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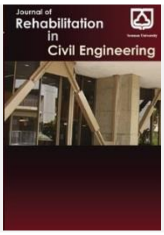

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Enhancing Mechanical Properties of Sands by Using Crushed Waste Glass as Reinforcement

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ABSTRACT

The published researches on the mechanical behaviour of granular soils reinforced with crushed glass particles from recycled glass waste is notably limited compared to studies involving glass powder. The disposal of waste glass presents significant environmental challenges, highlighting the need for innovative recycling solutions. This study investigates the use of crushed waste glass as a reinforcement material for sand to enhance its mechanical properties, offering a sustainable solution in geotechnical engineering. To achieve this goal, a series of direct shear experiments were conducted on three categories of river sand, each with a different mean particle size (D50 = 2.00 mm, 1.00 mm, and 0.63 mm). These sands were mixed with varying amounts of crushed waste glass (CWG = 0, 10, 20, and 30%) and subjected to three various normal stresses: 50, 200, and 400 kPa. The obtained data demonstrated clearly the combined impact of crushed waste glass and mean particle size on the angle of repose, internal friction angle, peak and residual friction angles, as well as the excess and maximum dilatancy angles for the sand-CWG mixtures. The results showed that as the crushed waste glass content (CWG) and mean particle size (D50) increased, the sand-CWG mixtures exhibited higher values of repose and internal friction angles. The study concludes that crushed waste glass can effectively reinforce sand, benefiting both waste recycling and construction material performance. These findings support sustainable civil engineering practices by reducing the environmental impact of waste glass and improving sandy soil performance. Future research should investigate the long-term durability and environmental impacts of using crushed glass in various geotechnical applications.

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1. Introduction

Coarse particle soils, characterized by loose packing, low plasticity, and limited shear strength, pose significant challenges in engineering applications. Addressing these challenges requires innovative approaches to enhance the mechanical properties of such soils. In recent years, researchers have explored the incorporation of various materials and techniques to improve the performance of coarse particle soils. For example, Namaei et al. conducted experimental and Finite Difference Method (FDM) studies to analyze the interaction between geogrid materials and coarse particle soils. Their findings contribute to the understanding of soil reinforcement techniques, elucidating the behavior of geogrid-soil systems under different loading conditions [1]. Kundu et al. examined the dynamic properties of fiber-reinforced sandy soils subjected to high cyclic strains. Their research sheds light on the effectiveness of fiber reinforcement in improving the resilience of coarse particle soils, particularly under dynamic loading scenarios [2]. Heidari Forozabadi et al. explored the utilization of ceramic-industry wastewater for stabilizing sandy subgrades through the deep mixing method and they highlighted the potential of industrial by-products in soil stabilization, offering sustainable solutions for infrastructure development [3]. Additionally, Ghareh et al. investigated the effects of waste rubber tire dimensions on the behavior of fine-grained soils, and they reported a significant insight into the potential of waste rubber tires as soil amendments, contributing to the development of environmentally friendly soil improvement techniques [4].

Nevertheless, the crushed glass can enhance the mechanical and geotechnical properties of soils, including their shear strength, permeability, and compressibility. This practice can also be beneficial for the environment as it allows the use of glass waste, which would otherwise be disposed of in landfills. Furthermore, numerous engineering applications, including the construction of buildings, roads, and bridges, evaluate the mechanical behaviour of soils. Therefore, gaining insight into the effect of crushed waste glass on soil mechanics can have practical implications for these fields [5,6]. Sherwany et al. investigated the impact of waste glass on the properties of problematic soils. Their research provided valuable insights into the potential of waste glass as a soil stabilizer, offering a sustainable solution for enhancing soil characteristics [7]. Kazmi et al. investigated the use of crushed waste glass (CWG) as a sustainable alternative to natural and manufactured sand, finding that CWG exhibits comparable shear strength and hydraulic conductivity properties, making it suitable for geotechnical applications. Additionally, this work has delved into the potential of waste glass in various civil engineering applications, reinforcing the view that waste glass can be a viable and sustainable alternative to traditional materials. This comprehensive review underscores the mechanical benefits and environmental sustainability of integrating waste glass into construction practices [8]. Their review also emphasized the mechanical and environmental advantages of using waste glass in civil engineering projects, noting improvements in compressive strength and a reduction in alkali-silica reaction (ASR) risks Kazmi et al. [9]. Further research by Más-López et al. explored the physical and mechanical characterization of eco-friendly pavements manufactured with glass waste. Their findings indicated significant improvements in unconfined compressive strength (UCS) and California bearing ratio (CBR) when glass waste was used for soil stabilization [10]. Similarly, Arrieta Baldovino et al. demonstrated the effectiveness of recycled-glass powder in soil stabilization, reporting enhanced soil strength and stability without posing environmental risks [11].

In the context of expansive soils, which pose significant challenges due to their volume change characteristics upon wetting and drying, studies have shown promising results for improving their properties using various mixtures. A study on the bearing capacity of footings on an expansive unsaturated bentonite–sand mixture reported improved load-bearing performance and reduced settlement, making this combination a viable option for foundation design in problematic soils Fattah et al. [12]. Another study focused on the behavior and characteristics of compacted expansive unsaturated bentonite-sand mixtures, finding that such mixtures exhibit enhanced mechanical properties and stability, which are critical for construction on expansive soils Fattah et al. [13]. These studies collectively underscore the feasibility and advantages of utilizing waste glass and expansive soil mixtures in geotechnical engineering, paving the way for more sustainable construction practices. By incorporating waste glass and optimizing expansive soil mixtures into construction materials, it is possible to achieve not only environmental sustainability but also improved performance and durability of geotechnical structures. Additionally, the geotechnical characteristics of a pure soil and combinations of this soil with glass powder were tested in a series of experiments by Zaid and Al-Hassnawi [14]. Their results showed the stress-strain relationship of the soil mixed with glass powder and dried for 3 days under specific humidity conditions. Additionally, they discovered that the percentage of glass powder in all samples rose with increasing compressive strength. Javed and Chakraborty investigated the influence of waste glass powder on soil enhancement. To do so, they performed a series of unconfined compression tests to obtain the initial properties of the soil and glass powder used. They found that increasing the proportion of glass powder added to the soil improved its unconfined compressive strength by up to 8%, and then decreased with the inclusion of 10% glass powder. This increase in UCS is explained by the presence of lime in the glass powder which acts as a binder for clays after hydration and improves bonding [15]. On the other hand, the decline in unconfined compressive strength after 10% glass powder addition might be attributed to a decrease in soil cohesion. Blayia et al. demonstrated that the addition of WGP improves the strength of expansive soils. Their study focused on mixtures of clay with waste glass powder, and they showed the relationship between internal friction angle (φ) and the inclusion of WGP to the expansive soil. They also investigated the relation between cohesion and the quantity of waste glass powder added in the expansive soil [16] [16]. Cabalar and Demir focused on the geotechnical properties of bentonite that had been treated with waste glass granules [17]. Two different sizes of glass waste were used in the experimental studies, namely fine waste glass (FWG) and coarse waste glass (CWG), in addition to bentonite clay samples. They showed that samples with coarse glass waste gave a higher maximum dry density (γd_{max}) and lower optimum moisture content (w_{opt}) values than those with fine glass waste. For example, for a 30% quantity of fine glass waste, the values of γd_{max} and w_{opt} were 14.24 kN/m^3 and 18.58%, respectively, while for a 30% quantity of coarse glass waste, the values of γd_{max} and w_{opt} were 14.94 kN/m^3 and 17.88%, respectively. This difference is explained by the fact that the quantity of clay particles that filled the voids in the samples with coarse glass waste was higher than in the samples with fine glass waste. Mohammad Ali et al. evaluated the impact of different amounts of recycled glass powder on the UCS of a geopolymer-stabilized soil over a period of 7 days [18]. They indicated that the unconfined compressive strength increased linearly up to an optimum value of 15% recycled glass powder, beyond which the strength began to decrease. This observation suggested that an increased concentration of glass powder results in excess material that did not react with the activating ingredient and remained in the sample. Since WGP consists of very fine particles with low adhesion, the addition of an increased amount of this material to the soil will reduce its strength.

On the other hand, the literature review revealed that various parameters can influence the shearing response, specifically the friction angle of the granular materials during evaluation. Notably, experimental studies published in the literature indicated that particle size and shape are particularly significant factors [19–26].Yang and Wei reported that adding fines with rounded particle shapes to host sands reduced the peak friction angle [27]. Furthermore, Xiao et al. discovered that the fines content of medium dense sands had an appropriate influence on the excess and maximum friction angle [28]. Additionally, Deng et al. studied the impact of particle size on the friction angles of sands. They discovered that as the particle size improved, the peak friction and peak dilation angles reduced due to the buckling of particle columns influenced by the slenderness of the grain column [29]. Azaiez et al. found that particle size was significant in studying the stress-dilatancy relationship, especially the friction angle of sand-fly ash mixtures [30]. Cherif Taiba et al. discovered links between natural sand critical state variables and particle morphological features, including overall regularity (OR), gradation, and packing density [31]. They found that these properties were related to the critical state parameters of the studied sandy soils. Meanwhile, Wang et al. examined the influence of particle size on the shear characteristics of soil under large-displacement and heat treatment conditions. Their findings proved that the particle size distribution significantly influenced the shearing resistance of soils, with smaller particle sizes resulting in greater residual shear strength [32]. Finally, Taibi et al. observed that the particle shape and fly ash content significantly impacted the excess and maximum friction angles of coarse-grained soils [33].

Besides, the published literature on the mechanical behaviour of granular soils reinforced with crushed glass particles from recycled glass waste is remarkably limited comparing to studies involving glass powder. Moreover, very limited numbers of publications in the literature have examined the effect of CWG on the mechanical behavior of sandy soils in terms of shear strength properties such as peak and residual friction angles, as well as dilatancy response characterized by the maximum dilatancy angle. Additionally, prior researches have not investigated the correlation between the peak friction angle, excess friction angle, and maximum dilatancy angle of sand admixture with the crushed waste glass. To investigate the impact of CWG proportions on the stress-dilatancy relation coarse soils, numerous direct shear tests were conducted on three types of granular materials derived from natural river sand "mean particle size" with D_{50}=0.63 mm, 1.00 mm, and 2.00 mm. crushed waste glass fractions (CWG=0, 10, 20, and 30%) were mixed with the sand samples using the dry pluviation method, resulting in an initial relative density of D_r=90%. After that, the samples were exposed to three normal stresses (σ_n=50, 200, and 400 kPa). This study also presents the validity of Bolton's stress-dilatancy relations for sand mixed with crushed waste glass content.

2. Materials

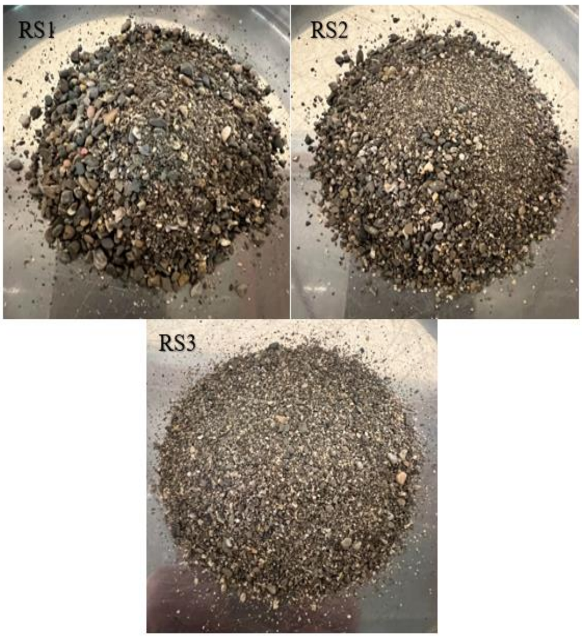
2.1. Sand

This study utilized three categories of river sand with different gradations to examine the impact of particle size properties. The categories included river sand (RS) and three variations with specific particle sizes: RS1 (D_{50}=2.00mm), RS2 (D_{50}=1.00mm), and RS3 (D_{50}=0.63mm). Figure 1 represents the distribution curves for each grain size calculated by ASTM International: D6913 [34]. Figure 2 illustrates the categorization of the tested materials. Table 1 provides the physical properties of the sands. Based on the Unified Soil Classification System (USCS), this soil is classified as poorly graded sand (SP).

2.2. Crushed waste glass

The waste glass (WG) employed in this study came from a broken window from a demolished building. It was initially obtained in a broken form and subsequently pulverized and sieved using a 4.00 mm diameter sieve. Figure 1(a) illustrates the various categories of river sand, while Figure 1(b) depicts the crushed waste glass utilized in the current study. Figure 2 illustrates the gradation curve of glass waste. The physical characteristics of the adopted materials are shown in Table 1.

Table 2 presents the chemical compositions of the crushed waste glass used in this investigation. Figure 3 presents the flowchart illustrating the process of the methodology used in this study.



(a)

(b)

Fig. 1. Granular materials evaluated in this study: **a-** River sand category, **b-** Crushed waste glass.

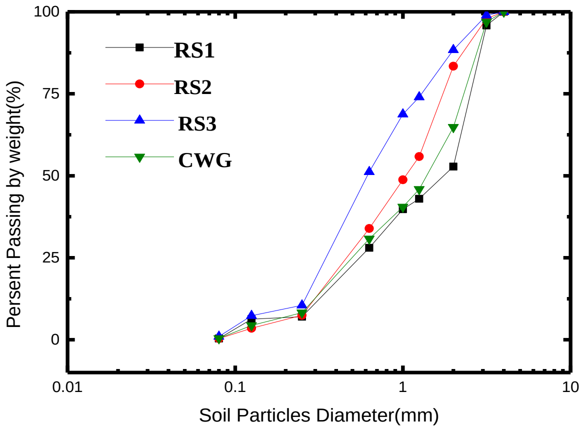


Fig. 2. River sand categories-crushed waste glass mixtures particle size distribution curves.

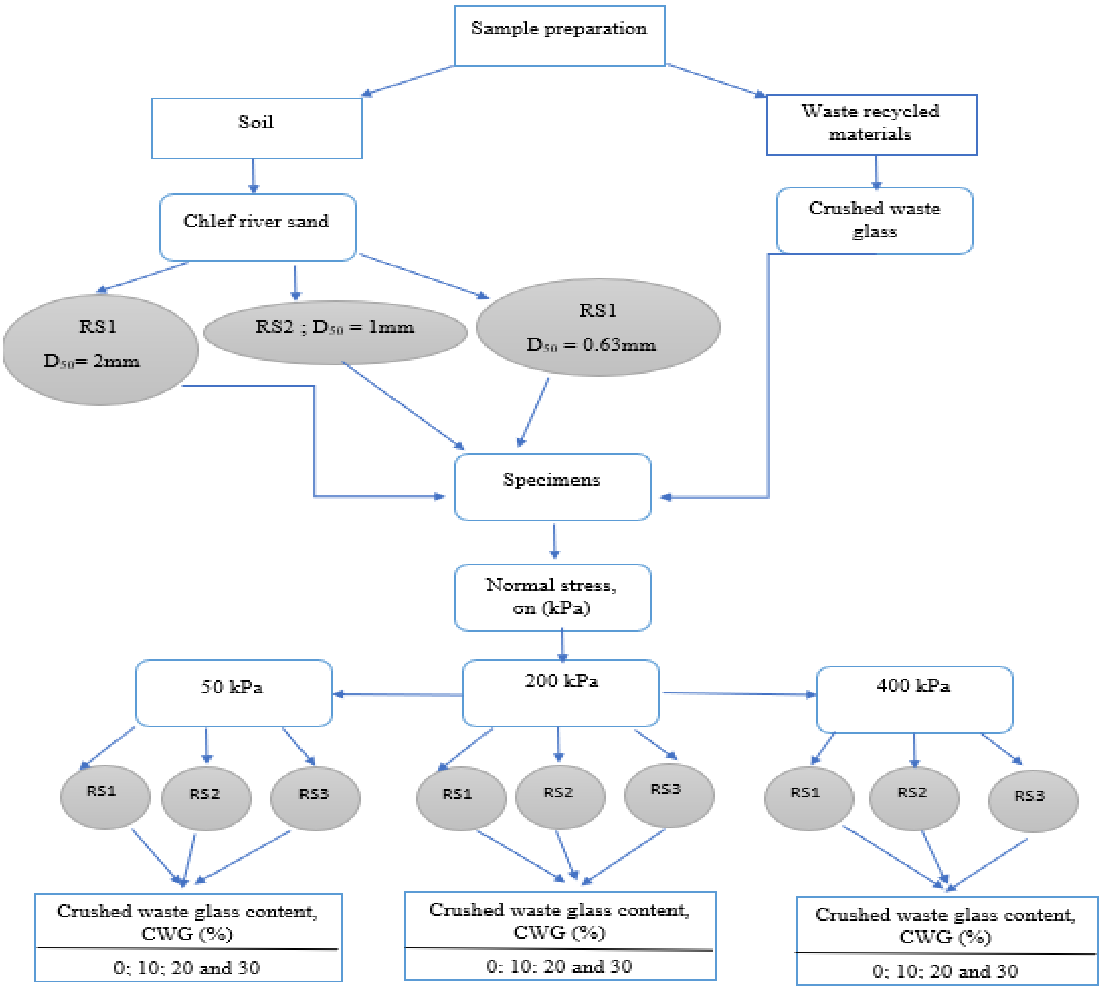


Fig. 3. Flowchart presenting the process of the methodology.

Table 1. Index properties of tested materials.

Granular material	Specific gravity, Gs	Mean particle size, D_{50}(mm)	Maximum void ratio, e_{max}	Minimum void ratio, e_{min}
RS1	2.65	2	0.657	0.407
RS2	2.65	1	0.725	0.45
RS3	2.65	0.63	0.751	0.457
Crushed waste glass	2.53	1.413	0.806	0.405

Table 2. Chemical composition of crushed waste glass.

Chemical Composition (%)	Sio_2	Al_2O_3	Fe_2O_3	CaO	MgO	So_3	K_2O	Na_2O	Cl	LoI
CWG	73.77	1.9	0.031	8.87	2.1	0.78	0.281	11.5	0.128	0.21

3. Laboratory testing program

3.1. Angle of repose tests

The angle of repose is a crucial factor in civil engineering, determining the steepest inclination at which a granular substance can be stacked without experiencing structural failure. This concept holds significant importance as it directly impacts the stability and safety of various constructions, such as dams, embankments, retaining walls, and slopes [35]. Literature encompasses multiple testing methodologies for quantifying the angle of repose (ϕ_{rep}) of granular materials. Extensive research indicates that the flowability of these materials is influenced by various factors, including particle shape, particle size, specific gravity, and moisture levels [36,37]. In the study conducted by Beakawi Al-Hashemi [38], the funnel technique was used to evaluate the effect of particle size parameters on (ϕ_{rep}) under free packing or free surface flow conditions. The experimental setup is depicted in Figure 4. In this setup, a granular material is poured into a funnel with an opening diameter of 13 mm. The material is allowed to descend under the influence of gravity from a height (H) of 40 mm until the maximum of the heap covers the funnel's discharge point. Subsequently, the angle of repose for a fixed heap height is calculated using the following definition (Equation 1):

$$\phi_{rep} = \tan^{-1} (2H/DZ) \quad (1)$$

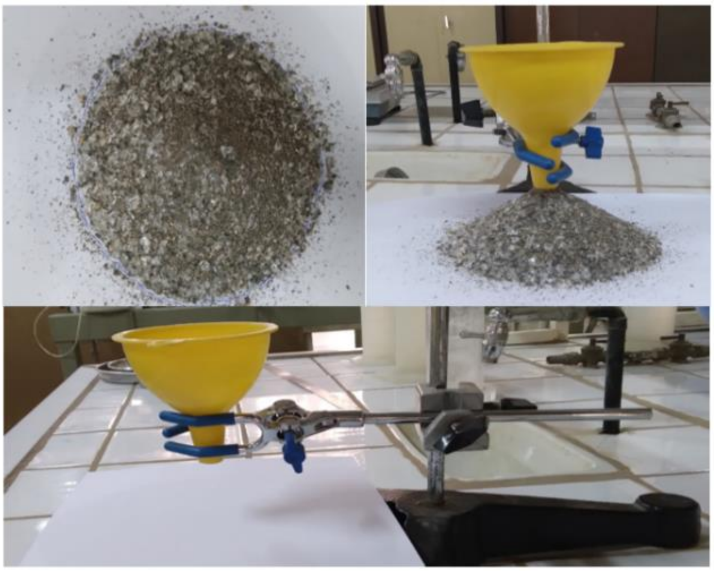


Fig. 4. Repose angle test of river sand-CWG mixtures.

3.2. Direct shear tests

Following the recommendations of NF P94-071-1 (1994) [39], a series of direct shear tests were performed on three types of dry river sand samples mixed with crushed waste glass contents (CWG = 0, 10, 20 and 30%). The samples of the sand-CWG combination were made to have an initial relative density of 90% (D_r). The direct shear device utilized in the test contained a metal loading cap on top that was subjected to standard force, as well as porous stones at the top and bottom to facilitate drainage (Figure 5). The specimens and rings were put in a tank, which was positioned on rollers, and the tank's exterior was subjected to shearing force. In order to reach the required initial dense state, the mixture samples were separated into three portions, rammered into a compacted form, and then put in a 60mm x 60mm x 25mm box. Then, three standard stresses (σ_n = 50, 200 and 400 kPa) in the shape of square plates were applied to the binary mixes. The data was gathered utilizing acquisition apparatus linked to a computer during the direct shear testing at a constant rate of 1 mm/min. Equation (2) was used to determine the mass of the samples, accounting for the relative density, target void ratio, maximum and minimum global void ratios, solid grain unit weight, total volume, and maximum and minimal global void ratios. The equation is formulated as follows:

$$\mathrm{ms} = (\mathrm{VT} \times \text{-}\gamma\mathrm{s}) / [1 + \mathrm{emax} \times (1 - \mathrm{Dr}) + \mathrm{Dr} \times \mathrm{emin}] \quad (2)$$

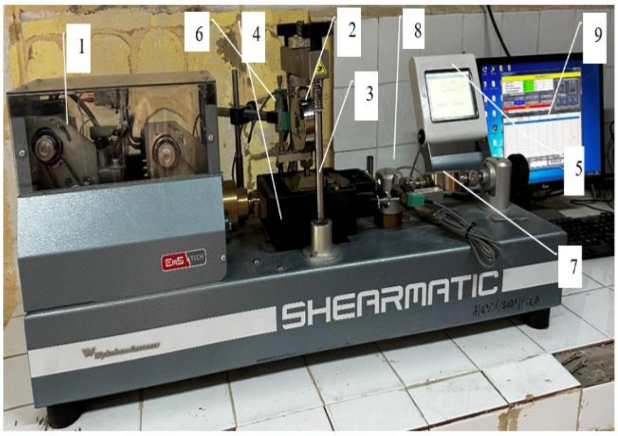


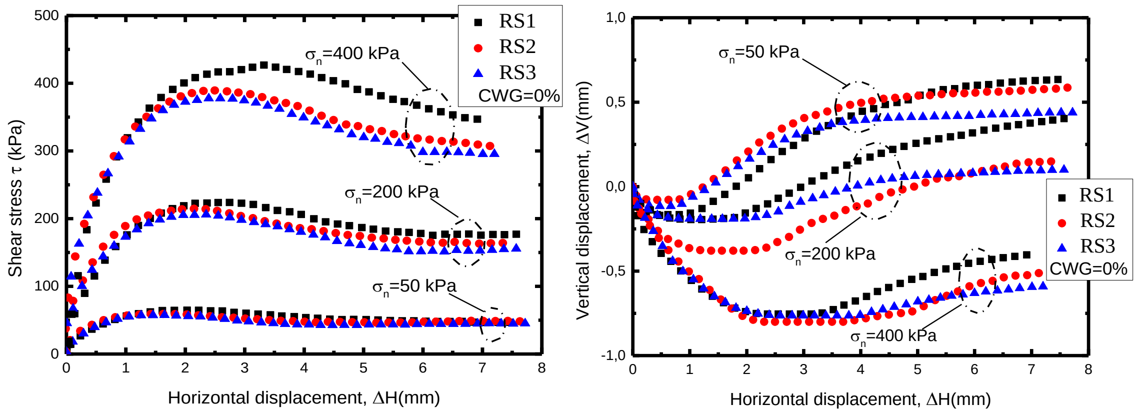
Fig. 5. Direct shear apparatus and the acquisition system used in the study.

Where;
1. Electro-mechanical servo-actutation
2. 10 kN vertical load cell
3. Shear box (not included, to be ordered separately)
4. Carriage
5. Touch screen display
6. 10 mm vertical displacement transducer
7. 10 kN horizontal load cell
8. 25 mm horizontal displacement transducer
9. Acquisition equipment

4. Results and discussion

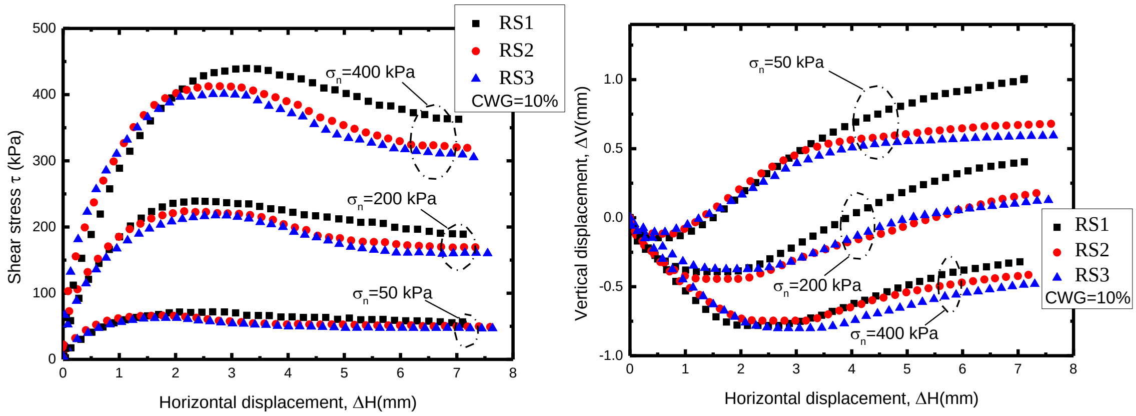
4.1. Experimental direct shear test results

In 36 direct shear tests conducted on poorly graded sands mixed with varying proportions of crushed waste glass content (CWG = 0, 10, 20, and 30%), Figures 6, 7, 8, and 9 illustrate the observed behaviors. The results demonstrate that the mixtures of dense sand and CWG predominantly exhibit dilative responses in the vertical displacement (ΔV) versus horizontal displacement (ΔH) plane, irrespective of the fraction of CWG. These findings highlight the dominance of volume change response in mobilizing peak shear strengths in the τ versus ΔH plane. The Figures clearly demonstrate that the poorly graded sand RS1 (D_{50}=2.00 mm) mixed with crushed waste glass (CWG) content exhibits higher peak shear strength and dilation compared to RS2 (D_{50}=1.00 mm)-CWG mixtures and RS3 (D_{50}=0.63 mm)-CWG mixtures. This confirms the crucial role of (D_{50}) in enhancing the peak shear strength and dilation of natural poorly graded sands, considering a specific percentage of crushed waste glass. Furthermore, expanding the normal stress (σn) from 50 kPa to 400 kPa (Figures 6a, 7a, 8a, 9a) resulted in the attainment of peak shear strengths at larger horizontal displacements. It intensified initial contraction (Figures 6b, 7b, 8b, 9b). Furthermore, when evaluating a specified crushed waste glass (CWG) content, the natural sand-CWG binary mixtures subjected to an initial normal stress of 400 kPa exhibit significantly higher peak shear strengths compared to the poorly graded sand admixtures with CWG proportions sheared under 200 and 50 kPa, respectively. In addition, Figures (10, 11, 12) present the shear stress vs horizontal displacement of the three categories of natural river sands integrating the crushed waste glass effects. Moreover, as depicted in Figures 10, 11, and 12, including of crushed waste glass has beneficial effects on the frictional resistance of the natural sands. With improved CWG content from 0% to 30%, the maximum shear strength is enhanced for a given initial normal stress. The contribution of crushed waste glass particles to enhancing the interparticle interactions between the poorly graded sands can be attributed to these results, consequently, amplifying the peak shear strengths of the examined soils. Furthermore, a rapid transition from peak to residual shear strength occurs in the post-peak softening regime, specifically within horizontal displacement ranges of approximately 4 to 7 mm (as depicted in Figures 10a, 11a and 12a). These findings align with the results reported by Disfani et al. [40,41].



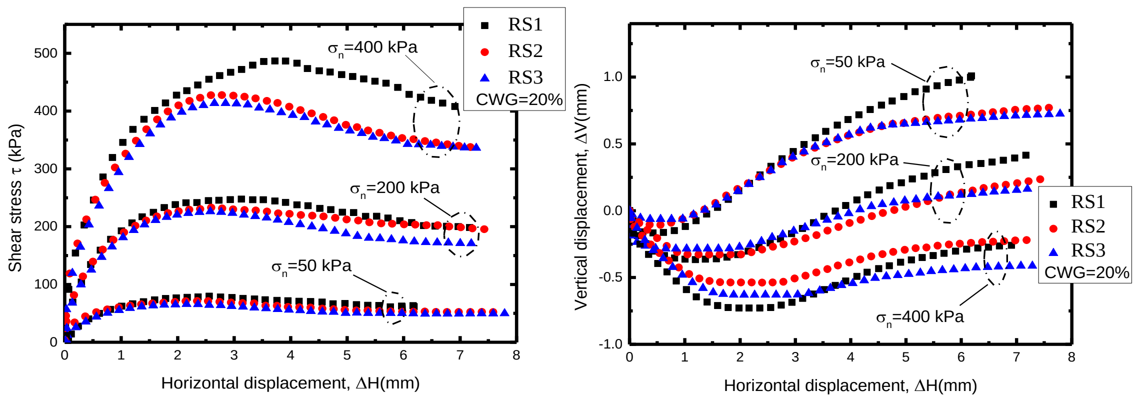
(a) (b)

Fig. 6. Mean particle size effects on shear stress variation of the mixtures (CWG=0%); a- τ versus ΔH, b- ΔV versus ΔH.



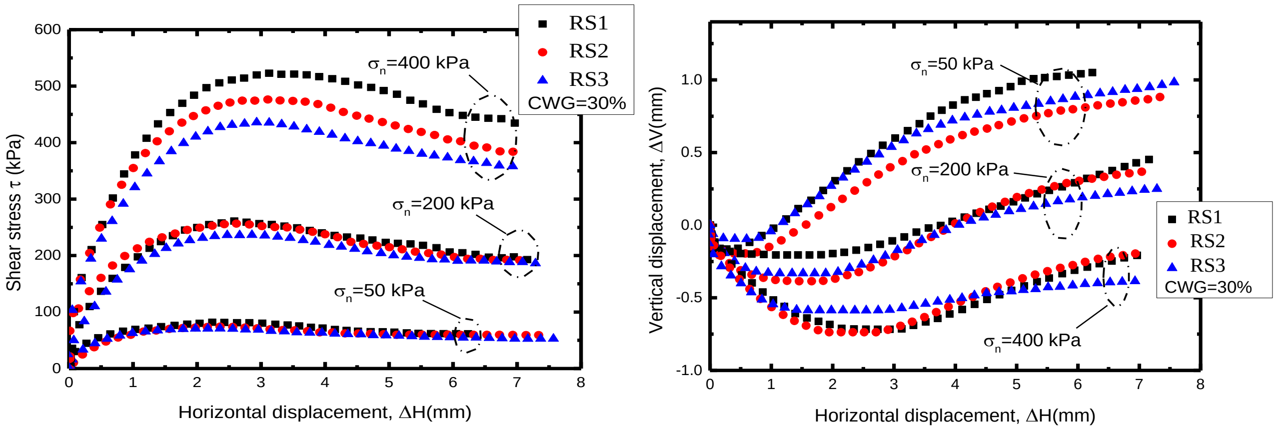
(a) (b)

Fig. 7. Mean particle size effects on shear stress variation of the mixtures (CWG=10%); a- τ versus ΔH, b- ΔV versus ΔH.



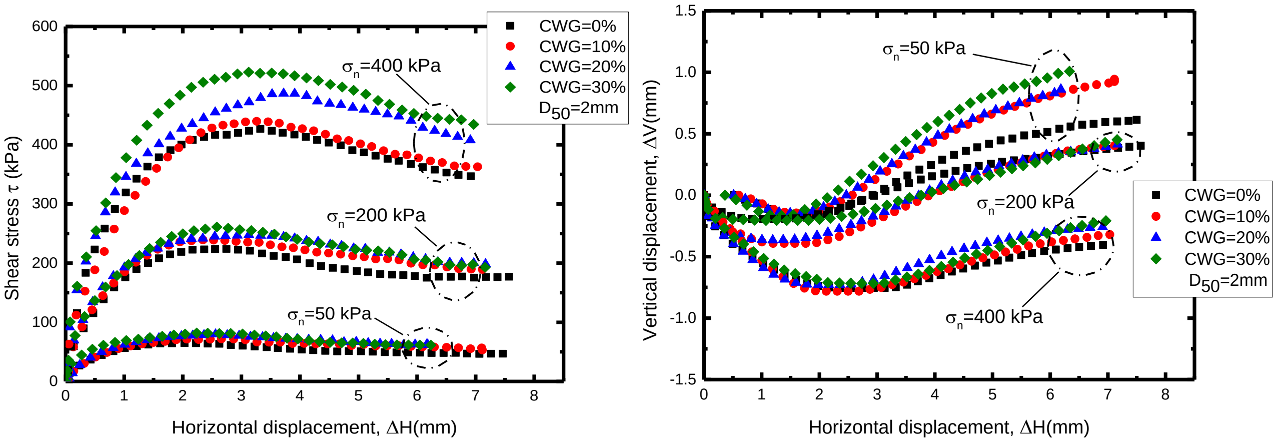
(a) (b)

Fig. 8. Mean particle size effects on shear stress variation of the mixtures (CWG=20%); a- τ versus ΔH, b- ΔV versus ΔH.



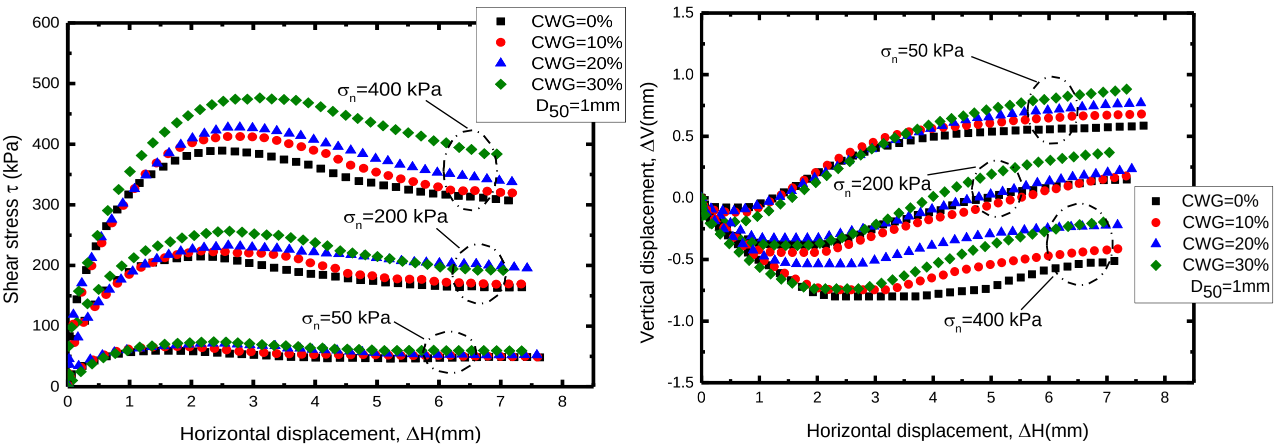
(a) (b)

Fig. 9. Mean particle size effects on shear stress variation of the mixtures (CWG=30%); a- τ versus ΔH, b- ΔV versus ΔH.



(a) (b)

Fig. 10. Crushed waste glass effects on shear stress variation of the tested materials (D_{50}=2.00mm); a- τ versus ΔH, b- ΔV versus ΔH.



(a) (b)

Fig. 11. Crushed waste glass effects on shear stress variation of the tested materials (D_{50}=1.00mm); a- τ versus ΔH, b- ΔV versus ΔH.

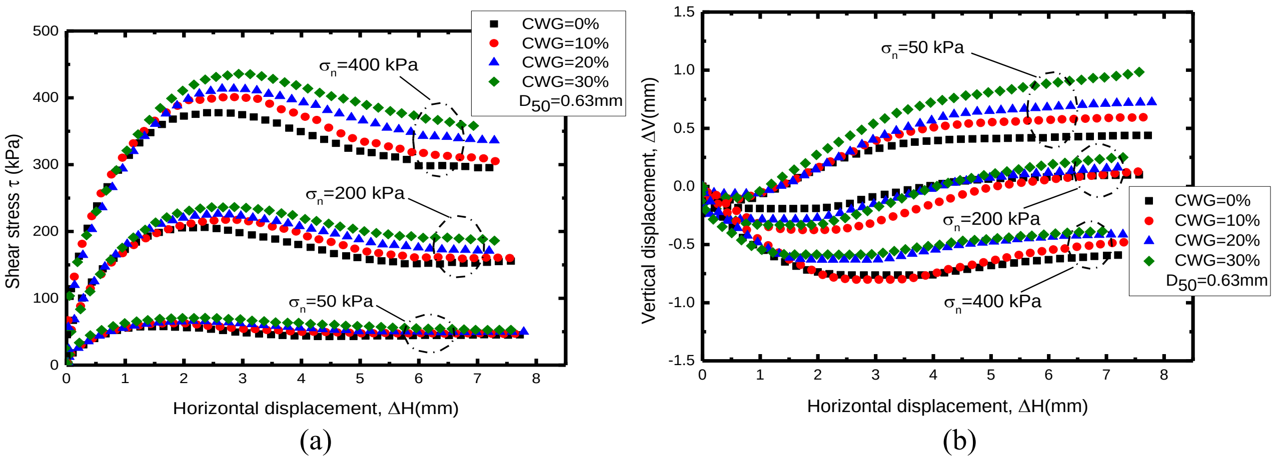


Fig. 12. Crushed waste glass effects on shear stress variation of the tested materials (D_{50}=0.63mm); a- τ versus ΔH, b- ΔV versus ΔH.

4.2. Internal friction angle and angle of repose

Figure 13 represents the relation between the internal friction angle and two factors: mean particle size and crushed waste glass content, which is illustrated. The results demonstrate that as (D_{50}) and the crushed waste glass percentages increase, the internal friction angle also increases for both pure sands and mixtures. This indicates that both mean particle size and crushed waste glass content significantly influence the enhancement of frictional resistance, specifically in terms of the internal friction angle, in natural sand-CWG mixtures. This phenomenon is caused by the interlocking of crushed waste glass particles with sand particles, resulting in a notable improve in the internal friction angle of the tested materials. The presence of crushed waste glass particles enhances the interlocking mechanism among the sand particles, contributing to the dilation response in the mixtures due to their lower deformability characteristics. Consequently, the contacts involving a harder element, such as the crushed waste glass particles, act as a substantial source of dilatancy. Furthermore, it is worth noting that for D_{50}=2.00 mm, an increase in crushed waste glass content of up to 30% leads to a higher internal friction angle (Figure 13b). This means that combinations having larger sand particles and a higher proportion of crushed waste glass display greater internal friction angles than mixtures containing smaller sand particles and a lower proportion of CWG.

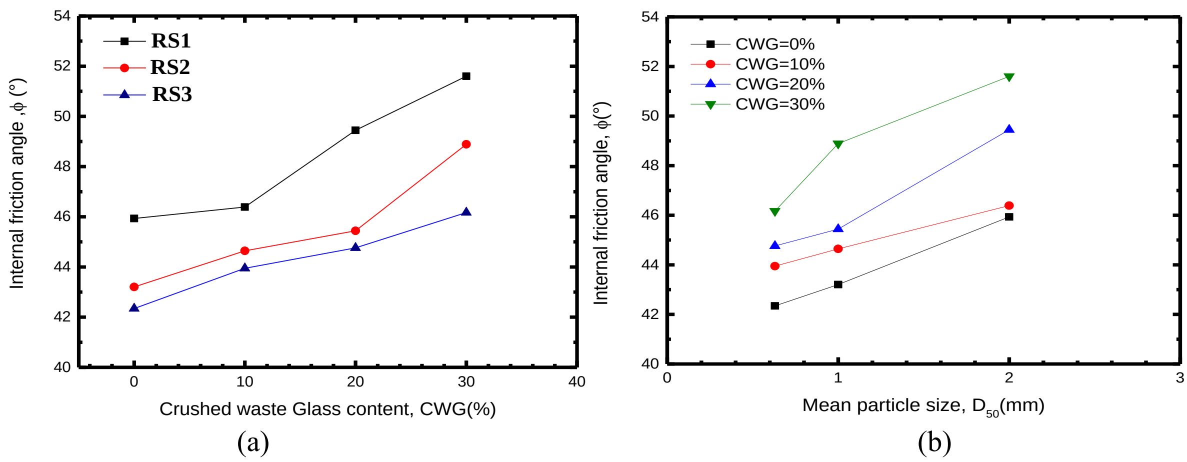


Fig. 13. Internal friction angle of the tested materials varies: a- internal friction angle versus D_{50}, b- internal friction angle versus CWG content.

Overall, Figure 14 illustrates the relation between variations in the angle of repose and two factors: (D_{50}) and (CWG) content. The figure clearly shows that the angle of repose enhanced as both the mean particle size (D_{50}) (Figure 14a) and crushed waste glass content (Figure 14b) increase for the tested soils. This observation confirms that the mean particle size is important for enhancing the angle of repose in natural sand-CWG mixtures. It is worth noting that the presence of sand particles' edges facilitates the rotation of particles during surface flow, leading to improvement in ϕ_{rep} as the mean particle size increases. Consequently, mixtures containing larger river sand particles (D_{50}=2.00 mm) and CWG exhibit a higher angle of repose values compared to mixtures containing smaller river sand particles (D_{50}=0.63 mm) and CWG, as shown in Figure 14a. Furthermore, the rise in the angle of repose with the addition of crushed waste glass (CWG) in the tested materials can be attributed to the type of particle contacts and the resulting improvement in interparticle friction angle. The interparticle friction angle is directly linked to the constant volume friction angle and varies depending on the granular material characteristics. In this case, the contacts between sand and CWG particles possess higher frictional strength compared to sand-sand contacts. This increased frictional strength is responsible for the observed enhancement as the amount of crushed waste glass contacts increases. This is verified by Figure 14b, which shows that combinations of poorly graded sand and CWG (30% content) have better angle of repose values than pure sand.

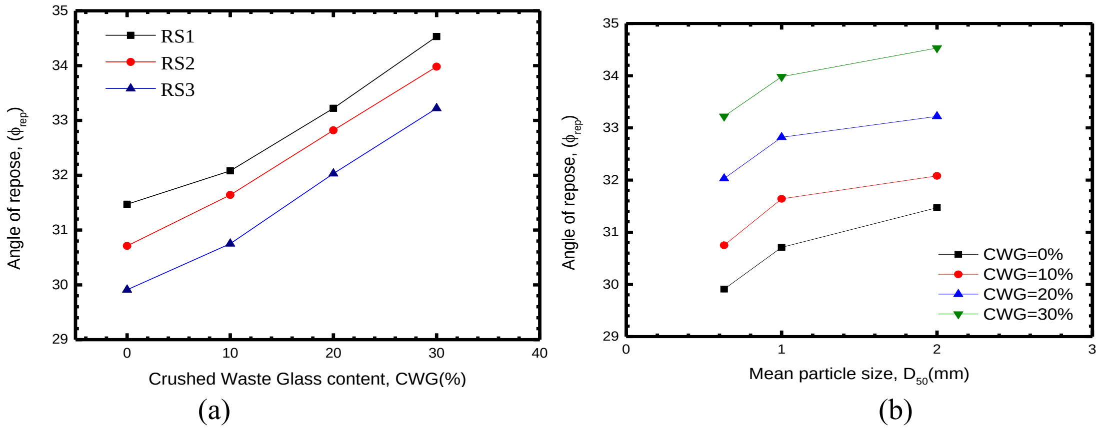


Fig. 14. Variation of angle of repose of the tested materials: a- ϕ_{rep} vs D_{50} b- ϕ_{rep} vs CWG content.

4.3. Peak and residual friction angles

In the realm of soil engineering, the peak and residual friction angles hold a pivotal role as fundamental properties. As V. Fioravante. point out, these angles are not just numbers but crucial elements in strength calculations [42]. Any modifications in these properties can wield a significant influence on the overall strength. The peak and residual friction angles (ϕ_{peak}, ϕ_{res}) are not arbitrary values but are precisely defined and determined through a specific calculation method [43–45]as:

$$\phi_{\text{peak}} = \tan^{-1}\left(\frac{\tau_p}{\sigma_n}\right) \tag{3}$$

$$and\ \phi_{res} = tan^{-1}\left(\frac{\tau_{res}}{\sigma_n}\right) \tag{4}$$

Where $\tau_{peak:}$ is the peak shear stress, τ_{res}: is the residual shear stress and σn is the applied normal stress. The interaction between the peak friction angle and the mean particle size and crushed waste glass content is illustrated in Figure 15. The relationship is examined for three different normal stresses (50, 200 and 400 kPa). The 3D plots clearly indicate that as the percentage of crushed waste glass increases from 0% to 30%, the peak friction angle also increases. This observation is consistent across all three plots (Figures 15a, 15b, and 15c). Additionally, the findings indicate that as the mean particle size grows, the maximum friction angle tends to rise. As a result, the maximum friction angle value is attained at a larger mean particle size of (D_{50} =2.00 mm). Specifically, when sand particles with a mean particle size of 2.00 mm are mixed with 30% crushed waste glass content, the peak friction angles are estimated to be ϕ_{peak}=58.609°, ϕ_{peak}=52.543°, and ϕ_{peak}=52.578° for the initial normal stresses of 50, 200, and 400 kPa, respectively. These values indicate a higher maximum friction angle for mixtures of larger sand particles with higher crushed waste glass content (30%).

Moreover, the relationship between ϕ_{peak} and D_{50}, as well as the crushed waste glass content, is not just a statistical correlation but a result strongly supported by the fitting surfaces obtained from the examined mixture samples. The fitting parameters exhibit high values, with R^2 coefficients of 0.97, 0.98, and 0.99 for the tested soils. This robust correlation between the peak friction angle and these factors can be attributed to a combination of factors, including the texture of the sand, the properties of the crushed waste glass, and the initial dense samples that were subjected to normal stress. These factors, when combined, play a crucial role in reducing void ratios inside soil assemblies, thereby leading to an increase in peak friction angles.

On the other hand, Figure 16 presents the relationship between the residual friction angle (ϕ_{res}) and both the (D_{50}) and (CWG) fractions. The figure clearly demonstrates that both D_{50} and CWG percentages have noticeable impacts on the residual friction angle of the studied mixtures. Specifically, when the CWG content increases from 0% to 30% at a constant mean particle size, the studied soils' residual friction angle is seen to have significantly increased. The CWG particles fill the spaces between the river sand particles, increasing the density of the mixture and explaining the observed trend. As a result, the frictional surfaces become more substantial, leading to a higher residual friction angle. Additionally, the relationship between the residual friction angle and both the D_{50} and CWG content is well-established based on the fitting surfaces derived for the analyzed mixture samples. The fitting parameters demonstrate strong agreement, as evidenced by high R^2 coefficients of 0.91, 0.92, and 0.98 for the tested soils.

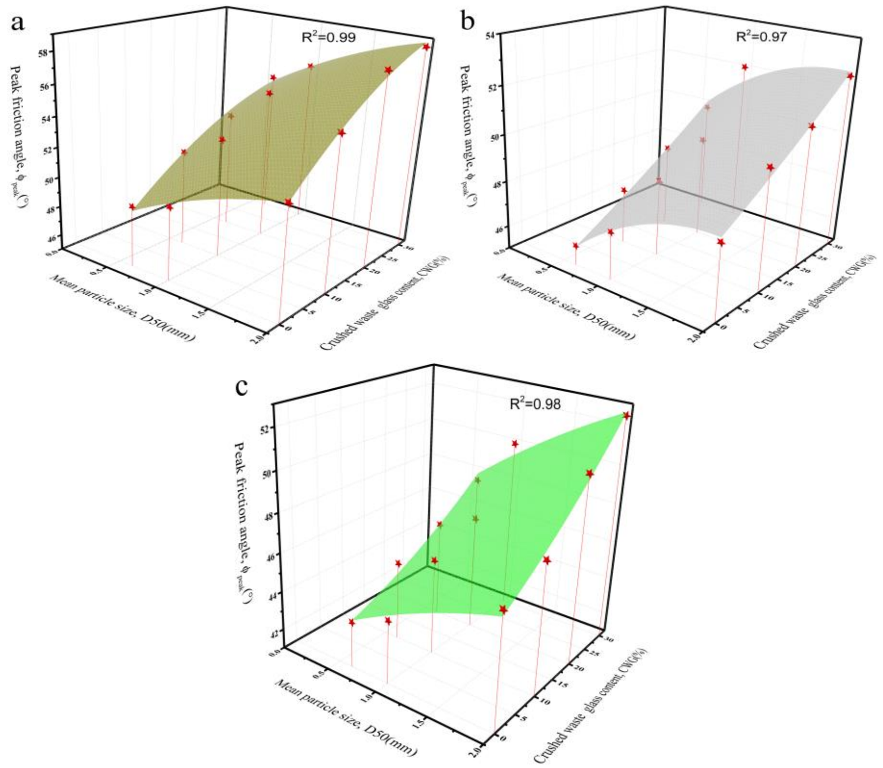


Fig. 15. Peak friction angle vs mean particle size and CWG content of the soils tested: **a** σ_n = 50 kPa, **b** σ_n = 200 kPa, **c** σ_n = 400 kPa.

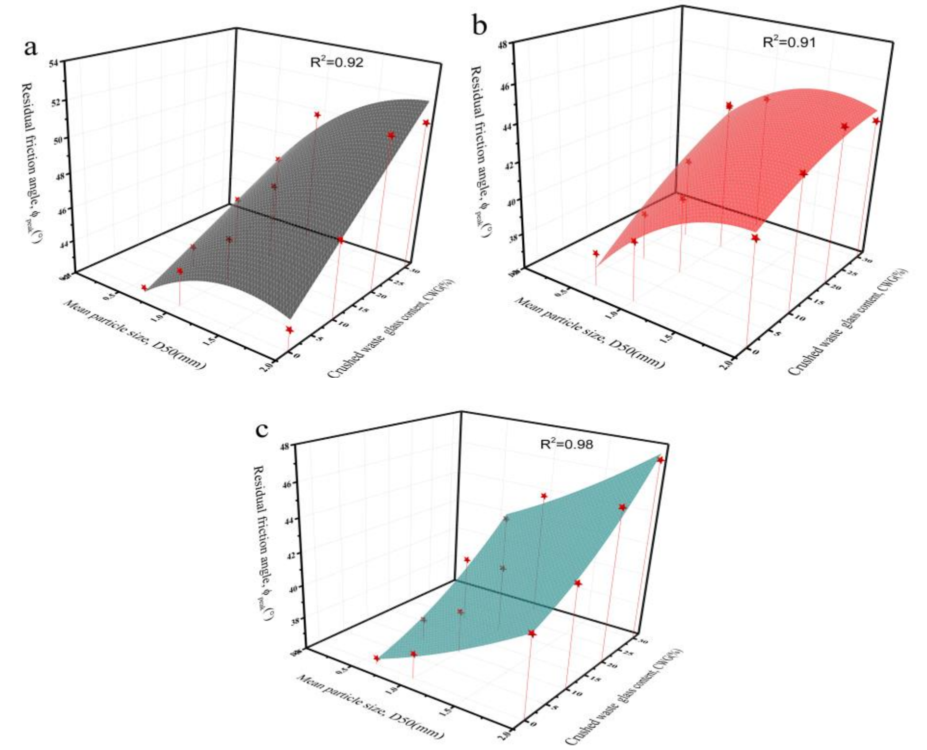


Fig. 16. Residual friction angle versus the mean particle size and the CWG content of the tested soils: **a** σ_n = 50 kPa, **b** σ_n = 200 kPa, **c** σ_n = 400 kPa.

4.4. Stress-dilation law

Numerous studies documented in the published literature have highlighted the potential expression of soil dilation through the utilization of the stress-dilatancy law. This law involves evaluating the correlation between the excess friction angle and the maximum dilatancy angle of granular materials as: $\phi ex = \alpha \times \Psi max$ (5)

Where (ϕ_{ex}) is the excess friction angle, α: is Bolton's dilatancy index and ψ_{max}: is the maximum dilatancy angle. In Figure 17, the relationship between (ϕ_{ex}) and maximum (ψ_{max}) is illustrated for three types of sand with various mean particle sizes such as D_{50} = 4.00 mm, 2.00 mm, and 0.63 mm. These sands were mixed with a proportion of waste crushed glass that varied from CWG = 0% to CWG = 30%. The figure reveals that the percentage of crushed waste glass has a considerable influence on the correlation between the excess friction angle and the maximum dilatancy angle of the materials under investigation. Specifically, it is observed that the excess friction angle shows a linear increase with the rising maximum dilatancy angle for both tested sand assemblies. As well, the values of Bolton's dilatancy index (α=0.96, 1.13, 0.46 for the first category (D_{50}=2.00mm), (α=1.31, 0.83, 0.47 for the second category (D_{50}= 1.00mm) and (α=1.23, 1.47 and 0.45 for the third category (D_{50}= 0.63mm) considering three normal stresses (50 kPa, 200 kPa and 400 kPa) respectively. Moreover, Figure 18 depicts the correlation between the dilatancy index (α) and the mean particle size (D_{50}) for various sand -CWG mixtures under three different normal stresses: 50, 200, and 400 kPa. According to the power function between them, the results show that the Bolton dilatancy index is very well associated with the mean particle size for the examined materials. Equation 5 may be used to express the relation between these two parameters:

$$\alpha = \alpha_0 \times {D_{50}}^{b} \tag{6}$$

Remarkably, the study revealed interesting values for the parameters α_0 and b. For the sand CWG mixtures subjected under normal stress (50 kPa), α_0 is determined to be 1.18, while b is found to be 0.23 Conversely, for the sand-CWG mixtures subjected under normal stress (200 kPa), α_0 is determined to be 1.13, and b is found to be 0.23 and for the sand-CWG mixtures subjected under normal stress (400 kPa), α_0 is determined to be 0.56, and b is found to be 0.6 By substituting equation (6) into equation (5), we obtain general strength-dilatancy relationships that take into account the effect of the (D_{50})for three types of sand-CWG mixtures under study. These regression equations can be used to characterize the relationship between the tested soils' excess friction angle and maximum friction angle. They may also be used to assess the stress-dilatancy correlations of sand mixed with crushed glass waste content.

$$\phi_{ex} = \left(\alpha_0 \times {D_{50}}^{b}\right) \times \psi_{max} \tag{7}$$

For the normal stress of 50 kPa

$$\phi_{ex} = \left(1.18 \times {D_{50}}^{0.23}\right) \times \psi_{max} \tag{7a}$$

For the normal stress of 200 kPa

$$\phi_{ex} = \left(1.13 \times {D_{50}}^{0.18}\right) \times \psi_{max} \tag{7b}$$

For the normal stress of 400 kPa

$$\phi_{ex} = \left(0.56 \times {D_{50}}^{0.6}\right) \times \psi_{max} \tag{7c}$$

Figure 19 demonstrates a comparison of the measured test data of the materials being tested with the excess friction angle predictions provided by Eqs (7a, 7b, 7c). Figure 19 shows that the suggested equations have the ability of effectively estimating the excess friction angles (ϕ_{ex}) for the three different mean particle sizes considered (D_{50}=2.00 mm, 1.00 mm, and 0.63 mm) under various crushed waste glass (CWG) contents and normal stresses. Furthermore, in Figure 19c, Eq (7c) yields significantly better estimates for the normal stress of 400 kPa. with R^2 values of 0.97 and 0.98, compared to Eqs (7a and 7b) in Figure 19a and 19b. This further supports the applicability of Bolton's stress-dilatancy relation to mixtures of sand with varying particle sizes and crushed waste glass content.

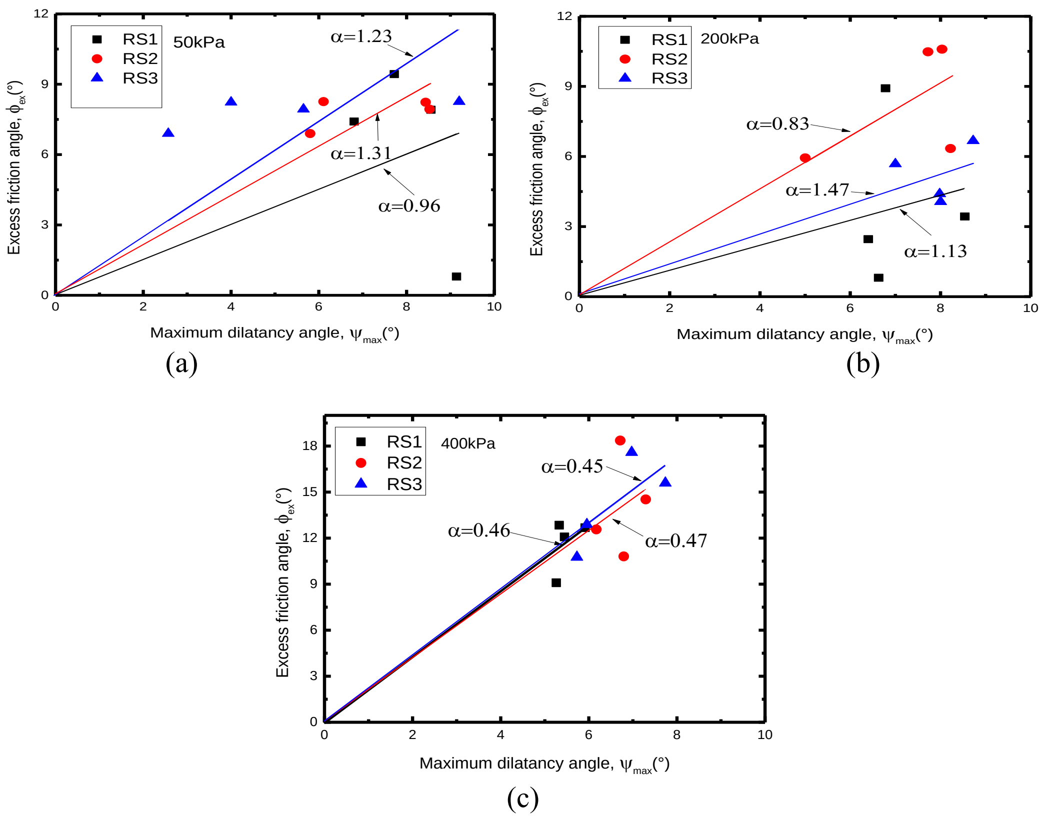


Fig. 17. Maximum dilatancy angle vs the excess friction angle of the studied soils; **a-** σ_n = 50 kPa, **b-** σ_n = 200 kPa, **c** -σ_n = 400 kPa.

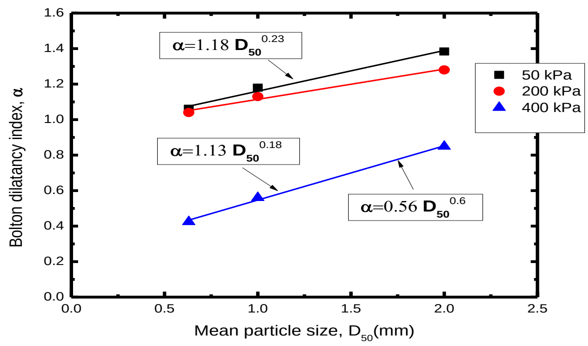


Fig. 18. Bolton dilatancy index versus mean particle size of the tested soils.

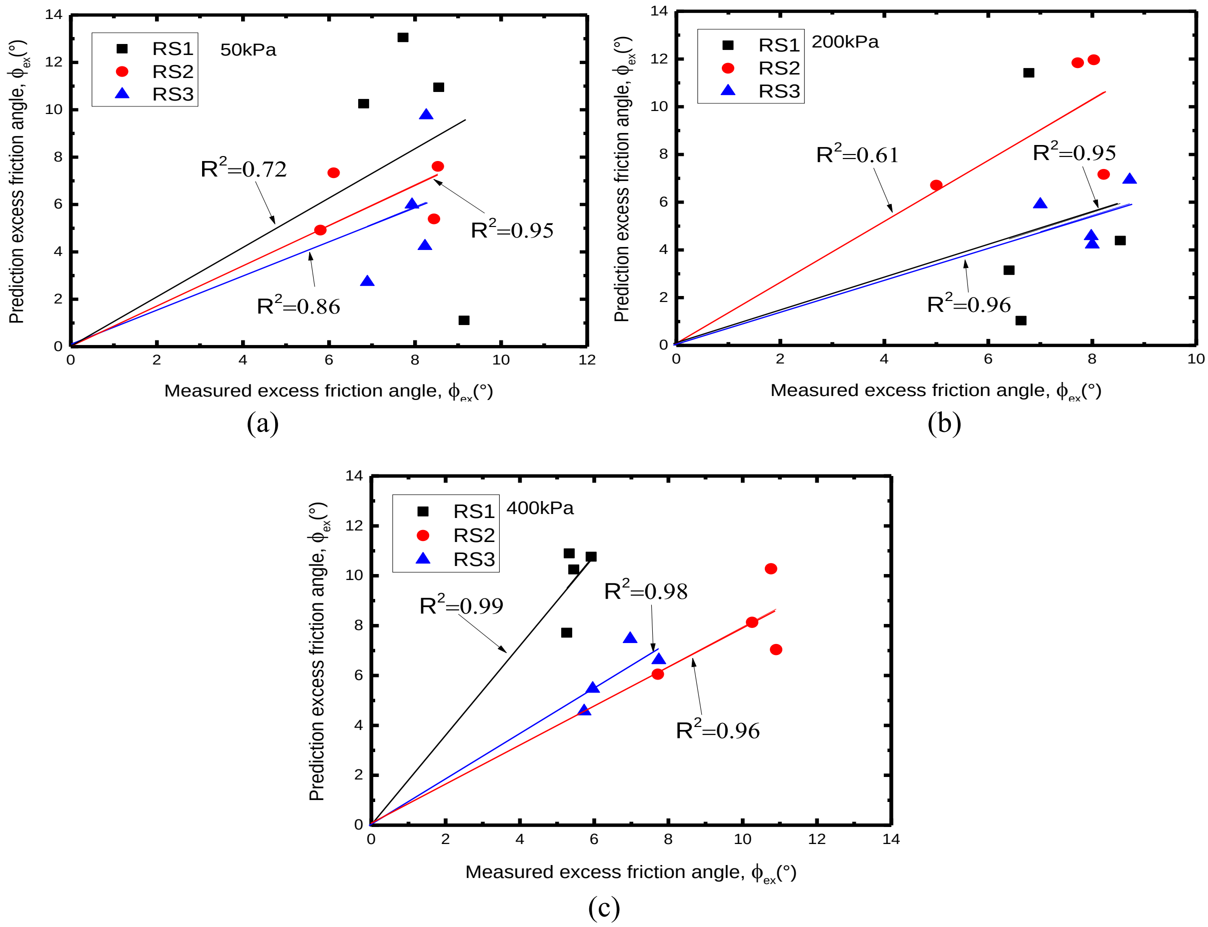


Fig. 19. Excess friction angle predicted versus measured for the examined mixtures: **a-** $\sigma_n = 50$ kPa, **b-** $\sigma_n = 200$ kPa, **c** -$\sigma_n = 400$ kPa.

5. Conclusion

The study aimed to examine the impact of mean particle size on the behavior of sands under various normal stress and different proportions of crushed waste glass content. To reach this aim, a series of direct shear experiments were performed on three categories of dry river sand, each with a various mean particle size (D_{50} = 2.00 mm, 1.00 mm, and 0.63 mm). These sands were combined with varied amounts of crushed waste glass (CWG = 0, 10%, 20%, and 30%). The samples were subsequently exposed to three distinct normal stresses: 50 kPa, 200 kPa, and 400 kPa. The results of this study support the following conclusions, which are consistent with previous findings from research:

- The investigation elucidates the nuanced relationship between mean particle size and the mechanical properties of sand-CWG mixtures. The study underscores the importance of considering particle characteristics in geotechnical analyses by observing the increase in both the angle of repose and internal friction angle with higher mean particle size and CWG content. The increase in the angle of repose can be attributed to the presence of sand particles with edges, which facilitate particle rotation during surface flow and consequently raise the angle of repose. Additionally, the inclusion of crushed waste glass particles promotes interlocking mechanisms among the sand particles, resulting in a dilation response within the mixtures. The lower deformability characteristics of crushed waste glass contribute to a significant increase in the internal friction angle of the tested soils. This insight enhances our understanding of granular materials and informs engineering practices related to soil stabilization and slope stability.
- The study's findings on the relationships between peak and residual friction angles, mean particle size, and CWG content give essential empirical data for constructing structures on granular soil foundations. By quantifying these correlations, engineers may make better judgments about material selection and structural design parameters, resulting in more robust and cost-effective infrastructure projects.
- The study examined the relationships between the excess friction angle and the maximum dilatancy angle of the sand-CWG mixtures. The investigation included the application of Bolton's stress-dilatancy relations to the mixtures of river sand and crushed waste glass. The test results substantiate the applicability of Bolton's stress-dilatancy relation to the sand-CWG mixtures by utilizing new empirical equations proposed in this research. These findings are significant in the context of utilizing granular soil materials in geotechnical applications, thereby providing a valuable approach for valorizing such materials.
- Overall, the achievements of this research extend beyond the specific experimental findings to encompass broader implications for geotechnical engineering practice. By elucidating the complex interactions between particle characteristics, stress conditions, and mechanical behavior, the study provides a solid foundation for advancing the utilization of granular soil-CWG mixtures in various engineering applications, thereby contributing to both environmental sustainability and technological innovation in the field.

List of notations

C_c: Coefficient of curvature

C_u: Coefficient of uniformity

D_{10}: Effective particle size

D_{50}: Mean particle size

D_{max}: Maximum grain diameter

D_{min}: Minimum grain diameter

D_r: Relative density

e: Void ratio index

e_{max}: Maximum void ratio

τ_{max}: Maximum shear stress

ϕ: Friction angle

ϕ_{peak}: Peak friction angle

ϕ_{res}: Residual friction angle

ΔH: Horizontal displacement

ΔV: Vertical displacement

ψ_{max}: Maximum dilatancy angle

ϕ_{ex}: Excess friction angle

$\phi_{ex\ (p)}$: Predicted Excess friction angle

e_{min}: Minimum void ratio

CWG: Crushed waste glass content

G_{s}: Specific gravity

σn: Normal stress

τ: Shear stress

$\phi_{ex\,(M)}$: Measured Excess friction angle

ϕ_{rep} : Angle de repose

α: Bolton dilatancy index

USCS: Unified classification system

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Conflict of Interest

There is no potential and actual conflict of interest including any financial, personal or other nature with people or organizations.

Authors contribution statement

Mohammed Megrousse: Conceptualization ; Data curation ; Formal analysis ; Investigation, Roles / Writing– original draft ; Writing – review & editing.

Youcef Mahmoudi: Project administration ; Resources; Supervision ; Validation ; Visualization

Abdellah Cherif Taiba: Methodology ; Resources ; Supervision; Visualization, Roles/Writing – original draft ; Writing – review & editing.

Mostefa Belkhatir: Roles / Writing – original draft ; Writing – review & editing.

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