Shear and Compression Characteristics of Recycled Glass-Tire Mixtures

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Abstract: Tire particles in the form of shreds, chips or crumbs, are normally mixed with sand to make suitable alternative backfill or embankment materials. This mixture of soft (tire) and rigid (sand) particles in their optimum ratio has been shown to provide reasonable engineering performance in terms of strength, permeability, durability and compressibility. In this study, mixtures of Fine Recycled Glass (FRG) and Tire Crumbs (TC) were evaluated through isotropic compression tests, as well as consolidated drained triaxial tests under 5 confinement levels. Four proportions of mixtures with gravimetric TC contents of 10 to 40% were evaluated in terms of shear and compression response. Results show that, increasing the TC content decreases the shear strength parameters and Young's modulus, and increases the compressibility of the mixture. Gravimetric TC content corresponding to the transition mixture in high and low confinements were between 10 and 20%, and 20 to 30%, respectively. In mixtures with a TC content less or greater than that of a transition mixture, FRG or TC skeleton was found to govern the behavior of the mixture. The outcomes of this research study were compared with results of investigations carried out on sand-rubber mixtures, and possible applications of this fully recycled product are discussed.

Keywords: Recycled Glass; Tire Crumb; Dilatancy; Compressibility

1 Introduction

Increasing stockpiles of waste tire and consequent environmental issues and associated hazards have led to research works, such as Masad, et al. (1996), Zornberg, et al. (2004), Rao and Dutta (2006), Lee, et al. (2007), Sheikh, et al. (2013) and Mashiri, et al. (2015), trying to find solutions for recycling and reuse of this waste material. One solution for reusing waste tires is using them in industries that consume large amounts of bulk materials, such as civil engineering construction industry. Waste tire is normally used in the forms of tire shreds, tire chips, and granulated rubber. According to ASTM (2008), particle size of granulated rubber (also known as tire crumb), tire chips and tire shreds are respectively, 425 μm to 12 mm, 12 to 50 mm, and 50 to 305 mm. Certain properties of waste tire, such as superior drainage capability, long term durability, resilience and high frictional resistance make it suitable for some civil engineering applications, such as highway embankments (Mashiri, et al., 2015, Zornberg, et al., 2004).

The suitability of crushed glass in form of recycled glass in civil engineering applications has been investigated in recent years (Disfani, et al., 2011, Grubb, et al., 2006, Ooi, et al., 2008, Taha and Nounu, 2008, Wartman, et al., 2004). The recycled glass produced in Victoria, Australia is mostly Fine Recycled Glass (FRG) with maximum particle size (D_{max}) of 4.75 mm (Disfani, et al., 2011). Experimental results show that the shear behavior and strength parameter of FRG are comparable to those of pure sand (Disfani, et al., 2011, Ooi, et al., 2008, Wartman, et al., 2004). While typical friction angle sands ranges from 28 to 38 for sands with rounded grains and from 30 to 45 for those with angular grains (Das, 2008), this property for well graded FRG ranges from 37 to 48 and for poorly graded FRG from 31 to 37 (Arulrajah, et al., 2013 a, Ooi, et al., 2008). Previous research work suggest FRG can replace sand in construction works such as road embankment fills, pipeline beddings, and road subbase layers (Taha and Nounu, 2008).

Mixing sand with tire particles (creating a blend of rigid and soft particles) in optimum ratio results in a blend stiff enough to carry loads and soft enough not to disintegrate under buckling (Lee, et al., 2007). Sand-tire mixtures are known for the lower void ratio and higher compressibility compared with pure sand, however, these are highly dependent on factors such as tire content and the ratio between the size of the tire and the sand particles (Kim and Santamarina, 2008). Normally, adding tire shreds and tire chips (D_{max}>12 mm) to sand results in mixtures with higher shear strength, whereas mixing tire crumbs (D_{max}<12 mm) results in lower shear strength compared with pure sand (Lee, et al., 2007, Mashiri, et al., 2015, Sheikh, et al., 2013, Zornberg, et al., 2004).

Lee, et al. (2007) defined a "transition mixture" with volumetric content of about 40% to 60% (gravimetric content of about 17% to about 27%). With this tire content, rubber particles separate sand particles at lower confining stresses, but at higher confining stresses sand-on-sand contact starts to prevails. In their research, the mean particle size (D_{50}) of tire crumb (TC) was about a quarter of sand. Kim and Santamarina (2008) worked on mixtures of sand-TC with D_{50} of TC about 10 times that of sand and concluded that blends with less than 30% volumetric content (gravimetric content of about 12%) of TC exhibit sand-like behavior and those with tire content greater than 70% (gravimetric content of about 32%) show rubber-like behavior. Sand-like behavior refers to the typical response of pure sand (such as Ottawa sand) under triaxial shearing while rubber-like behavior is similar to the response of a soft and elastic material, i.e., higher compressibility, not reaching a peak deviator stress, higher recoverable strain, and lower shear moduli (Kim and Santamarina, 2008, Lee, et al., 2007). A summary of the results obtained by previous researchers is presented in **Table 1.**

Even though several research works have been carried out on triaxial and compressibility behavior of sand/tire mixtures, no known research to date has addressed the applicability of glass/tire mixtures as a fully recycled civil engineering construction material. From perspective of granular material behavior, in the previous studies, both soft and flexible particles were uniformly/poorly graded, whereas in this research the FRG blend is a well-graded granular material. In a well graded blend a higher number of contacts between particles (coordination number) is achieved which influences the development of the force chain, and lowers the probability of particle breakage due to an extended distribution of forces transferred from one particle to another (Altuhafi and Coop, 2011). Accordingly, this research aims to investigate the mechanical behavior of mixtures of FRG (well-graded rigid particles) and TC (soft particle) through a series of triaxial shearing and isotropic compression tests.

2 Materials and Procedures

FRG and TC were obtained from recycling facilities in Victoria, Australia. Both FRG and TC were selected to have similar maximum particle size (D_{max}), being 4.75 mm. Particle size distribution of FRG and TC, as well as sand and TC used in Kim and Santamarina (2008), for comparison, are shown in **Figure 1(a)**. **Figures 1(b)** and **1(c)** are respectively images of FRG and TC used in this research.

Other physical properties of FRG and TC, including maximum particle size (D_{max}), and mean particle size (D_{50}) are presented in **Table 2**.

In this research, 4 blends of Glass-Tire Crumbs (GTC) with gravimetric tire crumb contents of 10% (GTC1), 20% (GTC2), 30% (GTC3), and 40% (GTC4) (hereafter referred as TC content) were chosen. TC content is defined according to Equation 1:

$$\mathbf{TC(\%)} = \frac{\text{Mass of TC}}{\text{Mass of FRG + Mass of TC}} \times 100 \qquad \textbf{Equation 1}$$

For triaxial specimens tamping method at 2% water content was used to compact samples inside a split mold mounted on the triaxial pedestal. Samples of GTC were compacted in 5 layers to prepare the specimens, ideally 50 mm in diameter and 100 mm in height. After tamping, placing the cap and sealing the specimen with O-rings, a vacuum pressure of 35 kPa was applied to the specimen according to ASTM (2011) and then the split mold was removed. For all blends a corresponding relative density of about 80% was achieved. Dry density (γ_d) of prepared specimens, maximum and minimum density (γ_{max} and γ_{min}, respectively) and relative density of the compacted GTC blends are presented in **Table 3**.

Consolidated Drained (CD) triaxial tests were conducted on GTC specimens according to ASTM (2011). a Skempton B-value of 95% was achieved for all specimens and then they were consolidated under the target confining pressure (σ_c), being 30, 60, 120, 240, and 480 kPa. Triaxial shearing was then carried out to an axial strain of 25%. Using the triaxial cell, compression response of GTC specimen under isotropic loading-unloading consolidation was also investigated. In this regard, five isotropic loading steps and five unloading steps of 30, 60, 120, 240, and 480 kPa, were applied.

3 Results and Discussion

Triaxial shear strength test results are discussed in this section.

3.1 Stress Paths and Failure Envelopes

Results of triaxial shearing are shown in **Figure 2** in form of deviatoric stress-mean normal effective stress (q-p' stress) path diagrams. Peak state and critical state envelopes are also presented in **Figure 2**. In a critical state, both stress-axial strain curve and volumetric strain–axial strain curve should reach a plateau. Regular granular soils normally reach a critical state after axial strains greater than 10% (Budhu, 2011). However, for sand-tire mixtures, reaching a critical state in a reasonable strain is difficult, especially in blends with a high tire content (Fu, et al., 2014). Therefore, shearing was allowed to proceed until reaching an axial strain of about 25% (end-of-test state). The end-of-test states hereafter are considered as critical states. It is worth mentioning that in previous studies on FRG (same material source as this research), post-test particle size analysis following one dimensional compression and triaxial shearing up to confining pressure of 480 kPa showed minimal to no breakage in FRG particles (Disfani, 2011). This was attributed to dense packing and well-graded gradation of FRG with a coefficient of uniformity of 7.3 and fine content of 4-5%.

The envelopes in **Figure 2** show that as TC content increases, critical state envelopes approach the peak state envelopes. In fact, the two envelopes could not be easily distinguished in blends with 30% and 40% tire content (GTC3 and GTC4). This is due to the rubber-like behavior of the blends with high TC content. Peak and critical state friction angles (ϕ) are reported in **Table 4**. For measurement of the friction angles, peak and critical stresses corresponding to three consecutive confining pressure ranges (i.e., 30-60-120 kPa, 60-120-240 kPa, and 120-240-480 kPa) were used.

Reduction of peak friction angle (ϕ_P) and end-of-test (critical) friction angle (ϕ_C) with the increase of the TC content suggested that tire crumbs do not contribute to increases in the shear strength of the blends. The reduction of both ϕ_P and ϕ_C with the increase in the confining stress level is also observed in **Table 4**. This is due to the fact that the failure envelope is a curve rather than a straight line, especially under confinements greater than 400 kPa (Das, 2008, Rowe, 1962).

Results presented in **Table 4** show a difference of respectively, three and two degrees between ϕ_P and ϕ_C for GTC1 and GTC2, whereas this difference for GTC3 and GTC4 was negligible. However, a difference of 5-13% between ϕ_P and ϕ_C has been reported in case of natural sand (Budhu, 2011). Adding tire crumbs resulted in achieving peak state in higher strains (close to end-of-test state) due to rubber-like behavior of sand-tire mixtures (Lee, et al., 2007). Eventually, by increasing the TC content critical state and peak state envelopes overlap and hence, the difference between ϕ_c and ϕ_p becomes negligible.

3.2 Influence of Confining Pressure and Tire Content

The typical stress-strain-volumetric response during triaxial shearing for GTC1 and GTC3 is shown in **Figure 3**. As the value of σ_c increased, the axial strain corresponding to peak deviatoric stress (q_P) shifts towards the end-of-test strain ($\varepsilon_a \approx 25\%$). Magnitude of σ_c also influences the compression-dilation behavior of mixtures. As the value of σ_c increased, compression increased and dilation decreased.

Figure 4 shows the increase in q_P by increasing σ_c in all GTC blends. This can be attributed to increased densification of specimens as the confinement increases (common for naturally occurring granular material such as sand) and the greater interlocking of aggregates under higher confining pressure caused by elastic deformation of tire crumbs.

Figure 5 shows the effects of TC content on stress-strain-volumetric response of all blends under σ_c values of 30, 120 kPa and 480 kPa. **Figure 5** indicates that increasing TC content results in shifting the axial strain corresponding to q_P towards higher strain values. This clearly shows a transition from strain softening behavior to strain hardening behavior with increasing TC content. Lee, et al. (2007) suggested that in a transition mixture, higher σ_c caused deformation in TC particles, resulting in sand-on-sand contact and accordingly, sand like behavior. However, as observed from **Figure 5(c)**, GTC2 and GTC3 hardly reached a peak deviatoric stress or a plateau in stress-strain plane. Kim and Santamarina (2008), however, suggested that for mixture with larger TC particle sizes compared to sand particles, higher confinement and accordingly, deformation of TC particles only resulted in filling the interfacial voids, rather than bringing about sand-on-sand contact, which seems to be the case in this research. Although, it should be noted that the size ratio in the former was 0.3, whereas this ratio was 10 in the latter.

Peak deviatoric stress versus TC content for all GTC blends is presented in **Figure 6**. In general, greater TC content in a blend caused lower q_P. Higher TC content results in a dominant rubber skeleton in the blend preventing rigid particles from contacting, even under higher confinements.

Elastic Young's modulus (E) of the GTC blends in two confinements of 30 kPa and 480 are presented in **Table 5**. These values and similar trends observed for other confinements showed the influence of TC content on Young's modulus of the blends. A significant drop of E values is observed between blends with 10% and 20% TC content, but slighter decrease of E values from 20% to 30% and 40% TC contents. This could be due to transition of the blends from a sand-like to a rubber –like blend by increasing the TC content from 10 to 20%. As the TC content increased and rubber skeleton governed the behavior, for a specific stress level, higher deformations occurred, which resulted in a reduction in slope of the stress-strain curve, i.e. Young's modulus.

3.3 Compressibility Behavior

Isotropic loading and unloading was conducted under a range of loading levels. Experimental results on time-dependent deformation (creep) of soil-rubber mixtures are scarce in the literature. However, based on the few research works in this area, such as Ngo and Valdes (2007), this time-dependent engineering response in application of sand-rubber mixtures in infrastructure constructions can be important in certain settlement considerations. In this research, despite of the fact that strain change was negligible after a maximum of about 15 minutes from the beginning of each step, each loading step was given a duration of minimum of about 2 hours for the creep deformation to be completed. **Figure 7** presents the results in form of ratio of void ratio at each loading step to initial void ratio

(e/e_i) versus effective stress (e-logP) curves for the GTC blends. Evidently, higher TC content resulted in greater compression index in loading steps. The e-logP curves obtained from unloading steps show the decreasing trend of slopes of the recompression lines from GTC1 to GTC4. This can partially be explained by the fact that TC particles were more resilient that FRG particles; hence higher TC content in a blend resulted in greater recoverable deformation. In addition, higher amount of particle breakage in blends with lower TC content caused greater permanent deformation.

Values of compression index (C_c) and recompression index (C_r) were subsequently calculated (based on void ratio-log p curves) and reported in **Table 6**. Results show that increasing TC content caused C_c values to increase. However, increment of C_c values from GTC1 to GTC2 was significantly greater than those from GTC2 to GTC3 and from GTC3 to GTC4. This can be explained by the transition of the blend from rigid particle behavior to soft particle behavior, by increasing the TC content from 10% to 20%, as evidenced by the results of triaxial strength tests.

4 Discussion

A comparison of the results obtained from literature review was presented in **Table 1**. In terms of determining a transition mixture, among mixtures of sand-TC, results of this research showed weaker correlation with those of Lee, et al. (2007) using blends with size ratio (tire/sand) of 0.3, but showed stronger correlation with those of Kim and Santamarina (2008) using blends with size ratio (tire/sand) of 10. The latter defines a transition mixture with gravimetric content of 12 to 27%, while these percentages in this research are proposed to be between 10 to 30%.

Application of sand-tire mixture in highway embankments has been highlighted and suggested in the literature, such as Masad, et al. (1996), Rao and Dutta (2006), and Edinçliler, et al. (2010), among others. These, normally, recommend an application such as construction of lightweight embankment fills. Mixtures of sand and tire shreds have been found suitable for embankments subjected to heavy loads, due to the reinforcing function of shreds and the added shear strength resulted from the reinforcing effect of tire shreds (Bosscher, et al., 1992). However, for solving the problem of high compressibility of these mixtures a minimum thickness of 1 m soil cover has been suggested

(Bosscher, et al., 1992). This soil cap also prevents the mixtures from self-heating. FRG has shown strength parameters comparable to sand and it is applicable in construction of transportation infrastructure (Disfani, et al., 2011, Ooi, et al., 2008). Hence, FRG-TC mixtures can be satisfactorily used in construction of lightweight embankments of highways, as discussed above.

5 Conclusion

In this research shear and compression behaviors of mixtures of Fine Recycled Glass (FRG) and Tire Crumbs (TC) were investigated through a series of triaxial and isotropic loading-unloading tests. Unlike previous studied, the materials used in this research were completely recycled materials. Moreover, it instead of mixing two uniformly graded materials, well graded FRG was mixed with tire crumbs. The following conclusions were drawn:

1. An increase in TC content resulted in a decrease in the peak deviatoric stress and peak friction angle (shear strength) of the blends. Also, by increasing the TC content, axial strain corresponding to peak deviatoric stress increased, and in higher TC contents (30 and 40%) this strain almost coincided with end-of-test strain.
2. Mixtures containing TC content greater than that of transition mixture behaved in a rubber-like manner and those with TC content less than transition mixture behaved in a sand-like manner. In this research, TC content of the transition mixture was 10 to 20% for higher confinements and 20 to 30% for lower confinements.
3. Increasing TC content from 10% to 20% caused a large drop in the Young's modulus of the mixture. This reduction was more significant under lower confinement.
4. Higher TC content resulted in higher compression index and higher recompression index. In other words, by increasing the TC content, compressibility of the mixture as well as its recoverable strain was increased.
5. A possible application of GTC blends as fill material for lightweight highway embankments has been proposed.

References

Altuhafi, F., and Coop, M. R. (2011). "Changes to Particle Characteristics Associated with the Compression of Sands." *Geotechnique*, 61(6), 459-471.

Arulrajah, A., Ali, M., Disfani, M., and Horpibulsuk, S. (2013 a). "Recycled-Glass Blends in Pavement Base/Subbase Applications: Laboratory and Field Evaluation." *Journal of Materials in Civil Engineering*, 26(7), 04014025.

ASTM (2008). "Standard Practice for Use of Scrap Tires in Civil Engineering Applications." ASTM D6270-08, West Conshohocken, PA.

ASTM (2011). "Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils." ASTM D7181, West Conshohocken, PA.

Bosscher, P. J., Edil, T. B., and Eldin, N. N. (1992). "Construction and Performance of a Shredded Waste Tire Test Embankment." *Transp Res Record*(1345), 44-52.

Budhu, M. (2011). *Soil Mechanics and Foundations*, Hoboken, NJ : Wiley, Hoboken, NJ.

Das, B. M. (2008). *Advanced Soil Mechanics*, Taylor & Francis, London.

Disfani, M. M. (2011). "Sustainable Use of Recycled Glass: Biosolids Blends in Road Applications." PhD Thesis, Swinburne University of Technology. Faculty of Engineering and Industrial Sciences. Centre for Sustainable Infrastructure.

Disfani, M. M., Arulrajah, A., Bo, M., and Hankour, R. (2011). "Recycled Crushed Glass in Road Work Applications." *Waste Management*, 31(11), 2341-2351.

Edinçliler, A., Baykal, G., and Saygılı, A. (2010). "Influence of Different Processing Techniques on the Mechanical Properties of Used Tires in Embankment Construction." *Waste management*, 30(6), 1073-1080.

Fu, R., Coop, M., and Li, X. (2014). "The Mechanics of a Compressive Sand Mixed with Tyre Rubber." *Géotechnique Letters*, 4(July-September), 238-243.

Grubb, D. G., Gallagher, P. M., Wartman, J., Liu, Y., and Carnivale III, M. (2006). "Laboratory Evaluation of Crushed Glass–Dredged Material Blends." *Journal of Geotechnical and Geoenvironmental Engineering*, 132(5), 562-576.

Kim, H.-K., and Santamarina, J. (2008). "Sand-Rubber Mixtures (Large Rubber Chips)." *Can Geotech J*, 45(10), 1457-1466.

Lee, J. S., Dodds, J., and Santamarina, J. C. (2007). "Behavior of Rigid-Soft Particle Mixtures." *Journal of Materials in Civil Engineering*, 19(2), 179-184.

Masad, E., Taha, R., Ho, C., and Papagiannakis, T. (1996). "Engineering Properties of Tire/Soil Mixtures as a Lightweight Fill Material." *Geotech Test J*(19).

Mashiri, M., Vinod, J., Sheikh, M. N., and Tsang, H.-H. (2015). "Shear Strength and Dilatancy Behaviour of Sand–Tyre Chip Mixtures." *Soils and Foundations*, 3(55), 517-528.

Ngo, A. T., and Valdes, J. R. (2007). "Creep of Sand–Rubber Mixtures." *Journal of materials in civil engineering*, 19(12), 1101-1105.

Ooi, P., Li, M., Sagario, M., and Song, Y. (2008). "Shear Strength Characteristics of Recycled Glass." *Transportation Research Record: Journal of the Transportation Research Board*(2059), 52-62.

Rao, G. V., and Dutta, R. (2006). "Compressibility and Strength Behaviour of Sand–Tyre Chip Mixtures." *Geotechnical & Geological Engineering*, 24(3), 711-724.

Rowe, P. W. "The Stress-Dilatancy Relation for Static Equilibrium of an Assembly of Particles in Contact." *Proc., Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, The Royal Society, 500-527.

Sheikh, M. N., Mashiri, M., Vinod, J., and Tsang, H.-H. (2013). "Shear and Compressibility Behavior of Sand–Tire Crumb Mixtures." *Journal of Materials in Civil Engineering*, 25(10), 1366-1374.

Taha, B., and Nounu, G. (2008). "Properties of Concrete Contains Mixed Colour Waste Recycled Glass as Sand and Cement Replacement." *Construction and Building Materials*, 22(5), 713-720.

Wartman, J., Grubb, D. G., and Nasim, A. (2004). "Select Engineering Characteristics of Crushed Glass." *Journal of Materials in Civil Engineering*, 16(6), 526-539.

Zornberg, J. G., Cabral, A. R., and Viratjandr, C. (2004). "Behaviour of Tire Shred - Sand Mixtures." *Can Geotech J*, 41(2), 227-241.

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Table 1. A summary of test results on sand-tire mixtures in the literature

Description / Source	Masad et al. (1996)	Zornberg et al. (2004)	Rao and Dutta (2006)	Lee et al. (2007)	Kim and Santamarina (2008)	Sheikh et al. (2013)
Rigid particle/ Classification	Sand/ Poorly Graded	Sand/ Poorly Graded	Sand/ Poorly Graded	Sand/ Poorly Graded	Sand/ Poorly Graded	Sand/ Poorly Graded
Soft (Tire) particle type	Crumbs	Shreds	Chips	Crumbs	Crumbs	Crumbs
D_{max} of rigid particles (mm)	0.42	--	1.2	1.18	1.18	1.18
D_{max} of tire particles (mm)	4.75	12.7-203.2	20	--	9.5	2.36 to 4.75
D_{50} of rigid particles (mm)	0.23	0.4	0.42	0.35	0.35	0.34
D_{50} of tire particles (mm)	3.7	≈ 100.0 (average)	20	0.09	3.5	1.39 to 2.2
Soft /rigid size ratio (using D_{50})	8.8	>200 (average)	47	0.3	10.0	4.1 to 6.5
Changes in shear strength by increasing Tire content	Decrease	Increase (till transition mixture)	Increase	Decrease	--	Decrease
Changes in compressibility by increasing Tire content	Increase	--	Increase	Increase	Increase	Increase
Tire content in transition mixture (%)	--	35	20	17-32	12-27	--

Table 2. Physical properties of FRG and TC

Material	Specific Gravity (G_s)	Water Absorption (%)	D_{max}	D_{50}	Coefficient of Uniformity	Coefficient of Curvature	USCS
FRG	2.48	1.81	4.75	0.73	7.5	2.9	SW
TC	1.14	2.86	4.75	3.04	2.1	0.4	SP

Table 3. Densities and relative densities of the GTC blends

Blend	GTC1	GTC2	GTC3	GTC4
Gravimetric TC content (%)	10	20	30	40
Gravimetric FRG content (%)	90	80	70	60
Volumetric TC content (%)	23.5	44.2	62.3	77.8
Volumetric FRG content (%)	76.5	55.8	37.7	22.2
γ_{min} (kg/m^3)	1214.9	1122.3	1035.2	973.7
γ_{max} (kg/m^3)	1648.0	1475.6	1334.2	1226.3
γ_d (kg/m^3)	1546.9	1387.7	1259.7	1163.9
Relative Density (%)	81.67	79.88	79.52	79.33

Table 4. Friction angles (ϕ) of GTC blends corresponding to peak and critical states

Blend	GTC1		GTC2		GTC3		GTC4	
State	Peak	Critical	Peak	Critical	Peak	Critical	Peak	Critical
Based on Results under σ_c = 30-60-120 kPa	40	37	39	37	37	37	37	37
Based on Results under σ_c = 60-120-240 kPa	40	38	37	35	34	34	33	33
Based on Results under σ_c = 120-240-480 kPa	35	33	32	31	30	30	29	29

Table 5. Values of Young's modulus (MPa) under confinements of σ_c = 30 and 480 kPa

Blend	GTC1	GTC2	GTC3	GTC4
E (MPa) at σ_c = 30 kPa	11.8	2.9	2.0	1.1
E (MPa) at σ_c = 480 kPa	31.8	15.4	11.4	8.5

Table 6. Compression and recompression index for GTC blends

Blend	GTC 1	GTC 2	GTC 3	GTC 4
Compression Index (C_c)	0.070	0.191	0.203	0.212
Recompression Index (C_r)	0.025	0.039	0.091	0.124

Figure 1

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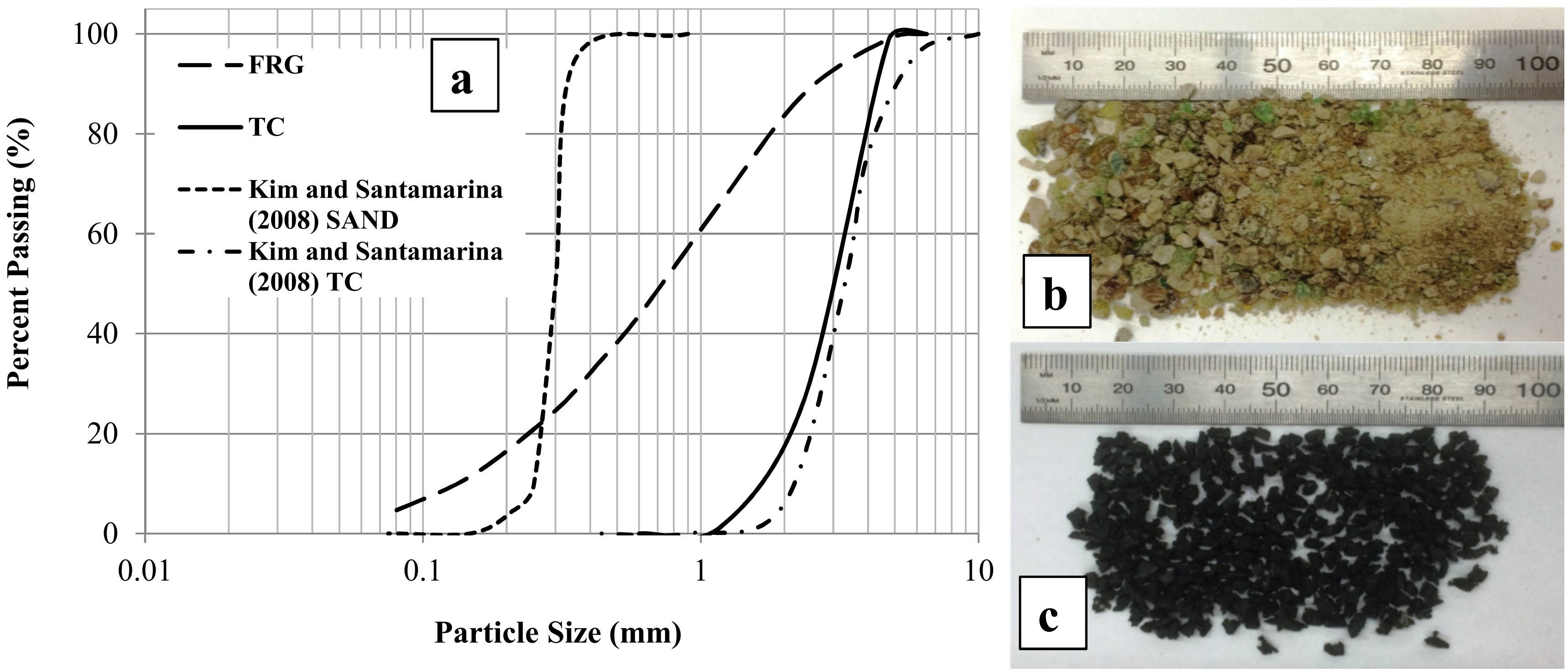

Figure 2

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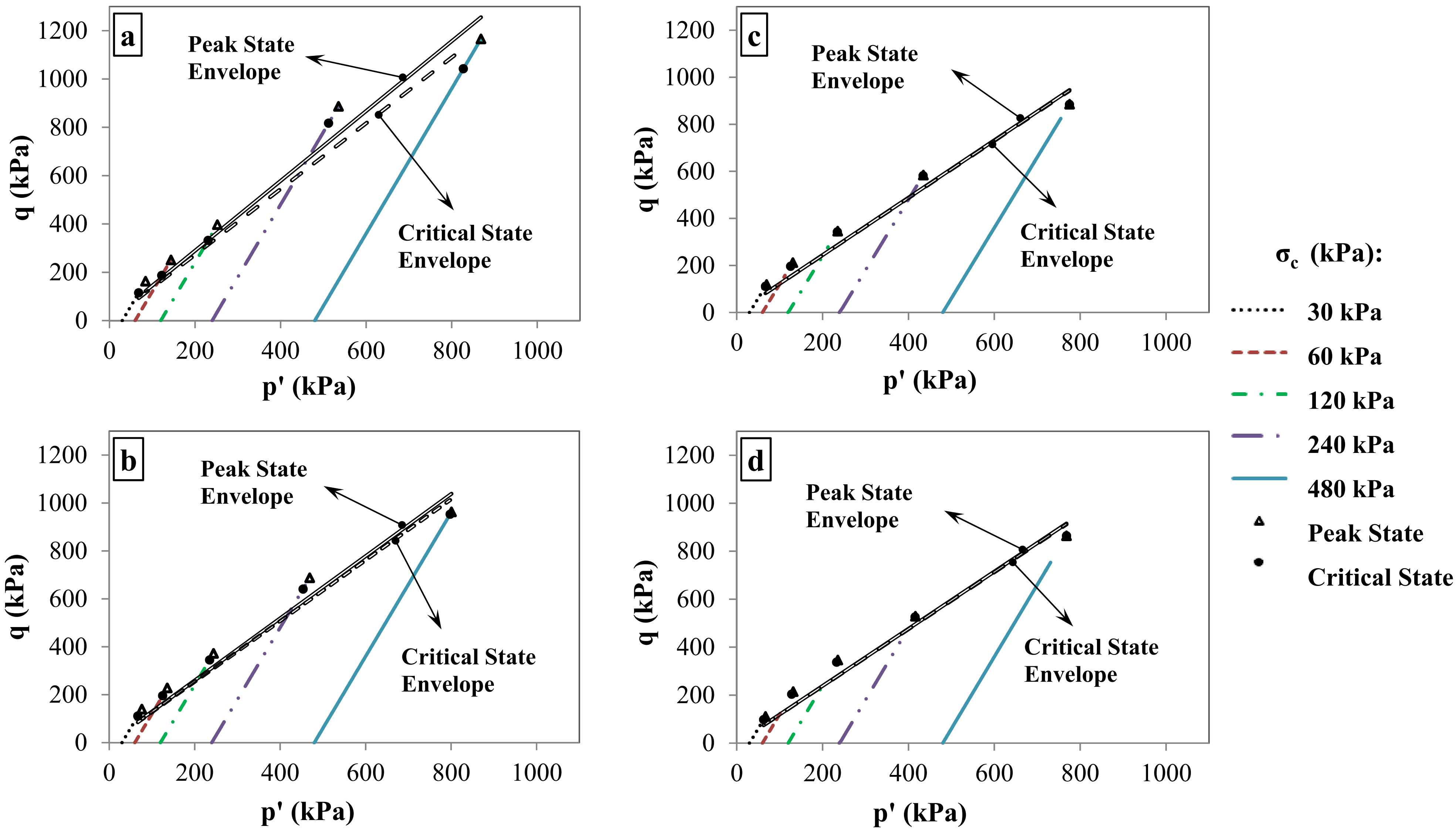

Figure 3

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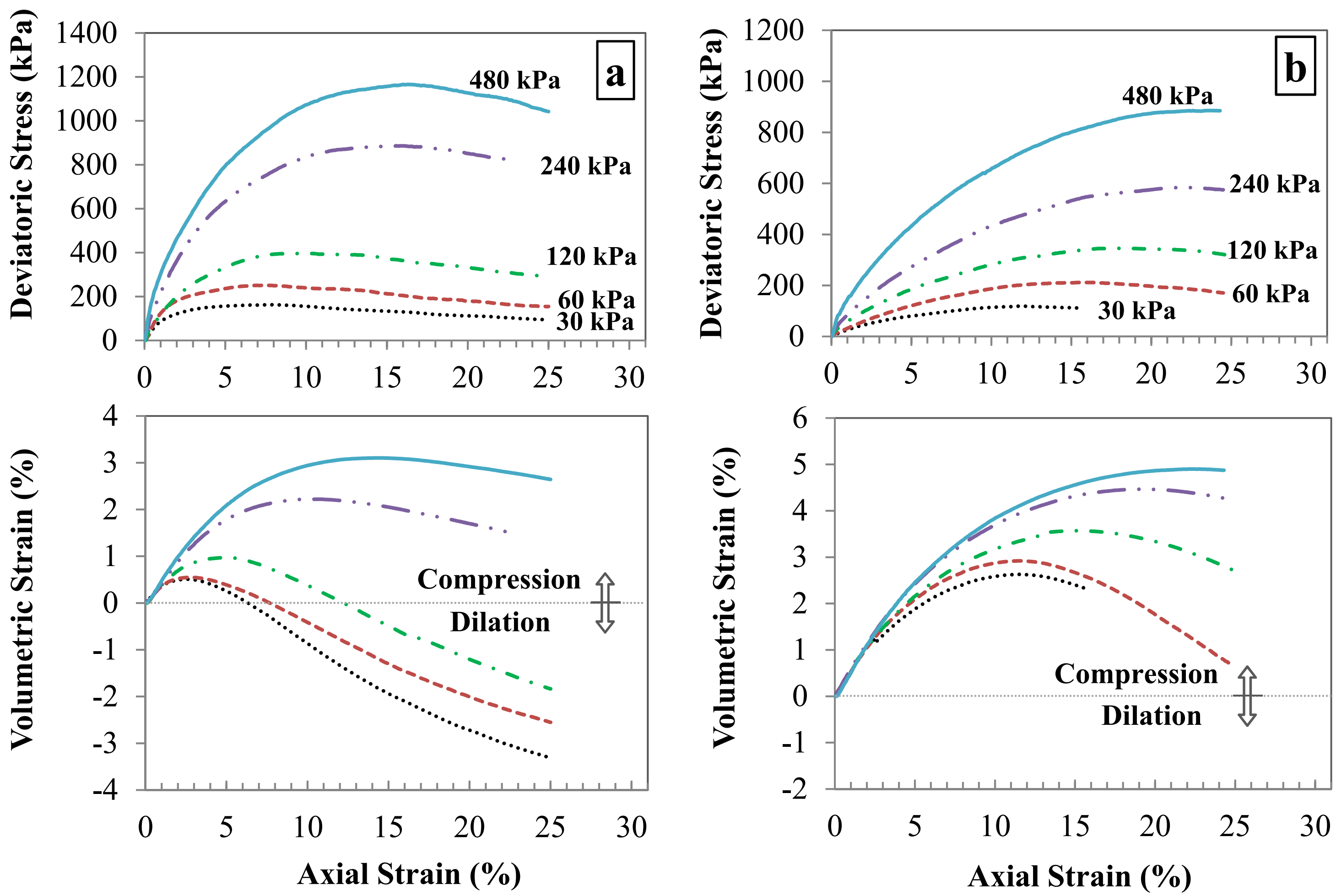
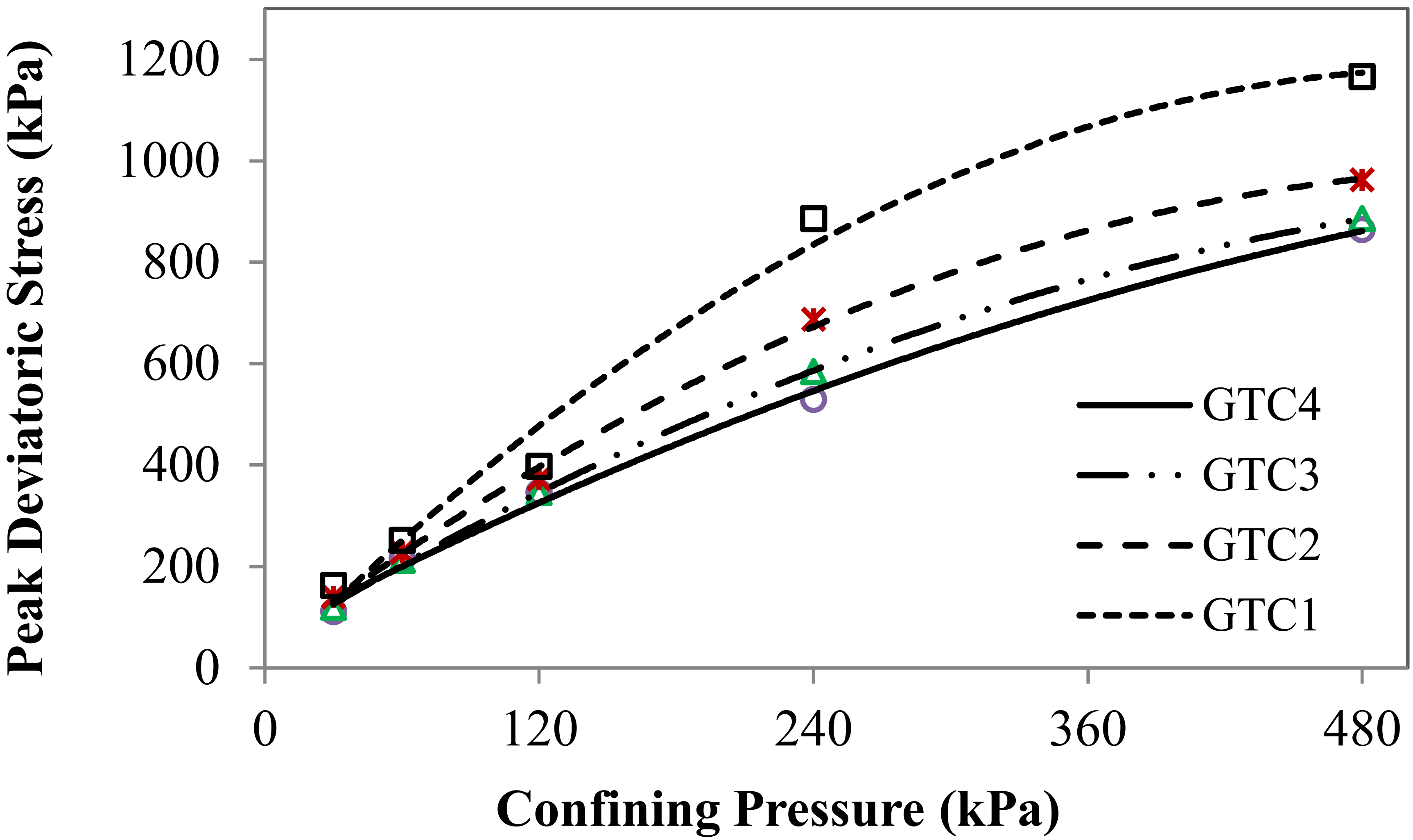
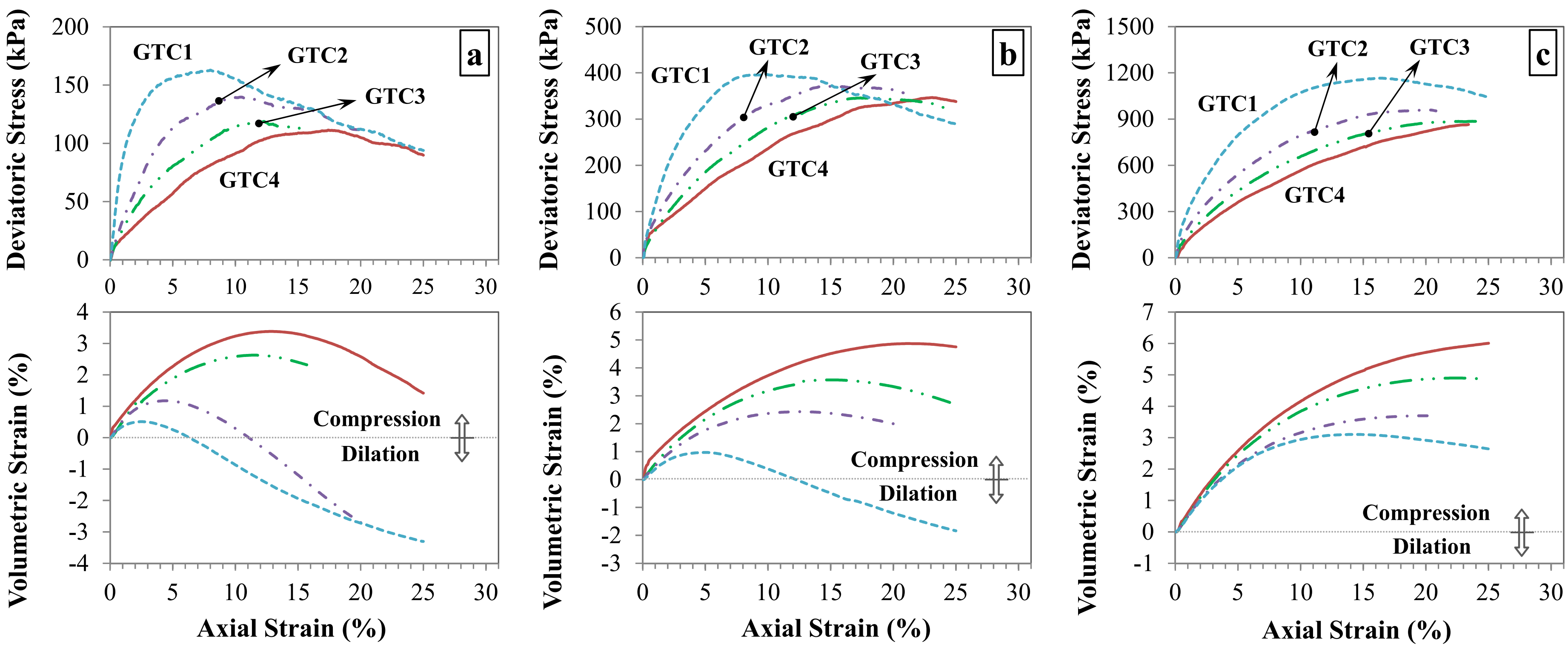



Peak Deviatoric Stress (kPa)
1200
1000
800
600
400
200
0
0
120
240
360
480
Confining Pressure (kPa)
GTC4
GTC3
GTC2
GTC1



Deviatoric Stress (kPa)
GTC1
GTC2
GTC3
GTC4
a
b
c
Volumetric Strain (%)
Compression
Dilation
Axial Strain (%)

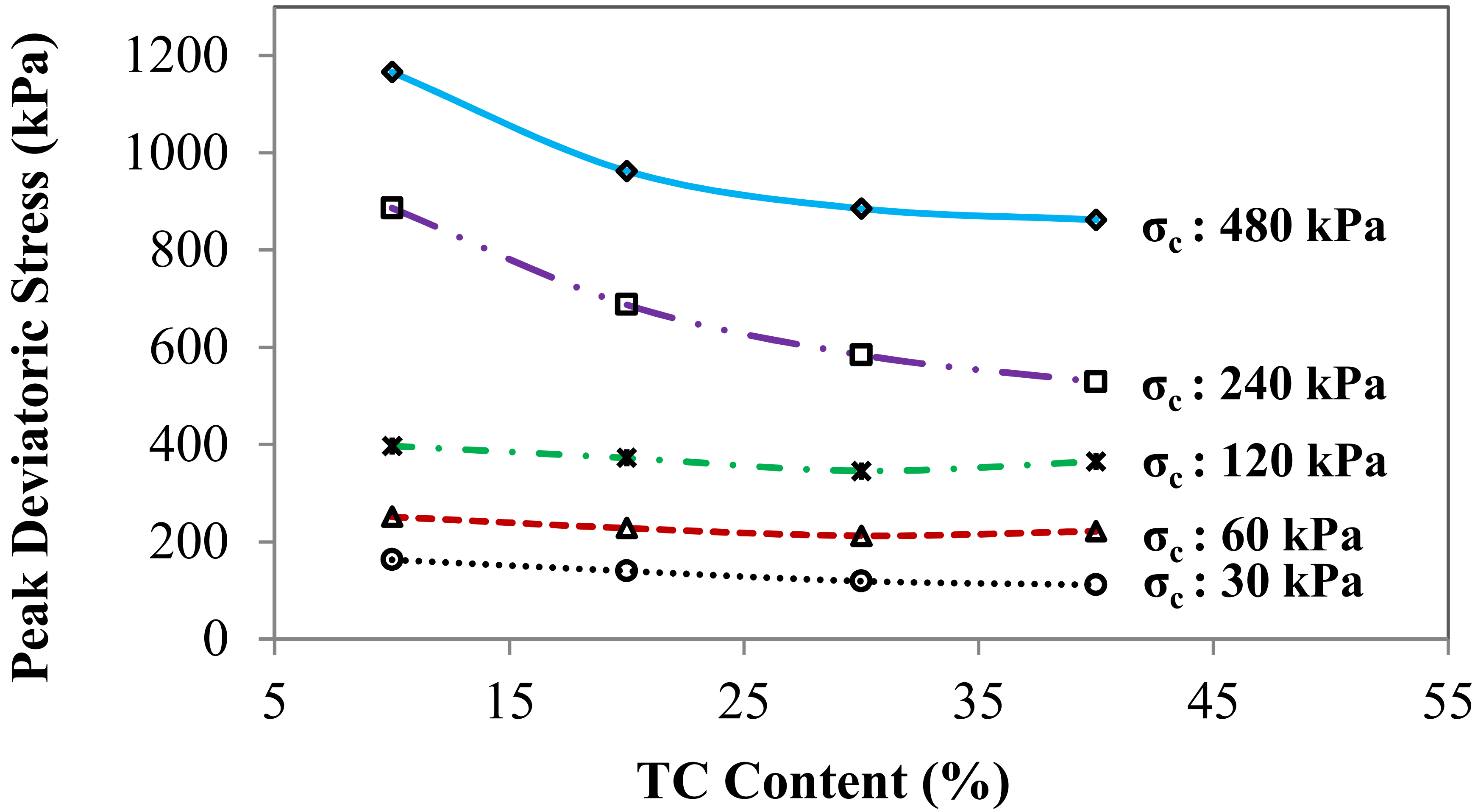
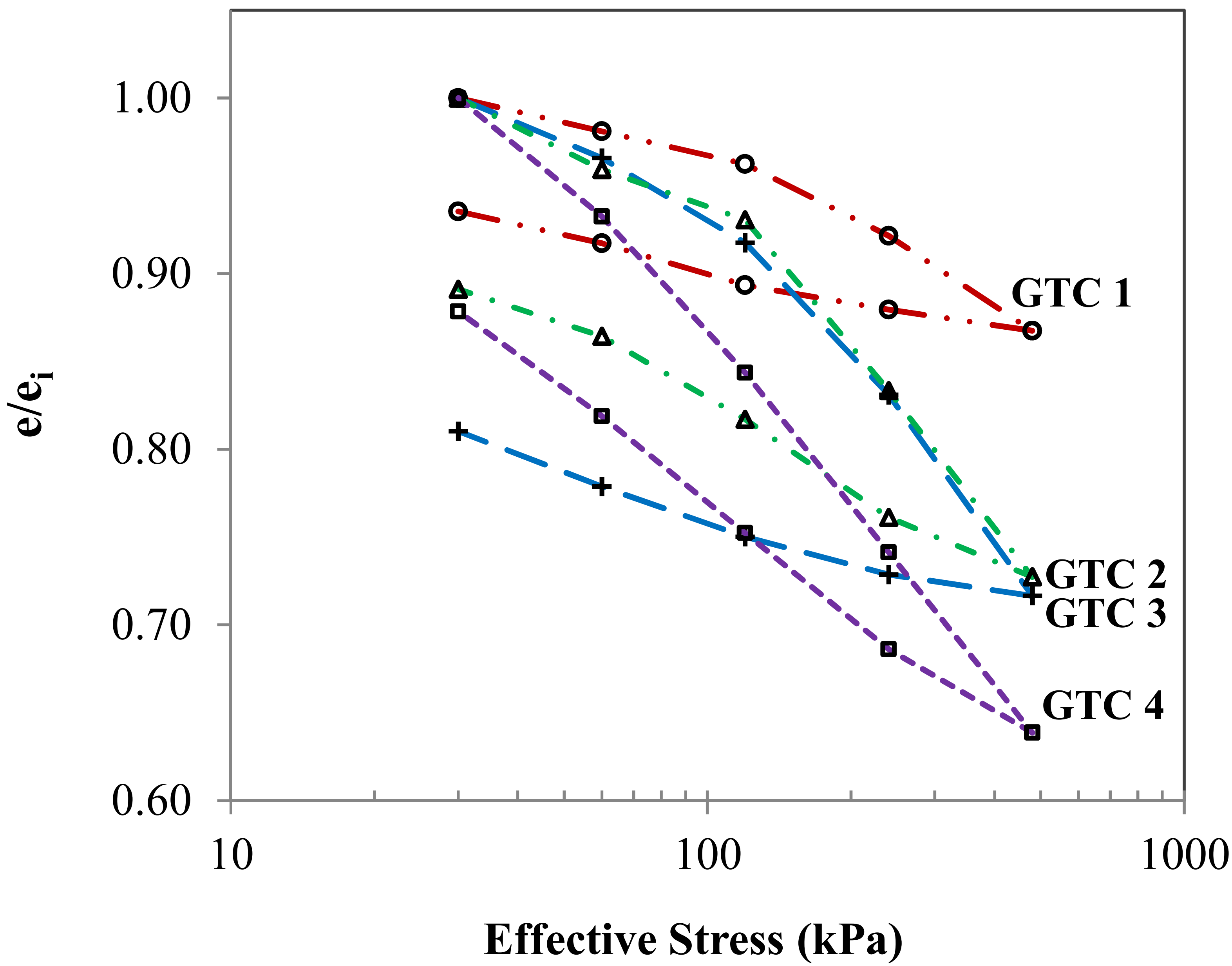

Peak Deviatoric Stress (kPa)
1200
1000
800
600
400
200
0
5
15
25
35
45
55
TC Content (%)
σc : 480 kPa
σc : 240 kPa
σc : 120 kPa
σc : 60 kPa
σc : 30 kPa

Figure 7



1.00
0.90
0.80
0.70
0.60
e/e$_i$
10
100
1000
Effective Stress (kPa)
GTC 1
GTC 2
GTC 3
GTC 4