# *Shear strength properties and stress–strain behavior of waste foundry sand*

# SHEAR STRENGTH PROPERTIES AND STRESS-STRAIN BEHAVIOR OF WASTE FOUNDRY SAND

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## ABSTRACT

This research evaluates the engineering properties of waste foundry sand (WFS) as a sustainable construction material. In this research study, extensive laboratory experiments, including X-ray fluorescence (XRF), pH value, particle size distribution, California bearing ratio (CBR) and consolidated drained (CD) direct shear and CD triaxial tests were conducted. In addition, for the comparison purpose, a similar testing program was applied to a control material, namely sand sized waste recycled glass (RG), which is an accepted construction material for geotechnical and pavement construction projects. Results indicated that although the strength properties of WFS were lower than those of RG, the WFS could meet the required characteristics to be used in applications such as engineering fill and road embankments. The outcomes of this research aim to increase the market demand for WFS as a solid waste by improving the construction industry's confidence in its performance. Using WFS as an alternative to natural sands in the construction activities can potentially have significant positive environmental impacts through reducing $CO_2$ emission, as well as preventing the expansion of landfills for the disposal of WFS.



**Keywords:** Foundry sand; recycled glass; recycled waste; shear strength; stress-dilatancy behavior; pavement.

## 1. INTRODUCTION

The natural resources that are currently being used in infrastructure construction projects are finite and will eventually deplete over time. Whilst the construction industry has faced a massive development over the past few decades, leading to an even higher demand for resources. Researchers and engineers hence seek improved construction practices that utilize recycled materials. In sustainable development projects, minimizing the consumption of natural resources is sought and the use of recycling methods, which do not compromise the quality, is emphasized. Engineering properties of various waste materials are hence being extensively studied, in different fields of the construction industry. Recycling of wastes not only can supply the needs of the construction industry but also can be a cost-effective alternative to the use of natural resources. Furthermore, the reuse of waste materials saves resources by reducing the need for landfill sites and is furthermore environmentally friendly [1].

Sand is overwhelmingly sought as one of the main construction materials used in various applications, such as concrete manufacturing, and landfills and in particular in pavement and geotechnical applications such as sub-grade fills, which is the focus of this research. This means the consumption of natural and economic resources to explore and excavate quarry sand and consequently emission of $CO_2$ [1, 2]. Sand is highly demanded for other industries such as metal casting industries, known as foundries. In foundries, sand is used for molding and casting of metals, mainly iron, and waste foundry sand (WFS) is a by-product of this process [3]. Abichou, et al. [4] reported that foundry sand was mainly composed of quartz sand, followed by 4-16% of a binding agent (normally bentonite), 2-10% coal and 2-5% water.

In foundries, sand is repeatedly reused until it is no longer acceptable as a casting mold and is transported for disposal to landfills as WFS [4]. Significant amounts of WFS are hence being produced annually. In 2016, more than 60 million tons of WFS was generated, the majority of which have ended up in landfills [5]. The utilization of WFS in the construction industry would hence be a step forward towards sustainability. This will not only reduce the landfill disposal costs and environmental concerns associated with this waste, but also help minimize the natural sand consumption as well as carbon footprints in the construction projects [2].

WFS has been studied and used mostly as an additive in the construction industry in various applications. Prabhu, et al. [6] used WFS in the production of concrete and reported that replacement of natural sands in concrete with up to 20% of WFS did not cause considerable loss in strength. Mynuddin, et al. [7] also reported that using 30% WFS, as a replacement to the natural aggregates, would cause no significant reduction in the mechanical performance of concrete. In order to promote the re-use of WFS, Iqbal, et al. [8] and Behnood and Golafshani [9] developed and validated models that predicted the mechanical properties of concrete made of WFS, such as compressive, flexural and splitting tensile strengths. In this regard, they developed comprehensive databases of mechanical properties of concrete incorporating WFS and utilized gene expression programming and machine learning techniques, respectively. de Matos, et al. [10] investigated the use of calcinated WFS as a filler to replace a percentage of cement in self-compacting mortars. Their results revealed that the replacement of up to 10% cement by the fine fraction (< 150 μm) of calcinated WFS as filler, negligibly altered the fresh and hardened performance of the mortar. Yazoghli-Marzouk, et al. [11] reported that WFS could be used in sub-base layers of pavements, but 6% of Portland cement, which is not a sustainable material, would be required to achieve the required engineering properties. Klinsky, et al. [12] stated that up to 60% of WFS could be used to replace lateritic sandy materials in the base layer of pavements subjected to low volumes of traffic. In hot mix asphalt, replacement of aggregates with up to 15% was recommended by Neto, et al. [13] without any reduction in the durability and mechanical performance.

Currently, only 10% of the generated WFS is being recycled for various applications, with the remaining 90% being destined to landfills. This is mainly because the WFS is being used as an additive and in relatively small portions for producing construction materials, such as concrete and hot mix asphalt [14], in spite of exhibiting soil-like properties [15] The application of WFS as an individual material could result in a significantly increased demand for this waste product. The engineering properties of WFS, however, needs to be investigated comprehensively, in order to resolve any uncertainties due to the limited knowledge of its performance in geotechnical engineering applications. In addition, concerns about the environmental impacts of using WFS has caused hesitations in using it as an individual construction material [14].

The potential leaching hazards of WFS have been studied recently by Arulrajah, et al. [16] as a separate phase of this research project. Based on their study, all potential metal contaminants, being Arsenic, Barium, Chromium, Copper, Lead, Nickel, Selenium, Vanadium, Zink and Mercury, met the EPA-Victoria [17] requirements for fill materials. Further, evaluation of the WFS leachate test results showed that the concentration of all heavy metals was lower than U.S. Environmental Protection Agency [18] upper limit for drinking water, except for the Lead. The concentration of Lead was close to the limit, however, could not be conclusively confirmed due to the precision of the leaching test results. However, Arulrajah, et al. [16] postulated that since the leachate testing was carried out using an aggressive acidic solution and not water with neutral pH, the possible marginally greater lead concentration should not result in contamination of the groundwater tables more than accepted fill or solid inert material would.

Geomaterials generally fail in shear and the ultimate load-resisting performance of geo-structures is controlled by shear strength [19]. This study aims at investigating various engineering characteristics of WFS, with a focus on shear strength properties, for possible usage as a pavement and geotechnical construction material. The evaluated engineering parameters are also benchmarked against those of recycled glass (RG), as a control material that has been widely adopted by industry [20, 21]. In Australia, for instance, Guide to Pavement Technology Part 4E: Recycled Materials [22], and Melbourne Retail Water Agencies' Sewarage Standards for Embedment [23], allow the application of RG as an individual pavement or geotechnical material, respectively. In this research study, a suite of tests, including potential of hydrogen [20], X-ray fluorescence (XRF), sieve analysis, standard Proctor compaction, California bearing ratio (CBR), consolidated drained (CD) direct shear and CD triaxial tests were conducted. To the best of authors' knowledge, this is the first time both direct shear and triaxial testing are carried out to study and compare the shear strength properties of the WFS. Furthermore, the dilatancy behavior of the WFS is discussed using the triaxial test results and compared with those of natural sands. The outcomes of this study will potentially encourage civil engineers to utilize WFS in large volumes in construction applications where the required engineering characteristics match those of natural sands.

## 2. MATERIALS AND METHODS

Two types of waste material namely WFS and RG were used in this study. The focus of this research was to assess the engineering properties of WSF, while RG was used as a control material for comparison purposes. Both WFS and RG were collected from local recycling companies in Melbourne. To remove any large debris potentially mixed with the WFS and RG during collection, samples were passed through a 2.36-mm sieve. The 2.36-mm value is the boundary between sand and gravel as per the AS 1726-2017 [24]. The natural moisture content of WFS and RG was 1.3% and 2.1%, respectively. The materials were oven-dried at 70°C for 24 hours. This was to ensure that higher temperatures do not degrade the mechanical properties of the materials. Samples were next stored in sealed plastic bags after quartering and passing through riffle boxes. **Figure 1** shows the WFS and RG used in the current study. The WFS had black particles with a sub-angular morphology. Although the RG was a mix of crushed glasses of various colors, it had a brown appearance with angular particles.

Several experiments were conducted to determine the chemical, physical and mechanical characteristics of WFS and RG. A summary of the testing regime is presented in **Table 1**. The chemical compounds of WFS and RG were determined by conducting X-ray fluorescence (XRF) test. The pH value of the materials was determined as per the AS-1289.4.3.1-1997 [25], where 30 g of dried materials were soaked in 75 mL of distilled water for 3 hours, after stirring for 2 minutes in order to calibrate the pH meter, buffer solutions with pH values of 10.01, 7.00 and 4.01 were used.

The particle size distribution of the materials was determined as per the AS 1289.3.6.1-2009 [26], where 0.075, 0.15, 0.3, 0.425, 0.6, 1.18, 1.7 and 2.36-mm sieves were used. Two samples of each material were tested and analyzed, and the average of two values was reported. The specific gravity of materials was determined by a pycnometer using method B as per the ASTM D854-14 [27]. In order to determine the optimum moisture content and maximum dry density of the WFS and RG, the standard compaction test specified in ASTM D698-15 [28] was conducted. Materials were compacted in three layers, by dropping a 2.5-kg hammer from a height of 305 mm for 25 times at each layer. The maximum and minimum dry density of both materials was determined following AS 1289.5.5.1 procedure [29]. These properties were required to prepare identical direct shear and triaxial samples with the relative density of approximately 70%.

The ASTM D1883-16 standard [30] was followed to determine the California bearing ratio (CBR) of WFS and RG. Both materials were compacted at their maximum dry density and optimum moisture content, obtained from the standard compaction tests. The compacted samples were subsequently immersed in water with a surcharge of 4.54 kg on placed top for 96 hours. Deformation gauges were used to measure possible swelling of the materials. Following the immersion period, samples were removed from the water, drained for 15 minutes and subjected to loading at a rate of 1.27 mm/min. After making the zero-point corrections, as per the ASTM D1883-16 [30], on the stress-penetration curves, the highest stress value corresponding to the penetration of 2.54 mm and 5.08 mm was reported as the CBR value.

Shear strength parameters of WFS and RG were determined using consolidated drained (CD) direct shear tests as well as CD triaxial tests. The procedure specified in ASTM D3080 / D3080M - 11 [31] was followed to conduct the direct shear tests. The materials were prepared in a circular shear box, with 73.1 mm diameter, at the optimum moisture content and relative density of 70%. Normal stresses of 30, 60, 120, 240 and 480 kPa were applied on saturated samples. Samples were subjected to consolidation for 90 minutes to ensure no more settlement would occur. Subsequent to the consolidation phase, the shearing was commenced at a rate of 0.5 mm/min, as per the ASTM D3080 / D3080M - 11 [31]. The tests were conducted using a fully automated direct shear machine that logged the data including horizontal and vertical displacements, applied normal stresses and induced shear stresses.

The CD triaxial tests, according to ASTM D7181 - 11 [32], were conducted on the WFS and RG to evaluate their stress-strain behavior and shear strength parameters under drained conditions. Cylindrical samples of 50 mm diameter and 100 mm height were prepared in split molds in 5 layers at the optimum moisture content by static loading to achieve a relative density of 70%. Samples were saturated in the triaxial cell and subjected to effective confining pressures of 30, 60, 120, 240 and 480 kPa, for consolidation and shearing. The shearing was conducted, subsequent to consolidation, at the strain rate of 0.2 %/mm. Using the CD triaxial test results, the modulus of elasticity (E) was obtained by dividing the deviator stress, within the initial linear section of the stress-strain curves, by the corresponding axial strain.

One of the important steps in modeling and interpreting the stress-strain response of sand is the correct analysis of its dilatancy [33]. The stress-dilatancy behavior of sands is typically presented in the form of stress ratio (q/p') versus dilatancy (D or $d\varepsilon_v/d\varepsilon_s$). In the stress-dilatancy plot, q is deviator stress, p′ is the mean effective stress, and $d\varepsilon_v$ and $d\varepsilon_s$ are changes in volumetric strain and shear strain, respectively. In order to investigate the stress-dilatancy response of the materials, three stress ratios were defined, being (1) the stress ratio where dilatancy crosses the stress ratio axis, or where $d\varepsilon_v/d\varepsilon_s = 0$ ($\eta_D$), (2) the peak stress ratio ($\eta_P$), and (3) the stress ratio at the end-of-test state ($\eta_C$). $\eta_D$ is the stress ratio corresponding to the point where the sample moves towards a dilative behavior from a compression behavior (even though, it may still be in the compression zone). $\eta_P$ is the stress ratio at the peak deviator stress obtained for each material. $\eta_C$ is the stress ratio at the end of the test, which is often referred to as critical stress ratio (M) if the critical state is reached at the end of the test.

## 3. RESULTS AND DISCUSSION

### 3.1 Basic Tests

**Figure 2** illustrates the chemical compounds of WFS and RG. The XRF analysis revealed that the composition of WFS was dominated by $SiO_2$ (84.14%) followed by $Al_2O_3$ (11.82%), $Fe_2O_3$ (1.53%) and CaO (1.51%). The presence of $Fe_2O_3$ in the WFS can be linked to the iron casting process in foundries. The RG was mainly composed of $SiO_2$ (80.12%) followed by CaO (13.58%) and $Al_2O_3$ (3.98%). The pH values of WFS and RG were 9.50 and 9.39, respectively, which were relatively close to each other. Although these values lie within the very strongly alkaline and extremely alkaline categories, no environmental risk would be posed to the environment when using the WFS and RG as engineering fill [34, 35].

The particle size distribution of both WFS and RG is illustrated in **Figure 3**. Results indicated that the WFS and RG had fine contents (particles smaller than 75 μm) of 1.34% and 4.25%, respectively. Analyses of the results revealed that the WFS was classified as a poorly-graded sand (SP) according to the Unified Soil Classification System (USCS), while the RG was classified as a well-graded sand (SW). Being a poorly-graded sand with low percentage of the particles coarser than 1 mm or finer than 0.15 mm may be an obstacle for WFS to be used as an individual material as its gradation does not fit within the requirements of the project. In such cases, a potential solution may be mixing WFS with coarser or finer (recycled) sands so that the requirements are met.

The results of standard compaction tests on the WFS and RG are shown in in **Figure 4**. The Zero Air Voids (ZAV) curves of both materials are also presented. Results indicated that the WFS had an optimum moisture content and maximum dry density of 12.50% and 1,750 $kg/m^3$, respectively. These values were 12.05% and 1,780 $kg/m^3$, respectively, for the RG. The higher optimum moisture content value of WFS could be attributed to its higher water absorption [5]. Although WFS had a higher specific gravity value than RG, the maximum dry density of the latter was slightly higher. The WFS had a slightly higher specific gravity value of 2.59 compared to that of RG at 2.48. This could potentially be due to better particle arrangements of RG as a well-graded sand, compared to that of the WFS as a poorly-graded sand. The minimum and maximum dry densities of WSF following AS 1289.5.5.1 method were 1,350 kg/m$^3$and 1,830 kg/m$^3$, respectively. These values for RG were determined to be 1,370 kg/m$^3$ and 1,810 kg/m$^3$, respectively.

The superior particle arrangement of RG may be the reason for the higher CBR value of RG at 39% compared to that of the WFS at 10.9%. According to specifications provided by local Australian road authorities [36], WFS can be used as an engineering fill material (Type A) and as pavement subgrade material, requiring a minimum CBR value of 6%. Neither of the two materials showed any notable swelling over the 96 hours of immersion in water.

### 3.2 Direct Shear Tests

The variation of shear strength together with vertical displacement against horizontal displacement, from the results of CD direct shear tests on the WFS and RG, are presented in **Figure 5**. Both materials showed a strain-hardening and loose sand behavior [37], except for the RG at lower applied effective normal stresses of 30 and 60 kPa. The shear strength of WFS was, however, lower than that of the RG at all effective normal stresses. This could be attributed to the mechanical abrasion and degradation of sand particles in the foundries [38].

Moreover, the WFS samples showed a contraction behavior under all applied effective normal stresses. This could be due to the WFS being poorly-graded and when subjected to stresses, particles were rearranged and more voids were filled resulting in the contraction of WFS samples. On the other hand, while at effective normal stresses of 120 kPa and higher, the RG samples showed a contraction, at effective normal stresses of 30 and 60 kPa, dilation of samples was observed. The RG was well-graded meaning it had a reasonably compact structure and hence, under low effective normal stresses of 30 and 60 kPa, shearing the samples caused the particles to roll over each other resulting in a rearrangement of particles and dilation. High effective normal stresses of 120 kPa and above, however, prevented the particles from rolling over each other and with the horizontal displacement, more interlocking of particles occurred that resulted in the contraction of samples.

**Figure 6** depicts the changes in peak shear strengths with applied effective normal stresses from the results of CD direct shear tests on the WFS and RG. Failure envelopes as well as the effective angle of friction (**Φ′**) values for both materials are also presented. Under all applied effective normal stresses, the RG had a higher shear strength compared to that of the WFS that was attributed to higher **Φ′** of RG at 39.1° compared to that of the WFS at 31.8°. As stated earlier, the RG particles had an angular morphology, while the WFS particles had a more sub-angular morphology. This can explain the higher **Φ′** value of RG compared to that of WFS.

### 3.3 Triaxial Tests

The results of CD triaxial tests on the WFS and RG in the form of changes in shear strength and vertical displacement with variation of axial strain are shown in **Figure 7**. Similar to the CD direct shear tests, WFS showed lower shear strengths compared to those of RG, at all confining pressures. It is expected that the abraded particles of WFS with lower surface roughness offer lower inter-particle friction and hence lower shear strength properties. This may require the necessity of WFS to be mixed with higher quality materials in order to meet the requirements of some projects. Another solution may be adopting higher safety factors for design purposes. As an example, for a WFS embankment fill, a slighter batter slope is required to be designed compared to that of a RG embankment to assure the stability of the embankment.

In terms of volumetric behavior, the WFS showed contraction behavior, similar to the direct shear test results, while the RG showed a contraction behavior up to a certain axial strain, followed by dilation thereafter. Mohr circles together with the Mohr-Coulomb failure envelope of the trixial tests on both WFS and RG are presented in **Figure 8**. The WFS had a **Φ′** value of 28.4°, which was lower than that of RG at 36.9°. This explained the lower shear strengths of WFS compared to those of the RG. **Figure 8** also shows that the failure envelope of RG had an intercept with the shear axis indicating cohesion for RG. This could be attributed to the apparent cohesion between the smooth surfaces of the RG particles. The presence of foreign materials, such as food and glue, within the RG particles, can also contribute to this apparent cohesion [20].

**Table 2** summarizes the results of analyses of CD triaxial tests on the WFS and RG in the form of **Φ′** and modulus of elasticity (E) values under various applied confining pressures. **Table 2** also presents typical **Φ′** values for natural sands with rounded and angular particles from [39]. The **Φ′** values for WFS and RG in **Table 2** were determined by analyzing the triaxial results at different ranges of applied confining pressures, taking into account 3 confining pressures at a time. The studied ranges were 30-120 kPa, 60-240 kPa and 120-480 kPa. In comparison with the typical effective friction angles of natural sands, WFS showed properties similar to that of loose sands with rounded particles, whereas RG's **Φ′** values were close to those of medium density sands with angular particles.

The **Φ′** values for the three ranges of applied confining pressures on the WFS were relatively close to that obtained for the whole range of applied confining pressures, i.e., 30 to 480 kPa. This suggested that the failure envelope for the WFS was almost linear, at least within the range of confining pressures studied here. On the other hand, the difference between the **Φ′** values for ranges of applied confining pressures and that obtained for the whole range of confining pressures for the RG was notable. The failure envelope for the RG was therefore non-linear. **Figure 9** shows the changes in the maximum deviatoric stresses of WFS and RG with the variation of confining pressures, from the results of CD triaxial tests. Similar to the failure envelopes, while the increase of maximum deviator stresses in the WFS had an almost linear relationship with confining pressure, this trend was non-linear for the RG.

Results presented in **Table 2** reveal that as the confining pressure was increased, the E values of both WFS and RG were enhanced, which was expected. The rate of increase was, however, much higher for the WFS compared to that of RG. Increasing the confining pressures from 30 kPa to 480 kPa resulted in a 1150% increase in E value for the WFS, while this increase was 294% for the RG. This showed that under higher confining pressures, the WFS would have a high stiffness that can be attributed to the high stiffness of the individual WFS particles. Comparing the obtained modulus of elasticity of WFS and RG with E values of natural sands [39] indicates that both WFS and RG exhibit loose to medium sand-like stress-strain behavior under lower confining pressure while their behavior under higher confining pressures are more similar to those of dense sands.

**Figure 10** shows the stress-dilatancy responses of WFS and RG under different confining pressures ($\sigma'_c$). Natural dense sands, under lower confining pressures typically show a clear dilatant behavior, in which after the transition from compression into dilation at D = 0 ($\eta_D$), reach a peak point ($\eta_P$) and finally hit an end-of-test point ($\eta_C$), which may be the critical state [40]. This stress-dilatancy behavior forms a hook shape at the dilation side of the stress ratio-dilatancy plot [40, 41]. However**,** unlike lower confining pressures, under higher confining stresses, sands remain in compression until they get to the end-of-test stage [40, 41]. In this case, $\eta_D$, $\eta_P$ and $\eta_C$ values are close and the hook shape is not observed. In general, for both materials, as the values of $\sigma'_c$ increased, the difference between $\eta_D$, $\eta_P$ and $\eta_C$ decreased, which matches the behavior of natural sands. Under $\sigma'_c$ of 60 kPa and greater for WFS and 120 kPa and greater for RG, values of $\eta_D$, $\eta_P$ and $\eta_C$ were almost equal and no distinct hook shape was observed in the plot. The values of M (or $\eta_C$) for WFS and RG were 1.15 and 1.56, respectively. This suggests that RG typically reaches a critical state at a higher stress ratio compared to WFS. Under $\sigma'_c$ of 30 kPa, WFS showed a behavior similar to dense natural sands under low confining pressure by exhibiting distinct values of 1.15, 1.51 and 1.32 for $\eta_D$, $\eta_P$ and $\eta_C$, respectively. RG triaxial samples under 30 kPa showed distinct values for $\eta_D$, $\eta_P$ and $\eta_C$ to be 1.60, 1.97 and 1.87, respectively. These values for confining pressure of 60 kPa were 1.56, 1.82 and 1.62, respectively. The resemblance between the stress-dilatancy behavior of WFS and RG with that of natural sands supports the suitability of these recycled materials for pavement and geotechnical construction applications.

## 4. CONCLUSIONS

The engineering properties of waste foundry sand (WFS) was investigated in this study with a focus on the shear strength parameters. Comparisons were also made with shear strength properties of recycled glass (RG) as a control material as well as natural sands . With the objective of evaluating the potential of utilizing WFS as a sustainable construction material, the following conclusions were made:

- The chemical composition of both WFS and RG was dominated by silica.. The pH values of both materials were 9.4-9.5 deeming them suitable for usage as a construction fill material without environmental risks.

- The WFS had more sub-angular particles and was classified as a poorly-graded sand, while the RG particles were angular and the RG was classified as a well-graded sand.
- The maximum dry densities obtained for WFS and RG were almost equal, whereas the optimum moisture content of WFS was about 0.5% greater than that of RG. This suggests that a greater amount of water is required for the field compaction of WFS.
- The CBR value of RG was approximately 4 times greater than that of WFS. However, with a CBR of about 11%, WFS indicates a desirable bearing capacity for being used as engineering fill or pavement subgrade material.
- Based on direct shear results, WFS had a lower shear strength compared to the RG, suggesting that a slighter embankment batter slope is required for WFS. The stress-strain behavior of WFS under CD direct shear test was similar to that of a loose sand with a strain hardening behavior. A similar trend of results was obtained through CD triaxial testing. Both WFS and RG indicated stress-dilatancy behavior, similar to those of natural sands.
- The failure envelope as the result of CD triaxial tests for the WFS was almost linear, while the RG had a non-linear failure envelope. Moreover, by increasing the confining pressure, the stiffness of WFS increased at a higher rate compared to that of the RG.

The results of this study showed that the WFS has inferior properties compared to RG, as well as natural sands with angular particles. Nevertheless, WFS could potentially be used as a construction material in embankments and pavement subgrades if pavement or geotechnical designers are provided with sufficient engineering properties of the material. This will not only reduce the environmental consequences of using natural sands in the construction industry but also prevent the continuously growth of lands being occupied as landfills for disposal of and also WFS being stockpiled in landfills.

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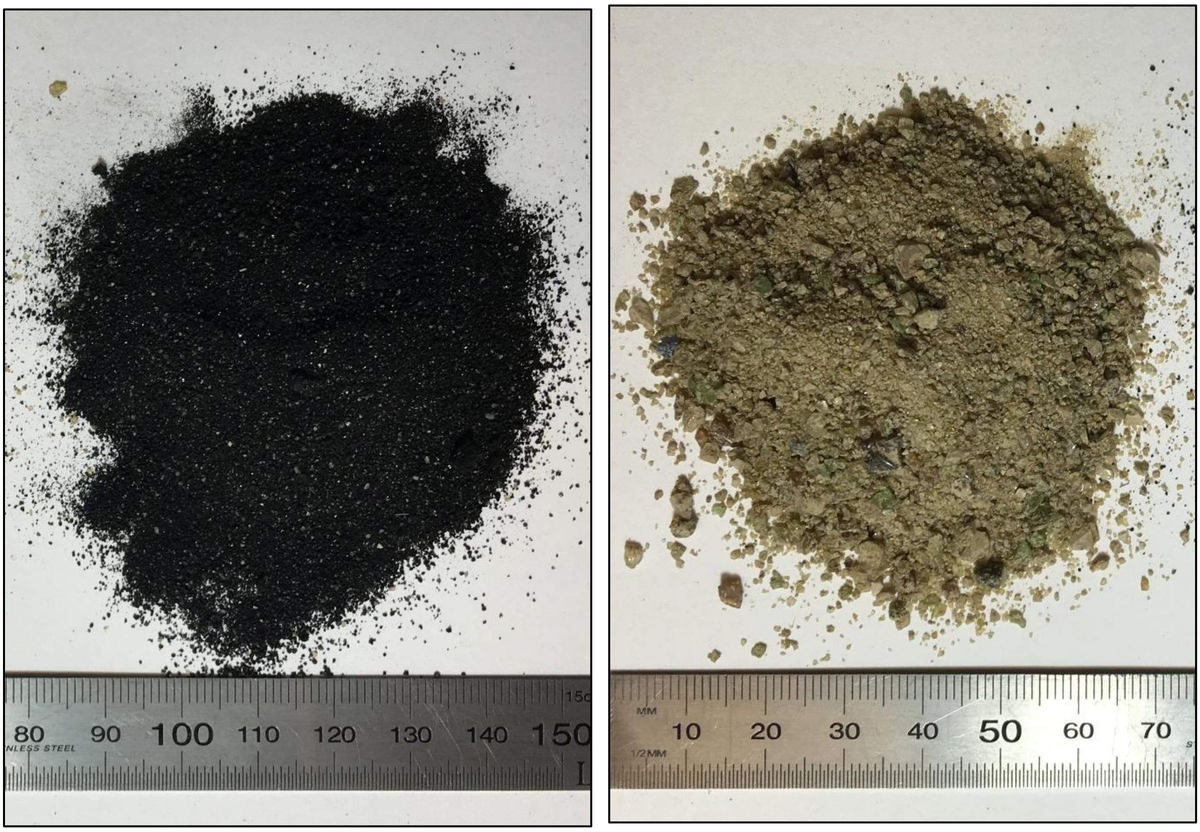
**Table 1.** Summary of the testing regimes for WFS and RG

| Test | Note |
|---|---|
| X-ray fluorescence (XRF) | For determination of chemical compound |
| pH value | Ratio: 30 g dried materials to 75 mL water [29] |
| Particle size distribution | Two samples for each material [26] |
| Specific gravity | Pycnometer method B [27] |
| Standard compaction test | [28] |
| Maximum and minimum dry density | [29] |
| California bearing ratio (CBR) | Loading rate: 1.27 mm/min [30] |
| Consolidated drained direct shear | Displacement rate: 0.5 mm/min [31] |
| Consolidated drained triaxial shear | Strain rate: 0.2%/min [32] |

**Table 2.** Effective friction angle and modulus of elasticity values for WFS and RG obtained from CD triaxial tests, in comparison with typical natural sands

| Parameter | WFS | RG | Natural Sand [+] (rounded particles) | Natural Sand [+] (angular particles) |
|---|---|---|---|---|
| Effective friction angle (**Φ′**) (°) | | | | |
| $\sigma'_c$[*]: 30-120 kPa | 26.9 | 41.7 | Loose: 27 - 30 | 30-35 |
| $\sigma'_c$: 60-240 kPa | 29.2 | 38.7 | Medium: 30 - 35 | 35-40 |
| $\sigma'_c$: 120-480 kPa | 28.5 | 35.5 | Dense: 35 - 38 | 40 - 45 |
| Modulus of elasticity (E) (MPa) | | | | |
| $\sigma'_c$: 30 kPa | 15.6 | 30.7 | | |
| $\sigma'_c$: 60 kPa | 18.6 | 31.4 | Loose Sand: | 10.0 - 28.0 |
| $\sigma'_c$: 120 kPa | 32.5 | 48.0 | | |
| $\sigma'_c$: 240 kPa | 58.3 | 74.6 | Dense Sand: | 35.0 - 70.0 |
| $\sigma'_c$: 480 kPa | 179.5 | 90.4 | | |

Note: [*] confining pressure; [+] from [39]




(a) (b)

**Figure 1.** Materials used in the current study: a) WFS and b) RG

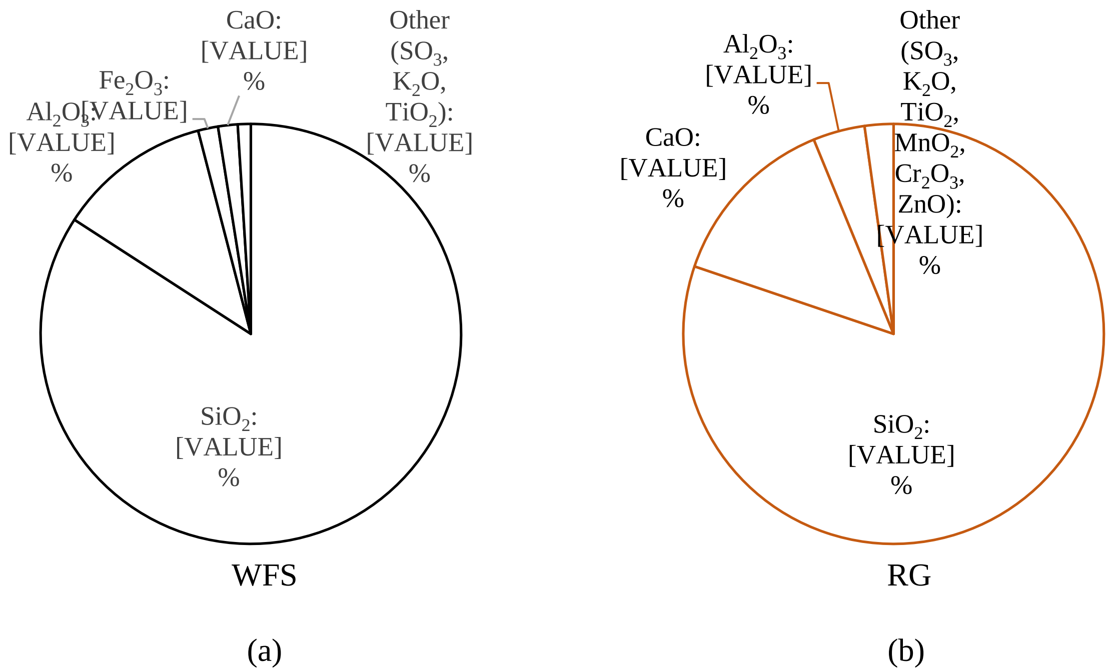



**Figure 2.** X-ray fluorescence (XRF) test results on: a) WFS and b) RG

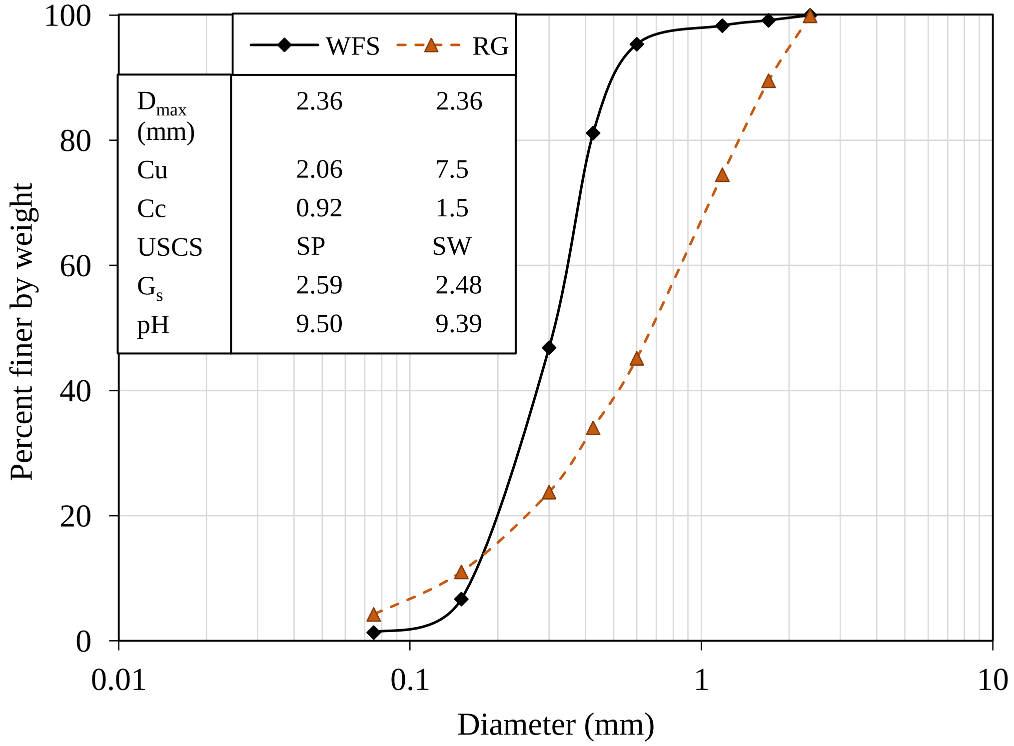



**Figure 3.** Particle size distribution of the WFS and RG

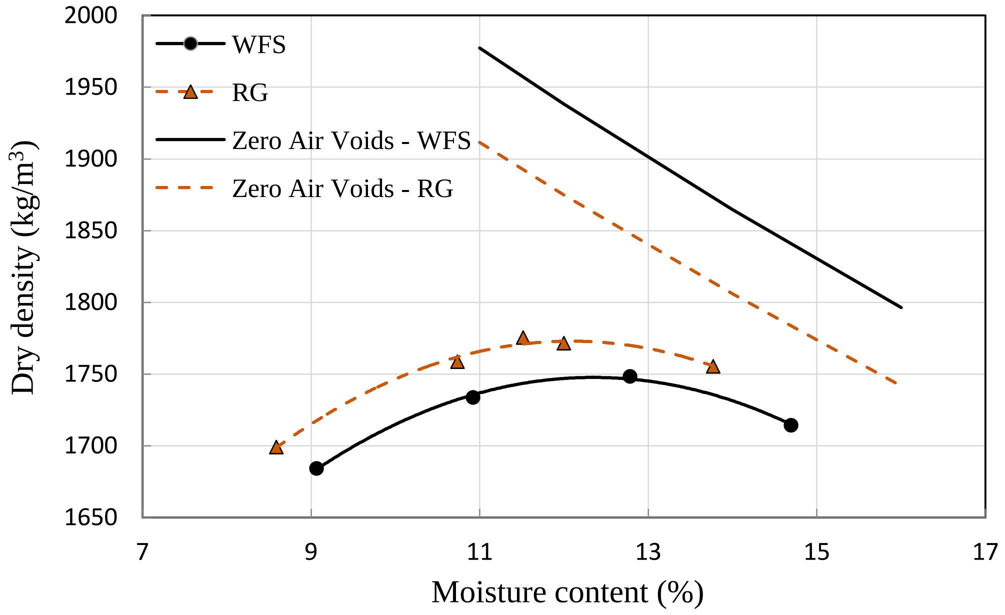



**Figure 4.** Compaction and zero air voids curves of the WFS and RG (modified from Arulrajah et al. [16])

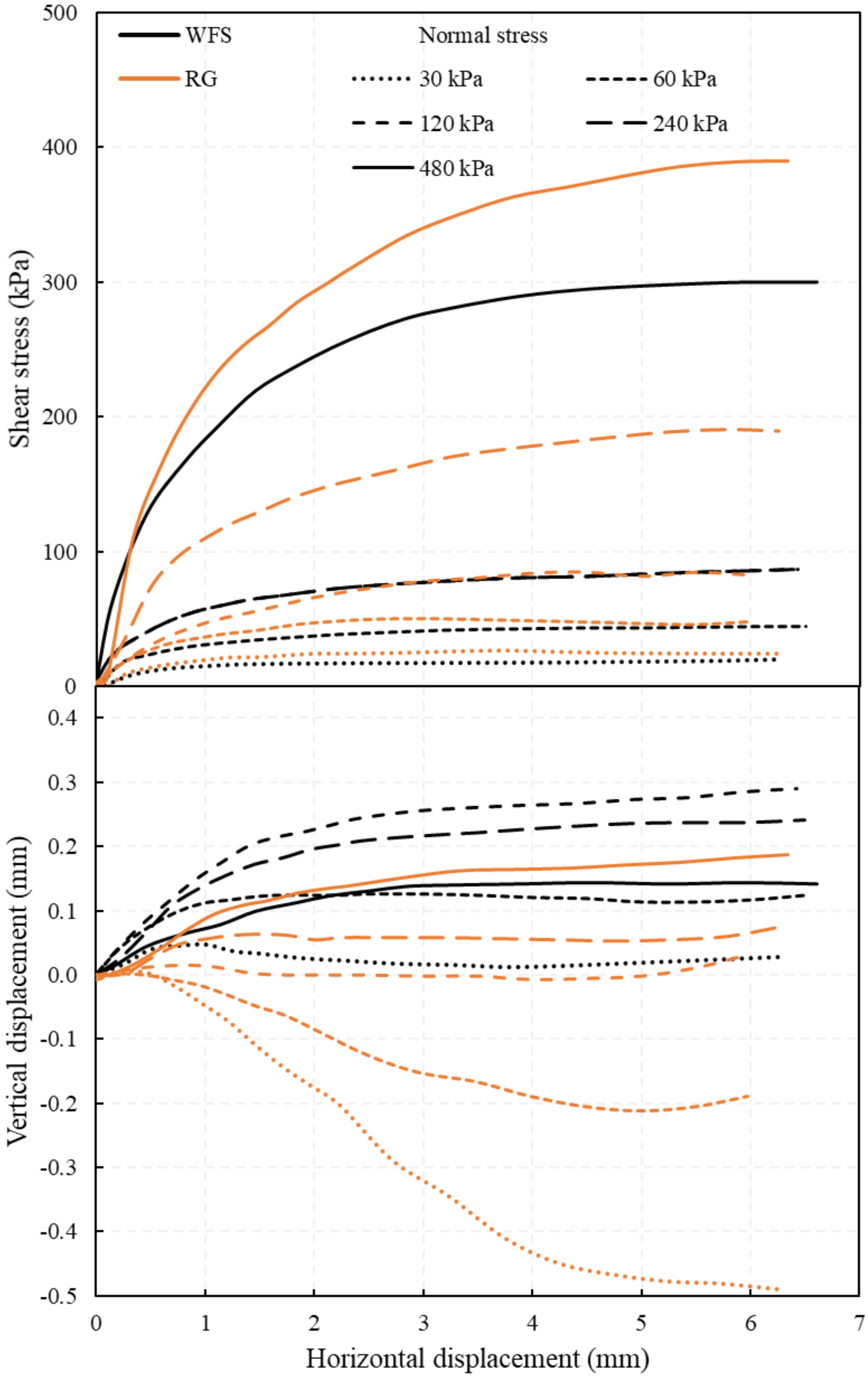



**Figure 5.** The variation of shear strength as well as vertical displacement with horizontal displacement, from the results of CD direct shear tests on the WFS and RG

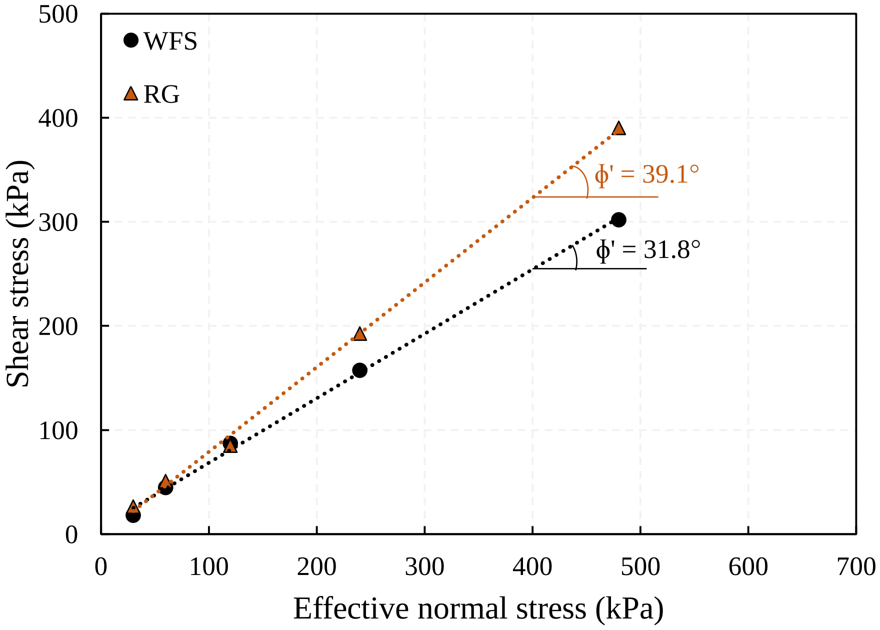



**Figure 6.** Failure envelope and shear strength parameters of the WFS and RG, from the results of CD direct shear tests

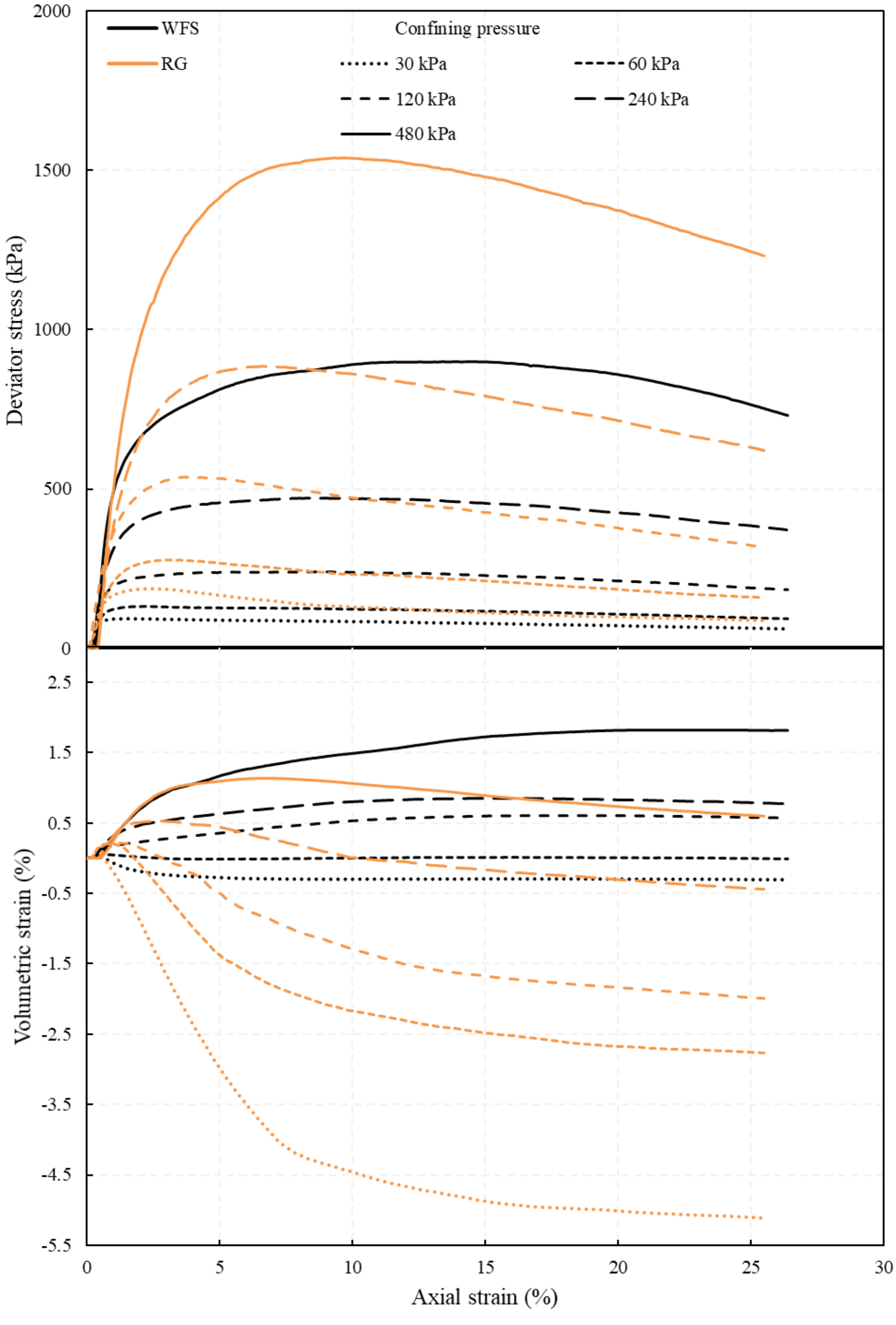



**Figure 7.** The variation of deviator stress as well as volumetric strain with axial strain, from the results of CD triaxial tests on the WFS and RG

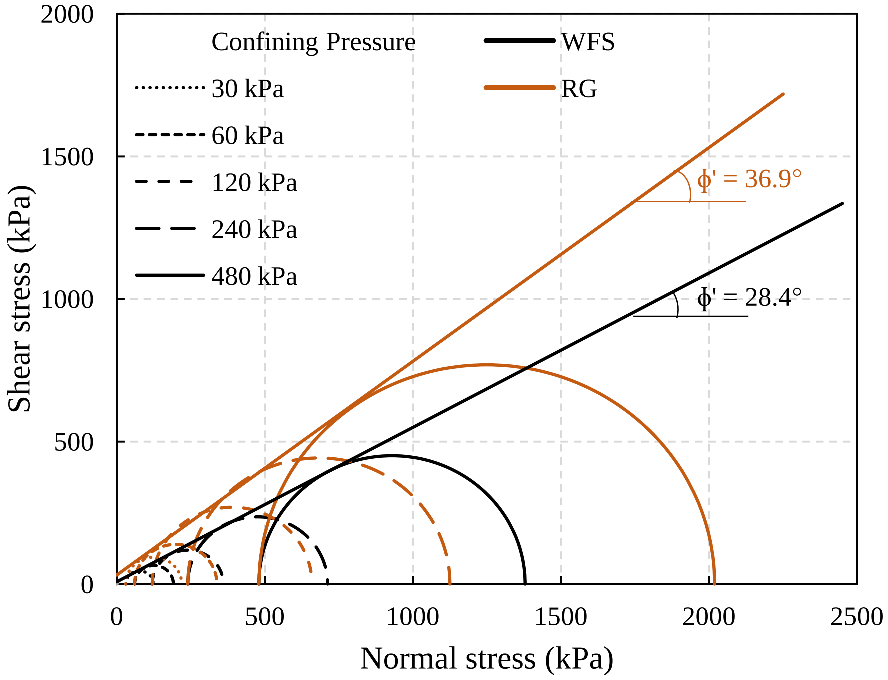



**Figure 8.** Mohr's circles and shear strength parameters of the WFS and RG, from the results of CD triaxial tests

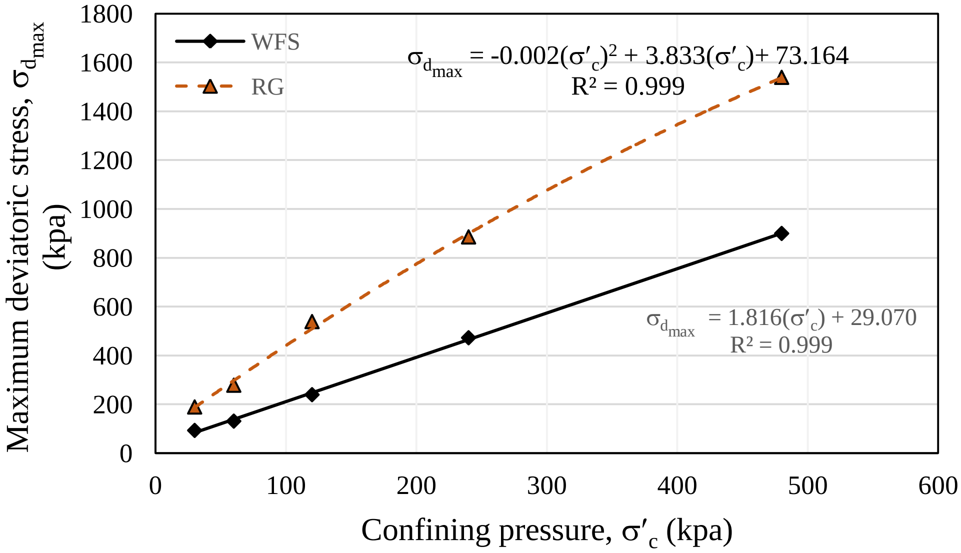



**Figure 9.** Variation of maximum deviator stress with confining pressure for WFS and RG

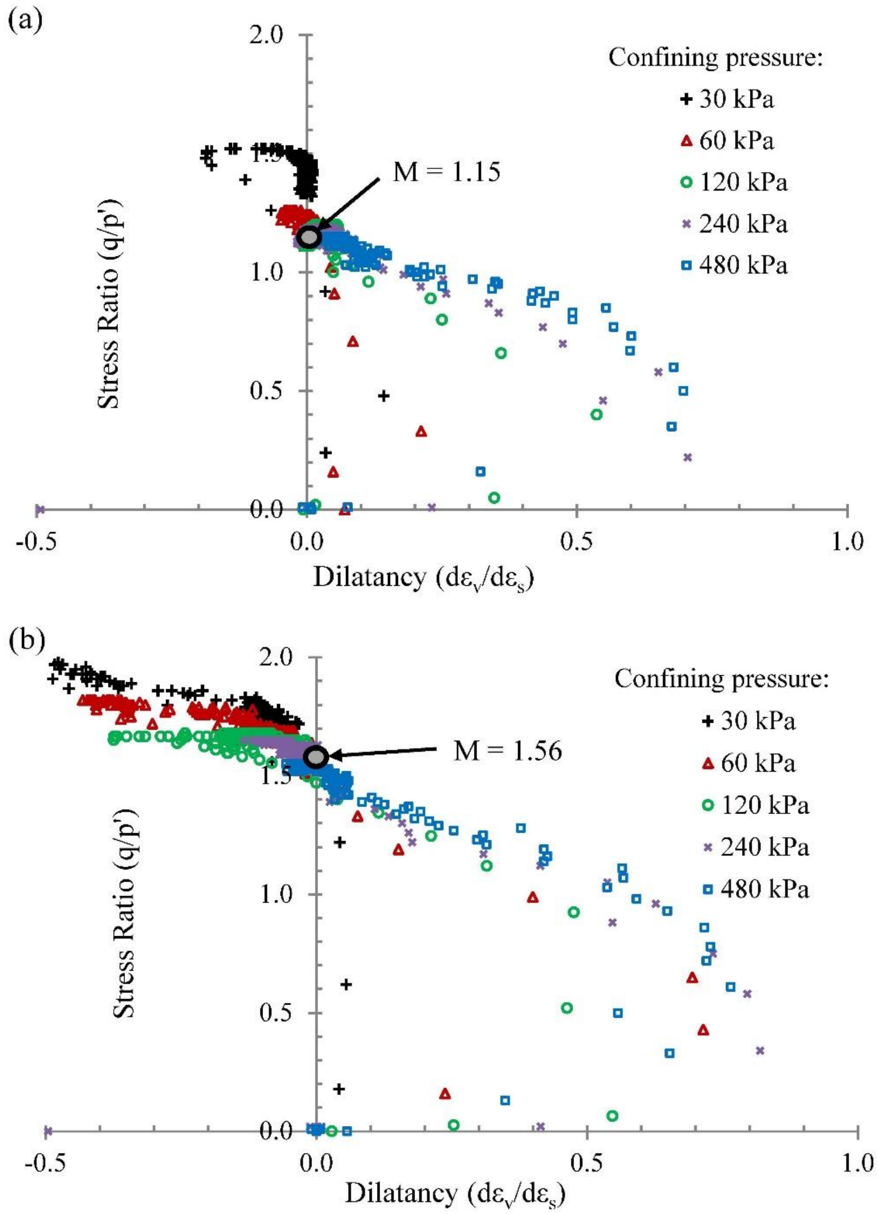



**Figure 10.** Stress-dilatancy of (a) WFS and (b) RG

*Highlights

## Research Highlights

- Bearing capacity and physical properties of waste foundry sand were studied.
- Shear strength properties of waste foundry sand were investigated using direct shear and triaxial testing.
- Stress-dilatancy behaviour of waste foundry sand was investigated.
- Comparison was made with recycled glass as an established recycled material.
- Waste foundry sand was found suitable as an engineered fill and road embankment fill material.