APPLICATION OF SEMI-RIGID COMPOSITE PERMEABLE PAVEMENTS IN ROAD NETWORK

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ABSTRACT

Use of Permeable Paving Systems (PPS) in road transport networks has been gaining more attention due to benefits such as minimising surface run-off, decreasing the risk of flash flooding and reducing pollutants deposited in waterways. Simultaneously the increasing stockpiles of waste tyre and its non-biodegradable nature leading to negative environmental impacts and associated hazards have posed increased attention to seek innovative sustainable solutions for reducing tyre stockpiles. Crumb rubber has enhanced properties that allow it to be a suitable substitution for rock aggregate in PPS. By using mixtures of tyre and rock aggregates and engineered level of binders the flexibility of PPS can be optimized based on the application to accommodate differential settlements thus reducing degradation and cracking commonly observed in conventional permeable pavement systems. This can ultimately lead to an increase in serviceability and minimising costly maintenance works and more importantly expand the range of applications permeable pavements can be used in. This study reports on the mechanical behaviour of a range of semi-rigid PPS products incorporating tyre crumbs for surface paving with high drainage capability for mitigation of storm-water run-off.

The transient stiffness-deformation behaviour of a range of permeable pavement systems with varying tyre crumb content and binder type under variable loadings was investigated. In the first step, different mixing ratios of crushed rocks (rigid aggregate) and tyre crumbs (soft aggregate) were tested in the laboratory to find the optimum mixtures fit for different applications. Constraint modulus and shear wave velocity tests were carried out to establish the mixtures which their performance changes from rigid-type to soft-type with varying pressure level. Results of this step provide an insight into the formation of force chains in the mixtures ultimately providing the most formidable mix ratio resulting in transitional soft to rigid behaviour.

In the next step different binder types (polyurethane based) and percentages were added to selected blends to investigate the performance of polymer bonded tyre-rock aggregates under static and dynamic loads. Test results suggest that the quality of binder only shows its impact for tyre contents higher than 30%. In blends with higher tyre contents the force chains mostly pass through tyre aggregates and hence the deformation of tyre aggregates puts more strain on binder film causing the lower grade binders to fail. Same low grade binders show satisfactory results when tested with mixtures up to 30% tyre content.

Preliminary test results suggest that the optimum mixture of tyre and rock aggregate with the right binder type and ratio can produce a permeable pavement system suitable for car parks and other lightly trafficked areas including pedestrian footpaths.

KEYWORDS*:*

Permeable pavement, waste tyre, transient rigid-soft aggregate mixtures, constraint modulus

1 INTRODUCTION

The rapid economic development of modern societies has led to a dramatic rise in waste generation. Disposal of end of life tyres is constantly increasing in Australia. Mountjoy, et al. (2015) reported that 51 million equivalent passenger units (EPU) of Australian tyres is entering the waste stream annually of which approximately 5% are recovered through recycling activities. The environmental impacts of landfilling the waste tyres along with the safety risks associated with maintenance of the landfills against fire hazards calls for innovative solutions of recycling this non-biodegradable waste back into engineering applications. There has been intensive research dedicated to assessment of hazards of disposing tyres to landfills (Ma and Hipel, 2016, Collins, et al., 1995). In addition, the mechanical properties of tyre scraps were analysed for industrial applications such as concrete manufacturing, pavement constructions, earthfills and highway embankments (Aisien, et al., 2006, Garga and O'shaughnessy, 2000). However, the high compressibility of tyre-derived aggregate (TDA) limits their use to marginal applications with low percentages. Although the load bearing capacity of TDA aggregates is relatively low, their high elastic flexibility can be utilized to accommodate the excessive differential settlement induced by reactive subgrades or vegetation in footpaths.

Conventional road pavements and footpaths in urban areas are typically hard impervious structures. Impermeable surfaces result in augmented surface runoff leading to flash flooding and pollution of waterways. Permeable pavements provide an innovative solution to reduce the impact of flash flooding on paved surfaces and is currently used for stormwater management in some urban areas and in particular to cover the footpath surfaces. However the lack of technical knowledge and legislation in this area of pavement technology has led to insufficient application within the Australian road construction industry (Shackel, et al., 2008).

Contrary to traditional impervious surfaces; permeable pavements permit percolation of water through surface layers alleviating harmful environmental impacts (Brattebo and Booth, 2003). Although the porous structure of conventional permeable pavements can be utilized to accommodate the excess run-off from flash flooding, the rigid contact between the aggregates is vulnerable to settlement-induced stresses, which in turn results in cracks and failure of pavements. This is quite common since permeable pavements are used in areas close to vegetation and also with a less robust structural base or subbase layer. This means small amount of subgrade movement is transferred to the pavement surface layer causing cracks and consequent damage. The flexibility of the permeable pavement surfaces that utilize tyre aggregates can to some extent accommodate the differential settlement reducing generation of cracks and pavement deterioration (Scholz and Grabowiecki, 2007, Mullaney, et al., 2015). Although TDA can facilitate the flexibility of the pavement layer, extreme incorporation of TDA can lead to a soft behaviour with lower load bearing capacity and high compressibility, which is not suitable for serviceability of the pavement surface. In this study, a transitional behaviour between soft behaviour (governed by TDA) and rigid behaviour (governed by rock aggregates) is defined and the stiffness of the pavement under low and high stress levels are presented. Waste tyre crumbs are studied as a potential substitute to virgin quarried rock aggregate in permeable pavement structures. Successful incorporation of tyre waste as raw materials for pavement construction provides a shift away from high-energy intensive processes involved in quarrying for natural rock. TDA presents a formidable alternative pavement material as it comprises a unique set of properties including uniform gradation (resulting in superior drainage performance), long-term durability, flexibility and resilience (prevents mechanical breakage) and high frictional properties.

2 BEHAVIOUR OF RIGID-SOFT MIXTURES

Granular mixtures can be re-moulded to provide enhanced mechanical and environmental properties. Anastasiadis, et al. (2012) reported that shear strength of rigid only mixtures could be improved with the use of rubber particles (soft particles). The mixture behaviour and properties are dependent on the content of soft particles and the size ratio of the soft particles to those of rigid particles. Kim and Santamarina (2008) reported that the two underlying factors that govern the suitability of mix design in rigid – soft material mixtures are:

- Volume ratio of rigid to rubber particles in the mixture (V_{TDA})
- Size ratio, $S_r = D_{50\ soft}/D_{50\ rigid}$ (D_{50} is the cumulative 50% point of diameter of particles size)

In this study to optimize the porous structure of permeable pavements (high porosity), the D_{50} of the soft and rigid particles was chosen to be essentially similar. The volume fraction of the soft aggregates in the blend was optimized during the experiments to achieve a transient rigid-soft mixture. Most of the research thus far has used sand as the rigid material along with different kinds of tyre scraps to investigate behaviour of rigid-soft mixtures. The impact of size ratio and volumetric content of rigid-soft aggregates based on previous research results is demonstrated in Figure 1. For intermediate volume percentages of soft aggregates, $0.4 < V_{rubber} < 0.6$, rigid particles would be separated at low stress levels by soft particles. By increasing the stress levels the contact between rigid particles increases as the soft particles deform. In these intermediate stresses the material is compressible within recoverable strain limits however at a certain point the rigid particles will form an arch over the soft aggregates trapped in between and load is carried through the rigid structure with minimal further deformation.

When the size ratio in the mixtures deviates too far from one, segregation of the aggregates is likely to occur and the mixes are generally form a compact structure with low porosity. Consequently, a size ratio close to one was selected for this research to develop a mixture with high infiltration capability. A variety of volume ratios (V_{TDA}) in the soft-rigid mixtures were investigated experimentally to obtain a relatively flexible mixture at low stresses (employing the soft aggregates properties) which transforms to a more rigid mix at higher stresses when rigid aggregates come into contact due to deformation of soft aggregates.

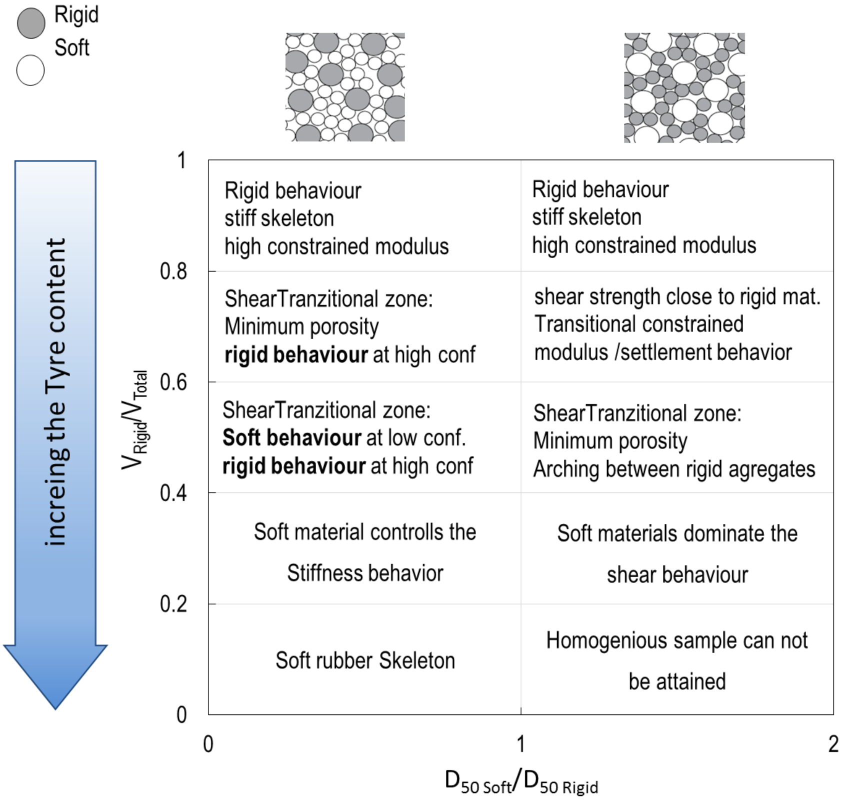

Figure 1: Impact of size ratio and volumetric content of soft aggregates on the overall behaviour of the mix

3 MATERIALS AND TEST METHODS

Round shape bulky Crushed Rock (CR) (with mean particle diameter D_{50} = 5 mm, specific gravity G_s = 2.95) and irregular shaped TDA (mean particle diameter D_{50} = 6.8 mm, specific gravity G_s = 1.06) aggregates were used in this study (Table 1). The size limitation was chosen to achieve higher void ratio and consequently higher permeability. The Zero-lateral strain compressibility and rebound potential of tyre–rock mixtures was tested in a modified oedometer cell with an internal diameter of 150 mm. The specimen height was 75 mm ± 2 mm. It is expected that side friction impacts the deformation; however, the diameter/height ratio of tested specimens was kept over 2.0 to minimize the impact of boundary conditions.

The volume fraction of TDA (V_{TDA}) was defined as the ratio between the volume of tyre aggregates and the total volume of tyre-rock blend. Mixtures were prepared with the volume fractions of tyre aggregates of: V_{TDA} = 0.0, 0.3, 0.4, 0.5, 0.6, 0.7, and 1.0. Preparation of homogeneous mixtures needs careful handling and was performed by funnelling the mixed aggregates into the mould to avoid segregation. Segregation is an inherent difficulty in granular mixtures (Kim and Santamarina, 2008) and can be caused by size differences, different density of the tyre and rock aggregates, stiffness, roughness and shape characteristics of the granular aggregates which all should be considered particularly in mixes with large tyre fractions (Edil and Bosscher, 1994). Hence, the samples were prepared with minimum vibration, funnelled in portions to avoid granular flow. The test procedure follows the steps of a conventional consolidation test outlined in ASTM D2435 (2011). The blends are prepared with a relative density of 70% and the vertical stress is applied in stages of 12, 21, 38, 72, 142, 280 and 558 kPa to monitor the changes in void ratio. The stages of loading reversed in the same sequence to monitor the behaviour under unloading. Since some blends showed time dependent behaviour, the settlements are recorded at the end of each stage, typically within 5 min or when the strain rate becomes insignificant. The under-compaction method suggested by Ladd (1978) was used for compaction of specimens to achieve uniform and homogeneous samples.

Table 1: Specification of rigid and soft aggregates

Material properties	Crushed Rock (CR)	Tyre Derived Aggregates (TDA)
Coefficient of uniformity, C_u	2.12	1.51
Coefficient of curvature, C_c	1.15	0.96
USCS[†]	GP[§]	GP[§]
Mean aggregates diameter, D_{50}, mm	5	6.8
Specific Gravity (G_s)	2.81	1.06
Water absorption (%)	2.80	1.11
Sphericity	0.76[*]	0.82[*]
Roundness	0.58[*]	0.38[*]
$\gamma_{d\ Max}$ (kg/m^3)	1589.3[‡]	595.9[‡]
$\gamma_{d\ Min}$ (kg/m^3)	1240.9[‡]	369.4[‡]

[†] USCS = unified soil classification system

[§] Poorly graded Gravel

[*] Calculated based on Cho, et al. (2004) suggestion

[‡] Measured based on ASTM D4253 (2016)

The modified oedometer cell is equipped with bender elements for measurement of shear wave velocity under different stress levels during the one-dimensional compression test. The transmitter bender element was mounted on the bottom pedestal of the cell and the receiver was fitted in the top loading cap. RIGOL DG1022 signal generator was used to generate a 10 V input sine shaped signal. The transmitted and received signal are digitized with a sampling frequency of 400 kHz. The simplified schematics of the modified oedometer cell and arrangements of the transmitter and receiver bender elements is shown in Figure 2.

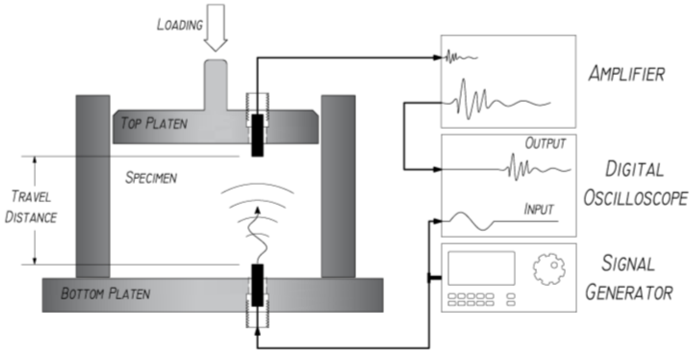

Figure 2: Schematics of the one-dimensional consolidation setup

4 RESULTS AND DISCUSSION

The accumulative vertical strain of different blends of CR and TDA is recorded by increasing the vertical stress levels. At each stress level, the vertical displacement at the top of the sample was recorded. The changes in vertical strain is translated into change in void ratio and plotted against the applied vertical stress to obtain a comparative settlement behaviour (Figure 3.a). The initial void ratio of almost all the blends are balanced around 1.0 for a relative density of 70% except for the specimen prepared with 100% of TDA due to difficulties in compacting the specimen. The plastic deformation of loading cycle for rigid aggregates (100% CR) reduces the void ratio to 0.9 and the elastic (recoverable deformation) after the unloading cycle is almost negligible. Similar to results presented by Kim & Santamarina (2008) and also Lee, et al. (2009) the deformation of the blends is controlled by the rigid aggregates up to V_{TDA} of 0.3 and despite the marginal increase to the elastic deformation, the plastic deformation stays within the same range. By increasing the TDA content beyond this level, the elastic deformation increases rapidly as can be observed from Figure **3**.a. The total elastic settlement at the end of loading sequence (558 kPa) for $V_{TDA} = 0.4$ is approximately twice as much as that of $V_{TDA} = 0.3$. The reduction of rigid aggregates (CR) contact decreases the cushioning effect of soil matrix structure support and leads to increase in elastic deformation of the specimen. The volumetric behaviour results obtained from the one-dimensional compression test shows that the transition from rigid behaviour to soft behaviour starts at the vicinity of 30% TDA. The dominant behaviour of rigid aggregates with higher stiffness and low volumetric strains changes noticeably after 30% TDA content. This change in behaviour transfers from rigid to soft behaviour gradually up to 50% TDA content, after which the soft materials take over and dominate the overall behaviour of the mixture (Figure 3.b).

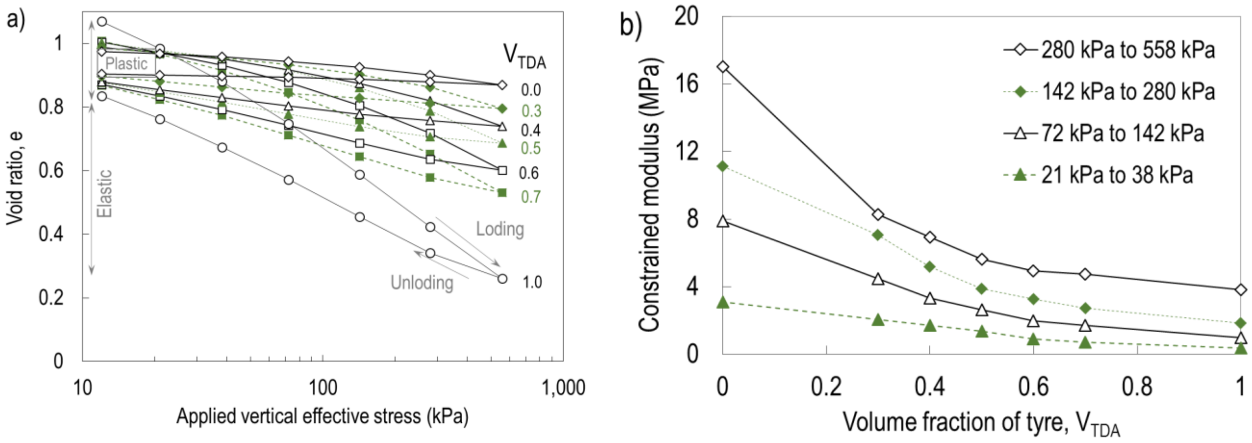

Figure 3: a) change in void ratio based on one-dimensional compression test b) Reduction of constrained modulus with addition of TDA

The constrained modulus which represents the ability of the blends in withstanding against the one dimensional deformation ($M = \Delta\sigma_v/\Delta\varepsilon_z$) was computed between successive loading steps. The semi-empirical power function suggested by Kim and Santamarina (2008) can be seen in the log–log scale presented in Figure 4. The constrained modulus is highly sensitive to V_{TDA} and also the type of binder.

$$M = M_1(\sigma'_v)^m \tag{1}$$

The constrained modulus at $\sigma'_v = 1$ kPa is defined as M_1, while m indicates the sensitivity of the mixture stiffness to stress levels (Figure 4.a). The constrained modulus experience a sharp decrease from $V_{TDA} = 0.0$ to $V_{TDA} = 0.3$ and then gradually decreases up to $V_{TDA} = 0.6$ after which the remaining stiffness is negligible (Figure 4.a). The sensitivity of the blend to the level of stress is almost constant up to $V_{TDA} = 0.5$ which shows that the rigid structure of particles is actively dominate the stiffness of the blend; however, increasing the TDA content beyond this point increases the sensitivity of blends to stress level significantly. The linear function of constrained modulus on the log-log scale shows the impact of confinement on improving the stiffness (Figure 4.b). The stiffness improvement is more significant for blends with higher TDA content.

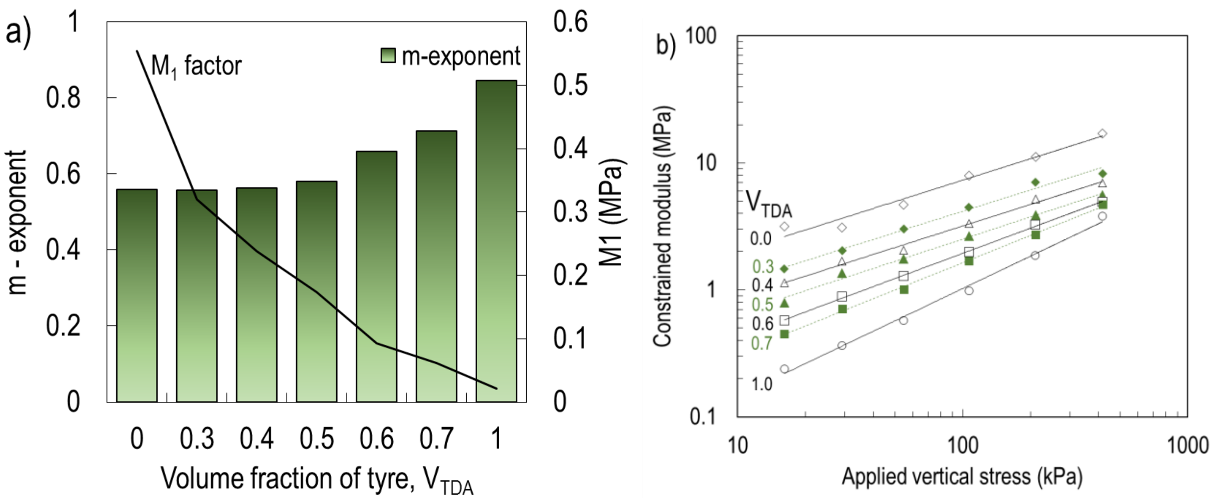

Figure 4: a) Coeficients of constrained modulus model b) Constrained modulus of soft-rigid blends under K_0 loading

The measured shear wave velocity closely demonstrates the observation made during the one-dimensional compression test. Figure 5.a shows the increase in the shear wave velocity in a log-log scale by increasing vertical stress. Similar to observation made from constrained modulus results, blends with TDA content less than 0.3 have shear velocities close to 100% rigid aggregates blend and blends with TDA content over 0.6 have low shear wave values close to 100% soft sample. A significant drop in shear wave velocity can be observed between V_{TDA} = 0.5 and 0.6. It is worth mentioning that collecting a meaningful received signal for samples with higher TDA content at low stresses was not possible.

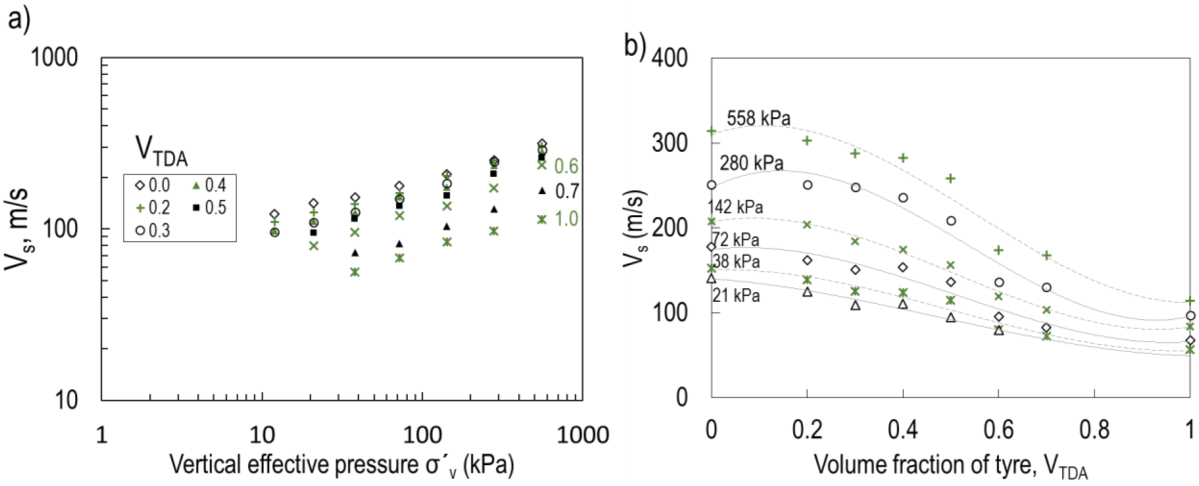

Figure 5: Variation of shear wave velocity in soft-rigid blends under K_0 loading with a) various verticall stress and b) volume fraction of TDA

Based on the observed results, blends with 30%, 40% and 50% TDA content (by volume) demonstrate the transitional behaviour between soft and rigid behaviour and were chosen as the optimized blend for preparation of PPS samples. The optimized blends were mixed with three different polyurethane based binder formulations having varying properties namely; strongest in compression, tension and setting time. Here on, they will be referred to as binder 1, binder 2 and binder 3 respectively. The binder content was also chosen as volumetric fraction of blends and chosen to be 10% of the volume of mixture. Although the addition of polyurethane binder reduces the volumetric fraction of soft and rigid aggregates in the mix, the ratio between the soft-rigid aggregates was similar to the unbound phase of testing (Table 2). Table 2 summarises the volume fractions of materials used in preparation of the blends and further displays targeted and actual density of the samples (after demoulding).

Table 2. Volume percentages and densities of PPS specimens prepared for one-dimensional tests

Specimen Identification	TDA content, (% by Volume)	CR (% by Volume)	Binder (% by Volume)	Targeted density at D_r = 70% (t/m^3)	Sample density (t/m^3)
50% TDA : 50% CR : 10% Binder	45.0	45.0	10	0.99	0.97
40% TDA : 60% CR : 10% Binder	36.0	54.0	10	1.07	1.05
30% TDA : 70% CR : 10% Binder	27.0	63.0	10	1.15	1.14

To further investigate the stiffness behaviour of the specimens under K_0 loading, the constrained modulus was measured from the deformation observed in the one-dimensional test on the bound samples with 10% binder for all 3 binders. Since the specimens are bound with the polyurethane binder, the loading was further continued to 1,116 kPa before proceeding to unloading path (Figure 6).

Generally, the constrained modulus of the samples stabilized with polyurethane are significantly higher than that of unbound specimens. The specimen with 30% TDA is insensitive to binder type and due to well-distributed force, chains between the rigid aggregates demonstrate minimum amount of settlement. Additionally the constrained modulus of the specimen increases by increasing the stress level similar to that of blend with no binder. However, when the TDA content increases to 40% and 50%, the reduction in rigid-rigid contact imposes compression strains on the binders. It should be noted that at vicinity of 100 kPa – 200 kPa the rate of increase in constrained modulus reduces in specimen with 40% TDA and flattens in specimen with 50% TDA. Since the compression and shear properties of the first two binders are similar, the deformations are minimal and constrained modulus shows similar increasing trend. Although the behaviour of specimens with binder 1 and 2 are similar for 30% TDA content, when the TDA content increases to 40% and 50%; the load bearing capability and deformability of the binder is becoming more important. Hence, specimens with binder 2 show a minor failure at the vicinity of 50 kPa that reduces the rate of increase in constrained modulus. Specimens with binder 1 experience this minor failure at a higher stress level, namely 200 kPa for samples with 40% TDA and 100 kPa for samples with 50% TDA. The lower compressive capability of binder 3 is vividly reflected on both compressibility and stiffness of the mixtures to the point that the constrained modulus starts to decline after the applied pressure level of 100 kPa. The deformability of TDA aggregates can potentially cause adhesive failure between the surface of soft TDA aggregates and the rigid binder at higher pressures, which eventually leads to sample failure.

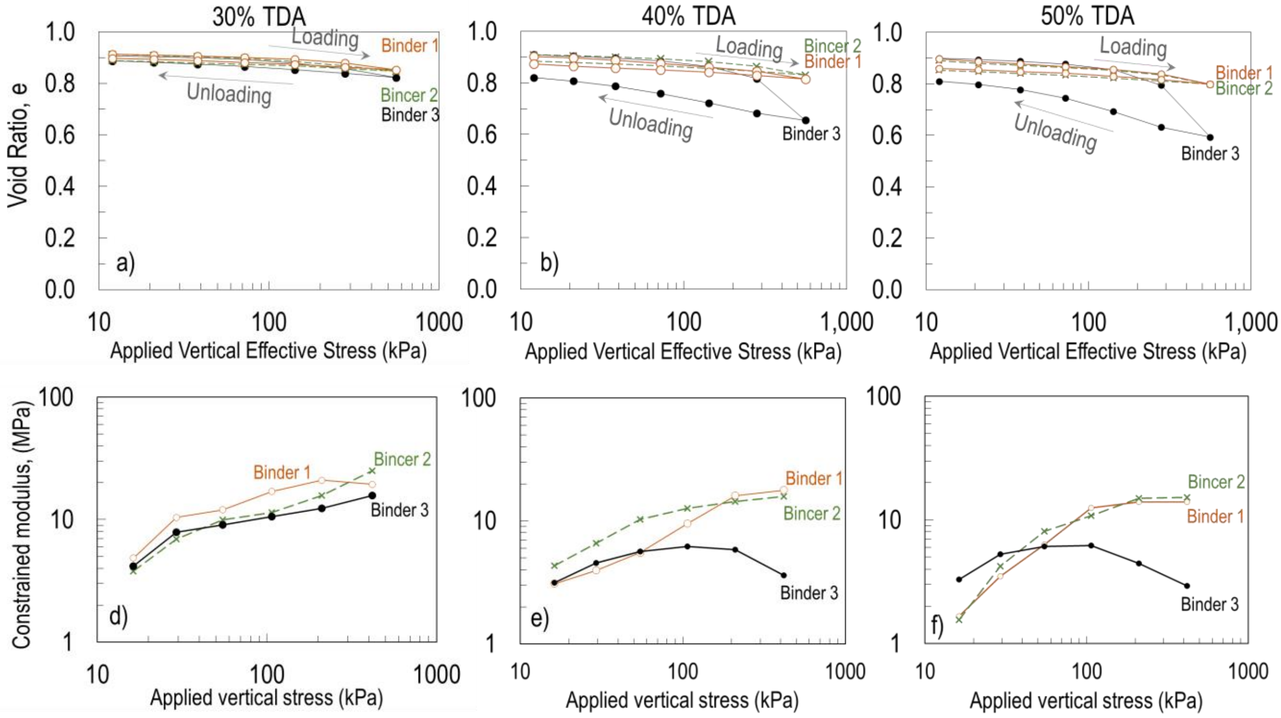

Figure 6: One-dimentional compresion of the rigid-soft blends and the calculated constrained modulus of the bound specimens

5 CONCLUSIONS

With increasing concerns on current unsustainable management of waste tyre in Australia, it is rudimentary that end of life tyres are put into useful applications. Tyre waste when not disposed of appropriately can cause significant negative environmental impacts due to its irregular shape and non-biodegradable nature. Therefore, this study investigates the feasibility of utilizing tyre-derived aggregates to formulate a permeable pavement composition that would yield high performance both mechanically and environmentally. Different compositions of tyre crumb-rock were tested with the use of TDA as a substitute for conventional crushed rock aggregate to evaluate the most formidable mix design for a permeable pavement. The rate of variation of constrained modulus and shear wave velocity obtained from one-dimensional compression test and shear wave velocity revealed that the rigid skeleton controls the behaviour for $V_{TDA} < 0.3$ while the tyre skeleton prevails at $V_{TDA} \geq 0.5$. The intermediate blends experience a transitional behaviour when tyre particles tend to be squeezed at high confinement and fill the interfacial voids and a considerable increase in rigid-to-rigid coordination is anticipated to increase the stiffness. The presented observations provide the basis for optimal design of heterogeneous granular materials made of rigid and soft aggregates for permeable pavement application. The transitional range can be utilized to allow the pavement to be flexible, when there is no stress imposed on the pavement mitigating formation of cracks. The same pavement will possess the ability to be rigid enough to withstand lightly trafficked loads when due to applied stress rigid particles come in contact forming rigid force chains. The overall constrained modulus of the soft-rigid blends is significantly increased by mixing the blend with polyurethane binder. The type and strength properties of the polyurethane binder plays a significant role at the overall strength of the blend particularly for samples with higher TDA content. More research need to be conducted to adapt the properties of the binder to complement the shortcomings of granular soft-rigid mixture.

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