# A COMPARISON OF THE PERFORMANCES OF POLYPROPYLENE AND RUBBER FIBERS IN COMPLETELY DECOMPOSED GRANITE

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**Abstract**

This fundamental study investigates how two very different types of fibers, very elongated polypropylene fibers with high tensile resistance, and larger rubber fibers with a smaller aspect ratio and low shear and Young's moduli affect the compression and shearing of a soil ~~the same host soil~~. The same host soil was used for both types of fibers, a well-graded decomposed granite. As well as providing a realistic base for the study with its well graded nature, the decomposed granite's tendency to contract upon shearing is used to highlight the underlying mechanisms causing any difference in behavior. The soil mixtures were prepared at an optimal fiber content for each kind. The general patterns of behavior of the reinforced soils, such as the stress-dilatancy behavior, and the normal compression and critical state lines, are compared. It is found that the specimens with rubber fibers are initially much less stiff than those with polypropylene fibers, so that they require larger deformations to reach failure. At failure, they can provide as much extra strength as polypropylene fibers if the rubber fiber-soil mixture has been consolidated to a low confining stress, although very much larger quantities are needed, even to the point of being unrealistic for engineering applications. At high confining pressures, the rubber fibers, which have become slack during compression, tend to lose in efficiency. The soil reinforced with polypropylene fibers develops consistently higher strength, but the compressive nature of the base soil has the effect of hindering their full mobilization as would be seen in a dilative soil.

**Keywords: geosynthetics;** residual soils; reinforced soils; laboratory tests

## INTRODUCTION

Adding discrete elements like fibers to soils with a view to improving their performance has been actively researched for two to three decades (e.g. Gray & Ohashi, 1983; Maher & Gray, 1990; Michalowshi & Cermak, 2003; Consoli et al., 1998, 2005; Zornberg, 2008; Diambra et al., 2007; Silva dos Santos et al., 2010; Gregory, 2011; Hamidi & Hooresfand, 2013; Correia et al., 2015; Miranda Pino & Baudet, 2015; Madhusudhan et al., 2017). Fibers commonly used in previous studies were made of polypropylene, polyester or fiber glass, but there is an increasing trend, as part of a global effort for sustainable development, to use fibers made of recycled materials such as tire or plastic waste (e.g. Consoli et al., 2002), or natural fibers such as sisal or coconut coir (e.g. Sivakumar Babu et al., 2008).

Fibers made of polypropylene or polyester have been found to provide the soil with a higher strength but with larger deformation at failure in both clayey (e.g. Maher & Ho, 1994) and sandy soils (e.g. Consoli et al., 1998; Silva dos Santos et al., 2010). These fibers work principally in tension, and it might be expected that they therefore perform better in dilative soils, although it has been found that they can also be mobilized during isotropic compression by anchoring between the soil grains (Consoli et al., 2005). In situ, fibers have been used effectively to reinforce shallow foundation sublayers (e.g. Consoli et al., 2003) and thin soil veneers on shallow slopes (Zornberg, 2008), or for the repair of localized failed slopes (Zornberg, 2008). Extensive laboratory studies have allowed the behavior of polypropylene fiber-uniform sand mixtures to be successfully described within the Critical State Framework (e.g. Silva dos Santos et al., 2010). The database on fibers made of recycled material, on the other hand, is less complete, most existing research tending to focus on rubber granules, chips or shreds rather than “fibers” (e.g. Valdes & Evans, 2008; Lee et al., 2007; Lee et al., 2014; Fu et al., 2015; 2017). Fundamental research has however been undertaken to study the possibility of using rubber additions as reinforcement. The results have shown that rubber must be added in very much larger proportions than e.g. polypropylene fibers in order to provide some improvement on the strength of the soil, the quantities varying between 10 and 40% depending on the host soil and the type of rubber additions (e.g. Edil & Bosscher, 1994; Foose et al., 1996; Zornberg et al., 2004; Edinçliler & Ayhan, 2010). The initial stiffness during shearing reduces with rubber content, i.e. the strain at which peak strength is achieved increases, (e.g. Zornberg et al., 2004; Özkul & Baykal, 2007), while the compressibility also increases with rubber content (e.g. Youwai & Bergado, 2003; Lee et al., 2010). Their suitability as reinforcing material is therefore far from clear. In this technical note, the fundamental behavior of polypropylene fiber-soil mixtures and rubber fiber-soil mixtures are compared, with no attempt to recommend either as reinforcing material in the decomposed granite or other soils, but the comparison does illuminate the likely mechanisms involved.

There are significant differences between the properties and use of polypropylene fibers and rubber fibers. Small amounts of polypropylene fibers are generally enough to reinforce the soil, while we know that rubber shreds typically need to be added to the soil in very large proportions even to the point of being impractical for many applications. A rubber content of the order of 35% has been found to maximize the effect on the shear strength, beyond which the behavior changes from sand-dominant to tire shred-dominant (Zornberg et al., 2004). The effect is more pronounced when using shreds with a higher aspect ratio e.g. ratios of 8 or above, closer to a fiber shape, although much larger in size. The material polypropylene possesses very high tensile resistance and stiffness, while rubber has low shear and Young's moduli and deforms severely under loading. These differences make it difficult to extrapolate from one material to the next. Different materials have also not been used in the same soil so that a comparison might be made.

The results shown in the following were obtained using two types of fibers, polypropylene fibers and rubber fibers, added to the same host soil so that a comparison can be made. Given the very different fiber properties and quantities of fibers used for each type, comparing individual tests would not be very meaningful, so here the approach has been to identify similarities and differences within general patterns of fundamental behavior described by the Critical State framework, and more particularly the stress-dilatancy behavior, the normal compression and critical state lines.

## MATERIALS, TESTING APPARATUS AND PROCEDURES

The base soil for the tests was a completely decomposed granite **(CDG)** from Hong Kong. Polypropylene (PP) and rubber fibers (RF) were added to the CDG as described below.

### *Materials*

The soil was obtained at Mt. Beacon, Kowloon Tong, Hong Kong. It is a well-graded completely decomposed granite containing about 20% fines. The main components of the soil are quartz, potassium feldspar and mica, with some kaolinite present in the clay fraction, giving a plasticity index of 16%. The particle size distribution of the soil is given in Figure 1. The maximum dry density determined by Proctor compaction was 18.9 kN/m$^3$ for an optimum water content of 11%. A complete description of the behavior of the CDG within the Critical State framework is available in Madhusudhan

& Baudet (2014). The choice of completely decomposed granite as host soil is that being well graded, it may be more representative of many natural soils than the uniform soils typically used in research. One aspect to highlight is that its contractive nature during compression and shearing will hinder rapid mobilization of the fibers, therefore emphasizing the different mechanisms by which the two types of fibers may interact with the soil.

The polypropylene fibers used (Fig. 2a) were similar to those used by Silva dos Santos et al. (2010) and purchased from a commercial company. The rubber fibers, also called buffings, are by-products of the tire re-treading industry and therefore consist entirely of recycled material (Fig. 2b). Their high aspect ratio compared to shreds or chips should be beneficial, and also should allow a more straightforward comparison with the polypropylene fibers. The properties of the two types of fiber are reported in detail later. The two sets of fiber-soil mixtures were prepared at very different fiber contents but which had been shown to provide the best performance for the decomposed granite for each fiber type (Fu et al., 2017; Madhusudhan et al., 2017). A quantity of 0.3% PP fibers by weight was used, which was based on previous studies (Silva dos Santos et al., 2010; Madhusudan et al., 2017). The quantities of rubber used for reinforcement are typically much higher (e.g. Edinçliler & Ayhan, 2010; Zornberg et al., 2004): in this study, 30% rubber fibers by weight were added to the decomposed granite. This amount was based on the study by Fu et al. (2017) who showed, albeit on a poorly graded soil, that the performance of rubber-soil mixtures improves with increasing content of rubber, but that it becomes very impractical to prepare soil mixtures with more than 30% rubber content.

*Testing, apparatus and procedures*

Triaxial compression tests were carried out on normally consolidated specimens of dimensions 60 mm x 120 mm or 76 mm x 152 mm at The University of Hong Kong and the City University of Hong Kong. Additional isotropic high pressure tests were performed at University College London on the unreinforced and PP-reinforced CDG in order to determine their normal compression and critical state lines. All shearing tests were strain controlled.

For both PP- and RF-fiber soil mixtures, the soil was first mixed at the optimum water content, then the fibers were mixed in. This ensured that the fibers remained well distributed in the specimen upon saturation. The polypropylene fibers, which come as “clumps”, were separated before testing by immersing in water and mixing slowly (Madhusudhan et al., 2017). This was not necessary for the rubber fibers. All specimens**,** with or without fibers**,** were moist-tamped into a mold in five to six layers, using the method of under-compaction (Ladd, 1978) to ensure that the bottom layers were not over-compacted. They were then installed on the triaxial pedestal. After being subjected to a small suction of about 20 kPa so that the initial dimensions of the specimens could be recorded, they were subjected to increments of cell and back pressure for saturation until a B-value above 95% was reached. One-dimensional compression tests were also performed in an oedometer cell of 40mm diameter with which vertical stresses up to 25 MPa could be reached. The apparatus used a floating ring setup so that wall friction was minimized.

Because of the large rubber contents, the different specific gravities of the tire shreds and the CDG were taken into account in the calculation of the void ratio, where both soil and reinforcement were counted as solids. Determining the initial void ratio of the specimens was nevertheless not straightforward, because of their irregular shape and their propensity to disintegrate when the membrane was removed, making taking the final dimensions or the final water content of the specimen difficult. Determining the initial void ratio of the specimens with polypropylene fibers was easier as they were used in much smaller proportion. This also meant that the specific gravity of PP fibers did not affect significantly the calculation of the void ratio.

The shearing tests were performed from normally consolidated states, at effective confining stresses between 50 and 500 kPa. Different void ratios were reached during consolidation under similar stress levels in the unreinforced and reinforced specimens, therefore the comparison between the two types of fibers is mainly based on how they affect the overall compressive and shearing behavior of the soil. This is achieved by examining the effects on the normal compression line (NCL), the critical state line (CSL) and the stress-dilatancy behavior, rather than by comparing individual test data for the same level of confinement. Some representative stress-strain-volume curves are shown nevertheless for completeness. A summary of the triaxial tests which are presented individually in this technical note is given in Table 1. The normal compression and critical state lines for the CDG and PP-soil mixtures reported in the figures were obtained from Madhusudhan & Baudet (2014) and Madhusudhan et al. (2017). Before analyzing the reinforced soil's response, the properties of the two types of fiber are examined.

## DIFFERENCE IN BEHAVIOR OF THE TWO TYPES OF FIBERS

Polypropylene is a tough but flexible material with good fatigue resistance. In civil engineering it is used in fiber form to increase the strength and ductility of concrete and reduce its cracking. The fibers used in this study were 24mm long with a diameter of 0.023mm, and could deform by up to 170% before breaking in tension (Consoli et al., 2005). Polypropylene fibers typically display non-linear viscoelastic behavior up to failure. The properties of the polypropylene (PP) fibers are summarized in Table 2.

Rubber is renowned for its elastic properties over a large range of strains. Most tire rubber available is synthetic. In a fiber form rubber is used for its damping properties, for example when used in turf. Despite having a low shear modulus, rubber has a very high bulk modulus because its Poisson’s ratio is close to 0.5 (Youwai & Bergado, 2003) so that there is no significant volumetric change during testing. Since the rubber fibers used in this study, 10.5mm length by 1.26mm diameter, came from a tire retreading garage, their properties were established in the laboratory by means of loading-unloading tension tests of which a typical response is shown in Figure 3. The initial behavior is very soft so that large displacements are required to mobilize strength. The behavior of the fibers in terms of load is recoverable, but hysteretic, up to at least 30mm displacement, which corresponds to about 300% strain. It is highly non-linear and would be even more highly non-linear in terms of stress. Many fibers were found to rupture at about 300% strain. The properties of the rubber fibers (RF) are also summarized in Table 2.

The rubber fibers were found to have extended typically to about 50mm with their diameter reducing to about 0.6mm before breaking, thus their aspect ratio changed by a significant amount during tensile deformation, by a factor of about 10 (from 8 to 83). A similar measurement could not be made on the polypropylene fibers because of their very small size, but it is unlikely that they would have suffered the same increase in aspect ratio. Both fibers have very low densities, which, in the case of rubber, typically used in large proportions, would result in a light soil mixture suitable for potential lightweight fill applications (Masad et al., 1996).

## COMPRESSION BEHAVIOR

The properties of the polypropylene and rubber fibers will affect the compressibility and strength of soil in different ways. The low shear and Young's moduli of the rubber allow the fibers to deform excessively during compression and shearing, leading to the RF-soil mixture being more compressible than the soil alone. In Figures 4 to 7, open symbols denote tests carried out on CDG specimens, closed symbols on specimens with polypropylene fibers, and plain or dashed lines with no symbols tests on specimens with rubber fibers.

The one-dimensional compression behavior is shown in Figure 4 where the compression curves of the RF-soil mixture plot with much steeper slopes than the PP-soil mixture and CDG. The curves for the rubber-soil mixtures only converge at stresses of about 500 kPa, becoming shallower and of similar compressibility to the unreinforced and PP-reinforced soil as stresses exceed 1,000 kPa and the specific volume, v, approaches unity. The rubber fiber-soil mixtures have substantially higher initial specific volumes, although after significant compression the normal compression lines of the three types of specimens plot in similar locations, with v = 1.4-1.9 for typical engineering stresses between 10 and 200 kPa. Beyond 200 kPa, the curves of the PP-soil mixtures plot the highest, and those with rubber fibers plot the lowest.

## **SHEARING BEHAVIOR**

The influence of the compression behavior during consolidation on the subsequent shearing is possibly that while the polypropylene fibers started being mobilized during the consolidation stage, the rubber fibers may have become slack under excessive compression of the RF-reinforced samples, therefore losing initial tensioning. The stress-strain-volume curves from representative tests performed at low (50 kPa) to medium (200-500 kPa) confining pressures are shown in Figure 5.

The different compressibilities of the three types of soil, and the fact that it was difficult to prepare the rubber fiber-soil mixtures at a required void ratio, meant that specimens tested under the same confining stress did not necessarily have the same specific volume at the start of shearing (Table 1). This must be kept in mind when comparing the responses in Figure 5, especially the volumetric response. The stress-strain curves, plotted as stress ratio q/p' against shear strains in Figure 5(a), highlight the existence of a stable critical state stress ratio equal to 1.57 for the CDG. The specimens containing polypropylene fibers reach a higher critical state stress ratio, especially if they were sheared under low confining pressure. The specimens containing rubber fibers also show a gain in strength at lower stresses, but at higher stresses they seem weaker than the CDG. At large strains close to failure, the RF-soil mixtures sheared at low confining pressure reach similar stress ratios at critical state to the PP-soil mixtures sheared at medium confining pressure, and it is interesting how very large amounts of inclusions of a different material do not change the critical state strength. One main difference to note is that the rubber-soil mixtures have much lower initial stiffness and therefore require larger strains to reach their maximum strength. This was noticed in the tests on individual rubber fibers shown in Figure 4. This was also found by Fu et al. (2017) from small strain measurements, with the shear modulus decreasing by about two thirds when adding 30% rubber fibers, and is a distinct disadvantage of rubber addition compared to the use of small amounts of polypropylene fibers which Heineck et al. (2005) found did not affect small strain stiffness. The volumetric response in Figure 5(b) emphasizes the high compressibility of the specimens with rubber when compared to the other two soils. The presence of polypropylene fibers seems to reduce the amount of compression during shearing, but no direct comparison can be made between soils since shearing was started from different void ratios. A stable volume also seemed to be reached at the end of shearing in all tests.

The strength envelopes (or critical state lines) were derived from the tests shown in Figure 5 and, in the case of the CDG and PP-soil mixure, additional tests detailed in Madhusudhan & Baudet (2014) and Madhusudhan et al. (2017) were also used (Figure 6). The slope of the critical state line, which takes account of higher pressure tests described in Madhusudhan et al. (2017), has increased by about 20% when adding polypropylene fibers, rising to an average of 1.90 from the value of 1.57 obtained for the CDG. This increase remains even at high pressures (Madhusudhan et al., 2017), unlike what was previously found with similar fibers in a uniform sand (Silva dos Santos et al., 2010), in which the rapid mobilization of tension in the fibers during dilation was lost as the soil became compressive at high stresses, giving a curved critical state line. The addition of rubber fibers provides a similar increase in strength to the polypropylene fibers for stresses up to about 150 kPa, although with a very much higher quantity of fibers added (30% RF as opposed to 0.3% PP). It is doubtful whether such a large amount of rubber as that required would ever be used, even for a lightweight backfill or embankment, however this study provides a useful comparison in understanding how fiber-soil mixtures work. The gain in strength due to the rubber fibers seems also to reduce quickly at higher stress levels, with the critical state line curving towards that of the CDG, which is another distinct drawback of their use. This was also observed by Fu et al. (2015, 2017) both for RF-soil mixtures made with compressive and dilative uniform sands. A similar conclusion was reached by Özkul & Baykal (2007) as well, who found that rubber fiber-clay mixtures could reach strengths similar to that of the pure clay if tested at low confining stresses. Here, a slope dependent on the stress level is proposed: $M = 1.57 (1 + a.e^{(-p'/b)})$, with a = 0.38 and b = 255 kPa for unit consistency. It is expected that for other fiber contents the values of a and b would vary.

The critical state lines are shown in the volumetric plane, v-lnp', in Figure 7. The small scatter observed in the data of the RF-soil mixtures is within ±0.03, and is a consequence of the difficulty in measuring the initial void ratio when large quantities of rubber are used, due to the irregular shape of the specimens and their propensity to disintegrate when the membrane is removed. The excessive compression of the rubber-soil mixture is reflected in the critical state line which has a steep slope, plotting parallel to the normal compression line. This forces the critical state line of the RF-soil mixture below the CSLs of the PP-soil mixture and CDG at larger stresses, and may contribute to explain the loss in strength in the rubber-soil mixture at large stresses. The NCL and CSL of the soil with polypropylene fibers, by comparison, have shallower slopes, plotting higher than and parallel to the normal compression and critical state lines of the CDG.

## STRESS-DILATANCY BEHAVIOR

The stress-dilatancy behavior, shown in Figure 8, can offer some insight to the response to shearing of the various soils. Here it is plotted in terms of total strains, where $\delta\varepsilon_v$ is the volumetric strain and $\delta\varepsilon_s$ is the shear strain. All the specimens show predominantly contractive behavior (i.e. the compression rate, $\delta\varepsilon_v/\delta\varepsilon_s$, is positive), even at low confining stresses. In the initial stages of the tests, when the compression rate is higher than 0.15, the strength is mobilized at similar rates of compression for the soil and its mixtures. As was seen in Figures 5 and 6, the specimens containing polypropylene fibers and those containing rubber fibers that were tested at low confining stress mobilize extra strength, with stress ratios above those of the CDG. The PP-soil specimens, in particular the specimen tested at low confining pressure, experience an acceleration in the rate of gain of strength towards critical state. The rubber fibers seem to mobilize strength steadily, the specimens sheared at low confining pressure reaching stress ratios higher than those of the CDG at larger strains, when the specimens approach a constant volume state (i.e. compression rate below 0.15). The specimens which were sheared at confining stresses in excess of 150 kPa do not quite reach the same level of strength, as was observed in Figures 5 and 6, although the q/p' ratio was still increasing slightly at the end of the test (Figure 5(a)).

## DISCUSSION AND CONCLUSION

The behaviors highlighted in compression and shearing may be useful to understand the relative influences of the volumetric and shear strains on the performance of the two types of fibers, bearing in mind that only one fiber content was used for each fiber type, and that the fiber contents were very different. Significantly larger volumetric strains are experienced by the RF-soil mixture than by the PP-soil mixture and the CDG, due to the compressive nature of the CDG, with its significant fines content, and the low shear and Young's moduli of the rubber. These compressive strains have the effect that the fibers become slack during consolidation. By comparison, the compressibility of the soil with polypropylene fibers is similar to that of the soil alone, much lower than that of the soil with rubber fibers, particularly at lower stresses.

At the start of shearing, when volumetric strains dominate the behavior, the polypropylene fibers convey extra strength to the soil, and while the three soils seem to develop strength at the same rate in that the stress-dilatancy gradients are similar, they reach different stress ratios at a given compression rate.

As the shear strains start dominating the behavior, i.e. when the rate of volumetric strain decreases towards zero, a marked difference is observed as the polypropylene fibers start mobilizing strength at a higher rate, while no significant difference is observed in the RF-soil mixture and CDG. The stress ratios reached by the PP-soil mixtures are lower than those that were observed in a uniform soil by Silva dos Santos et al. (2010), who saw a very marked increase in strength during dilation, but the gain in strength does not diminish with stress level for the CDG. This indicates that the propylene fibers work better when the rate of compression decreases, and that the compressive nature of the CDG delays the fibers mobilizing their tensile strength to large strains. The high number of contacts between soil and fibers, due to the presence of fines in the CDG, should also be beneficial to the transfer of force from the soil to the fibers and may explain the absence of reduction in angle of shearing resistance with stress level observed in dilative soils. It also agrees with results from numerical analyses in which the fiber-soil interaction is modelled as a shear-lag effect (Diambra & Ibraim, 2015).

By comparison, the RF-soil specimen which compressed to a low confining stress before shearing does reach a strength similar to that reached by some PP-soil specimens, perhaps due to the fact that it experienced less volumetric change during consolidation. The RF-soil specimens compressed to higher confining stress reach a strength equal to or lower than that of the unreinforced soil, resulting in the critical state line curving towards that of the CDG. The same was observed in pure sand by Fu et al. (2015, 2017), thus in the case of the rubber fibers, the larger number of contacts in the decomposed granite does not seem to benefit the strength. Instead, the compressive nature of the fibers combined with that of the soil at higher stresses seems to delay the mobilization of their strength and reduce its effect. The lower initial stiffness also delays reaching failure until large deformations are attained. Observations of the fibers after test indicated that a small proportion of both types were broken during shearing, possibly by nipping (Fu et al., 2015; Madhusudhan et al., 2017). It was noted that some of the PP fibers were extended, but not the RF fibers. The polypropylene fibers might therefore have been extended past their breakage limit, while the rubber fibers would have needed larger deformations to reach the same state and a higher mobilized strength.

Without aiming at giving any practical recommendation, it is clear from this study that adding polypropylene fibers to the CDG improves its strength and stiffness, while adding rubber fibers does not seem to benefit significantly the soil's performance. One should remember that the motivation behind studying rubber-soil mixtures stems from environmental concerns. This fundamental study shows that if added in large quantities, rubber fibers can reach reasonable strengths, sometimes comparable to that of polypropylene-soil mixtures, however the significant proportion of rubber in the soil makes it very much less stiff and more compressible.

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Table 1 Summary of tests

| Test name* | $v_0$ | $v_c$ | $p'_c$ (kPa) | OCR | Test type |
|---|---|---|---|---|---|
| UR50 | 1.51 | 1.47 | 45 | 1 | CID |
| UR500 | 1.50 | 1.34 | 494 | 1 | CID |
| RF50 | 1.65 | 1.59 | 50 | 1 | CID |
| RF200 | 1.63 | 1.40 | 199 | 1 | CID |
| RF300 | 1.66 | 1.40 | 298 | 1 | CID |
| PP50 | 1.52 | 1.50 | 49 | 1 | CID |
| PP200 | 1.54 | 1.46 | 203 | 1 | CID |

UR: unreinforced; RF: rubber fibers; PP: polypropylene fibers; $v_0$: initial specific volume; $v_c$: specific volume after consolidation; $p'_c$: confining effective pressure at the end of consolidation

Table 2 Properties of the two types of fiber

| Fiber type | Length (mm) | Diameter (mm) | Aspect ratio | Relative density | Tensile strength (MPa) | Elastic modulus* (MPa) | Deformation at rupture (%) |
|---|---|---|---|---|---|---|---|
| Polypropylene | 24 | 0.023 | 1043 | 0.91 | 120 | 3,000 | 80-170 |
| Rubber | 10.5 | 1.26 | 8 | 1.15 | 65 | 5,000 | 230-400 |

*determined from the linear range of the stress-strain response

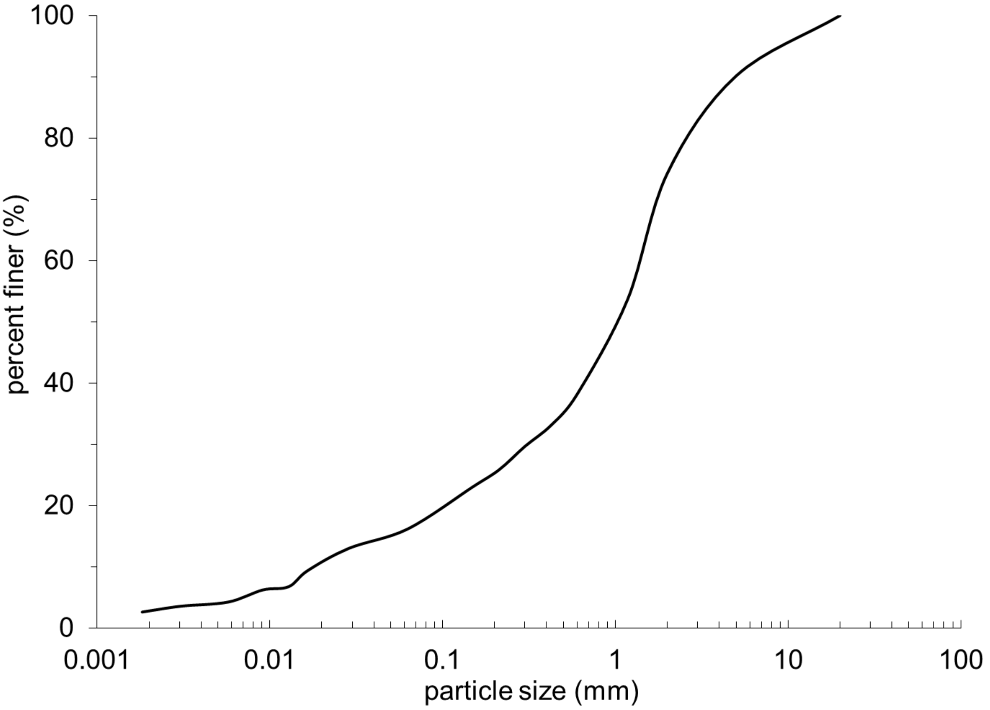



Figure 1 Particle size distribution of the completely decomposed granite

(a)


(b)

Figure 2 Photographs of the (a) polypropylene fibers (24 mm x 0.023 mm) (b) rubber fibers (10.5 mm x 1.26 mm)

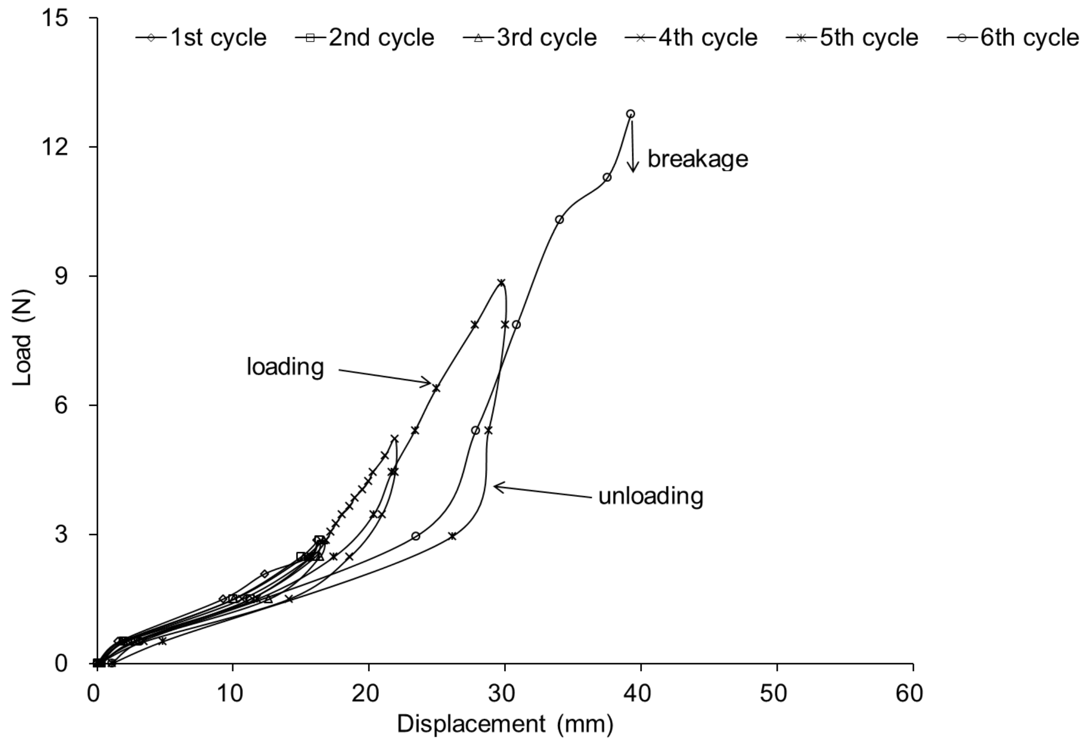



Figure 3 Elastic behavior of the rubber fibers during tensile loading-unloading

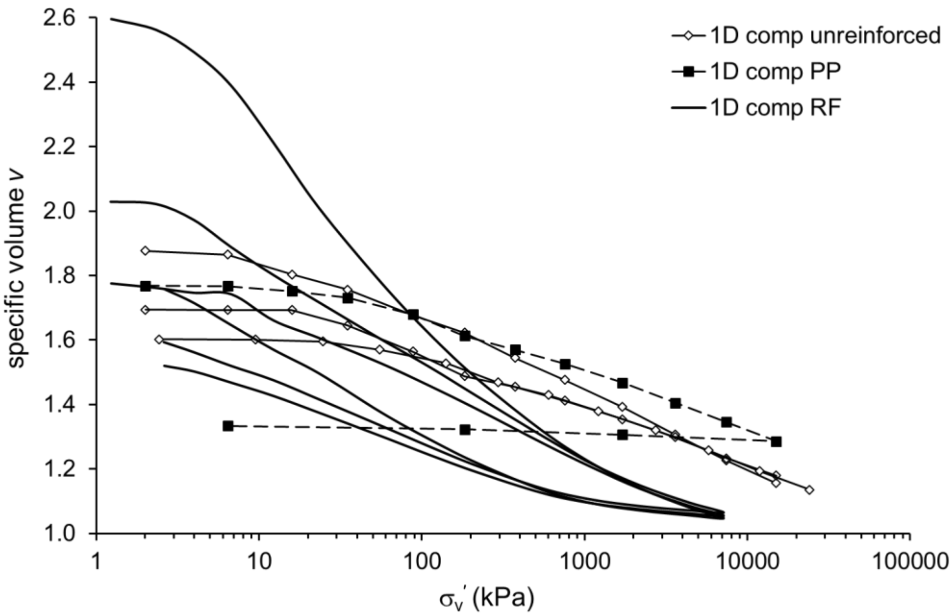
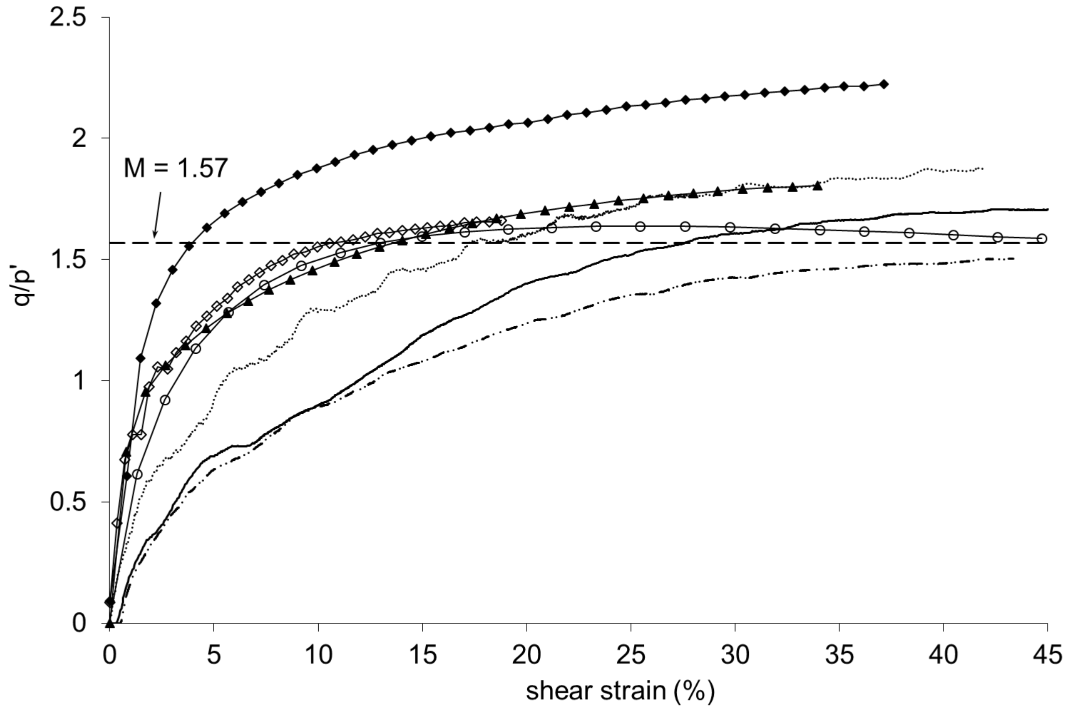
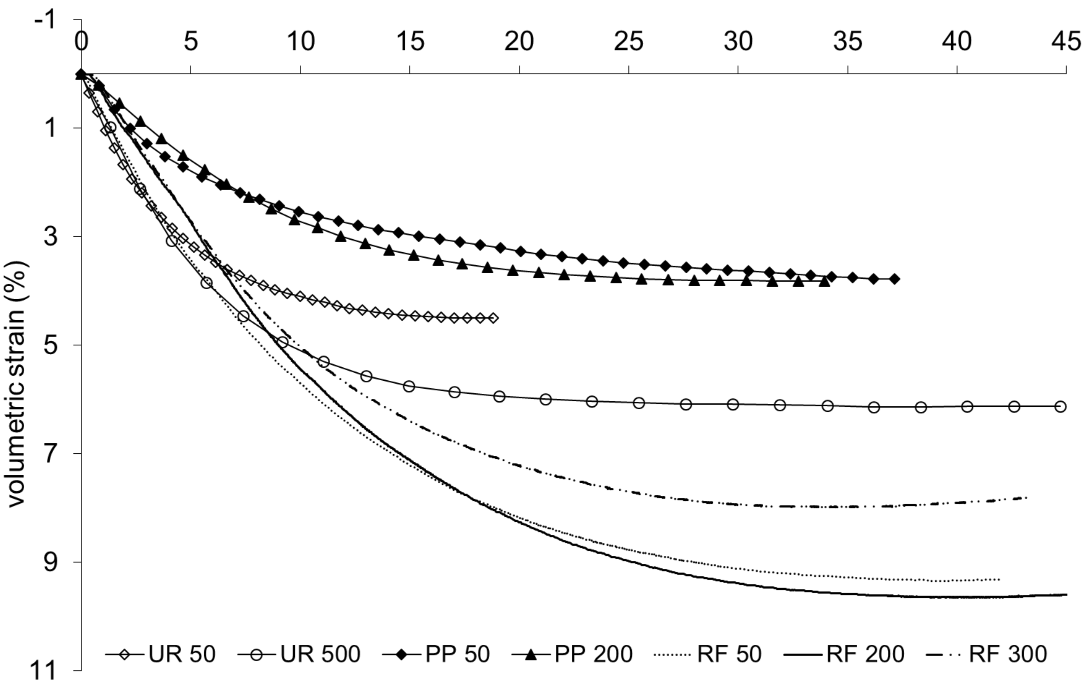



Figure 4 Compressibility of the unreinforced and reinforced CDG during one-dimensional compression




(a)




(b)

Figure 5 Examples of response of the three soils under low and medium stress (a) stress-strain (b) volumetric curves

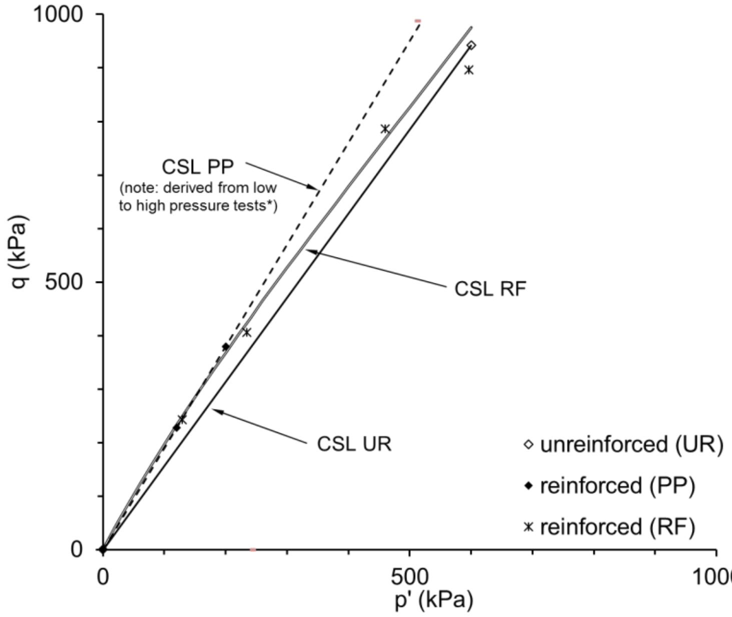



Figure 6 Critical state lines in stress plane (data for the unreinforced and PP specimens from Madhusudhan & Baudet, 2014 and Madhusudhan et al., 2017, respectively). *Note that some additional tests data are shown for the unreinforced and PP-reinforced specimens, which are not all reported in Table 1.

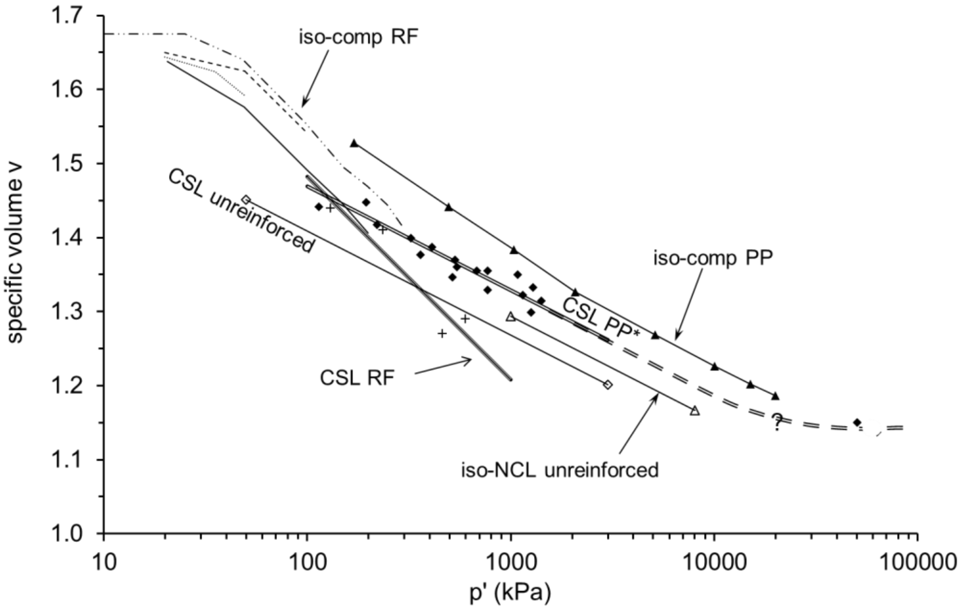



Figure 7 Critical state lines in volumetric plane (data for the unreinforced and PP specimens from Madhusudhan & Baudet, 2014 and Madhusudhan et al., 2017, respectively). *Note that this figure shows all tests performed on the PP-reinforced specimens, which are not all shown in Table 1. The open symbols are only used to characterize the lines, and do not mark any particular test.

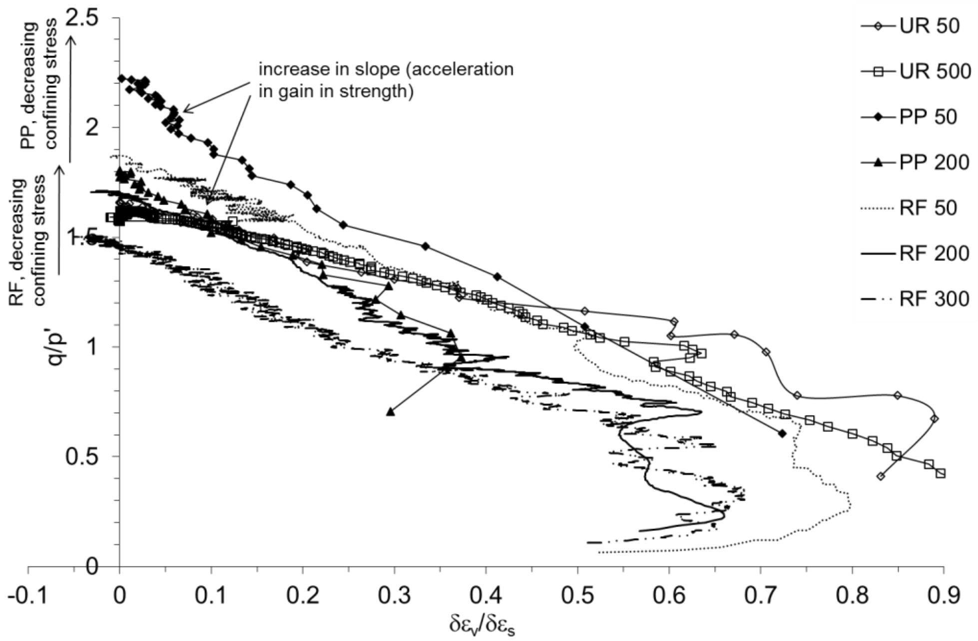



Figure 8 Comparison of stress-dilatancy behaviors