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Impact of recycled concrete aggregate particle size on the strength of soil mixtures for subgrade improvement

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ABSTRACT

Subgrade improvement applications have extensively investigated the financial and ecological benefits of utilizing recycled concrete aggregate (RCA) waste. This solution has been widely studied in recent decades. This study presents the findings of the relationship between different sizes of recycled concrete aggregate (RCA) particles and certain properties of SRCA blends by adding cement. The test results showed that adding RCA with cement to unstabilized soil significantly improved its compressive strength behavior. Incorporating RCA into the soil mixture can more than double its compressive strength. Integrating larger RCA particle sizes into unstabilized soil decreased the optimum moisture content (OMC) while increasing the maximum dry density (MDD). Conversely, using finer RCA particle sizes in soil mixtures increased the compressive strength compared to larger RCA particles. This blend of RCA-stabilized expansive soil is suitable for subgrade improvement applications, such as building low-traffic volume roads and ensuring embankment stability.

1. INTRODUCTION

Modern urbanization is accelerating in all countries throughout the world. Large-scale architectural creations can be found everywhere in Vietnam. Contemporary works are replacing outdated architectural works, which are increasingly fashionable. Each building project, after demolition, generates a significant amount of waste, and how construction waste is processed is always a source of concern and a challenging environmental problem. Disposing of materials such as fly ash, construction debris, brick dust, and agricultural residues risks harming the environment and demands effective solutions. Simply disposing of this waste in a landfill is very likely to damage the soil and water environment. One potential option is to use these waste materials in large-scale construction, such as for land reclamation, as aggregate for concrete, or as additives for cement-based materials (Devil et al., 2020).

Construction waste can be recycled by sorting, crushing, and screening into recycled aggregate. This recycled aggregate can be utilized to produce concrete for road construction and soil stabilization. Recycling discarded materials is essential for sustainable practices. Construction projects, including civil engineering and transportation, demand more aggregates than are currently available. Utilizing construction waste can help fulfil some of the need for natural aggregates. Construction waste-derived aggregates come in various particle sizes, with larger ones suitable for base materials and concrete applications. Smaller aggregates can enhance soil stability, ultimately bolstering ground compressive strength (Arul et al., 2014).

In construction, soil subgrade quality is vital for foundation stability. Soil types differ in strength, with some possessing high compressive strength that is perfect for supporting tall buildings. Conversely, weak ground soils with low strength and significant deformation present difficulties in creating suitable foundations unless addressed effectively. Soil stabilization refers to enhancing the engineering properties of soft soil through the use of stabilizing agents or additives. Soil stabilization encompasses three primary methods: mechanical stabilization, chemical stabilization, and polymer stabilization. Historically, materials like lime, cement, and bitumen have been used for soil stabilization (Sangeetha et al., 2022). Even though these materials enhance the soil's workability and durability, they can have detrimental effects on the environment, such as carbonation and sulfide attack. The utilization of construction waste for soil stabilization not only enhances soil strength but also helps to reduce the negative environmental effects resulting from illegal dumping, carbonation, and sulfidation. Additionally, it lessens the demand for limited landfill space (Sangeetha et al., 2022).

A variety of research has investigated the application of waste from construction and demolition as recycled aggregates in pavement projects such as asphalt mixtures, highway road bases, and subbases. Several experiments were carried out in the laboratory to investigate the application of recycled concrete aggregates (RCAs) sourced from construction and demolition waste (CDW) in hot-mix asphalt (HMA) for use in pavement base courses. The findings indicated that the combinations demonstrated favorable engineering characteristics (Leite et al., 2011; Lee et al., 2012; Qasrawi and Asi, 2016). The study conducted by Poon and Chan (2006) investigated the feasibility of using reused concrete aggregates and pulverized clay bricks as components in unbound aggregates for the subbase. The findings indicated that fully substituting natural aggregates with reclaimed concrete aggregates in the foundation led to a decrease in dry density and an increase in the optimum moisture content of the base material. Arul et al. (2014) investigated the physical characteristics of various common recycled materials sourced from the demolition of construction projects. Subsequently, the research assessed and examined the possible applications of these recycled materials, ranging from foundations to pavements. In a research investigation focused on the durability of concrete mixtures made from recycled aggregates and cement, Kondeti et al. (2024) examined various characteristics, including compressive strength, flexural strength, tensile strength, elastic modulus, shrinkage, and fatigue of the mixtures. The concrete mixes using recycled aggregates included combinations of natural coarse aggregate and recycled concrete aggregate, with replacement levels of recycled aggregate varying from 0% to 100%. The amount of cement in the chosen mixes ranged from 3% to 7%. Consistent with previous research, the findings indicated that the cement content had a more pronounced impact on the strength and performance attributes of the concrete mix. In contrast, the recycled aggregate content had a relatively negligible effect. The research results indicated that certain parameters of clay soil changed with the incorporation of cement and finely crushed aggregates from concrete. These changes included a reduction in plasticity index and increases in compressive strength, tensile strength, and California bearing ratio (Kerni et al., 2015).

Clayed soils, which are known as expansive soils, are considered being of poor quality because they have extremely high levels of swelling and shrinkage. The low shear strength and inadequate drainage of these soils pose significant challenges. With the rapid development of the construction sector, the limited availability of land compels individuals to construct on weak and susceptible terrain. The support from clay sub-grades may be insufficient, especially when they are saturated. Soils with high plasticity can also shrink and expand greatly when moisture conditions change. The variations in volume related to changes in moisture can lead to vertical displacement of the pavement, while the strength of the subgrade can be compromised due to decreased compaction of the subgrade, which would speed up pavement deterioration. Construction wastes have attracted attention for their widespread use in stabilizing expansive soils. The addition of RCA reduces volumetric strain. Moreover, incorporating RCA into unstabilized soil slightly reduces cohesion and significantly increases the internal friction angle. The ratio of strength to stiffness of unstabilized soil also improves when stabilized with RCA. Consequently, rural roadway projects with low traffic flow can incorporate recycled RCA material as part of the base, and weak soil on embankments can be reinforced by replacing it with this material. (Sharma and Sharma, 2019). Earlier research on the strength of soil-cement and recycled aggregate (SRCA) mixtures primarily concentrated on the effects of RCA content, whereas the impact of RCA particle size has yet to be addressed. The strength of the SRCA mixture for pavement subgrade improvement is evaluated using laboratory tests to assess the impact of RCA particle size in this study.

2. MATERIALS AND METHOD

The main emphasis of this research is on the strength under compression of clayey soil, in which recycled concrete aggregates (RCA) are used partially, with different particle sizes.

2.1. Clayey soil sample

The clayey soil samples, also known as expansive soil, have been collected from unused land in Can Tho City, Vietnam. The properties of clayey soil are given in Table 1. Clayey soils are commonly found in southern Vietnam and are characterized by their heavy clay composition, ranging from clay to loam and typically appearing light to dark grey. When dry, clayey soil contracts, becomes extremely hard, and exhibits a strong bearing capacity. When exposed to moisture, these soil types expand and become loose, losing their ability to bear loads. The expansion behavior of these soil types is significantly influenced by their mineralogical composition, which typically contains high levels of montmorillonite and illite minerals (Rajiv et al., 2023). The soil with a plasticity index (PI) of 20.6% is classified as medium plastic soil according to ASTM D4318. Materials that have a high plasticity index can be challenging to handle in construction due to their tendency to be unstable and sticky when they are wet. (Gregory et al., 2008)

The experimental soil sample was air-dried and then spread in a thin layer on a clean rubber sheet. A wooden tool was used to crush the soil roughly, then it was mixed well. After that, the sample was reduced using the quartering method, which involves spreading the soil sample thinly and cutting two perpendicular lines through the center of the soil pile. Two opposite parts were then taken to form one sample.

2.2. Recycle concrete aggregates (RCA)

This study collected conventional reinforced concrete (RC) blocks from deconstructed old structures, which exhibited a compressive strength of approximately 15 MPa. Subsequently, the steel reinforcement from these samples will be removed before the concrete is crushed into aggregate. After the crushing process, granular recycled concrete aggregate (RCA) materials with grain sizes ranging from 0.075 mm to 19 mm were obtained (Figure 1). In this study, four particle size types were adopted, including fine aggregate (FG) 2.36 - 4.75 mm; small aggregate (SG) 4.75 - 9.5 mm; medium aggregate (MG) 4.75 - 19 mm; and large aggregate (MG) 9.5 - 19 mm. Table 2 shows the properties of RCA.

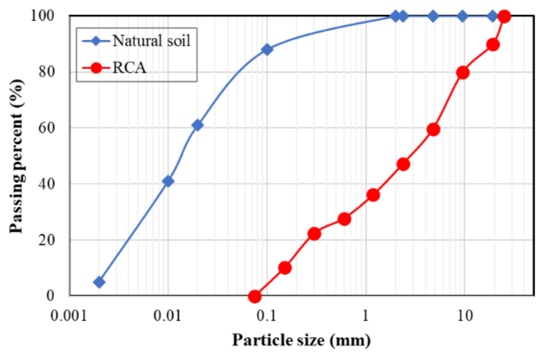


Figure 1. Grain size distribution curves for soil and recycled concrete aggregate

Table 1. Characteristics of clay

Properties	Value
Classification	CL
Specific gravity, G	2.68
Maximum particle size, mm	0.1
Grain-Size Analysis	
Gravel	0
Sand	12
Silt	47
Clay	41
LL, %	39.3
PL, %	18.7
PI, %	20.6
Optimum Moisture Content, %	22.38
Dry Density, kN/m^3	14.5

2.3. Experimental methodology

2.3.1. Los Angeles Abrasion tests

Particle crushing and degradation are major concerns in specific geotechnical applications; therefore, a thorough assessment of this issue is essential when using recycled materials in geotechnical engineering (Sivakumar et al., 2004)

The Los Angeles (LA) abrasion test assesses aggregate toughness and its ability to withstand various forms of abrasion, such as crushing, degradation, and disintegration. The aggregate sample is placed into a rotating steel drum, accompanied by steel balls to induce abrasion through collision. The number of revolutions of the steel drum is automatically determined based on the grain size of the aggregate sample. Once the designated number of revolutions is finished, the sample is removed from the steel drum. Next, the material is extracted from the machine and subjected to pre-screening through a sieve with an opening larger than 1.7 mm to eliminate large particles. LA abrasion value represents the mass loss of the sample before and following the testing. (ASTM C131-03).

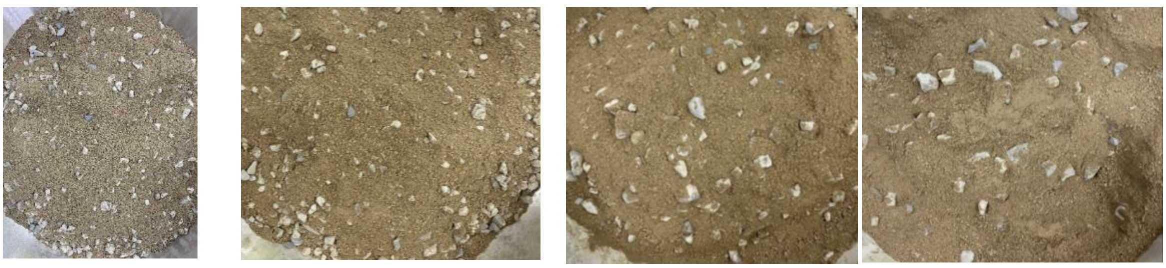
As per the pavement design specifications in Vietnam, the LA abrasion value for aggregates used in road subgrades must not go beyond 35%. (TCVN 8859:2023). The RCA investigated in this study complies with this maximum criterion (Table 2). This suggests that RCA may be suitable for use in the subbase of the road. In this research, the LA abrasion value for RCA aggregate was measured at 28.9%, which is above the 25% and 28% abrasion values noted for recycled concrete by Courard et al. (2010) and Arul et al. (2014), respectively, yet it still adhered to Vietnamese standards.

Table 2. Engineering parameters of RCA materials

Properties	Value
Specific gravity, G	2.54
Liquid Limit	-
Plastic Limit	-
Plasticity Index	NP
Optimum Moisture Content, %	13.8
Dry Density, kN/m^3	24.9
Water absorption, %	2.3
Los Angeles abrasion loss, %	28.9
Coefficient of uniformity (C_u)	31.67
Coefficient of curvature (C_c)	1.14

2.3.2. Compaction test

Compaction tests have been conducted on four soil mixtures and RCA types, including FG, SG, MG, and LG (Figure 2). The mix in the study involved replacing 30% of the weight of the soil with RCA. This specific percentage was chosen because when the RCA content exceeded 30%, there were no noticeable differences in bulk density or moisture content, as reported by Hidalgo et al. (2023).



(a) (b) (c) (d)

Figure 2. Types of soil mixtures and RCA: (a) FG, (b) SG, (c) MG), (d) LG

Divide the prepared sample (35kg for 5 molds) into 5 equal parts and then mix each part with an appropriate amount of water to create a series of samples with varying moisture content. The goal is to ensure that the optimal moisture value determined after the experiment falls within the middle range of the 5 sample moisture values. Label the material samples from 1 to 5 based on increasing sample moisture. Place the mixed moist sample parts in a sealed container for approximately 4 hours of incubation. The clayey soil begins with a moisture content of 10% during the first test, with subsequent tests increasing by 5% for clay. The series of samples that have been prepared will be compressed sequentially, starting with the sample with the least amount of moisture and ending with the sample containing the highest moisture content (TCVN 12790:2020). The primary tools utilized for the standard compaction test consist of a mold measuring 152.4 mm in diameter and a 2.5 kg hammer. The prepared soil sample is placed into the mold and compacted in layers. For this experiment, each sample is compacted into 3 layers, with each layer being of equal thickness after compaction. During compaction, the hammer falls freely and is moved after each impact to ensure an even distribution of compaction strokes across the surface of the sample. Upon completion of the compaction process, remove the mold belt and employ a scraper to level the sample surface with the top edge of the mold. Subsequently, the soil will be extruded from the mold, and a sample of material will be taken from the core of the soil mass, placed in a moisture-retaining container, and dried to determine its moisture content. The compaction process concludes when the unit weight of the sample decreases or ceases to increase, and there are at least two compacted samples with the highest and lowest moisture contents. The procedure is repeated until all 5 samples are finished. The optimum moisture content for compaction (OMC) is established by examining the curve that illustrates the correlation between moisture content and dry density. This moisture content-dry density graph is created using the moisture content and dry density data from the compacted samples. The x-coordinate that aligns with the highest point of this curve represents the optimum compaction moisture content. Table 3 presents the optimal compaction moisture content and the highest dry density values for soil samples enhanced with RCA of various particle sizes.

2.3.3. Unconfined compressive strength (UCS) test

The Unconfined Compression Strength (UCS) test is a widely used and straightforward test that can be conducted with basic laboratory equipment. The cylindrical soil sample is subjected to vertical loading. This experiment can be performed under conditions that are either strain-controlled or stress-controlled. The unconfined compressive strength (UCS) refers to the compressive stress at which the specimen fails while being compressed (Arul et al., 2014).

2.3.4. Compression test specimen preparation

The study utilized a mold with a diameter of 4 inches (101.6 mm) and a height of 4,584 inches (116.4 mm) to create UCS samples for testing materials with 30% or less retained on the 19.0 mm sieve (ASTM D1633-17) (Figures 3 and 4).

Before **After**

Figure 3. UCS samples for testing

(a) (b) (c) (d)

Figure 4. Cross-area of soil mixtures and RCA samples: (a) FG, (b) SG, (c) MG, (d) LG

Table 3. Standard Proctor results for different mixes

Mixture	RCA content (%)	Maximum Dry Density (kN/m^3)	Optimum Moisture Content (%)
S0	0	1.45	22.38
FG	30	1.49	22.04
SG	30	1.52	21.16
MG	30	1.65	20.26
LG	30	1.67	20.12

Along with soil and the recycled aggregate, the UCS test samples included 5% and 7% cement by weight to enhance inter-particle bonding. Table 4 details the component ratios in the SRCA mixture. The samples were subsequently conditioned in a climate chamber for 7 and 28 days at a steady temperature of 25°C.

Table 4. Component ratios in the SRCA mixtures

Mixture symbol	Soil (%)	Type of RCA	Cement (%)
S0	100	0	0
FG-5	65	FG	5
SG-5	65	SG	5
MG-5	65	MG	5
LG-5	65	LG	5
FG-7	63	FG	7
SG-7	63	SG	7
MG-7	63	MG	7
LG-7	63	LG	7

UCS apparatus setup

The samples were compacted using a modified comparative effort within the mold. To begin, place the pads at each end of the specimen. Center the specimen on the lower compression plate of the testing device. Next, position the upper compression plate over the specimen and adjust the apparatus until the component that transmits the compressive load makes contact with the upper compression plate. Then, zero is the deformation indicator. Testing was conducted by applying the load to produce a deformation speed at a 1 mm/min rate on the samples. Figure 5 shows the UCS apparatus setup for testing with large specimens.

3. RESULTS AND DISCUSSION

The compaction and compressive strength in expansive soils are influenced by varying particle sizes of RCA, as detailed in the following section.

Figure 5. Unconfined compressive test (UCS) apparatus

3.1. Compaction of soil mixtures and RCA

The mixture's compaction level was assessed by carrying out various standard Proctor tests to study how the particle sizes of RCA (recycled concrete aggregate) affected it. The tests considered the particle size of RCA as shown in Table 3. The maximum unit weight and optimal moisture for mixtures of different-sized RCA particles and soil were determined from the standard Proctor tests, and the results are displayed in Figures 6 and 7. As illustrated in Figure 6, the initial dry density rose at a swift pace. With a gradual increase in water content, this value slowly declined. The graphs depicting the correlation between moisture content and dry density of SRCA samples in this research were akin to those of the previous research (Cabalar et al., 2016; Wang et al., 2021; Hidalgo et al., 2023).

The research results demonstrated that an increase in aggregate particle size leads to a reduction in optimal moisture content while concurrently causing an increase in maximum dry density (Figure 7). In this study, the LG (large grain grading - 19 mm) value of MDD reaches 1.67 kN/m^3, while the finer particles, FG, have a value of 1.49 kN/m^3. The relationship between OMC and the particle size of RCA leads to a contract tendency. The porosity of the samples decreases as the grain size increases. In contrast, there is a positive correlation between particle size and dry density, with bulk density rising as the average grain size increases. Typically, when two aggregates share the same density, the one with higher porosity will exhibit a lower dry density compared to the aggregate with less porosity. (Atapou et al., 2018; *Ok et al., 2020; Wang et al., 2021*). Conversely, at first, the soil sample is made up of fine particles; when recycled concrete aggregate (RCA) is added to the mixture, it assists in the rearrangement of the particles, as the fine particles fill in the voids, leading to a decrease in the void ratio and subsequently lowering the optimum water content of the mixture.

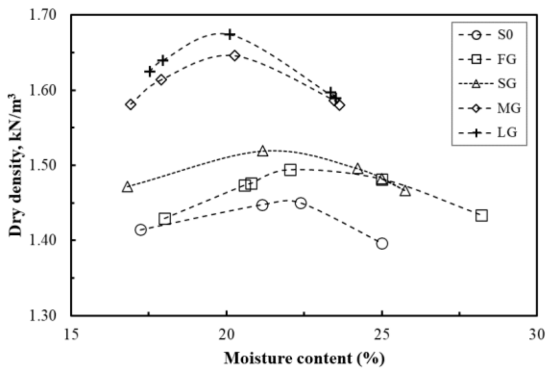


Figure 6. Standard Proctor RCA and soil mixture tests

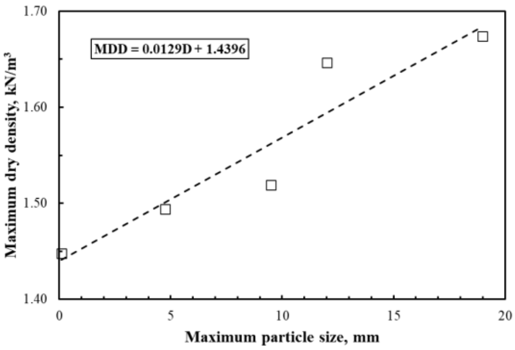
The following regression equations demonstrated the linear correlation between RCA particle size/MDD and RCA particle size/OMC for the test samples:

MDD = 0.0129D + 1.4396 (coefficient of determination, R2 = 0.878)

OMC = -0.1344D + 22.4 (coefficient of determination, R2 = 0.896)

Where: D: particle size of RCA

The findings indicate that both models have R2 coefficients of 0.878 and 0.896, which are close to 1.0 (A value nearer to 1 suggests a superior model, signifying that a majority of the variation in the MDD and OMC variables is attributed to the independent variable, namely grain size). This indicates that almost 90% of the variation in the dependent variables MDD and OMC within the dataset has been explained. This demonstrates that the chosen model is suitable and that the correlation between grain size and MDD and OMC values can be regarded as a linear relationship. Figure 7 clearly shows that the size of RCA particles is positively correlated with their maximum dry density (MDD), while the correlation between RCA size and optimal moisture content (OMC) is negative. A slope of 0.0129 indicates the predicted variation in MDD (in kN/m²) for each one millimeter increase in particle size. Similarly, a slope of 0.1344 indicates a predicted variation of OMC (in percentage) for every one-millimeter decrease in particle size.



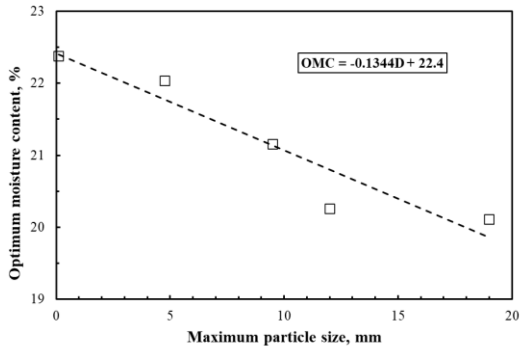


Figure 7. The relationship between MDD, OMC, and particle sizes of mixtures

(Note that: MDD: maximum dry density, OMC: optimum moisture content, and D: particle size of RCA)

3.2. Stress-strain behavior of SRCA

To assess how various SRCA combinations influence the compressive strength characteristics of cohesive soil blends, a set of UCS tests was performed.

Adding RCA to clay soil usually decreases its strength because substituting coarse particles for clay in the mixture decreases the amount of binder (clay) used. This reduction weakens the adhesion between the coarse particles, making the sample more susceptible to damage when it is removed from the mold. (Cabalar et al., 2017). So, in this investigation, two ratios of cement were added into SRAC mixtures, including 5% and 7% of dry weight, respectively (Wang et al., 2003).

The stress-strain behavior results of various SRCA mixtures at 7 and 28 days are depicted in Figure 8. With increasing axial strain, the compressive stress initially increased rapidly, then decreased slowly, and finally stabilized with minimal variation. The compressive stress-axial strain curve can be divided into two stages. Typically, for SRCA specimens, the compressive stress-strain curve exhibits ductile behavior. At first, the compressive stress rises quickly to a peak that occurs at approximately 5% strain. Following this, the strain continues to increase slowly while the stress levels off.

Like normal mixtures, the amount of cement included in the SRCA sample and the duration of curing have a beneficial impact on the compressive strength of the SRCA mixture. The UCS of the SRCA stabilized by different cementitious contents over time is shown in Figure 8. Higher cement content and longer curing times resulted in stronger specimens.

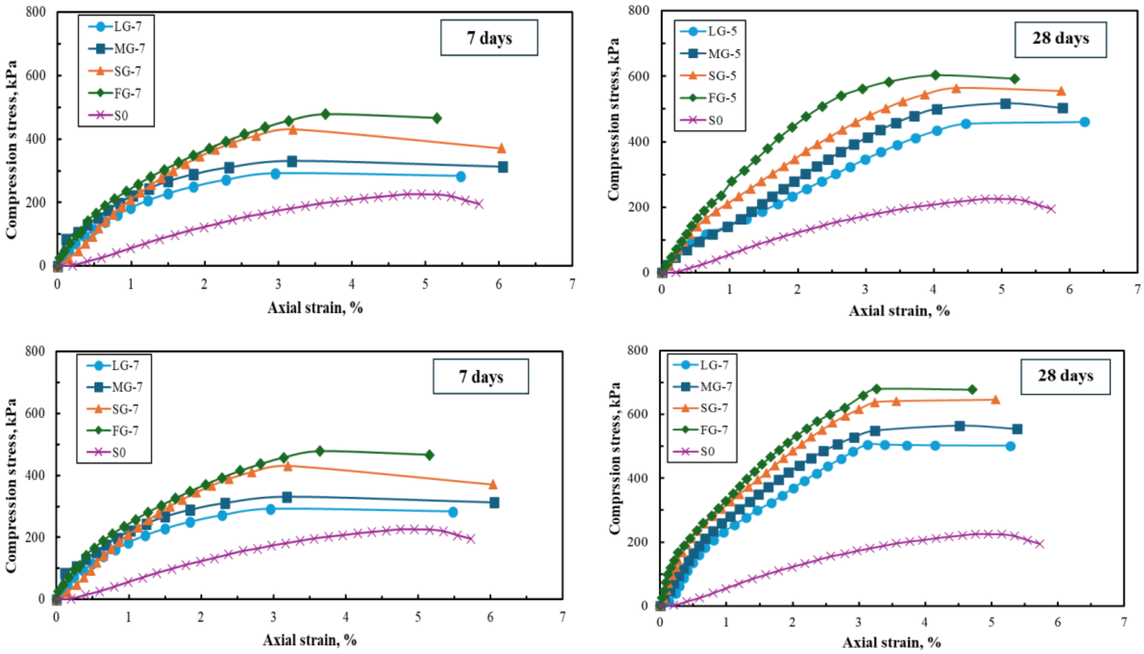


Fig 8. Compression stress-strain curves of various SRCA blends at different curing periods

3.2.1. Impact of cement composition and curing duration on SRCA strength

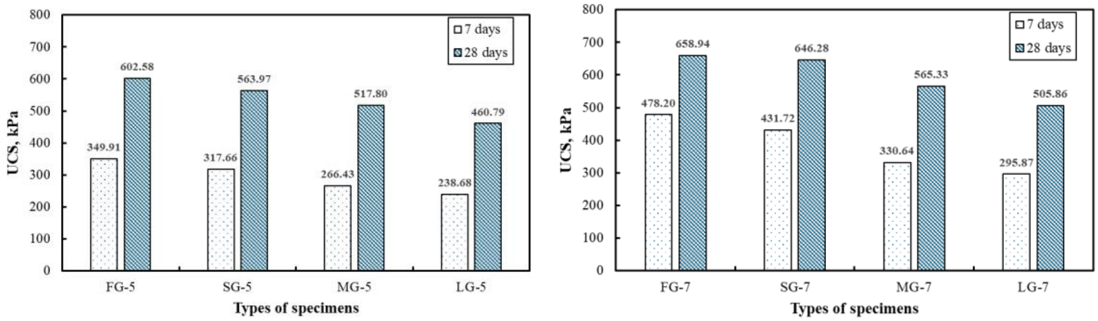
In Figure 8, it is evident that the unconfined compressive strength (UCS) of mixtures is influenced by the cement content. When comparing mixtures at the same level of curing, the UCS value for SRCA blends with a 7% cement ratio is approximately 1.2 times higher than that of mixtures with a 5% cement ratio. However, when cured at 28 days, although the UCS of 7% mixtures was still higher than that of 5% mixtures, the UCS only increased by more than 1.0 times.

Similar to the cementitious content, the curing period is longer, and the unconfined compressive strength (UCS) of SRCA increases significantly. The UCS of all SRCA blends reaches significant values at 28 days (approximately 2.0 times higher compared to 7 days) (Figure 9).

The results show that the properties of soil mixtures in the presence of RCA are consistent with other material studies involving binders and curing times.

3.2.2. The impact of RCA particle size on SRCA strength

When 5% to 7% of Portland cement is used to stabilize the SRCA, the maximum unconfined compressive strength (UCS) of the smaller RCA particle size blend achieves a higher value than the larger RCA particle size blend (Figure 9). This result is similar to that of Lasisi and Ogunjide (1984) on lateritic soils. The maximum unconfined compressive strength (UCS) for the FG-7 sample is approximately 478.2 kPa after 7 days. After 28 days, the strength increases moderately, reaching about 658.94 kPa for the FG-7 sample, which is 1.37 times the strength of 7 days. In contrast, the UCS for the LG-7 specimen is only 295.87 kPa at 7 days and 505.86 kPa at 28 days (Figure 9b). The compressive strength of the specimens in this case is mainly influenced by the bonding between the binder and the particles. Finer particles will enhance the bonding between them, whereas this effect is restricted in larger particles. This is in agreement with the outcome of Lasisi and Ogunjide (1984).



(a) *(b)*

Fig 9. Effect of Curing Duration on UCS

4. CONCLUSION

In this study, we carried out unconfined compressive tests on mixed clayey soil with various RCA particle sizes. Based on the experimental investigations, the following conclusions were reached:

– Recycled concrete aggregates (RCA) are generally suitable substitutes for natural aggregates in geotechnical applications. The compressive strength of SRCA mixtures in the presence of RCA and binder increased significantly. The compressive strength can be increased more than 2 times when replacing RCA into soil mixture.

– The incorporation of recycled concrete aggregate (RCA) into clayey soil decreases the optimal moisture content of the mixtures. Furthermore, the maximum dry density of the RCA increases with the inclusion of larger particle sizes. However, with the same RCA addition content, the distinction between dry density and optimum moisture content between mixtures with different particle sizes is not significant.

– The compression strength of the mixture of cohesive soil and RCA is significantly affected by the size of the RCA particles, as indicated by the results. Remarkably, it was found that the smaller the grain size range, the higher the compressive strength. At 28 days of curing, the mixture with large particles increased the compressive strength by about 2 times while the mixture with small particles could increase the compressive strength by more than 3 times.

– The compressive strength of SRCA specimens increased with higher cement content and longer curing time. At 7 days of curing, the compressive strength of SRCA specimens with 7% cement was much higher than that of specimens with 5% cement content. However, as the curing time increased, the difference was not significant.

Notably, this study did not consider the effects of the various RCA contents. Only certain representative values based on published research guidelines were examined for cement content and curing period.

It is crucial to highlight that research on long-term behavior and cost analysis is still limited. The cost of stabilizing the subgrade is a crucial consideration for any improvement project. Using alternatives like hauling fill from other locations can be quite expensive. The expansion of clayey soil has been shown to be significantly reduced by SRCA mixtures. If these mixtures are effective, they are likely to be more cost-effective than using Portland cement alone. The specific cost will depend on the availability of RCA and cement, as well as the transportation distances involved. Further research is needed to fully explore the commercial application of SRCA in soil stabilization.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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