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**Research Paper / Makale**

# Experimental Study on Long-Term Strength and Performance of Rammed Earth Stabilized with Mineral Admixtures

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**Abstract:** The significance and appreciation of sustainability is rising within the construction industry in the recent past. Conventional rammed earth construction is an ancient form of construction which has many benefits in terms of sustainability. Rammed Earth (RE) in current years, together with other earth-building methods, has been increasingly finding acceptance in many countries worldwide. The overall target of this study is to understand the long-term performance of stabilized RE when exposed to temperature and moisture effects, along with its compressive strength and modulus of elasticity. An experimental investigation was conducted to determine the performance as per the relevant Indian Standard code. Rammed earth was stabilized with cement and Ground Granulated Blast Furnace Slag (GGBS). Twelve cycles of alternate wetting and drying tests were conducted on stabilized RE to evaluate its performance. Performance of stabilized RE was enhanced with a clay content of 12.4% and at higher GGBS content. Also, a substantial increase in long-term compressive strength was noticed with the addition of GGBS. After the 12th cycle of wetting and drying tests, the percentage reduction in mass was 1.6%, which is negligibly small for an exposed earthen surface without a plastering cover.

**Keywords**: Rammed earth, Ground granulated blast furnace slag, cement, compressive strength, performance

# Mineral Katkılarla Stabilize Edilmiş Sıkıştırılmış Toprağın Uzun Vadeli Dayanımı ve Performansı Üzerine Deneysel Çalışma

**Öz:** Sürdürülebilirliğin önemi ve takdiri, yakın geçmişte inşaat sektöründe artıyor. Konvansiyonel sıkıştırılmış toprak inşaatı, sürdürülebilirlik açısından birçok faydası olan eski bir inşaat şeklidir. Rammed Earth (RE) son yıllarda diğer toprak inşa yöntemleriyle birlikte dünyanın birçok ülkesinde giderek daha fazla kabul görmektedir. Bu çalışmanın genel hedefi, sıcaklık ve nem etkilerine maruz kaldığında, basınç dayanımı ve elastikiyet modülü ile birlikte stabilize RE'nin uzun vadeli performansını anlamaktır. İlgili Hint Standart koduna göre performansı belirlemek için deneysel bir araştırma yapılmıştır. Sıkıştırılmış toprak, çimento ve Öğütülmüş Granül Yüksek Fırın Cürufu (GGBS) ile stabilize edilmiştir. Performansını değerlendirmek için stabilize RE üzerinde on iki döngü alternatif ıslatma ve kurutma testi yapıldı. Stabilize RE'nin performansı %12.4 kil içeriği ve daha yüksek GGBS içeriği ile geliştirilmiştir. Ayrıca, GGBS'nin eklenmesiyle uzun vadeli basınç dayanımında önemli bir artış fark edildi. Islanma ve kuruma testlerinin 12. döngüsünden sonra, kütledeki azalma yüzdesi %1.6 olmuştur; bu, sıva kaplaması olmayan açıkta kalan bir toprak yüzey için ihmal edilebilecek kadar küçüktür.

**Anahtar Kelimeler:** Sıkıştırılmış toprak, öğütülmüş yüksek fırın cürufu, çimento, basınç dayanımı, performans

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## 1. Introduction

Rammed earth is a building material with a composition of soil, sand, and clay with or without cement that is majorly used for the construction of small-scale buildings. The construction technique of rammed earth has continued for several decades. It is an old method that has been rejuvenated recently as one of the suitable sustainable building materials used in the construction of natural buildings [1]. Rammed earth uses less carbon dioxide during its preparation and consumes less embodied energy [2]. Rammed earth walls are constructed by compacting moist soil in layers between rigid formwork. When forms are removed, and the rammed earth is cured, it results in a sturdy wall. Rammed earth structures can be used for both load-bearing and non-load-bearing applications and are being used worldwide.

When the rammed earth technique is applied in modern construction, its performance is found to be relatively lower than that of conventional building materials. Hence, a diverse category of additives is required to stabilize rammed earth to improve the mechanical properties as well as durability. Furthermore, the additives enhance the behavior of rammed earth by physical and chemical reactions with the soil particles in the presence of water in the mixture [3].

The use of stabilizers such as cement or lime has been majorly observed for the past few decades since it is easily accessible and provides the required strength with performance characteristics [4]. Portland cement is the most commonly used stabilizer which significantly increases the initial compressive strength and durability of rammed earth [5-7]. Cement content greater than 4% provides higher strength and also enhances the durability properties of rammed earth. A study [8] concluded that a cement content of 6% or higher provided higher compressive strength. The composition of the soil is important to know the amount of cement to be used during RE construction. Cement content of more than 15% is considered too expensive [9]. It is necessary to establish and create bonds that do not disintegrate in the moisture with inert matters of rammed earth in order to achieve higher strengths. This can be achieved by higher cement dosages leading to the availability of more cementitious material [10]. Studies on the cement-stabilized rammed earth showed that the durability characteristics appreciably improved, and shrinkage decreased considerably compared with unstabilized rammed earth [5, 11].

In addition to cement or lime, in the past few years, stabilizers that can be mixed to enhance the cementitious and pozzolanic properties have been in study. The commonly used stabilizers in rammed earth like cement or lime will affect the output of carbon emissions and the energy consumption of buildings [6]. Since cement releases, a greater amount of carbon dioxide into the atmosphere, researchers have been trying to reduce the consumption of cement [12, 13]. Therefore, it is required to study the appropriate additives for proper application as a replacement for the conventional stabilizers to reduce the environmental impacts like temperature and humidity variations. In a study by Siddiqua and Barreto [14], fly ash and calcium carbide residue were used as binders along with cement in stabilized RE. The specimens were tested for compressive strength after 3-, 7-, 28- and 60-days curing periods. The results indicated that the compressive strength gain at 60 days was by an average of 0.23 MPa, which showed that the strength increment was insignificant. In another study [15], for soil stabilized with fly ash, the maximum compressive strength gained at 28 days was 1.2 MPa and at 120 days was 2 MPa. The increment even after 120 was very small. In the case of clayey soil [16], the stabilizing effect of cement with fly ash was studied and a small increment in the compressive strength from 1.4 MPa at 28 days to 2.2 MPa at 90 days was observed. Hence, it is seen that fly ash does not aid strength gain significantly for both short-term and also for long-term curing periods for compacted earth.

However, the stabilizers used should be such that they can improve the mechanical properties of rammed earth materials. One such material is Ground Granulated Blast Furnace Slag (GGBS).

GGBS is a by-product that is produced during the manufacture of iron which is formed by the combination of iron ore with limestone flux [17]. GGBS has been widely used as a partial replacement for cement in concrete [18, 19]. The fineness of GGBS particles is an important factor affecting the strength development. GGBS with a smaller specific surface area causes a decrease in strength, hence it is important to have GGBS particles finer than that cement particles, because of their slow reaction [20]. GGBS has a higher proportion of long-term strength-enhancing calcium silicate hydrates (CSH) than that of concrete made with Ordinary Portland cement and reduced content of free lime, which does not contribute to concrete strength [21]. When GGBS is added to soil, it reacts with the silica compounds present in the soil matrix forming a cementitious compound that helps in enhancing the strength of the soil [22]. A study showed that fly ash mixed with GGBS could improve the physical properties and strength of expansive soils with limited addition of chemical additives like lime [23]. From previous research, it was seen that with an increase in GGBS content beyond 25%, the strength reduced due to the presence of dispensable GGBS particles which did not contribute to the pozzolanic reactions because of the unavailability of water [22, 25]. These properties of GGBS have shown to have the great perspective to be used as stabilizing agents in soils used for rammed earth. From the above literature, it can be seen that GGBS exhibited a better reactivity when used along with cement as a stabilizing agent and hence, GGBS was used in this investigation.

Most of the studies involving rammed earth are done to test its mechanical properties whereas a very limited study is done regarding its performance characteristics. Durability is a rigorous standard to be met and studying the ability of the structure to withstand rain, chemical attack, seasonal wetting-drying and freeze-thaw cycles needs more thorough research. The alternate wetting and drying cycles used in this research are as per the procedure described in Indian Standard code IS 4332 – Part IV [26], where the soil samples are completely immersed in water and then kept in an oven for complete drying. After drying, the specimens are given two firm strokes on their surfaces using a standard wire-scratch brush. This process is repeated for 12 cycles and the loss or reduction in mass of the sample is noted. This method is relatively severe when compared to the actual field conditions. Each cycle is assumed to represent the changes in annual weather conditions from dry to wet seasons. Durability and performance are considered satisfactory if the reduction in mass after 12 cycles of wetting and drying does not exceed 12% of the total mass of RE [27, 28].

The use of the rammed earth technique is constrained due to its poor performance in durability, resistance to friction, and flexural strength in comparison with conventional building materials. Rammed earth elements without any protective layers are exposed to elements of nature like moisture and temperature which depreciates their mechanical properties [29]. This work focuses on understanding the effect of GGBS used as an admixture with cement and their combined effect on the compressive strength and performance characteristics of stabilized rammed earth.

## 2. Materials

### 2.1. Soil

The soil used in this study has a sand content of more than 50% with kaolinite as the predominant clay mineral and is obtained from Bagalur, Bengaluru, and Karnataka, India.

Table 1 provides the properties of the soil after laboratory testing. The grain size distribution curve of the natural soil used is shown in Figure 1. The maximum size of soil particles is 4.75 mm. Figure 2 shows the mineralogical composition of the soil determined by X-Ray Diffraction (XRD) analysis and it is seen that the predominant clay mineral of this soil is Kaolinite.

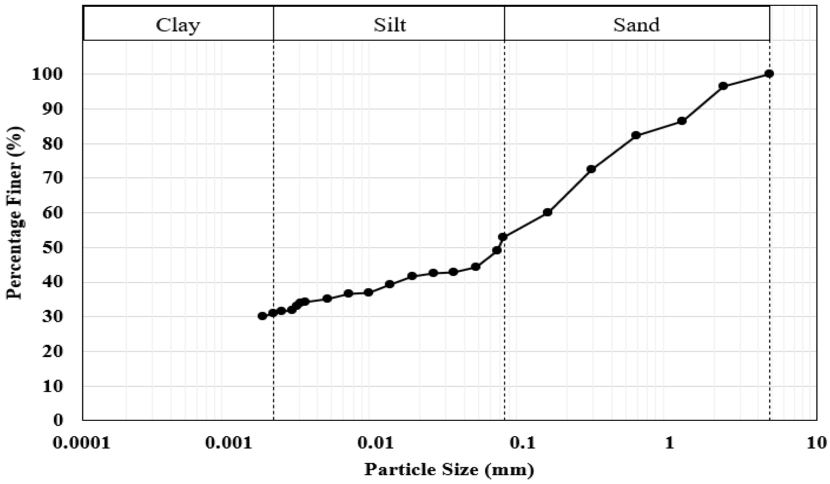


**Figure 1**. Grain Size Distribution Curve of Natural Soil

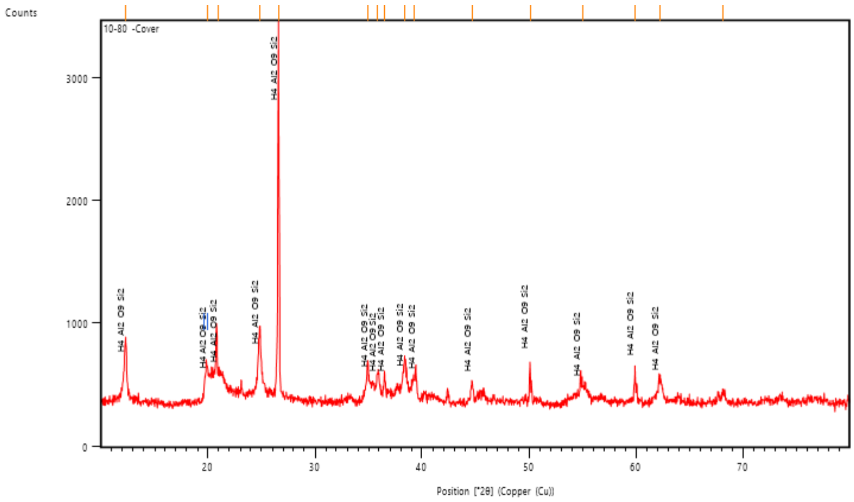


**Figure 2.** Mineralogical Properties of Natural Soil from XRD analysis

**Table 1.** Properties of natural soil

| Sl. No. | Properties | Values |
|---|---|---|
| 1. | *Particle Size Distribution* | |
| | Sand (%) | 53.4 |
| | Silt (%) | 14.5 |
| | Clay (%) | 32.1 |
| | D10 (mm) | - |
| | D30 (mm) | 0.0017 |
| | D60 (mm) | 0.1487 |
| 2. | *Atterberg's Limits* | |
| | Liquid Limit (%) | 33.6 |
| | Plastic Limit (%) | 19.7 |
| | Plasticity Index | 13.9 |
| | Shrinkage Limit (%) | 16 |
| 3. | *USCS Classification* | SC |
| 4. | *Specific Gravity* | 2.69 |
| 5. | *Compaction Characteristics* | |
| | Optimum Moisture Content (%) | 14.6 |
| | Maximum Dry Density (kN/m$^3$) | 19.1 |
| 6. | *Predominant Clay Mineral* | Kaolinite |

### 2.2. Manufacture Sand

Manufactured Sand (M-Sand) belonging to Zone II gradation of Indian Standard Code was used as fine aggregate in various mix ratios to reduce the amount of clay in the natural soil. The fineness modulus of manufactured sand used is 2.89. The mix ratio of modified soil is tabulated in Table 2. The clay percentage of reconstituted soils used in this experimental program is 12.4%, 16%, and 31%.

**Table 2.** Mix proportion of modified soil and m-sand mix

| Mix Ratio (by weight) | | Clay Content (%) [modified] | Specimen Notation |
|---|---|---|---|
| Natural Soil | M-Sand | | |
| 1 | 0 | 31 | Set1 |
| 1 | 1 | 16 | Set2 |
| 1 | 1.5 | 12.4 | Set3 |

### 2.3. Portland Cement and Ground Granulated Blast Furnace Slag (GGBS)

Ordinary Portland cement of grade 53, as per the Indian Standard code, was used to stabilize the rammed earth. The cement content was kept constant at 5% throughout the study. Ground Granulated Blast Furnace Slag (GGBS), an industrial waste product was procured from a steel plant in Bellary, Karnataka, India. As seen from previous research, the optimum quantity of GGBS for strength gain is less than 25% [24, 25]. Hence, in this experimental study GGBS varied in percentages of 7, 14, and 20% was used. The physical properties of GGBS are tabulated in Table 3.

**Table 3.** Physical Properties of GGBS

| Properties | Value |
|---|---|
| Colour | White |
| Specific Gravity | 2.83 |
| Liquid Limit (%) | 29 |
| Lime Reactivity (MPa) | 6.5 |
| Specific Surface Area (kg/m$^2$) | 312.5 |

## 3. Experimental Method

### 3.1. Material Mix Proportion

Cylindrical specimens of diameter 150 mm and height 300 mm for both unstabilized and stabilized rammed earth were cast and tested for compressive strength and performance characteristics. The materials were mixed and cast in the proportions as tabulated in Table 4. The densities of all the mixes were kept constant at 19 kN/m$^3$ since this is the commonly adopted density at the site. The cement contents for stabilized rammed earth were kept constant at 5%. A total of 90 specimens were tested for 28 days and 90 days for compressive strengths and were also evaluated for their performance characteristics.

### 3.2. Moulds and Rammers

A cylindrical mould with a diameter of 150 mm and a height of 400 mm was used for casting the rammed earth specimens. Two types of rammers were used for compacting the soil. A square rammer of height 900 mm and weight 3.78 kg having a square base plate of 100 mm width with 20 mm thickness was used. Another semi-circular rammer of height 900 mm and weight of 2.77 kg having a semi-circular base plate of 140 mm diameter with 20 mm thickness was also used. To have an effective bonding between the layers of the rammed earth specimens, an indenter with a conical bottom was used.

**Table 4.** Material Proportions of Rammed earth

| Set | Mix Notation | Cement | GGBS |
|---|---|---|---|
| Set1 | S11 | - | - |
| | S12 | 5 | - |
| | S13 | 5 | 7 |
| | S14 | 5 | 14 |
| | S15 | 5 | 20 |
| Set2 | S21 | - | - |
| | S22 | 5 | - |
| | S23 | 5 | 7 |
| | S24 | 5 | 14 |
| | S25 | 5 | 20 |
| Set3 | S31 | - | - |
| | S32 | 5 | - |
| | S33 | 5 | 7 |
| | S34 | 5 | 14 |
| | S35 | 5 | 20 |

### 3.3. Performance Test

The cylindrical specimens with dimensions of 300 mm in height and 150 mm in diameter were used to conduct the performance study. The procedure followed for testing the rammed earth specimen, was as per IS 4332 (Part IV). Method of alternate drying and wetting for cement stabilized soils was adopted. The specimen was oven-dried before immersing in water and its dry weight was noted. The specimen was submerged in water at room temperature of 28°C for 5 hours and then removed. Then they were oven-dried at a temperature of 70°C for 42 hours. The specimen was taken out from the oven and then the performance test was carried out by conducting an abrasion test with the standard wire brush as shown in Figure 3. The surface of the specimen was gently scrubbed with the wire brush by giving two strokes on each surface with the brush.

**Figure 3.** Wire Scratch Brush (as per IS 4332)

Wire scratch brush used was made of mild steel bristles 50 mm long and16 mm wide with a thickness of 0.45 mm, assembled in 50 groups of 10 bristles each and mounted to form 5 longitudinal rows and 10 transverse rows of bristles on a 190 mm X 65 mm hardwood block which confirms to IS 4332. About 18-20 mild strokes are given to induce abrasion on the entire surface of the specimen. This completes one cycle of performance study. Each cycle of alternate drying-wetting and scrubbing with a wire brush is assumed to represent summer and rainy seasonal exposure of the surface of rammed earth.

In total 12 cycles of abrasion, tests were carried out in the performance study, representing 12 cycles of dry and wet seasons. The percentage weight loss of the specimen was evaluated after each cycle which is an indicator of the loss of mass of the specimen when exposed to heat, humidity, and moisture. After 12 cycles of performance, the test was completed and the compressive strength of the specimen was evaluated and compared with the compressive strength of the specimen before the performance test.

### 3 4. Compression Test

Rammed earth cylindrical specimens were tested in the Universal Testing Machine (UTM) for compressive strength and the initial tangent modulus was noted. Capping for the specimen at the top and bottom surface of the specimen was made using a rich cement mortar of rich mix 1:3 with a thickness of 10 mm. An extensometer with a least count of 1 micron was fixed onto the specimen to measure the strain. A circular mild steel plate of thickness of 20 mm was provided on top of the specimen to ensure uniform load application on the specimen. Testing of rammed earth specimen was carried out in wet condition after 28-day of curing. The strain was recorded till failure load. Initial Tangent Modulus and also the resulting compressive strength was determined with stress-strain curves. The test setup is shown in Figure 4.

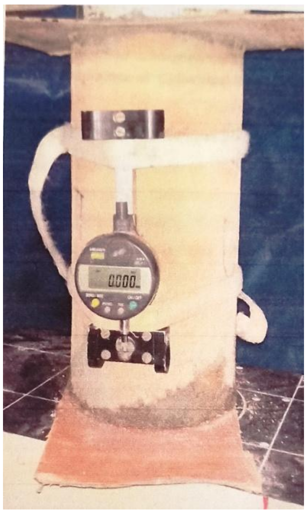

**Figure 4.** Setup for Compression Testing

## 4. Results and Discussion

### 4.1. Effect of GGBS on wet compressive strength and initial tangent modulus

The compressive strength of rammed earth cylinders was examined after 28 days by testing them in wet conditions. Results of compressive strength on rammed earth specimens are presented in Table 5. A total of 15 mix proportions and 45 rammed earth specimens were tested for 28-day compressive strength. It can be seen that with the addition of cement and GGBS, the compressive strength has increased by more than 100%. With an increase in the percentage of GGBS of cement stabilized rammed earth, the wet compressive strength has increased substantially. With the addition of GGBS, a larger improvement in strength for stabilized rammed earth can be observed from 0.83 MPa to 3.51 MPa. The highest wet compressive strength of 3.51 MPa was obtained for the mix containing a clay content of 12.4% and GGBS content of 20%. Figure 5 shows the variation of wet compressive strengths for different mixes. This increase may be due to a higher amount of GGBS leading to a good sand fraction which provided a denser soil matrix. The strength increment for rammed earth with 20% GGBS is seen for all mixes, which may be due to the hydration and slow pozzolanic reactions between the compounds formed in the soil, such as silicates of alumina and oxides of calcium with GGBS, which in turn form a strong bond between the soil mixtures [30]. The resulting slow pozzolanic reaction may also assist in enhancing the long-term strength of the mix with the addition of GGBS. The initial tangent modulus (ITM) for specimens with GGBS varies between 1770 MPa to 3573 MPa and increases with an increase in the percentage of GGBS. The ITM increases by 74% with an increase in the percentage of GGBS. The failure modes observed during the specimens' compression tests correspond to the brittle type of failure (Figure 6).

**Table 5.** Wet Compressive Strength and Initial Tangent Modulus of stabilized rammed earth

| Mix Notation | Wet Compressive Strength in MPa | Initial Tangent Modulus in MPa | Moisture Content at time of testing in % |
|---|---|---|---|
| S11 | 0.61 | 153 | 6.5 |
| S12 | 0.73 | 584 | 13.9 |
| S13 | 0.83 | 1574 | 14.7 |
| S14 | 1.13 | 2378 | 14.2 |
| S15 | 1.39 | 2744 | 15.2 |
| S21 | 0.32 | 178 | 6.2 |
| S22 | 0.88 | 753 | 13.6 |
| S23 | 1.55 | 1770 | 13.4 |
| S24 | 1.8 | 2485 | 13.1 |
| S25 | 3.18 | 3239 | 13.5 |
| S31 | 0.27 | 245 | 5.4 |
| S32 | 0.93 | 946 | 11.6 |
| S33 | 1.88 | 2051 | 12.3 |
| S34 | 2.3 | 3065 | 12.1 |
| S35 | 4.51 | 3573 | 11.7 |

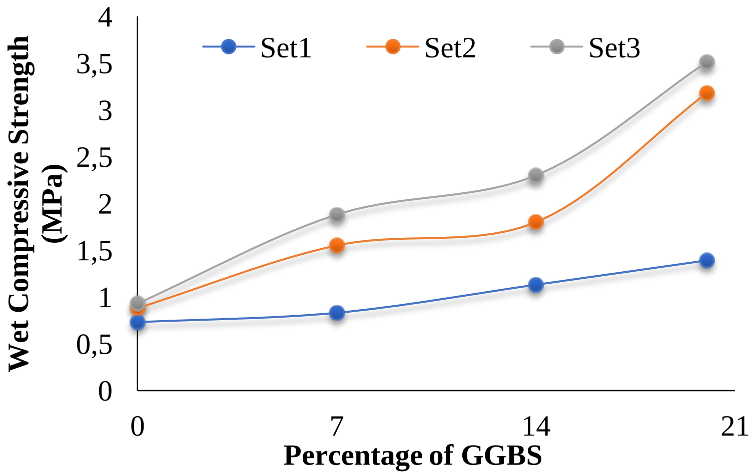


**Figure 5.** Variation of wet compressive strength with the percentage of GGBS

**Figure 6.** Typical failure pattern of rammed earth compression specimen

### 4.2. Effect of GGBS on Performance Characteristics

The performance test was carried out by alternative wetting and drying of the specimens for 12 cycles. The unstabilized rammed earth specimens lost their integrity after immersion in water and hence, their results are not reported. The mixes with 31% clay content did not show a high improvement in their performance characteristics when compared to the other mixes. The performance of the mix with 12.4% clay, 5%cement, and 20% GGBS has shown enhanced performance characteristics compared to the mix with 16% clay. For all the mixes containing 20% GGBS, a very high improvement in performance characteristics is seen in comparison with mixes containing lower percentages of GGBS.

**Table 6.** Performance characteristics of rammed earth

| Mix Notation | Oven-Dried Weight of Specimen in g | Percentage Reduction in weight | | | |
|---|---|---|---|---|---|
| | | After 3rd cycle | After 6th cycle | After 9th cycle | After 12th cycle |
| S12 | 9808 | 2.76 | - | - | - |
| S13 | 9738 | 2.88 | 4.17 | 5.86 | 7.49 |
| S14 | 9715 | 2.50 | 3.84 | 4.99 | 6.68 |
| S15 | 9890 | 2.06 | 3.76 | 4.80 | 6.33 |
| S22 | 10646 | 2.67 | 3.88 | 4.80 | 6.32 |
| S23 | 10456 | 2.08 | 3.24 | 4.47 | 5.62 |
| S24 | 10575 | 2.04 | 2.96 | 3.93 | 5.15 |
| S25 | 10332 | 1.44 | 2.64 | 3.48 | 4.92 |
| S32 | 10732 | 1.69 | 2.88 | 4.01 | 5.07 |
| S33 | 10662 | 0.97 | 1.49 | 2.56 | 3.18 |
| S34 | 10514 | 0.67 | 0.91 | 1.46 | 1.74 |
| S35 | 10665 | 0.51 | 0.83 | 1.28 | 1.61 |

The reason due to the enhanced performance may be because of the improvement in coverage of the surface area of clay particles with finer particles of GGBS thus inducing stability of RE. Also, with an increase in GGBS content, the formation of micropores after the completion of wetting-drying cycles is reduced leading to enhancement in its performance characteristics. As the result, the scope for the reaction of clay minerals with moisture is reduced to a great extent. The reduction in mass for mix S35 (with 20% GGBS) after 12 cycles is about 1.6%, whereas for mix S32 (without GGBS) mass decreased by 5%. This is appreciable for earthen walls exposed to temperature and humidity without the cover of plastering. Similarly, for other mix ratios, the results obtained were similar. Hence, erosion resistance due to wetting and drying cycles is improved with an increase in GGBS content. The detailed results of performance on all the mixes are shown in Table 6. The images of specimens before and after the performance test are shown in Figure 7.

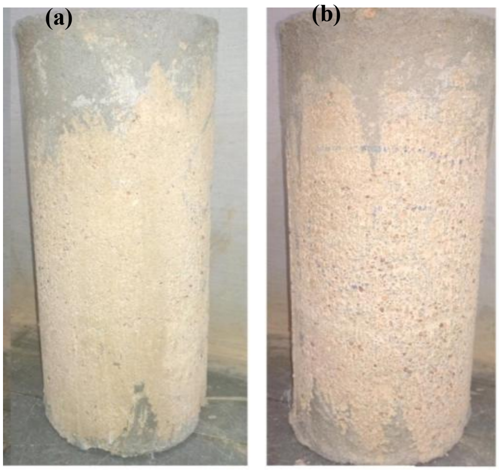


**Figure 7.** Specimens (a) before and (b) after the performance test

### 4.3. Effect of GGBS on Long-Term Wet Compressive Strength

The wet compressive strength of rammed earth specimens was determined for the specimen after the performance test at 90 days. The specimens that underwent wetting and drying cycles exhibited a higher compressive strength when compared with the same mixtures under normal curing. The wet compressive strength of specimens of all series shows a continuous increase with time.

**Table 7.** Wet compressive strength before and after performance test

| Mix Notation | Wet Compressive Strength at 28 days (before performance test) in MPa | Wet Compressive Strength at 90 days (after performance test) in MPa | The moisture content at the time of testing (%) |
|---|---|---|---|
| S13 | 0.83 | 1.42 | 15.0 |
| S14 | 1.13 | 1.98 | 14.6 |
| S15 | 1.39 | 4.02 | 14.3 |
| S22 | 0.88 | 1.76 | 14.6 |
| S23 | 1.55 | 3.45 | 13.8 |
| S24 | 1.8 | 3.96 | 13.5 |
| S25 | 3.18 | 4.30 | 13.9 |
| S32 | 0.93 | 2.26 | 12.5 |
| S33 | 1.88 | 3.68 | 12.8 |
| S34 | 2.3 | 4.02 | 12.0 |
| S35 | 4.51 | 6.23 | 12.7 |

The specimens prepared with GGBS in combination with cement have shown a definite increase in strength when compared with the specimens prepared with only cement at 90 days of curing time. As the percentage of GGBS increased, the long-term wet compressive strength also increased. The increase in strength with time is higher for RE prepared with 20% GGBS irrespective of clay content. The highest long-term compressive strength of 6.23 MPa was obtained for RE with a clay content of 12.4% and GGBS content of 20%. The average increase in wet compressive strength was 78% for specimens after 90 day curing period when compared to the 28-day curing period. Thus, it can be concluded that GGBS has contributed to the long-term strength which is due to the slow pozzolanic reaction of the cementitious compounds in the rammed earth specimens. Since the pozzolanic reaction depends on the availability of calcium hydroxide and the reaction is slow, it takes a longer time for gaining higher strengths. The detailed results of wet compressive strength are shown in Table 7. Figure 8 shows the variation in strength for different mixes before and after performance tests.

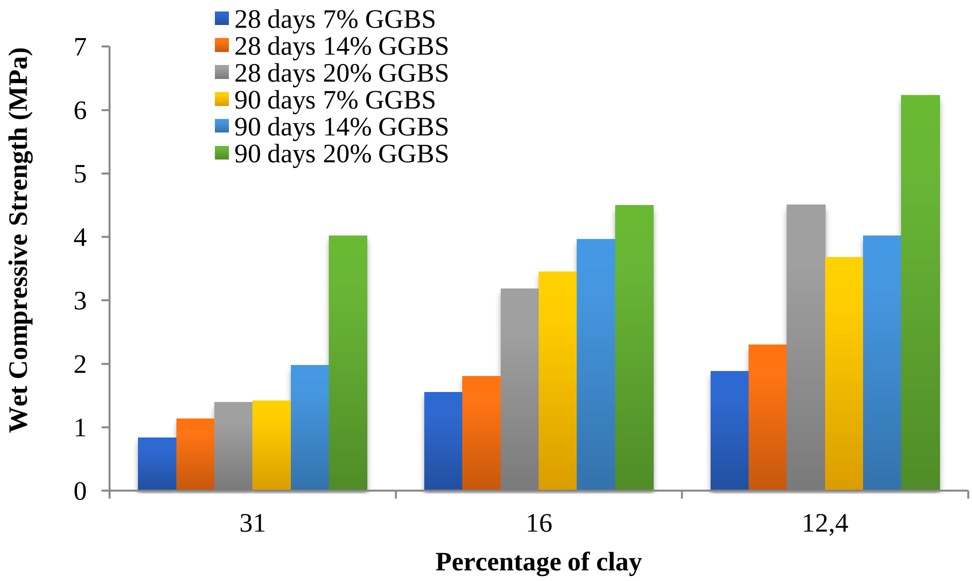


**Figure 8.** Variation in wet compressive strength for different mixes at curing periods of 28 days and 90 days before and after performance tests

## 5. Conclusions

The experimental results revealed that the rammed earth cylinders prepared with 20% GGBS and 5% cement having a clay percentage of 12.4% yielded the highest compressive strength of 4.51 MPa in wet conditions at 28 days. It was also observed that the performance characteristics of rammed earth specimen with 5% cement and 20% GGBS after 12 cycles of wetting-drying with abrasion improved when clay content reduced from 31% to 12.4% and had a minimal loss of mass of 1.6% which is appreciable for exposed earthen mass. The enhancement in the performance characteristics may be because of improved coverage of the surface area of expansive clay particles due to the addition of GGBS. This might have stabilized the clay particles and prevented their expansion. The wet compressive strength after the performance test at 90 days was 6.23 MPa which is an increase of 78% when compared with 28-day compressive strength, indicating that GGBS has contributed to long-term strength gain. Higher amounts of GGBS correspond to better durability and performance for any given percentage of cement. Hence, it can be concluded that a minimum quantity of cement of 5% is sufficient for constructing rammed earth with an optimum quantity of GGBS, to get better performance when exposed to atmospheric action.

## Authors' Contributions

NVA designed the structure and wrote up the article. HRM carried out the experimental work and the theoretical calculations. PPK is the overall supervisor of the project.
All authors read and approved the final manuscript.

## Competing Interests

The authors declare that they have no competing interests.

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