Compacted Expansive Elastic Silt and Tyre Powder Waste

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Abstract. Building on/with expansive soils with no treatment brings complications. Compacted expansive soils specifically fall short in satisfying the minimum requirements for transport embankment infrastructures, requiring the adoption of hauled virgin mineral aggregates or a sustainable alternative. Use of hauled aggregates comes at a high carbon and economical cost. On average, every 9m high embankment built with quarried/hauled soils cost 12600 $MJ.m^{-2}$ Embodied Energy (EE). A prospect of using mixed cutting-arising expansive soils with industrial/domestic wastes can reduce the carbon cost and ease the pressure on landfills. The widespread use of recycled materials has been extensively limited due to concerns over their long-term performance, generally low shear strength and stiffness. In this contribution, hydromechanical properties of a waste tyre sand-sized rubber (a mixture of polybutadiene, polyisoprene, elastomers, and styrene-butadiene) and expansive silt is studied, allowing the short- and long-term behaviour of optimum compacted composites to be better established. The inclusion of tyre shred substantially decreased the swelling potential/pressure and modestly lowered the compression index. Silt-Tyre powder replacement lowered the bulk density, allowing construction of lighter reinforced earth structures. The shear strength and stiffness decreased on addition of tyre powder, yet the contribution of matric suction to the shear strength remained constant for tyre shred contents up to 20%. Reinforced soils adopted a ductile post-peak plastic behaviour with enhanced failure strain, offering the opportunity to build more flexible subgrades as recommended for expansive soils. Residual water content and tyre shred content are directly correlated; tyre-reinforced silt showed a greater capacity of water storage (than natural silts) and hence a sustainable solution to waterlogging and surficial flooding particularly in urban settings. Crushed fine tyre shred mixed with expansive silts/sands at 15 to 20 wt% appear to offer the maximum reduction in swelling-shrinking properties at minimum cracking, strength loss and enhanced compressibility expenses.

Keywords: Embankment; Compaction; Expansive; Hydromechanical; Tyre

1. Introduction

According to DEFRA (2015), the discarded waste tyres in the UK sum up just over 55 mega tones per annum ($MT.a^{-1}$). Being almost not biodegradable, around 34% of waste tyres are landfilled, 22% is used for energy recovery (e.g. burning in cement kilns), and 21% is shredded to raw material (Viridis and TRL 2003). Possible use of recycled waste tyres in infrastructure road pavements and embankments can significantly ease the pressure on landfills. Use of rubber shreds in road works (from non-reusable tyres) has recently attracted some attention (Moghaddas Tafreshi and Norouzi, 2015); The behaviour of soil-shredded tyre geo-composites however continues to be a matter of dispute.

According to the Mineral Products Association (MPA), The current total consumed construction material in the UK sums at 424.1 million tonnes per annum ($MT.a^{-1}$), 225 $MT.a^{-1}$ of which are aggregates sourced from 513 quarries across the UK, including 63$MT.a^{-1}$ of recycled and secondary (MPA 2016). This is a sharp rise from 125.9 $MT.a^{-1}$ of aggregates produced and consumed in 1998, that costed 0.532 $MT.a^{-1}$ emissions (0.531 $MT.a^{-1}$ carbon dioxide) and generated 58.7 $MT.a^{-1}$ wastes (Smith et al, 2000). A tangible proportion of aggregates are used in maintenance and construction of transport infrastructure cuttings and embankments. The demand for aggregates for rehabilitation of distressed embankments and building future fills/subgrades where the natural ground is not favourable has been escalating in the past years, so too the demand for greater use of public funds to finance the construction. In 2013-14, the maintenance cost of the 20,000km long highway and rail embankments summed about £1.62bn (NetworkRail, 2013), roughly a fifth of the total construction output (HM Treasury, 2010). Thereby, there remains remarkable scope for furthering the knowledge of recycled aggregate products, particularly the non-silica-based types. Partial replacement of virgin aggregates with recycled wastes will also contribute to UK's pledge to cut the global carbon emission by 25% by 2050 (O'Riordan and Phear, 2012).

The use of recycled tyre as a replacement to aggregates in concrete has attracted considerable attention in the past two decades (Eldin and Senouci 1993, Topçu 1995, Albano et al., 2005, Marie and Quiasrawi 2012 and Su et al., 2015). In the groundworks industry, the shredded waste tyre is used, to limited extents, to build lightweight composite materials mainly suitable for backfilling retaining walls. The shredded tyre is a non-toxic waste material and once mixed with soil, will have no known adverse effect on the

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quality of groundwater (Humphrey et al. 1997; Liu et al. 2000). The geotechnical properties of recycled tyre - sand composites are widely studied in Edil and Bosscher (1994), Foose et al., (1996), Lee et al., (1999), Youwai and Bergado (2003), Bergado et al., (2005), Dutta and Rao (2009), Rahgozar and Saberian (2016) Reddy et al., (2016) and Mashiri t al., (2017) Kim et al., (2018). Karabash and Cabalar (2015) did several tests on sand-tyre compositions and reported that tyre crumb to sand decreases Young's modulus, deviatoric stress and brittleness, and can lead to elevated levels of pore water pressure. Terzi et al., (2015) proposed that shredded tyre-sand mixtures have a scope to be effectively used as backfill material for buried pipe installations. Trouzine et al., (2012) reported on a relatively greater reduction in swelling-shrinking properties for CH clays (as compared with CL clays), reinforced with tyre fibre. This was at the cost of enhanced compression and re-compression indices. Signes et al., (2016) limited the compression index enhancement to rubber contents above 15%. The implications of shredded tyre and soil grading was surveyed in Shahin et al., (2011). Ho et al., (2010) showed that mixing rubber chips with soft clay has a negligible effect on the composite’s shear strength, but increases the failure strain, and hence adds to ductility. Signes et al., (2016) reported an increase in drained shear strength of clays on addition of rubber fibres and attributed this to rubber’s contribution to friction angle. They however reported a decrease in the undrained shear strength for rubber inclusions greater than 5%. Kim et al., (2011) mixed three waste tyre powders (of different mean equivalent diameter) with fly ash. They showed that an increase in the tyre powder content lowers the shear strength, as internal friction angle decreases. These findings agreed with the earlier findings in Teymur et al. (2010), where an increase in the shredded tyre content decreased the shear strength of cement-stabilised sand soils. Seda (2007) investigated the behaviour of mixed fine-grained waste tyre rubber and Colorado expansive clays. They showed that maximum dry unit weight is inversely proportional with the tyre content, mainly due to the lower density and specific gravity of the rubber material. Adding the waste tyre to expansive soils, however, decreased both swelling potential and compressibility. Geosynthetic reinforced materials used in embankments and backfills can generally lower the lateral deflections, earth pressures and settlement, and add to the bearing capacity (Koerner 1994; Bernal et al., 1997; Keskin and Laman 2014).

Over the past decade, the unwelcomed implications of building with/on expansive soils have cost the UK economy an estimated £3 billion (at an estimated rate of £300 million to £500 million per annum – see Pritchard et al., 2013). This figure sums to over $15 billion annually in the United States (Nelson and Miller 1992), almost half of which is related to damages to pavements (Chen 1988). Globally, over £400 million a year (Driscoll and Crilly, 2000) worth of successful insurance claims is associated with the problem of swelling-shrinkage. This paper will test the prospects of using shredded tyre - excavation won expansive silts in building subgrades for foundations and embankments for transport infrastructure.

In this study, composite soil-tyre materials were compacted at optimum water content, to simulate common engineering embankments. To determine the optimum tyre shred content in geo-composites, physical, mechanical and hydraulic properties as well as Soil Water Characteristic Curves were experimentally determined for base and improved testing specimens. The procedures and testing objectives are presented alongside results in subsequent sections. Findings from this research will inform the groundworks and the tyre recycling industry and facilitates the replacement of shredded tyre waste with virgin/recycled mineral aggregates. Tyre fibre-reinforced fine soils have received substantial attention, yet, the long-term hydro-mechanical response of such composites have remained a matter of debate. This contribution will examine the physico-mechanical properties of tyre-reinforced expansive silts in relevance with their water retention properties.

2. Preparation of Test Samples

2.1 Materials

The expansive soil used in this study is an active high plasticity calcareous clayey sandy silt (MH), obtained from Famagusta Cyprus. The soil is the produce of weathering of the Pliocene Nicosia marl that outcrops across central Mesaoria basin (Harrison et al., 2008), and have reportedly caused extensive visible damage to local transport infrastructure and buildings across the island (Loukidis et al., 2016). The mineralogical composition of Pliocene Nicosia marl is quantified in Acar et al., (2007), based on X-ray diffraction analysis on seven samples, showing smectite and illite of 19.3±6.8% and 11.1±4.8% in order (total mineralogy), 23.6±5.6% calcium carbonate, and a remarkably high 3337.5±3.9.2 part per million (ppm) Na^+ cation in soil solution, which then leads to elevated soil solution pH levels. The soil was obtained from open trenches from an approximately 1.5-2.2m below ground level. The utilised tyre is by-products of waste vehicle tyres supplied by Rubber Land factory in Nicosia, North Cyprus. The utilised tyre consists of a complex mixture of polybutadiene, polyisoprene, elastomers, and styrene-butadiene; the tyre was milled to particles sizing 0.1 mm to 1.1 mm. Grading curves for the base material and milled tyre are presented in Figure 1.

2.2 Preparation of Samples

The soil (silt) and shredded tyre were air-dried under ambient conditions and mixed thoroughly into six compositions. The dry mass of tyre was varied from 0% to 10, 20, 30, 40 and 100% in composite samples. The dry silt-tyre powder mixtures were then thoroughly mixed with deionized water (to attain relevant optimum water content) and allowed to mellow for 24 hours in sealed plastic bags for the water to uniformly distribute throughout the pore spaces. Wet composite soils were then compacted in compliance with ASTM D698–07, allowing undisturbed test specimens of varied dimensions to be extracted from.

3. Experimental Programme

3.1 Physical properties

Consistency limit and linear shrinkage tests were carried out in accordance with ASTM D4318-10 standard on expansive silt and silt-tyre composite samples and presented in Figure 2. Measured consistency limits are in good agreement with recent efforts on Nicosia marl (45% to 65% liquid limit, and 19% to 35% plasticity index in Loukidis et al., 2016) and inversely proportional with tyre powder content, allowing the transition from MH (original soil) to CL (lean clay) with increasing tyre content. The remarkable decrease in plasticity limit on addition of tyre wastes to expansive silt led to an early rise in the plasticity index for specimens with 10% tyre content.

Plastic Limit water content is the lower-bound water content at which soil begins to behave plastic, thereby arguably corresponds to high suction levels in a two-phase state and the pendular state of capillary meniscus in soil. Liquid Limit water content is the upper-bound water content above which soil loses shear strength and enters a state of liquidity. At particle level, this happens as the thickness of the thinnest possible water film increases to levels at which air begins to form continuous phases and passing, through micro-pores, into macro-pores. Consequent modifications at particle contact points lead to structural (packing) collapse and a capillary transition from the maximum pendular level to funicular state. A detailed account is given in Assadi-Langroudi and Jefferson (2016). On addition (and compaction) of small amounts of shredded tyre (200μm-100μm) to silt, large tyre particles sit in a matrix of clayey silt. Plastic, in comparison with crystalline and amorphous forms of quartz (i.e. here silt), hydrated silica and phyllosilicates exhibits much lesser adhesion surface energy given its more regular orientation of atomic groups on surfaces and consequently limited surficial electrical charges. This leads to formation of a flocculated matrix of clay along the plastic-soil interface, whereby micro-pores adopt a relatively greater share of pore spaces. The openly-packed structures at soil-plastic interface function as preferred water pathways (Assadi-Langroudi and Yasrobi, 2013), facilitate the early formation of funicular meniscus water films and lowers the Plastic Limit.

Findings here contrast that of Cetin et al., (2006); they suggested marginal variations in the plastic limit on addition of tyre to clay before a subsequent gradual decrease. Given the proven control of PI on the activity of expansive soils, for the volumetric change behaviour of fills to be in admissible ranges, the use <10% by dry mass of sand-sized shredded tyre should generally be avoided. Shrinkage limit decreased almost linearly with the shredded tyre content. Lower shrinkage limits restrict the range of service water content through which crack formation in compacted fills is less likely.

Shrinkage Limit is a proxy for the potential of soil to develop tensile cracks on horizontal tensile strains (caused by coagulation of clay flakes). When tensile strains exceed a critical strain, predominantly controlled by soils geochemical composition, desiccation cracks begin to develop. Recently, Ghadr and Assadi-Langroudi (2018) examined a range of expansive sandy clay specimens and showed that clay content and angularity of soil's sand fraction are inversely proportional with the shrinkage limit (SL) and minimum void ratio. This is consistent with findings here. Composite soils such as the tyre-silt system here are broadly bi-modal (in particle and pore size distribution), thereby exhibiting structure-based hydromechanical properties when unsaturated. As such, in addition to clay content, the size, sorting and shape of tyre particles have significant control on suction at shrinkage limit and therefore pattern of desiccation cracks. This remains a matter of research interest.

Composites containing >40% sand-sized shredded tyre effectively transform the composites to granular soils that are likely to offer extensively reduced shear strength (particularly in short-term). Zornberg et al., (2004) suggested a 35% optimum tyre shred content for clean angular sand backfill soils. For expansive silts, this optimum content ranges between 15% (to avoid mixtures with high PIs and activity) and 30% (to avoid excessive loss of shear strength and too low shrinkage limits).

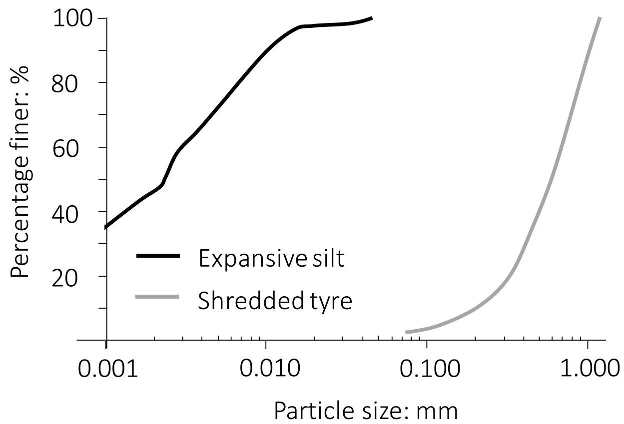

Fig. 1 particle size distribution

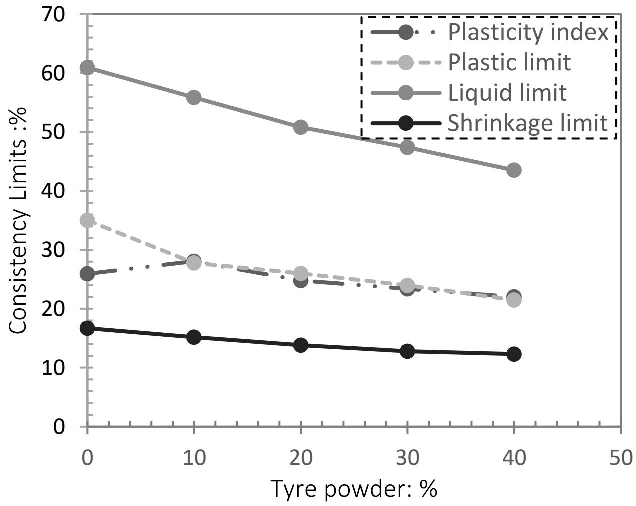

Fig. 2 Effect of tyre powder content on index properties

Table 1 summarizes the physical properties for the six testing compositions obtained experimentally in compliance with the ASTM (D854, D4318 and D698).

Table 1 Mix proportions and physical properties of specimens

	Composition		G_s	USCS	SL	PL	LL	PI	$\gamma_{d(max)}$	w_{opt}
	Silt	Tyre	-	-	%	%	%	%	$kN.m^{-3}$	%
S1	100	0	2.62	MH	16.70	35.0	60.93	25.93	14.70	26
S2	0	100	1.45	-		NPI	NPI	NPI	-	-
S3	90	10	2.42		15.20	27.8	55.84	28.10	-	-
S4	80	20	2.26		13.83	26.0	50.82	24.82	12.97	25
S5	70	30	2.11		12.82	24.0	47.39	23.39	12.57	22
S6	60	40	1.98		12.33	21.5	43.51	22.01	-	-

The specific gravity decreased with tyre powder content. This agrees with the very low 1.45 $Mg.m^{-3}$ particle density of shredded test tyre and offers the prospects of building lightweight fills which benefit from lower time-based subgrade settlements. The optimum water content and maximum dry unit weight of elastic silt and its mixtures were performed according to ASTM standard and are outlined in Table 1. On replacement of fine-grained minerals with tyre powder, composites become relatively coarser, leading to a decrease in the optimum water content. Maximum dry density is inversely proportional to the tyre content due to the relatively lower particle density of plastic tyre as compared with mineral grains. Findings are consistent with previous similar efforts (Signes et al., 2016; Edil and Bosscher, 1994). To this end, lower dry density, optimum water content and specific gravity, together with lower activity of silt-tyre mixtures make these composites ideal lightweight and sustainable alternatives to granular backfill materials.

3.2 Strength and Large-Strain Stiffness

Unconfined compressive strength tests were carried out on expansive silt and composite soil specimens to establish the effect of tyre inclusion on strength (peak stress in stress-strain curves in Fig. 3) and stiffness (i.e. Secant Elastic Modulus or the slope of the stress-strain curve from zero stress to stress at 50% of the peak strength in Fig. 2). The three test samples were compacted to maximum dry density. In Figure 3, the tyre content is varied from 0% (in S1) to 30% (in S5) – see Table 1.

Cohesion (i.e. inter-particle adhesion) in a soil can be stemmed from one of a combination of factors (Assadi-Langroudi 2014): (1) Inter-crystalline cohesion between clay platelets, (2) adhesion between quartz and clay, (3) adhesion between quartz and oxide (4) adhesion between oxide and sulphate, (5) adhesion between clay and oxide, (6) adhesion between clay and carbonates, and (7) chemically weathered clay. Given the mineralogical composition of parent expansive silt, the cohesion in specimen S1 is of clay-clay, quartz-clay, and clay-carbonate types. Plasticity and cohesion between clay platelets form when clay flakes adhere one to another, and when surface tension develop on water meniscus: hydrophilous clay platelets gain a net negative surficial charge as a result of random arrangements of their surface molecules. In presence of free cations or water dipoles, high levels of adhesion develop between wet clay platelets.

This facilitates their mutual coherence. When clay platelets approach one to another, their electric double layers overlap. Cloud thickness begins to reduce at elevated/high levels of electrolyte concentrations or in presence of divalent cations. Attractive forces develop and lead to coagulation. Low contents of shredded tyre inclusions are not likely to have a measurable effect on clay-clay adhesion.

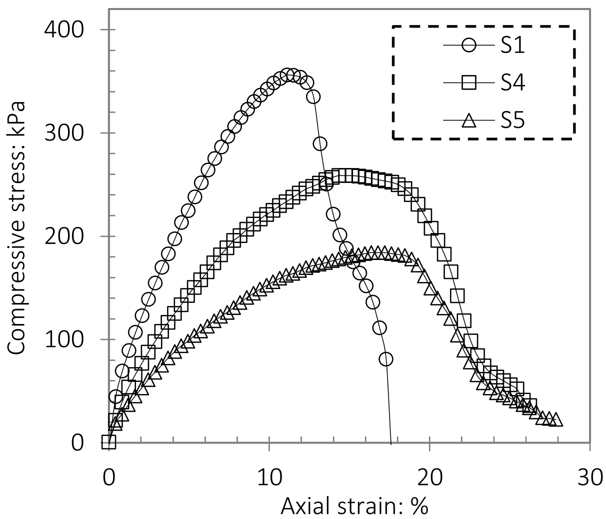

Fig. 3 Stress-strain patterns from unconfined compressive strength experiments

The Nicosia formation clayey silts used in the present study are known to be calcareous (Harrison et al., 2008), thereby clay-carbonate inter-particle adhesion is the second cohesive mechanism in the parent soil. Pozzolanic reaction is a suite of ion exchange events, specifically associated with pH-dependent charges on clays' edge: The pH-dependent positive charge on the edge of clay flakes turn into negative at elevated pH levels at soil solution phase. This leads to deprotonation at clay hydroxyl sites (i.e. liberation of hydrogen atoms from the hydroxyl tail). In presence of abundant levels of calcium cation (as in the study site), Na^+ at a stern layer is exchanged for Ca^{2+}, to join the negatively charged deprotonated hydroxyl tails. The consequent raise in pH of the soil solution facilitates further deprotonation and formation of strong Calcium Silicate Hydrate (CSH) gel cements. The two new bonding agents supply large levels of cohesion and shear strength in clayey soils and add a degree of brittleness to their stress-strain behaviour. Replacing clays with tyres will decrease the cation load, cohesion, strength and brittleness. This agrees with Figure 3, where tyre inclusion appears to add to the failure strain and enhance the ductility. Recently and from a different perspective, Alqahtani et al., (2017) attributed the ductile behaviour to relatively greater deformability of plastic particles and consequent 'diffused boundaries' between particles and bonding matter/matrix.

3.3 Swelling Potential

Oedometric free swelling tests were carried out in compliance with the ASTM standard D2435/D2435M. Composite specimens were compacted to their maximum dry unit weight into 50mm diameter conventional oedometer rings embedded within standard compaction mould. Based on findings of Assadi-Langroudi and Yasrobi (2009), the rate of swelling for expansive silts (or very sandy expansive clays) compacted at optimum water content is independent from the drainage pathways (i.e. vertical, horizontal, or combined), even though pore water generally tends to move through preferred pathways in sandy silty clay soils. To this end, during the course of wetting, specimens here were allowed axial drainage only. Specimens were initially allowed to swell under 7 kPa seating pressure. Free swelling index is plotted against the logarithm of wetting time in Figure 4.

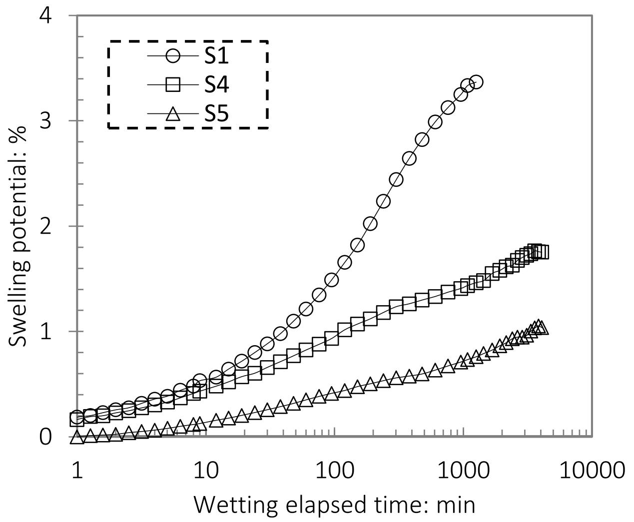

Fig. 4 Swelling potential ($i_s = \frac{\Delta e}{1+e_0}$) against wetting time

A significant decrease in the swelling index and rate of primary and secondary swelling was recorded on the addition of tyre powder (to 30% by mass). Reduction in swelling could be partly due to the dilation of sharp shredded tyre particles. Assadi-Langroudi and Yasrobi (2009) presented a suite of electron microscope images of silty sandy clay loams showing formation of stable macro-pores in soil medium and in between clay aggregates on the addition of sand-sized inclusions. Macro-pores attain their stability from the surrounding sharp sand-sized particles and through their interlocking effect. Fresh macro-pore spaces provide space and accommodate intra-lattice swelling, which then restricts the wetted-induced changes in soils voids ratio. More recently, Su et al., (2015) presented sets of electron microscopy images, showing the jagged texture of crushed rubber aggregates similar to the milled tyre particles used in this research (in size and density). The rough surface of tyre aggregates increases the share of inter-assemblage pore spaces from the total voids, with elastic silts sitting in and bridging macro-pore spaces.

3.4 Consolidation

1D consolidation oedometer tests were carried out in compliance with the ASTM D2435 standard. In Figure 5, the voids ratio is plotted against effective consolidation pressure. The slope of the virgin line (i.e. compression index) was found to decrease on addition of tyre particles. Observations tie in with the substantially lower compressibility of tyre powder. Pre-consolidation pressure, which can be a measure of bonding quality between the minerals, and between minerals and tyre particles appeared to be almost independent of the tyre powder content. This is consistent with the non-plastic and predominantly frictional nature of plastic tyre. Constant volume swelling pressure significantly reduced with increasing tyre powder content.

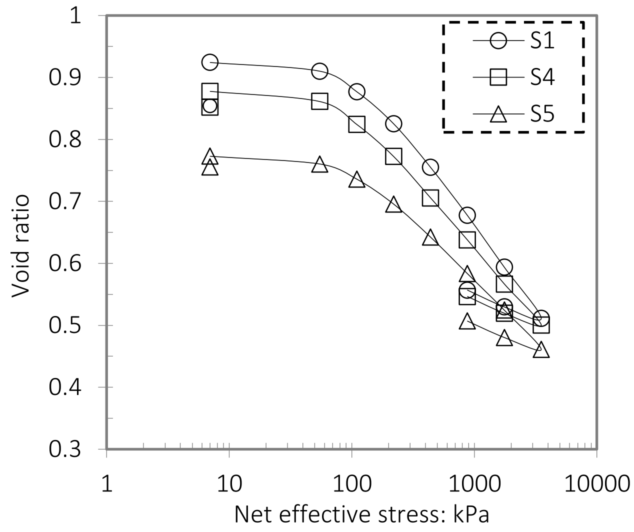

Fig. 5 1D consolidation e-logσ' curve

3.5 Water Retention Properties

A suite of experimental and numerical methods was utilised to measure the water retention properties of testing composites. The Soil Water Characteristic Curve (SWCC) relates the soil matric suction ψ to water content (by mass or volume). In desorption phase, water content of a soil decreases with increasing soil suction (i.e. drying protocol).

SWCC inputs were initially obtained from a series of filter paper tests on expansive silt and composite silt-tyre samples. The test allows measuring matric suction values in a surplus of 1500kPa and is arguably the most widely used method for soil. The expansive silt and silt-tyre specimens were compacted to maximum dry unit weight and saturated thereafter under 7kPa seating pressure in 50mm diameter oedometer rings. The specimens were then allowed to air-dry whilst water content was frequently recorded. The specimens were brought in direct intimate contact with Whatman No. 42 filter paper discs, inside tightly sealed containers encapsulated in airtight Styrofoam boxes. The Styrofoam boxes were filled with glass wool and capped using sealing tapes to allow good insulation. The boxes were kept under constant 22°C temperature in an environmental chamber. Filter papers were weighed up every 7 to 10 days (equilibrium time) for suction determination. The Fredlund and Xing FX (Eq. 1 and 2) and van Genuchten vGM (Eq. 3) numerical models were used to build the SWCC curves. The Van Genuchten (1980) equation has been widely used by many researchers and is endorsed in Leong and Rahardjo (1997) and Fredlund and Xing (1994) as sets of equations that provide the finest SWCC models for a wide variety of soils.

$$w(\psi) = c(\psi)\frac{w_s}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right\}^m} \qquad (1)$$

where $w(\psi)$ is the gravimetric unsaturated water content, w_s is the saturated gravimetric water content, 'a' is a soil parameter linked to the Air Entry Value (AEV) (ψ_a), 'n' is a soil parameter relevant to the slope at the curvature point (near the air- entry value) on the SWCC, 'm' is a soil parameter related to the residual water content, ψ is soil suction in kPa, ψ_r demarcates soil suction in kPa that corresponds with the residual water content (w_r), and $c(\psi)$ is correction factor as given in Eq. (2).

$$c(\psi) = 1 - \frac{ln\left(1 + \frac{\psi}{\psi_r}\right)}{ln\left[1 + \left(\frac{1000000}{\psi_r}\right)\right]} \qquad (2)$$

$$w(\psi) = \frac{w_s}{\{1 + (a\psi)^n\}^m} \qquad (3)$$

where w_s and ψ have the same definitions as in Eq. (1), 'a' is a soil parameter linked to the Air Entry Value (AEV) (ψ_a), and 'n' is a soil parameter relevant to the rate of water removal from the soil, when the AEV has been reached. The Air Entry Value is the matric suction at which air commences to enter the largest pores in a soil (Fredlund and Xing, 1994) and occurs roughly at the SWCC's point of maximum curvature, which itself is dependent on the quantified amount of water in soil (Fredlund et al., 2011) and hence the soil packing state. The Soil Vision computer programme (Soil Vision Systems Ltd. 1999) was adopted for the regression analysis.

Figure 6 presents the SWCCs drawn using fitting parameters (summarised in Table 4) through best-fitting the filter paper test data using a least-squares algorithm (Van Genuchten 1980; Fredlund and Xing, 1994).

Table 2 SWCC curve-fitting parameters for four test specimens

	Fredlund and Xing (1994)							Van Genuchten (1980)					
	a kPa	n	m	h kPa	R^2	w_R: %	AEV: kPa	a	n	m	R^2	w_R: %	AEV : kPa
S1	2499.93	0.858	1.008	92850	0.993	5.7	578.18	0.0004	0.6892	0.6086	0.98	0.0	224.64
S4	642.73	20	0.108	1286.6	0.996	19.9	532.10	8.205	0.694	0.942	0.993	0.0	725.6
S5	2499.9	1.56	0.635	31698	0.902	8.5	1192.74	0.00016	2.32	0.329	0.983	0.0	3535

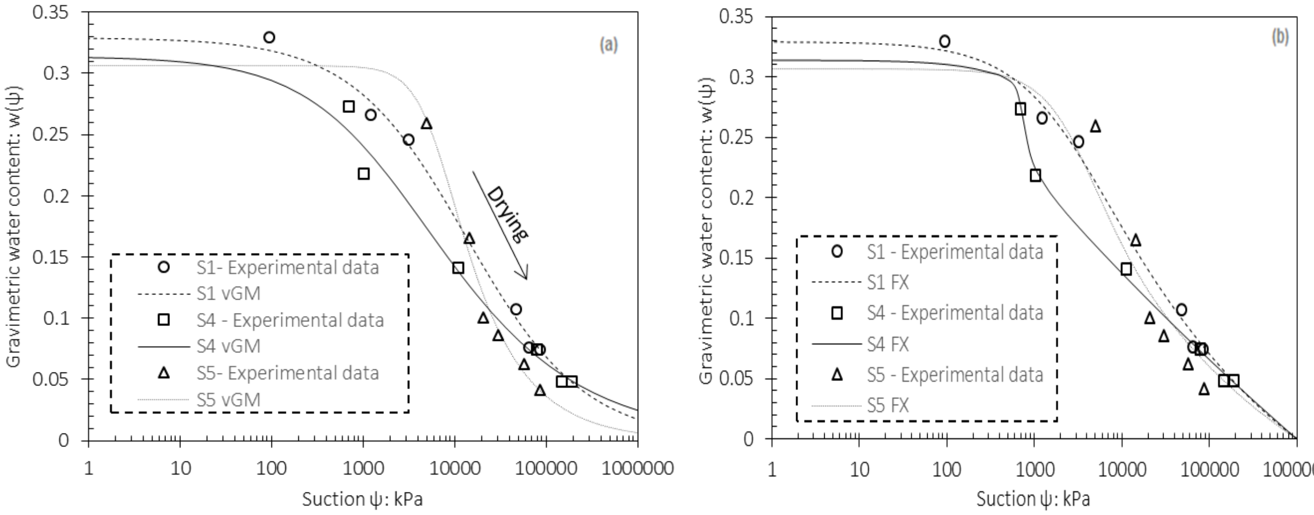

Fig. 6 SWCC Curves (a) fit to van Genuchten (vGM) model; (b) fit to Fredlund and Xing (FX) model

Table 3 Volumetric change, strength and stiffness parameters

	Composition		q_u	ε_f	E	e_1	i_s	t_s	σ'_p	C_c	C_s	σ'_c
	Silt	Tyre	kPa	%	kPa		%	min	kPa			kPa
S1	100	0	400	12.8	3125.0	0.92	3.4	930	220	0.243	0.109	125
S4	80	20	235	14.0	1678.6	0.88	1.3	400	100	0.215	0.073	90
S5	70	30	184	17.4	1057.5	0.75	0.6	300	90	0.183	0.089	140

4. Conclusive Discussions

Table 3 summaries the strength, stiffness and compressibility parameters of expansive silt and composite silt-tyre shred test specimens (within the 15%-30% optimum tyre content range). Tyre content appears to have a marginal impact on consolidation properties; with an exception of the compression index which shows a modest decrease on increasing tyre shred content. Elasticity modulus (i.e. large strain stiffness) drop sharply with tyre shred content, so too the unconfined compressive strength, swelling pressure and swelling potential. Figure 7 shows that on a 10% increase in the tyre content to 30%, the decrease in swelling properties is very modest, making 30% tyre fibre content a less attractive design proportion.

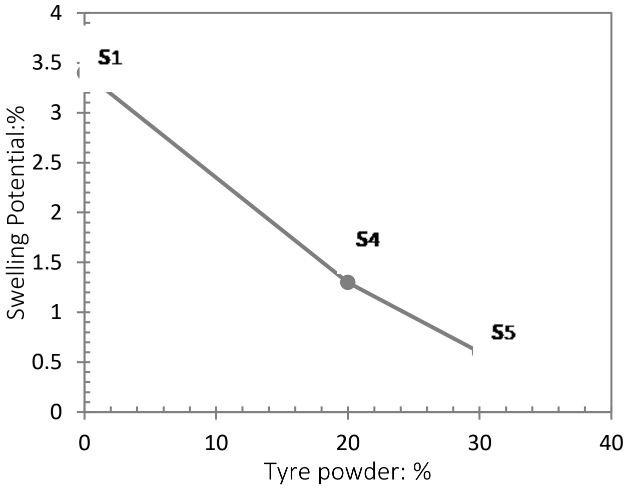

Fig. 7 Effect of tyre powder content on swelling potential

From the FX model readings, residual water content increases on the addition of tyre shred and peaks at 20% Tyre content. A greater residual water content allows greater water storage capacity in a soil and delayed surficial waterlogging in the event of heavy rainfall. The difference between Air Entry Value in expansive silt and composites with 20% tyre shred appears to be marginal. Thereby, the matric suction's contribution to the shear strength on the drying path (in a surplus of net stress) appears to be independent of the tyre shred content up to 20%. The water retention characterises confirm the conclusions drawn from the mechanical and physical test results. Tyre shred particles should ideally be crushed into fine sand-sized range and mixed with expansive silts at a 1-4 dry mass ratio (20% of mass).

5. Conclusions

Building transport subgrade and embankment infrastructure by mixed composites of shredded tyre waste and cutting-arising expansive soils can ease the pressure on landfills, reduce the carbon footprint and ease the pressure on virgin aggregate quarries. On systematic examination of hydro-mechanical properties of such mixtures, a 1-4 (tyre rubber – soil) ratio is tentatively proposed to the groundworks industry. Swelling properties of test samples were investigated through measurements of swelling pressure, swelling potential, and consistency limits. Linear shrinkage tests were conducted to survey the relevance of crack formation and service water content. SWCCs were built to draw out the residual water content and likelihood of waterlogging in the event of extreme rainfall. Compressibility and strength were tested through a combination of 1D consolidation and unconfined compressive strength experiments. The powder inclusion generally reduced the swelling potential, modestly lowered the compression index, and lowered the bulk density of composites (offering a prospect of lightweight earth structures). The decrease in the optimum water content on the addition of tyre powder improves workability. The shear strength and stiffness decreased on addition of tyre powder, yet the contribution of matric suction to the shear strength remained constant for tyre shred contents up to 20%. Benefitting from a bimodal microstructure, residual water content increased significantly at 20% tyre shred content, allowing the accommodation of greater volumes of water in the pore network in the event of intense rainfall. The ductility and failure strain both increased, offering the opportunity to build more flexible subgrades as recommended for expansive soils.

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