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Abstract

This paper presents experimental results on the shear modulus of sand-tyre chip (STCh) mixtures. A series of bender element tests was carried out on specimens of sand mixed with varying proportions of tyre chips (TCh). Tests were carried out on STCh mixtures at a constant initial relative density of 50% for different initial effective confining pressures. The bender element test results indicate that the maximum shear modulus of the STCh mixtures increases with effective confining pressure and decreases with the gravimetric proportion of TCh, which ranged from 23 to 138 kPa and 0 to 40%, respectively. However, the strain-controlled cyclic triaxial test results show that the shear modulus at large shear strains decreases with increasing single-amplitude shear strain as a function of the proportion of TCh in the mixture. The lower the proportion of TCh, the larger the degradation observed. The modified Hardin and Drnevich mathematical formulation adequately captures the variation in shear modulus of the STCh mixtures for a wide range of shear strain amplitudes.

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Shear modulus of sand-tyre chip mixtures

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ABSTRACT

This paper presents experimental results on the shear modulus of sand–tyre chip mixtures (STCh). A series of bender element tests have been carried out on specimens of sand mixed with varying proportions of tyre chips (TCh). Tests were carried out on sand-tyre chip (STCh) mixtures at a constant initial relative density of 50% for different initial effective confining pressure. The bender element test results highlight that the maximum shear modulus of STCh mixtures increases with effective confining pressure and decreases with gravimetric proportion of TCh ranged from 23 to 138 kPa and 0 to 40%, respectively. However, strain-controlled cyclic triaxial test results show that the shear modulus at large shear strains decreased with increasing single-amplitude shear strain as a function of the proportion of TCh in the mixture. The lower the TCh the larger the degradation observed. The modified Hardin and Drnevich (1972) mathematical formulation adequately captures the variation of shear modulus of STCh mixtures for a wide range of shear strain amplitudes.

Keywords: Fabric/structure of soils, Strength & testing of materials, Buildings, structures & design.

INTRODUCTION

In the last two decades, the use of mixtures of sand and scrap tyre derived materials in major civil engineering projects has been investigated especially for environmentally-friendly reuse of scrap tyre as a light-weight backfill material or vibration isolation of foundations (e.g. Humphrey et al. 1993, Tsang et al. 2012, Rajesh et al. 2015). Despite the amount of research carried out on soils and scrap tyre derived materials (e.g. Ahmed 1993, Edil and Bosscher 1994, Foote et al. 1996, Tatlisoz et al. 1998, Youwai and Bergado 2003, Zornberg et al. 2004, Ghazavi and Sakhi 2005, Hataf and Rahimi 2005, Dunham-Friel and Carraro 2011, Sheikh et al. 2013, Balunaini, et al. 2014, Mashiri et al. 2015a and Mashiri et al. 2015b) and the discovery of their beneficial engineering properties, environmentally sustainable use of scrap tyres in civil engineering applications is still limited. This limited application of scrap tyres in civil engineering infrastructure development may be due to limited number of research investigations on the dynamic properties of STCh mixtures (Feng and Sutter 2000; Tsang et al. 2012 and Mashiri et al. 2005a). In addition, the sources and the recycling methods available to recycle scrap tyres may be very different, which may require comprehensive experimental investigations to determine sand-scrap tyre mixture properties during cyclic loading. Hence, there is a clear need to investigate the dynamic properties of soil and scrap tyre derived materials mixtures. The strain dependent dynamic properties such as shear modulus and damping ratio are very important parameters for the analysis and design of geotechnical structures. According to ASTM D 6270-12 tyre chips (TCh) and tyre shreds refer to pieces of scrap tyres having basic geometric shape with nominal dimension ranging from 12 to 50 mm and 50 to 305 mm, respectively. Granulated rubber is defined as particulate rubber composed of mainly non-spherical particles with maximum dimensions from below 425 μm to 12 mm. Tyre chips may have most of the wire reinforcement removed, whereas no wire reinforcement removal is expected for tyre shreds. Granulated rubber is typically free of any

wire reinforcement. Essentially, granulated rubber consists of small pieces of pure rubber no larger than corn kernels. Due to the scrap tyre recycling process employed to produce granulated rubber, most additional materials originally present in scrap tyres (e.g. wire reinforcement, synthetic reinforcement, etc.) have already been removed by the time a granulated rubber stack is formed. Conversely, tyre chips are relatively larger pieces of tyre derived aggregate, TDA, (typically the size of a gravel) that may also include reinforcing elements such as polymeric fibers (of various types) and/or steel fibers from remaining wire reinforcement. Thus, tyre chips look and behave more like a composite material whereas granulated rubber is made of (and behave more like) a single material (i.e., just rubber). This study focuses mainly on the effect of tyre chips (TCh) on the shear modulus of sand-tyre chip (STCh) mixtures.

The addition of scrap tyres as tyre derived aggregate (TDA) (i.e., tyre chips and shreds) to sand during monotonic tests was reported to improve the shear strength of sand (Ahmed 1993; Edil and Bosscher 1994; Foote et al. 1996; Ghazavi and Sakhi 2005; Rao and Dutta 2006; Zornberg et al. 2004; Mashiri et al. 2015a). On the other hand, the addition of scrap tyre as granulated rubber (i.e., tyre crumbs) to sand was reported to reduce the shear strength of sand (Kawata et al. 2008; Masad et al. 1996; Sheikh et al. 2013; Youwai and Bergado 2003). Recent studies have examined the cyclic behaviour and dynamic properties of sand and scrap tyre derived materials (e.g., Feng and Sutter 2000, Lee et al. 2007; Hyodo et al. 2007, Promputthangkoon and Hyde 2007, Uchimira et al. 2007, Kim and Santamarina 2008; Lee et al. 2010, Anastasiadis et al. 2012, Nakhaei et al. 2012, Senetakis et al. 2012, Kaneko et al. 2013a, and Kaneko et al. 2013b). Feng and Sutter (2000) presented the results of torsional resonant column tests on sand-granulated rubber mixtures at different confining pressures. The shear modulus of sand-granulated rubber mixtures was strongly influenced by the volumetric proportion of granulated rubber in the mixture. Edinçliler et al. (2004) carried out

cyclic triaxial tests on a mixture of sand and tyre buffing, vulcanised rubber obtained from used tyres, at different initial confining pressures. The shear modulus of the mixture increased with the increase in confining pressure. Lee et al. (2007) reported that fabric plays a key role on the maximum shear modulus (G_{max}) of sand- granulated rubber mixtures. The G_{max} of sand-granulated rubber mixtures is a measure of fabric arrangement and depends on the nature of the inter-particle contact and coordination. Based on resonant column tests, Senetakis et al. (2012) reported that G_{max} increased as the effective confining pressure increased, and decreased with the increase of the amount of granulated rubber. Nakhaei et al. (2012) developed modulus reduction curve for granulated rubber based on the results of undrained cyclic triaxial tests. So far only limited information (e.g. Mashiri et al. 2016) is available on the dynamic properties of STCh mixtures. Mashiri et al (2016) reported the liquefaction potential and dynamic properties of the STCh mixtures for wide range of shear strain levels. However, detailed information on the maximum shear modulus of STCh mixtures was not provided. Therefore, the current study has as objective the investigation of the maximum shear modulus and the development of a semi-empirical mathematical model for STCh mixtures.

In this study, laboratory experiments were carried out using a triaxial apparatus equipped with bender elements (BE) to investigate the influence of the amount of TCh and effective confining stress on the shear modulus of STCh mixtures. In addition, strain-controlled cyclic triaxial tests were carried out to investigate the shear modulus degradation of STCh mixtures for a wide range of shear strains. Cyclic triaxial tests were carried out at a single level of effective confining stress, but specimens were subjected to various levels of single-amplitude shear strains and reconstituted using different proportions of TCh in the STCh mixtures.

MATERIALS TESTED

The particle size distribution of the sand tested is presented in Figure 1a. The sand is classified as poorly graded (SP) according to ASTM D 2487-11. Tyre chips without any wire reinforcement were cut into rectangular shapes for uniform thickness (smallest dimension) of approximately 6 mm to minimise the effect of particle size variations on the experimental results. The aspect ratio of the tyre chips was 2.8. The maximum width and length of tyre chips did not exceed 8 and 22 mm, respectively (see Figure 1b). The specific gravities of the sand and tyre chips tested are 2.62 and 1.12, respectively. STCh mixtures with different gravimetric proportions (χ) of TCh were tested. The TCh percentages ($\chi\%$) considered in this study are $\chi=0, 10, 20, 30$ and 40% . STCh specimens were prepared at an initial relative density of 50% based on the minimum and maximum void ratios of the STCh mixtures (Table 1). More details on the properties of sand, tyre chips can be found in Mashiri et al. (2015a).

BENDER ELEMENT TESTING

$$V_s = \frac{l_{tt}}{t_t} \quad (1)$$

$$G_{max} = \rho V_s^2 \quad (2)$$

Theoretical Background

Bender element (BE) tests consist of applying an input voltage to a transmitter element (top cap insert) to generate a shear wave that propagates through the specimen and then obtaining a response on the receiver (base pedestal insert) as the output signal. The input voltage has a defined amplitude, shape and frequency, while the output signal is normally attenuated and

more distorted than the input signal (Viana da Fonseca et al. 2009). The travel time (t_t) of the propagating wave between the source and the receiver elements and the effective length of the specimen (l_t) are used to define the shear wave velocity (V_s) (Eq. 1). The maximum shear modulus (G_{max}) can be calculated using Eq. 2. This shear modulus corresponds to a shear strain of 10^{-5} (Dyvik et al. 1985).

where G_{max} is the maximum shear modulus (kPa), ρ is the total density of the specimen in kg/m^3 and V_s is the shear wave velocity in m/s.

In this study, π -point identification method (e.g., Broccanelli and Rinaldi 1998, Blewett et al. 1999, Greening et al. 2003 and Viana da Fonseca et al. 2009) was used to determine the travel time. This method uses continuous harmonic waves as the input. The source and receiver signals are observed directly to determine the phase between them. A π -point or phase frequency is defined when the frequency of the source and receiver are in perfect phase shift since the phase angle between the waves is a multiple of $\pm \pi$. Plotting of the phase frequencies versus the phase angles results in an approximately linear relationship in which the slope of the curve is proportional to the travel time (Viana da Fonseca et al. 2009).

Identifying the π -point in the test results of bender element for different frequencies is carried out by identifying the peaks of the source wave and the first peak of the receiver wave. These peaks are illustrated in Figure 2, in which P_1 and P_2 are the source peak and receiver peak, respectively. The velocity from P_1 to P_2 is calculated by considering l_t and the travel time from P_1 to P_2 :

$$v_{pp} = \frac{l_t}{(t_{p_2} - t_{p_1})} \quad (3)$$

where t_{p_1} and t_{p_2} are the travel times to P_1 and P_2 , respectively.

By simple substitution, the number of π point (N) can be written in terms of the frequency (f) and the travel time between P_1 and P_2 :

$$N = f (t_{p_2} - t_{p_1}) \quad (4)$$

More details on the mathematical derivation of Eq.4 can be found elsewhere (e.g., Viana da Fonseca et al. 2009, and Mashiri 2014). The time of travel to P_1 (t_{p1}) and P_2 (t_{p2}) are determined for all the frequencies of the bender element tests for a particular specimen and effective confining pressure. Then the number of wavelengths (N) or number of π point are calculated and plotted versus the frequency (f). The slope of the curve determines the travel time (t_t).

$$t_t = \frac{\Delta N}{\Delta f} \quad (5)$$

Testing Procedure

BE tests were carried out in a triaxial cell using a GDS-BES system. The bender elements are bonded into the standard inserts fixed to the top cap and base pedestal. The bender elements are 11.15 mm long, 1.7 mm wide, and protrude by 1.5 mm above the insert surface. A source wave amplitude of 14 V with a stacking of 10 sampled signals was chosen to maximize the signal-to-noise ratio (SNR). Test frequencies of the source waves were carefully selected to improve the clarity of the interpretation of the output data (Viana da Fonseca et al. 2009). In this investigation, a sine wave pulse signal was used to determine the travel time for the calculation of the shear wave velocity of STCh mixtures.

Specimens of STCh mixtures with diameter and height equal to 50 and 100 mm, respectively, were used at this stage. Specimens were saturated ($B > 0.95$) and isotropically consolidated to

effective confining stresses (σ'_3) of 23, 46, 69 and 138 kPa according to ASTM D 7181-11. BE measurements were carried out after completion of each one of the four consolidation stages mentioned above. After each consolidation stage, specimen volume and void ratio values were updated based on the corresponding specimen volume changes (i.e., backpressure line) measured during each stage. The specimen height was calculated assuming the specimen deformed isotropically during isotropic consolidation. The end of a stage was deemed completed after at least 5 to 10 BE tests were conducted at different frequencies for a particular specimen of STCh mixture. The effective length of the specimen (l_{tt}) was determined by the distance between the two bender elements, and because the elements protrude by 1.5 mm, the effective length in mm was calculated as:

$$l_{tt} = H_0 - 2 \times 1.5 \quad (6)$$

where H_0 is the height of the specimen after the corresponding consolidation stage. The effective length (l_{tt}) and density (ρ) of the specimen of STCh mixture after each stage of consolidation for the BE tests are shown in Table 2.

Discussion of Bender Element Test Results

The results of the output signals for STCh(10%) at an effective confining pressure $\sigma'_3=23$ kPa is shown in Figure 3. Also, three different zones (distortion, clarity of the output signal and near-field effect) are presented in Figure 4. It is noted that the zones of distortion, clarity of the output wave and of near-field effect vary with σ'_3 (i.e., confining pressure) and gravimetric proportion of TCh (χ) (i.e., STCh($\chi\%$) mixture). Fig.3 reveals a slightly distorted interference at the rigid boundary for frequencies greater than 6 kHz resulting in a possible underestimated travel time. In addition, for source wave frequencies less than 3 kHz, the number of wavelengths (N) <2 , indicates the presence of near-field effect (Arulnathan et al. 1998) and a possible overestimated travel time. Distortion at the rigid boundary was

determined by visual inspection of the clarity of the output wave rather than the ratio of wave length (λ) to bender element insert's length (l_b) as suggested by Arulnathan et al. (1998). Hence, the frequencies used to determine the travel time were selected by visual inspection based on the clarity of the output waves limiting $N > 2$.

Figure 4 represents the test results of the sweep of frequencies from the π -point identification method for different STCh mixtures. It is evident from the figure that N varies linearly with f , irrespective of the proportion of tyre chips. For a particular value of f , N increases with percentage of STCh. The slope of N - f curve was used to calculate the travel time (t_t) (Eq. 5) for the different STCh mixtures at $\sigma'_3 = 138$ kPa. The same procedure was carried out for other STCh mixtures at $\sigma'_3 = 23, 46$ and 69 kPa.

Figure 5 shows the travel time for STCh mixtures at different σ'_3 . It is evident from Figure 5 that the travel time decreases with the increase in the σ'_3 and increases with the increase in the gravimetric proportion ($\chi\%$) of TCh in the STCh mixture. The increase in the effective confining pressure on a particular STCh mixture decreases the void ratio of the specimen and consequently increases the density of the specimen and decreases the travel time of the shear wave. Similarly, the inclusion of the TCh has a greater impact on the reduction of density of the specimen, contributing to the increase in the travel time.

Table 2 shows the shear wave velocity (V_s) for the STCh mixtures at different confining pressures. The V_s seems to decrease with the increase in the gravimetric proportion of TCh.

The maximum shear modulus (G_{max}) was calculated according to (Eq. 2) for STCh mixtures with the proportion of TCh, $\chi = 0\%, 10\%, 20\%, 30\%$ and 40% . Figure 6 presents the variation of maximum shear modulus (G_{max}) of STCh mixtures with effective confining pressure. It is evident that G_{max} increases with the increase in σ'_3 for all the STCh mixtures. However, G_{max} decreased with an increase in the proportion of TCh at any particular σ'_3 . This may be due to

the elastic nature of pure tyre chips (rubber), as well as a result of the decreasing density of STCh mixtures due to increasing TCh content and the corresponding decrease in shear wave velocity as a result of TCh addition. As a single type of tyre chips with specific dimensions was used in the BE tests, scale effects were not considered in this study. Observed results may also reflect the characteristics of the materials and specimen tested and may not be extrapolated for other testing conditions.

CYCLIC TRIAXIAL TESTING

Testing Procedure

A series of strain-controlled undrained triaxial tests were carried out to determine the large strain shear modulus of STCh mixtures for different proportions of TCh. The STCh specimens of size 100 mm in diameter and 200 mm in height were prepared using dry deposition method. The mould was filled in three layers of premixed STCh and the desired relative density of 50% was achieved by gently tamping the sides of the mould. The samples were then saturated with de-aired water using back pressure saturation and consolidated to an isotropic effective confining pressure of 69 kPa (~ 10 PSI). The undrained cyclic tests were carried out at a constant frequency of 1 Hz and single-amplitude shear strains (γ_{sa}) of 0.15%, 0.23%, 0.38% and 0.50%. All cyclic tests were continued until the ratio of pore water pressure change (Δu) to initial effective confining pressure ($\Delta u/\sigma'_3$) $\cong 1$. More details on the specimen preparation and test details can be found elsewhere (e.g., Mashiri et al. 2015a, b and Mashiri et al. 2016).

Discussion of Cyclic Triaxial Test Results

Figure 7 a shows the typical variation of deviator stress q ($\sigma'_1 - \sigma'_3$) with effective mean stress $p'[(\sigma'_1 + 2\sigma'_3)/3]$ for different gravimetric proportion of tyre chips for a shear strain amplitude

(γ_{sa}) of 0.38% (where σ'_1 and σ'_3 are the major and minor effective principal stresses respectively). It seems that deviator stress decreases with decreasing mean p' and reaches zero indicating liquefaction at $\gamma_{sa} = 0.38\%$ irrespective of χ . This decrease in deviator stress with decreasing mean p' may be due to the increase in the pore water pressure (Fig. 7b) (Mashiri et al. 2016) and relatively low stiffness of TCh. Moreover, Fig. 7a (CT=0%) shows a material behaviour that is stiffer in compression than in extension (specimen anisotropy), as it would be expected for an uncemented clean sand. Conversely, Fig. 7a (CT=40%) shows a perfectly symmetric response, which suggests that tyre chip dilution into the sand fabric makes the fabric of the sand-tyre chip mixture more isotropic than its original clean sand counterpart.

Figure 8 shows the variation of shear modulus corresponding to the first cycle data. It can be observed from Fig. 8 that the shear modulus decreases with an increase in the shear strain for all the STCh mixtures. A decrease in the shear modulus with an increase in the proportion ($\chi\%$) of TCh occurred for shear strains less than 0.18%. Afterwards, the shear modulus of STCh(0%) gradually became smaller than the shear modulus of the STCh mixtures with $\chi \geq 10\%$. This reduction in the shear modulus for STCh(0%) with an increase in the shear strain was attributed to a reduction of sand inter-particle contact due to the rapid generation of pore-water pressure leading to liquefaction.

SHEAR MODULUS OF STCh MIXTURES AT SMALL TO MEDIUM SHEAR STRAINS

The shear modulus curves for STCh mixtures at small to medium shear strains ($\gamma < 0.15\%$) can be estimated by the reference shear strain (γ_r) concept (Hardin and Drnevich, 1972):

$$G = \frac{G_{max}}{1 + \frac{\gamma}{\gamma_r} \left(1 + a \exp \left(-b \frac{\gamma}{\gamma_r} \right) \right)} \quad (7)$$

where a and b are the soil constants.

Determination of the reference shear strain for STCh mixtures

The reference shear strain is a parameter defined as the ratio of the maximum shear stress at failure to the maximum shear modulus (τ_{max}/G_{max}). The values of τ_{max} were obtained from the monotonic experimental data at $\sigma'_3=69$ kPa for STCh(0%), STCh(10%), STCh(35%) and STCh(40%) (Mashiri et al. 2015a). However, no data were available for τ_{max} for STCh(20%) and STCh(30%) at $\sigma'_3=69$ kPa. Therefore, the τ_{max} for STCh(20%) and STCh(30%) were estimated by assuming a linear relationship between the ratio of τ_{max} at $\sigma'_3=69$ kPa and τ_{max} at $\sigma'_3=138$ kPa from the STCh mixtures at $\chi=10\%$, 35% and 40%. The values of τ_{max} at $\sigma'_3=69$ kPa for STCh(20%) and STCh(30%) were calculated using the corresponding value of $\alpha(\chi)$ obtained from Fig 9. In Fig. 9, $\alpha(\chi)$ is defined as the ratio of $\tau_{max(69\text{ kPa})}(\chi)$ to $\tau_{max(138\text{ kPa})}(\chi)$. The reference strains for the STCh mixtures used to determine the shear modulus curves are reported in Table 3.

Determination of parameters a and b

The soil constants a and b for the STCh mixtures were determined by statistical curve fitting according to Eq. 7 of the BE tests results and experimental data at large shear strains. The parameters a and b , and the G_{max} normalised by the atmospheric pressure (i.e., G_{max}/p_a where $p_a = 101.3$ kPa) for different proportions of TCh at an effective confining pressure of 69 kPa (Fig. 10). It is clear from the Fig. 10 that both parameters a and b decrease with the increase in G_{max}/p_a . Two empirical relationships were proposed to estimate the STCh mixture parameters a and b in terms of the normalised G_{max} of STCh mixtures. It is noted that the following empirical equations have been developed for a σ'_3 of 69 kPa and relative density of 50% considered for the study. The proposed equations (8 & 9) predicts the values of 'a' & 'b' for different proportion of tyre chips and confining pressure considered for the study.

$$a = -3.63 \ln \left(\frac{G_{max}(\chi)}{p_a} \right) + 26.65 \quad (8)$$

$$b = -0.40 \ln \left(\frac{G_{max}(\chi)}{p_a} \right) + 2.44 \quad (9)$$

Shear modulus curves of STCh mixtures for wide range of shear strain levels

Figure 11 shows the validation of the proposed equations (Eq.7) with the shear modulus determined from the bender element test and cyclic triaxial test for STCh mixtures at $\chi = 0, 10, 20, 30$ and 40% at $\sigma'_3 = 69$ kPa and $D_r = 50\%$. It is shown that the reference strain concept clearly captured the variation in the shear modulus with the shear strain for STCh mixtures at different proportions of TCh for wide range of shear strain level. As anticipated, the shear modulus decreases with increase in the shear strain amplitude and proportion of tyre chips. It is noted that the predicted shear modulus of STCh mixtures in the shear strain range of 0.00002% to 0.1% needs further experimental research investigations using torsional shear, cyclic simple shear and/or resonant column apparatus. Scale effects may also be considered in future studies to assess the effect of maximum particle size to minimum specimen dimension ratios on G_{max} , which was not taken into account in the present study due to BE equipment size limitations.

CONCLUSIONS

This paper presents the effect of tyre chips on the shear modulus of sand-tyre chip mixtures. The maximum shear modulus (G_{max}) for soil-tyre chip mixtures was determined from bender element tests. The G_{max} of STCh mixtures depends on the proportion of TCh. The lower densities of STCh mixtures due to the increase in TCh is reflected in the lower values of G_{max} for STCh mixtures at a given σ'_3 . The increase in the σ'_3 increases the value of G_{max} for all STCh mixtures.

The shear modulus of STCh mixtures from strain controlled undrained cyclic triaxial testing at large strains are influenced by the single amplitude shear strain and proportion of TCh in STCh mixture. The shear modulus decreases with an increase in the single amplitude shear strain irrespective of STCh mixtures. The modified Hardin and Drnevich (1972) model was used to capture the variation of shear modulus of STCh for a wide range of shear strains. This mathematical model clearly captures the variation of shear modulus with shear strain for sand-tyre chip mixtures with different percentages of tyre chips. However, the shear modulus of STCh mixtures in the shear strain range of 0.00002% to 0.1 % needs further experimental research investigations.

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Table. 1: $e_{\max}$ and $e_{\min}$ of STCh mixtures (according to ASTM D4253, 2006)

χ (%)	0	10	20	30	40
$e_{\min}$	0.55	0.44	0.34	0.27	0.25
$e_{\max}$	0.77	0.66	0.52	0.45	0.49

Table.2: Parameters used for determining V_s

Mixture	σ_3' (kPa)	l_{tt} (mm) (Eq.6)	t_t (ms) (Eq. 5)	ρ (kg/m ³)	V_s (m/s)
STCh(0%)	23	96.95	0.5574	1585	173.94
	46	96.93	0.4943	1586	196.09
	69	96.90	0.4471	1587	216.73
	138	96.84	0.3752	1590	258.1
STCh(10%)	23	96.96	0.6415	1492	151.14
	43	96.89	0.5494	1495	176.35
	69	96.84	0.4982	1497	194.37
	138	96.73	0.4191	1502	230.80
STCh(20%)	23	96.95	0.6312	1448	153.60
	46	96.88	0.5472	1451	177.05
	69	96.83	0.5057	1453	191.49
	138	96.70	0.4349	1459	222.36
STCh(30%)	23	96.93	0.7356	1376	131.76
	46	96.83	0.6264	1380	154.58
	69	96.77	0.5755	1383	168.14
	138	96.62	0.4937	1389	195.70
STCh(40%)	23	96.90	0.8619	1246	112.43
	46	96.78	0.7314	1251	132.31
	69	96.69	0.6661	1254	145.16
	138	96.50	0.5825	1262	165.66

Table 3: Reference strains (γ_r) for STCh mixtures

χ (%)	G_{max} (kPa)	τ_{max} (kPa)	γ_r (%)
0	74553	108	0.14
10	56566	106	0.19
20	53271	117*	0.22
30	39103	120*	0.31
40	26429	111	0.42

(*: estimated values)

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