



STRENGTH & MICROSTRUCTURE OF CLAY (CL) STABILIZED WITH RECYCLED CONCRETE, WASTE GLASS, AND WASTE STEEL

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ABSTRACT: Because of the accumulation of industrial waste products resulting from the growing industrial development, critical environmental issues related to their disposal have arisen. The feasibility of using recycled crushed concrete (RC), waste glass (WG), and waste steel (WS) as stabilizers for clay soil (CL) at the lowest possible cost has been assessed in this research paper. Standard Proctor compaction and unconfined compressive strength (UCS) tests were implemented. Moreover, scanning electron microscopy (SEM) was performed to evaluate the effect of waste-material percentages (5%, 10%, and 15%) on the soil's geotechnical and microstructural behavior. Compaction results showed the maximum dry unit weight increasing by up to 7.3%, 5.0%, and 2.8% for RC, WG, and WS, respectively. Furthermore, adding waste materials resulted in a noticeable increase in the strength of clay soil; this gain scaled gradually with the RC ratio, reaching 94% at 15%. WG improved strength by up to 35.1% at 10%, beyond which no further gain was observed. The highest increase was 132%, recorded at 5% WS, followed by a decline at higher percentages. Accordingly, 15% RC, 10% WG, and 5% WS were identified as the optimum percentages. SEM revealed that RC was associated with a strengthening network that interlaced with the clay; the WG effect was limited to filling voids with little bonding. At the same time, WS improved particle interlocking although it caused localized microcracks. Differences in particle size ranges among the three materials as well as the absence of leaching tests for WS are noted as limitations, with TCLP and XRD analyses recommended for future work.

Keywords: Recycled crushed concrete; Waste glass; Waste steel; Unconfined compressive strength; SEM microstructure.

1. INTRODUCTION

Undesirable properties of soil, such as low bearing strength and high compressibility, are generally considered characteristics of clay soils. Because one-fifth of Iraq's land area consists of clay soils, they pose a challenge to modern construction requirements [1]. The requirement to modify the properties of weak soils applies not only to residential buildings but also to a wide range of engineering applications, making the enhancement of their load-bearing capacity essential. The economic transformations and shifts in consumption patterns that Iraq has undergone since 2003 have exacerbated environmental pressures. The overconsumption of raw materials and inadequate waste management infrastructure are among the greatest obstacles to sustainable development [2]. Accordingly, the rise in construction and industrial waste has become a challenge to urban planning, in conjunction with urban growth and the depletion of natural resources. To overcome the shortage of raw materials and maintain engineering projects, there is a trend towards recycling this waste and using it as

an alternative to conventional soil improvement materials. The choice of these wastes is due to their low energy consumption, high availability, low cost, and high binding capacity, all of which meet the requirements for suitable construction materials [3]. The studies were not limited to conventional waste but extended to evaluating the influence of a range of industrial and agricultural waste on soil properties. For instance, four types of recycled aggregate (ceramics, glass, slag, and roof tiles) were examined for use in cold-mix paving, and the recycled ceramic aggregate showed the lowest temperature rise, making it the most suitable option for cold pavements [4]. Furthermore, adding 5% coconut husk ash (agricultural waste) to soil improved the soil's elastic response to deformation, helping reduce the potential for soil liquefaction [5]. To strengthen weak soil beneath roads and buildings, a study assessed the development of an ecologically friendly, cement-free material made from geopolymers formed from construction waste powder combined with recycled glass silica [6]. Three essential kinds of waste have been focused on: concrete, glass, and steel. While these materials can

theoretically be recycled, operational and economic constraints often limit their recyclability. One common obstacle to recycling and reusing construction and demolition waste is the poor quality of the recycled materials [7]. Inefficient glass collection methods, high recycling costs, and limited market demand for recycled glass have caused a large portion of this material to end up in waste disposal sites [8]. Similarly, a study confirms that fine waste (shavings and dust) generated in recycling processes creates operational obstacles and reduces recovery efficiency, thereby decreasing their economic viability [9]. This study proposes using waste materials (concrete, glass, and steel) for soil stabilization as a useful recycling option that reduces landfill dependency because these materials are low in value and challenging to recycle.

1.1 Recycled Crushed Concrete (RC)

Recycling materials helps protect the environment by limiting the depletion of natural resources and reducing the need to construct new waste disposal sites; the use of recycled crushed concrete reduces energy consumption by 85%, carbon dioxide emissions by 90%, and the use of waste disposal sites by 85% [10,11]. These environmental and economic benefits are consistent with numerous laboratory findings showing that adding recycled concrete waste to clay soil improves its properties significantly and enables its use in a variety of engineering applications. A study reported that adding construction waste at proportions ranging from 12% to 24% to the soil led to an increase in its strength, due to the filling of soil voids with fine particles of construction and demolition waste [12]. Also, recycled concrete aggregates (5%, 10%, and 15%) with clay soil enhanced the strength and deformation behavior of clay soils, with treated soil exhibiting greater dilative behavior and higher shearing strength than untreated clay [13]. Incorporating 5–30% recycled crushed concrete into soft soil improves undrained shear strength and reduces compressibility [14]. Furthermore, laboratory tests on expansive soil showed that adding 4–24% construction and demolition waste decreased maximum dry density and optimum moisture content, while 24% CDW improved permeability, UCS, CBR, and secant modulus [15].

1.2 Waste Glass (WG)

Numerous studies have shown the effectiveness of waste glass in improving soil geotechnical properties. Adding 12% waste soda lime glass powder to clay decreased the swelling value from

5.5% to 1.65% [16]. Replacing 40% of the soil with glass increased shear strength and CBR values by considerable amounts [17]. Furthermore, the effect of adding glass waste at varying concentrations (3%, 5%, 7%, and 9%) on the properties of low-plasticity clay soil was examined. The results showed that adding glass powder improved soil properties, but increasing the content to 7% decreased shear strength [18]. Adding 8% of waste glass powder to loose soils increased modified Proctor values and significantly improved CBR [19]. Using various percentages (10, 20, and 25%) of waste glass as an additive in three clayey soils reduced the optimum water content and increased the maximum dry density; additionally, it improved the strength characteristics of the clayey soils [20]. The addition of 20% glass waste to low-plasticity clay resulted in a 6% decrease in the maximum bulk density and an increase in the CBR modulus (unsoaked and soaked) of 67% and 300%, respectively, yielding a 110% improvement in ultimate compressive strength. This is attributed to the finer particle size distribution of the silica-rich glass powder, which fills the voids between particles [21]. The addition of 15% coarse glass waste to bentonite clay decreased the Atterberg limits, the rate of free swelling, and the swelling pressure [22]. Another study showed that adding 10% of crushed glass to clayey soil increased the unconfined compressive strength. Additionally, the scanning electron microscope showed that the glass particles have a rough surface, indicating they are more resistant to friction [23].

1.3 Waste Steel (WS)

Despite a lack of interest in iron and steel waste compared to concrete and glass waste, these materials have revealed substantial potential for soil improvement. Various types of iron and steel waste have been used for soil stabilization. Researchers observed that adding 15% steel filings to clay soil increased the California Bearing Ratio by 189.47% [24]. Simultaneously, to improve expensive oil, 10% steel factory dust was used in another study which resulted in an increase of 32% in unconfined compressive strength [25]. Alternatively, a study was conducted by adding 25% steel slag to stabilize expansive soil. As a result, an increase in compressive strength was observed from 64.3 kPa to 170.6 kPa [26]. Iron slag was used in combination with hydraulic cement and biochar during the stabilization of sediments dredged from drainage channels to obtain a significant unconfined compressive strength exceeding 900 kPa [27]. Nevertheless, most of the prior studies have focused on steel by-products, such as slag or fine dust. In this

study, it was processed using steel waste (milled, sieved, and heat-treated) to investigate their effect on clay soil behavior which remains largely unexplored. The mentioned steel waste varies in behavior and composition from steel slag or raw industrial dust. The percentages of waste material in this study were selected to be 5%, 10%, and 15%, based on prior studies by [13,23,24]. Although RC and WG are well documented, WS has been the focus of only a few studies. Consequently, the novelty of this study lies in the systematic comparison of the three materials under similar conditions, with a focus on WS as an alternative that has not been studied sufficiently. This paper is organized in four sections. The significance of the research, its novelty and originality are discussed in section 2. While the description of the used materials (natural soil, recycled crushed concrete, glass waste, and steel waste) as well as the experimental procedures, including sample preparation, compaction tests, and unconfined compressive strength tests are explained in section 3. Moreover, the experimental results are displayed and discussed in section 4. The key conclusions and presents practical recommendations for selecting the most suitable waste material for soil stabilization in engineering uses are summarized in section 5.

2. RESEARCH SIGNIFICANCE

Although Recycled concrete (RC) and glass waste (WG) have been widely investigated for clay soil improvement, treated steel waste (WS) has not been sufficiently explored as a stabilizing material. A clear research gap was observed. Hence, the novelty of this study does not lie in the stabilization of recycled concrete or glass waste, but rather in performing a comparative experimental assessment of three local waste materials, with a particular focus on treated steel waste as the least-studied material for stabilizing low-plasticity clay soils, as well as determining the optimal percentage of each material.

3. MATERIALS AND PROCEDURES

The disturbed soil was collected from the southern Baghdad construction site at depths of 0.5 to 2 meters below the ground surface. Figure 1 represents the distribution of the soil and waste materials in terms of the grain size. Laboratory tests were performed on the soils according to ASTM standards, as outlined in [28]. The properties of the natural soil utilized in this study exhibited a liquid limit (LL) of 38%, a plastic limit (PL) of 24%, a plasticity index (PI) of 14%, and the moisture content at natural conditions was 14.2%. The specific gravity

(Gs) of the soil was 2.68, and the pH was 7.9.

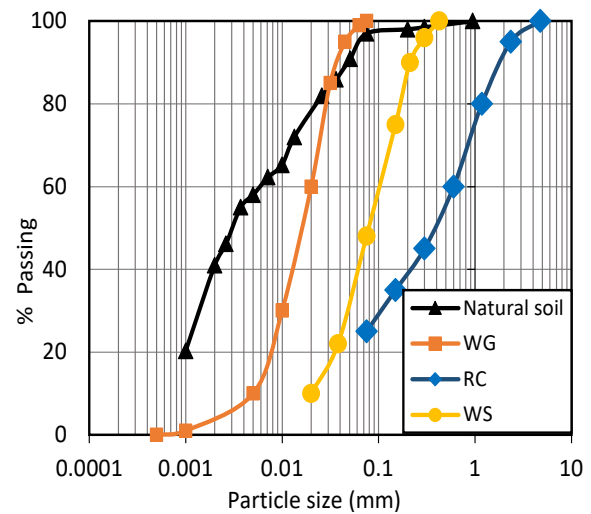


Fig.1 Grain size distribution of the natural soil and waste materials.

Analysis of the particle size distribution (Fig.1) revealed that the soil was composed of 15% sand, 35% silt, and 50% clay; the soil is classified by the Unified Soil Classification System (USCS) as low-plasticity clay (CL). Standard Proctor compaction tests yielded a maximum dry density (MDD) of 17.9 kN/m³ at an optimum moisture content (OMC) of 15.3%, and the saturation degree after standard compaction was about 89%. The unconfined compressive strength (UCS) of the natural soil was 48.5 kPa, with a failure strain of 8.1%, as shown in Fig.8. The chemical composition of both the soil and the waste materials, as determined by energy-dispersive spectroscopy (EDS) analysis is shown in Table 1.

Table 1. Chemical elements of the natural soil and waste materials.

Element %	Natural soil	RC	WG	WS
C	10.8	-	-	1
O	51	40.7	50.9	3
Na	0.6	1.5	7.5	-
Mg	2.8	1.4	0.8	-
Al	4.8	4.3	0.5	-
Si	15.4	35.8	31.6	1.5
Cl	0.2	-	-	-
K	0.8	2.2	-	-
Ca	9.7	10.9	5.2	-
Ni	-	-	-	8
Ti	0.3	-	-	-
Fe	3.4	1.4	0.5	67.8
Cr	-	-	-	18.4

The recycled crushed concrete (RC) was prepared by: Firstly, the concrete waste was crushed with a hammer to produce fine particles of varying sizes and shapes, which were then further reduced to small pieces in a ball mill; Secondly, sieving the resultant fine fraction through a No. 4 (4.75 mm) sieve to remove larger particles. Finally, a recycled crushed concrete at replacement percentages of 5%, 10%, and 15% (by dry soil weight) was mixed with the soil, as shown in Figure 2.



Fig.2 Mixing the dry soil with recycled crushed concrete (RC).

Waste glass (WG) for use as a soil additive was prepared through several steps: (1) from municipal waste empty, bottles were collected, alongside discarded glass from a demolished structure; (2) to remove dust and debris, the glass was cleaned and broken into small pieces using a hammer. To prevent scattering, it was covered with a cloth; and (3) the glass was then ground into a powder and sieved through a No. 200 (75 μ m) sieve. Then, the glass powder (WG) was mixed with natural soil in varying percentages (5%, 10%, and 15%), as illustrated in Fig. 3.



Fig.3 Mixing the dry soil with waste glass (WG).

The waste steel was obtained from steel manufacturing processes in Baghdad and prepared by: (1) to remove any oils and moisture, the raw material was cleaned, and then milled it into small pieces; (2) to reduce the moisture content and stabilize the waste steel, it was passed through a No. 40 (0.425 mm) sieve firstly and then heated for three hours at 300–350°C in an electric oven; and (3) the waste steel was blended with soil at varying percentages (5%, 10%, and 15%), as displayed in Fig.

4. To ensure homogeneity, soil and waste materials were mixed (e.g., 5 g of waste per 100 g of dry soil) and thoroughly blended.



Fig.4 Mixing the dry soil with waste steel (WS).

Samples were coded as 'Soil+X% material' (e.g., Soil+5% RC, Soil+10% WG, Soil+15% WS), where X denotes the percentage added by dry soil weight. The amount of water corresponding to the specific optimum moisture content for each particular mixture, as determined from the individual Proctor compaction curves (Fig.s 6-8), was added gradually to the mixture until the required consistency was reached. The mixture was compacted in three layers in the mold to achieve its respective maximum dry unit weight in accordance with ASTM D698 [29]. The specimens were extracted with a height of 76 mm and a diameter of 38 mm. For each additive type and percentage, three cylindrical specimens were prepared. The specimens were wrapped in plastic film and stored in an airtight container at 25 ± 1 °C and 95% relative humidity for 7 days. Unconfined compressive strength (UCS) tests were conducted to assess the effect of varying percentages of waste materials (recycled crushed concrete, waste glass, and waste steel) on the stress–strain behavior of clay soil according to ASTM D2166 [30]. Each specimen was tested in a compression testing machine at a vertical displacement rate of 0.5 mm/min until failure occurred. Fig. 5 summarizes the methodology and testing program adopted in this study.

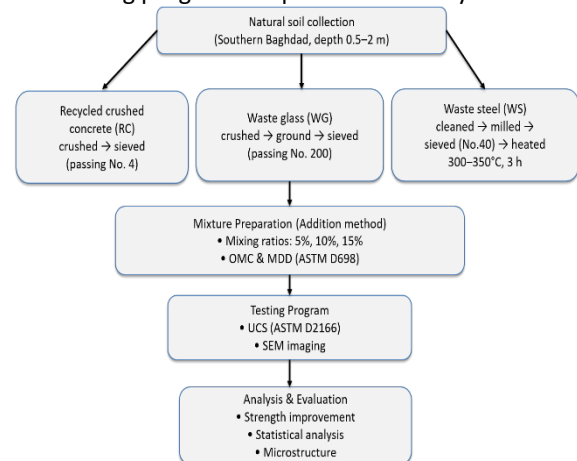


Fig.5 Flowchart of the experimental methodology.

4. RESULTS AND DISCUSSION

4.1 Proctor compaction test

Figure 6 illustrates the relationship of maximum dry unit weight ($\gamma_d, \max$) to optimal moisture content (OMC) for both natural soil and soil mixed with varying proportions of recycled crushed concrete (RC). The results show that $\gamma_d, \max$ and OMC increased with RC percentage up to 10%. However, a slight reduction at 15% was observed. This nonlinear trend is similar to the findings of [13]. The increase in the maximum dry unit weight at 5–10% RC is due to pozzolanic activity, which enhances inter-particle bonding. On the other hand, the decline in $\gamma_d, \max$ at 15% RC was occurred because of the accumulation of clay particles around the RC particles. As a result, compaction was hindered and porosity was elevated, as it was observed by [31].

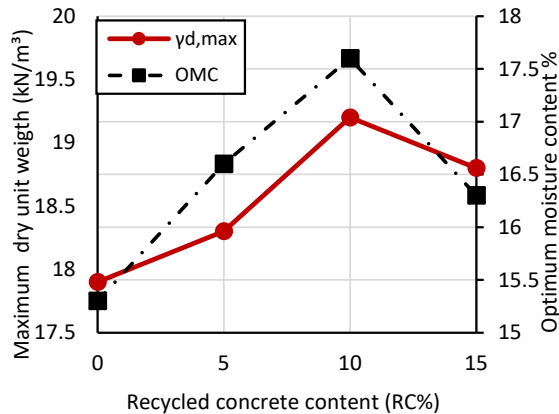


Fig.6 Effect of recycled crushed concrete (RC) content on the maximum dry unit weight and optimum water content of the soil.

Furthermore, the increase in OMC with RC content was associated with the porous nature of RC particles, which absorb additional moisture, as noted by [32]. Accordingly, the most effective enhancement of compaction properties is at 10% RC. The results of Standard Proctor tests on soil blended with waste glass (WG) at different percentages (5%, 10%, and 15%) are presented in Fig. 7. It was observed that adding WG to clay soil enhanced compaction characteristics up to 10% content. At 10% WG, the ($\gamma_d, \max$) increased from 17.9 kN/m³ for the natural soil to 18.8 kN/m³. At the same time, the OMC declined from 15.3% to 14.5%. This finding is compatible with the results presented by [33]. The increase in soil $\gamma_d, \max$ is attributed to the fact that the voids in the soil structure are filled with fine glass particles, resulting in a denser soil. The reduction in water content is linked to WG's limited adsorption capacity. At a 15% WG content, $\gamma_d, \max$ increased

slightly to 19.0 kN/m³, while the optimum moisture content (OMC) rose marginally to 15%. These results indicate that further addition of WG may reduce compaction efficiency because of particle agglomeration and decreased packing density.

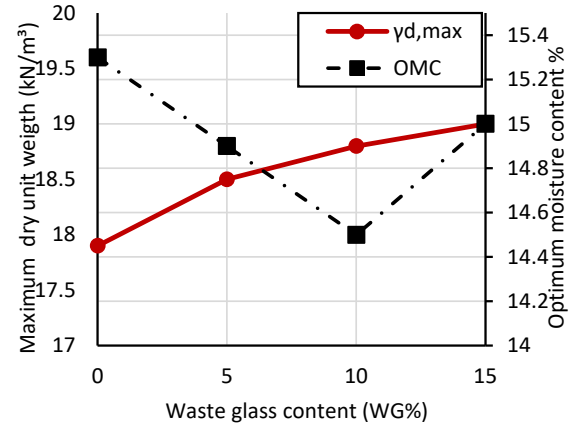


Fig.7 Effect of waste glass (WG) content on the maximum dry unit weight and optimum water content of the soil.

Figure 8 illustrates the effect of waste steel (WS) addition on the compaction characteristics of the clay soil. The maximum dry unit weight of the natural soil rose from 17.9 kN/m³ to 18.4 kN/m³ at 5% WS, but decreased to 17.7 kN/m³ and 17.3 kN/m³ at 10% and 15% WS, respectively. The increase in $\gamma_d, \max$, which peaks at 5% WS, is attributed to the reinforcing impact of WS, which improves particle interlocking.

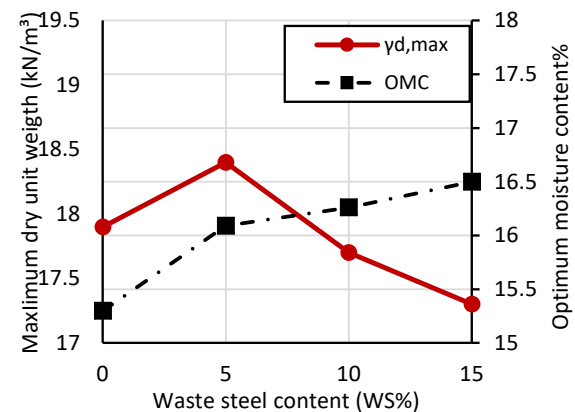


Fig.8 Effect of the waste steel (WS) content on the maximum dry unit weight and optimum water content of the soil.

Conversely, the decrease in ($\gamma_d, \max$) at higher WS content is linked to the WS particle size distribution shown in Fig. 1, which contains a large proportion of fine particles; this leads to an increase in specific surface area and disrupts soil packing, resulting in higher void ratios and lower dry unit weight. The increase in optimum moisture content

(OMC) with increasing WS content is due to the rough, irregular surfaces of the WS particles, which require additional water to enable the arrangement of soil particles during compaction.

4.2 Unconfined Compressive Strength (UCS)

Figure 9 illustrates the stress-strain curves of natural soil blended with recycled crushed concrete (RC). Based on the results, the unconfined compressive strength (q_u) increased consistently with increasing RC content. This linear increase in strength is in line with previous studies indicating that the UCS of clay soil rises with an increase in the recycled concrete aggregate content [34]. The results in Table 2 indicate that the most significant increase (94%) in the q_u value of the treated soil occurred at an additive percentage of 15%. The lowest increase in q_u (22.9%) occurred at a 5% additive level. The noticeable increase in q_u is attributed to mechanical contacts between coarse RC particles and clay particles. Furthermore, the Pozzolanic reactions of unhydrated residual cement in RC may have contributed to the formation of binder materials, thereby increasing cohesion. This result is aligned with the findings of [34].

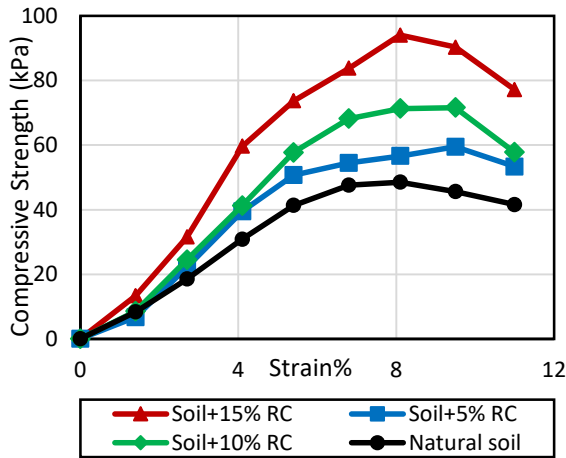


Fig.9 Effect of recycled crushed concrete (RC) content on unconfined compressive strength.

Figure 10 illustrates the UCS results for both natural clay soil and soil mixed with different percentages of waste glass powder (WG). According to Table 2, the q_u rose to 60 kPa at 5% WG. Furthermore, the q_u was 65.6 kPa and 65.6 kPa at 10% and 15% WG, respectively. The variation in q_u (35.1%) at a 10% WG content is mainly due to the micro-filling effect, as WG can fill voids of clayey soil. These results are consistent with those reported in [33]. Recent studies have shown the effective use of glass powder to improve soil properties [22, 35]. One study reported a marked improvement in the properties of bentonite clay upon the addition of

15% ground glass [22]. However, the optimal proportion in the current study was 10%, which may be due to the lower plasticity of the soil used (CL) in comparison to bentonite, combined with the smaller particle size of the glass used (fine <0.075 mm) compared to the coarse glass (2 mm) used in their study [22]. This interpretation is supported by a study reporting that the optimal percentage of glass powder is about 9%, which falls squarely within the range of optimal percentages identified in this study [35]. The smooth surfaces of WG, which were not significantly chemically affected under the current 7 day treatment conditions, exhibited limited adhesion strength, which explains why no increase in soil q_u was observed at 15% WG.

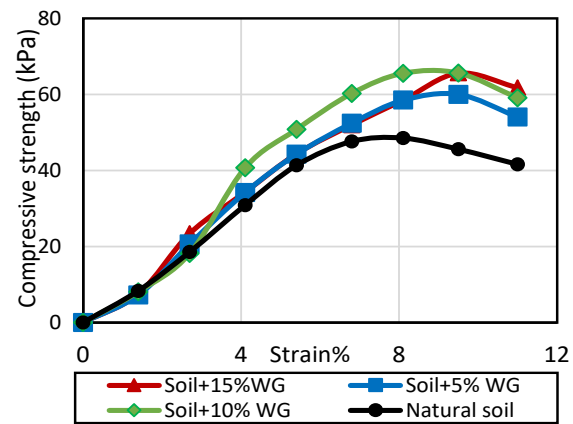


Fig.10 Effect of waste glass (WG) content on unconfined compressive strength.

Table 2. Unconfined compressive strength test results for soil samples

Soil sample	q_u , kPa	SD $\pm$ kPa	CV %	q_u variation (%)
Natural soil	48.5	3.2	6.6	-
Soil+5% RC	59.5	3	5	22.9
Soil+10% RC	71.6	3.6	5	47.6
Soil+15% RC	94.1	4.7	5	94
Soil+5% WG	60.0	3	5	23.7
Soil+10%WG	65.6	3.1	4.7	35.1
Soil+15%WG	65.6	3.2	4.9	35.1
Soil+5% WS	112.5	5.6	5	132
Soil+10% WS	84.1	3.4	4	73.2
Soil+15% WS	69.9	3.5	5	44.1

The unconfined compressive strength (q_u) of soil samples mixed with 5, 10, and 15% WS was recorded as 112.5 kPa, 84.1 kPa, and 69.9 kPa, respectively, as presented in Fig. 11. In Table 2, the results indicate a nonlinear behavior, characterized by an initial enhancement in unconfined compressive strength, followed by a gradual decrease as the WS% increases; however, q_u remains higher than that of

the natural soil. The increase of about 132% in q_u at 5% is due to the WS acting as soil reinforcement fibers, enhancing the interlock between soil particles. However, at higher percentages, the wide gradation and significant fine fraction of WS (Fig. 1) result in a higher void ratio, which leads to weakened soil homogeneity and reduced strength. Based on the comparative analysis for the unconfined compressive test of soil mixed with three waste materials (RC, WG, and WS), the highest strength (112.5 kPa) was achieved with the addition of 5% WS. The reason behind this high strength was due to the superior mechanical interlocking from its sharp, angular particles. The comparison is shown in Table 2. Adding RC showed a consistent, incremental increase in strength, reaching 94.1 kPa at 15% due to its pozzolanic activity, driven by its calcium-rich (10.9%) composition, as shown in Table 1. WG showed moderate improvement, with a strength reaching 65.6 kPa at 10%, primarily due to the filler effect of its fine particles, but this was limited by its smooth surface and the lack of chemical reaction. Comparing the effects of waste materials on soil strength, WS exhibited the greatest improvement, though there are challenges in terms of controlling the percentage and long-term durability. In addition, the RC provides a better balance between chemical reactions and cohesion.

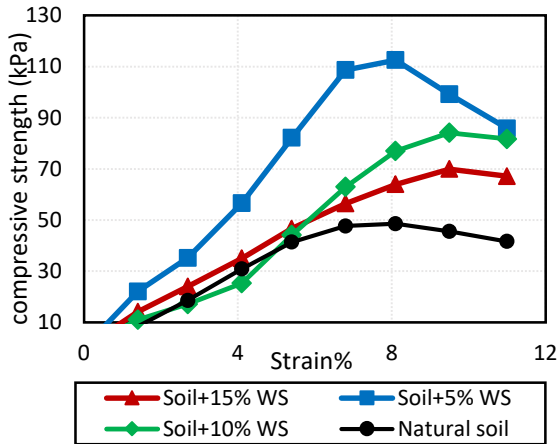


Fig.11 Effect of the waste steel (WS) content on unconfined compressive strength.

The statistical comparison, as shown in Table 2 and Fig. 12, indicated that all mixtures showed a significant enhancement in strength compared to the natural soil. These results are consistent with recently published studies on the stabilization by recycled concrete [34], glass waste [22, 35], and steel waste [24]. The increases between successive percentage ratios exceeded the standard deviation for RC-treated soil, confirming a continuous improvement up to 15%. As for soil treated with WG, the slight difference between 10% (65.6 ± 3.1) and

15% (65.6 ± 3.2) fell within the margin of error, making 10% the most practical and economical choice. Meanwhile, the strength of the treated soil with WS peaked at 5% (112.5 ± 5.6) and then declined sharply at higher percentages, with differences far exceeding the standard deviation, confirming that increasing the WS percentage above 5% statistically reduces strength.

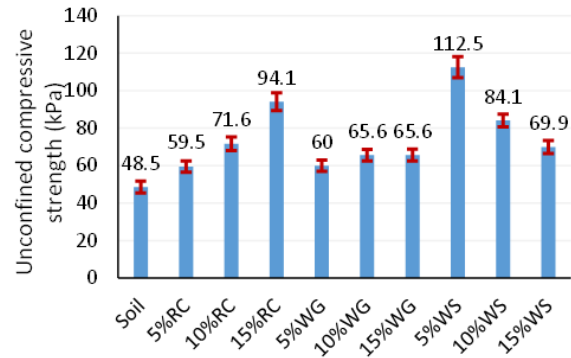


Fig 12 Average unconfined compressive strength of natural and treated soil samples. The error bars represent ± 1 standard deviation (SD)

The stress-strain curves in Figs 9 to 11 show that the stiffness and post-peak behavior of the soil differed markedly among the three materials. The secant modulus was calculated at 50% of the peak stress as follows equation:

$$E_{50} = \frac{q_u/2}{\epsilon_{50}} \quad (1)$$

Where q_u is the peak unconfined compressive strength and ϵ_{50} is the axial strain corresponding to 50% of the peak stress. The secant modulus (E_{50}) of the natural soil was approximately 725 kPa, and this value increased steadily with increasing RC content, reaching 1355 kPa at 15% RC, a trend that correlates well with the possible cementitious bonds observed in the SEM images (Fig. 14). On the other hand, soil treated with WS showed different behavior; at 5%, the stiffness increased sharply to 1,378 kPa, the highest value recorded in this study, but the samples also lost about 25% of their strength between the peak and a strain of 11%, a clear indication of brittle failure. This is consistent with the microcracks observed around the steel particles in Fig. 16. Interestingly, this brittleness largely disappeared at WS contents of 10% and 15%, where both the stiffness and the loss of strength after reaching the peak decreased significantly, suggesting that as the void content increases, the soil fails in a more gradual, ductile manner rather than snapping after the peak. WG followed yet another pattern: across all three percentages, its E_{50} stayed in a narrower

range (roughly 818–908 kPa), as well as post-peak losses were consistently the lowest among the three materials. This aligns with SEM observation that WG mainly fills voids without forming strong bonds, so there is little structure left to fracture once the peak is reached. Taken together, these results suggest the achievement of largest strength gain with WS but at the expense of brittleness, RC offers a steadier balance between strength and stiffness, and WG, although weaker in absolute terms, deforms the most predictably, which may matter as much as peak strength in some field applications.

4.3 Scanning Electron Microscopy

To evaluate the influence of different waste materials on clay soil (CL) fabric, we used a scanning electron microscope (SEM). The natural soil structure consists primarily of parallel layers with interconnected voids between them. Additionally, these structures are characterized by both cohesive and non-cohesive regions that are demonstrated by the scanning electron microscope analysis and shown in Fig. 13.

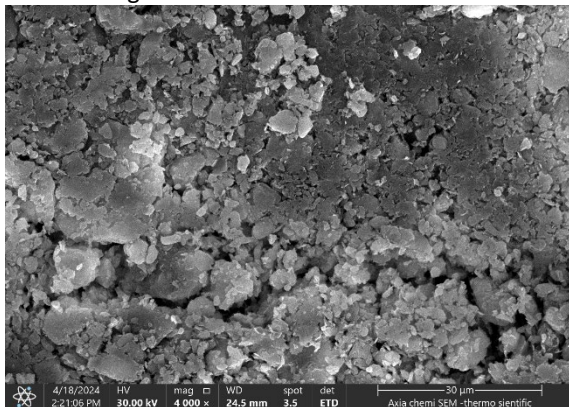


Fig.13 SEM image of natural soil at a magnification of 4000×.

Figure 14 illustrates the microstructure of soil mixed with 10% recycled crushed concrete. It clearly shows a significant reduction in voids and a more cohesive, denser structure. This densification and micro-bonding are directly related to two factors: (1) the effect of fine particles of the RC acting as fillers, (2) pozzolanic reactions facilitated by the high content of calcium oxide (CaO) (10.9%) and silica (SiO₂) in the RC (see Table 1). These reactions are consistent with the possible formation of cementitious gels (C-S-H), which bind the clay particles and enhance cohesion, thereby explaining the gradual increase in strength with increasing RC content. Figure 15 illustrates the effect of adding 10% of WG on the soil microstructure. The primary

mechanism is physical filling, in which fine glass particles occupy the pores between clay matrix particles, resulting in a denser fabric than in natural soil. This behavior correlates with the chemical composition of the silica-rich (31.6%) WG, which showed a limited effect under the present curing conditions. In addition, the smooth, non-porous surfaces of the glass particles provide limited friction and do not form strong adhesive bonds with the clay sheets. On the other hand, Figure 16 shows the SEM images of natural soil blended with 5% of waste steel (WS). The image (a) demonstrated that WS forms a mechanical support structure in clay soil, thereby enhancing mechanical strength through the hardness of the metal particles. In contrast, the SEM image (b) revealed microcracks around the steel particles; these cracks are likely due to thermal expansion/contraction and a hardness mismatch between the mineral and the clay. Despite the high iron content (67.8%), as shown in Table 1, which imparts strength to the soil, the poor chemical cohesion and the presence of these micro-defects explain the trend of a peak followed by a decline in resistance.

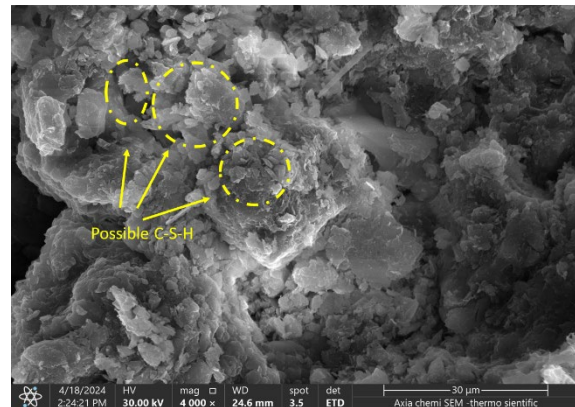


Fig.14 SEM image of soil blended with RC at a magnification of 4000×.

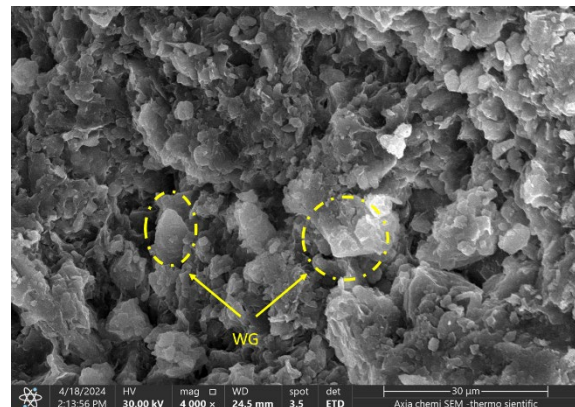


Fig.15 SEM image of soil blended with WG at a magnification of 4000×.

4.4 Particle Size Effects

It is worth noting that the waste materials were prepared with different sieve sizes consistent with those sieve sizes adopted in prior studies [14, 18, 26]. Therefore, the differences in behavior are not related to chemical composition alone, but are also influenced by particle size, shape, and surface area. The smaller size of WG helped fill voids, while the roughness of RC contributed to mechanical interlocking, and WS acted as reinforcing fibers at low percentages. Accordingly, this study is considered a practical evaluation of the materials under their respective standard preparation methods, with a recommendation for future work to standardize particle sizes to isolate these effects. Although this study focuses on improving soil strength, it is worth noting that WS contains high levels of Fe and Cr (Table 1), which may pose long-term environmental risks due to leaching of these metals into the soil. Since no leaching tests were performed, this limitation is acknowledged as one of the constraints of the current study.

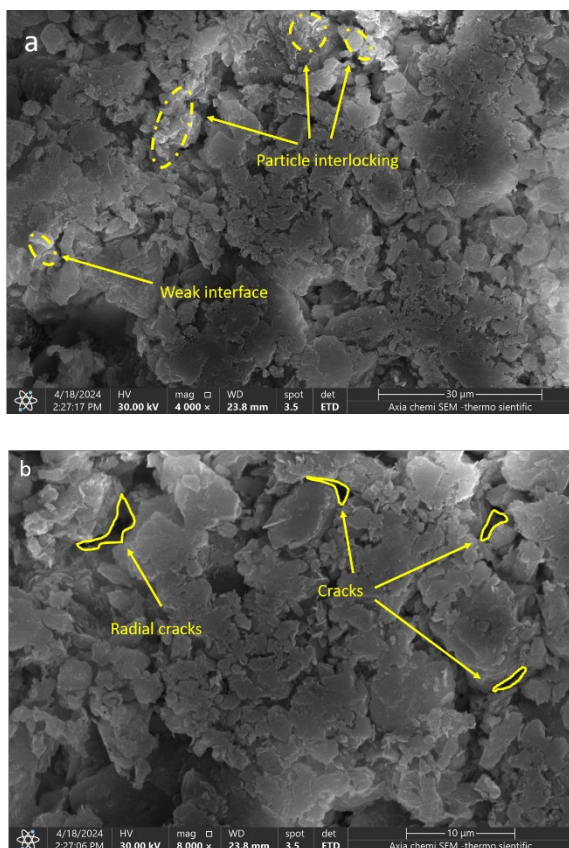


Fig.16 SEM images of soil blended with WS at a magnification of (a) 4000×, (b) 8000×.

5. CONCLUSION

The investigation of the effect of using three industrial waste materials as additives for clay soil was the goal for the current study. The key conclusions are:

- The addition of recycled crushed concrete (RC) to clay soil progressively improved compaction properties and unconfined compressive strength. The best performance of RC was at 15%. This improvement is attributed to a synergistic mechanism that combines granular reinforcement with possible pozzolanic reactions driven by its calcium-rich composition, thereby forming cementitious bonds and increasing the soil matrix density.
- The effect of waste glass (WG) on increasing density and reducing the optimum moisture content was observed at 10%, due to its fine grains filling the soil voids. However, the smooth surface of WG, together with its limited chemical contribution under the present 7-day curing condition, resulted in limited adhesion, leading to only a slight and stable improvement.
- Because of the metal particles acting as mechanical reinforcement fibers, waste steel (WS) showed the most significant increase in strength at low percentages (5%). However, increasing the content to 10–15% led to a decline in strength due to a lack of homogeneity.
- Since mixed waste is difficult for recycling, using it during the construction cycle as a soil stabilizer instead of disposing of it in landfills provides a practical solution with direct engineering benefits and promotes the circular economy.
- In terms of material behavior, 5% WS gave the highest strength but was also the most brittle and raised some concern due to its chromium content. WG at 10% performed best in terms of ductility, while RC at 15% struck a reasonable balance between strength and stiffness. It should be kept in mind that these trends are based on 7-day results; longer curing periods (28 and 56 days) and durability testing would be needed to confirm how well they hold up for actual field use.
- A few limitations should be noted. The three waste materials were not tested at the same particle size, and curing was limited to 7 days. In addition, since WS contains noticeable amounts of Cr and Fe, leaching tests (e.g., TCLP) were not performed in this study; such tests are recommended in future

work to verify its environmental safety before field-scale application.

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