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Static and dynamic loading effects on the strength characteristic of municipal solid waste (MSW) fines reinforced with geosynthetics

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Abstract. The study investigates the influence of geonet and non-woven geotextile reinforcement on the strength performance of municipal solid waste (MSW fines). A set of unconsolidated undrained static and dynamic triaxial tests was conducted on the reinforced MSW fines samples by a varying number of reinforcement layers (0, 1, 2 and 3) to investigate the stress-strain and strength behaviour of the composite material. The MSW fines (particle size $<$ 4.75 mm) inherently exhibit limited mechanical strength and required the use of additional ground improvement procedures to make them suitable for practical field applications. Although laboratory tests have shown improvements in the static strength of the investigated MSW fines when reinforced, due to the lack of any observed improvements in its dynamic strength characteristics, concerns continue regarding the viability of using this composite material in high seismic zones.

Keywords. MSW fines; geonet; geotextile; reinforcement; stress-strain; strength performance.

1. Introduction

The world is dealing with the solid waste problem and its management. It was reported that global waste generation is on a trajectory that would surpass a total of 11 million tonnes a day by 2100 [1]. Landfill mining could be a very useful technique to reclaim and reuse the excavated waste and reduce the accumulated old dumps where the reclaimed site could be used for other purposes. MSW fines contribute to the major portions of the old landfills. The fine fractions adopted in the literature depend on the sieve size adopted for the study, i.e., 4 mm [2], 4.75 mm [3], 10 mm [4], 20 mm [5] 40 mm [6]. In this study, only a particular subset of waste particles—those less than 4.75 mm—were regarded as Municipal Solid Waste (MSW) fines. It is interesting to note that the majority of prior research efforts have been devoted to the physical and chemical characterization of MSW. Furthermore, the bulk of available literature has mostly focused on the field and laboratory studies but has only provided a few insights into the static and dynamic features of MSW. These findings are essential for understanding the behaviour of waste material and are crucial for the creation of better design and management strategies for landfills [7–18]. It is vital to remember that the mined material, in particular the MSW fines, may need to be treated first using chemical, mechanical, or biological methods before being put to use again. Due to the material's existence of some essential chemical components, this treatment is essential.

This study has tackled a fundamental issue, which pertains to enhancing the mechanical strength of aged MSW fines that have been extracted from landfill sites. The best strategy was found to be geosynthetic reinforcement of these particles, which is consistent with long-standing techniques used for soil enhancement. Geosynthetics are planar products made of either polymetric (polypropylene, polyester, polyethylene, polyamide, PVC, etc.) or natural materials (made of natural fibers: jute, coir, cotton, wool, etc.). There are multiple uses of geotextiles in the design of municipal solid waste landfills mainly related to separation, filtration, drainage, reinforcement, and cushioning. Sometimes even the foundation soil of the landfill requires stabilization and reinforcement using geotextiles, geogrids, or randomly distributed fiber reinforcements. The general parameters that influence the interaction of the material with geogrids or geonets are properties of the material and test method, position and the number of geogrid layers, stiffness, size, and shape of geogrid aperture [19]. Geogrids are generally used for vertical expansion (increasing the height of waste mass) of landfills and their slope reinforcement. High-strength geotextiles and geogrids provided for structural support to the cover systems have been widely reported in the past [20–22]. The tensile strength of the reinforcement and the efficiency with which the

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reinforcement is anchored at the berms determine the stability of the landfill cover system.

In conventional soil reinforcement, geosynthetics are widely used for steep slope stability, retaining walls, increasing resistance to traffic load, and foundation treatment [23]. Many studies investigated soils or other wastes like coal ashes reinforcement mechanisms through field and laboratory tests [24, 25]. Also, few studies have concluded that geogrids mainly reinforce lateral restraint, and improve bearing capacity, and the tensioned membrane effect [26, 27]. In the past, extensive field monitoring of reinforced soils-structures has also been a part of research to extensively examine the stress state and assess the engineering performance of such systems [28–30]. The particle size and shape, as well as the mechanical, chemical, and engineering behaviour, of MSW fines are different from those of the ordinary soils. When compared to reinforced soils, reinforced MSW may exhibit different engineering behaviour. Because the theories that apply to reinforced soils may not apply perfectly to reinforced MSW, long-term field monitoring is necessary to assess the engineering performance of the reinforced waste [31].

Researchers have been rigorously searching for ways to turn different waste types, including industrial, agricultural, and municipal waste, into useful civil engineering materials or applications to facilitate their extensive reuse. This study focuses on the use of MSW fines, a subset of municipal solid waste (MSW) that resembles soil and is thought to be a possible soil substitute in real-world field applications. This investigation's main goal has been to thoroughly evaluate the mechanical behaviour and strength features of MSW fines when reinforced to throw light on their applicability for engineering applications.

2. Material properties

2.1 *MSW fines*

The municipal solid waste was collected from an open dumpsite near Ramana, Varanasi (Uttar Pradesh), India, and segregated manually. The MSW fines, i.e., particles below 4.75 mm which contribute about 60% of the total weight of the waste were considered for the present study. The considered waste is categorized as non-plastic poorly graded silty sand (specific gravity=2.32), according to the Unified Soil Classification System (USCS). The collection and segregation process, geotechnical (static and dynamic) properties, chemical properties, elemental analysis, and surface morphology of the considered waste have been discussed in past studies done by Rawat and Mohanty [15, 16].

2.2 *Geotextile*

The present study employed needle-punched and thermally bonded polypropylene non-woven geotextile. Non-woven geotextile gives more permeability with a low characteristic opening size which makes them suitable to use for sub-surface drainage, erosion control applications, and road stabilization over wet moisture-sensitive soils. The properties of the geotextile are summarised in table 1.

2.3 *Geonet*

Geonets are integrally fused jointed polymer grids that have high dimensional stability and junction strength. They are made of high-density polyethylene (HDPE) which is protected against environmental and ultraviolet degradation. Geonets are used for slope erosion control, landscaping, retaining wall and toe wall gabions, drainage, and protecting layers for pipelines. The properties of the geonet considered for the present study are illustrated in table 1. The reinforcement materials used in the study are shown in figure 1.

3. Experimental study

3.1 *Testing program*

In the current investigation, two sets of triaxial tests were conducted, encompassing both unreinforced and reinforced Municipal Solid Waste (MSW) fine samples with geotextile and geonet materials. These tests were conducted under unconsolidated undrained (UU) conditions, encompassing both static and dynamic loading scenarios. Flow chart in figure 2 provides a thorough description of the testing techniques and the experimental procedure for this investigation. For all static and dynamic triaxial tests, the studied MSW fines were reinforced (with geotextile and geonet) in 1, 2, and 3 layers, while all other variables were held constant. A series of strain-controlled

Table 1. Properties of the reinforcing materials.

Properties	Geotextile (non-woven)	Geonet
Thickness (mm)	1.2	3
Tensile strength (kN/m)	10	–
Elongation at break (%)	50	–
CBR puncture resistance (N)	1600	–
Dynamic cone drop (mm)	28	–
Permeability (m/s)	$115*10^{-3}$	–
Mass per unit area (g/m^2)	120	730
Aperture shape and size (mm)	–	Diamond 8*6 (±0.25)
Thickness at the joint (mm)	–	3.1(±0.25)
Max. strength kN/m	–	7.68

[*] As per the manufacturer specifications (TUFLEX geosynthetics)

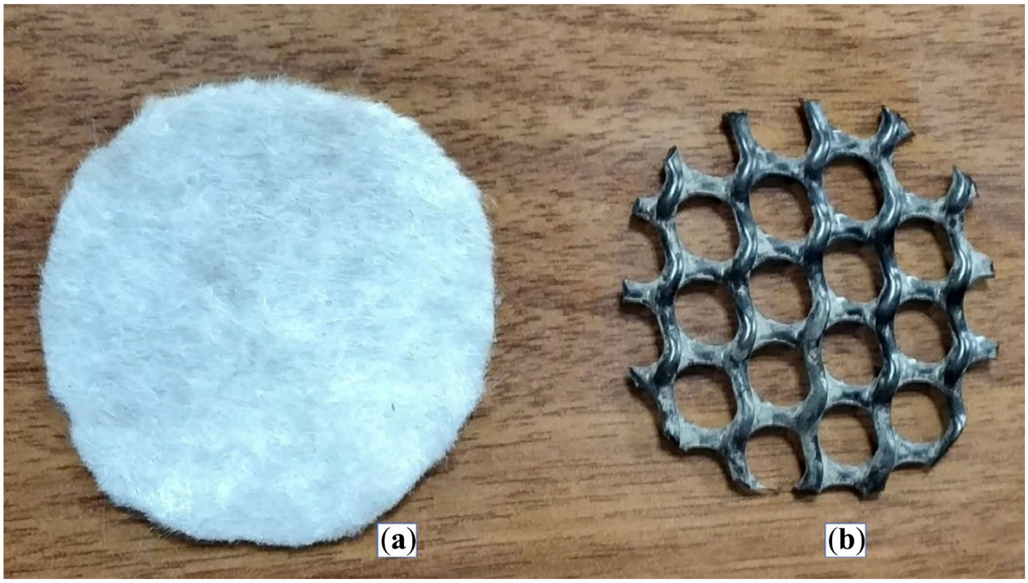


Figure 1. Reinforcing materials used in the present study (**a**) Geotextile and (**b**) Geonet.

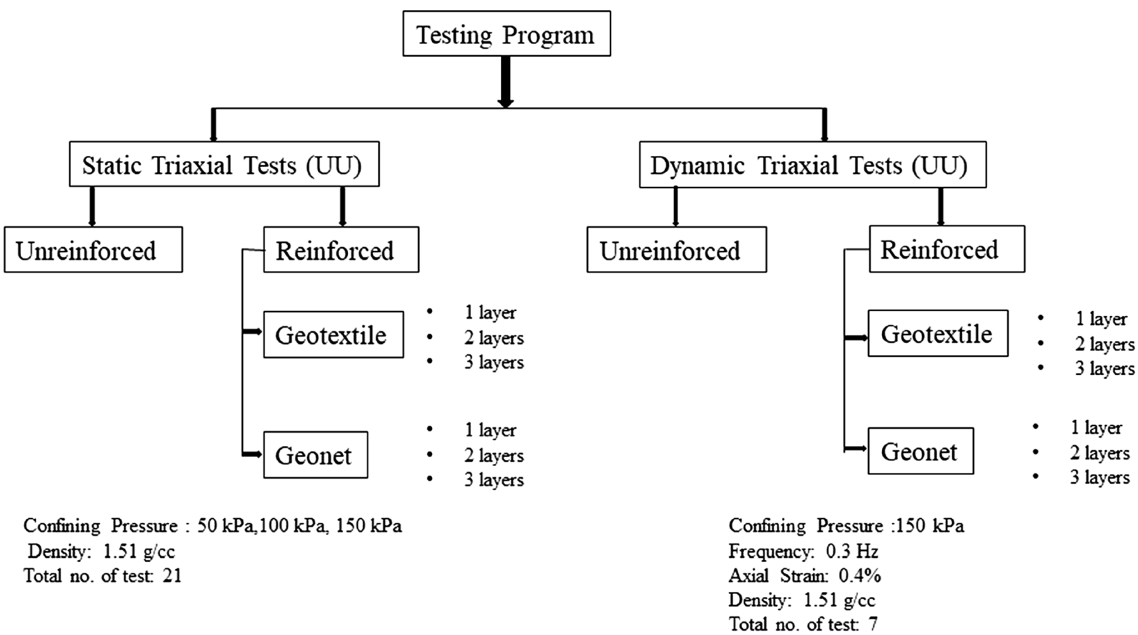


Figure 2. Flow chart of the testing program considered for the present study.

static and cyclic unconsolidated undrained (UU) triaxial tests were performed at a maximum dry density of the specimen. The specimens for the static triaxial tests were tested under a strain rate of 1.2 mm/min and for three confining pressures (σ_3: 50, 100, and 150 kPa) according to IS: 2720 part 11 [32]. The dynamic triaxial tests were conducted on the reinforced samples as per ASTM D3999 [33] by keeping all other parameters constant (confining pressure (150 kPa), axial strain (4%), and frequency (0.3 Hz)). The static (cohesion: c and angle of friction: ϕ) and dynamic (shear modulus: G and damping ratio: D) strength parameters for different reinforcements were computed and analysed through the test results.

3.2 *Sample preparation*

The samples were meticulously prepared with varying levels of reinforcement, specifically 0, 1, 2, and 3 layers of both geotextile and geonet materials. These reinforcement layers were evenly spaced within the MSW fines, as visually depicted in figure 3. Notably, all the reinforcement

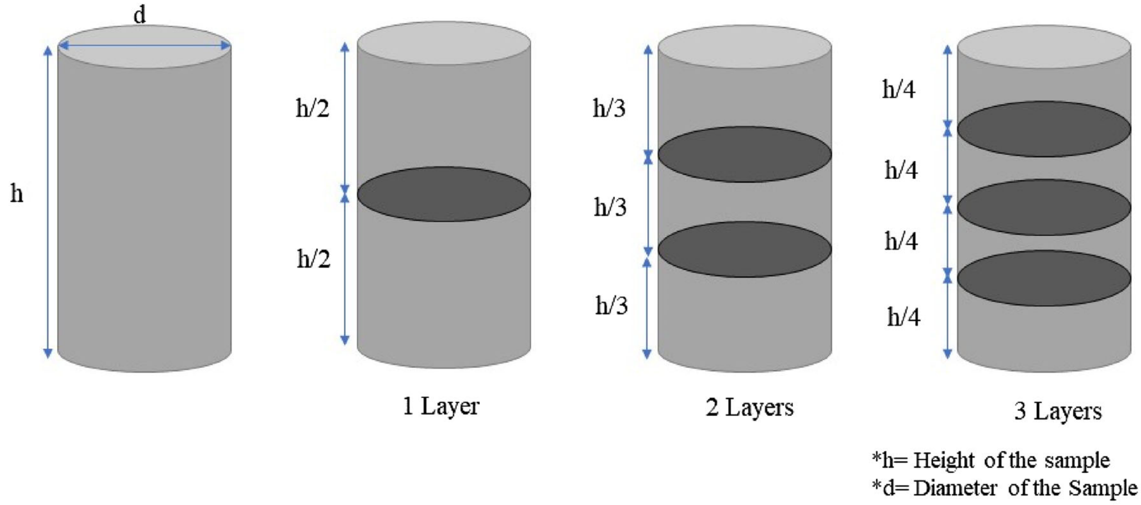


Figure 3. Geosynthetics arrangements considered for the present study.

layers were positioned in a flat, planar orientation, without any inclination, to maintain a consistent and uniform arrangement for the testing specimens. The samples of the considered MSW fines were prepared at MDD (maximum dry density) and OMC (optimum moisture content), i.e., 1.51 g/cc and 18.40%, respectively. The size of the samples was fixed, i.e., height of the sample (h): 76 mm and diameter of the sample (d): 38 mm for the static triaxial test and (h):100 mm and (d): 50 mm for the dynamic triaxial test. The samples were prepared by the moist tamping technique of specimen preparation [34]. The unreinforced sample was compacted in four equal layers in a split mould. Each layer was tamped 25 times and density was ensured after every layer. Similarly, the reinforced samples were prepared for 1, 2, and 3 layers of geotextile and geonet reinforcement. In the first case, the reinforcement was placed in the middle of the sample by dividing the split mould into four equal parts and compacting the first two layers as mentioned above for the unreinforced sample preparation, and then after placing the reinforcement, another two layers were compacted. For the 2-layered reinforcement, the sample was compacted in equal layers, and after each layer, the reinforcement was placed ensuring the height after each compaction. In 3-layered reinforcement, the sample was compacted in four layers as mentioned above by placing the reinforcement after each layer of compaction.

4. Experimental results and discussion

4.1 *Strength performance of reinforced MSW fines under static loading condition*

Reinforcement serves to enhance the mechanical properties of the soil by imparting tensile strength to the material, and effectively mitigating the deformation. In this study, the samples were meticulously prepared as outlined in section 3.2. Subsequently, the strength characteristics of these samples were thoroughly analysed under static loading conditions. To assess the impact of reinforcement, a comparative evaluation of the failure patterns of the specimens was conducted both before and after the testing, and the results of this comparison are illustrated in figure 4. It can be observed that for both the reinforcements in the case of the single layer (figure 4d and g) top bulging is predominant whereas in the double layers (figure 4e and h) the maximum bulging can be seen in the middle portion of the specimen. A similar kind of bulging failure was observed in the case of reinforced coarse soil and fly ash specimens [35, 36]. In the case of three-layered reinforcement, the maximum bulging can be seen in the top layer for geotextile (figure 4f), whereas for geonet the maximum bulging was seen in the middle section of the specimen (figure 4i).

4.1.1 *Strength performance of geotextile reinforced MSW fines* The stress-strain behaviour of MSW fines, both with and without geotextile reinforcement, is presented in figure 5a, with the confining pressure (σ_3) consistently held at 150 kPa. Notably, at a lower strain level of 3%, there is minimal discernible improvement observed with the incorporation of additional layers of reinforcement. The maximum strain increment of 16.17% can be seen for 1-layer reinforcement. Above 3% strain, the 3-layered reinforcement shows maximum stress increment from 33.72% (6% strain) to 63.46% (18% strain) as compared to the unreinforced MSW fine samples. In the case of 2-layered reinforcement, a reduction in the stress is observed when compared to the conditions with 1-layer reinforcement. Specifically, the percentage of stress decrement decreases from 45.45% to 8.33% as the strain level increases. Higher strain levels had no effect on the stress levels for either the unreinforced or the 1-layer reinforcement situations. This behaviour suggests that yielding started to happen after the strain level reached 6%. At high strain levels, a phenomenon known as "strain hardening" becomes evident in the case of MSW fine samples reinforced with 2 and 3 layers of reinforcement. The reinforcing mechanism of geosynthetics has been reported by Shukla [37]. As the samples are subjected to normal load only, the deformed geosynthetic provides vertical support to the overlying material. This transfer of stresses from soil to geosynthetics mechanism is known as the membrane effect [38].

In the case of reinforced sand with geotextile, it was observed that reinforcement greatly increases the deviator stress, especially under low confining pressure, which is because of the geotextile's poor tensile strength at high elongation [39], whereas in the present study reinforcement increases the deviator stress but also shows improvement with the increment in confining pressure.

The enhancement in strength with the increasing confining pressure is evident, as illustrated in figure 6a. This trend is applicable to both reinforced and unreinforced soils and is consistent with the findings of this study. Notably, the most significant improvement in shear strength is observed in the case of 3-layered reinforced MSW fine samples at every level of confining pressure. The average shear strength plot (figure 7) also verified maximum improvement in the case of 3-layered reinforced MSW fine samples. The improvement in the average shear strength, in this case, is more than 100% for unreinforced MSW fine samples. The same improvement in strength can be observed (figure 8a) from Mohr circle representation at failure (at σ_3=150 kPa).

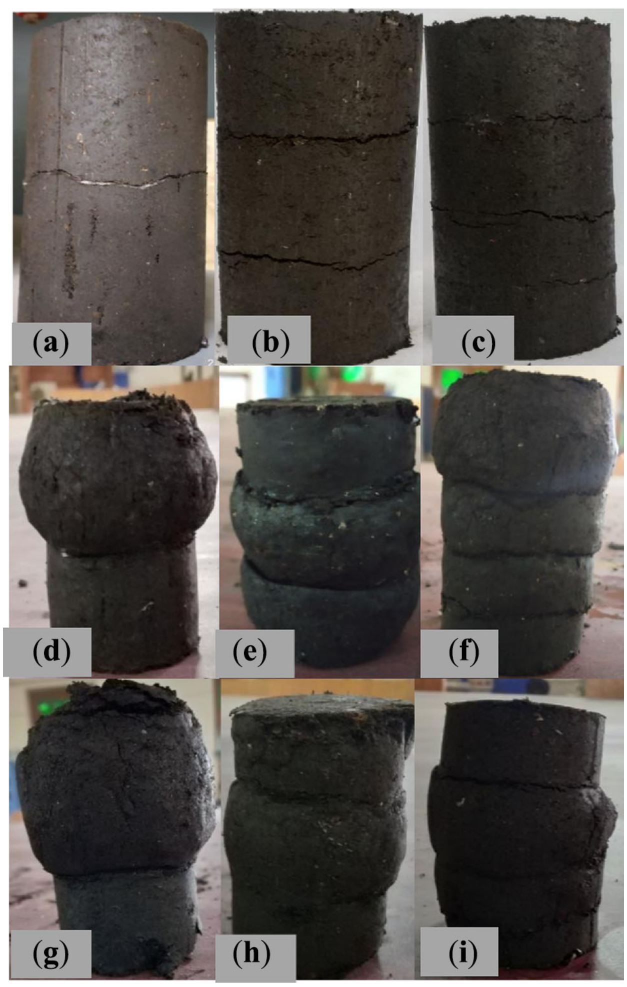


Figure 4. Sample images. (**a**) 1-layer reinforcement, (**b**) 2-layered reinforcement, and (**c**) 3-layered reinforcement before failure and failure pattern images of sample for (**d**) 1-layer geotextile reinforcement, (**e**) 2-layered geotextile reinforcement, (**f**) 3-layered geotextile reinforcement, (**g**) 1-layer geonet reinforcement, (**h**) 2-layered geonet reinforcement and (**i**) 3-layered geonet reinforcement at confining pressure of 150 kPa.

4.1.2 *Strength performance of geonet reinforced MSW fines* The stress-strain behaviour of MSW fines with and without geonet reinforcement (as shown in figure 5b) demonstrates that at a lower strain threshold of 3%, there is no obvious difference in stress levels when increasing the number of reinforcing layers from 2 to 3. However, as strain reach higher levels, the increments in stress exhibit a notably linear relationship with the addition of reinforcement layers. Specifically, at an 18% strain, the increment in deviator stress is approximately 10%, 25%, and 41% for samples reinforced with 1, 2, and 3 layers, respectively, when compared to the unreinforced MSW fines. Similar trends of strain hardening can be seen for 2 and 3-layered reinforcements in this case also. The relationship between strength and the number of reinforcement layers, in conjunction with varying confining pressures, is visually represented in figure 6b. This graphical depiction supports the trend of strength enhancement that can be seen with an increase in both the amount of confining pressure and the number of reinforcement layers. However, it is worth noting that, in comparison to MSW fines reinforced with geotextiles, the percentage improvement in peak shear strength for the case of geonet reinforcement is relatively lower. This observation can be further substantiated by referring to figure 7, which presents a comparison of the average shear strength between the two reinforced scenarios. In instances involving 1 and 2-layered reinforcements, the disparity between them is relatively minimal. However, it is noteworthy that when compared to the unreinforced MSW fines, the geotextile and geonet reinforcement both show an average strength gain of around 111% and 63%, respectively. The increment in Mohr circle diameter (figure 8b) with reinforcement also shows an improvement in the shear strength.

The comparison of the cohesion and friction angle data from the current study with those from the previous investigations involving various composite reinforcement materials, such as randomly distributed (natural and

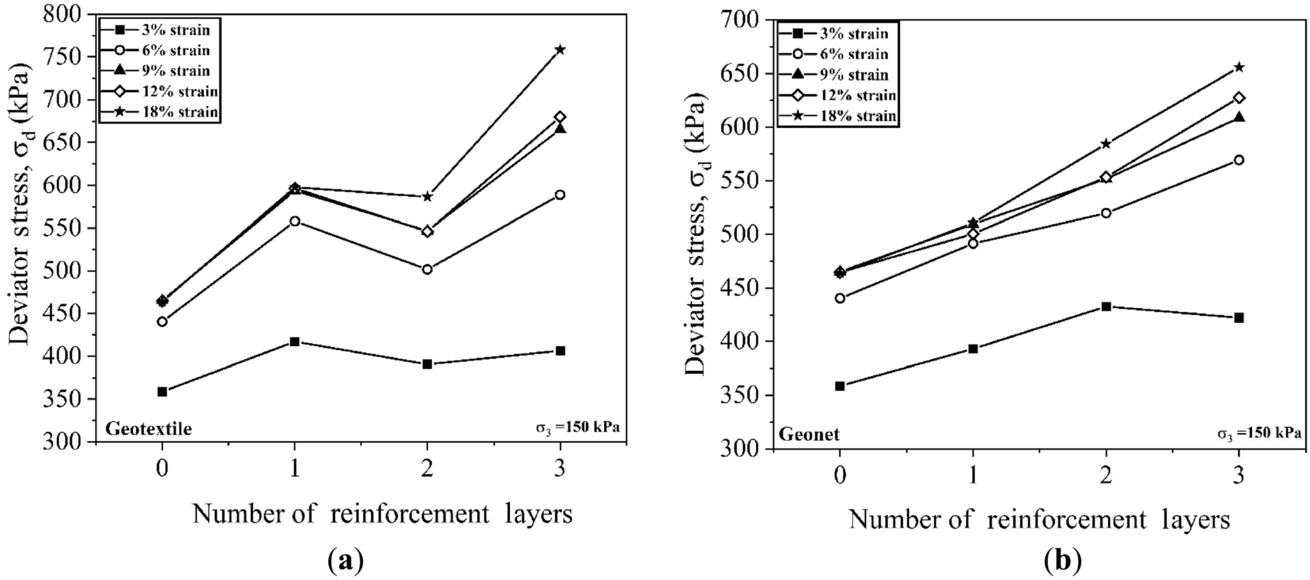


Figure 5. Deviator stress variation with number of reinforcement layers for (**a**) Geotextile and (**b**) Geonet at confining pressure of 150 kPa

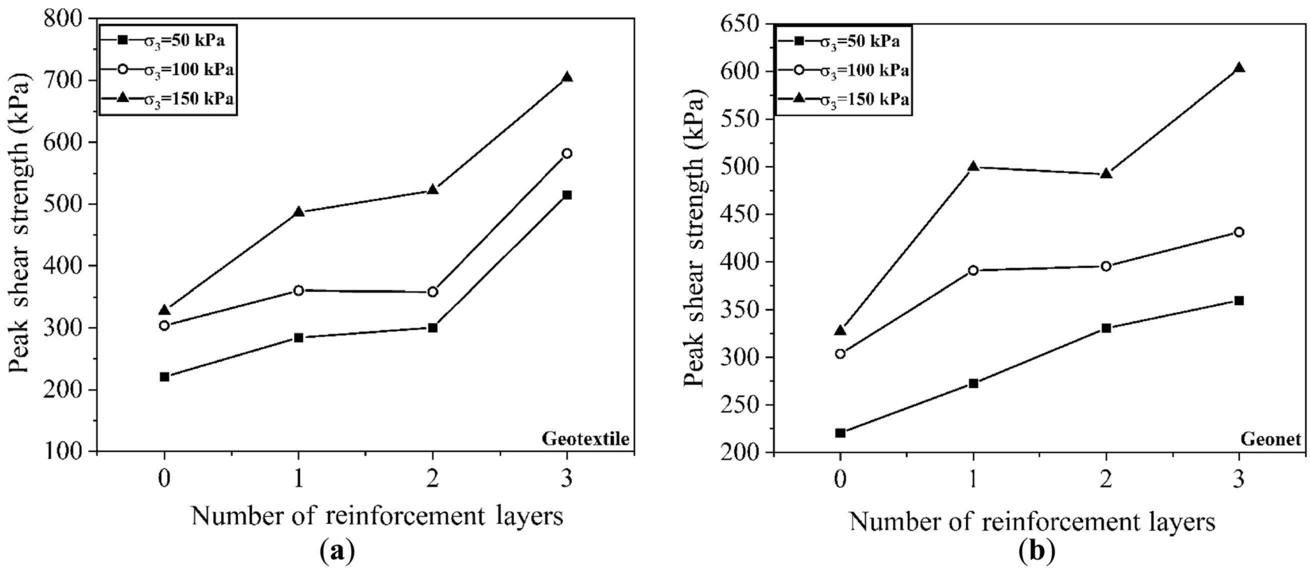


Figure 6. Peak shear strength variation with number of reinforcement layers for (**a**) Geotextile and (**b**) Geonet for varying confining pressures (50,100 and 150 kPa).

artificial) fibers and layered geosynthetics, is presented in figure 9a and b. It is evident that the friction angle values obtained in the present study closely align with those reported in the literature, indicating a consistent trend across different research efforts. Furthermore, there is minimal disparity between the friction angle values attributed to the two types of reinforcement materials employed in the present study, namely geonet and geotextile. Additionally, cohesion values in this study fall within the same range as those found in reinforced sand (coarse grain) or fly ash when compared to those from prior research using reinforced materials or soils. This shows that reinforced MSW fines behaved somewhat consistently in terms of cohesion behaviour when compared to the other reinforced materials or soil types examined in the earlier research.

4.1.3 *MSW fines–geosynthetic strength ratio* The strength ratio parameter (SR) is defined as the maximum

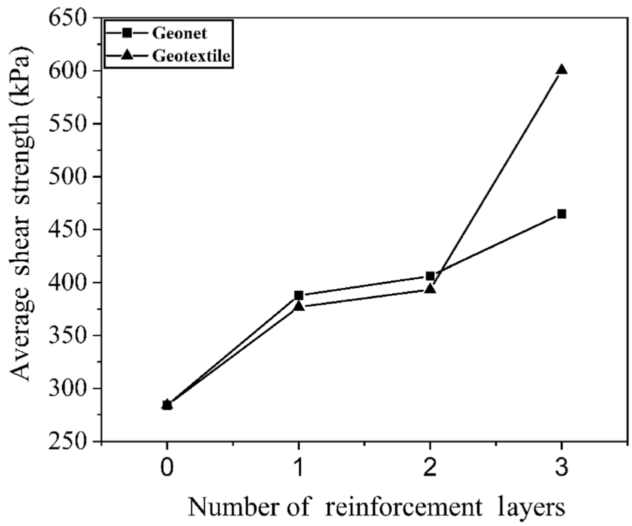


Figure 7. Average shear strength comparison of geotextile and geonet.

deviator stress in the case of reinforced soil ($\sigma_d{}^R{}_{max}$) to the maximum deviator stress of the unreinforced ($\sigma_d{}^{UR}{}_{max}$) one, shown in eq. (1) [39, 40].

$$SR = \frac{\sigma_{d\,max}^{R}}{\sigma_{d\ \ max}^{UR}} \tag{1}$$

The maximum deviator stress and the accompanying strength ratio (SR) for various combinations of reinforcing layers and confining pressures are summarized in table 2. The data clearly indicates that for a given confining pressure, the SR exhibits an upward trend as the number of reinforcement layers (geotextile and geonet) increases. This pattern supports the findings in the reinforced sand examples and emphasizes the beneficial effects of the reinforcing layers on the strength ratio [36, 39, 41]. In the current investigation, the results portray a picture that is somewhat different from the sand instance. In the case of the sand, geosynthetics were seen to increase the material's shear strength when there was low confining pressure. The improvements in shear strength are, however, more obvious in the context of this investigation at greater confining pressures, particularly above 150 kPa. This variation in behaviour brings attention to the complex and material-specific impacts of the geosynthetics on shear strength and emphasizes the significance of taking the unique properties of the material being reinforced into account.

4.2 *Strength performance of reinforced MSW fines under dynamic loading condition*

Unconsolidated undrained (UU) cyclic triaxial tests were conducted on both the unreinforced and reinforced samples of MSW fines. The objective was to assess the enhancements in dynamic strength parameters, specifically the dynamic shear modulus (G) and damping ratio (D), resulting from the application of reinforcement layers. The deviator stress and the axial strain variation for 10 cycles for the unreinforced (figure 10a) and reinforced MSW fines with geotextile (figure 10b, c, and d) and geonet (figure 10e, f, and g) show that there is no improvement of deviator stress with any number of reinforcement layers or reinforcement type. The same can be concluded from figure 11a

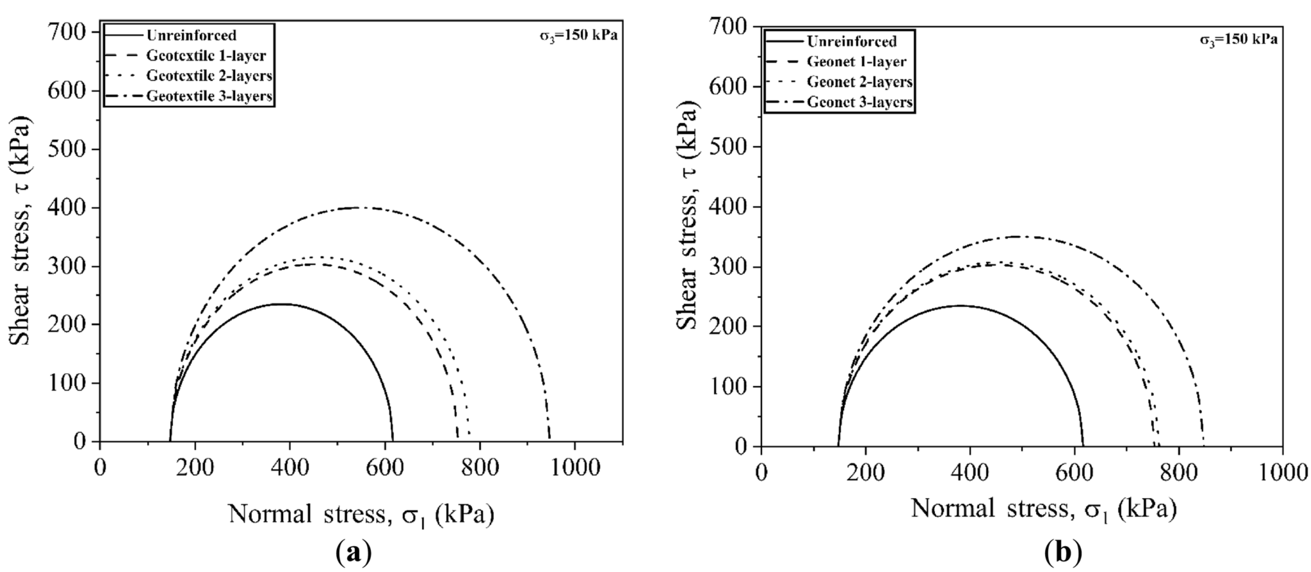


Figure 8. Mohr circles for unreinforced and reinforced (**a**) Geotextile and (**b**) Geonet at confining pressure of 150 kPa.

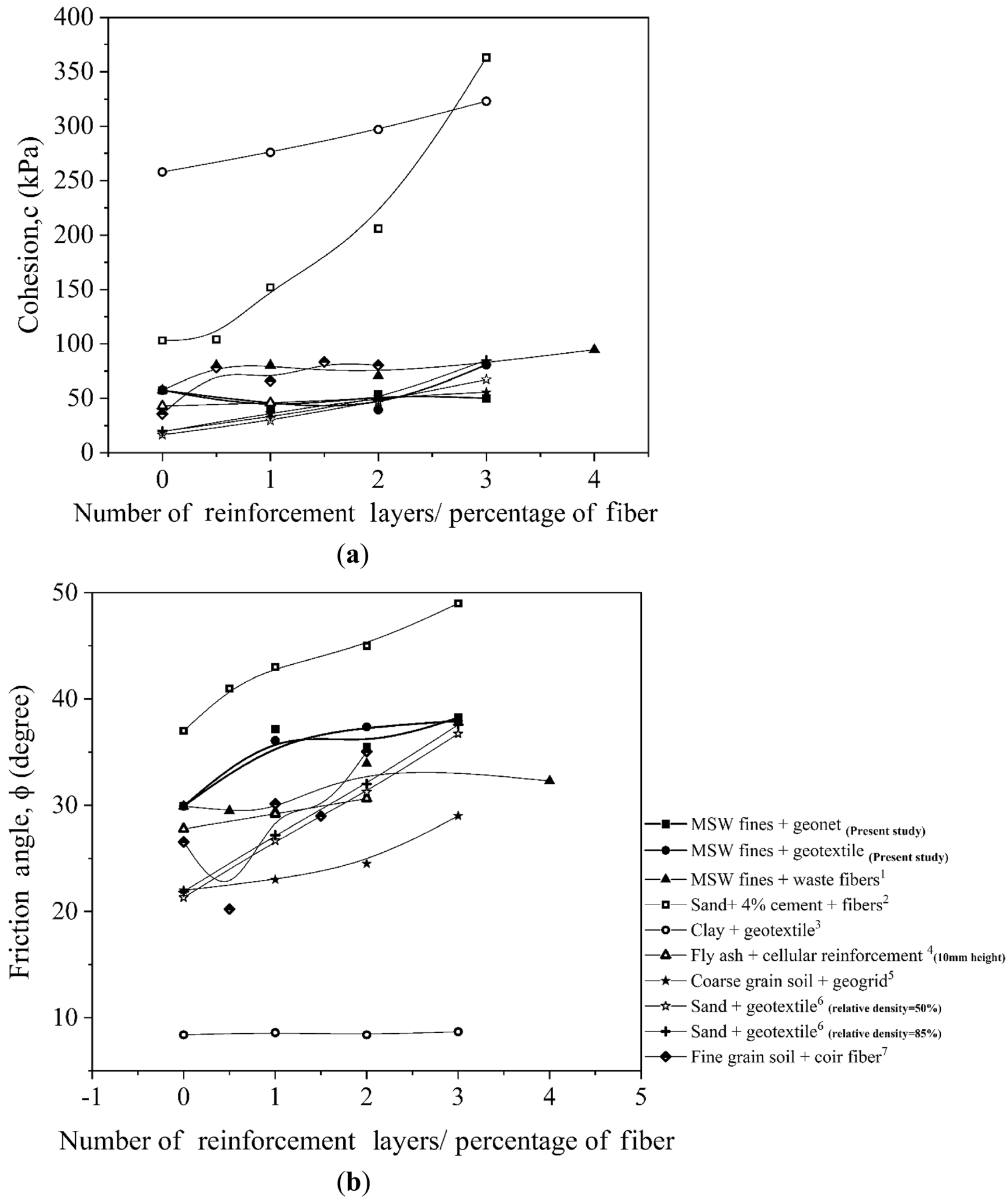


Figure 9. Comparison of present study (**a**) cohesion (c) and (**b**) friction angle (ϕ) with other composite reinforced studies. (Note: 1 [15]; 2 [44]; 3 [45]; 4 [35]; 5 [36]; 6 [46]; 7 [47])

and b where the area enclosed by the hysteresis loop for the 1st cycles has been compared for both reinforcement types and the unreinforced MSW fines have the largest loop area as compared to the reinforced ones. The stress-controlled cyclic tests on dry sand and silty sand show a decrease in the cyclic ductility (area of hysteresis loop) with an increase in the geotextile layers from 1 to 3 which is due to an increase in the soil strength and reduction in the strain at constant stress as the distance between geotextile layers decreases [42]. In the present case which is a strain-controlled cyclic triaxial test, the inclusion of geosynthetic layers decreases the area of the loop which is due to the decrease in soil strength and reduction in stress at a constant strain.

Comparing the dynamic strength parameters (G_{avg} and D_{avg} values are averages of the first 10 cycles) of the unreinforced and reinforced MSW fine samples presented in table 3, it can be noticed that there is a decrease or no

Table 2. Strength ratio values obtained from the experimental study.

		Geotextile		Geonet	
No. of layers	σ_3 (kPa)	$\sigma_{d(max)}$ (kPa)	SR	$\sigma_{d(max)}$ (kPa)	SR
0 (UR)	50	283.72	1	283.72	1
	100	428.00	1	428.00	1
	150	469.59	1	469.59	1
1 (R)	50	328.89	1.16	307.21	1.08
	100	433.00	1.01	463.40	1.08
	150	606.40	1.29	606.44	1.29
2 (R)	50	341.31	1.20	388.53	1.37
	100	416.80	0.97	479.51	1.12
	150	631.10	1.34	615.20	1.31
3 (R)	50	557.48	1.96	392.79	1.38
	100	643.20	1.50	483.40	1.13
	150	799.64	1.70	701.01	1.49

* UR Unreinforced, R Reinforced, σ_3 Confining pressure, $\sigma_{d(max)}$ Maximum deviator stress, SR Strength ratio

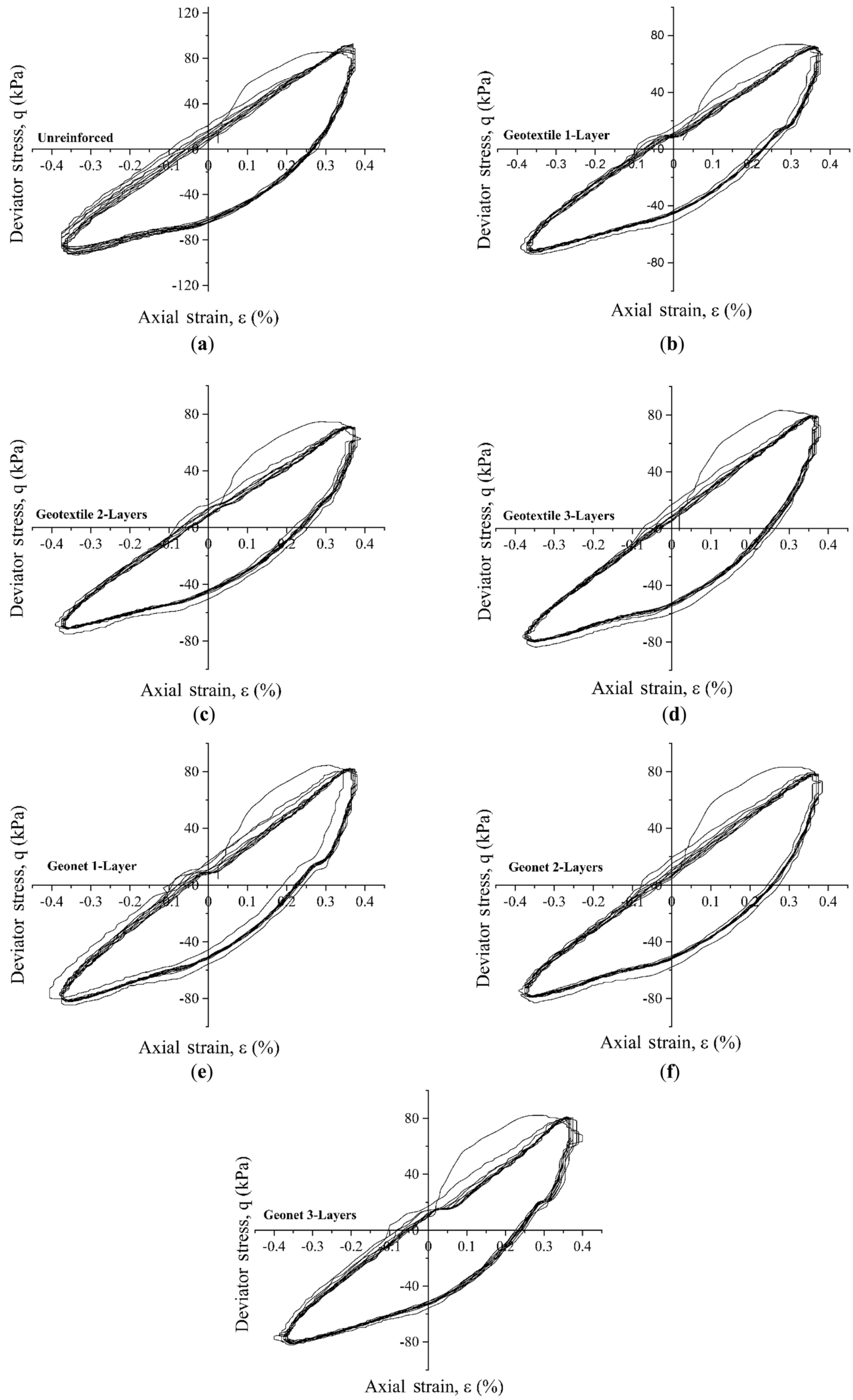
improvement in G value with the increase in the number of reinforcement layers in both cases and D value has no significant variation. However, pond ash (categorized as inorganic silts of low plasticity with a specific gravity of 2.18) reinforced with geotextile (1 and 3 layers) shows improvement in secant shear modulus, friction angle, and liquefaction resistance with reinforcement [43]. The results of this study differ from those that were found in other studies. It is important to recognize that a variety of factors, including the test type carried out, the sample preparation methodology used, the characteristics of the geosynthetic materials used, the inherent material properties of the MSW fines, and various loading parameters, can affect how well MSW fines perform. A conclusion that can be drawn from the present observations is that adding reinforcement to MSW fines does not increase the material's cyclic strength. The horizontal arrangement of the reinforcing layers within the sample may be responsible for this disparity, which may have led to discontinuities in the material structure. In static loading scenarios, the applied load is predominantly vertical, representing a compressive force, and the reinforcement layers effectively distribute this load within the sample. However, when subjected to cyclic loading, the sample undergoes a series of alternating compressive and expansive loading cycles. In this context, the presence of discontinuities introduced by the reinforcement layers subdivides the sample into distinct sections, each of which functions independently during the cyclic loading process. It is worth noting that while the reinforced samples exhibit commendable performance under compressive loading conditions, they face challenges when exposed to tension. This phenomenon suggests that the reinforcement strategy employed here is more effective in handling compressive forces but is less suited to resist tensile forces experienced during cyclic loading.

While the introduction of the reinforcement does not lead to an enhancement in the dynamic shear modulus (G), it is worth noting that G exhibits improvements as the number of loading cycles increases. However, these improvements are relatively modest for the reinforced MSW fines, whereas in the unreinforced cases, there is a consistent and notable increase in G, progressing from 7500 to 9000 kPa, as illustrated in figure 12a and b. These tests were conducted under unconsolidated undrained conditions. During the application of cyclic loading, the sample experienced compaction and did not exhibit rebound behaviour, as observed in the case of reinforced samples. This compaction effect contributed to the continuous improvement in the cyclic shear strength for the unreinforced MSW fines after each cycle.

Regardless of the type of reinforcement or the number of layers used, the damping ratio shows a reduction with an increase in the number of loading cycles. Unexpectedly, as shown in figure 12c and d, the greatest damping ratio was recorded for the 2-layered reinforcement arrangement in both the cases.

4.3 *Comparative analysis of strength under static and dynamic loading conditions*

The enhancement in the static strength characteristics of the examined waste material is readily evident with the incorporation of geosynthetic materials into MSW fines. As substantiated in the preceding sections and corroborated by the data presented in figure 13a, this improvement is particularly pronounced. For instance, geotextile-reinforced MSW fines exhibit a significant maximum deviator stress enhancement, reaching 70% when compared to their unreinforced counterparts, notably in the case of 3-layered reinforcement, at a confining pressure of 150 kPa. In comparison, the improvement for geonet reinforcement is somewhat more constrained and is capped at 45%. Comparing the results for dynamic loading under similar reinforcement, confining pressure and density conditions the strength performance reduces drastically and is confirmed in figure 13b, where the maximum deviator stress reduction can be seen at around 34% for 2-layered geotextile reinforcement and 26% in the case of 1-layer geonet reinforcement.


Unreinforced
Deviator stress, q (kPa)
Axial strain, ε (%)
(a)
Geotextile 1-Layer
Deviator stress, q (kPa)
Axial strain, ε (%)
(b)
Geotextile 2-Layers
Deviator stress, q (kPa)
Axial strain, ε (%)
(c)
Geotextile 3-Layers
Deviator stress, q (kPa)
Axial strain, ε (%)
(d)
Geonet 1-Layer
Deviator stress, q (kPa)
Axial strain, ε (%)
(e)
Geonet 2-Layers
Deviator stress, q (kPa)
Axial strain, ε (%)
(f)
Geonet 3-Layers
Deviator stress, q (kPa)
Axial strain, ε (%)
(g)

◀**Figure 10.** Deviator stress vs axial strain plot (10 cycles) for (**a**) unreinforced (**b**) 1-layer geotextile (**c**) 2-layered geotextile (**d**) 3-layered geotextile (**e**) 1-layer geonet (**f**) 2-layered geonet and (**g**) 3-layered geonet.

A static to-dynamic strength ratio parameter ($SR_{S/D}$) is evaluated which is defined as the maximum deviator stress in the case in static loading condition ($\sigma_{d(max)}$) to the maximum deviator stress in dynamic loading condition ($q_{(max)}$) keeping conditions like density, confining pressure, number of layers, and type of reinforcement consistent in both the loading conditions, shown in eq. (2)

$$SR_{S/D} = \sigma_{d(max)} / q_{(max)} \qquad (2)$$

Figure 13c shows the plot of $SR_{S/D}$ of the two considered reinforcements with the number of included layers. The ratio defines that 2-layered geotextile reinforcement provides better results and is comparable to the 3-layered geonet reinforced MSW fines under specific defined conditions.

5. Conclusions

The study focused on the laboratory investigation of Municipal Solid Waste (MSW) fines reinforced with geosynthetics (geotextile and geonet) across varying reinforcement layer counts (1, 2 and 3) and subjected to static and cyclic loading conditions. The findings indicate that while the static behaviour of the MSW fines with geosynthetics mimics soil reinforcement, no significant improvement in the dynamic strength was observed. Notably, static triaxial tests demonstrated marginal changes in the strength parameters with increasing reinforcement layers, albeit with an overall average shear strength improvement,

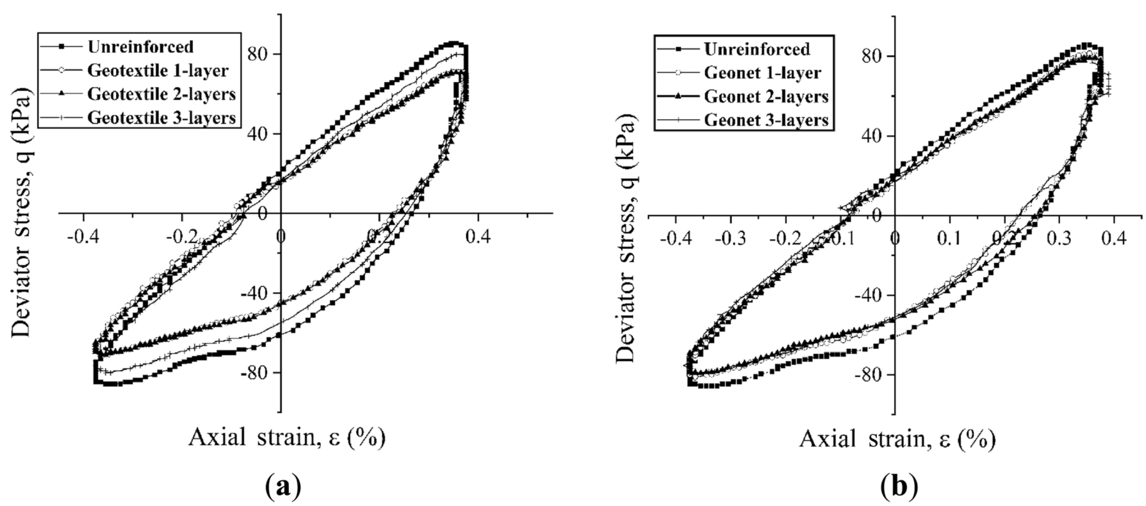


Figure 11. Comparison of hysteresis loop (1st cycle) for unreinforced and (**a**) geotextile reinforced, and (**b**) geonet reinforced MSW fines.

Table 3. Variation of dynamic shear strength parameter with the number of reinforcement layers.

No. of layers	Geotextile: Dynamic shear modulus (G_{avg}) kPa	Geotextile: Damping ratio (D_{avg}) %	Geonet: Dynamic shear modulus (G_{avg}) kPa	Geonet: Damping ratio (D_{avg}) %
0	80.27	26.20	80.26	26.20
1	63.15	25.57	71.99	24.52
2	62.09	27.98	69.50	27.71
3	71.08	22.69	71.68	27.19

* G_{avg} and D_{avg} values are average of first 10 cycles

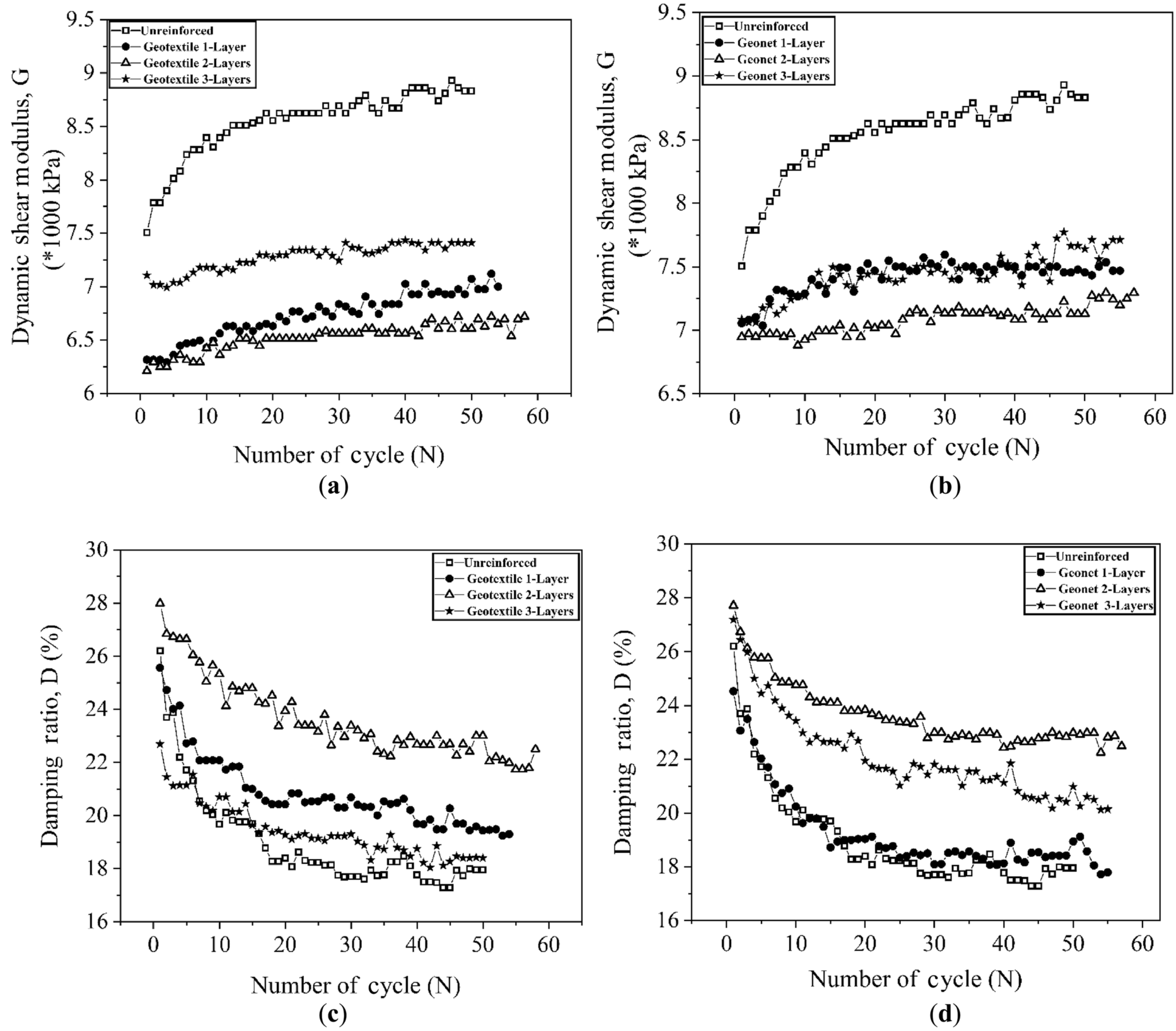


Figure 12. Dynamic shear modulus (G) variation with number of cycle (N) for unreinforced and (**a**) geotextile reinforced, and (**b**) geonet reinforced MSW fines and Damping ratio (D) variation with number of cycle (N) for unreinforced and (**c**) geotextile reinforced and (**d**) geonet reinforced MSW fines.

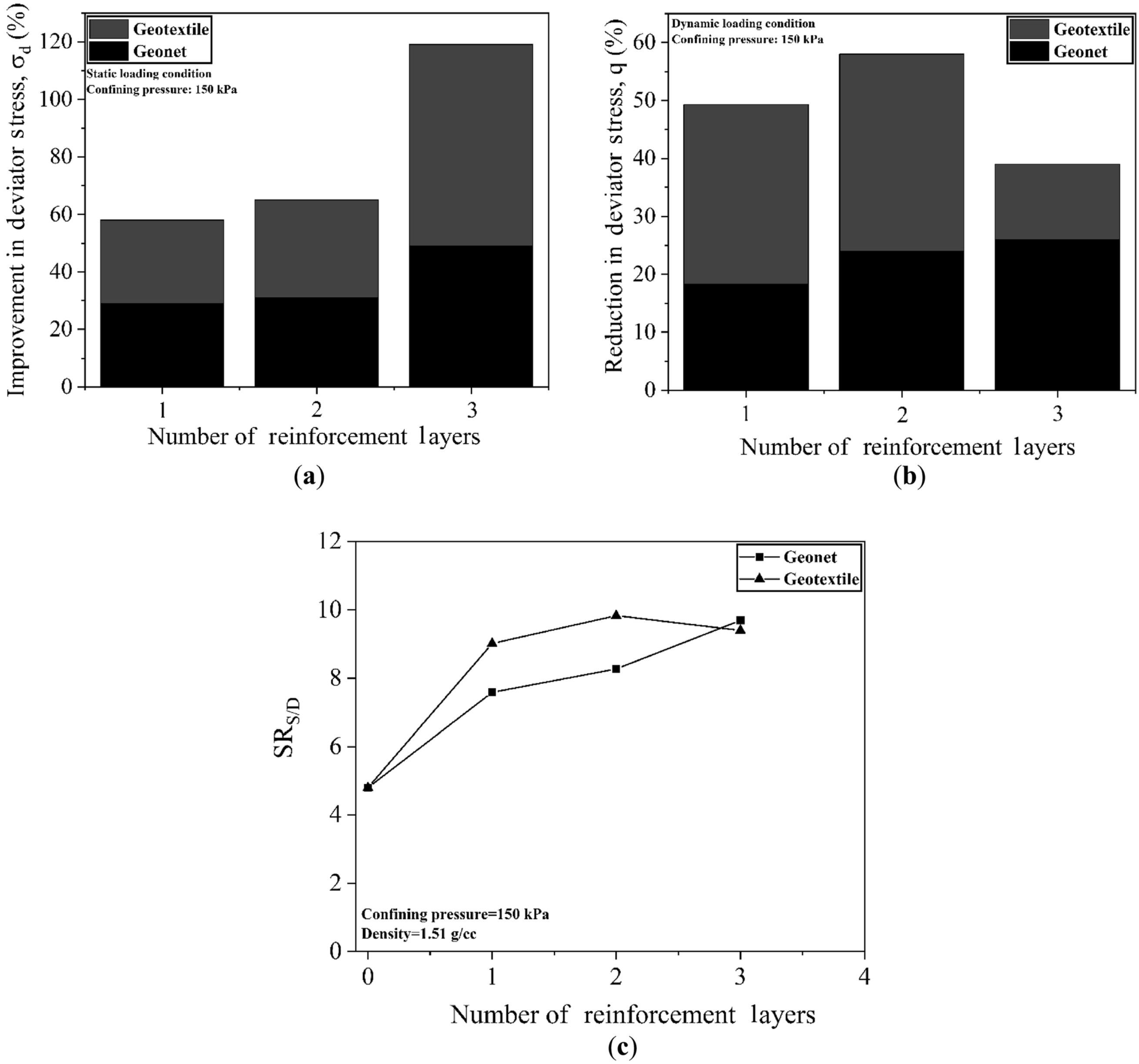


Figure 13. (**a**) Deviator stress improvement with reinforcement layers (static loading conditions), (**b**) Deviator stress reduction with reinforcement layers (dynamic loading conditions) and (**c**) static to dynamic strength ratio ($SR_{S/D}$) with number of reinforcement layers.

particularly evident with geotextile in the case of 3-layered reinforcement. Furthermore, shear strength displayed a correlation with the confining pressure, reaching its zenith with a 3-layered reinforcement system, as validated by strength ratio assessments. Unfortunately, the dynamic assessment did not reveal enhancements in the dynamic strength or cyclic performance. Nonetheless, the Strength Ratio ($SR_{S/D}$) suggested potential advantages for 2-layered reinforced MSW fines with geotextile under specific conditions. In conclusion, MSW fines' static strength improvement when reinforced with geosynthetics renders them suitable for the geotechnical applications under static loading, but their efficacy in high seismic zones remains limited. This study acknowledges its limitations, including sample size, limited number of tests, preparation methods, machine dimensions, and a constrained parameter investigation. Therefore, it recommends large-scale in-situ tests or field implementation for a more comprehensive evaluation of this composite material's strength performance.

List of symbols

c	Cohesion
D	Damping ratio
d	Diameter of the sample
G	Dynamic shear modulus

h	Height of the sample
MDD	Maximum dry density
MSW	Municipal solid waste
OMC	Optimum moisture content
q	Deviator stress (in dynamic loading condition)
R	Reinforced
SR	Strength ratio parameter
UR	Unreinforced
USCS	Unified soil classification system
UU	Unconsolidated undrained
ε	Axial strain
ϕ	Angle of friction
σ_d	Deviator stress (in static loading condition)
σ_1	Normal stress
σ_3	Confining pressure
τ	Shear stress

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Declarations

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