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Consistency limits and compaction characteristics of clay soils containing rubber waste

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The aim of the study reported in this paper was to develop practical correlative models capable of predicting the compaction characteristics of clay soils blended with rubber from waste vehicle tyres. Four different clay soils, ranging from intermediate to high plasticity, were adopted for the test programme and each was blended with four different percentages of ground rubber waste. The test programme consisted of cone penetration (consistency limits) and standard Proctor compaction tests. As a result of ground rubber inclusion, the consistency limits and compaction characteristics all exhibited a linear decreasing trend with increase in rubber content. The rate of decrease, however, was greater for the high-plasticity clays. Simple correlative models, linking the compaction characteristics to the consistency limits, were suggested and validated by statistical techniques. The proposed models provide a practical procedure towards predicting the compaction characteristics of ground rubber–clay blends without the hurdles of conducting laboratory compaction tests, and thus can be implemented in practice for preliminary assessments.

Notation

G_{sm}	average specific gravity of ground rubber–clay mix
G_{sr}	specific gravity of ground rubber
G_{ss}	specific gravity of soil solids
I_F	flow index
I_P	plasticity index
R^2	coefficient of determination
R_c	rubber content (by weight)
R_c^M	median rubber content
w	water content
w_L	liquid limit
w_{opt}	optimum water content
w_P	plastic limit
w_P^M	plastic limit corresponding to R_c^M
w_{Po}	plastic limit for the virgin clay
γ_d	dry unit weight
γ_{dmax}	maximum dry unit weight
γ_{dP}	dry unit weight at plastic limit
γ_w	unit weight of water
δ	cone penetration
η	coefficient of plastic limit reduction
χ	average ratio of I_P to I_F

1. Introduction

The design and construction of geotechnical structures often necessitate incorporating low-graded clay soils, with high moisture susceptibility (and plasticity) and low bearing capacity, in the construction. Common solutions to counteract the adversities associated with such soils include soil replacement

(i.e. replacing the poor-quality clay soil with desired quarried materials) or attempting to improve the problematic soil by means of stabilisation techniques. Currently, two stabilisation schemes are in vogue for clay soils – namely, chemical and mechanical stabilisation (Soltani *et al.*, 2017a). The chemical scheme makes use of chemical binders, which initiate a series of short- and long-term chemical reactions in the clay–binder medium, thereby amending the soil fabric into a coherent matrix of improved mechanical performance. Common binders include agents of traditional (e.g. cement, lime and fly ash) or non-traditional (e.g. polymers, resins and sulfonated oils) categories, both of which have been well documented in the literature (e.g. Estabragh *et al.*, 2013, 2014; Georgees *et al.*, 2015; Jha and Sivapullaiah, 2016; Mirzababaei *et al.*, 2009; Soltani *et al.*, 2017b). The mechanical technique often involves the placement of randomly or specifically engineered reinforcements (e.g. natural and synthetic fibres) in the soil regime, thereby engendering a spatial three-dimensional reinforcement network in favour of weaving (or interlocking) the soil grains into a unitary mass of improved mechanical performance (e.g. Estabragh *et al.*, 2016; Mirzababaei *et al.*, 2017, 2018; Soltani *et al.*, 2018a; Tang *et al.*, 2010; Wang *et al.*, 2017). Lately, many developed and developing countries have initiated the transition towards ‘sustainable infrastructure’, a concept which fosters the beneficial reuse of solid wastes and/or industrial by-products as a replacement for conventional quarried materials (such as sand) and/or stabilisation agents, thereby conserving natural resources as well as reducing the level of greenhouse gas emissions. Promising replacements, based on recent studies, include recycled tyre rubbers, waste textiles,

demolition wastes, kiln and quarry dusts, and silicate/calcium geopolymers (e.g. Al-Amoudi *et al.*, 2017; Alazigha *et al.*, 2016; Arulrajah *et al.*, 2017; Kua *et al.*, 2017; Mirzababaei *et al.*, 2013a, 2013b; Soosan *et al.*, 2005).

Waste tyre rubbers are being generated at an increasing rate throughout the world. Such materials are bulky in nature, owing to their low weight-to-volume ratio, and thus consume valuable landfill space upon disposal. As such, local communities and governmental agencies have been increasingly encouraged to recycle and hence reuse waste tyres as part of the infrastructure system. The rubber–soil blend is showing great promise in several respects – for example, reduced unit weight, enhanced strength and ductility, increased permeability and reduced moisture susceptibility (i.e. swell–shrink capacity), which can facilitate the production and placement of sustainable earth fills such as road and railway embankments (e.g. Cabalar *et al.*, 2014; Cetin *et al.*, 2006; Özkul and Baykal, 2007; Perez *et al.*, 2017; Signes *et al.*, 2016; Soltani *et al.*, 2018b, 2018c; Srivastava *et al.*, 2014; Trouzine *et al.*, 2012; Wang *et al.*, 2018; Yadav and Tiwari, 2017a, 2017b). When placed in a flowable condition, the rubber–soil blend outperforms conventional soil backfills by enabling the placement of particles into any irregular or inaccessible space without significant compaction efforts (ACI R229 (ACI, 2013)). The advantages of rubber-mixed soils in engineering performance, which natural soils rarely exhibit, suggest a promising path towards sustainability without compromising performance. Although these materials are promising, the leaching of heavy metals from rubber particles (into the soil mass and/or water bodies) could raise some environmental concerns. In such cases, most documented studies have reported that the degree of soil and water contamination both remain within the allowable limits provided by various health and environmental agencies. When paired with coarse-grained soils, however, the rubber–soil blend should be stabilised by means of chemical binders to meet the required environmental standards (see Yadav and Tiwari (2017c) for more details).

A review of the literature indicates a rather common emphasis on the application of coarse-grained tyre rubber material in the form of fibres, shreds and aggregates. Such materials, however, would be associated with implementation difficulties when dealing with cohesive clay soils (e.g. mixing difficulties and hence non-uniform distribution of rubber particles in the soil regime). As such, types of recycled tyres less often considered for this purpose, such as fine ground rubber (GR), offer the advantage of better workability, and thus demand further investigation. Quite clearly, a vital step towards the production and placement of suitable rubber–clay earth fills is compaction. In this context, the maximum dry unit weight has been reported to decrease with increase in rubber content, while the reported trends for optimum water content still remain rather inconsistent (e.g. Al-Tabbaa *et al.*, 1997; Cetin

et al., 2006; Kalkan, 2013; Priyadarshee *et al.*, 2018; Seda *et al.*, 2007). In comparison, limited studies (e.g. Cetin *et al.*, 2006; Srivastava *et al.*, 2014; Trouzine *et al.*, 2012) have been conducted on the consistency limits, the results of which have yet been systematically correlated with other geotechnical properties such as the compaction characteristics. With rubber–soil blends gaining ground as a viable geomaterial in practice, the need for an efficient and simple tool to adequately predict its performance, in terms of compaction, arises as an inevitable necessity. If developed, such a predictive toolbox would help the practising engineer to arrive at reliable rubber–soil design choices without the hurdles of conducting time-consuming laboratory compaction tests. Although numerous attempts have been made to correlate the compaction characteristics with the consistency limits for natural fine-grained soils (e.g. Blotz *et al.*, 1998; Di Matteo *et al.*, 2009; Gurtug and Sridharan, 2002, 2004; Gurtug *et al.*, 2018; Nagaraj *et al.*, 2015; Pandian *et al.*, 1997; Pillai and Vinod, 2016; Sivrikaya *et al.*, 2008; Sridharan and Nagaraj, 2005), such correlative models have yet to be developed for rubber-mixed soils.

In this study, a series of cone penetration (consistency limits) and standard Proctor compaction tests were carried out on various ground rubber–clay (GRC) blends (prepared with four different clay soils) to generate a reliable database allowing for the development of simple correlative models capable of predicting the compaction characteristics of GRC blends as a function of the composite's consistency limits. The models proposed in the present study provide a practical procedure towards predicting the compaction characteristics of GRC blends without the need for conducting time-consuming compaction tests.

2. Materials

2.1 Clay soils

Four different soils consisting of both natural and commercial soils, covering a wide range of plasticity characteristics, were adopted for the experimental programme. The natural soils, hereafter denoted as soils RC1 and RC2, consisted of reddish-brown clays sourced from a landfill site located at Adelaide, South Australia. The commercial soils were supplied by a local manufacturer, and included kaolinite (hereafter termed soil K) and a mixture of 85% kaolinite and 15% sodium-activated bentonite (hereafter termed soil KB). The physical and mechanical properties of the soils, determined as per relevant ASTM and Australian standards, are summarised in Table 1. The liquid limit w_L and plasticity index I_P were measured as $w_L = 44\%$ and $I_P = 22\%$ for soil K, and $w_L = 47\%$ and $I_P = 29\%$ for soil RC1, from which both soils were characterised as 'clay with intermediate plasticity' (CI) in accordance with the Unified Soil Classification System (USCS). The soils KB and RC2, however, were graded as 'clay with high plasticity' (CH), exhibiting w_L and I_P values of 59% and 31% for soil KB, and 78% and 57% for soil RC2, respectively.

Table 1. Physical and mechanical properties of the clay soils

Properties	Soil K	Soil RC1	Soil KB	Soil RC2	Standard designation
Specific gravity, G_{ss}	2.69	2.67	2.71	2.72	ASTM D854-14 (ASTM, 2014)
Grain-size distribution					
Clay (<2 μm): %	49	37	53	44	ASTM D422-07 (ASTM, 2007)
Silt (2–75 μm): %	50	32	46	36	
Fine sand (0.075–0.425 mm): %	1	19	1	14	
Medium sand (0.425–2 mm): %	0	8	0	5	
Coarse sand (2–4.75 mm): %	0	5	0	1	
Consistency limits and classification					
Liquid limit, w_L : %	44	47	59	78	AS 1289-3-9-1-15 ^a (SA, 2015)
Plastic limit, w_P : %	22	18	28	21	AS 1289-3-2-1-09 ^b (SA, 2009)
Plasticity index, $I_P (= w_L - w_P)$: %	22	29	31	57	AS 1289-3-3-1-09 (SA, 2009)
USCS classification	CI ^c	CI	CH ^d	CH	ASTM D2487-11 (ASTM, 2011)
Compaction characteristics					
Optimum water content, w_{opt} : %	21	16	25	19	ASTM D698-12 (ASTM, 2012)
Maximum dry unit weight, γ_{dmax} : kN/m^3	15.45	16.41	14.61	15.84	

^aCone penetration method (see Section 3.1 for details)

^bConventional rolling thread method (see Section 3.1 for details)

^cClay with intermediate plasticity

^dClay with high plasticity

2.2 Ground rubber

Commercially available GR, supplied by a local distributor, was used as the reinforcing agent. The conventional grain-size (or sieve) analysis, carried out in accordance with the ASTM D422-07 (ASTM, 2007) standard, indicated that GR is similar in size to medium-fine sand, with particles ranging between 1.18 mm and 75 μm . The particle diameters corresponding to 10, 30 and 60% finer were measured as $D_{10} = 0.182$ mm, $D_{30} = 0.334$ mm and $D_{60} = 0.513$ mm. The uniformity (i.e. $C_u = D_{60}/D_{10}$) and curvature (i.e. $C_c = D_{30}^2/D_{10}D_{60}$) coefficients were therefore obtained as $C_u = 2.81$ and $C_c = 1.20$, from which GR was classified as ‘poorly graded’ in accordance with the USCS criteria. Figure 1 depicts microscopic micrographs of the rubber particles at three different magnification ratios

(Figure 1(a): $1\times$ magnification; Figure 1(b): $50\times$ magnification; and Figure 1(c): $200\times$ magnification). As shown in Figure 1(b), the rubber particles are non-spherical and highly irregular in shape. Moreover, a series of cavity-like micro-cracks are distributed along the rubber’s surface (see Figure 1(c)), thus making for a rough surface texture. Such surface features may potentially promote adhesion and/or induce interfacial friction between the rubber particles and the soil grains, thereby altering the soil fabric into a coherent matrix of enhanced mechanical performance (Soltani *et al.*, 2018b). The physical properties and chemical composition of GR, as supplied by the manufacturer, are provided in Table 2. The specific gravity of GR was found to be $G_{sr} = 1.09$, which is lower by two-fold approximately than the standard value of $G_{ss} = 2.65$ reported for most soils.

Figure 1. Ground rubber (GR) particles at different magnification ratios (modified from Soltani *et al.*, 2018b): (a) $1\times$ magnification; (b) $50\times$ magnification; (c) $200\times$ magnification

Table 2. Physical properties and chemical composition of GR

Properties	Value/description
Physical properties	
Solubility in water	Insoluble
Water adsorption	Negligible (<4%)
Resistance to acid/alkaline	Excellent
Softening point: °C	170
Specific gravity, G_{sr}	1.09
Grain-size distribution and classification ^a	
D_{10} : mm ^b	0.182
D_{30} : mm	0.334
D_{50} : mm	0.478
D_{60} : mm	0.513
Coefficient of uniformity, C_u ^c	2.81
Coefficient of curvature, C_c ^d	1.20
USCS classification	Poorly graded sand (SP)
Chemical composition	
Styrene–butadiene copolymer: %	55
Acetone extract: %	5–20
Carbon black: %	25–35
Zinc oxide: %	2–3
Sulfur: %	1–3

^aASTM D422-07 (ASTM, 2007) method

^bParticle diameter corresponding to 10% finer

^c $C_u = D_{60}/D_{10}$

^d $C_c = D_{30}^2/D_{10}D_{60}$

3. Test programme

Each of the four soil choices – namely, soils K, RC1, KB and RC2 – was blended with GR at four varying rubber contents (defined as GR to dry soil weight ratio) – that is, $R_c = 5, 10, 20$ and 30% – and further tested for consistency limits and compaction characteristics. Hereafter, a simple coding system, defined as KR x , RC1R x , KBR x and RC2R x (where R $x = x\%$ GR), will be adopted to designate the various mix designs. As a consequence of rubber particles floating in water, standard procedures outlined in ASTM D854-14 (ASTM, 2014) for measuring the specific gravity of solids were not applicable. Therefore, the specific gravity for various GRC blends was estimated by the following theoretical relationship (Soltani *et al.*, 2018b)

$$1. \quad G_{sm} = \frac{G_{ss}G_{sr}(W_s + W_r)}{W_sG_{sr} + W_rG_{ss}}$$

where G_{sm} is the average specific gravity of GRC blends; W_s is the weight of dry soil; W_r is the weight of GR; G_{ss} is the specific gravity of soil solids (see Table 1); and G_{sr} is the specific gravity of GR particles (= 1.09).

3.1 Consistency limits

The virgin clays and various GRC blends were tested for consistency limits – namely, the liquid limit w_L , plastic limit w_P and plasticity index I_P ($= w_L - w_P$), following the Australian code of practice (see relevant standard designations in Table 1). The liquid limit was obtained by means of the cone

penetration method. The weight and conical angle of the cone were 80 g and 30° , respectively. The required amount of material (either virgin or GR-blended clay) was divided into six equal portions, each portion paired with a predetermined amount of water, and thoroughly mixed by mechanical effort to obtain slurries of uniform consistency. The resulting slurries were then remoulded into rigid cups, measuring 53 mm in diameter and 40 mm height, and placed in contact with the cone penetrometer for testing. The cone was allowed to freely penetrate into each sample for approximately 5 s. The depth of penetration was measured by means of a digital dial gauge to the nearest 0.1 mm. As a result of the test, a linear change in water content w against the corresponding cone penetration δ , commonly referred to as the flow curve, can be observed. Test results are plotted over the w – $\log_{10}\delta$ space, the slope of which is defined as the flow index – that is, $I_F = \Delta w / \Delta \log_{10}\delta$ (Sridharan *et al.*, 1999). Furthermore, the water content at which the cone penetration reaches $\delta = 20$ mm is taken as the liquid limit.

The rolling thread method is currently in vogue for direct measurement of the plastic limit. The water content at which a mass of soil (or material) begins to crumble when manually rolled into a thread of approximately 3.2 mm (dia.) is taken as the plastic limit. Quite clearly, the rolling thread method is highly subjective and therefore inevitably biased by personal judgements, which leads to inconsistent and often non-reproducible results among different operators. Moreover, it has been the authors' experience that this particular methodology would not be suitable for geomaterials containing notable non-plastic hydrophobic (i.e. low water adsorption capacity) fractions (despite the geomaterial's plastic response in the presence of water). The rubber's elastic character and hydrophobic nature make for a rather difficult, although possible, implementation of the conventional rolling thread technique. Although the rubber inclusion would most certainly lead to a reduced plastic limit, it is not possible to arrive at a certain/unique value with confidence following the current methodology. Such difficulties are essentially similar to those encountered for natural soils containing notable fractions of sand and silt, which have been well documented in the literature (e.g. Prakash and Sridharan, 2006, 2012). Among the available experimental alternatives for indirect measurement of the plastic limit, the flow index method suggests a rather practical and objective scheme, which is also supported by robust empirical observations as well as solid fundamental evidence (see Sridharan *et al.* (1999) for details). The flow index method states that the plasticity index is proportional to the flow index (obtained from the cone penetration test) – that is, $I_P \propto I_F$ and thus can be estimated by

$$2. \quad I_P = \chi I_F$$

where χ = empirical coefficient.

Therefore, the plastic limit can be estimated with a known liquid limit (obtained from the cone penetration test) by

$$3. \quad w_P = w_L - \chi I_F$$

The empirical coefficient χ falls between 0.71 and 0.74, which was calibrated based on conventional rolling thread tests conducted on 121 soil samples of widely varying plasticity characteristics and geological origin (Sridharan *et al.*, 1999). As a typical example, and to provide further verification of $\chi = 0.71\text{--}0.74$, Figure 2 illustrates the variations of the plasticity index I_P ($I_P = w_L - w_P$ where w_P = plastic limit obtained by the rolling thread method) against the flow index I_F for the virgin clays used in the present study. As demonstrated in the figure, a perfect correlation in the form of $I_P = 0.715 I_F$ (with $R^2 = 0.997$) can be obtained between the plasticity and flow indices, which complies well with that suggested by Sridharan *et al.* (1999). Therefore, to avoid the difficulties associated with implementing the conventional rolling thread technique to various GRC blends, the plastic limit for both the virgin clays and various GRC blends was estimated by means of Equation 3 (with $\chi = 0.715$). Hereafter, the term plastic limit will refer to that obtained by means of the flow index method.

3.2 Compaction studies

Standard Proctor compaction tests were carried out on the virgin clays and various GRC blends in accordance with the ASTM D698-12 (ASTM, 2012) standard. The required amount of material (either virgin or GR-blended clay) was divided into six equal portions, each portion paired with a pre-determined amount of water, and thoroughly mixed by hand. Extensive care was taken to pulverise the lumped particles, aiming for homogeneity of the mixtures. The moist mixtures

Figure 2. Variations of the conventional plasticity index plotted against the flow index for the virgin clays

were sealed in plastic bags and allowed to cure for a period of 24 h, ensuring even distribution of moisture throughout the composite mass. The cured mixtures were then subjected to the conventional standard Proctor compaction test to arrive at the dry unit weight–water content relationship, and thus quantify the optimum water content and the maximum dry unit weight.

4. Statistical analysis

The consistency limits, obtained as per Section 3.1, were each independently plotted against the corresponding optimum water contents, and further examined for single-coefficient linear correlations – that is, $w_{opt} = \beta x$ (w_{opt} is the optimum water content; $x = w_L$, w_P or I_P ; and β is the regression coefficient or fitting parameter). The most appropriate consistency parameter (capable of adequately estimating the optimum water content for various GRC blends) was then selected and coupled with basic volume–mass relations to arrive at a semi-empirical relationship for the maximum dry unit weight. The accuracy of the proposed correlative models for both the optimum water content and the maximum dry unit weight was then examined by means of statistical fit-measure indices.

5. Results and discussion

5.1 Effect of GR on consistency limits

The flow curves for the virgin clays and various GRC blends prepared with soils K, RC1, KB and RC2 are provided in Figures 3(a), 3(b), 3(c) and 3(d), respectively. As a result of GR inclusion, the flow curve exhibited a major downward shift over the $w\text{--}\log_{10}\delta$ space (w is the water content and δ is the cone penetration), indicating a significant reduction in the liquid limit (compare the water contents at $\delta = 20$ mm). Meanwhile, the slope of the flow curve was also observed to decrease with increase in rubber content, leading to a notable reduction in the flow index I_F and hence the plasticity index I_P ($I_P = 0.715 I_F$). As a typical case, the virgin clay KB resulted in $I_F = 45.12\%$, while the inclusion of 5, 10, 20 and 30% GR resulted in $I_F = 43.23\%$, 42.00%, 40.67% and 37.74%, respectively (see Figure 3(c)).

Figures 4(a), 4(b), 4(c) and 4(d) illustrate the variations of the consistency limits – namely, the liquid limit w_L , plastic limit w_P ($w_P = w_L - 0.715 I_F$) and plasticity index I_P ($I_P = 0.715 I_F$), against rubber content R_c for the virgin clays and various GRC blends prepared with soils K, RC1, KB and RC2, respectively. The higher the rubber content the lower the consistency limits, following a linear monotonic decreasing trend. As a typical case, the virgin clay KB resulted in $w_L = 59\%$, while the inclusion of 5, 10, 20 and 30% GR resulted in $w_L = 57$, 53, 51 and 46%, respectively (see Figure 4(c)). The rate of decrease in w_L , w_P and I_P with respect to R_c – represented by the slope of a typical linear trend line fitted through the desired dataset (i.e. $\Delta y / \Delta R_c$, where $y = w_L$, w_P or I_P) – was observed to be dependent on the type of soil, with

Figure 3. Flow curves for the virgin clays and various GRC blends: (a) soil K; (b) soil RC1; (c) soil KB; (d) soil RC2

the CH soils (i.e. soils KB and RC2) exhibiting a greater tendency for reduction compared with the CI soils (i.e. soils K and RC1). In terms of the liquid limit, for instance, the soils KB and RC2 resulted in $\Delta w_L / \Delta R_c = -0.425$ and -0.456 , respectively. For the soils K and RC1, however, these values dropped to -0.347 and -0.401 , respectively.

Figure 5 illustrates the location of the tested mix designs on Casagrande's plasticity chart (Figure 5(a): soils K and KB; Figure 5(b): soils RC1 and RC2). For a given type of soil, the variations of I_P against w_L followed a linear path (see the arrowed lines labelled '1' and '2' in Figure 5), with relatively lower slopes (i.e. $\Delta I_P / \Delta w_L$) compared with that of the 'A' and 'U' lines of the plasticity chart. Furthermore, the value of $\Delta I_P / \Delta w_L$ was dependent on the type of soil, with the CH soils (i.e. soils KB and RC2) exhibiting greater slopes compared with that of the CI soils (i.e. soils K and RC1). The soils KB and RC2 resulted in $\Delta I_P / \Delta w_L = 0.383$ and 0.517 , respectively. For the soils K and RC1, however, these values changed to

0.329 and 0.395, respectively. For a given type of soil, an increase in rubber content relocated the soil towards lower plasticity regions (follow the arrowed lines '1' and '2' in Figure 5), while mainly maintaining the original USCS classification observed for the virgin soil. Two exceptions, however, were the soils K and KB at $R_c = 30\%$, which transitioned from the CI and CH categories to CL ('clay with low plasticity') and CI categories, respectively (see KR30 and KBR30 in Figure 5(a)).

The consistency limits, the liquid limit in particular, can be employed to infer the development of soil fabric (Kim and Palomino, 2009; Soltani *et al.*, 2018b; Wroth and Wood, 1978). A decrease in the liquid limit, as is the case with GRC blends (see Figure 4), implies that a face-to-face aggregated (or dispersed) fabric dominates the GRC matrix (Mitchell and Soga, 2005). As opposed to the edge-to-face flocculated fabric, a face-to-face aggregated fabric offers less resistance to shear (or cone penetration), which in turn leads to lower liquid limits

Figure 4. Variations of the consistency limits against rubber content for the virgin clays and various GRC blends: (a) soil K; (b) soil RC1; (c) soil KB; (d) soil RC2

(i.e. the 20 mm cone penetration is achieved at lower water contents). Moreover, reduction in the consistency limits as a result of GR inclusion can be attributed to the lower specific surface area and water adsorption capacity of the rubber particles compared with the soil grains (Cetin *et al.*, 2006; Srivastava *et al.*, 2014; Trouzine *et al.*, 2012). The consistency limits are primarily a function of the soil's clay (or fines) content, with higher clay contents exhibiting higher liquid and plastic limits. Quite clearly, an increase in rubber content substitutes a larger portion of the clay content with non-plastic hydrophobic rubber particles, thus leading to a further decrease of the consistency limits.

5.2 Effect of GR on compaction characteristics

Standard Proctor compaction curves, along with corresponding specific gravities (obtained as per Equation 1) and zero-air voids (ZAV) saturation lines, for the virgin clays and various GRC blends prepared with soils K, RC1, KB and RC2 are

provided in Figures 6(a), 6(b), 6(c) and 6(d), respectively. For a given type of soil, the higher the rubber content the lower the average specific gravity G_{sm} , following a monotonic decreasing trend. As a result of GR inclusion, the compaction locus exhibited a major downward-leftward translation over the γ_d - w space (γ_d is the dry unit weight and w is the water content), indicating a significant reduction in both the optimum water content w_{opt} and the maximum dry unit weight γ_{dmax} . Such results foster the use of GR as a viable lightweight alternative for common quarry materials such as sand. For a given type of soil, the peak (or optimum) points followed a linear decreasing trend with increase in rubber content R_c (follow the arrowed lines in Figure 6), thereby signifying the existence of a linear relationship for both w_{opt} and γ_{dmax} with R_c . The linear tendency for reduction is in compliance with that reported in most of the existing literature sources (e.g. Cabalar *et al.*, 2014; Signes *et al.*, 2016; Yadav and Tiwari, 2017a).

Figure 5. Location of the tested mix designs on Casagrande's plasticity chart: (a) soils K and KB; (b) soils RC1 and RC2

Figures 7(a) and 7(b) illustrate the variations of the compaction characteristics – namely, w_{opt} and γ_{dmax} – against R_c for the tested mix designs, respectively. The higher the rubber content the lower the compaction characteristics, following a linear monotonic decreasing trend. The virgin clay KB, for instance, resulted in $w_{opt} = 25\%$ ($\gamma_{dmax} = 14.61 \text{ kN/m}^3$), while the inclusion of 5, 10, 20 and 30% GR resulted in $w_{opt} = 24\%$ ($\gamma_{dmax} = 14.27 \text{ kN/m}^3$), 22% ($\gamma_{dmax} = 14.16 \text{ kN/m}^3$), 21% ($\gamma_{dmax} = 13.71 \text{ kN/m}^3$) and 18% ($\gamma_{dmax} = 13.17 \text{ kN/m}^3$), respectively. Similarly to the consistency limits (see Figure 4), the rate of decrease in w_{opt} with respect to R_c – represented by the slope of a typical linear trend line fitted through a desired $w_{opt}-R_c$ dataset (i.e. $\Delta w_{opt}/\Delta R_c$) – was observed to be dependent on the type of soil, with the CH soils (i.e. soils KB and RC2) exhibiting a greater tendency for reduction compared with the CI soils (i.e. soils K and RC1). As demonstrated in Figure 7(a), the soils KB and RC2 resulted in $\Delta w_{opt}/\Delta R_c = -0.224$ and -0.196 , respectively. For the soils K and RC1, however, these values dropped to -0.160 and -0.114 , respectively. On the contrary, as depicted in Figure 7(b), an opposite effect can be concluded for γ_{dmax} , as

$\Delta \gamma_{dmax}/\Delta R_c$ was observed to be slightly higher for the CI soils compared with that of the CH soils (i.e. $\Delta \gamma_{dmax}/\Delta R_c = -0.052$, -0.059 , -0.046 and -0.043 for soils K, RC1, KB and RC2, respectively).

Reduction in the compaction characteristics as a result of GR inclusion can be attributed to the lower specific gravity and hydrophobic nature of the rubber particles compared with the soil grains (Cabalar *et al.*, 2014; Özkul and Baykal, 2007; Signes *et al.*, 2016). Similarly to the consistency limits, the optimum water content is primarily a function of the soil's clay/fines content, with higher clay contents exhibiting a higher optimum water content. Consequently, an increase in rubber content substitutes a larger portion of the clay content with hydrophobic rubber particles, which in turn leads to a further decrease of the optimum water content. The maximum dry unit weight is proportional to the composite's specific gravity, with higher specific gravities yielding a higher maximum dry unit weight. As such, an increase in rubber content substitutes a larger portion of the soil (with a high specific gravity) with low-specific-gravity rubber particles, which leads to a further decrease of the composite's average specific gravity (see G_{sm} values in Figure 6) and hence its maximum dry unit weight. Moreover, the elastic (or rebound) response of GR to dynamic energy during compaction may potentially reduce the compaction efficiency, and thus contribute to a lower maximum dry unit weight (Yadav and Tiwari, 2017b).

5.3 Compaction characteristics as a function of consistency limits

The conventional compaction test, although simple in terms of procedure, has been widely regarded as a laborious and time-consuming task (Sridharan and Sivapullaiah, 2005). Although numerous attempts have been made in the past to correlate the compaction characteristics with the consistency limits, such correlative models have not yet been extended to GRC blends (or other similar geomaterials). As such, the present section will be devoted to the development of practical models capable of predicting the compaction characteristics of GRC blends as a function of the consistency limits.

Figure 8 illustrates the variations of the optimum water content w_{opt} (data presented in Figure 7(a)) against the consistency limits – namely, the liquid limit w_L , plastic limit w_P and plasticity index I_p (data presented in Figures 4(a)–4(d)), for the tested mix designs (Figure 8(a): $w_{opt}-w_L$; Figure 8(b): $w_{opt}-w_P$; and Figure 8(c): $w_{opt}-I_p$). As depicted in Figures 8(a) and 8(c), w_L and I_p both exhibit weak correlations with w_{opt} , and thus are deemed as unsuitable for model development. The ineptness of the liquid limit in predicting the compaction characteristics of natural fine-grained soils was first recognised by Sridharan and Nagaraj (2005), and was attributed to the fact that soils having the same liquid limit (but different plasticity characteristics) often exhibit different compaction behaviour. On the contrary, w_P exhibits a rather strong correlation

Figure 6. Standard Proctor compaction curves for the virgin clays and various GRC blends: (a) soil K; (b) soil RC1; (c) soil KB; (d) soil RC2

(with $R^2 = 0.950$) in the form of a single-coefficient linear function with w_{opt} (see Figure 8(b)), which can be given as

$$4. \quad w_{opt} = 0.941w_p$$

Although some scatter can be observed with respect to Equation 4, all data points lie between the upper and lower 95% prediction bands, thus indicating no particular outliers associated with the predictions (see Figure 8(b)). Interestingly, the proposed model given in Equation 4 complies well with those suggested in the literature for natural soils (but with a slightly different coefficient compared to 0.941) – for example, $w_{opt} = 0.92w_p$ (Sridharan and Nagaraj, 2005) and $w_{opt} = 0.84w_p$ (Nagaraj *et al.*, 2015).

It is well accepted that the maximum dry unit weight γ_{dmax} is proportional to the dry unit weight at the plastic limit water content with a presumptive saturation degree of 100% (Gurtug and Sridharan, 2002, 2004; Gurtug *et al.*, 2018; Pillai and

Vinod, 2016). Making use of basic volume–mass relations, the dry unit weight at plastic limit γ_{dP} can be expressed as

$$5. \quad \gamma_{dP} = \frac{G_{sm}\gamma_w}{1 + G_{sm}w_p}$$

where G_{sm} is the average specific gravity of GRC blends (values presented in Figure 6); and γ_w is the unit weight of water ($= 9.81 \text{ kN/m}^3$).

The variations of γ_{dmax} (data presented in Figure 7(b)) were plotted against γ_{dP} (obtained as per Equation 5) for the various mix designs, and the results are provided in Figure 9. A similar correlation to that observed between w_{opt} and w_p also exists between γ_{dmax} and γ_{dP} (with $R^2 = 0.942$), which can be expressed as

$$6. \quad \gamma_{dmax} = 0.932\gamma_{dP} = \frac{0.932G_{sm}\gamma_w}{1 + G_{sm}w_p}$$

(a)

(b)

Figure 7. Variations of the compaction characteristics plotted against rubber content for the tested mix designs: (a) optimum water content; (b) maximum dry unit weight

As depicted in Figure 9, all data points with respect to Equation 6 position themselves between the upper and lower 95% prediction bands, thereby suggesting no particular outliers associated with the predictions. Previous studies such as Gurtug and Sridharan (2002) have suggested a different coefficient of 0.98 for natural fine-grained soils – that is, $\gamma_{dmax} = 0.98\gamma_{dP}$, which is slightly higher compared to the 0.932 obtained in the present study. This may be attributed to the lower average specific gravity of GRC blends compared with that of the virgin clays, which in turn gives rise to lower γ_{dP} values.

Figures 10(a) and 10(b) illustrate the variations of both the actual and predicted w_{opt} and γ_{dmax} data against rubber content R_c for the tested mix designs, respectively. The proposed models – that is, Equation 4 for w_{opt} and Equation 6 for γ_{dmax} , comply well with experimental observations, as evident with the clustering of actual and predicted data in the figures.

(a)

(b)

(c)

Figure 8. Variations of the optimum water content plotted against the consistency limits for the tested mix designs: (a) liquid limit; (b) plastic limit; (c) plasticity index

Figure 9. Variations of the maximum dry unit weight plotted against the dry unit weight at the plastic limit for the tested mix designs

Most of the predicted values perfectly overlap with their actual counterparts, thus signifying an excellent capacity to simulate the compaction characteristics of GRC blends by means of the plastic limit. In general, a reliable empirical model can be characterised as one that maintains a perfect balance between the apparent correlation and the exhibited error (or accuracy). The former is taken into consideration by means of the coefficient of determination R^2 , with values closer to unity implying a stronger correlation. The latter is commonly examined by means of the normalised root-mean-square error (NRMSE) (in %) and the mean absolute percentage error (MAPE) (in %), with values closer to zero representing a higher degree of accuracy (Soltani *et al.*, 2018d). The NRMSE and MAPE indices can be obtained by the following

$$7. \quad \text{NRMSE} = \frac{\sqrt{(1/N) \sum_{i=1}^N (y_{mi} - y_{ai})^2}}{y_{a \max} - y_{a \min}} \times 100$$

$$8. \quad \text{MAPE} = \frac{1}{N} \sum_{i=1}^N \left| \frac{y_{mi} - y_{ai}}{y_{ai}} \right| \times 100$$

where y_m is the predicted value of the dependent variable y ($=w_{\text{opt}}$ or γ_{dmax}); y_a is the actual value of the dependent variable y (data presented in Figure 7); $y_{a \max}$ is the maximum value of y_a data; $y_{a \min}$ is the minimum value of y_a data; i is the index of summation; and N is the number of data points used for model development ($=20$, consisting of four virgin clays and 16 GRC blends).

The suggested models for w_{opt} (Equation 4) and γ_{dmax} (Equation 6), respectively, resulted in R^2 values of 0.950 and 0.942, thus implying that approximately 95% of the variations

in experimental observations are captured and further explained by the proposed correlative models. The NRMSE and MAPE indices were, respectively, found to be 6.73% and 4.09% for w_{opt} , and 6.05% and 1.18% for γ_{dmax} , thereby indicating an average offset of approximately 5% associated with the predictive capacity of the proposed models.

As demonstrated in Figures 4(a)–4(d), the plastic limit w_P exhibited a linear relationship with rubber content R_c . For a given type of soil, it is therefore possible to write the following

$$9. \quad w_P = w_{P0} - \eta R_c$$

where w_{P0} is the plastic limit for the virgin clay (%) and η is the coefficient of plastic limit reduction (dimensionless).

The coefficient of plastic limit reduction η can be estimated by one plastic limit measurement for an arbitrary GRC blend. The choice of rubber content for the GRC blend would be arbitrary. From a statistical perspective, however, a median rubber content, taken as half the predefined maximum rubber content, is expected to provide a more reliable estimate of η (Mirzababaei *et al.*, 2018). For the present study where $R_c \leq 30\%$, a median rubber content would be 15%. Consider the following designations

- R_c^M = an arbitrary median rubber content
- w_P^M = plastic limit corresponding to an arbitrary median rubber content R_c^M (obtained in accordance with the flow index method, as outlined in Section 3.1).

Therefore, the following can be derived for η

$$10. \quad \eta = \frac{w_{P0} - w_P^M}{R_c^M}$$

By substituting the recent Equation 9 into Equation 4, it is possible to derive the following for w_{opt}

$$11. \quad w_{\text{opt}} = 0.941(w_{P0} - \eta R_c)$$

Similarly, by substituting Equation 9 into Equation 6, γ_{dmax} can be expressed as

$$12. \quad \gamma_{\text{dmax}} = 0.932 \gamma_{\text{dp}} = \frac{0.932 G_{\text{sm}} \gamma_w}{1 + G_{\text{sm}}(w_{P0} - \eta R_c)}$$

Although the original models given in Equations 4 and 6 offer a fairly practical procedure towards predicting the compaction characteristics of GRC blends without the hurdles of

Figure 10. Variations of both the actual and predicted compaction data plotted against rubber content for the tested mix designs: (a) optimum water content (predicted by Equation 4); (b) maximum dry unit weight (predicted by Equation 6)

conducting the conventional compaction test, the procedure may still be somewhat time-consuming, since a separate plastic limit measurement is to be carried out for each desired rubber content. The newly developed models given in Equations 11 and 12, however, suggest a more practical approach, one that requires only two plastic limit measurements (i.e. w_{p0} , which is the plastic limit for the virgin clay; and w_p^M , which is the plastic limit corresponding to an arbitrary median rubber content R_c^M) to arrive at an estimate of the compaction characteristics over a wide range of desired rubber contents. Similar correlative models may also be developed for different

compaction energy levels, and thus to arrive at a unified framework capable of predicting the compaction characteristics of GRC blends for any desired rubber content and/or rational compaction energy level.

6. Conclusions

The following conclusions can be drawn from this study.

- As a result of GR inclusion, the consistency limits – namely, the liquid limit w_L , plastic limit w_p ($w_p = w_L - 0.715 I_F$, where I_F = flow index) and plasticity

index I_P ($I_P = 0.715I_F$), exhibited a linear monotonic decreasing trend with increase in rubber content. The rate of decrease in w_L , w_B , I_F and I_P was dependent on the type of soil, with the CH soils (high-plasticity clays) exhibiting a greater tendency for reduction compared with that of the CI soils (intermediate-plasticity clays).

- As a result of GR inclusion, the compaction characteristics – that is, the optimum water content w_{opt} and the maximum dry unit weight γ_{dmax} – exhibited a linear monotonic decreasing trend with increase in rubber content. Similarly to the consistency limits, the rate of decrease in w_{opt} was dependent on the type of soil, with the CH soils exhibiting a greater tendency for reduction. The rate of decrease in γ_{dmax} , however, was less influenced by the type of soil. Such results foster the use of GRC blends as a viable lightweight material for the construction of sustainable earth fills, thus serving a variety of infrastructure needs – for example, road/railway embankments, retaining walls and bridge abutments.
- The compaction characteristics were strongly correlated with the plastic limit. In this case, simple correlative models in the form of $w_{opt} = 0.941w_P$ and $\gamma_{dmax} = 0.932\gamma_{dP}$ (γ_{dP} is the dry unit weight at plastic limit water content with a presumptive saturation degree of 100%) were obtained for the optimum water content and the maximum dry unit weight, respectively. The predictive capacity of the proposed models was examined and further validated by statistical techniques. The proposed correlative models offer a practical procedure towards predicting the compaction characteristics of GRC blends without the hurdles of conducting the conventional compaction test, and hence can be implemented in practice for preliminary assessments.

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