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Sustainable Solution on Desiccation Crack Mitigation with Recycled Glass Sand

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Abstract. Desiccation cracking is a frequent natural phenomenon that occurs in drying soil and has a significant negative impact on the mechanical and hydraulic properties of clay or geomaterials in various engineering applications. In this study, recycled glass sand (RGS) was used to reduce the plasticity of clay soil and mitigate desiccation cracks in clay soils. The effect of the RGS particle size and content was investigated using a desiccation crack observation test. Digital image processing technology was used to evaluate the crack rate, length, width, and area during the observation test. The results reveal that the cracking rate was inversely proportional to the RGS content and directly proportional to the RGS particle size. For instance, the cracking rate of clay soil treated with 25% RGS with a particle size of 0.15 mm was reduced to 0.17% compared with untreated soil. The strengths of the untreated and RGS-treated soils were evaluated through unconfined compression tests. The unconfined compressive strength of the RGS-treated clay soil decreased slightly with the addition of RGS. In general, the addition of RGS has great potential for mitigating desiccation cracks in clay soils.

1. Introduction

Soil desiccation cracks are natural phenomena induced by the evaporation of water from the topsoil. Cracks arise in the soil when the shrinkage stress on the soil surface exceeds the soil tensile strength or when volume shrinkage is restricted [1]. The existence of cracks modifies the water transfer path and permeability of the soil [2,3], accelerating the mobility of gas, water, and soil particles in the soil while increasing the soil hydraulic conductivity [4]. Furthermore, the presence of cracks in the soil destroys its internal structure, reducing its mechanical strength and compressibility [5]. However, if cracks in geo-infrastructures, such as highway embankments, cutting slopes, earth dams, and foundations, are exposed long-term, they can indirectly result in hazardous situations, including foundation damage and slope instability [6,8]. For example, an ongoing drought in Europe caused widespread foundation soil cracking, which in turn caused several structures to crack and resulted in significant financial losses from 1988 to 1992 [9,10]. In 2007, approximately 1,200 reservoir dams in Chongqing, China, suffered serious cracks owing to long-term drought [11]. In the US, the Stockton and Wister dams cracked owing to drought, inducing pipe surges, and finally collapsing [12]. Therefore, mitigating soil desiccation cracks as the frequency of extreme droughts increases is essential.

Traditional methods utilize chemicals such as cement, silica fume, and lime to strengthen topsoil. However, these materials emit harmful gases and suspended particles during production, increased soil pH, and have large environmental impacts during construction [13,14]. In addition, cement and lime do not completely eliminate soil cracking when the initial soil water content is low [15,16]. In recent years, researchers have employed sand, MICP technology, and fiber addition to mitigate soil cracks. This method is less harmful to the environment and effectively mitigates soil cracks compared to traditional methods [17,19]. However, sand is a limited natural resource and approximately 15 billion tons of sand are mined globally every year [20]. Therefore, identifying sand substitutes that can mitigate soil desiccation cracks is critical.

With global growth in glass applications, the amount of waste glass produced has increased significantly [21]. Managing waste glass has become a major issue [21,22]. For example, the US generates approximately 11 million tons of waste glass each year, but only approximately 27% of the glass is collected and recycled, with the remaining 73% dumped in landfills [23]. Waste glass is processed and reused in engineering, which not only reduces the consumption of natural resources such as sand, but also relieves pressure on landfills [21]. Recycled glass sand (RGS) is artificial sand manufactured from waste glasses. In recent years, RGS have been used as a substitute for natural sand in civil engineering applications [21]. For example, RGS is utilized as a concrete aggregate, lightweight engineering material, asphalt aggregate, and 3D printing concrete aggregate [21,24]. However, few studies have investigated the application of RGS for soil desiccation crack mitigation. Therefore, quantitative research is required to better understand the effects of RGS on the generation and development of soil cracks.

Hence, the primary objective of this investigation was to mitigate the desiccation cracking of clays using RGS. A series of soil desiccation crack tests were performed, and the development of cracks was monitored and recorded. The CIAS image processing technology was used to quantitatively investigate soil cracking. Furthermore, UCS testing was utilized to investigate the influence of RGS particle size and content on clay strength. This research is advantageous for the reuse of waste glass as well as the sustainable development of the environment.

2. Materials and methods

2.1. Soil

Soil was collected from the Mississippi area in the USA. The soil was dried, crushed using a soil crusher, and sieved to 2 mm in the laboratory. The specific physical properties are listed in table 1.

Table 1. Property of clayey soil.

Soil properties	Plasticity limit (%)	Liquid limit (%)	Plasticity index (%)	Soil classification
Value	34.5	25	9.5	CL

2.2. Recycled glass sand

The RGS used in this study was provided by Glass Half-Full, and the waste glass was broken into fine glass particles using an Andela 05 L machine. Before the experiment, the glass sand was sieved to generate sand with five distinct particle sizes (0.85, 0.425, 0.25, 0.15, and 0.075 mm). Figure 1 shows the RGS sand with a particle size of 0.85 mm.

Figure 1. Recycled glass sand with a particle size of 0.85 mm.

2.3. Specimen preparation and set up

2.3.1. Specimen preparation

In this study, direct mixing was applied to mix the soil and glass sand under dry conditions, as adopted by Divya et al. (2014) and Tang et al. (2012) [26,27]. The reproducibility of the test results was controlled by varying the soil mass (30 g by the weight of dry soil). Initially, clay soil and RGS were mixed, and then water was added to obtain a saturated slurry. The moisture content of the slurry was almost 70%, which was double the liquid limit. The mixture was then poured into a 71.5 mm diameter plate. The plate was placed on a vibrating device for 5 min to release air bubbles trapped in the mixture. Finally, the prepared plate was moved to the device shown in figure 2 (temperature of 40±2°C) for drying until the weight of the plate was stabilized, indicating that the drying was complete. A digital camera positioned above the specimen was used to record the development of the soil crack patterns during drying. The procedure for preparing the specimens treated with 25% RGS is as follows:

1. 30 g of dry soil was added to the container and 7.5 g of RGS (equation 1) was weighed into the container and then mixed well.

$$RGS\ content = \frac{M_{RGS}}{M_S}, \tag{1}$$

where M_{BP} is the mass of RGS and M_S is the mass of dry soil.

2. Water was added to obtain a saturated slurry. The moisture content of the slurry was almost 70%, which was double the liquid limit.
3. The mixture was poured into a 71.5 mm diameter plate. The plate was placed on a vibrating device for 5 min to release air bubbles trapped in the mixture.
4. Finally, the prepared plate was transferred to a device for drying.

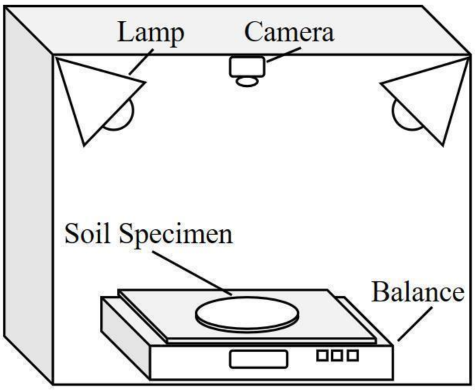


Figure 2. Schema of experimental setup.

2.3.2. Experimental procedure

Dry clayey soil was mixed with RGS at six different weight ratios (5, 10, 15, 20, 25, and 30%). The RGS was sieved into five different sizes. A 71.5 mm mold was used to investigate desiccation cracks in RGS-treated clay. Untreated soil samples were used as controls. A total of 25 tests were performed, and the specific program is detailed in table 2.

Table 2. Experiment parameters.

Soil	The particle sizes of glass sand (mm)	Glass sand content (%)
Clay	0	0
	0.85 0.425 0.25 0.15 0.075	5, 10, 15, 20 25, 30

2.3.3. Image processing and analysis system
Quantitative crack analysis is a vital technique for analyzing the evolution of soil cracks because it can help determine the relevant features among randomly distributed crack grids. The Crack Image Analysis System (CIAS) developed by Nanjing University was employed in this investigation to further analyze soil cracking and development patterns [28]. Parameters such as the total soil crack rate (R_{sc}: crack area relative to the total soil area), average crack width (W_{av}), and average crack length (L_{av}) were calculated using the CIAS system.

2.3.4. Unconfined compression stress test
The effects of different RGS contents and particle sizes on the strength of RGS-treated soil were evaluated using unconfined compression stress (UCS) tests. The axial strain rate was regulated at 1% strain/min during the UCS testing, which was conducted in accordance with ASTM D2166.

3. Results and discussion

3.1. Development process of desiccation cracks
The crack pattern development process of the untreated soil is shown in figure 3. The crack generation process for clay was separated into four stages. (i) The saturation stage (figure 3(a)). The moisture content of the sample decreased steadily as the water on its surface evaporated; however, no cracks were formed. (ii) The main crack formation stage (figures 3(b)–3(d)). Cracks occurred at the borders of the sample and subsequently progressed toward the center of the area as the moisture content steadily decreased from 37%. When the moisture content decreased to 17%, the main cracks were formed. (iii) The secondary crack formation stage (figures 3(e)–3(g)). Secondary cracks developed perpendicular to the direction of the main cracks when the water content decreased from 17 to 4%. Meanwhile, the widths of the main cracks increased gradually. (iv) Stable stage (figure 3(h)). When the moisture content of the sample was less than 4%, desiccation cracks developed completely, and the geometric structure of the crack grid became stable and did not change further as the moisture content decreased.

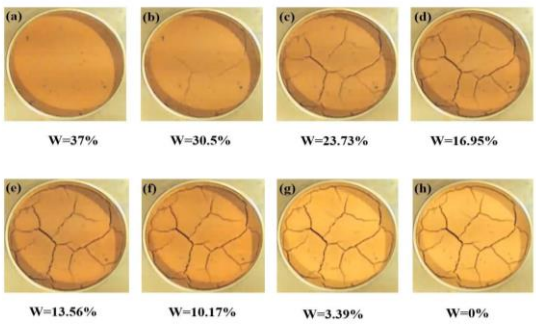


Figure 3. Desiccation crack pattern of soil treated with RGS with different contents and particle sizes.

Tang et al. (2011) investigated changes in the moisture content of soil samples during the generation of soil desiccation cracks [3]. In [3], the process of clay desiccation cracking was divided into three main phases: constant rate of evaporation, reduced rate of evaporation, and stabilization. This result is similar to the experimental results obtained in this study. The desiccation cracks that occurred in the clay were mainly due to the capillary suction generated in the upper soil of the second-stage sample. The capillary suction and effective stress between the soil particles steadily increased as the moisture content of the sample gradually decreased. Therefore, cracks occurred when the tensile stress exceeded the effective stress between the clay particles in the upper soil tensile-stress field [3]. Additionally, the main crack pattern of the soil was “T” and “Y” in this study.

3.2. Effect of RGS on soil desiccation cracks
A typical untreated soil desiccation crack pattern is shown in figure 4, and the soil treated with different RGS contents and particle sizes is shown in figure 5. The development of soil desiccation cracks was effectively mitigated by the addition of RGS compared with the untreated soil sample in figure 4. For example, for a RGS particle size of 0.25 mm, as the RGS content of the soil increased, the number of wide cracks gradually decreased, and the fine cracks increased significantly. The morphology of the cracks changed from regular to irregular and some individual cracks that did not intersect with other cracks were formed. In addition, the smoothness of the cracks was affected by the RGS content. Compared to figure 4, the morphology of the soil cracks became more tortuous as the RGS content increased.

Figure 4. Typically untreated soil desiccation crack pattern.

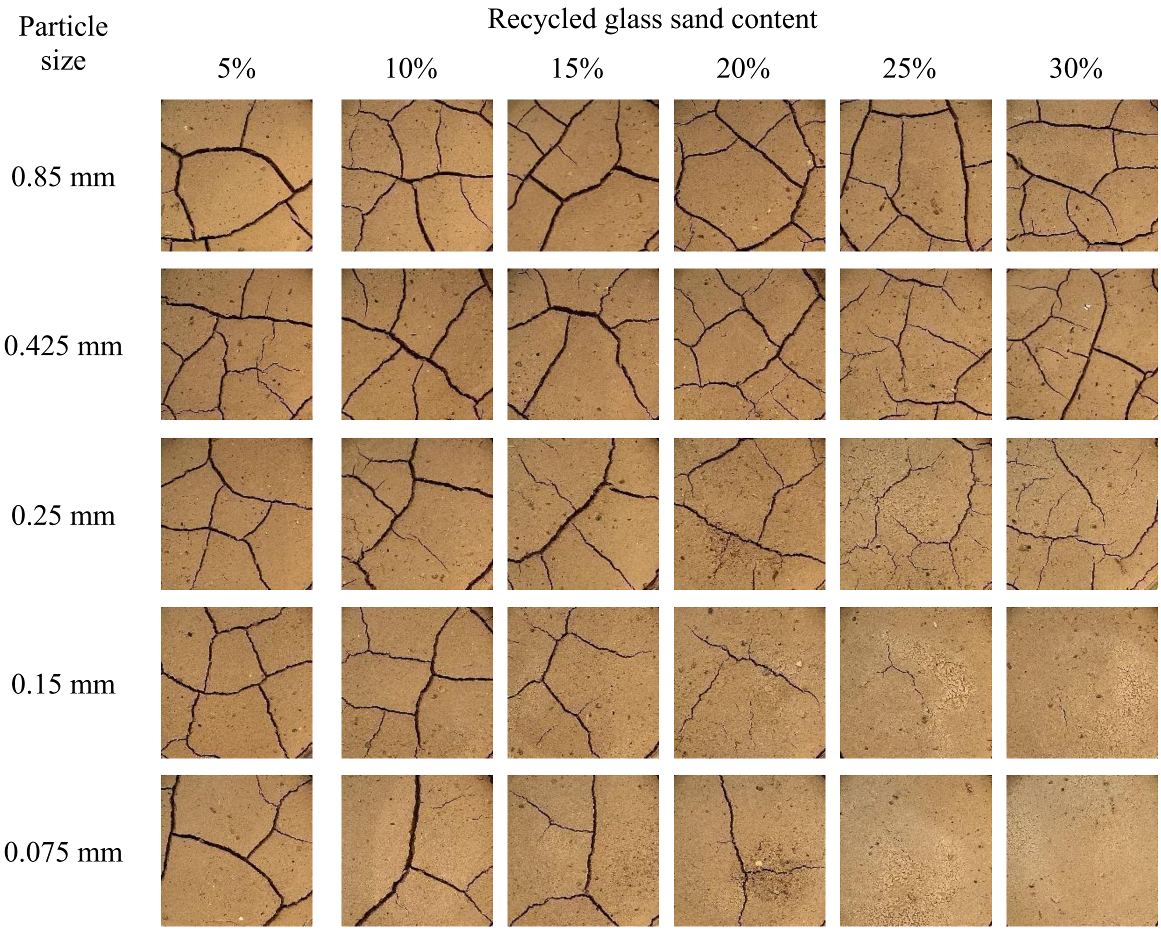
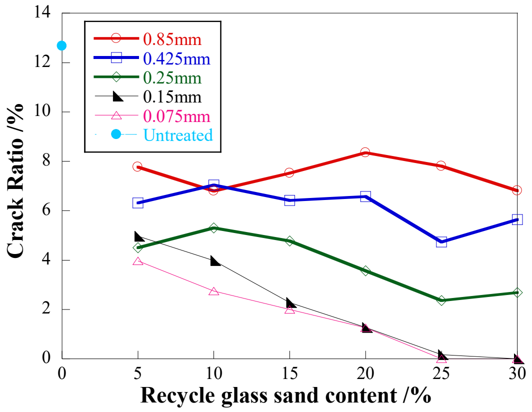


Figure 5. Desiccation crack pattern of soil treated with RGS with different contents and particle sizes.

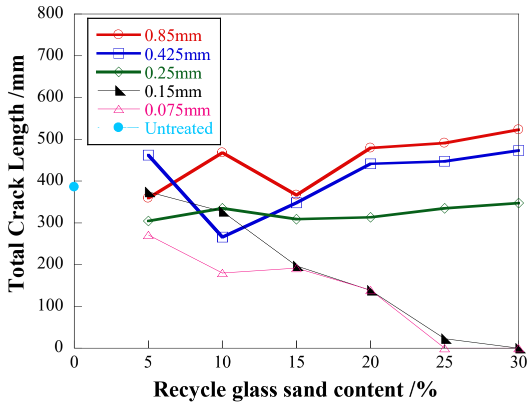
Additionally, the mitigation effects of the different RGS particle sizes on soil desiccation cracks varied significantly. Compared with figure 4, the cracking morphology of the soil treated with 0.85- and 0.425-mm RGS was affected slightly. However, 0.15- and 0.075-mm RGS showed a substantial effect in mitigating the number and morphology of soil cracks. Kleppe et al. (1985) studied the effects of sand content on soil cracking [25] and showed that soil desiccation cracks disappear when the sand content is approximately 80% of the soil mass [25]. This indicates that the addition of sand to the soil can alleviate the generation of soil desiccation cracks. This is consistent with the results of the present study. However, the desiccation cracking rates of soil treated with approximately 30% RGS were effectively reduced compared with those of natural sand. This was because the natural sand had smooth surfaces on the sand particles owing to the scouring action of the water flow, whereas the RGS material had a more angular shape. The angular shape increased the friction between the RGS and soil particles and improved the soil integrity. Consequently, desiccation cracking in the soil treated with RGS was effectively reduced.

3.3. Quantitative analysis of cracks

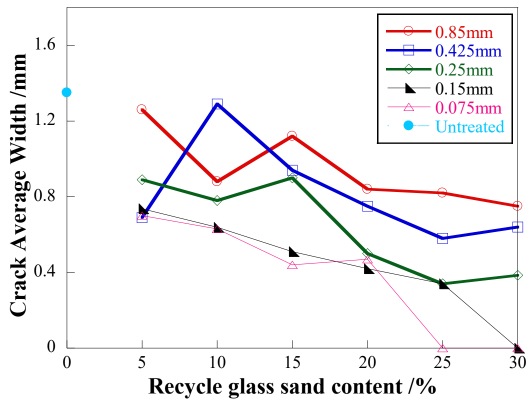
The desiccation crack morphology of each sample was quantitatively analyzed using CIAS, and the results are shown in figure 6. It can be seen that the addition of RGS effectively mitigated the development of soil desiccation cracks. For example, the R_{sc} of the soil samples without RGS treatment was approximately 12.5%, while the R_{sc} of samples treated with 5% RGS was reduced to approximately 8%. Additionally, the mitigation of soil cracks by RGS varied based on particle size. As the RGS content gradually increased from 5 to 30%, the R_{sc} of the soil treated with 0.85- and 0.425-mm RGS fluctuated between 6 and 8%, whereas the R_{sc} of the soil samples treated with 0.15- and 0.075-mm RGS gradually decreased to 0. At the same time, L_{av} and W_{av} were affected by the RGS content and particle size. As can be observed from figures 6b and 6c, the L_{av} and W_{av} of soil treated with 0.15- and 0.075-mm RGS steadily decreased as the RGS content rose, but the soil treated with 0.85-, 0.425-, and 0.25-mm RGS only slightly changed. Therefore, the desiccation cracks in the soil treated with 0.15- and 0.075-mm RGS were effectively mitigated.



(a)



(b)



(c)

Figure 6. Desiccation crack pattern of soil treated with glass sand with different contents and particle sizes. (a) Crack rate of specimen, (b) total crack length of specimen, and (c) average width of the specimen.

According to Tang et al. (2021), key factors affecting soil cracks include soil properties, clay content, soil density, and salinity [26]. To further investigate the effect of adding RGS on soil properties, soils treated with different particle sizes were analyzed for liquid and plastic limits, and the experimental results are shown in table 3. In this experiment, the clay content of the RGS-treated soil sample was lower than that of the untreated soil sample, and the plasticity index of the soil sample was lower. As shown in table 3, the plasticity index of the RGS-treated soils decreases gradually with decreasing RGS particle size. For example, the plastic index of the soil treated with 0.15- and 0.075-mm RGS decreased by 45 and 65%, respectively, but the plastic index of the soil treated with 0.85-mm RGS decreased by only about 2.1%. Tang et al. (2008) investigated the relationship between the soil cracking rate and soil plasticity index [28]. The results indicate that the soil surface cracking rate and average crack width increased with the soil plasticity index [28]. This is consistent with the results of the present study. Therefore, adding RGS can effectively reduce the plasticity index of the soil, thereby mitigating the generation of soil desiccation cracks.

Table 3 Property of soil treated with different particle RGS.

	Plasticity limit (%)	Liquid limit (%)	Plasticity index (%)
Untreated	34.5	25	9.5
0.85 mm	27.4	18.1	9.3
0.425 mm	30.1	22.2	7.9
0.25 mm	23.64	16.7	7
0.15 mm	25.2	20	5.2
0.075 mm	26.4	23.1	3.3

3.4. Effect of RGS on soil UCS.

The samples with 10% (dry soil mass) 0.85-mm RGS, 5% 0.425-mm RGS, and 25% 0.25-, 0.15-, and 0.075-mm RGS were chosen for UCS analysis in figure 7. As shown, the UCS of the soil treated with 0.85- and 0.425-mm RGS was not altered, whereas that of the soil treated with fine-particle RGS decreased. For example, the UCS of soil treated with 0.15- and 0.075-mm RGS declined by approximately 11 and 30%, respectively. Yin et al. (2021) investigated clay and sand mixtures and showed that when the clay content exceeded 41%, the sand particles were surrounded by clay particles, and the mixture strength was the same as clay [29]. However, the arrangement of clay particles inside the sample was disrupted by the RGS particles [30]; thus, the UCS of the clay treated with RGS was reduced. In summary, 25% 0.15-mm RGS is recommended to mitigate desiccation cracks in drying soil.

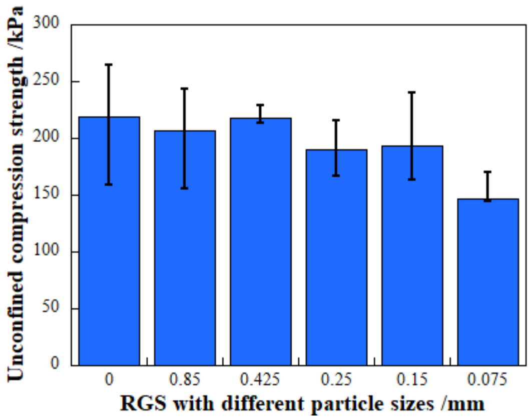


Figure 7. UCS of soil mixed with different particle sizes RGS.

4. Conclusion

In this study, RGS were used to mitigate soil desiccation cracks. The effects of RGS with different particle sizes and contents on soil cracking were studied, and the CIAS system was used to quantitatively analyze the crack patterns. The following conclusions were drawn based on the experimental results.

(1) The crack patterns in the untreated soil were mostly "T" and "Y" shaped. The formation of soil desiccation cracks was divided into four stages, and the formation of cracks was mainly concentrated in the second and third stages, in which the secondary cracks were perpendicular to the main cracks.

(2) Soil cracking was affected more by the RGS particle size than by the RGS content, and the soil cracking rates were significantly reduced with the addition of fine-grained RGS.

(3) Desiccation cracks in the soil can be effectively mitigated by the addition of RGS. The crack rate of the soil treated with 25% fine-grained RGS (0.15 mm) decreased by 0.17%.

(4) The UCS decreased in soils treated with fine-grained RGS; soils treated with 25% RGS with particles sizes of 0.15 and 0.075 mm showed UCS decreases of approximately 11 and 33%, respectively.

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