Shear strength and dilatancy behaviour of sand-tyre chip mixtures

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Abstract
Sand-tyre chip (STCh) mixtures can be used in many geotechnical applications as alternative backfill material. The reuse of scrap tyres in STCh mixtures can effectively address growing environmental concerns and, at the same time, provide solutions to geotechnical problems associated with low soil shear strength and high dilatancy. In this paper, the shear strength and dilatancy behaviour of STCh mixtures have been investigated. A series of monotonic triaxial tests has been carried out on sand mixed with various proportions of tyre chips. It has been found that tyre chips significantly influence the shear strength and the dilatancy behaviour of STCh mixtures. The effects of confinement and relative density on the shear strength, dilatancy and initial tangent modulus of the STCh mixtures have also been investigated. Moreover, a dilatancy model for STCh mixtures has been proposed and validated with the experimental results.

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Shear Strength and Dilatancy Behaviour of Sand–Tyre Chip Mixtures

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Nomenclatures

BSE: Bounding Shear Envelope

$c_\alpha$,: Intercepts of shear envelopes (.. : d (dilatancy), b (bounding), CSR)

CSL: Critical State Line

CSR: Constant stress ratio

CSRSE: Constant stress ratio shear envelope

$C_u$: Uniformity coefficient

$C_c$: Coefficient of gradation

d: Dilatancy

D: Specimen diameter (mm)

D50: Specimen of 50 mm diameter and 100 mm height

D100: Specimen of 100 mm diameter and 200 mm height

d$_0$: Dilatancy parameter

1, $d_2, d_3, d_4$: Calibration parameters for $d_b$

d$_b$: Dilatancy at peak stress

$d_{eq}^p$: Variation of the plastic volumetric strain

$d_{eq}^p$: Variation of the plastic deviatoric strain

$D_r$: Relative density

DSE: Dilatancy Shear Envelope in stress ratio-dilatancy relationship

e..: State Line (.. : d (dilatancy), b (bounding), CSR)

$e_{p,:}$: State line void ratio at $p'=1$ kPa (.. : csl (critical), d (dilatancy), b (bounding), CSR)

$e_{m}(\chi\%):$ Void ratio of matrix material with $\chi\%$ of TCh

$e_{max,m}$: Maximum matrix void ratio

$e_{max,s}$: Maximum sand void ratio

$e_{max,STCh}$: Maximum void ratio curve for STCh mixture at different percentages of TCh

$e_{max,TCh}$: Maximum TCh void ratio

$e_{max}$: Maximum void ratio of a given material

$e_{min,s}$: Minimum sand void ratio

$e_{min,STCh}$: Minimum void ratio curve for STCh mixture at different percentages of TCh

$e_{min,TCh}$: Minimum TCh void ratio

$e_{sm}$: Sand matrix void ratio

$e_{TChm}$: TCh matrix void ratio

$G_{s,Sand}$: Specific gravity of sand
Specific gravity of TCh: $G_{s,TCh}$

Specific gravity of STCh mixture: $G_s$

Initial tangent modulus: ITM

Tyre chip length (mm): L

Frictional constant parameter ($\ldots$: d (dilatancy), b (bounding), CSR): $M_{..}$

Equivalent frictional parameter ($\ldots$: d (dilatancy), b (bounding), CSR): $M^*_{..}$

Dilatancy parameter in stress ratio-dilatancy relationship: $m$

Total mass of STCh for a given $\chi\%$ (kg): $m_t$

Effective mean stress (kPa): $p_0'$

Atmosphere pressure (101.3 kPa): $p_u$

Intercepts q-p' plane ($\ldots$: d (dilatancy), b (bounding), CSR): $q_{0.}$

STCh: Sand-tyre chip

TCh: Tyre chips

Volume of specimen ($m^3$): V

Volume of particles of matrix material for $\chi\%$ at a volume $V$ ($m^3$): $V_{pm}(\chi\%)$

Volume of void of mixture for $\chi\%$ at a volume $V$ ($m^3$): $V_{void}(\chi\%)$

Tyre chip width (mm): W

Dry unit weight (kN/m$^3$): $\gamma$

Axial strain (%): $\varepsilon$

Deviatoric strain (%): $\varepsilon_q$

Volumetric strain (%): $\varepsilon_p$

Effective stress ratio: $\eta^*$

State line index ($\ldots$: csl (critical), d (dilatancy), b (bounding), CSR): $\lambda_{..}$

Effective confining pressure (kPa): $\sigma_3'$

Shear envelope friction angle ($\ldots$: d (dilatancy), b (bounding), CSR): $\phi_{..}$

Gravimetric percentage of tyre chips: $\chi$

State parameter: $\psi$

Modified state parameter ($\ldots$: d (dilatancy), b (bounding)): $\psi^*$
Shear Strength and Dilatancy Behaviour of Sand–Tyre Chip Mixtures

ABSTRACT

Sand-tyre chips (STCh) mixture can be used in many geotechnical applications as an alternative backfill material. The reuse of scrap tyres in STCh mixture can effectively address growing environmental concerns and at the same time provide solutions to geotechnical problems associated with low soil shear strength and high dilatancy. In this paper, shear strength and dilatancy behaviour of STCh mixture have been investigated. A series of monotonic triaxial tests have been carried out on sand mixed with varying proportions of TCh. It has been found that TCh significantly influences the shear strength and the dilatancy behaviour of STCh mixture. The effects of confinement and relative density on the shear strength, dilatancy and initial tangent modulus of the STCh mixture have also been investigated. Moreover, a dilatancy model for STCh mixture has been proposed and validated with experimental results.

Key words: tyre, sand-tyre chips mixture, triaxial testing, shear strength, dilatancy, initial tangent modulus
1. Introduction

The volume of scrap (end-of-life) tyres generated every year is increasing due to increase in the number of vehicles worldwide. It is estimated that 1.5 billion tyres reached their end of life every year in recent years (ETRMA, 2012). In the early 1990s, about one billion scrap tyres were stockpiled in the USA. In addition, the rate of recovery of the scrap tyres was only 11% (RMA 2009). In the EU in 1994 the recovery rate of scrap tyres was 38% (ETRMA, 2006). The ban on the disposal of scrap tyres in landfills together with the effective scrap tyre management programs have increased the scrap tyre recovery rate in many countries.

At present, the recovery rate of the scrap tyres has been increased to 80-95% in the USA, Japan and EU (ETRMA, 2012). Hence, scrap tyres have become an available important secondary raw material (ETRMA, 2011), which can be effectively used in civil engineering projects. The unique properties of scrap tyres (tyre shreds or tyre chips) that are significant for civil engineering applications include low density, good insulation properties, good drainage capability, good long-term durability, high compressibility and low earth pressure.

Despite the beneficial engineering properties of scrap tyres, in 2010 only 7.4% of the scrap tyres in the European Union (ETRMA 2011) and in 2011 only 7.8% of the scrap tyres in the USA (RMA 2011) were used in Civil Engineering applications. This might be because of lack of adequate ways and methods for environmentally friendly recycle of reuse of scrap tyres in civil engineering application.

The present uses of scrap tyres (tyre shreds or tyre chips) in civil engineering applications include soil reinforcement in road construction, ground erosion control, slope stabilization, thermal insulation, back fill for retaining wall and bridge abutment, edge drains and pipe trenches, septic system construction, light-rail construction, landfill construction and building...
foundations. However, pure tyre shreds or tyre chips (TCh) may be susceptible to exothermic reactions (Gacke et al. 1997 and Humphrey 1996). Moreover, the use of pure tyre shreds or TCh may compromise the serviceability of permanent geotechnical structures, as tyre shreds and TCh are highly compressible. Hence, research in recent years has been directed towards the use of sand-scrap tyre mixture (Tsang et al. 2012), which is not vulnerable to exothermic reaction (Zornberg et al. 2004). Furthermore, the compressibility of sand-scrap tyre mixture has been found to be significantly less (Bosscher et al. 1997).

The addition of scrap tyres (tyre shreds or tyre chips) in sand was found to improve the shear strength of sand (Ahmed 1993; Edil and Bosscher 1994; Foose et al. 1996; Ghazavi and Sakhi 2005; Rao and Dutta 2006 and Zornberg et al. 2004). However, the addition of tyre crumbs (granulated rubber) in sand was found to reduce the shear strength of sand (Kawata et al. 2008; Masad et al. 1996; Sheikh et al. 2013 and Youwai and Bergado 2003) although the ductility capacity (Sheikh et al. 2010) of the mixture has been found substantial (Sheikh et al. 2013). On the other hand, sand-scrap tyre mixtures were reported to undergo large deformation without distinct peak or failure (Ahmed 1993; Edil and Bosscher 1994; Kawata et al. 2008; Masad et al. 1996; Sheikh et al. 2013; Tatlisoz et al. 1998; Youwai and Bergado 2003 and Zornberg et al. 2004). In addition, sand-scrap tyre mixtures were reported to have low shear modulus and high damping ratio (e.g., Anastasiadis et al. 2012, Kaneko et al. 2013a and Kaneko et al. 2013b), low liquefaction potential (Kaneko et al. 2013a and Kaneko et al. 2013b) and remarkable damping and seismic isolation properties (Kaneko et al. 2013a). Edil and Bosscher (1994), Ahmed (1993), Kawata et al. (2008) and Zornberg et al. (2004) reported that the compaction effort showed negligible effect on the shear strength of sand-tyre chips (STCh) mixtures. The maximum improvement of shear strength was observed for the mixture with TCh content (gravimetric) of 39%, and the optimum density (minimum
void) of the STCh mixture was observed for TCh contents (gravimetric) of 38% to 40% (Ahmed 1993). Ahmed (1993) and Zornberg (2004) observed that the behaviour of sand-tyre shred mixture varied from sand-like to rubber-like with increasing proportion of tyres in the mixture. The differences in the behaviour of sand-scrap tyre mixture were further investigated in Kim and Santamarina (2008), Lee et al. (2007), and Lee et al. (2010). The authors identified, by analysing the small-strain shear modulus \( G_{\text{m}} \) of the mixture, that the mixture exhibits transition from a rigid to a soft granular skeleton with the proportion (%) of tyres in the mixture. The parameters that control the skeleton (behavioural zones) of the mixture were found to be dependent on the relative size of sand and rubber particles and the proportion of tyres in the mixture. The identification of the behavioural zones (sand-like, sand-rubber, and rubber-like) of sand-scrap tyre mixture is fundamental for its use in geotechnical engineering projects. Furthermore, the efficiency of packing influences the behaviour of binary material with high differences in the specific gravities of the constituent materials, rather than the dry unit weight of the binary mixture (Edil and Bosscher 1994).

In this paper, the proportions of TCh in STCh mixture that control the formation of skeleton have been determined using matrix void ratio \( e_m \). The behaviour of STCh mixture for different proportions of TCh under same effective confining pressure, relative density and strain rate has been investigated using monotonic drained triaxial tests. Considering the importance of dilatancy behaviour of the mixture, a dilatancy model for STCh mixture has also been proposed and validated with experimental results. In the dilatancy model, the absence of critical state in the STCh mixture at large deformations has been effectively addressed by the modification of critical state framework to constant stress ratio (CSR).
2. Materials and Methodology

The scrap tyres used in this study are classified as tyre chips (TCh) according to ASTM D 6270. TCh without any steel belt were cut into rectangular shapes for uniform thickness (smaller dimension) of approximately 6 mm. The aspect ratio of tyre chips was 2.8. The maximum width of the TCh is 8 mm (inset (a) in Figure 1). It is noted that the width and thickness of TCh were kept less than 1/6 of the specimen diameter (D) to avoid sample size effect on experimental results. The specific gravity of the TCh ($G_s,TCh$) was 1.12.

The particle size distribution of the sand used in this study has been shown in Figure 1. The Inset (b) in Figure 1 shows the properties of the sand. The sand is classified as poorly graded (SP). The particle size distribution of the sand is close to the sand used in Zornberg et al. (2004). Void ratios for sand, TCh, and STCh mixtures were obtained according to the testing procedures in ASTM D 4253 and ASTM D 4254. However, few additional measures were taken to achieve homogeneous STCh mixture: (i) premixing of sand and TCh; and (ii) a scoop was used instead of the 13 mm funnel recommended by the Standards. It is noted that, segregations was evident for the mixture with TCh content (gravimetric) greater than 40%.

The proportions of TCh by mass, $\chi\%$, in STCh mixtures considered in this study are 0%, 10%, 20%, 30%, 35% and 40%. The corresponding proportions of TCh by volume in STCh mixtures are 0%, 21%, 37%, 50%, 56% and 61%, respectively. The minimum and maximum void ratios of TCh were found as 0.83 and 1.30, respectively. The maximum and minimum void ratios of STCh mixtures ($e_{max,STCh}$ and $e_{min,STCh}$) for different mix proportions are shown in Figure 2.
The specimens D50 (50 mm diameter x 100 mm height) for the consolidated drained (CD) monotonic triaxial tests for different mix proportions have been prepared for the dry mass $m_t$, considering the void ratio the STCh which is a function of the proportion of TCh. The void ratio of the mixture ($e_{STCh}$) is obtained from Figure 2 for a desired relative density and a given proportion ($\chi\%$) of TCh. The specimens were prepared using the dry deposition method in Ishihara (1996), where a scoop was used, instead of cone shaped funnel, due to the size of the TCh. STCh mixture samples were prepared in three layers. Every layer was compacted by carefully tamping the walls of the mould. Afterwards, the samples were saturated to a $B$-value >0.95 using back pressure saturation technique (ASTM D 7181-11). The drained shear tests were then carried out at a strain rate of 0.2 $\%$/min and there was no excess pore pressure developed during shearing. Additionally, a set of drained tests have been conducted on large specimens, D100 (100 mm diameter x 200 mm height), to check the effect of sample size (D50 and D100) on the shear strength and dilatancy of STCh mixture (35% TCh) at effective confining pressure of 69 kPa and relative density of 50%.

3. Experimental Results

3.1 Void ratios

The dependence of maximum and minimum void ratios of STCh mixture ($e_{max,STCh}$ and $e_{min,STCh}$) on the proportion of TCh in the mixture has been shown in Figure 2. It is important to note that the curves presented in Figure 2 may be dependent on the properties (shape and size) of the TCh and sand. It can be observed that $e_{max,STCh}$ and $e_{min,STCh}$ initially decrease with the increase in the percentage of TCh contents for up to 35% (by mass). Afterwards, $e_{max,STCh}$ and $e_{min,STCh}$ increase with the increase in the TCh contents. The lowest values of $e_{max,STCh}$ and
\( e_{\text{min,STCh}} \) have been observed to be 0.46 and 0.25, respectively, for the mixture with 35% of TCh (STCh(35%)). The concept of skeleton material reported in Kim and Santamarina (2008) and Lee et al. (2007) can be used to explain the behaviour of STCh mixture. A skeleton is formed when particles of the same material are in contact with each other and are able to transfer loads. The material forming the skeleton becomes the matrix material. The matrix void ratio \( (e_m) \) is defined by:

\[
e_m(\chi) = \frac{V_{\text{void}}(\chi)}{V_{\text{pm}}(\chi)}
\]  

where \( V_{\text{void}} \) is the total volume of void in the mixture and \( V_{\text{pm}} \) is the volume of the particles in the matrix material.

The matrix void ratio \( (e_m) \) is dependent on the percentage of TCh in the STCh mixture. The maximum matrix void ratio \( (e_{\text{max,m}}) \) feasible is the maximum void ratio \( (e_{\text{max,m}} = e_{\text{max}}) \) of the individual matrix materials in the mixture. This condition enables to determine the two percentages of TCh at which sand and rubber (tyre) stop forming the matrix material. Figure 3 illustrates the variation of STCh void ratio \( (e_{50\%,\text{STCh}}) \), sand matrix void ratio \( (e_{sm}) \) and TCh matrix void ratio \( (e_{TChm}) \) with the percentage of TCh for a relative density \( D_r=50\% \). The intersection of the \( e_{sm} \) curve with the maximum void ratio of sand \( (e_{\text{max,s}}) \) identifies the maximum percentage of TCh up to which sand forms the skeleton (TCh=35%). Any increase above this percentage of TCh in the mixture will force inter-granular void of sand to be greater than \( e_{\text{max,s}} \). Therefore, TCh becomes the matrix material forming the skeleton material of STCh mixture, and sand fills some of the TCh voids, causing segregation. On the other hand, the interception of the \( e_{TChm} \) curve with \( e_{\text{max,TCh}} \) identifies the percentage of TCh in the mixture.
mixture from which TCh begins forming the skeleton (TCh=18%). Any decrease below this percentage of TCh in STCh mixture will increase the inter-chips void and hence tyre chips may not remain in contact with each other. In such a case, sand forms the skeleton and becomes the matrix material. Between 18% and 35% of TCh in the mixture, the skeleton is formed by both sand and TCh, such that sand and TCh collectively contribute towards the load transfer.

Based on the above analyses, two percentages of TCh have been used to define three behavioural zones that explain the mechanism of STCh mixture (Figure 3). This is in agreement with the observations reported in Ahmed (1993) and Zornberg et al. (2004). Zone 1 corresponds to sand-like behaviour where sand forms the skeleton (TCh<18%). In Zone 2, sand and rubber form a binary skeleton (18%≤ TCh≤ 35%). Zone 3 corresponds to rubber-like behaviour where rubber forms the skeleton (TCh>35%).

Furthermore, the minimum voids in the STCh mixture for $D_r= 50\%$ and 80% have been achieved at gravimetric ratios of 35% and 40%, respectively, which are in agreement with Ahmed (1993). To fully exploit the beneficial properties of rubber, it is recommended that the STCh mixtures used in geotechnical engineering projects should contain proportions of TCh within the zone two. The percentages of TCh will depend of the properties of the TCh, sand and relative density of the mixture. In this study, the percentages of TCh range between 18% and 35% for $D_r= 50\%$.

3.2 Effect of the proportions of TCh
Laboratory tests have been carried out for 0, 10, 20, 30, 35 and 40% (by mass) of TCh at a constant relative density of 50% and an effective confining pressure of 138 kPa and up approximately 35% of axial strain (\(\varepsilon\)). However, the STCh mixture specimens showed a clear shear failure plane to all the tests and did not exhibit critical state behaviour at shear strain \(\varepsilon=35\%\). Figures 4 and 5 show the deviatoric stress versus deviatoric strain and volumetric strain versus deviatoric strain behaviours of STCh mixture for different proportions of TCh in the mixture. The deviator stress increases with increase in percentage of tyre chips up to 20% and thereafter decreases slightly with the increase in tyre chips. Meanwhile, it is evident from Figure 5 that the dilative behaviour of dense sand decreases with the inclusion of TCh. The dilative behaviour of STCh mixture has been found to decrease with the increase in the percentage of TCh in the mixture.

The three behavioural zones of STCh mixture (sand-like, sand-rubber and rubber-like) mentioned previously are evident in Figures 4 and 5. STCh(0%) and STCh(10%) clearly show the properties of the sand-like behaviour. The inclusion of low percentages of TCh reduces the sand matrix void ratio and increases the sand matrix relative density developing higher strength, initial tangent modulus and dilatancy, as observed in the behaviour of STCh(10%) in Figures 4 and 5. The rubber like behaviour has been observed for STCh(40%). STCh(40%) slightly improves the shear strength of sand but the improvement is lower than that for STCh(35%). At this percentage of TCh, the STCh mixture shows significant reduction of the initial tangent modulus and dilatancy, which are the properties found in rubber. The sand-rubber behaviour has been observed for STCh(20%), STCh(30%) and STCh(35%). These mixtures show improvement in the deviatoric stress and ductility.
capacity, ability of sustain large deformations without failure, together with the reduction in
the initial tangent modulus and dilatancy with the increase in percentage of TCh up to 35%,
demonstrating that skeleton is formed by both sand and rubber.

The highest amount of TCh incorporated into the sand without compromising with the shear
strength of sand but with the reduction of sand dilatancy has been observed in STCh(35%)
for the properties of TCh and sand used in this study. However, it is noted that the aspect
ratio, shape and size of TCh may influence the determination of optimum percentage of tyre
chips. Further research investigations are required for correctly predicting an optimum STCh
mixture for geotechnical engineering projects.

3.3 Effect of Confining Pressure ($\sigma_3'$)

Figures 6 and 7 present the effect of confining pressure on the shear strength and dilative
behaviours of STCh(35%) in comparison with those of STCh(0%) (pure sand). Tests have
been conducted for effective confining pressures of 23, 43, 69 and 138 kPa at initial relative
density of 50%. It is evident from Figures 6 and 7 that confining pressure has significant
influence on the shear strength and dilative behaviour of STCh mixture. As expected, the
deviator stress increases and dilation decreases with the increase in the confining pressure
(Figures 6 and 7). Figures 6 and 7 also compares the effect of sample size (D50 and D100) on
the shear strength and dilatancy behaviour of STCh(35%) at effective confining pressure of
69 KPa. The effect of the sample size (D50 and D100) has insignificant influences on the
peak shear strength and dilatancy of the STCh mixtures.

3.4 Effect of Relative Density
Figures 8 and 9 show the comparisons of deviatoric stress versus deviatoric strain and volumetric strain versus the deviatoric strain behaviour of STCh(35%) and STCh(0%). Tests have been conducted for the STCh mixtures having initial relative densities of 25%, 50% and 75% at a constant effective confining pressure of 69 kPa. It is evident from Figures 8 and 9 that the relative density affects the shear and dilative behaviour of STCh mixture, although to a lesser extent. Both deviatoric stress and dilation increase with an increase in the relative density of the STCh mixture. Furthermore, at all relative densities, STCh(35%) shows greater strength improvement and significant reduction in the dilatancy and the initial tangent modulus compared to those of STCh(0%).

3.5 Initial Tangent Modulus (ITM)

Figure 10 shows the initial tangent moduli (ITMs) of STCh mixtures. It can be observed from Figure 10 that the ITM of STCh(10%) is higher than the ITM of STCh(0%). This can be explained by the fact that up to 10% TCh contents in the mixture, sand forms the skeleton of the matrix material whilst sand void ratio has been reduced by the presence of TCh (sand-like behaviour). It is observed that increase in TCh content beyond 18% decreases the initial tangent modulus of the mixture and this is mainly due to the active involvement of TCh as matrix material. The reduction of the ITM can also be due to the initial compressibility behaviour STCh mixture, (Edil et al. 1994).

Figure 11 shows the variation of ITM for STCh(35%) and STC(0%) with effective confining pressure. It is observed that ITM for STCh(35%) and STCh(0%) increases slightly with the effective confining pressure. As the effective confining pressure increases, the sand matrix
void ratio decreases. This causes higher sand inter-particles contacts which contribute to the increase of ITM.

Figure 12 shows the variation of ITM with relative density of STCh mixture. The increase in the relative density causes an increase in the ITM. The ITM of STCh(0%) is significantly higher than the ITM of STCh(35%) for the same relative density.

3.6 Comparison with other published results

Direct comparison with other published results may be complicated, as the experimental investigation results depend on a number of parameters including specimen preparation, type of scrap tyres, size and aspect ratio of scrap tyres, confining pressure and the type of equipment used. Nevertheless, the results of this study have been compared with two previous investigations (triaxial test results) on STCh mixtures with similar gravimetric percentages of TCh under similar effective confining pressure. The peak deviatoric stress and the volumetric strain at peak deviatoric stress of STCh(35%) at different effective confining pressures were compared with the experimental results in Zornberg et al. (2004) and Youwai et al. (2003). Zornberg et al. (2004) specimens had tyre chips with aspect ratio of 4 (Table 1). The specimens were prepared with sand matrix (relative density of 55%) and 38% of TCh. The triaxial tests were carried out on dry specimens. On the other hand, Youwai et al. (2003) carried out triaxial tests on saturated specimens of sand with tyre crumbs of aspect ratio 1 and the specimens were prepared under dynamic compaction. Youwai et al. (2003) specimens had 30% of tyre crumbs (Table 1).
Figure 13 shows the peak deviatoric stress and the volumetric strain at peak deviatoric stress at different effective confining pressure. Youwai et al. (2003) results show lower peak deviatoric stress mainly due to the inclusion tyre crumbs, rather than tyre chips. Zornberg et al. (2004) shows a higher value of peak deviator stress, which can be attributed to the size of the TCh, compared to the TCh used in this study. In terms of the volumetric strain at peak deviatoric stress, Zornberg et al. (2004) specimens show more dilative behaviour and Youwai et al. (2003) shows less dilative behaviour than the specimens used this study. This is mainly due to the size and aspect ratio of the scrap tyres (Zornberg et al. 2004). Despite the difference on the scrap tyres and test conditions, the findings of this research compares well with the finding of previous investigations.

3.7 Dilatancy behaviour

Figures 14(a-c) show the variation of effective stress ratio ($\eta^* = q/p'$) with dilatancy for STCh mixtures in Zones 1, 2 and 3, respectively. Figure 14a shows the dilatancy behaviour exhibited by STCh(0%) and STCh(10%). It is evident that stress ratio increases with dilatancy irrespective of TCh contents. In this zone, the STCh(10%) shows higher value of $\eta^*$ with $d$ compared to that of sand. Figure 14b shows the $\eta^*$-$d$ behaviour for STCh(20%), STCh(30%) and STCh(35%). These mixtures show unique values of stress ratios ($\eta^*$) at $d=0$ and also at peak stress ratio. However, the slope of the curves increases with the increase in the percentage of TCh contents. The STCh mixture in Zone 3 (TCh=40%) shows similar value of stress ratio at $d=0$ as in Zone 2. However, STCh(40%) achieves a lower peak stress ratio than that for the mixtures in the Zone 2, as expected, since rubber is the only matrix material in Zone 3. It is noted that the post peak dilatancy behaviour decreases for all STCh mixtures.
Figures 15(a-b) show the influence of the initial effective mean stress ($p'_0$) ($p'_0 = \sigma'_3$) for STCh(0%) and STCh(35%), respectively. It is noted that the term effective mean stress instead of effective confining pressure has been used for modelling the dilatancy behaviour of STCh mixtures in the following section, especially for the ease of explanation. It can be observed that the effective mean stress has significant influence on the dilatancy behaviour of STCh mixture. It is evident from Figures 15(a-b) that the stress ratio and dilatancy at peak stress decrease with the increase in $p'_0$. It is noted that initial slope of the dilatancy curve remains constant irrespective of $p'_0$. However, the initial slope of dilatancy for STCh(35%) has been observed to be higher than that of STCh (0%) at all confining pressures. Figure 15b clearly highlights that inclusion of tyre chips decreases the dilatancy of sand. The post peak dilatancy has been found to be decreased at all confining pressures.

Figure 16 presents the effect of relative density ($D_r$) on the $\eta^*$-$d$ behaviour for STCh(0%) and STCh(35%). It is evident that $\eta^*$ increases with the increase in the $D_r$ for both STCh(0%) and STCh(35%). However, the slope of the dilatancy for STCh(35%) has been observed not affected by $D_r$. As expected, the dilatancy for STCh(35%) is significantly lower than that of sand. The post peak dilatancy has been found to be decreased for all $D_r$.

The dilatancy is a fundamental aspect of soil behaviour and is described by the tendency of soil to change volume during shearing (Houlsby 1991 and Taheri et al. 2012). It significantly affects the behaviour of constrained soils. It has been demonstrated from the experimental
investigations that inclusion of TCh in sand (i.e., STCh mixture) controls softening, reduction of strength after peak and further controls the dilatancy of pure sand at all confining pressures. The improvement of sand shear strength together with the reduction of dilatancy behaviour makes STCh mixture an attractive construction material for geotechnical engineering projects. The dilatancy behaviour of STCh mixture has been further investigated and a dilatancy model for STCh mixtures has been developed in Section 4.

4 Dilatancy Model for STCh Mixtures

The dilatancy behaviour of STCh mixture is influenced by the stress ratio ($\eta^*$), percentage of tyre chips ($\chi\%$), effective mean stress ($p_0'$) and relative density ($D_r$). Therefore, the dilatancy ($d=d\varepsilon_p^p/d\varepsilon_q^p$) can be expressed as:

$$\frac{d\varepsilon_p^p}{d\varepsilon_q^p} = f(\eta^*, \chi\%, p_0', D_r)$$

(2)

Li and Dafalias (2000) proposed a stress ratio-dilatancy relationship for sand as:

$$d = d_0 \left( \exp^{\psi m} - \frac{\eta^*}{M} \right)$$

(3)

where, $d_0$ and $m$ are the parameters of the soil mixture, $\psi$ is the state parameter, $M$ is the critical stress ratio and $\eta^*$ is the effective stress ratio. Youwai and Bergado (2003) applied Equation (3) to predict the behaviour of shredded tyre-sand mixtures.
The state parameter ($\psi$), introduced by Been and Jefferies (1985), can be expressed as a function of effective mean stress and void ratio:

$$\psi = e - (e_{csl} - \lambda \ln(p'))$$  \hspace{1cm} (4)

where $e$ is the current void ratio of the material at mean stress $p'$, and $e_{csl}$ and $\lambda_{csl}$ are parameters defining the critical state line (CSL) in the $e$-$p'$ plane.

It is noted that the critical state as defined for conventional soils ($d=0$ and $d\eta^*=0$) does not occur for STCh mixture. Youwai and Bergado (2003) described that the deformation of STCh mixture was due to rearrangement of particles and deformation of tyre chips particles. In the present study it has been observed that at large axial strains ($\geq 20\%$) and $d\eta^*=0$, the dilatancy significantly decreases after softening although $d>0$. Therefore, the conventional critical state may not be obtained for STCh mixture. This slight tendency to dilate after softening may be due to the deformation of the tyre chips in the mixture. This condition of large axial strain ($\varepsilon$) together with $d\equiv 0$ and $d\eta^*=0$ will be referred herein as constant stress ratio (CSR).

The behaviour of the stress ratio-dilatancy curves (Figure 14) clearly shows three stress ratios of interest, $\eta^*(d=0)$, $\eta^*$ (peak) and $\eta^*$ (CSR). Each of these three stress ratios has been directly associated with the three conditions found in the triaxial tests results: $\eta^*(d=0)$ with $\varepsilon_p=\min (\varepsilon_p$ =volumetric strain); $\eta^*$ (peak) with $q=q_{peak}$ (peak deviatoric stress); and $\eta^*$ (CSR) with $\varepsilon\geq 20\%$ and $d\equiv 0$ and $d\eta=0$. A shear envelope has been defined for each of these conditions (Figure 17). Figure 17 shows the variation of shear stress with normal stress for three shear envelopes.
namely dilatancy shear envelope (DSE) ($\varepsilon_p=\text{min}$), bounding shear envelope (BSE) (peak strength) and constant stress ratio shear envelope (CSRSE) ($\varepsilon \geq 20\%$ and $d = 0$ and $d\eta = 0$) for STCh of 35%. It is evident from Figure 17 that the friction angle increases from the DSE to the BSE. However, the friction angle slightly decreases for the CSRSE due to the strain-softening behaviour of STCh(35%). The three shear envelopes for STCh(35%) (i.e., DSE, BSE and CSRSE) show linearity within the range of confining pressure used in this study (23 kPa to 138 kPa). The DSE, BSE and CSRSE for STCh(35%) exhibit cohesion intercepts ($c_0$). These apparent cohesion intercepts are due to of extrapolation of the shear envelopes for low confining pressure (confining pressures below 23 kPa). The cohesion intercepts may facilitate the modelling of the STCh mixture as the nonlinearity of the shear envelopes that might present at low confining pressures may be ignored. It is noted that Humphrey et al. (1993), Masad et al. (1996), Rao and Dutta (2006), Tatlisoz et al. (1998), Youwai et al. (2003) and Zornberg et al. (2004) also reported cohesion intercepts for STCh mixtures.

Three surfaces in the $q$-$p'$ plane corresponding to each shear envelope have been generated using the same concept of the frictional constant parameter $M$. The CSR surface in the $q$-$p'$ plane is defined by the frictional constant parameter at CSR ($M_{\text{CSR}}$). Similarly, $M_d$ is the frictional constant parameter for dilatancy surface at $d=0$. The dilatancy surface corresponds to the transformation phase where the material changes from contractive to dilative (Li and Dafalias 2000). The frictional constant parameter at peak has been associated with the bounding surface $M_p$. This surface captures the strain-hardening properties of the material. The respective frictional constants ($M_d$, $M_p$ and $M_{\text{CSR}}$) and the corresponding intercepts have been calculated according to Equations (5-6). To prevent negative stresses at low normal
stresses, the introduction of a cap surface at $p_0'=0$ and $\eta^* = \eta$ (stress ratio of the stress path, $\eta=3$ for CD triaxial tests) is required.

\[ M_{d,b,CSR} = \frac{6\sin\phi_{d,b,CSR}}{3 - \sin\phi_{d,b,CSR}} \]  
(5)

\[ q_{0d,b,CSR} = \frac{3}{\sqrt{2}} c_{0d,b,CSR} \]  
(6)

where $M_{d,b,CSR}$ is the stress ratio, $q_{0d,b,CSR}$ is the intercept in $q-p'$ plane, $c_{0d,b,CSR}$ is the intercept in shear envelope and $\phi_{d,b,CSR}$ is friction angle for dilatancy surface, bounding surface and CSR respectively. The three surfaces in the $q-p'$ plane have been shown in Figure 18. It is evident that each surface also has an intercept. The experimental data corresponding to the three conditions ($d=0$, peak and CSR) for STCh(35%) have also been included in Figure 18. It is evident that the generation of the surfaces through the shear envelopes can predict the stress ratios.

In Equation (3), $\eta^*$ and $M$ are referred to the origin of the $q-p'$ plane. An equivalent frictional constant, $(M^*)$ for each surface referred to the origin of the $q-p'$ plane has been defined in terms of $p_0'$ and $q_0$.

\[ M^*_{d,b,CSR} = \frac{q_{d,b,c}}{p_{d,b,c}} \]  
(7)

where

\[ q_{d,b,CSR} = M_{d,b,CSR} p_{d,b,CSR}' + q_0 \]  
(8)
\[ p'_{d,b,CSR} = \left(\frac{q_{0d,b,CSR} + \eta p'_0}{\eta - M_{d,b,CSR}}\right) \]

(9)

and \( \eta \) is the effective stress path (\( \eta=3 \) for CD triaxial tests), \( M_{d,b,CSR} \) and \( q_{0d,b,CSR} \) are the frictional constants and equivalent intercepts in the \( q-p' \) plane.

For the three conditions previously mentioned, three state lines have been defined in the \( e-p' \) plane, dilatancy state line \( (e_d) \), bounding state line \( (e_b) \) and CSR state line \( (e_{CSR}) \) (Figure 19).

Each of the state lines is defined by the state line indexes \( \lambda_{d,b,CSR} \) and the state line void ratios \( e_{d,b,CSR} \), STCh parameters. From Figure 19, it can be observed that after the CSR condition has been achieved, the void ratio keeps increasing within the \( e_{CSR} \). This confirms the slight tendency to dilate after softening of the STCh mixtures at large deformations. Thus, a unique CSL could not be established for STCh mixtures (Shipton and Coop 2012). The state parameter \( (\psi) \) adopted in the present study will be referred to the constant stress state line \( (e_{CSR}) \) and named as a modified state parameter \( \psi^* \).

The parameter \( m \) can be calculated at minimum volumetric strain, i.e. \( d=0 \), \( \eta^* = M_d^* \) and \( \psi^* = \psi_d^* \). Hence,

\[ m = \frac{1}{\psi_d^*} \ln \left( \frac{M_d^*}{M_{CSR}^*} \right) \]

(10)
The dilatancy modified state parameter $\psi^*_{d}$ is a STCh mixture parameter given by the vertical distance between $e_{CSR}$ and $e_d$ at effective mean stress at the transformation phase $p_d'$ (Figure 19). Since the frictional constants, $M^*_d$ and $M^*_{CSR}$, vary with $p_0'$, $m$ depends directly on the initial effective mean stress $p_0'$. 

The dilatancy parameter $d_0$ can be calibrated at $M^*_b$ (bounding surface) in terms of dilatancy at peak ($d_b$), where $\eta^* = M^*_b$, $\psi^* = \psi^*_b$ and $d = d_b$. Therefore, $d_0$ can be written as:

$$d_0 = \frac{d_b}{\left( e^{\psi^*} - \frac{M^*_b}{M^*_{CSR}} \right)}$$  \hspace{1cm} (11)

The bounding modified state parameter $\psi^*_b$ is a STCh mixture parameter defined by the vertical distance of $e_b$ and $e_{CSR}$ at effective mean stress at peak stress $p_b'$ (Figure 19).

The value of $d_b$ has been found variable and inversely proportional to the initial mean stress as observed in Figure 15b. A linear relationship has been established to define $d_b$ in terms of a normalized $p_0'$ for STCh(35%):

$$d_b = d_2 - d_1 \frac{p_0'}{p_{at}}$$  \hspace{1cm} (12)

where $d_1$ and $d_2$ are constant calibration parameters of the STCh mixture and $p_{at} = 101.3$ kPa, atmospheric pressure. Figure 20 shows the correlation of the parameter $d_b$ with the normalized initial effective stress $p_0'/p_{at}$. 

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The material parameters, calibration data and generated model parameters have been included in Table 2. These data can be obtained from three CD triaxial tests at different initial effective mean stresses, \( p_0' \). Figure 21 illustrates the dilatancy model prediction using Equation (3) with \( \psi^* \) and \( M^*_{CSR} \) for STCh(35%) at different initial effective mean stresses. The dilatancy model clearly captures the behaviour of the STCh mixtures.

It has been observed that the values of the equivalent frictional parameters (e.g. \( M^*_{CSR} \), \( M^*_d \), and \( M^*_b \)) for STCh in Zone 2 and at \( p_0' = 138 \) kPa are not influenced by the percentage of TCh in the mixture. However, the slope of the dilatancy of these STCh mixtures has been found to increase with the increase in the percentage of TCh in the mixture (Figure 14b). It is clear that the slope of the dilatancy for these mixtures is mainly controlled by the value of \( d_b \). A linear relationship has been established to define \( d_b \) in terms of \( \chi\% \) at \( p_0' = 138 \) kPa:

\[
d_b = f (\chi\%) = d_3 - d_4 \chi
\]  

(13)

where \( d_3 \) and \( d_4 \) are calibration parameters for \( 10\% \leq \chi\% \leq 35\% \) at \( p_0' = 138 \) kPa. Figure 20 shows the correlation of the parameter \( d_b \) with the percentage of TCh at 138 kPa.

Figure 22 shows stress ratio versus dilatancy, test results and dilatancy model prediction, for mixtures in Zone 2 at \( p_0' = 138 \) kPa. The model parameters used to predict the behaviour of the mixtures are the ones corresponding to TCh=35%, assuming that the variation of \( \psi^*_d \) and \( \psi^*_b \) for mixtures in Zone 2 is not significant except for \( d_b \). The values of \( d_b \) have been
calculated from Equation (13). It is evident that the model captures very well the dilatancy behaviour of STCh mixtures in Zone 2. As the optimum STCh mixture can be obtained in Zone 2 (sand-rubber behaviour), the dilatancy model developed herein is mainly applicable for Zone 2. Nevertheless, the dilatancy model presented can be applicable even for Zone 1 and Zone 3, if correct set of parameters ($\phi_{d,b,CSR}$, $c_{0d,b,CSR}$, $\lambda_{d,b,CSR}$ and $e_{\Gamma d,b,CSR}$) are provided.

5 Summary and Conclusions

This paper presents the results of triaxial tests carried out on sand-tyre chips (STCh) mixtures. The behaviour of STCh mixture has been found to be significantly influenced by the percentage of tyre chips (TCh). Three behavioural zones (Zone 1: sand-like, Zone 2: sand-rubber and Zone 3: rubber-like) have been identified. A simple method, based on the identification of two percentages of TCh contents in the mixture, has been proposed to define the behavioural zones of STCh mixtures. Zone 1 has been defined as the mixtures having sand as matrix material, i.e., sand forms the skeleton of the mixture. Zone 2 is constituted by binary matrix where both sand and TCh form the skeleton of the mixture. Significant shear strength improvement together with the reduction in the dilatancy has been observed in Zone 2. In Zone 3, rubber forms the skeleton and the behaviour of the mixture is rubber-like. The mixture in this zone showed similar level of strength of sand albeit with significant reduction in the dilatancy and initial tangent modulus (ITM). In this zone, segregation of the materials has been observed as TCh voids are not fully filled by sand.
STCh(35%) has been identified as the optimum STCh mixture for the TCh used in this study as it includes considerable amount of TCh with significant reduction in the dilatancy and increase in the shear strength of pure sand. It is noted that STCh(35%) is constituted of 65% of sand and 35% of TCh by mass, reducing an average 17% of the sand mass and recycling approximate 460 kg of tyres for each cubic meter of STCh mixture. The influences of confining pressure and relative density have been investigated for STCh(35%). As expected, the shear strength has been found to increase with the increase in the effective confining pressure and initial relative density. On the other hand, the dilatancy has been found to decrease with the increase in the effective confining pressure but increase with the increase in the initial relative density of the mixture. In all cases, STCh(35%) shows improved shear strength with a significant reduction of dilatancy. ITM generally increases with the increase in the confining pressure due to increased interactions between sand matrix and TCh matrix. ITM has been found to increase with the increase in the initial relative density of STCh mixture.

The dilatancy behaviour of STCh mixtures has been modelled with a modified dilatancy function introduced by Li and Dafalias (2000). The dilatancy, bounding and constant stress ratio surfaces in the $q-p'$ have been generated from the shear envelopes at three defined conditions: minimum volumetric strain, peak shear strength and constant stress ratio (CSR), respectively. The presence of cohesion intercepts in the shear envelopes have been represented in the $q-p$ plane by the introduction friction parameters ($M_{CSR}$, $M_d$ and $M_b$) and cohesion intercepts ($q_{0CSR}$, $q_{0d}$ and $q_{0b}$). Their equivalent friction parameters ($M^*_{CSR}$, $M^*_d$, and $M^*_b$) have been introduced to reflect variation of these friction parameters with the initial conditions of STCh. In $e-p'$ plane, the dilatancy, bounding and CSR state lines have been
introduced along with the modified state parameter \( \psi' \) referred to the \( e_{CSR} \) instead of the CSL as for conventional soils.

The calibration parameter \( d_b \) has been found to be dependent on the initial mean stress and the percentage of TCh. Two linear calibration relationships have been established to determine \( d_b \). The dilatancy function well predicts the behaviour of STCh mixtures. Although the dilatancy model has been developed based on the experimental investigations of STCh(35%) in Zone 2, such model can also be applicable for mixtures in other behavioural zones if correct set of parameters is used.

Acknowledgements

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References


Figure 1: Sieve analysis of beach sand used in this study – Picture of Tyre Chips

- **Beach Sand**

- **Tyre Chips (TCh)**
  - $D_{50} = 0.35$ mm
  - $D_{10} = 0.24$ mm
  - $D_{30} = 0.30$ mm
  - $D_{60} = 0.38$ mm
  - $C_u = 1.58$
  - $C_c = 0.99$
  - $e_{\text{min,s}} = 0.55$
  - $e_{\text{max,s}} = 0.77$
  - $G_{s,\text{Sand}} = 2.62$

Figure 2: Minimum and maximum void ratios of STCh mixtures for different proportions of TCh

- **Minimum Void Ratio**
- **Maximum Void Ratio**
Figure 3: Behavioural zones of STCh mixtures ($D_r=50\%$)

Figure 4: Deviatoric stress-deviatoric strain behaviour of STCh mixtures ($D_r=50\%; \sigma'_3=138$ kPa) with different proportions of TCh
Figure 5: Volumetric strain-deviatoric strain behaviour of STCh mixtures ($D_r=50\%$; $\sigma'_3=138$ kPa) with different proportions of TCh.

Figure 6: Influence of effective confining pressure ($\sigma'_3$) on deviatoric stress-deviatoric strain behaviour of STCh(35\%) and STCh(0\%) ($D_r=50\%$)
Figure 7: Influence of effective confining pressure on volumetric strain-deviatoric strain behaviour of STCh(35%) and STCh(0%) ($\sigma_3' = 50\%$)

Figure 8: Influence of relative density ($D_r$) on deviatoric stress-deviatoric strain behaviour of STCh(35%) and STCh(0%) ($\sigma_3' = 69\, \text{kPa}$)
Figure 9: Influence of relative density on volumetric strain-deviatoric strain behaviour of STCh(35%) and STCh(0%) ($\sigma_3'=69$ kPa)

Figure 10: Variation of initial tangent modulus (ITM) with the percentage of TCh in the STCh mixture ($D_r=50\%$; $\sigma_3'=138$ kPa)
Figure 11: Variation of initial tangent modulus (ITM) of STCh(35%) and STCh(0%) with effective confining pressure ($D_r=50\%$)

Figure 12: Variation of initial tangent modulus (ITM) of STCh(35%) and STCh(0%) with relative density ($\sigma_3'=69 \text{ kPa}$)
Figure 13: Peak deviatoric stress versus Effective confining pressure and Volumetric strain at peak deviatoric strain versus Effective confining pressure for experimental data, Youwai et al. (2003) and Zornberg et al. (2004) (See Table 1 for properties of specimens and tests)
Figure 14: Stress ratio-versus dilatancy for STCh mixtures ($D_r=50\%$; $\sigma' = 138$ kPa): a) Zone 1: sand-like, b) Zone 2: sand-rubber and, c) Zone 3: rubber-like
Figure 15: Stress ratio versus dilatancy for STCh mixtures (D_r=50%) at different initial effective mean stresses (p_0): a) STCh(0%) and b) STCh(35%).
Figure 16: Stress ratio versus dilatancy for STCh(35%) and STCh(0%) at different relative densities (\(p'_0=69\) kPa)

Figure 17: Shear envelopes for STCh(35%) at minimum volumetric strain, peak deviatoric stress and constant stress ratio (\(D_r=50\%\))
Figure 18: Dilatancy, bounding and constant stress ratio surfaces for STCh(35\%) in the $q$-$p'$ plane ($D_r=50\%$)

Figure 19: Void ratio versus effective mean stress – Dilatancy, bounding and constant stress ratio state lines for STCh(35\%) ($D_r=50\%$)
Figure 20: Variation of dilatancy parameter $d_b$: i) for STCh(35%) at different normalized initial mean stresses, ii) for $p_0'=138$ kPa at different percentages of TCh.

$$d_b = f(\chi\%) \quad \text{Eq. (13)}$$

$$d_b = f(p_0'/p_{at}) \quad \text{Eq. (12)}$$

Figure 21: Comparison of tests results and model predictions (stress ratio versus dilatancy) for STCh(35%) at different initial effective mean stresses $p_0'$ ($D_r=50\%)$.

$$\eta^* = \frac{p_0'}{p_{at}}$$
Figure 22: Comparison of tests results and model predictions (stress ratio versus dilatancy) for STCh mixtures in Zone 2 ($p_0'=138$ kPa; $D_r=50\%$)
<table>
<thead>
<tr>
<th>Reference</th>
<th>$\sigma'$ (kPa)</th>
<th>Scrap tyre</th>
<th>Specimen</th>
<th>% of scrap tyre</th>
<th>$\gamma$ (kN/m$^3$)</th>
<th>L Length (mm)</th>
<th>W Width (mm)</th>
<th>Aspect Ratio L/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>23, 46, 69 &amp; 138</td>
<td>Tyre Chips</td>
<td>Saturated</td>
<td>35</td>
<td>12.90</td>
<td>20</td>
<td>6 to 8</td>
<td>2.8</td>
</tr>
<tr>
<td>Zornberg et al. (2004)</td>
<td>48.3, 103.5 &amp; 207</td>
<td>Tyre Chips</td>
<td>Dry</td>
<td>38</td>
<td>15.64</td>
<td>50.8</td>
<td>12.7</td>
<td>4</td>
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<tr>
<td>Youwai et al. (2003)</td>
<td>50, 100 &amp; 200</td>
<td>Tyre Crumbs</td>
<td>Saturated</td>
<td>30</td>
<td>14.43</td>
<td>4&lt; L&lt;16</td>
<td>4&lt; W&lt;16</td>
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</tbody>
</table>
Table 2: Parameters of dilatancy, bounding and constant stress ratio surfaces for STCh(35%) and calibration data

<table>
<thead>
<tr>
<th>Surface</th>
<th>Friction Angle (Deg)</th>
<th>Frictional Constant</th>
<th>Cohesion Intercept (kPa)</th>
<th>$q-p'$ plane intercept (kPa)</th>
<th>$e_\Gamma$ at $p'=1$ (kPa)</th>
<th>Slope CSR</th>
<th>State Parameter</th>
<th>Initial Conditions</th>
<th>Dilatancy Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilatancy</td>
<td>$\phi_d=27.6$</td>
<td>$M_d=1.09$</td>
<td>$c_0d=13.7$</td>
<td>$q_{0d}=29.06$</td>
<td>$0.3865$</td>
<td>$\lambda=0.01$</td>
<td>$\psi_d=-0.0455$</td>
<td>$p_0'=23$ kPa</td>
<td>$d_b$ for STCh(35%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M_d^<em>=1.33^{(</em>)}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e_0=0.3522$</td>
<td>Eq. (10)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$m_{(23 \text{ kPa})}=3.37$</td>
<td>Eq. (12)</td>
</tr>
<tr>
<td>Bounding</td>
<td>$\phi_b=39.3$</td>
<td>$M_b=1.60$</td>
<td>$c_{0b}=20.9$</td>
<td>$q_{0b}=44.33$</td>
<td>$0.4155$</td>
<td></td>
<td>$\psi_b=-0.0165$</td>
<td>$p_0'=69$ kPa</td>
<td>$d_b$ for TCh in Zone 2 at 138 kPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M_b^<em>=1.85^{(</em>)}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e_0=0.3465$</td>
<td>Eq. (13)</td>
</tr>
<tr>
<td>Constant Stress Ratio</td>
<td>$\phi_{CSR}=33.8$</td>
<td>$M_{CSR}=1.36$</td>
<td>$c_{0CSR}=22.2$</td>
<td>$q_{0CSR}=47.09$</td>
<td>$0.432$</td>
<td></td>
<td></td>
<td>$p_0'=138$ kPa</td>
<td>$m_{(138 \text{ kPa})}=4.98$</td>
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<tr>
<td></td>
<td></td>
<td>$M_{CSR}^<em>=1.67^{(</em>)}$</td>
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<td></td>
<td></td>
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<td></td>
<td>$e_0=0.3390$</td>
<td>$d_3=0.77$, $d_4=1.44$</td>
</tr>
</tbody>
</table>

$^{(*)}: M_d, M_b$ and $M_{CSR}$ have been calculated at $p_0'=69$ kPa