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Research Article

Cement-Stabilized Granular Volcanic Ash Materials for Construction of Low-Traffic Roads in Yemen

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Granular volcanic ash (GVA) is a volcanic activity material with low density, high porosity, and other undesirable properties that must be improved prior to use in any construction. This material can be considered an alternative for use in road building, given its availability in many locations and in large quantities in Yemen. This article aims to investigate the potential use of GVA for the construction of roads in Yemen when treated with cement stabilizer. Two types of GVA materials with different colors were selected and referred to as red and black GVA materials. Tests performed included the unconfined compressive strength (UCS), compaction, indirect tensile strength (ITS), wetting–drying durability test, and ultrasonic pulse velocity (UPV) test for samples curried for 7 and 28 days. For each GVA–cement mixture, the cement content varied as 2%, 5%, and 8% by dry weight of GVA. Test results revealed that the compaction energy applied during sample preparation led to a significant reduction in the finesse modulus for red and black coarse GVA materials, with reductions of 10% and 23%, respectively. In addition, the cement content and curing period had a significant effect on UCS, ITS, and UPV for cement-treated GVA. The applicable quantity of cement required stabilizing GVA and achieving the base course specification for strength and durability criteria in flexible pavement with low traffic is 8% cement.

1. Introduction

Granular volcanic ash (GVA) materials are widely distributed in various parts of Yemen. These materials spread above the area of Yemen, estimated at more than 17,000 km^2 [1], as shown in Figure 1.

Materials such as these are related with recent volcanic activity. Moreover, GVA materials range from basaltic to andesitic; silica (40%–60% SiO_2) and alumina (Al_2O_3) are the two most important and crucial ingredients in GVA [2, 3]. Other pozzolanic oxides, such as ferric oxide (Fe_2O_3) and magnesium oxide (MgO), which are frequently found in acidic rock, can also be present in trace amounts in GVA [4, 5].

The GVA colors vary from dark gray and black to red color, mostly because of the iron oxides it contains [3, 6, 7]. When exposed to oxidation, the iridescent dark gray surface of some volcanic slags can become a rich reddish brown color [2–4]. GVA materials are cost-effective and easily excavatable natural aggregates characterized by their lightweight, low specific gravity, rough surfaces, nonplasticity particles with poor gradations, and high voids, with porosity exceeding 60% [8, 9]. These materials form after an eruption, wherein gas-charged lava blobs are propelled into the air, cool during flight, and settle as volcanic rock with holes created by trapped gas bubbles [10]. This condition results in a high abrasion value, where the aggregate crushing and Los Angeles abrasion exceed the ASTM specifications, accompanied by high water absorption [5, 8, 11–13]. As a result, these materials have been regarded as undesirable since their strength and engineering characteristics do not meet the specifications necessary for utilization as foundation soil for buildings or pavement applications [14–16]. Then, they are normally refused in preference for expensive alternatives such as crushed stone. But often, these alternatives are not locally obtainable, and therefore, extra cost and time are incurred as a result of carrying of massive quantities in vehicles. If, as a replacement for these alternatives, the properties of locally available materials such as volcanic

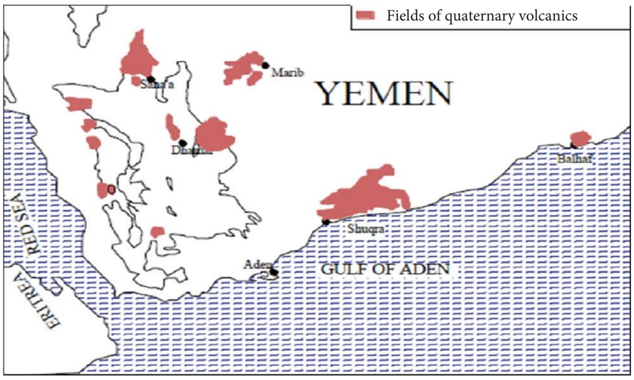


FIGURE 1: Yemen's main sources of quaternary granular volcanic ash [1].

ash materials can be improved by stabilization methods, at that time financial and environmental benefits can be achieved [7, 17].

Soil stabilization is a mechanical or chemical treatment of soil for alteration of one or more properties [18]. Chemical stabilization is a typical practice that involves the use of chemical compounds or combinations [19, 20]. The cement and lime are the most commonly utilized traditional chemical stabilizers [20, 21]. The large amount needed to improve soil strength and the long cure durations are common problems when using these stabilizers [22, 23]. Cement-stabilized soil is utilized in a variety of geotechnical applications, including subgrade for pavement [24, 25], embankment building, and slope protection, and has demonstrated significant economic and environmental advantages [26–29]. According to the Portland Cement Association (PCA) [30] and the American Concrete Institute (ACI) [31], the mixture procedures stipulate that cement can be added as a percentage of the weight of dry soil, with concentrations ranging from 2% to 11%. In addition, they recommend that a minimum strength be achieved after 7–28 days of curing. When cement is added to soil, it stimulates the formation of connections between soil grains, resulting in increased strength and resistance to drying and wetting processes [22, 32–34]. The alkaline composition of GVA, with low silica content, eliminates alkali–silica reactivity with Portland cement [35], making it a suitable material for cement-bound granular layers. Some researchers [36, 37] used fine soil with lime or cement for GVA stabilization. Their assessment, based on compaction and strength indicators, such as CBR and UCS, after 3 days of curing, revealed an increase in the strength of GVA because of the stabilizer. In the Azores Archipelago [26], two types of scoriae were stabilized using cement as a more cost-effective alternative for low-traffic roadways. The mixture's strength was assessed using tests for indirect tensile strength (ITS) and unconfined compressive strength (UCS). He discovered that volcanic scoria treated with 4%–6% cement content had good mechanical performance when used as a sub-base layer in cement-bound granular layers. Berhanu [38] determined that the properties of cinder gravel can be improved by stabilization with 12% fine soil and 5% cement, making it suitable for use as a heavily trafficked base course. Shiferaw [39] investigated the strength and geotechnical characteristics of cinder gravel stabilized with natural pozzolana (volcanic ash) at varying concentrations and curing times for use in road construction. He discovered that these factors increased the cinder gravel's strength and properties. Teshome [6] explored the use of volcanic ash in a 20% mix ratio with natural gravel. Tests were conducted to determine the maximum dry density (MDD), CBR, and abrasion resistance. According to Ethiopian rural communities, the use of GVA is appropriate and suitable to construct pavement with low-volume traffic. It must be combined with a plastic, cohesive substance, such as clay. An experiment involving the use of GVA and fine ash at ratios of 20%–60% was carried out in Ethiopia. MDD and CBR were tested [40]. Other researchers [3, 41] reported that limited applications of VA at 12% with gravel for pavement subgrade construction in Kenyan regions have shown excellent results. The project involved conducting tests on CBR, Atterberg limits (including liquid limit (LL) and plastic limit (PL)), plasticity index (PI), and sieve analysis.

However, there are relatively few studies available on the durability test, ultrasonic pulse velocity (UPV) test on cement-stabilized GVA, and strength for long-time curing. Although these materials are abundant in Yemen, removing them during the construction of any project is time-consuming and costly. Therefore, in this article, the feasibility of cement-treated GVA materials as an economical alternative to the construction of roads with low-volume traffic in Yemen has been evaluated. Two types of GVA from the same cones at the Sana'a region were investigated for this evaluation. The performance of the GVA–cement mixture included cement content (2%, 5%, and 8% by dry weight of GVA), and the curing period (7 and 28) days was assessed over UCS, durability, ITS, and UPV tests.

2. Materials and Methods

This section contains details on the materials and equipment utilized in this investigation. In addition, the testing methodologies used to assess the mechanical performance of GVA–cement mixes were presented.

2.1. Material Used

2.1.1. GVA Material. Two types of GVA material were selected in this research. These GVA types differ in color, with one being red (referred to as red GVA) and the other being gray to black (referred to as black GVA). Figure 2 shows a sample of each GVA material type.

The GVA materials were taken from the Mathbah region, which is located to the northwest of Sana'a, Yemen's capital. These two GVA materials have grain size distribution, as shown in Figure 3. The main geotechnical properties of the two GVA materials used are tabulated in Table 1. Furthermore, the chemical composition of the GVA components is presented in Table 2. Corresponding to the Unified Soil Classification System and ASTM D2487 [31], these GVA materials are classed as poorly graded gravel (GP).

2.1.2. Cement. In the study, ordinary Portland cement (OPC—Type I), according to ASTM C150 [31], produced locally (Amran Cement Factory) was utilized. The cement particles

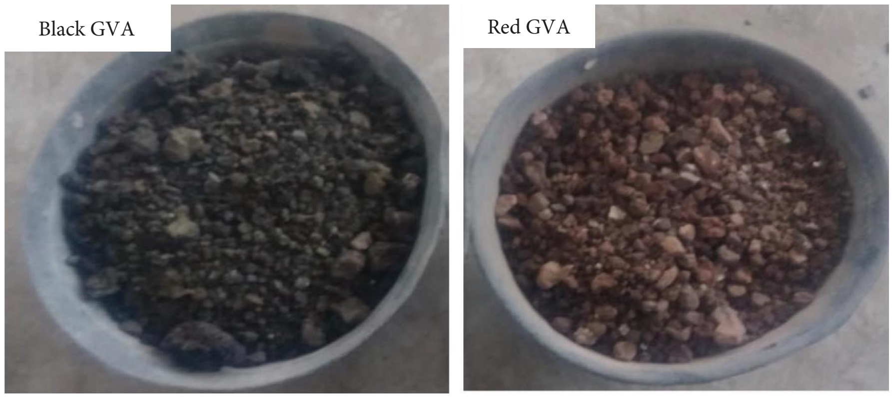
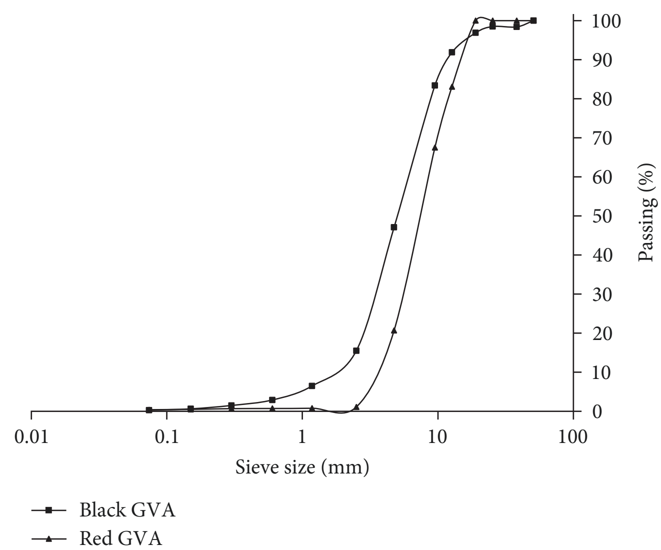


Figure 2: Sample of black and red GVA.



	Sieve size (mm)	38.1	25.4	19	12.7	9.5	4.75	2.5	1.18	0.6	0.3	0.15	0.074
Passing (%)	Red GVA	100	100	100	83.1	67.5	20.7	1.1	0.78	0.72	0.68	0.50	0.40
	Black GVA	98.4	98.5	96.9	91.9	83.4	47.1	15.5	6.5	2.9	1.5	0.63	0.3

Figure 3: Grain size distribution curve of black and red GVA.

had a specific gravity of 3.15. The chemical composition of cement is displayed in Table 2.

2.1.3. Water. In some tests, tap water was used and distilled as required by the testing procedures.

2.2. GVA Materials–Cement Mixtures. The dry GVA was mixed with the target cement content, and the mixture was then manually mixed to achieve homogeneity. Then, the target moisture content was then added to the mixture, which was well-mixed to ensure that the water was spread uniformly. The time it took to prepare GVA–cement mixture and prepare samples by compaction was always less than the initial setting time of the OPC used, which is 45 min, according to ASTM C150 [31].

2.2.1. Compaction Characteristics of GVA–Cement Mixture. The compaction curves for GVA and GVA–cement mixes with varying cement percentages were evaluated using a series of modified proctor compaction tests. ASTM D1557 and ASTM D558 were used to conduct all tests [31].

2.2.2. Specimen Preparation. Figure 4 illustrates cylindrical samples for the UCS, ITS, durability, and UPV tests that were prepared by adding the specified cement content (2%, 5%, and 8% by dry weight of GVA) to dried GVA materials, as shown in Table 3, and mixing them until they had a uniform color. The mixture was blended thoroughly until it was distributed uniformly after having been moistened to the optimum moisture content (OMC). The mixture was transferred to a cylindrical mold of 70 mm diameter and 140 mm height

Table 1: Geotechnical characteristics of two GVA materials.

Property	Value		Test standard [31]
	Red GVA	Black GVA	
Apparent specific gravity (Gs)	2.51	2.11	ASTM C 127 and ASTM C 128
Water absorption %	13.37	18.23	
Los angeles abrasion %	48	55.9	ASTM C131
Liquid Limit (LL)	Nonplastic	Nonplastic	ASTM D4318
Plasticity Index (P I)	Nonplastic	Nonplastic	
Gravel (80–4.75 mm) %	79.29	52.93	ASTM D421
Sand (4.75–0.075 mm) %	20.31	46.77	
Fines (less than 0.075 mm) %	0.4	0.30	
Uniformity coefficient (Cu)	1	3	
Coefficient of curvature (Cc)	2.3	1.2	
Classification by unified soil system	(GP)	(GP)	ASTM D2487
Classification by AASHTO system	A-1-a (0)	A-1-a (0)	ASTM D3282
Fineness modulus	5.26	5.47	ASTM C125

Table 2: Chemical composition of cement and GVA.

Composition	Average value		
	Amran portland cement % [42]	Black GVA % [43]	Red GVA % [44]
SiO_2	21.8	47.2	46.6
Al_2O_3	—	19.2	16.7
Fe_2O_3	2.65	11.6	12.5
CaO	65.7	8.1	9.3
MgO	2.64	4.2	7.8
K_2O	0.0	1.2	0.9
Na_2O	0.65	4.8	2.7
SO_3	—	0.03	0.1
P_2O_3	—	0.5	0.4
TiO_2	—	1.7	2.1
LOI	1.2	0.5	0.7

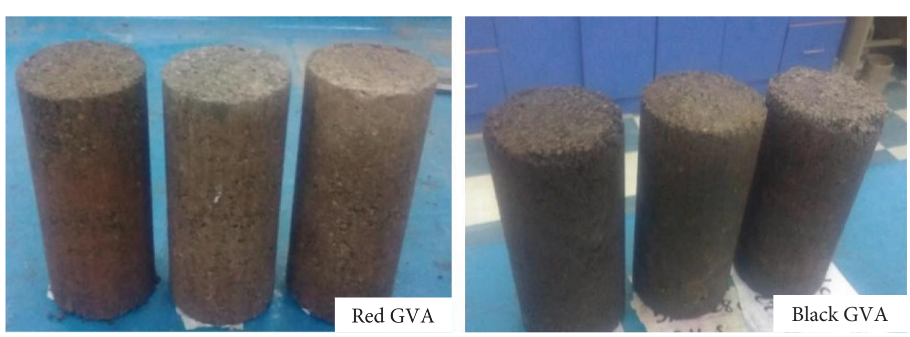


Figure 4: Compacted specimens of red and black GVA for UCS, ITS, durability, and UPV tests.

(slenderness ratio 2) in order to compact the specimens into three separate layers; the surfaces between every layer were thoroughly scarified to bond the layers together. The compacted specimen was with care extracted out of the mold after the molding process was complete. It was then wrapped in plastic and left to cure for 7 and 28 days in a humid environment at a temperature of (20 ± 2°C), with relative humidity of more than 95%.

2.3. Tests

2.3.1. UCS Test. UCS is considered one of the most significant criteria for determining the amount of cement that's

Table 3: Sample requirement of GVA and cement at maximum dry density.

$\left(\frac{\text{Cement}}{\text{GVA}}\right)\%$	Proportion GVA: cement	Black GVA sample for 540 cm^3 of molding		Red GVA sample for 540 cm^3 of molding	
		GVA (g)	Cement (g)	GVA (g)	Cement (g)
2	98 : 02	767.6	15.4	825.9	16.5
5	95 : 05	766.3	38.3	828.0	41.4
8	93 : 07	780.0	62.4	865.0	69.2

(a) (b)

Figure 5: Ultrasonic pulse velocity test: (a) test equipment; (b) UPV measurement.

required for the stabilization of soil through assessing the stiffness and strength of the soil–cement mixture [23]. For stabilized base and sub-base, most of the specifications for the road are used UCS values as criteria [27]. Therefore, the UCS tests were conducted in this study on samples of GVA stabilized by cement curried for 7 and 28 days. After the samples were curried, the weight, diameter, and length of the specimens were measured. Three samples were subjected to a UCS test in agreement with ASTM D1633 [31], and the average value was taken into consideration. The sample is loaded at a constant axial displacement of about 1.25 mm/min. The applied load and resulting displacement are measured with a calibrated proving ring and dial gauge, respectively.

2.3.2. ITS Test. The samples in this study were evaluated for ITS in accordance with Brazilian Standard Association NBR7222 [45]. After a 7 and 28-day curing period, the cylindrical specimen of the GVA–cement mixture was placed horizontally between two plates attached to the base and a loading frame with an approved ring. The load was then applied at a constant rate of 1.25 mm per minute, and a dial gauge was utilized to measure the strain during the test; when the failure occurred, a vertical crack was observed along the diameter of the samples. The following equation is used to compute tensile strength:

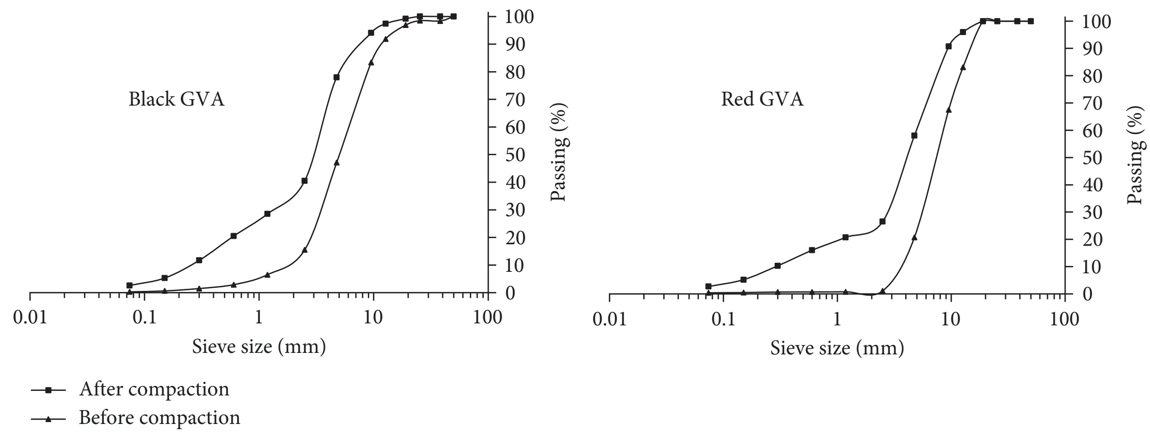
$$\text{Indirect tensile strength} = \frac{2P}{\pi d L}\,(\text{MPa}), \tag{1}$$

where P is the maximum load applied (in N), L is the sample thickness (in mm), and d is the sample diameter (in mm).

2.3.3. Durability (Wetting–Drying) Test. The methodology used for this test depends on the Japan Highway Society [46], and it has similarities to the ASTM D 559 [31] specifications. When the curing time of samples (7 and 28 days) is finished, the samples are taken from the curing room and subjected to the wetting–drying test. The samples were dried for 24 hr in room temperature air before spending another 24 hr immersed in water. This process represents a 48 hr cycle of drying and wetting. After the 12 wetting–drying cycles were completed, the samples were weighed and tested for UCS, and each tested sample's moisture content was determined in order to calculate the weight loss of GVA–cement samples.

2.3.4. UPV Test. As nondestructive testing according to ASTM C597 [31, 47], the UPV can be utilized to investigate the performance of GVA stabilized by cement through density, stiffness, and strength for pavement application. For this purpose, the PUNDIT—plus ultrasonic velocity test system was utilized in this work for collecting all pulse velocity data. Following the completion of the curing time (7 and 28 days), the dimensions of the GVA–cement specimen were accurately measured, and the UPV was determined by contacting the transducers (with 50 mm diameter and 55 kHz frequency, as seen in Figure 5(a)) at the ends of the specimens with a water-based jelly for good coupling to ensure full contact between the sample and transducers as shown in Figure 5(b). The UPV was calculated using the equation:

$$\text{Ultrasonic pulse velocity} = \frac{L}{t}\,(\text{m/s}), \tag{2}$$



Sieve size (mm)			38.1	25.4	19	12.7	9.5	4.75	2.5	1.18	0.6	0.3	0.15	0.074
Passing (%)	Red GVA	Before compaction	100	100	100	83.1	67.5	20.7	1.1	0.78	0.72	0.68	0.50	0.40
		After compaction	100	100	100	96.0	90.7	58.0	26.5	20.7	16.0	10.3	5.2	2.7
	Black GVA	Before compaction	98.4	98.5	96.9	91.9	83.4	47.1	15.5	6.5	2.9	1.5	0.63	0.3
		After compaction	100	100	99.2	97.4	94.1	78.0	40.5	28.5	20.5	11.7	5.3	2.6

Figure 6: Grain size distribution curve of black and red GVA before and after of compaction.

where L is the sample length (in cm), and t is the transmission time (in μs), which was shown on the PUNDIT-Plus digital screen.

3. Results and Discussion

3.1. Compaction Characteristics

3.1.1. Effect of the Compaction Energy Used on the Gradation of GVA Materials. Figure 6 shows the grain size distribution curve (GSDC) for both types of GVA materials before and after using the modified Proctor compaction procedures to produce the samples. Figure 6 reveals that GSDC has undergone major changes in the gradation and finesse modulus of coarse GVA materials, and a similar result was found by Crucho et al. [26]. The finesse modulus (according to ASTM C125 [31]) before and after compaction was 5.26 and 4.73 for red GVA and 5.47 and 4.22 for black GVA, respectively. The relative reduction of finesse modulus for red and black coarse GVA materials was −10% and −23%, respectively. The reduction in finesse modulus after compaction is related to the accumulation of fine aggregate resulting from the breakdown of the coarse aggregate in GVA materials, causing a reduction in the cumulative percentage retained in sieves. The fineness modulus of coarse aggregate is equal to the sum of the cumulative percentage retained divided by 100. The reduction of finesse modulus of black GVA is larger than that of red GVA under the same compaction energy. This finding is attributed to the lower density (specific gravity of black GVA is 2.11), larger voids, weaker resistance to the impact energy, and abrasion (Los Angeles abrasion is 55.9%) of black GVA materials compared with red GVA materials (specific gravity of red GVA is 2.51, and Los Angeles abrasion is 48%). Finally, the gradation of both GVA materials was poorly graded gravel before compaction. However, gravel became poorly and well-graded sand for red and black GVA materials, respectively, after compaction. This change in gradation is attributed to the abrasion of GVA materials under the effect of compaction energy.

3.1.2. Effect of Cement Content on GVA Material Compaction Curve Characteristics. The compaction curves for GVA materials and GVA–cement mixtures with different cement contents considered in this study are illustrated in Figure 7. Figure 7 indicates that increasing the cement content increased the optimum water content for both GVA types. This finding can be attributed to an increase in fine cement materials and more water required for cement hydration. In addition, Figure 7 shows that adding cement to the GVA–cement mixture improves the MDD. This finding is clearly shown in Figure 8, where summary results are displayed to highlight the effect of cement content on the optimum water content and MDD.

Figure 8 illustrates the influence of cement percentage on the OMC and the MDD of red and black GVA materials. As shown in Figure 8, the OMC and MDD for both GVA materials increase with the cement content, and this relationship is similar to that observed by Ali [36]. Therefore, the very fine particles of cement fill up the voids existing between the GVA materials, which require additional water to reach the MDD. Furthermore, cement has a specific gravity (3.15) greater than GVA materials (red GVA 2.51 and black GVA 2.11), resulting in an increase in dry density as observed on red and black GVA materials. By contrast, the OMC of red GVA is less than that of black GVA at the same cement content. This phenomenon is due to the higher percentage of fine materials after compaction for black GVA than for red GVA. Thus, the surface area of black GVA particles is increased, requiring more water to reach to OMC. Conversely, the MDD of red

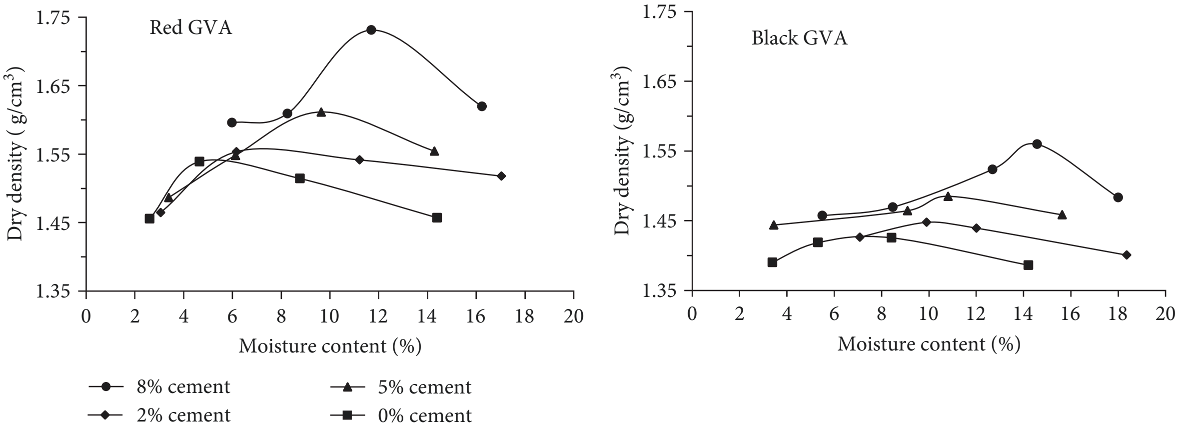


Figure 7: Compaction curves of red and black GVA with different cement contents.

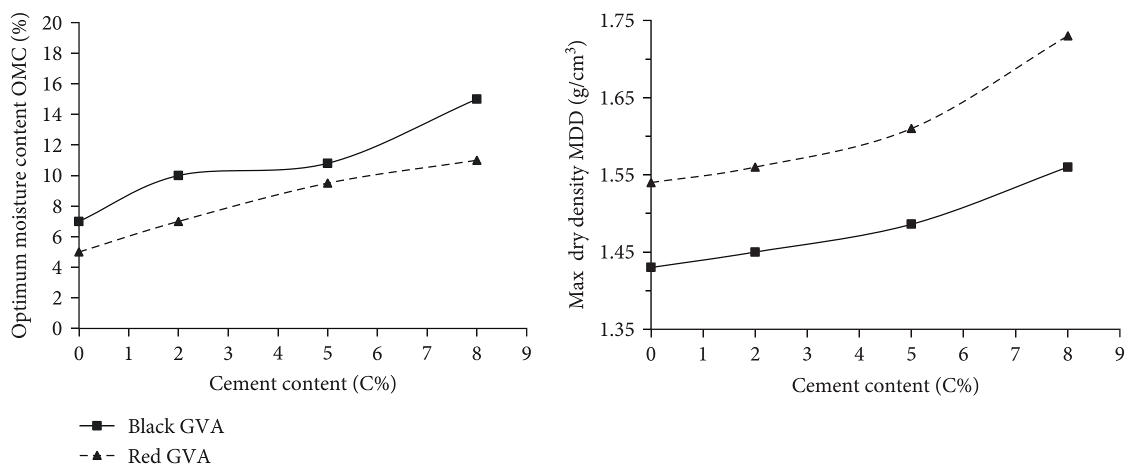


Figure 8: Effect of cement content on MDD and OMC of GVA.

GVA is larger than that of black GVA at the same cement content. This phenomenon is attributed to the larger specific gravity of red GVA 2.51 than that of black GVA 2.11. Both GVA materials generally have nearly the same compaction behavior.

3.2. Strength Performance

3.2.1. UCS. Figure 9 illustrates the correlation between cement content and UCS for black and red GVA after curing times of 7 and 28 days, with the coefficient of variation on the UCS results ranging from 3% to 13% for both GVA types. Furthermore, variations in UCS can be explained in part by the repeatability of the test procedure and minor variability in material properties, such as particle size distribution and particle density. Figure 9 reveals that the UCS for both GVA types increased with the cement content. This phenomenon is attributed to the increase in cement content, which allows the filling of hydration products of the cement in the pores of the matrix and increases the rigidity of its structure by creating numerous hard bonds between the GVA particles. Furthermore, an increase in UCS at the same cement amount was caused by a long curing period. This phenomenon is expected to be attributed to hardened GVA–cement structures and pore reduction due to the long curing process, leading to an increase in strength.

Figure 9 also shows that the UCS for black GVA is higher than that for red GVA at the same cement contents and curing periods. This phenomenon is due to the finer black GVA particles than the red GVA particles. Therefore, most of the cement particles covered all the surface area of the particle, resulting in an improvement in strength and a rigid bond between the cement and GVA particles.

For the mixed design of the base pavement layers, the PCA recommended using the minimum quantity of cement that produced a UCS greater than 2.07 MPa after 7 days of curing [30]. The ACI also specifies that the 7-day UCS for chemically stabilized bases is 1.72 MPa [48]. Furthermore, the Portuguese Infrastructure Agency requires a minimum 28-day UCS of 1 MPa [49]. According to the Australian road design guidelines, the UCS must be greater than 2.5 MPa after 28 days of curing time for pavements with low traffic and 4 MPa for main roads with heavy traffic [50]. As a consequence of the results shown in Figure 9, black and red GVA with 8% cement content fulfilled the criteria for utilizing cement-stabilized GVA for the construction of low-traffic roads.

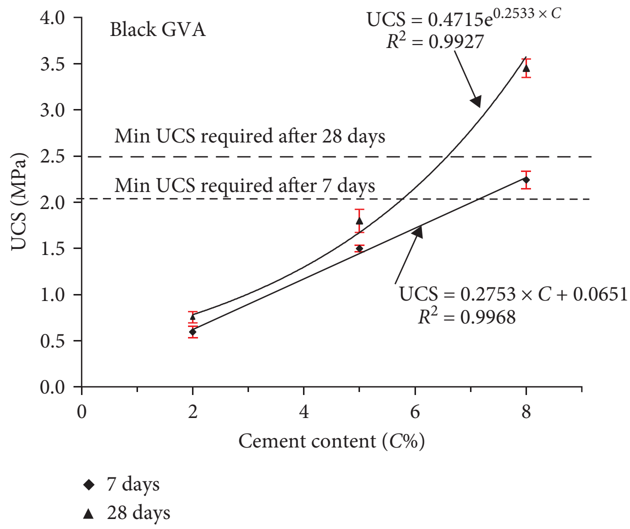


Figure 9: UCS of black and red GVA after 7 and 28 days curing at different cement contents.

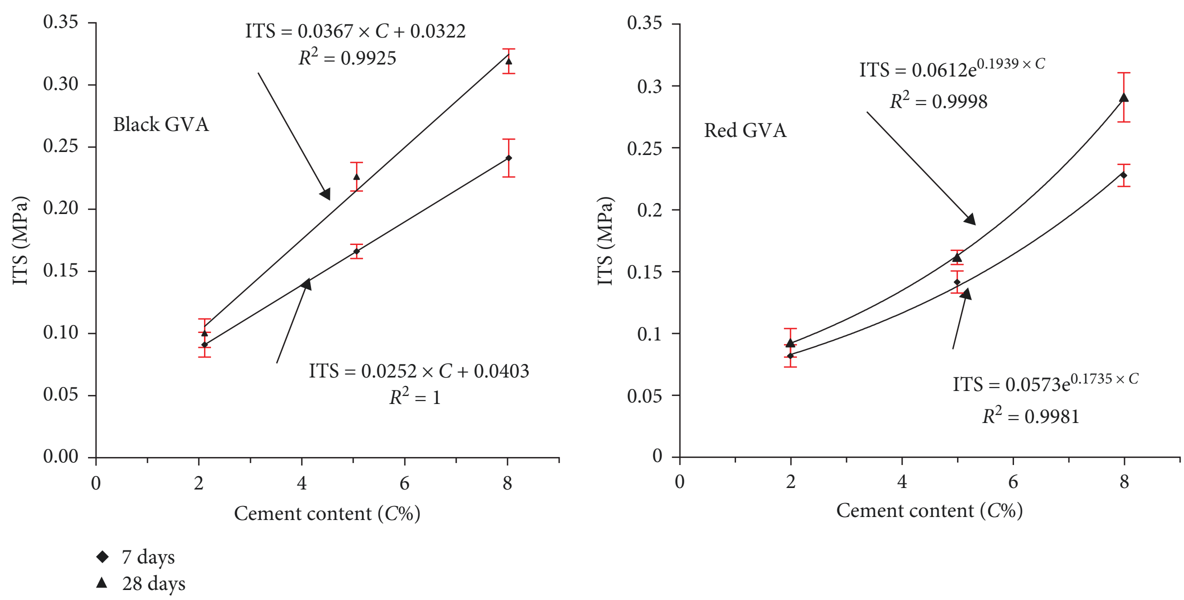


Figure 10: ITS of black and red GVA at different cement contents after 7 and 28 days curing.

3.2.2. ITS. As illustrated in Figure 10, the ITS of cement-treated GVA specimens increased with cement content and curing time, with the coefficient of variation on the ITS results range between 3% and 13% for both GVA types. This phenomenon is due to increased and strengthened bonding in the GVA–cement combination, as previously discussed. Both GVA types with 2% cement content showed equivalent ITS after 7 and 28 days of curing, as presented in Figure 10. However, the black GVA had greater ITS than the red GVA at 5% and 8% cement contents. This effect is explained by smaller black GVA grain size particles than red GVA grain size particles, resulting in fewer spaces between particles that are filled with cement to achieve a strong bond and increase in strength. Furthermore, Figure 10 shows that when the amount of cement was increased, black GVA demonstrated an approximately linear increase in ITS, whereas red GVA demonstrated an almost exponential regression increase in ITS. These variations in regression shape can be partly explained by material differences and test procedure repeatability. The minimum value for the 7-day ITS of cement-stabilized materials with low traffic is 0.2 MPa, according to the South African Pavement Engineering Manual [32] standards for infrastructure agencies [51]. Therefore, both types of GVA treated by cement at an 8% amount satisfy the standards for using GVA in low-traffic pavement construction.

3.3. Durability Performance. Two techniques were used to determine the effects of wetting–drying cycles on the durability of the GVA–cement mixture.

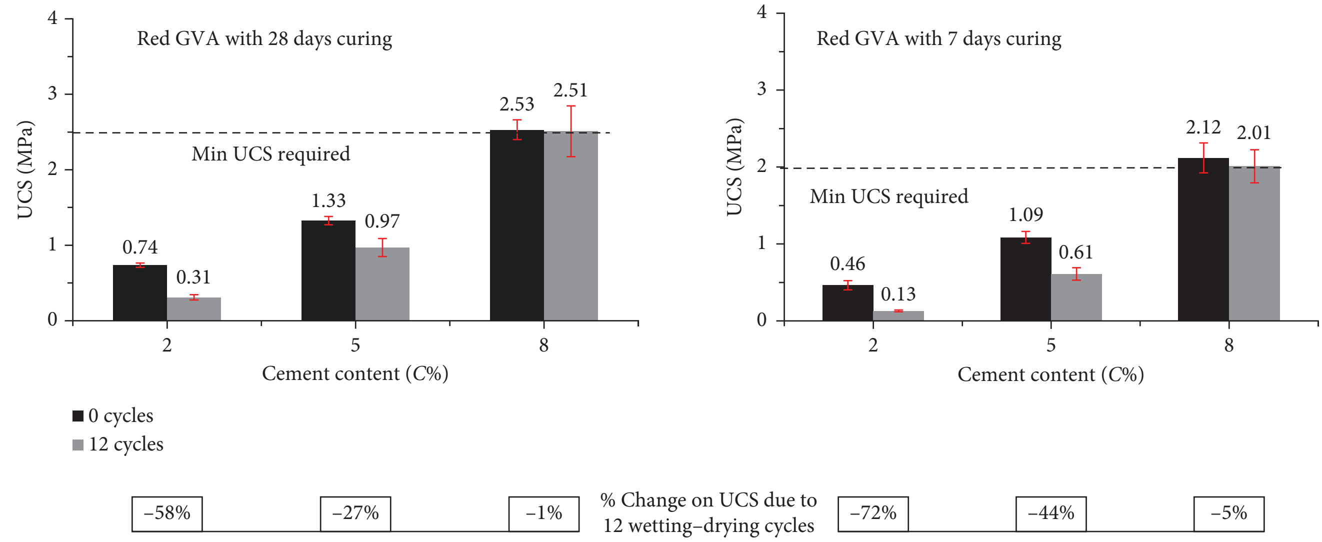


Figure 11: UCS of red GVA with cement content after 7 and 28 days curing before and after 12 wetting–drying cycles.

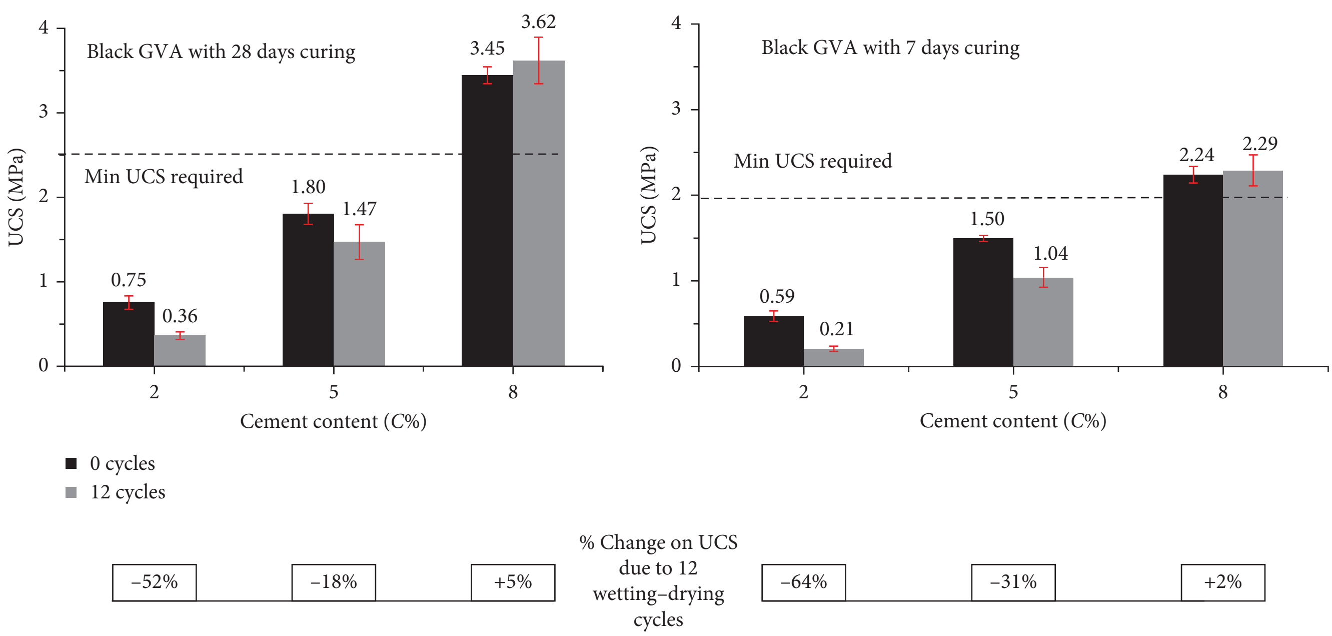


Figure 12: UCS of black GVA with cement content after 7 and 28 days curing before and after 12 wetting–drying cycles.

3.3.1. Effect of the Wetting-Drying Cycles on UCS. Figures 11 and 12 show the effects of 12 wetting–drying cycles on the UCS of red and black GVA stabilized by different cement contents after 7 and 28 days of curing, respectively. Figures 11 and 12 reveal that UCS decreases due to wetting–drying cycles. However, the decrease in UCS is dependent on the cement content and curing time. The results revealed that samples with higher cement content and a longer curing time are more resistant to wetting–drying durability than those with lower cement content and a shorter curing time. This phenomenon indicates that increasing the cement percentage and curing time improved the resistance of the specimen to environmental influences due to a strong and hard bond between the grains of the GVA–cement combination. Figures 11 and 12 also show that specimens of red and black GVA with 2% and 5% cement content, as well as those of red GVA with 8% cement content, curried for 7 and 28 days and subjected to 12 wetting–drying cycles, had a lower UCS than the same specimens that did not undergo any durability testing. These strength losses may be attributed to deterioration caused by the cyclic wetting–drying processes. By contrast, the UCS of the black GVA samples with 8% cement content, which were exposed to 12 wetting–drying cycles after a 7 and 28 days curing period, was significantly higher than the samples that did not undergo the wetting–drying action. This phenomenon is possibly due to the samples with high fine particles and cement contents needing additional water for the completion of the pozzolanic reaction based on the role of water as a

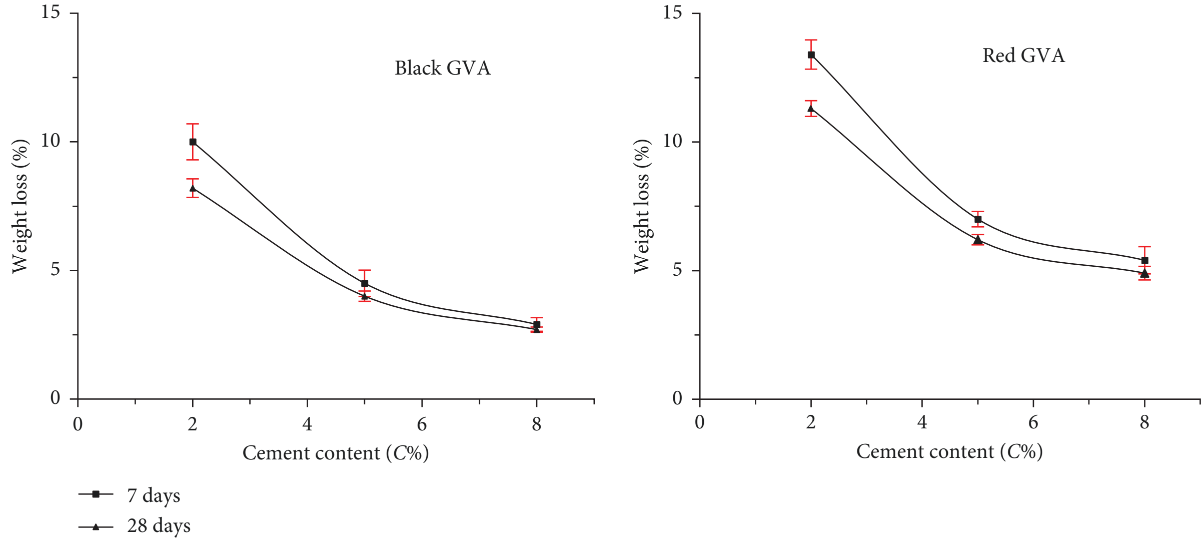


Figure 13: Variation of weight loss with cement content for black and red GVA after 7 and 28 days curing.

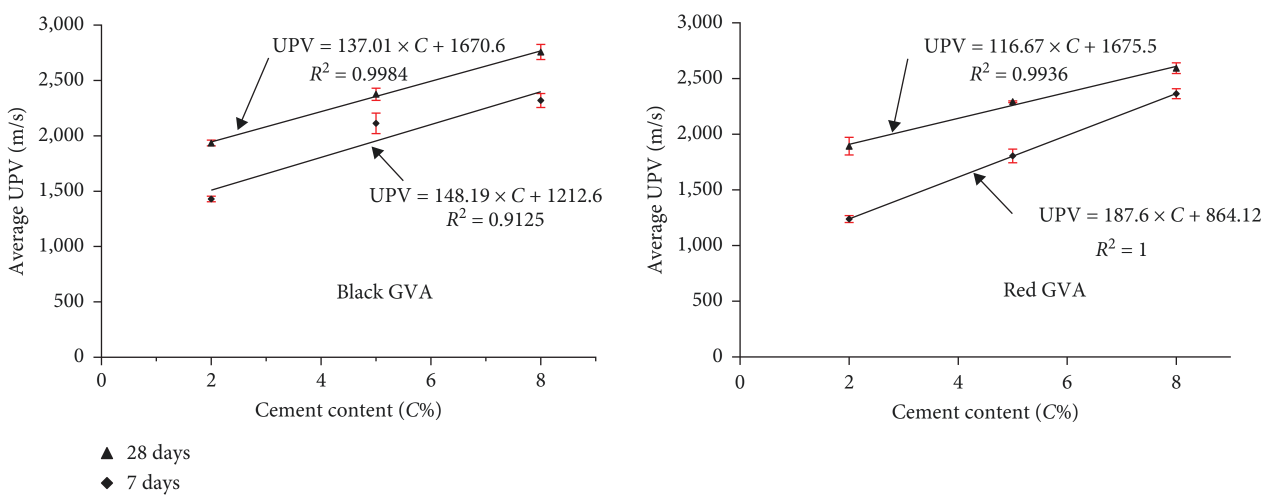


Figure 14: UPV of black and red GVA at different cement contents after 7 and 28 days curing.

catalyst, thereby strengthening the bond. Figure 12 shows that after 7 and 28 days of curing, the 12 wetting–drying cycles at 2% cement dosage led to a −72% and −58% reduction in UCS of red GVA, respectively. However, the decrease at 8% cement was −5% and −1% after 7 and 28 days of curing, respectively. On the contrary, the reduction in UCS of black GVA caused by 12 wetting–drying cycles at 2% cement content was −64% and −52%, respectively, after 7 and 28 days of curing, respectively. Furthermore, the UCS of black GVA increased by approximately 2% and 5% after 12 wetting–drying cycles at 8% cement and 7 and 28 days of curing time, respectively. The coefficient of variation of the UCS results ranges from 5% to 15% for all samples. For example, in specimens with 8% cement content cured for 7 days, the coefficient of variation for the UCS before and after 12 cycles was 9% and 11% for the red GVA and 4% and 8% for the black GVA. Furthermore, changes in UCS can be explained in part by the repeatability of the test procedure and minor variability in material properties, such as particle size distribution and particle density. For pavements with low traffic, the Australian road design guidelines required a UCS of at least 2.5 MPa following a 28-day curing period [39]. Moreover, the PCA suggested utilizing the minimum amount of cement needed to achieve a UCS greater than 2.07 MPa after 7 days of curing [36]. Consequently, at 8% cement content, the black and red GVA meet the strength requirements.

3.3.2. Effect of the Wetting–Drying Cycles on Loss of Weight. Figure 13 shows the effect of cement content and curing time on the weight loss of GVA cement mixtures, including both types of GVA, with the coefficient of variation on the ITS results range between 4% to 11% for both GVA types. Figure 13 reveals that weight loss for both GVA types decreases as cement content and cure time increase. This decrease in weight loss with increasing cement content and curing time is attributed to the strengthening of bonds between the GVA grains, as previously mentioned.

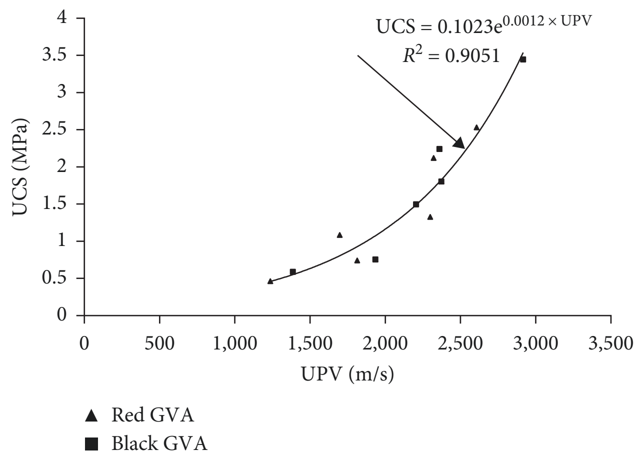


Figure 15: Variation of UCS with UPV of GVA–cement samples.

ASTM D559 indicates that the weight loss of soil–cement mixtures after 12 wetting–drying cycles must not exceed 14% [52]. Therefore, the black and red GVA fulfill the weight loss criteria at a cement content of 2%.

3.4. UPV. Figure 14 illustrates the relationship between pulse travel velocity and cement content in GVA–cement samples, with the coefficient of variation on the UPV results range from 1% to 4% for all GVA types. An increase in cement content and curing time raises ultrasonic velocity. This increase might be attributed to the pozzolanic reaction caused by the curing process, which creates cementitious chemicals, mineral crystals, and bonds that increase the stiffness of GVA as the cement amount and cure time increase. Furthermore, the UPV is influenced by the GVA type, which is related to an increase in the density of the GVA–cement mixture. By contrast, UPV increases approximately linearly with rising cement amounts, which agrees with previous studies on cemented materials [53, 54].

Furthermore, Figure 15 shows that the relationship chart of the UPV and UCS of GVA–cement samples was drawn by exponential regression of all data points, and its coefficient of determination (R^2) is 0.9051, which is similar to other studies on the evaluation of properties of stabilized mixes [47, 55, 56]. The strength of GVA–cement samples may be estimated in a nondestructive and rapid way by using this relationship curve with a UPV value.

4. Conclusions and Recommendations

The following conclusions can be obtained from the test results:

(1) The compaction energy effect on the shape of GSDC and gradation of both types of GVA materials.

(2) Raising the amount of cement in red and black GVA materials increased their MDD and OMC.

(3) The UCS and ITS for both GVA types increased cement content and curing time. Additionally, at an 8% cement content, the UCS and ITS of the black and red GVA satisfy the criteria.

(4) Black GVA fulfills the weight loss criteria at a cement content of 3%, while red GVA fulfills this criterion at a cement content of 5%. This finding might be due to the larger particles of red GVA than black GVA and the need for additional cement content to fill the voids among the particles.

(5) The maximum content of the three criteria (UCS, ITS, and weight loss) must be considered to estimate the minimum cement content for GVA stabilization. Therefore, the minimum cement content for both GVA materials is 8%.

(6) Significant improvements in UPV in cement-treated GVA specimens were detected in relation to cement content and curing times. Furthermore, an important correlation was observed between UCS and UPV.

(7) Results of this study showed the potential of cement as a stabilizing agent in improving the properties of GVA for the construction of roads. Further investigation must be conducted to study the effect of additional factors not included in this study, such as stabilizers, including lime. As the study also aims to evaluate the behavior of the cement-treated GVA under more traffic loading conditions, such as flexural strength, flexural elastic modulus, and fatigue. Furthermore, additional insights into long-term properties should be obtained through various durability tests, such as the freezing-and-thawing test.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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