post-peak region. If the material is brittle in nature, the TI is zero. It is calculated using the equation from a typical stress-strain diagram [28] as shown in Fig. 7:

$$TI = \frac{Ae-Ap}{\varepsilon-\varepsilon p} \quad (2)$$

Where Ae = area under the stress- strain curve up to strain Ɛ; Ap = area under the stress- strain curve up to strain Ɛp; Ɛp= strain corresponding to peak strain; Ɛ = strain at the point of failure.

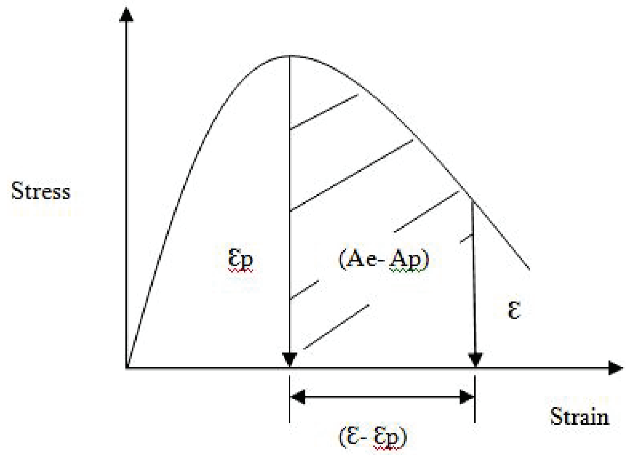

Fig. 7- Typical Stress-strain curves for calculation of TI

Fig. 8 illustrates the effect of rubber content on TI for 28 days cured specimens under (a) UCS and (b) STS tests. It can be seen from Fig. 8(a) that the TI of 3% and 6% cemented clayey soil sample are zero, which indicates that there is no post –peak load and material is brittle in nature. With the inclusion of crumb rubber up to 5% in both 3% and 6% cemented clayey soil samples, the TI increases after that it decreases. It also increases with an increase in cement content. Interestingly, TI of specimens having 6% cement and 2.5% crumb rubber the TI is zero. These results indicate that up to 5% crumb rubber content has a potential to resist the sudden failure of the material. Fig. 8(b) reveals the variation of TI for 28 days cured specimens under STS tests. The variation of TI follows the same guidelines as for UCS tests. TI values in STS tests are comparatively lower that than of UCS tests, which indicate that crumb rubber, have the lesser potential to resist the tensile cracks.

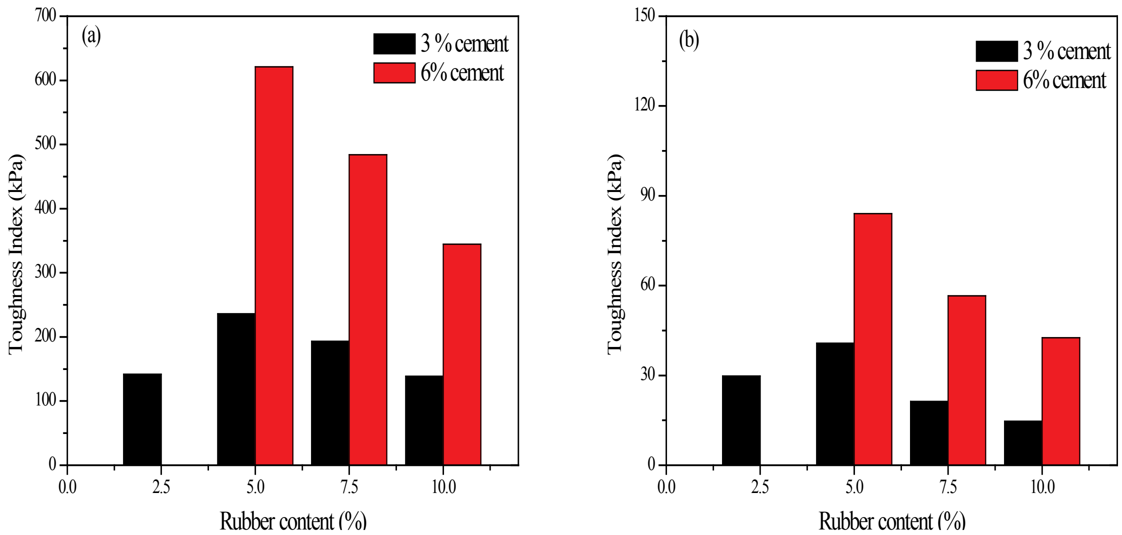

Fig. 8- The effect of cement and rubber content on TI for 28 days cured specimens under (a) UCS; (b) STS test.

4.5 Effect of cement and crumb rubber on the failure characteristics

The failure characteristics of the specimens under UCS test are illustrated in Fig 9. It is observed that the addition of cement and crumb rubber have a momentous influence on the failure characteristics of the composite. Long and broad vertical cracks are seen in the cemented clayey soil samples, which are responsible for the catastrophic failure of the samples as shown in Fig. 9(b). With the inclusion of crumb rubber in cemented clayey soil, big cracks vanishes and multiple cracks appear instead of it with the addition of 5% rubber in 3% cement treated clayey soil, which improves the post-peak strength in compression. The formation of multiple cracks is due to (i) evolution of tensile stress on the surface of rubber particle; (ii) soft aggregate like behaviour of crumb rubber in the specimens; (iii) lower young's modulus of the crumb rubber as compare to cemented clay specimens [29]. Staggered cracks are observed in specimens containing 7.5% crumb rubber and 6% cement in clayey soil (Fig. 9(d)).

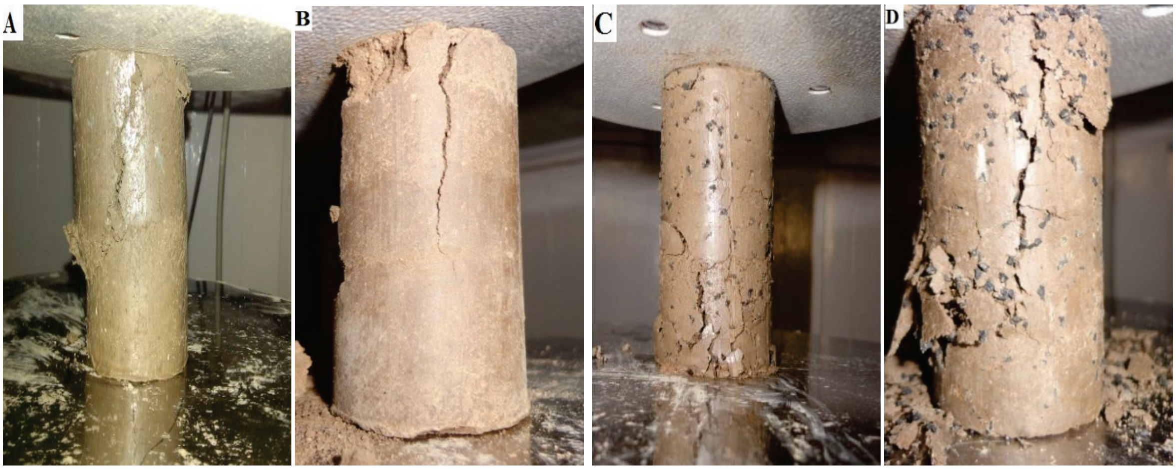

Fig. 9- Effect of cement and rubber content on the failure characteristics in compression: (a) clayey soil; (b) 6% cement –modified clayey soil; (c) 5% rubber and 3% cement –modified clayey soil; (d) 7.5% rubber and 6% cement- modified clayey soil

Fig. 10(a) shows the failure characteristics of 6% cement modified clayey soil in tension. Failure along the central vertical plane is observed. Numerous multiple cracks are observed in specimens containing 3% cement and 5% rubber, which is responsible for the marginal improvement in the post-peak region.

Fig. 10- Effect of cement and rubber content on the failure characteristics in tension: (a) 6% cement-modified clayey soil; (b) 5% rubber and 3% cement –modified clayey soil.

4.6 Effect of cement and crumb rubber on the CBR value

Fig. 11(a)-(b) presents the effect of crumb rubber and cement content on the CBR value of clayey soil in both Unsoaked and soaked conditions. CBR value of clayey soil steadily decreases with the increase in percentage of rubber content for both the conditions. CBR value decreased from 10.59% to 6.86% with the addition of crumb rubber from 0% to 10% in unsoaked conditions. The decline in the CBR value is due to the high compressibility of crumb rubber particles, which lower the resistance to the penetration. As can be seen in Fig 9, the cement content increases the CBR value of clayey soil. CBR values of cemented clayey soil in soaked condition are found to be more than the unsoaked conditions. With the inclusion of crumb rubber in the cemented clay, the CBR value decreases as the rubber content increases.

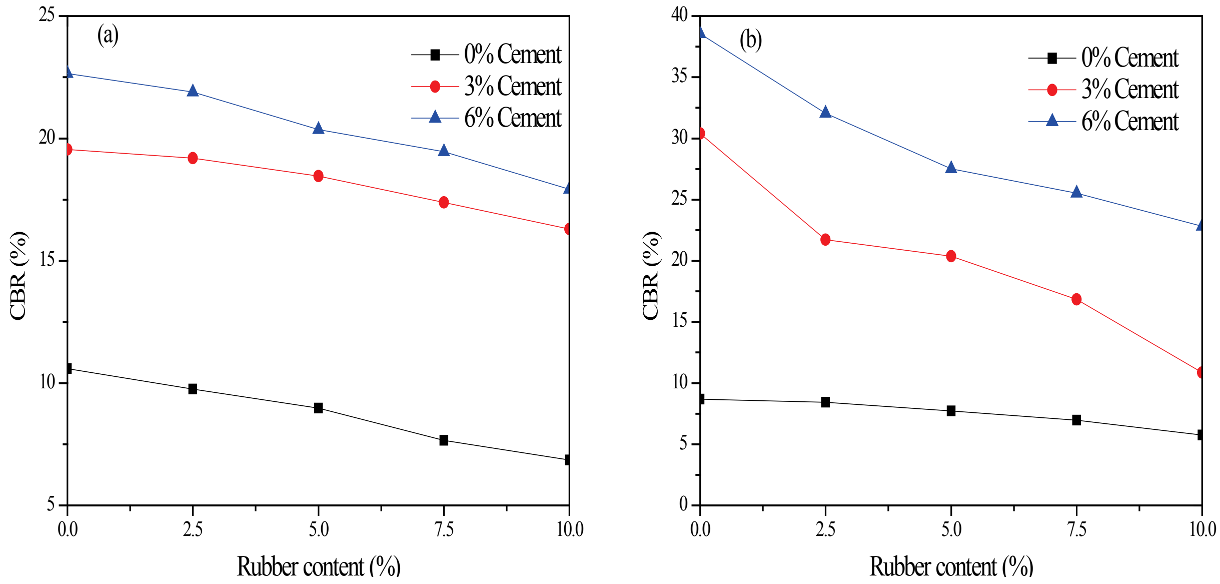

Fig. 11- Effect of rubber content the CBR values (a) Unsoaked condition (b) Soaked conditions

4.7 Effect of cement and crumb rubber on the swelling pressure

Fig. 12 illustrates the effect of cement and crumb rubber on the swelling pressure of clayey soil. The swelling pressure of clayey soil steadily decreases with increase in the cement and crumb rubber content. With the addition of 3% and 6% cement, the swelling pressure decreases from70 kPa to 45.53 kPa and 26 kPa respectively. The formation of cementation bond in the material is the possible reason for the retardation in swelling pressure. Inclusion of crumb rubber reduces the swelling pressure too. The formation of drainage path for the dissipation of pore pressure in the composite reduces the swelling pressure [14]. More encouraging results are obtained for controlling the swelling pressure when both cement and crumb rubber is incorporated with the clayey soil.

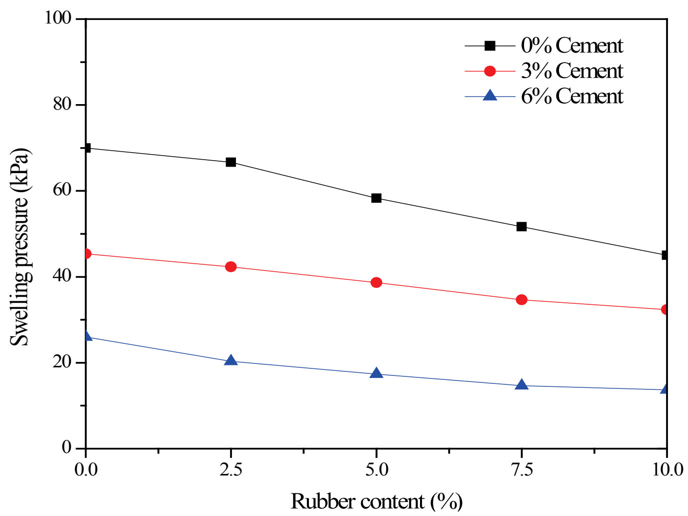

Fig. 12- Effect of rubber content on the swelling pressure

4.8 SEM analysis

Fig. 13 shows the SEM micrographs of the cement-rubber modified clayey soil. The dark portions represent the void in the sample. The compacted clayey soil samples containing more voids are shown in Fig. 13(a). The cementitious products such as C-S-H gel can be clearly seen in Fig. 13(b), of clayey soil containing 6% cement. The porous spaces of clayey soil are filled by cementitious products, which increase the strength of the clayey soil. The presence of a gap at the interface of the cemented clayey soil and rubber particle can be visualized in Fig. 13(c) results in lowering the strength of the specimen.

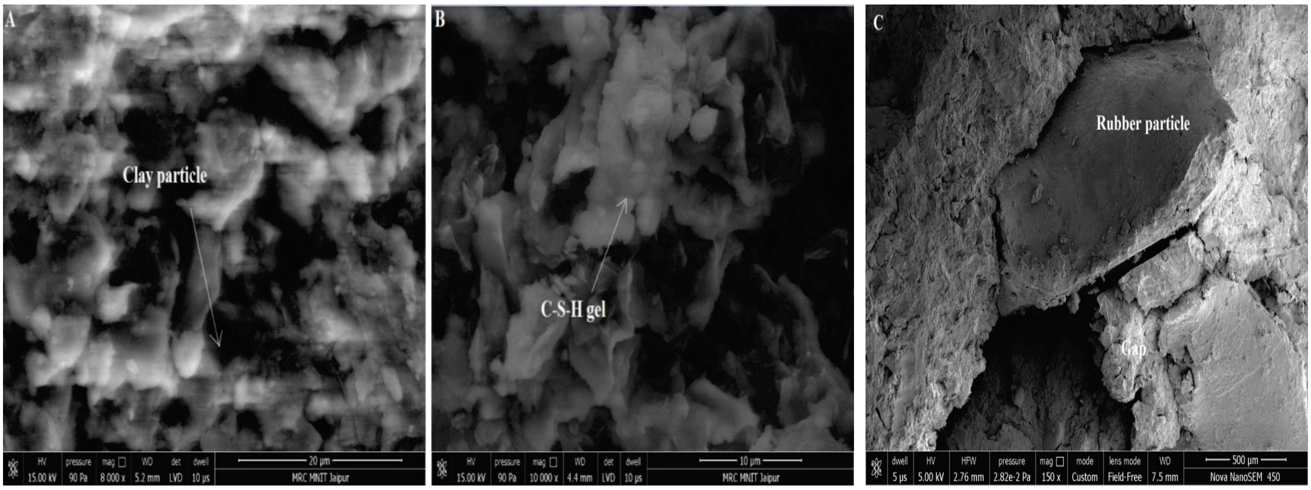

Fig. 13- SEM images of cement-rubber-modified clayey soil with (a) clayey soil only; (b) 6% cement; (c) 5% rubber and 6% cement.

5 Conclusions

The conclusions derived from this investigation are as follows:

- ✓ The cement, crumb rubber and cement-crumb rubber mixtures decreased the maximum dry unit weight. Although the optimum moisture content of the clayey soil increased with increasing the cement. It is observed that it decreases as the rubber content increases.
- ✓ The UCS and STS test results indicated that the addition of crumb rubber in the cemented clayey soil decreases the UCS. The axial and diametral strain increases with the increase in rubber content up to 5% after that it starts decreasing, but the rate of reduction in diametral strain is more.
- ✓ Maximum TI values are obtained by addition of 5% crumb rubber in the cemented clayey soil in both compression and tension. TI values in STS tests are comparatively lower that than of UCS tests.
- ✓ CBR values and swelling pressure decrease with the addition of crumb rubber in the cemented clayey soil. Soaked CBR values of crumb rubber-cement clayey soil are more than that of unsoaked CBR values.
- ✓ Visualization of the SEM showed that the pores of compacted clayey soil are filled with the cement and a gap at the interface of the rubber particle and rest of the composite.
- ✓ The test result reveals that the crumb rubber and cement have significance on improving the engineering properties of clayey soil for geotechnical application point of view. It has positive effects on the improving the post- peak strength in both tension and compression. The combination of cemented clay incorporated with crumb rubber helps to control swelling pressure more efficiently.

Hence, it is concluded that the crumb rubber (up to 5%) and cement can be used for improving the geotechnical properties of the clayey soil. In addition, the incorporation of crumb rubber in the cemented clayey soil potentially reduces the reinforcement cost and solves the problem associated with its disposal. The enormous utilization of waste crumb rubber for improving geotechnical properties of uncemented/cemented clay helps to solve the health and environmental problems associated with the disposal of this hazardous waste.

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