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SHEAR RESISTANCE IMPROVEMENT OF OIL-CONTAMINATED BALLAST LAYER WITH RUBBER SHRED INCLUSIONS

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ABSTRACT: Railway ballast, which form an integral part of rail tracks, is highly susceptible to subsistence due to both vibration transmitted by the passing trains, as well as the breakage of ballasts with repeated impact. The resulting subsistence necessitates regular monitoring and maintenance, involving cost- and time-consuming remedial actions, such as stone-blowing and ballast renewal. Measures to minimize the wear and tear effect are therefore desirable to prolong the lifespan of the ballast layer. It is even more critical when the ballast is contaminated with oil and grease from braking wheels and leakages. This paper describes the inclusion of rubber shreds (≤10 mm in length, 1.5 mm thick) derived from the inner tubes of motorcycle tyres in oil-contaminated ballast layer for shear resistance improvement. The tests are mainly carried out in a standard direct shear test setup, i.e. shear box measuring 60 mm x 60 mm. Granitic stones of suitable sizes were sieved and used as representative samples of typical ballast. The samples were soaked in lubricant oil for 14 days to simulate the contamination. The direct shear test results indicated rubber shreds inclusion could effectively improve the shear resistance of ballast and expedient in deformation control with increased ductility of the composites. This could potentially improve absorption of impact, hence reduction of breakages of the ballasts. Clearly both mechanisms contribute to the overall reduced subsistence, accompanied by an increase in the shear resistance. However, further investigations in a dynamic test setup are necessary for verifications prior to field implementation.

Keywords: ballasted track, oil-contamination, rubber shreds, shear box test, settlement, displacement

1. INTRODUCTION

Railway ballasted tracks were laid down since the eighteenth century [1]. Railway track systems and related infrastructure are regularly upgraded to cater for the growing needs of commuters and commerce (Fig. 1). Indeed innovations in railway engineering are very much focused on the railway tracks to ensure better travel comfort and safety. A railway track can be generally divided into two parts, namely the superstructure and substructure. The superstructure normally consists of the rails, sleepers, rail pads and fastening, while the substructure comprises the ballasts, sub-ballast and subgrade layers as shown in Fig. 2.

Ballast is made up of stones which are rough in shape to improve the interlocking efficiency. Typically, the ballast layer is constructed with angular-shaped gravels between 22 to 63 mm particle size, lain to thickness of 300-500 mm. The geomaterials used as ballast are mostly dolomite, rheolite, gneiss, basalt, granite and quartzite in the range of medium to coarse gravel sized aggregates [2]. According to Pires and Dumont [3], good quality ballast should also have high specific gravity, high shear strength, high toughness and hardness. In addition, ballast should be resistant to weathering with a tough surface to minimize the formation of hairline cracks due to the harsh elements [4].

Being the upper most layer in the substructure, the ballast layer plays a crucial part in transmitting and distributing the wheel load to the rail track foundation as well as to support the rails and sleepers [2]. With time, the ballast would undergo wear and tear from both the axle weight of passing trains and weathering effects, leading to damage and gradation changes of the material. The vertical and horizontal movements caused by traffic loads also lead to deformation and densification of the ballast [5]. This deterioration would result in 'fouling', a phenomenon which compromises the performance of the railway tracks as the ballast layer suffers unduly settlement and water-logging. The severity of fouling is dependent on the type of material, the degree of fouling and chemical composition of the invasive water [6]. Degradation of the ballast layer is usually manifested as 'pumping', i.e. a continuous loop of ballast and subgrade movement which creates on up-down motion of a passing train [1, 10]. This negatively affects the comfort of passengers on board, and exerts greater wearing effect on the rolling stock [7].

According to Bhanitiz [8], macroscopic stresses from external loading cause particle breakage in the ballast, which in turn increases the inter-particle stresses of the smaller, broken stones at more contact points. The combined effect of which is hastened deterioration of the ballast, with heightened ineffective load transfer and distribution among the particulate ballast. It is therefore important to ensure sufficient shear resistance of the ballast layer for good performance of the railway tracks. Referring to the established Mohr-Coulomb's theory, the shear strength of granular materials varies linearly with the applied stress. However, as pointed out by Indraratna *et al.* [9], non-linear stress-strain behaviour can be obtained when soils are sheared at high stresses, or when rocks are subjected to low normal stresses. Furthermore, it was found that the tensile stresses could be reduced as loads are distributed over more contact points with progressive shearing, where the ballast are packed more closely with reduced voids between them.

Ballast could also be contaminated by grease and lubricant oil from leaky braking wheels and fuel leakage from the trains. When the ballast layer is contaminated with either grease or oil, the clogged voids could significantly decrease the track drainage capacity. Imposed load from passing trains would then cause a surge in the pore water pressure due to the reduced drainage capacity [10]. The intruding oil could also affect the overall shear resistance as the ballast slip over one another instead of interlocking. Rubber inclusion is proposed as a solution to this problem. The Rubber Manufacture Association of U.S [11] reported that discarded rubber, especially waste tyres, is among the main contributors to the volume of solid wastes at dump sites. Many of these used rubber tyres and inner tubes are left stockpiled in landfills or illegally dumped, causing unnecessary threat and risks to the environment, such as fire hazards and resistance to decomposition [12]. It would therefore be expedient if these discarded rubber products can be somehow reused. Used tyres, for example, have been shown to be successfully used in geotechnical applications, including slope and riverbank stabilization works, e.g. the application of scrap tyres as earth reinforcement for repair the tropical residual soil slope [13] and as a drainage material for geotechnical purposes [14].

In this paper, it is proposed that the discarded inner tubes, which are thin and relatively flexible, be processed to be used as inclusions in the ballast layer. The rubber inclusion could enhance the shear resistance and deformation of the ballast subjected to the wear and tear effects as discussed earlier [15]. Note that new motorcycle tyre inner tubes were used in the present study to investigate the potential usability of the material without the aging effect. Ordinary engine oil for motorcycles was used as the artificial contaminant. The rubber inclusions were prepared in shredded form to simulate fibre reinforcement found in geotechnical ground improvement techniques.

Fig. 1 Ballasted track
(Depot KTM Gemas Malaysia, 2013)

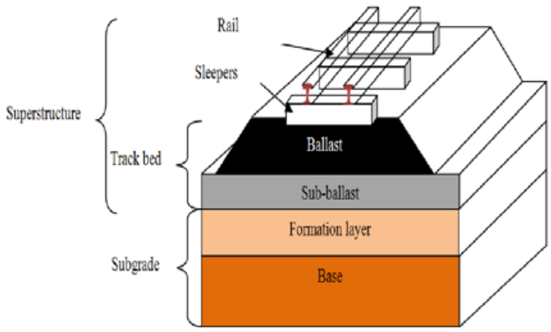

Fig. 2 Cross-section for a typical rail track system

2. MATERIALS AND METHODS

2.1 Test materials

Granitic aggregates were used in the present study as substitute of the ballast. A common igneous rock derivation, the granitic aggregates (ballast) particles had sharp angular edges. The physical properties were evaluated using standard test procedures prescribed in BS 1377 (1990) [16]. With a particle size distribution of 99 % of the particles coarser than 4.75 mm diameter and less than 2% of particles finer than 0.15 mm (Fig. 3), the material was categorized as gravels. The average percentage of wear was found to be 20 %, i.e. within the range 10-20 % as stipulated in BS 812 (1990) [17]. This indicates that the aggregates could provide high resistance against impact forces compared with flaky and elongated stones. The angular-shaped granitic aggregates between the particle sizes of 6.3 to 1.5 mm clearly fulfilled the criteria of particle shape [18]. Note that the aggregates were placed in the shearbox in loose form with no tamping applied. Care was taken to ensure consistent mass of the material, with or without rubber inclusions, for samples' consistency assurance.

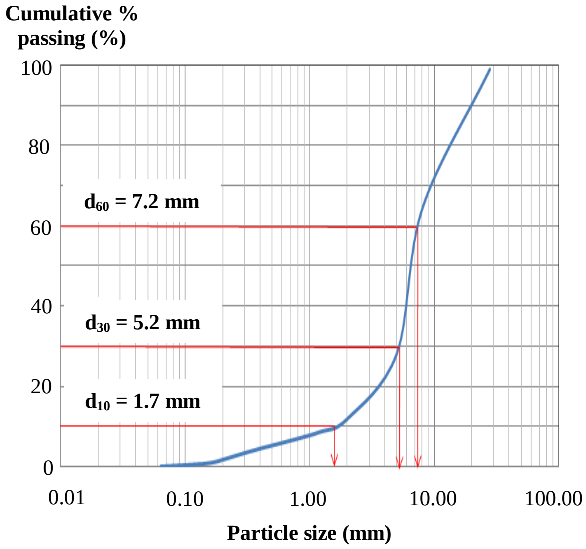

Fig. 3 Particle size distribution of aggregates used in DST

2.2 Preparation of test specimens

The shredded rubber were derived from inner tubes of motorcycle tyres, cut and shaped to produce course and fine shreds for the study. The coarse shreds were 20 mm long while the fine shreds were kept at 10 mm in length (Fig. 4). The different sized rubber shreds were expected to provide different contact area with the ballast, resulting in variations of shear resistance mobilized (Fig. 5). The thickness of the inner tube was approximately 1.5 mm. Lubricant oil was used to simulate the ballast-contaminating oil. This lubricant oil is majority content of base oil with additives. Lubrication oil or lube oil is the most commonly widely used because of the possible applications. Prior to the test, the gravels were soaked with lubricant oil for 14 days to simulate the contamination.

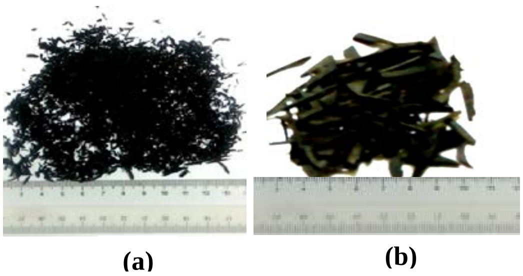

Fig. 4 Fine- and coarse- shredded rubber

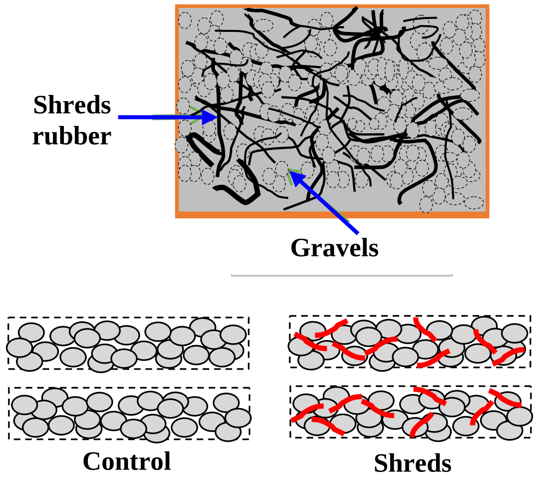

Fig. 5 Schematic diagram for rubber inclusions in the simulated ballast layer

2.3 Direct Shear Test (DST)

The direct shear test was performed to determine the shear resistance enhancement of the ballast aggregates with rubber shred inclusion (Fig. 6). Four main parameters were derived from the tests: τ (shear stress), ε_h (horizontal strain), σ_v (vertical stress), ε_v (axial strain) and ϕ (friction angle). The oil-soaked ballast aggregates were prepared in three configurations, namely CS, SH(C) and SH(F), representing the blank or control specimen, specimens with course and fine rubber shred inclusions respectively. Control specimens (CS) were also prepared and tested as reference data. Fixed static loads were applied to exert vertical stress during the tests, i.e. 5, 7 and 9 kPa. The vertical stress is indicated in brackets at the end of the specimen's notation. Note that the aggregate particle size range was carefully chosen to suit the shearbox dimensions without compromising the shearing mechanism. Indeed, the aggregate used were approximately 10 times smaller than the actual ballast used in rail tracks, i.e. 300-500 mm. The shear box test was conducted at a shearing rate of 0.22 mm/minute as per standard test procedure [16].

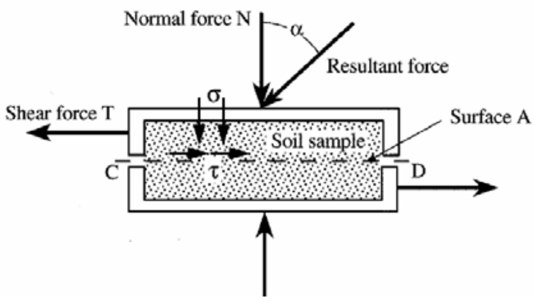

Fig. 6 Schematic of shear box test [19]

3. RESULTS: ANALYSIS AND DISCUSSIONS

The shear stress (τ) - shear strain (γ) plots are shown in Fig. 7. Shear strain (γ) was derived by dividing the horizontal displacement (δ_h) with the sample's original height (h_o). As the samples are loosely placed in the shearbox without given any tamping or compaction, the stress-strain plots were as expected of a loose granular material bring sheared. This is apparent where there were no clearly definable peaks in the plots shown in Fig. 7. Interestingly, as shown in Fig. 7(a), the comparable 'dry' specimens with no prior soaking in oil (denoted 'D') did not seem to respond very differently towards shearing. However at σ_v = 9 kPa, CS(0)(9) did attain a much higher τ than its oil-contaminated counterpart, suggesting the adverse effect of the oil in reducing shear resistance of the ballast. Other irregularities in the τ-γ plots are mainly attributed to the variable angularity and sizes of the aggregates used.

Higher stresses induced greater displacement and strain, though the rubber shred inclusions clearly restrained deformation better than the aggregates alone. As can be noted from the plots in Fig. 7, at 5 % γ, τ increased in the ascending order of CS < SH(F) < SH(C), with SH(C) recording an additional 10 % shear resistance compared to the CS sample. This suggests that the course rubber shreds produced more effective frictional contact with the aggregates. The larger surfaces of the course shreds would have provided more exposed planes of contact with the aggregates, where the angular edges formed a firm grip with the rubber shreds when sheared.

As in all samples, with or without rubber shred inclusions, the shear stress was found to increase with the vertical stress applied. This is to be expected as the frictional resistance increased under greater compression loads. It is also apparent that all the plots rose almost linearly before gradually reaching a plateau. The plateau observed in all cases could be attributed to maximum shear resistance being exceeded, and the samples lapsing into continuous deformation with no more volume change, i.e. shear deformation. This is verifiable with Fig. 8 where the vertical and horizontal displacements were plotted against each other.

Note the constant δ_v with increasing δ_h at the turn of the δ_v-δ_h plots (Fig. 8). The plateau indicates change in shape unaccompanied by change in volume. However the samples also showed variations in the onset of the plateau, in the ascending order of SH(F) < SH(C) < CS. Indeed, SH(F) displayed greater resistance against vertical displacement initially, before undergoing significant settlement from approximately δ_h = 0.3 mm. Constant δ_v was not attained till about δ_h 0.5 mm. On the other hand, the CS and SH(C) samples did not show such curvatures in the δ_v-δ_h plots, i.e. an almost linear departure from the origin before the plateau was reached. This could be suggestive of the finer rubber shreds giving more effective control of the aggregate-rubber composite's deformation, as depicted by the earlier lock-in of δ_v (see onset of plateau) in the plots of SH(F). Nonetheless very similar final δ_v was recorded for all samples, pointing to the dominating effect of the primary material in the composite, i.e. the aggregates or ballast.

Fig. 9 compiles the volumetric strain (ε_{vol}) and shear strain (ε_h) according to the vertical stress applied, where ε_{vol} was derived by dividing the compressional or negative vertical displacement (-δ_v) with the sample's original height (h_o). It can be noticed that the y-axis has the positive ε_{vol} plotted downwards, i.e. uplifting of the shearbox cap during shearing would be charted as negative ε_{vol} while dropping of the cap would be recorded as positive ε_{vol}. As such, the continuous downward trend of the plots in Fig. 9 indicates reduced height of the sample caused by contraction of the sample being sheared. This corresponds with a consistent decrease in ε_{vol} for all samples, with or without rubber inclusions. The compression or seeming contraction of the samples at the beginning of the tests points to an initially loose sample of granular material less densely packed than the critical void ratio. The loosely packed sample must undergo densification to form a suitable particulate arrangement before steady shear can take place, for shear, i.e. attainment of the critical void ratio.

It would also appear that vertical stress predominated the samples' shearing to failure, with constant ε_{vol} attained at higher γ with increase vertical stress applied. Besides, the ratio of ε_{vol}/γ (derived by the gradient of the average linear section of the plots) prior to stabilization of ε_{vol} can be observed to increase slightly with the magnitude of vertical stress applied in the duration of shearing, suggestive of more significant settlement accompanied by greater shear deformation. Interestingly, the absence of dilation even at the beginning of the tests hints at either particle breakage and/or compression of the rubber inclusions as shearing took place. It is however not discernible in the present study if the shape of the rubber inclusions influenced the cushioning effect.

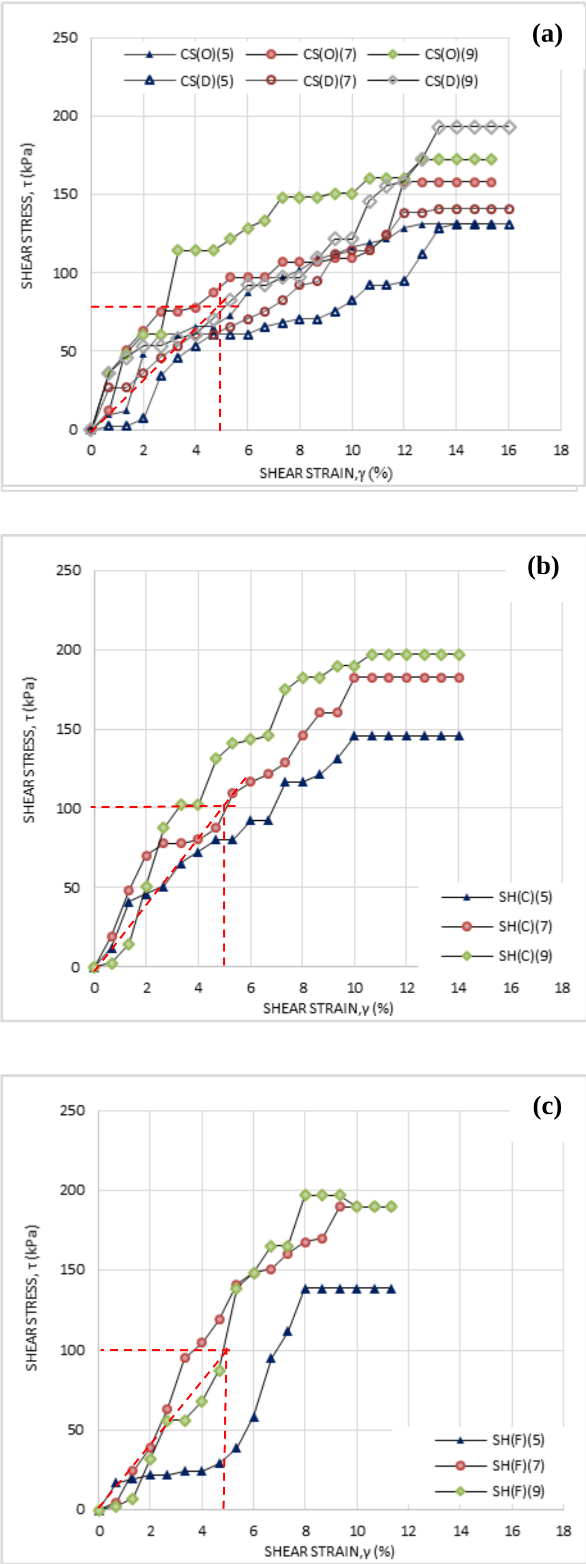

Fig. 7 Shear stress (τ) – shear strain (γ) plots for all specimens

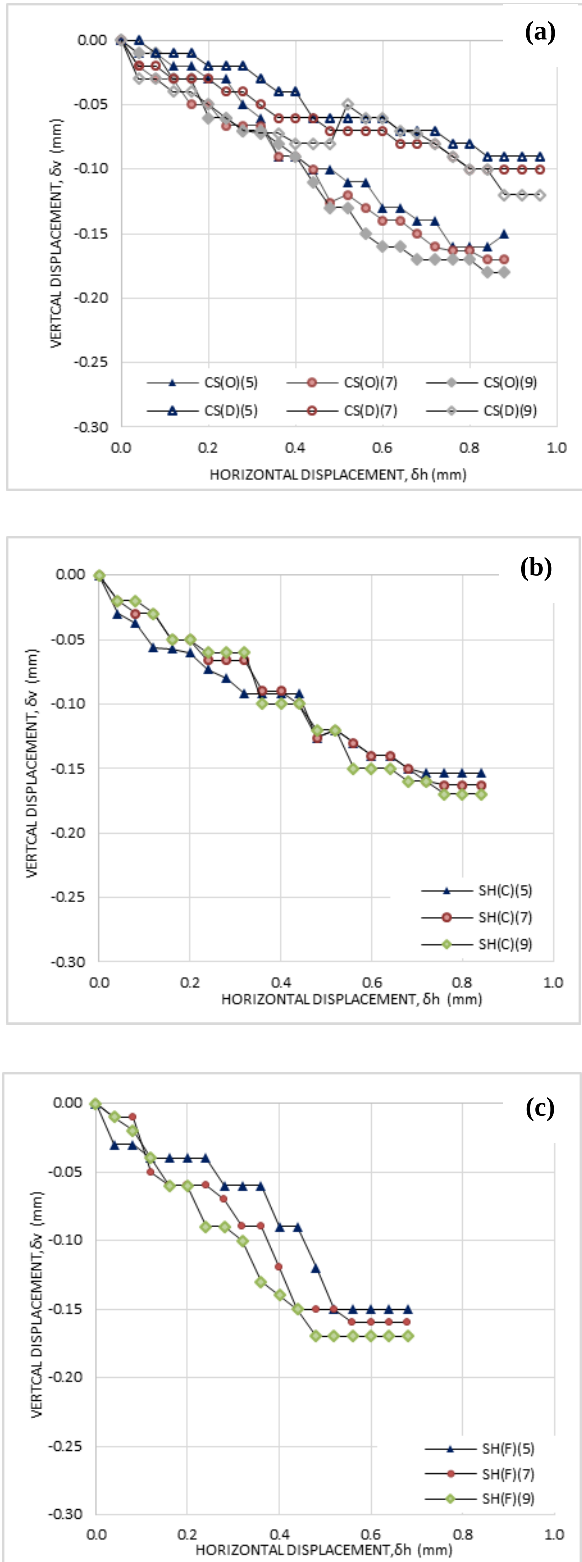

Fig. 8 Vertical (δ_v) - horizontal displacement (δ_h) plots for all specimens

Fig. 10 shows the shear envelope in the plot of shear stress (τ) vs. vertical stress (σ_v). Summary of the resulting internal frictional (ϕ) and dilational (Ψ_{max}) angles are shown in Table 1. Apparently the rubber inclusions produced a greater shear resistance in the simulated ballast, as can be seen from the overlying plots for both SH(C) and SH(F).

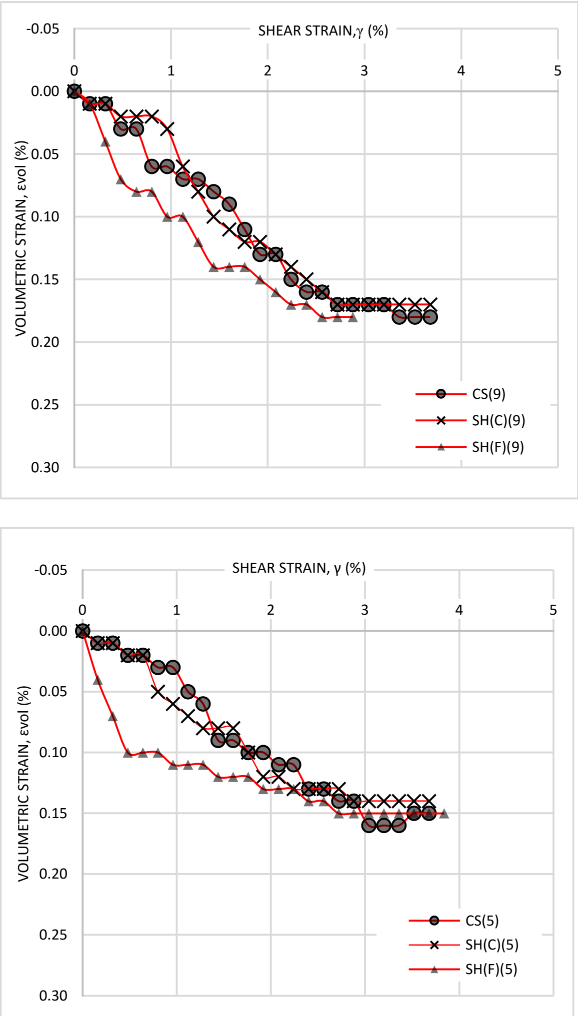

Fig. 9 Volumetric (ε_{vol}) and shear (γ) strains for all specimens

SH(F). Nonetheless the shape of the rubber inclusions did not seem to affect the resulting shear envelope, as shown by the overlapping plots of SH(C) and SH(F). In addition, the friction angle derived from the τ-σ_v plot's gradient was not found to differ significantly, i.e. $\phi \approx 88^{\circ}$. These results correspond with earlier discussions that while the rubber inclusions effectively improved the ballast's shear resistance in an oil-contaminated condition, effect of the shape of the rubber inclusions was not quite distinguishable.

4. CONCLUSIONS

The rubber inclusions were found to effectively improve the shear resistance of simulated ballast layer. The course rubber shreds were good for mobilizing greater shear resistance, i.e. CS < SH(F) < SH(C), and the fine shreds were potentially expedient in limiting deformation of the ballast. Besides, as the rubber shreds were added in small quantities, the shearing mechanism is very much dominated by the aggregates or ballast with records of similar ultimate measurements. A larger scale shearbox test would enable better monitoring of how the shape of the rubber inclusions affects the shearing mechanism of the ballast-rubber composite. Other future aspects to be examined include complementary effect of course-fine rubber shred mixtures in the ballast, effects of dosage variations and drainage characteristics of the composite.

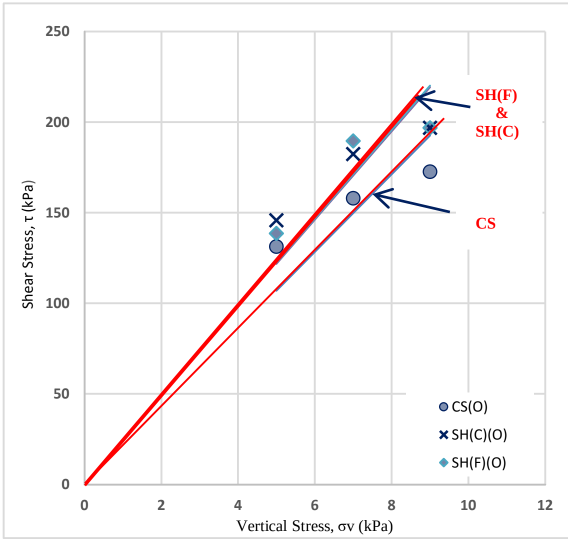

Fig. 10 Shear envelopes for all specimens

Table 1 Summary of frictional (ϕ) and dilational (Ψ_{max}) angles

Specimens	τ_f (kPa)	$\phi(^{\circ})$	$\Psi_{max}(^{\circ})$
CS	80	87	12.0
SH(C)	100	88	12.7
SH(F)	100	87	15.7

5. ACKNOWLEDGEMENTS

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