



# Shear Strength and Consolidation Behaviour of Kaolin Clay Reinforced with a Granular Column Backfilled with Crushed Waste Glass

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**Abstract** Granular columns are commonly used for ground improvement. However, minimal research is presently available on the effect of backfill particle size on the geotechnical performance of granular column-reinforced soil. Geo-environmentally, using crushed waste glass (CWG) as a sustainable replacement for depleting traditional construction sands could offer a cleaner feedstock to backfill granular

columns while helping recycle growing stockpiles of waste glass, potentially supporting the circular economy transition and decarbonisation of the construction industry. Given these multi-pronged motivations, this study investigated the shear strength and consolidation behaviour of kaolin reinforced with a CWG granular column. Three different particle size ranges (PSR) of CWG were discretely used to install a granular column in the kaolin bed, including fine (0.50–1.0 mm), medium (1.0–1.7 mm) and coarse (1.7–3.35 mm) particles with median particle sizes of 0.78 mm, 1.42 mm and 2.30 mm, respectively. The geocomposite containing a medium CWG column showed the highest increase in friction angle, increasing from 14.0° for kaolin only specimens to 20.7° for the geocomposites. Similarly, the consolidation

The Video Abstract has been updated.

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behaviour of reinforced kaolin (geocomposites) was typically superior to that of kaolin only specimens. Notably, installing a coarse, medium or fine CWG column decreased the average compression index ( $C_c$ ) of the geocomposites by almost 17%, 35% or 50%, respectively, compared to that of the kaolin only specimens. Given the promising results of this initial study, some suggestions are provided for future studies on assessing the application of CWG as an alternative backfill and sustainable geomaterial in granular column construction.

**Keywords** Granular columns · Ground improvement · Circular economy · Depleting traditional construction sands · Crushed waste glass · Sustainable geomaterial

## 1 Introduction

Granular columns are traditionally used as a ground improvement technique in a variety of soils. Typically, a vibroflot is used to create, in the soil to be improved, a granular column containing stiffer sand/stone with a relatively high friction angle, creating a composite in the ground with greater average strength and stiffness than that of the untreated in situ ground (McCabe et al. 2007; Vahedian et al. 2014; Najjar et al. 2012). Several studies have demonstrated that installing a granular column typically improves the shear strength and settlement behaviour of the reinforced soil compared to the unreinforced soil (Abdelhamid et al. 2023; Borges 2023; Islam et al. 2023; Mazumder et al. 2023; Mohamadi Merse et al. 2023; Shukla et al. 2023). The column backfill material is commonly selected based on suitability, economy and availability (Baumann and Bauer 1974; Zukri and Nazir 2018). Crushed stone is often preferred due to its high friction angle and stiffness (Al Saudi et al. 2016). However, sand could also be used where crushed stone is unavailable (Kadhim et al. 2018). The properties of column material play a crucial role in the geotechnical performance of granular columns

(Nazari Afshar and Ghazavi 2014; Sulovska and Stacho 2018). The material should be fit for purpose, requiring it to be hard, inert, free-draining and capable of creating a granular column with a relatively high friction angle (Serridge 2005). Barksdale and Bachus (1983) proposed various gradings to select a suitable column backfill. They suggested that the sand used should be well-graded, contain less than 15% fines (particles passing the #200 sieve), and have a mean diameter of at least 0.2 mm. (Serridge 2004) proposed that the aggregate impact value (AIV) and aggregate crushing value (ACV) of the column material should be less than 30% to avoid unacceptable damage to the aggregates under crushing or impact forces. The geotechnical parameters and behaviour of sands used to backfill granular columns can be examined by some relevant past publications (Andreou et al. 2008; Craig and Al-Khafaji 1997; Guetif et al. 2007; Najjar et al. 2010; Sivakumar et al. 2004; Xu et al. 2018). Hence, depending on the standards used, the sand/stone must satisfy a set of requirements to qualify for use as column backfill.

Previous studies have investigated the effect of various parameters on the performance of granular columns. These include relative density, particle shape, gradation, fines content and durability parameters of the column backfill, together with the area replacement ratio, the column penetration ratio, stress concentration factor, and others. Amongst many geomechanical parameters, particle size is the fundamental parameter that substantially influences the geotechnical behaviour of granular materials (Sitharam and Nimbkar 2000). IS 15284 (2003) broadly suggests that well-graded granular materials ranging from 2 to 75 mm may be used as column backfill. However, almost no specifications are currently available in the published scientific literature on the optimal particle size range (PSR) of column backfill (Al Saudi et al. 2016). Siahaan et al. (2018) also mentioned that the role of particle size of the column backfill on the geotechnical behaviour of granular columns remains relatively under-researched.

Traditionally, natural aggregates have been used to create granular columns (Chidiroglou et al. 2009). However, given the increasing volumes of waste and growing scarcity of virgin aggregates (sand and stone), waste materials could provide a sustainable alternative to traditional construction aggregates (Kazmi et al. 2022; van Genuchten

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2023; Jefferson et al. 2010). The world faces a shortage of natural and quarried (manufactured) sand (Bendixen et al. 2019). Nearly 50 billion tonnes of sand and gravel are mined worldwide every year, which is equivalent to approximately 18 kg per person per day, more than sufficient to blanket the entire United Kingdom (Beiser 2019). Australia alone consumes around 130 million tonnes of aggregates in concrete annually (Papadikis et al. 2019). Currently, the rate of sand mining exceeds that of its natural renewal Peduzzi (2014), predisposing this seemingly infinite resource to depletion (Cousins 2019). The ever-escalating volumes of waste glass could substitute natural and quarried (manufactured) sand in various geotechnical construction applications (Kazmi et al. 2020a, b; Kazmi et al. 2019). Both materials possess a comparable chemical composition, with crushed waste glass (CWG) showing geotechnical parameters similar to those of traditional construction sands (Basireddy et al. 2021; Kazmi et al. 2021; Serati et al. 2021). The Mohs Hardness value of crushed waste glass typically lies around 5.5 (Omoding et al. 2021; Pahlevani and Sahajwalla 2018; Riding et al. 2018; Sanij et al. 2019), while that of silica sand/gravel generally lies between 6 and 7 (James and Broad 1983; Koppatz et al. 2011; Wille and Naaman 2013). Crushed waste glass could offer huge potential for use as column backfill in granular column construction; however, almost no detailed study is yet available to date presenting the geotechnical performance of granular columns containing CWG (Blewett and Woodward

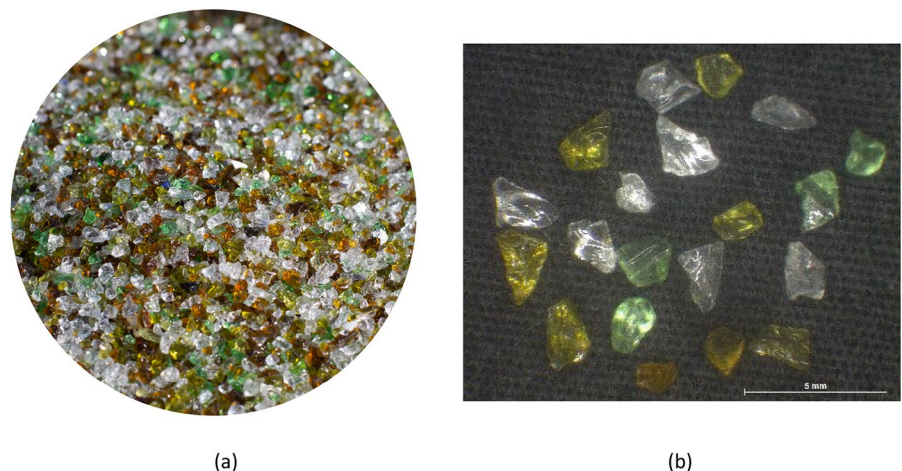
1998; Kazmi et al. 2021; Zukri and Nazir 2018). If the use of CWG in granular columns turns out to be feasible, it could help reduce the consumption of natural and quarried sand, recycle waste glass and provide sustainability benefits. This study presents the shear strength and consolidation behaviour of geocomposites (granular column-reinforced soil) containing a granular column made up of three different PSRs of CWG. Figure 1 shows the ordinary image and micrograph of CWG.

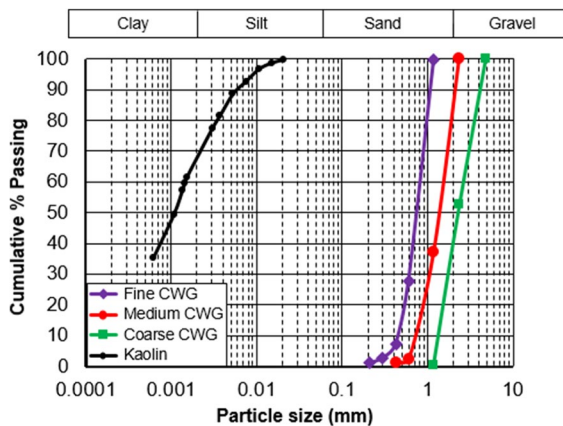
## 2 Materials and Equipment

### 2.1 Material Properties

This study used kaolin and CWG as base and column backfilling materials, respectively. Three different PSRs of CWG were discretely used to create a granular column in the middle of the kaolin bed. Firstly, geotechnical characterisation testing was performed, followed by shear strength and consolidation testing. The particle size distribution (PSD) curves and characterisation results of all test materials are given in Fig. 2 and Table 1, respectively. The CWG used in this study was sourced from a commercial supplier, Enviro Sand, in Brisbane, Australia. The kaolin used had a median particle diameter of 0.0012 mm (Mishra et al. 2018, 2020; Mishra and Scheuermann 2021). Several researchers have previously studied various geotechnical parameters of kaolin (Bore et al. 2021; Bore et al. 2016a,

**Fig. 1** **a** Ordinary image of CWG, and **b** optical microscopic image of CWG





**Fig. 2** Particle size distribution curves of the test materials (adapted from Kazmi et al. 2021 and Xu et al. 2018)

b; Bore, Wagner, & Scheuermann, 2016; Mishra et al. 2019). All CWG PSRs had uniform gradation, thereby eliminating the effect of the gradation of the CWG on the performance of the geocomposites.

## 2.2 Test Equipment

### 2.2.1 Direct Shear Tests

The shear strength tests were performed using an advanced high-precision large direct shear machine (LDSM), ADS-300, produced by Wille Geotechnik

(Germany). The LDSM is connected to a computer equipped with automatic data logging capability and has four linear variable differential transformers (LVDTs) placed on each corner of the top-loading cap to monitor vertical displacement and tilt. The LDSM automatically stops if the tilting surpasses 10% of the specimen depth. The LVDTs give the average settlement value. The dimensions of all the cubic geocomposites tested for their shear strength were length, width and depth equal to 150 mm. Figure 3 shows the LDSM used.

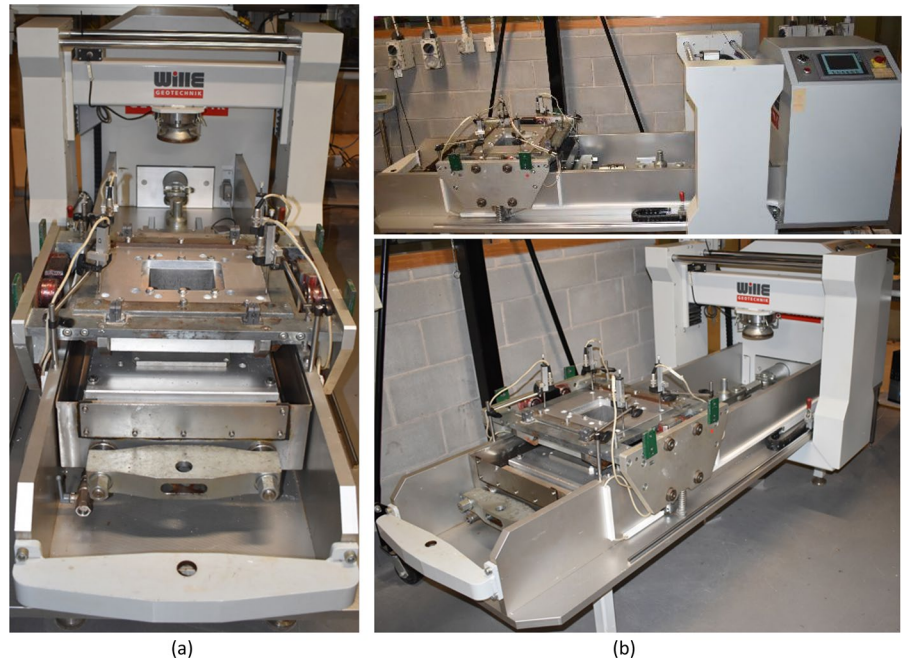
### 2.2.2 Consolidation Tests

The consolidation testing was conducted on the kaolin specimen and the geocomposites using a large consolidometer (LC) containing a cylindrical cell of 150 mm diameter with a cross-sectional area of 177 cm<sup>2</sup>. The consolidometer is 410 mm high and is equipped with six spirally fixed pore water pressure (PWP) transducers at a vertically regular spacing of 40 mm, plus a base PWP transducer. Before preparing the specimens, all the porous stones and PWP transducers in the consolidometer cell were de-aired and saturated. The cylinder is constructed of stainless steel and is sufficiently stiff to prevent deformation under the highest vertical load allowed. The LC features two load cells, one above the piston to record the applied force from the top load generator and the

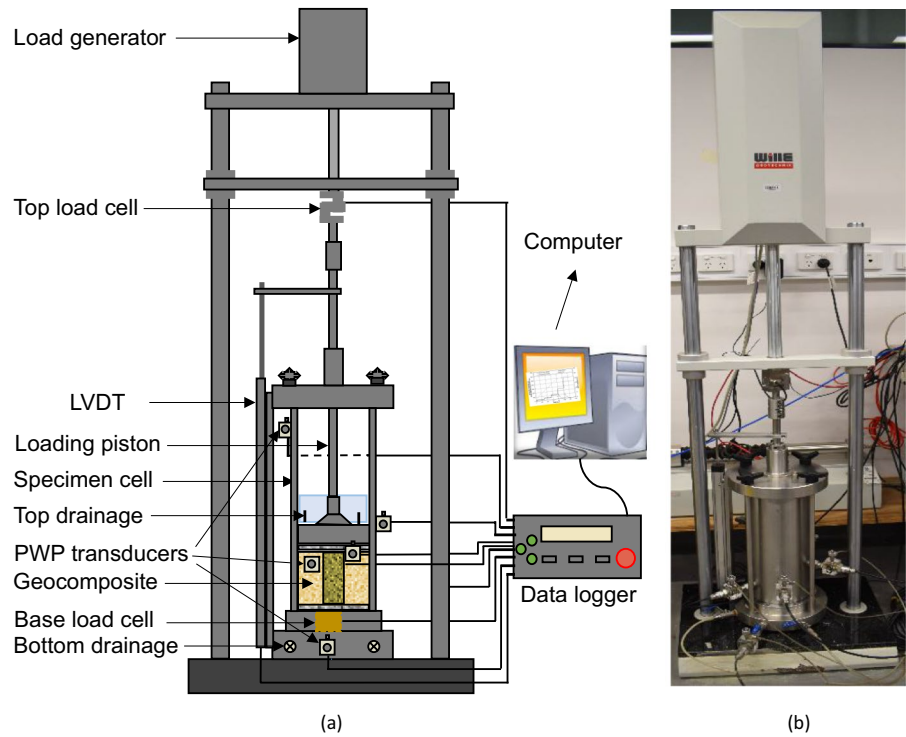
**Table 1** Geotechnical characterisation results of the test materials (adapted from Kazmi et al. 2021; Xu et al. 2018)

| Parameter   | Fine CWG | Medium CWG | Coarse CWG | Kaolin |
|---|----------|------------|------------|--------|
| Specific gravity  | 2.53     | 2.50       | 2.50       | 2.61   |
| Minimum void ratio  | 0.73     | 0.37       | 0.70       | –      |
| Maximum void ratio  | 0.99     | 0.79       | 0.77       | –      |
| Median particle diameter (mm)                                 | 0.78     | 1.42       | 2.30       | 0.0012 |
| D <sub>10</sub> (mm)  | 0.46     | 0.73       | 1.39       | –      |
| Minimum dry density (g/cm <sup>3</sup> or mg/m <sup>3</sup> ) | 1.27     | 1.39       | 1.41       | –      |
| Maximum dry density (g/cm <sup>3</sup> or mg/m <sup>3</sup> ) | 1.46     | 1.82       | 1.47       | –      |
| Liquid limit (%)  | –        | –          | –          | 90     |
| Plastic limit (%)   | –        | –          | –          | 35     |
| Plasticity index (%)  | –        | –          | –          | 55     |
| F <sub>200</sub> (%)  | –        | –          | –          | 69     |
| Particle size range (mm)                                      | 0.50–1.0 | 1.0–1.7    | 1.7–3.35   | –      |
| Unified soil classification system (USCS) rating              | SP       | SP         | SP         | CH     |
| Peak shear strength under 50 kPa applied normal stress (kPa)  | –        | –          | –          | 15.7   |

**Fig. 3** Large direct shear machine (ADS-300, Wille Geotechnik)



**Fig. 4** **a** Schematic diagram and **b** photograph of the large consolidometer (adapted from Islam et al. 2020)



**Table 2** Plan of the direct shear tests (adapted from Kazmi et al. 2022)

| Specimen/geocomposite    | Applied normal stress (kPa) | Shear rate (mm/min) | Test type    | Equipment   |
|--------------------------|-----------------------------|---------------------|--------------|-------------|
| Kaolin only              | 12.5, 25, 50 and 100        | 0.02                | Single-stage | LDS machine |
| Fine CWG column-kaolin   | 12.5, 25 and 50             | 0.02                | Single-stage | LDS machine |
| Medium CWG column-kaolin | 12.5, 25, 50 and 100        | 0.02                | Single-stage | LDS machine |
| Coarse CWG column-kaolin | 12.5, 25 and 50             | 0.02                | Single-stage | LDS machine |

other at the base of the cell to log the load transmitted to the base of the specimen (Islam et al. 2021). An LVDT is attached to the shaft near the piston to record the settlement of the specimen. Figure 4 shows the schematic diagram and photograph of the LC.

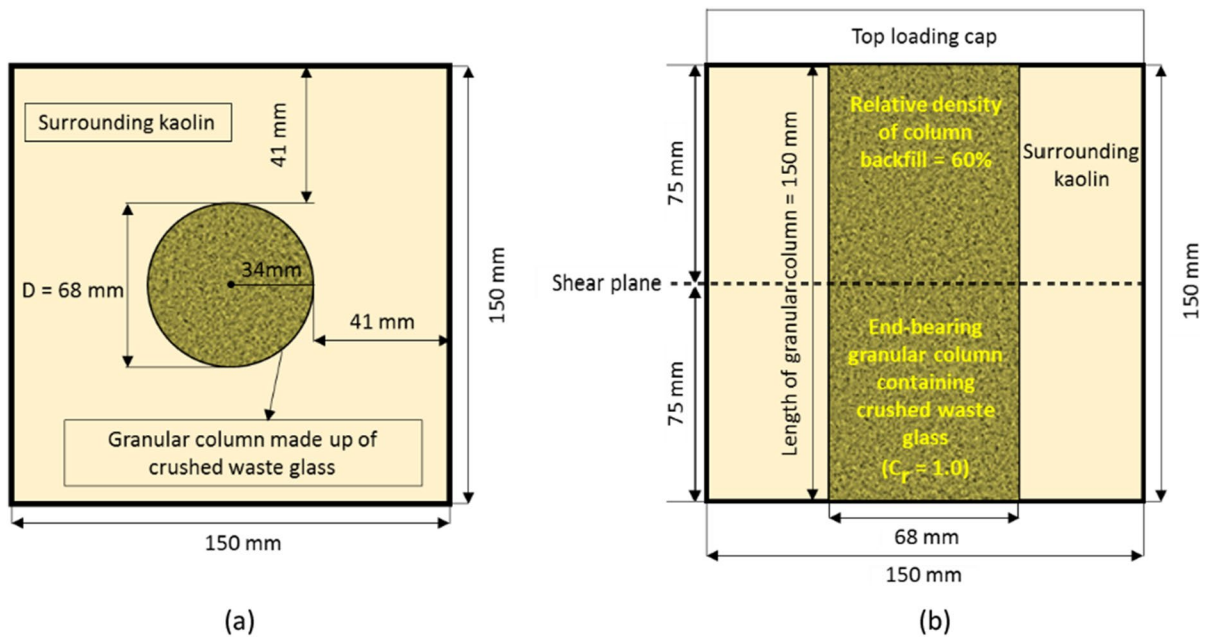
### 3 Experimental Methodology

#### 3.1 Direct Shear Tests

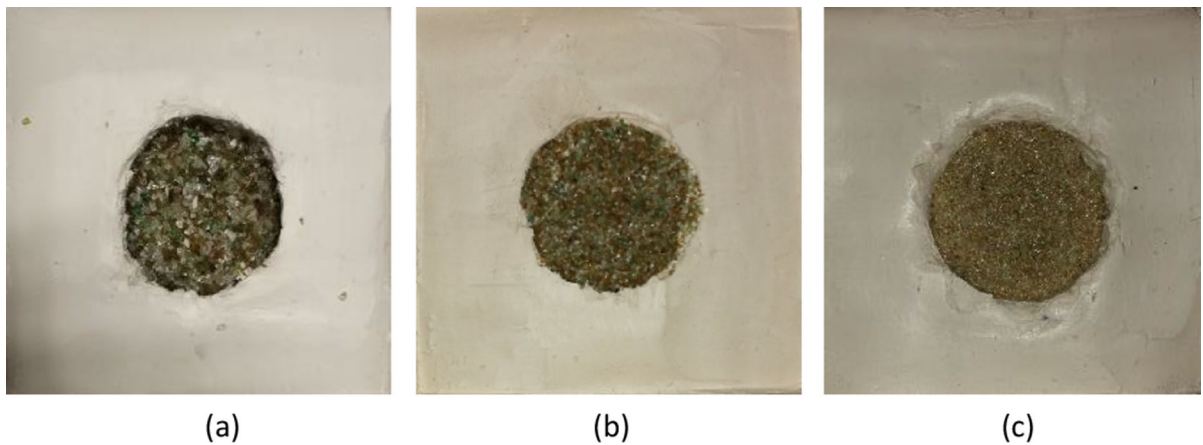
Direct shear tests were conducted on the geocomposites and kaolin only specimens. Table 2 summarises the specifications of the direct shear tests performed. The kaolin was prepared at an average consistency index, liquidity index and gravimetric moisture content of 61%, 38% and 56%, respectively. The dry unit weight of the kaolin bed was kept constant at 10 kN/m<sup>3</sup> in all tests. This dry unit weight is close to what is typically found under field conditions for soft clays and was also practically convenient to achieve during specimen preparation. The kaolin bed was prepared by compacting the pre-weighed kaolin into three identical layers, each 50 mm thick, using a hand tamper. A thin-walled polyvinyl chloride (PVC) tube with an external diameter of 68 mm and thickness of 2.5 mm was used to install an end-bearing granular column in the middle of the kaolin bed using the replacement method. The relative density (RD) of the column backfill was 60%, selected based on practical considerations. The PVC tube was slowly pushed vertically and concentrically into the kaolin till it touched the shear box base. Once the PVC tube was fully penetrated, the kaolin inside the tube was removed. The preweighed CWG corresponding to the given RD was introduced into the hole through a funnel. The mass of the column backfill corresponding to 60% relative density at the given height was determined. When the hole was created in the kaolin bed, the mass of dry

sand was compacted to fit into the height corresponding to 60% relative density. The PVC tube was subsequently withdrawn such that there was no disturbance to the surrounding kaolin. The column penetration ratio ( $c_r$ ), the depth of the column to the depth of the specimen, and the length to diameter ( $L/D$ ) ratio of the column were kept constant at 1.0 and 2.2, respectively. The column length was kept the same as that of the specimen (150 mm) to ensure the granular column remains end-bearing ( $c_r = 1.0$ ). The end-bearing granular columns are typically more effective than the floating ones in enhancing the bearing capacity of soft soils and decreasing the induced settlements under cyclic and monotonic loading (Shahu et al. 2023). The area replacement ratio ( $A_r$ ) used to prepare the geocomposites was 16%, with a column diameter of 68 mm positioned concentrically at the centre of the geocomposite, maintaining a sufficient gap between the column boundary and the shear box to prevent the influence of the boundary effect. The typical  $A_r$  used in design varies from 10 to 40%. Besides achieving the required  $A_r$ , another reason for selecting the given column diameter ( $D = 68$  mm) was to ensure that the length of the column remains within its critical length. Altogether, the specimen preparation procedure adopted had good reproducibility. It may be a good idea for future studies to modify the CWG column's length and diameter such that it becomes a floating CWG column and then test the geocomposites, allowing some comparison between the performance of an end bearing or floating CWG column.

The prepared geocomposites in this study were subjected to single-stage stress-controlled direct shear experiments at a steady shear rate of 0.02 mm/min. The kaolin only specimens and medium CWG column-kaolin geocomposites were tested under 12.5 kPa, 25 kPa and 50 kPa applied normal stress. The fine CWG column-kaolin and coarse CWG column-kaolin geocomposites were tested under



**Fig. 5** Typical **a** plan of the geocomposite and **b** cross-section of the geocomposite for the shear strength test (adapted from Kazmi et al. 2022)



**Fig. 6** Test setup prepared in the shear box for **a** coarse CWG column-kaolin geocomposite, **b** medium CWG column-kaolin geocomposite, **c** fine CWG column-kaolin geocomposite

12.5 kPa, 25 kPa, 50 kPa and 100 kPa applied normal stresses. The normal stresses selected in this study ensured that the kaolin did not squeeze out of the shear box at the split during the tests. The direct shear test was terminated when the shear stress

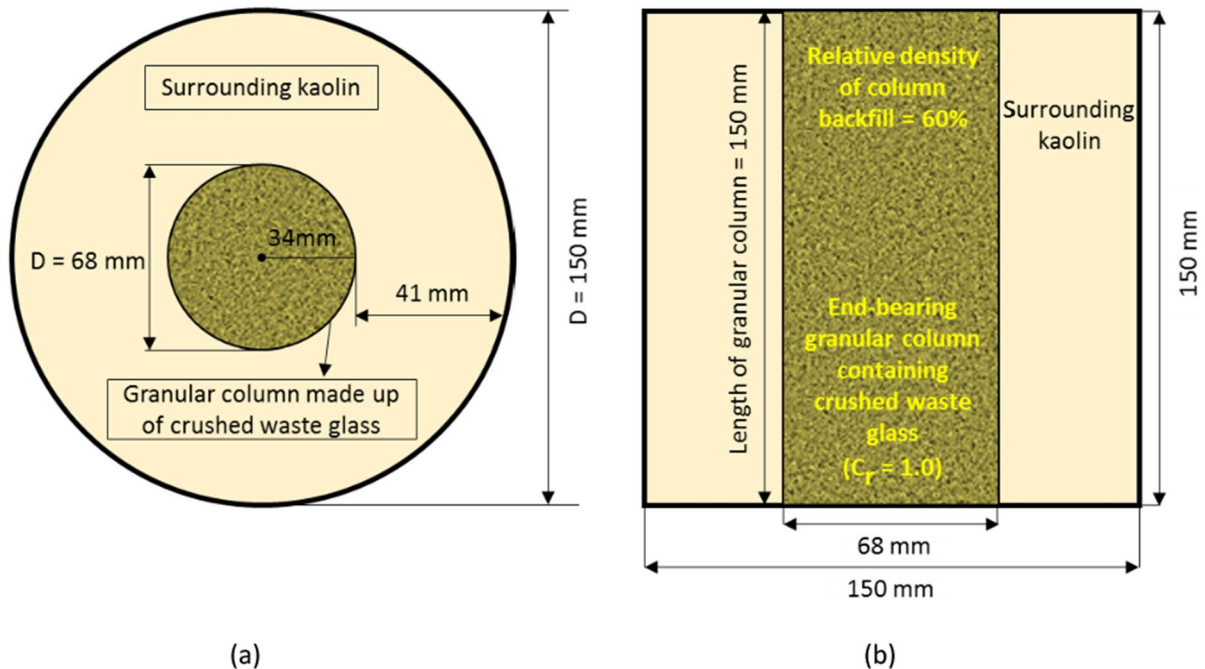
became uniform, or the horizontal displacement hit 24 mm, whichever occurred first. Figure 5 shows the typical plan and cross-section of the reinforced kaolin (geocomposite). Figure 6 shows the

geocomposites containing a granular column with three different PSRs of CWG.

### 3.2 Consolidation Tests

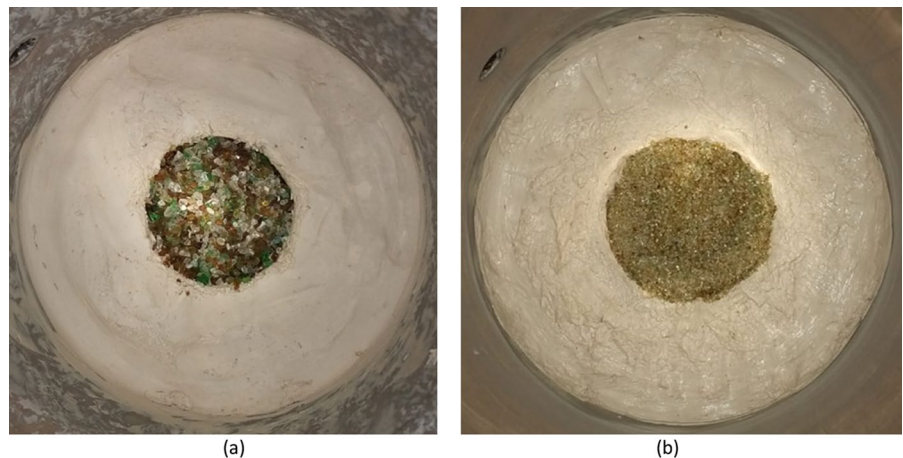
With a height and diameter of 150 mm, the kaolin specimens and the geocomposites were prepared using almost similar geometric and geotechnical parameters as the direct shear tests to ensure

consistent test conditions. The dry unit weight and average gravimetric water content of the kaolin bed were  $10 \text{ kN/m}^3$  and 56%, respectively, in all tests. An end-bearing granular column containing CWG was installed in the middle of the kaolin bed at an  $A_r$  and  $L/D$  ratio of 16% and 2.2, respectively. The RD of column backfill (CWG) was kept constant at 60%. The consolidation test comprised the loading stage only. Three vertical stresses of 12.5 kPa, 25 kPa and 50 kPa



**Fig. 7** Typical **a** plan of the geocomposite in the consolidation cell and **b** cross-section of the geocomposite in the consolidation cell

**Fig. 8** Experimental setup prepared in the consolidation cell for **a** coarse CWG column-kaolin geocomposite and **b** fine CWG column-kaolin geocomposite



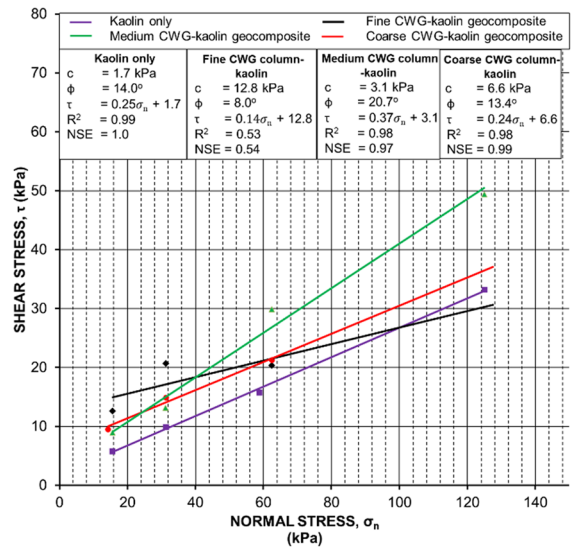


were applied (the same stresses as used in the direct shear testing). The loading started from 12.5 kPa, and the stress kept increasing at a load increment ratio equal to 1.0 until 50 kPa was reached. The specimen was kept under each stress until the settlement became constant. All the readings were automatically stored through a data logger, and the data collection frequency was approximately 10 s. Figure 7 shows the typical plan and cross-section of the geocomposite in the consolidation cell. Figure 8 illustrates geocomposites prepared in the consolidation cell.

### 4 Experimental Results and Discussion

#### 4.1 Shear Strength Tests

The results of the direct shear tests were used to plot the shear strength envelopes that were best-fitted through the Mohr–Coulomb failure criterion. The computed peak shear stresses and applied normal stresses were area-corrected. Two fitting parameters, the coefficient of determination ( $R^2$ ) and the Nash–Sutcliffe model efficiency coefficient (NSE), were used to determine the goodness-of-fit of the envelopes. According to the criteria suggested by Chiew and McMahon (1993), the goodness-of-fit of all the shear-strength envelopes except for the fine CWG column-kaolin geocomposite can be categorised as "perfect" ( $NSE \geq 0.93$ ). The relatively higher void ratio of the fine CWG particles at the given RD in the column would have caused the surrounding kaolin to mix with the fine CWG column, creating a weaker smear zone and potentially reducing the strength of the column. A "repeat" test was performed on the fine CWG column-kaolin geocomposite under 50 kPa applied normal stress to confirm the finding of the original test. The peak shear strength value obtained from the repeat test was very close to that of the original test, with a percentage difference of



**Fig. 9** Peak shear strength envelopes of the kaolin only specimens and the geocomposites (adapted from Kazmi et al. 2022)

less than 6%, endorsing the validity of the presented results. Table 3 presents the shear strength parameters of the kaolin only specimens and the geocomposites. Figure 9 illustrates the peak shear strength envelopes of the kaolin only specimens and the geocomposites.

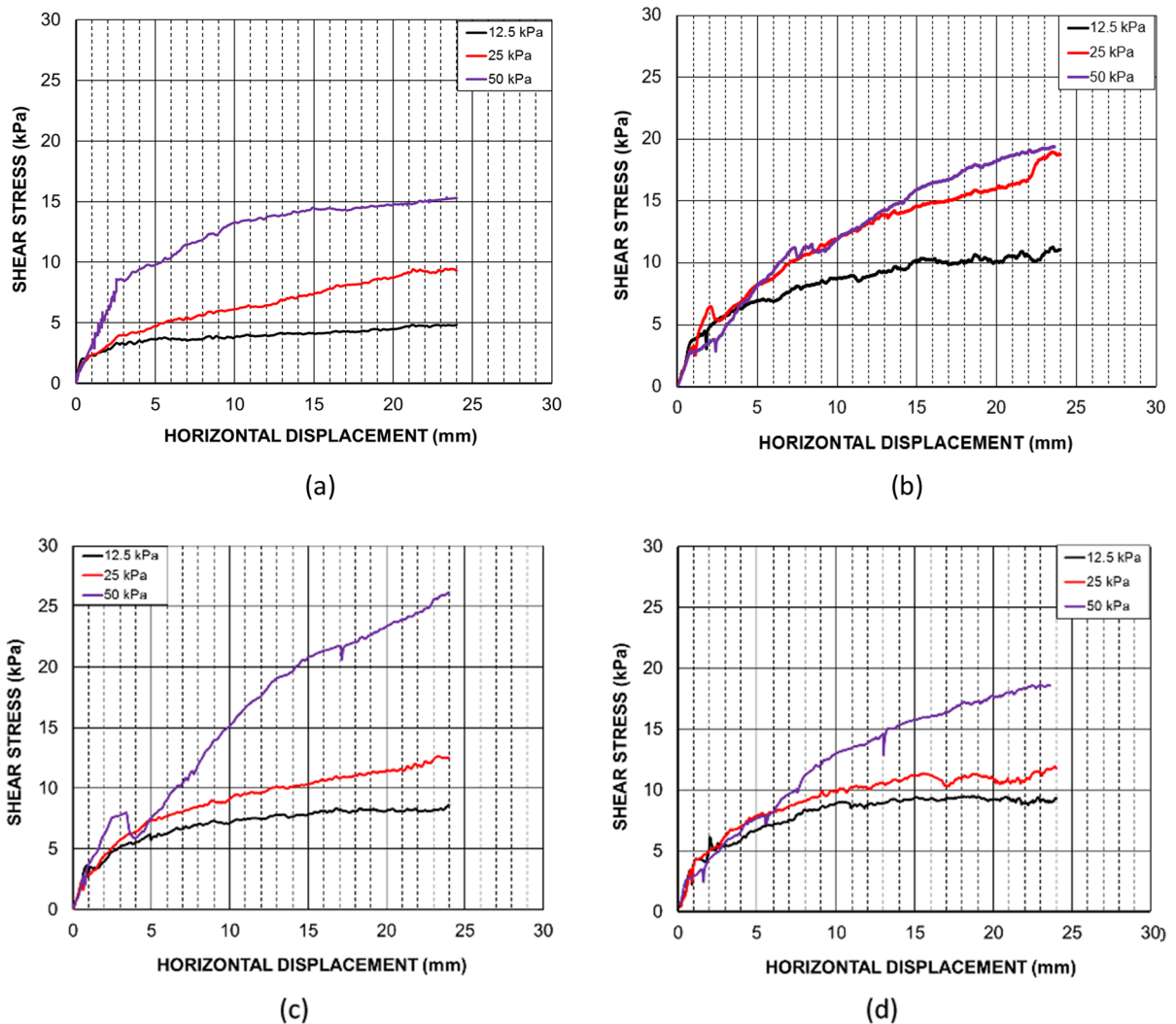
The cohesion and friction angle of kaolin only specimens were found to be 1.7 kPa and 14.0°, respectively. The relatively lower cohesion of kaolin only specimens (1.7 kPa) could potentially be due to a relatively higher moisture content (56%) of the kaolin bed. Introducing a granular column of any given PSR of CWG generally increased the peak shear strength of the reinforced kaolin compared to that of the kaolin only specimen. The results showed that the cohesion of geocomposites containing a fine, medium or coarse CWG column increased by nearly 653%, 82% and 288%, respectively, compared to that of the kaolin only specimens. This increase in cohesion of the geocomposite is consistent with the trends of some

**Table 3** Peak shear strength parameters of the kaolin only specimens and the geocomposites (adapted from Kazmi et al. 2021)

|                             | Kaolin only | Fine CWG column-kaolin geocomposite | Medium CWG column-kaolin geocomposite | Coarse CWG column-kaolin geocomposite |
|-----------------------------|-------------|-------------------------------------|---------------------------------------|---------------------------------------|
| Cohesion (kPa)              | 1.7         | 12.8                                | 3.1                                   | 6.6                                   |
| Internal friction angle (°) | 14.0        | 8.0                                 | 20.7                                  | 13.4                                  |

previous studies reporting an increase in the cohesion of the geocomposite after the sand column installation compared to the unreinforced kaolin (Marto et al. 2014; Xu et al. 2018). It was found that the fine CWG column-kaolin geocomposites had the lowest friction angle ( $8.0^\circ$ ) and highest cohesion (12.8 kPa) among all the specimens tested. The goodness-of-fit of the failure envelope for the fine CWG column-geocomposite was relatively low ( $R^2=0.53$ ), potentially due to a greater influence of the smear effect. The geocomposites containing a medium CWG column showed the highest friction angle ( $20.7^\circ$ ) among

all tested specimens. This could be due to the highest placement density (lowest void ratio) of the medium CWG particles ( $1610 \text{ kg/m}^3$ ), corresponding to 60% RD compared to that of the other two PSRs of CWG. Previous studies also showed that an increase in the density of sands increases their friction angle, partly due to the reduction in void ratio, potentially leading to enhanced particle interlocking (Andersen and Schjetne 2013; Basudhar and Acharya 2020; Mujtaba et al. 2018). The higher placement density of the medium CWG particles would have led to a higher friction angle between its particles, coupled with



**Fig. 10** Shear stress-horizontal displacement behaviour of: **a** the kaolin only specimens, **b** the fine CWG column-kaolin geocomposites, **c** the medium CWG column-kaolin geocom-

posites, and **d** the coarse CWG column-kaolin geocomposites (adapted from Kazmi et al. 2022)

greater particle interlock, ultimately increasing the overall friction angle of the medium CWG column-kaolin geocomposite.

The shear stress-horizontal displacement graphs (Fig. 10) show that installing a CWG column of any PSR increased the shear stress of the geocomposites under most normal stresses compared to that of the kaolin only specimens. Some fluctuations were also observed in the shear stress during the shearing (or increase in horizontal displacement) of the geocomposites, particularly for those geocomposites containing a fine or coarse CWG column, potentially due to the expansion of micro-cracks and the rearrangement of CWG particles during shearing. Another potential reason for these shear stress fluctuations could be disturbances in the smear zone between the column and surrounding kaolin during shearing, causing some mixing of the CWG with the surrounding kaolin. Also, the shear stress fluctuations could partly be due to the relatively slightly lower dry unit weight of the kaolin bed ( $10 \text{ kN/m}^3$ ), as a higher dry unit weight of the kaolin bed is expected to provide relatively better passive resistance to the CWG column.

Installing a fine CWG column increased the cohesion of the geocomposite to 12.8 kPa but decreased its friction angle to  $8.0^\circ$ . The peak shear strength of the geocomposite containing a fine CWG column increased relatively sharply under 12.5 kPa and 25 kPa applied stress but, surprisingly, slightly decreased under 50 kPa stress. The potential reasons for this marginal decrease in shear strength under 50 kPa applied stress include, firstly, the placement density of the fine CWG column corresponding to 60% RD ( $1376 \text{ kg/m}^3$ ), which was the lowest of all other CWG columns, ultimately causing a sizeable reduction in the height of the column under higher vertical stresses. Secondly, the friction angle of CWG decreases with decreasing particle size, reducing particle grain interlock in the fine CWG column (Kazmi, Serati, et al. 2020). Thirdly, the relatively higher void ratio of the fine CWG particles at the given RD in the column would have caused the surrounding kaolin to mix with the fine CWG column, creating a weaker smear zone and potentially reducing the strength of the column.

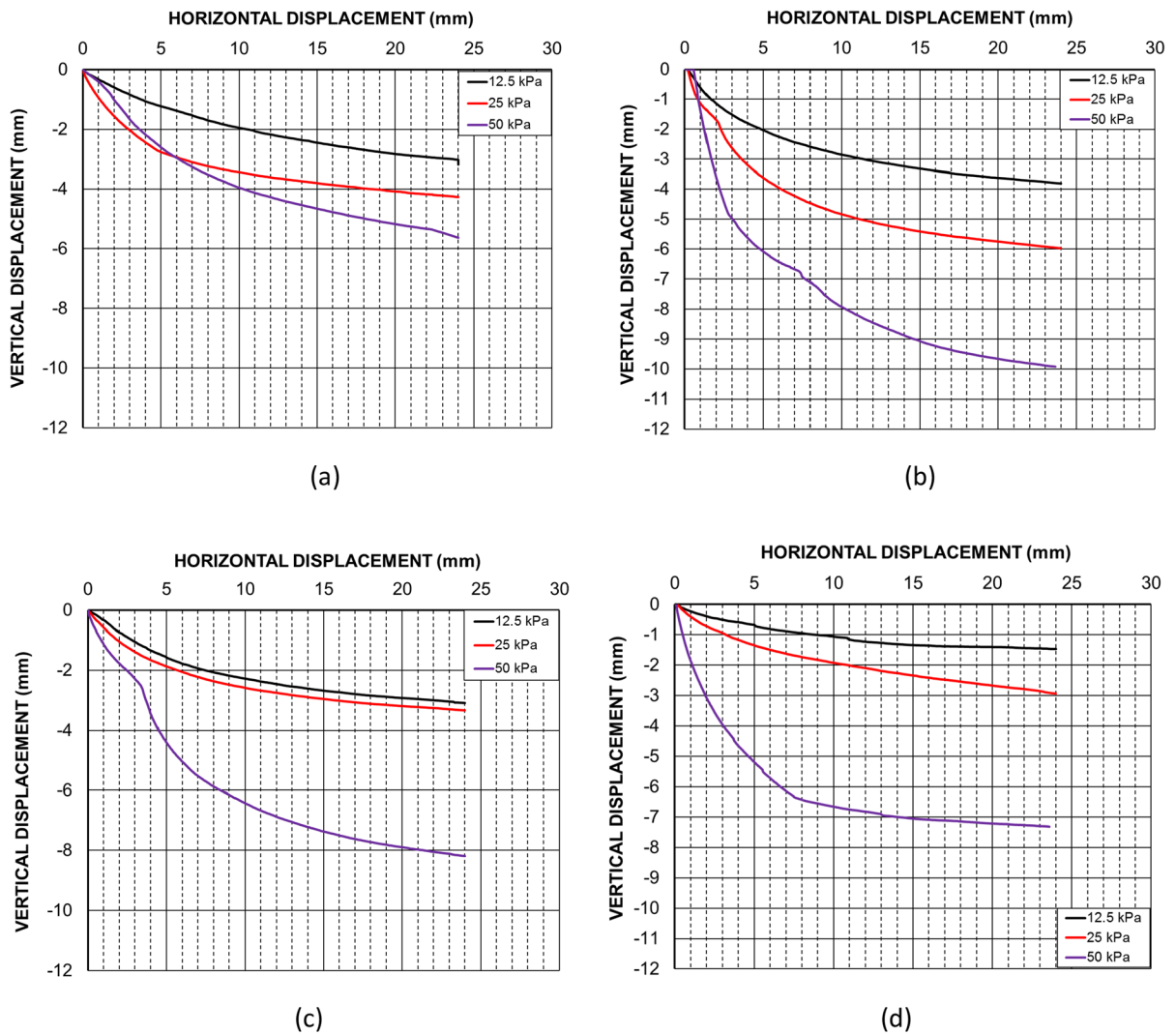
Typically, the horizontal-vertical displacement graphs (Fig. 11) show that the vertical displacement during the shearing of the geocomposites containing a CWG column of any given PSR was higher than

that of the kaolin only specimen. The potential reason for this observation could be water drainage from the kaolin due to the higher permeability of the CWG column, leading to higher vertical displacement. Xu et al. (2018) also observed that including a sand column in kaolin considerably increased the vertical displacement of the geocomposite compared to that of the kaolin only specimen. Moreover, it was observed that the geocomposites containing a fine CWG column underwent higher vertical displacement during shearing, possibly due to the lowest placement density of fine CWG particles corresponding to 60% RD than that containing a medium or coarse CWG column.

#### 4.2 Consolidation Tests

Table 4 shows the average parameters obtained from the consolidation tests. The average effective stress ( $\sigma'$ ) applied to the specimens was determined using the equation developed by Islam et al. (2021). The coefficient of consolidation ( $c_v$ ) depends on hydraulic conductivity ( $k$ ), the coefficient of volume compressibility ( $m_v$ ) and the unit weight of pore fluid ( $\gamma_w$ ). The  $c_v$  denotes the rate at which a saturated clay experiences one-dimensional consolidation upon a rise in applied stress (Robinson and Allam 1998). Two graphical methods are typically used to determine the values of  $c_v$ , including the logarithm-of-time method proposed by (Casagrande and Fadum (1940) and the square-root-of-time method proposed by Taylor (1942). This study used the logarithm-of-time method to determine  $c_v$ . The results show that the average  $c_v$  of kaolin only specimens is  $0.0014 \text{ cm}^2/\text{s}$ , which is similar to what is reported by Xu et al. (2018). However, the average  $c_v$  of geocomposites containing a coarse, medium or fine CWG column increased compared to that of the kaolin only specimens to  $0.363 \text{ cm}^2/\text{s}$ ,  $0.112 \text{ cm}^2/\text{s}$  and  $0.045 \text{ cm}^2/\text{s}$ , respectively.

The results demonstrate that installing a CWG column of any PSR significantly increases the  $c_v$  of the reinforced kaolin. Installing a coarse, medium or fine CWG column increased the  $c_v$  of the geocomposite to almost 259 times, 80 times or 32 times, respectively. This increase in  $c_v$  is partly due to the increased hydraulic conductivity of the geocomposite caused by the drainage ability of the CWG column. In particular, installing a coarse CWG column showed the



**Fig. 11** Horizontal-vertical displacement behaviour of: **a** the kaolin only specimens, **b** the fine CWG column-kaolin geocomposites, **c** the medium CWG column-kaolin geocompos-

ites, and **d** the coarse CWG column-kaolin geocomposites (adapted from Kazmi et al. 20221)

**Table 4** Average parameters obtained from the consolidation tests

|                                       | Coefficient of consolidation $c_v$ (cm <sup>2</sup> /s) | Compression index ( $C_c$ ) | Coefficient of secondary compression ( $C_{\alpha}$ ) | Coefficient of volume compressibility ( $m_v$ ) kPa <sup>-1</sup> | Hydraulic conductivity (k) m/s |
|---------------------------------------|---|-----------------------------|---|---|--------------------------------|
| Kaolin only specimen                  | 0.0014  | 0.34                        | 0.052   | 0.0053  | $7.20 \times 10^{-9}$          |
| Coarse CWG column-kaolin geocomposite | 0.363   | 0.28                        | 0.030   | 0.0025  | $8.90 \times 10^{-7}$          |
| Medium CWG column-kaolin geocomposite | 0.112   | 0.22                        | 0.024   | 0.0019  | $2.410 \times 10^{-7}$         |
| Fine CWG column-kaolin geocomposite   | 0.045   | 0.17                        | 0.020   | 0.0016  | $6.77 \times 10^{-8}$          |

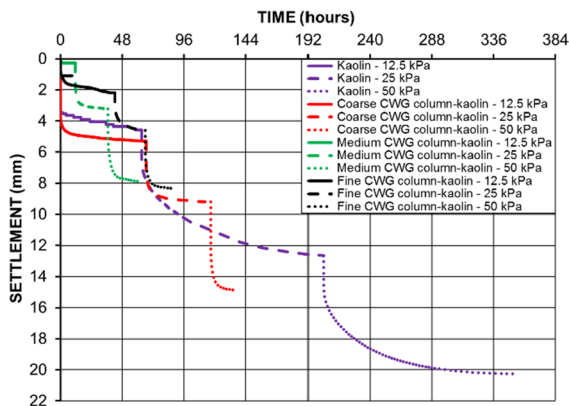
highest increase in the  $k$  value of the geocomposite. This is due to the higher hydraulic conductivity of the coarse CWG column (Bareither et al. 2008). Another important parameter is the coefficient of volume compressibility, which is used to estimate the primary consolidation settlement of fine-grained and organic soils (Canakci et al. 2017). The results also show that the  $m_v$  of the kaolin only specimen was  $0.0053 \text{ kPa}^{-1}$ , which decreased to  $0.0025 \text{ kPa}^{-1}$ ,  $0.0019 \text{ kPa}^{-1}$  and  $0.0016 \text{ kPa}^{-1}$  for coarse CWG column-kaolin, medium CWG column-kaolin and fine CWG column-kaolin geocomposite, respectively. In other words, installing a CWG column of any given PSR increased the stiffness of the geocomposite.

Consolidation often significantly increases the shear strength of soils (Singh et al. 2010). The consolidation results show that installing a granular column backfilled with any given material considerably increased the consolidation in reinforced kaolin, which would have increased the shear strength of the geocomposites. The decreasing void ratio (Fig. 13) also endorses a potential increase in the shear strength of the geocomposites due to the consolidation provided by the higher hydraulic conductivity of the granular column.

The compression index ( $C_c$ ) is commonly used to determine the consolidation settlement of clay. It represents the slope of the virgin compression curve, which is the linear part of the  $e$ -log ( $\sigma'$ ) curve (Ozer et al. 2008). The value of  $C_c$  is different for each type of soil; for example, for clay and laterite  $C_c$  typically lies between 0.258 and 0.968 and between 0.101 and 0.940, respectively (Ibrahim et al. 2012). Similarly, the coefficient of secondary compression ( $C_\alpha$ ) is typically used to characterise secondary consolidation or creep, which occurs under constant effective stress because of the plastic adjustment of soil fabrics. The results show that reinforcing the kaolin with a CWG column of any PSR reduced the average  $C_c$  and  $C_\alpha$  values of the geocomposites, indicating that installing a CWG column would reduce the settlement. Installing a coarse, medium or fine CWG column decreased the average  $C_c$  of the geocomposites by almost 17%, 35% or 50%, respectively, compared to that of the kaolin only specimens. Likewise, including a coarse, medium or fine CWG column decreased the average  $C_\alpha$  of the geocomposites by nearly 42%, 54% and 61%, respectively, compared

to that of the kaolin only specimens. The decrease in  $C_c$  and  $C_\alpha$  values of the reinforced soil compared to those of the unreinforced soil is consistent with the findings of several previous studies (Canakci et al. 2017; Xu et al. 2018). Also, the average  $m_v$  of the geocomposites containing a coarse, medium or fine CWG column decreased by nearly 53%, 64% or 69%, respectively, compared to that of the kaolin only specimens. The average  $k$  value of the kaolin only specimens was found to be  $7.20 \times 10^{-9} \text{ m/s}$ , while the average  $k$  values of the geocomposites containing a coarse, medium or fine CWG column increased to  $8.90 \times 10^{-7} \text{ m/s}$ ,  $2.40 \times 10^{-7}$  and  $6.77 \times 10^{-8} \text{ m/s}$ , respectively, due to the higher permeability of CWG column. Several studies have confirmed that particle size can significantly influence the hydraulic conductivity of sands (Cabalar and Akbulut 2016; Choo et al. 2016). The increase in the drainage of the reinforced soil (soil reinforced with a granular column) is largely due to the higher permeability of a granular column, as has been previously reported (Badanagki et al. 2018; Hosseinpour et al. 2016).

The coefficient of consolidation is a crucial parameter for consolidation analysis and denotes the rate at which a saturated clay experiences one-dimensional consolidation upon increasing stress (Robinson and Allam 1998). The lower the  $c_v$ , the longer soil usually takes to achieve a specific degree of consolidation. This study found that the average  $c_v$  of kaolin specimen is  $0.0014 \text{ cm}^2/\text{s}$ , which is similar to what was reported by Xu et al. (2018). The results show that installing a CWG column of any PSR significantly increases the average  $c_v$  of the reinforced kaolin. Including a coarse, medium or fine CWG column increased the average  $c_v$  of the geocomposite to almost 259 times, 80 times or 32 times, respectively. This increase in average  $c_v$  is partly due to the increase in hydraulic conductivity of the geocomposite caused by the drainage ability of the CWG column. In particular, including a coarse CWG column showed the highest increase in the average  $k$  value of the geocomposite. This is due to the higher hydraulic conductivity of the coarse CWG column (Bareither et al. 2008). The results show that installing a coarse, medium or fine CWG column increased the average  $k$  value of the geocomposite by nearly 123 times, 33 times or 9 times, respectively, compared to that of the kaolin only specimen. Another important parameter is the



**Fig. 12** Settlement-time plots for the kaolin specimen and the geocomposites

coefficient of volume compressibility, which is used to estimate the primary consolidation settlement of fine-grained and organic soils (Canakci et al. 2017). The results also show that the average  $m_v$  of the kaolin specimen was  $0.0053 \text{ kPa}^{-1}$ , which decreased to  $0.0025 \text{ kPa}^{-1}$ ,  $0.0019 \text{ kPa}^{-1}$  and  $0.0016 \text{ kPa}^{-1}$  for coarse CWG column-kaolin, medium CWG column-kaolin and fine CWG column-kaolin geocomposite, respectively. In other words, installing a CWG column of any given PSR increased the average stiffness of the geocomposite significantly.

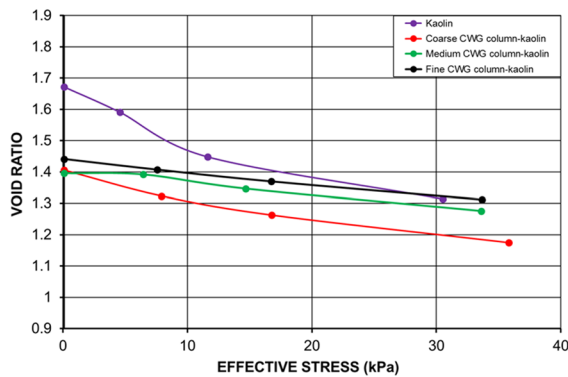
The compressibility of soils is typically influenced by their in situ effective stress, void ratio, and the nature and arrangement of particles. Figure 12 shows the derived time-settlement plots for the kaolin only specimen and all the geocomposites tested. It reveals that the settlement typically increases with applied stress for both the kaolin specimen and the geocomposites. Compared to all the specimens tested, the kaolin only specimen showed the highest settlement and took the longest time to settle. Installing a CWG column of any PSR considerably reduced the time required for consolidation settlement due to the accelerated drainage provided by the CWG column. For example, the consolidation time of medium CWG column-kaolin geocomposite under 50 kPa applied vertical stress decreased by approximately 80% compared to that of the kaolin only specimen. Also, the geocomposites mostly showed resistance to the applied stresses higher than that of the kaolin only specimen due to the higher friction angle and hydraulic conductivity of CWG particles (Cooper and Rose

1999; Kazmi et al. 2021). Figure 13 illustrates the void ratio-effective stress ( $e-\sigma'$ ) plot. The void ratio of the geocomposites reached a smaller value than that of the kaolin only specimen. The geocomposite containing a coarse CWG column showed the maximum reduction in the final void ratio due to its higher hydraulic conductivity.

## 5 Conclusion

This study examined the effect of the particle size of CWG columns installed in kaolin on the overall shear strength and consolidation behaviour of the geocomposite. Three different PSRs of CWG were used to create a CWG column in the centre of the kaolin bed. Below are the key findings:

- Overall, the shear strength and consolidation behaviour of kaolin reinforced with a CWG column (geocomposite) was found to be sensitive to the PSR of CWG used.
- Installing a CWG column of any given PSR in kaolin increased the peak shear strength of the geocomposite compared to that of the kaolin only specimen. The geocomposites containing a medium CWG column demonstrated the highest increase in friction angle, climbing from  $14.0^\circ$  for kaolin only specimens to  $20.7^\circ$  for the medium CWG column-kaolin geocomposites, potentially because of the higher placement density of the medium CWG particles in the column compared to that of the coarse or fine CWG particles in the column, corresponding to given RD.
- The fine CWG column-kaolin geocomposite showed a marginal decrease in its peak shear stress under 50 kPa applied stress, compared to the shear stress corresponding to 25 kPa applied stress. Potential reasons for this could be the lower placement density (higher void ratio) of the fine CWG particles in the column (corresponding to the given RD), plus the mixing of the surrounding kaolin and the column, creating a weaker smear zone that reduced the stability of the column.
- Geocomposites containing any given PSR of the CWG column had consolidation behaviour superior to that of the kaolin only specimen.
- The geocomposite containing a coarse CWG column showed the highest increase in the average



**Fig. 13** Void ratio-settlement plots for the kaolin specimen and the geocomposites

coefficient of consolidation ( $c_v$ ) compared to that of the kaolin only specimen due to the higher average hydraulic conductivity of the geocomposite.

- Installing a CWG column of any given PSR in the kaolin bed increased the average hydraulic conductivity of the geocomposite significantly due to the higher drainage ability of the CWG column. The geocomposite containing a coarse CWG column showed the highest average hydraulic conductivity, followed by that containing a medium or fine CWG column.
- The average  $C_c$ ,  $C_\alpha$  and  $m_v$  values of the geocomposite containing a CWG column of any given PSR decreased compared to that of the kaolin only specimen.
- The kaolin only specimen typically showed the highest settlement and took the longest time to settle compared to all the geocomposites tested.
- The void ratio of the geocomposite containing a CWG column of any given PSR reduced quicker than that of the kaolin only specimen, with the coarse CWG column-kaolin geocomposite showing the maximum reduction in void ratio.

Being among the initial studies of the shear strength and consolidation behaviour of kaolin reinforced with a CWG column, this study is expected to serve as a platform for future research on this topic. This study suggests investigating the effect of particle gradation, angularity, surface roughness, and density of the CWG column on the geocomposite and the effects of groups of CWG columns. This study focused on analysing the peak shear strength of the geocomposites,

so it would be helpful if future studies shed light on the residual shear strength behaviour of the geocomposites. It is also suggested to test the geocomposites for shear strength under more normal stresses and perform repeat tests on the specimens under each normal stress, alongside comparing the geotechnical behaviour of the geocomposites containing a granular column backfilled separately with different PSRs of CWG and prepared at the same placement density to help determine the effective particle size of CWG as a granular column backfill in future studies. Simultaneously, the effect of geosynthetic encasement around CWG columns is proposed to be studied. Large-scale model and field tests should also be carried out to confirm the results of laboratory-scale tests. The effects of CWG on the parameters of other constitutive (e.g., critical state) soil models can be investigated. Moreover, from a broader civil engineering viewpoint, the findings of this study encourage investigating and potentially using CWG as a drainage blanket, backfill in embankments and base or sub-base material in road pavements.

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#### Declarations

**Conflict of interest** The authors have not disclosed any competing interests

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