

Article

Compressive Strengths of Cube vs. Cored Specimens of Cement Stabilized Rammed Earth Compared with ANOVA

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Abstract: Cement-stabilized rammed earth (CSRE) is a variation of the traditional rammed earth building material, which has been used since ancient times, strengthened by the addition of a stabilizer in the form of Portland cement. This article compares the compressive strength of CSRE determined from specimens cored from structural walls and those molded in the laboratory. Both types of specimens underwent a 120-day curing period. The tests were conducted on specimens with various grain sizes and cement content. An analysis of variance (ANOVA) was performed on the obtained results to determine whether it is possible to establish a conversion factor between the compressive strength values obtained from laboratory-molded cubic samples and those from cored samples extracted from the CSRE structure. The study revealed that the compressive strength of CSRE increases significantly over the curing period, with substantial strength gains observed up to 120 days. The results indicated no statistically significant difference in the mean unconfined compressive strength (UCS) between cubic and cored specimens for certain mixtures, suggesting that a shape coefficient factor may not be necessary for calculating CSRE compressive strength in laboratory settings. However, for other mixtures, normal distribution was not confirmed. These findings have implications for the standardization and practical application of CSRE in construction, highlighting the need for longer curing periods to achieve optimal strength and the potential to simplify testing protocols.



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Keywords: rammed earth; cement stabilized rammed earth; compressive strength; analysis of variance; ANOVA; specimen shape

1. Introduction

Rammed earth (RE) is a sustainable construction material in which the main component is inorganic soil, which can be obtained directly from the construction site and used to form monolithic walls [1]. Unlike concrete, the grain curve of rammed earth may also contain a clay fraction. To increase mechanical strength and durability, Portland cement is often added as a stabilizer, resulting in cement-stabilized rammed earth (CSRE) [2,3]. However, the amount of cement used is much smaller than that in concrete mixtures. For safe durability, including resistance to frost, 9% cement by mass of the dry earth mixture is typically used [4]. Research has shown that other stabilizers, such as biopolymers [5] or a combination of coal aggregate and lime [6], can also be viable alternatives.

CSRE walls are built by ramming layers of a moist, loose mixture within formwork, which is moved once the wall reaches the desired height. Due to the local acquisition of raw soil and the minimal use of cement, CSRE has a low environmental impact. Despite these benefits, the popularity of rammed earth construction remains low, primarily due to the lack of design standards and comprehensive studies on this construction method [7].

Compressive strength tests of materials often show different results compared to the compressive strength of structural elements. Standards such as EN 13791 [8] allow for determining the strength class of concrete based on specimens cored from the structure and

laboratory-molded specimens. The absence of international standards for CSRE highlights the need for multicriteria material assessments, as unconfined compressive strength (UCS) alone may not sufficiently describe the material's mechanical properties [9].

For CSRE, there is little correlation between the compressive strength of laboratory specimens and finished construction elements. Singular studies comparing the strengths of rammed and cored cylinders found the difference to be negligible (around 2%) [10]. Such correlations are crucial for the safe design of buildings using this eco-friendly material. Similar experimental investigations have been documented in the literature [11]. Researchers have found significant differences in strength between molded and cored specimens, with molded specimens generally exhibiting higher mechanical strength. Specimens compacted in small molds typically have higher strength than wall elements.

The compressive strength of CSRE was typically tested after about 28 days of specimen curing, as documented in references [10–30], analogous to concrete testing according to EN 206 [31]. For concretes with Portland cement (CEM I), compressive strength after 28 days is only slightly lower than the maximum value. However, for other types of cement, such as blast furnace cement (CEM III) or multi-component cement (CEM V), strength increases over a much longer period of time. Thus, concretes using CEM III and CEM V are often tested after longer curing periods, such as 56 days, 90 days, or more, to assess compressive strength accurately. For CSRE, the unfired clay in the soil slows down the setting of Portland cement, resulting in a longer period of strength increase beyond 28 days. In the article [32], the UCS of the CSRE specimens showed that at 60 days of curing, the strength of the cube specimens was between 109% and 125% of their strength at 30 days; at 90 days, the strength ranged from 110% to 135% of the 30-day strength; and at 120 days, the strength was between 110% and 140% of what it was at 30 days. Additionally, the strength of non-stabilized rammed earth walls has been shown to increase with drying over time, well beyond the 1-month period [33].

Moreover, raw earth consists of numerous minerals that slow down the development of compressive strength in CSRE, primarily due to the deceleration of the hydration process of cement [29,30]. Therefore, it is reasonable to assume that the compressive strength of CSRE continues to develop significantly even after 28 days. To test this hypothesis, destructive tests should be conducted after extended periods.

In research [28], the impact of the shape and size of CSRE specimens on compressive strength was investigated (Figure 1). Specimens were tested with 10% and 20% cement contents. They were cured in high-humidity conditions for 28 days and, after this period, dried for 10 days at ambient temperature. The obtained results are shown in Figure 2. It was demonstrated that compressive strength decreases with increasing size. Furthermore, for a cement content of 10%, the strength is relatively close and increases with a higher cement content. In the case of cylindrical samples, compressive strength decreases as the diameter of the sample increases. For samples of this shape, the differences in values are noticeable regardless of the cement content.

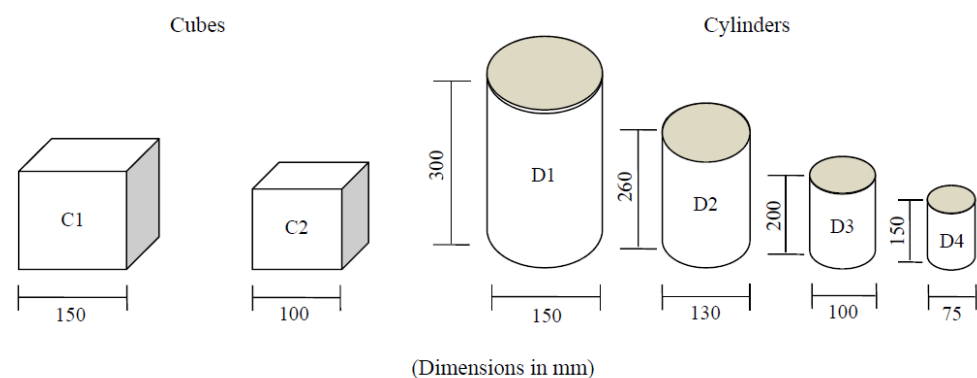


Figure 1. Types of specimens tested in [28].

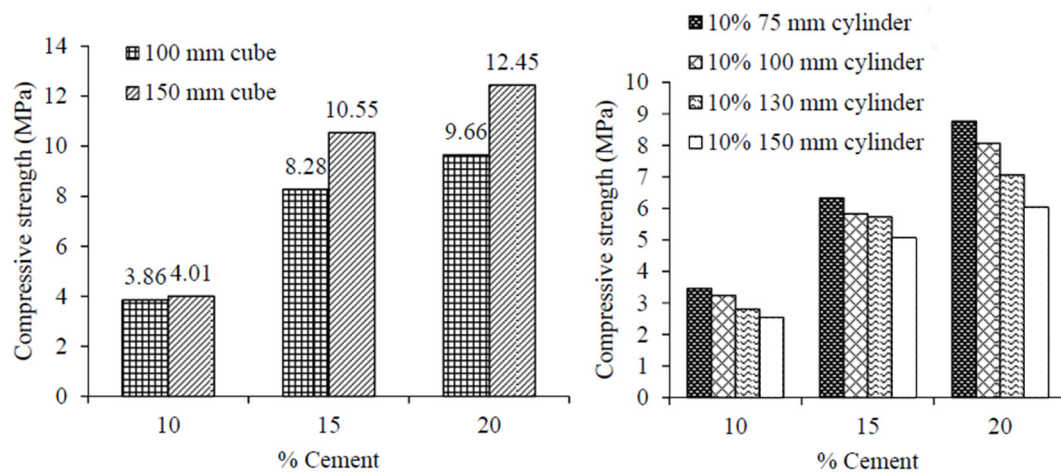


Figure 2. Influence of size and shape on CSRE compressive strength at different cement content levels [28].

In the article [27], the authors demonstrated that the geometry of the samples (cylinders or prisms) does not affect compressive strength. They recommend producing cylinders instead of prisms because cylinders generally have fewer defects than prisms, which experience stress concentration due to sharp edges. In any case, an aspect ratio of 2 should be chosen for the geometry of the samples. Importantly, the publication concludes that it is possible to obtain representative results for in situ walls by testing cylinders in the laboratory.

In the article [11], the authors compared laboratory-molded specimens with cored specimens. The element from which the cored specimens are made is shown in Figure 3. The results of their study are shown in Figure 4. The obtained results indicate that the compressive strength of cored specimens is always lower than that of molded specimens. It is worth noting that the specimens were cured for a typical laboratory period. Although the authors do not specify the exact curing time, they mention that all specimens and panels were tested after a minimum curing time of 28 days. In each series, exactly 10% cement by soil mass was used. Using the proctor compaction test, the optimum moisture content (OMC) was obtained.



Figure 3. Coring specimens from the CSRE element. The specimens were cored both vertically and horizontally [11].

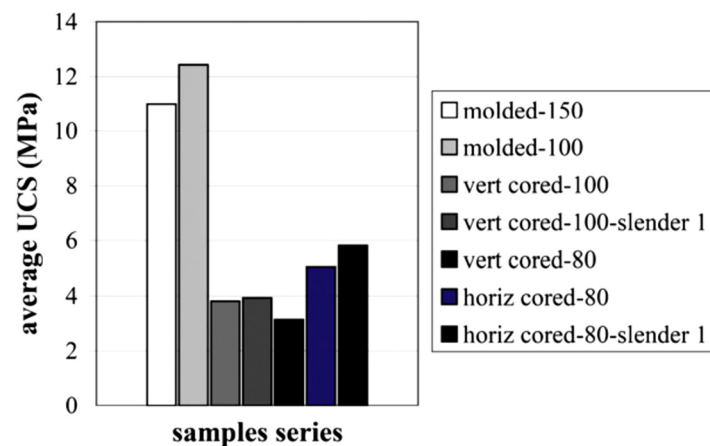


Figure 4. Average compressive strength of molded or cored specimen series. Numbers (150, 100, 80) indicate the specimen's diameter in millimeters (mm). Slender 1 indicates samples with slenderness ratio equal to 1 [11].

The amount of cement added to CSRE will impact its mechanical strength and durability, especially in regions with many days per year where temperatures fluctuate around 0 °C. In the article [23], the results of tests on rammed earth based on the amount of cement used in the mix are presented. According to the authors, although the results indicate that all specimens without cement exhibited a compressive strength above 1.5 MPa, they are highly susceptible to water damage if not properly protected or maintained. Considering the impact of atmospheric conditions, there is significant potential for the use of cement-stabilized rammed earth, which provides adequate strength and durability as opposed to non-stabilized earth, for standard residential houses (one to two stories). The authors' research showed that using a 5% cement addition to soil consisting of 20% clay (<1.7 mm), 60% sand, and 20% gravel results in a compressive strength of 7.783 MPa [23]. Although the production of CSRE is associated with substantial greenhouse gas emissions, these emissions are relatively lower compared to fired bricks and concrete.

The obtained compressive strength result is high considering only a 5% cement addition. Additionally, the curing period before testing was interestingly short. The article states that these samples were cured by spraying with water three to four times daily for 1–3 days, and then were fully submerged in water for an additional 3–4 days. This means that the curing time for these specific samples was between 4 and 7 days in total, taking into account both methods of curing. Furthermore, the authors in the text noted that depending on the thickness of the wall, full curing could take several months or more, which suggests a much longer potential curing time for larger structures or full-scale walls [23]. Depending on the climate conditions, the following properties of compacted soil are considered critical for its durability: linear shrinkage, the ratio of wet to dry compressive strength, resistance to water erosion caused by pressurized jets, resistance to cyclic wetting and drying, and frost resistance. All these CSRE properties were tested in [4]. The results (Table 1) showed that rammed earth in warm climates needs 6% cement, while in cold climates (due to frost resistance), it requires at least 9% cement. Moreover, not all mixtures (based on grain size) with such cement additions fulfill the durability requirements. As proven in the article, the grain size distribution is a crucial factor for CSRE durability, even though it is not commonly emphasized in other publications.

Table 1. CSRE Durability test results. Green color is used to indicate mixtures that meet the criteria for a given durability characteristic. The three-digit numbers 703 and 433 indicate the proportions of fractions: sand, gravel, and silt + clay fractions. Values in the green cells of the table indicate compliance with the requirements, while values in the red cells indicate non-compliance with the standards [4].

Criterion and Critical Value		0 % Cement		6% Cement		9% Cement	
		703	433	703	433	703	433
Linear shrinkage < 0.5%		0.46%	0.42%	0.36%	0.34%	0.33%	0.24%
Resistance to water erosion	Ratio of susceptibility to water erosion ≤ 2	3	2	1	1	1	1
	Surface condition after exposure to water	Deep losses on the surface of the whole sample			No damage		
Wet to dry compressive strength ratio > 0.33		Not tested		0.33	0.44	0.42	0.43
Frost resistance after 25 cycles	Compressive strength decrease < 20%	Not tested		100%	100%	5.8%	6.3%
	Mass loss < 5%	Not tested		7.24%	7.24%	6.36%	2.51%

According to another review of earthen building materials, the most commonly used solution is stabilization with the addition of Portland cement, typically comprising 4–8% by mass [34]. It should be noted that cement stabilization not only negates the reduced carbon footprint and embodied energy of earthen materials but also affects the recyclability of the material after its service life. Additionally, cement stabilization adversely impacts the hygric properties as well [34]. Two primary metrics that can assist in assessing the environmental friendliness of a construction method are CO₂ emissions and embedded energy. Both of these parameters significantly increase for stabilized rammed earth (SRE) compared to non-stabilized rammed earth (URE), as illustrated in Table 2 prepared by Ávila et al. in [Characterization of the mechanical and physical properties of stabilized rammed earth: A review]. In fact, the embodied energy of CSRE walls increases linearly with the cement content [embodied energy in cement-stabilized rammed earth walls]. For instance, a wall with 8% cement in stabilized rammed earth (SRE) results in more than 14 times the CO₂ emissions and 10 times the embodied energy compared to an equivalent wall constructed with non-stabilized rammed earth [35].

Table 2. CO₂ emissions and embodied energy per cubic meter of RE [35].

Additives	CO ₂ Emissions [kg]	Reference	Embodied Energy [MJ]	Reference
None	3–9	[36,37]	49	[9]
2.5% cement	42	[36]	–	–
4% cement	–	–	280	[38]
5% cement	86	[36]	–	–
6% cement	–	–	400	[38]
7.5–8% cement	131	[36,39]	500	[38]
10% cement	179	[36]	630	[38]
12% cement	–	–	750	[38]

Due to energy-intensive manufacturing processes, cement production is one of the largest sources of global greenhouse gas emissions. The cement industry alone is responsible for over 6% of global warming and anthropogenic greenhouse gas emissions [40]. Therefore, there is a growing interest in more ecological alternatives beyond just cement and lime stabilization. This perspective has led to the emergence of geopolymers as a viable alternative to cement [41].

Compressive strength tests on CSRE were conducted on cubic specimens from various mixtures and after different maturation periods. The intent of the study was to determine the maturation time after which the increase in compressive strength becomes less pronounced. Subsequently, from the prepared CSRE wall panels, specimens were cored after

this maturation period and subjected to compressive strength tests. Next, an analysis of variance (ANOVA) was conducted on the obtained results to determine if a conversion factor could be established between the laboratory results on cubic samples and those cored from the CSRE structure.

2. Materials and Methods

2.1. Soil Mixtures Properties

Four groups of specimens were prepared, each differing in their particle size distribution curves (Figure 1) and the quantity of Portland cement CEM 42.5 R added to the soil mixture, at either 6% or 9%. The samples were labeled with codes that specify the soil type and cement content; for example, ‘703-6’ indicates the sample contains soil from particle size distribution 703 (as shown in Figure 5) with a 6% cement addition. The three-digit soil grading symbols represent the proportions of sand, gravel, and silt with clay; for example, ‘703’ means that the soil consists of 70% sand and 30% silt and clay fraction. Aggregate types and their granular arrangement after compaction are usually omitted in existing norms [42]. Cement was added to the dry soil and mixed until uniform. Then, water was added to ensure the optimum moisture content (OMC).

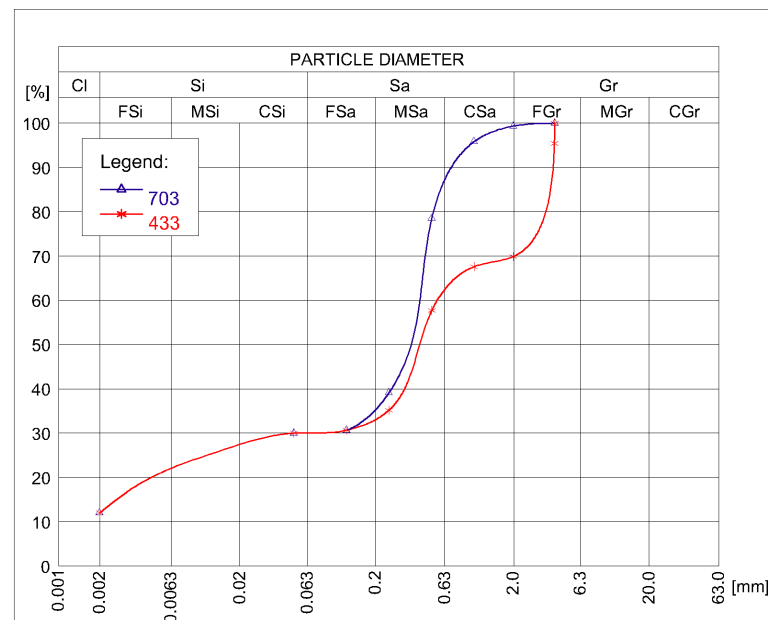


Figure 5. Particle size distribution of soil mixtures used in tests.

The Optimum Moisture Content (OMC) is the amount of water in the soil at which maximum dry density is achieved during compaction. The Proctor method is often used to determine this, in accordance with the EN 13286-2 standard [43]. This method involves layering the soil in a cylinder, where each layer is compacted using a specified number of blows from a rammer dropped from a fixed height. It should be noted that the term “optimum moisture content” should be consistently specified, with a footnote defining the specific compaction conditions. To achieve the maximum dry density of the samples being tested, the determination of OMC should be conducted as close as possible to the method of sample compaction to be tested [4]. Therefore, in this research, the OMC was determined on cubic samples, which were formed in three equal layers by dropping a 6.5 kg rammer from a height of 30 cm onto the surface of the moist mixture within a steel mold (Figure 6). This method of forming 100 mm samples was proposed by Hall and Djerbib in [44]. The OMC for the same soil–cement mixtures was determined by the authors in previous studies (Figure 7).

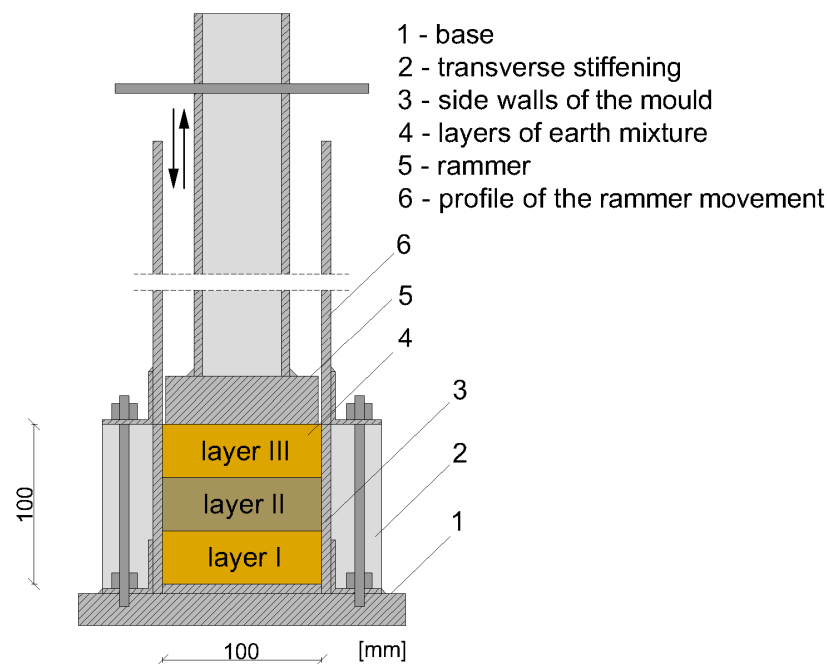


Figure 6. Cubical specimen compaction method.

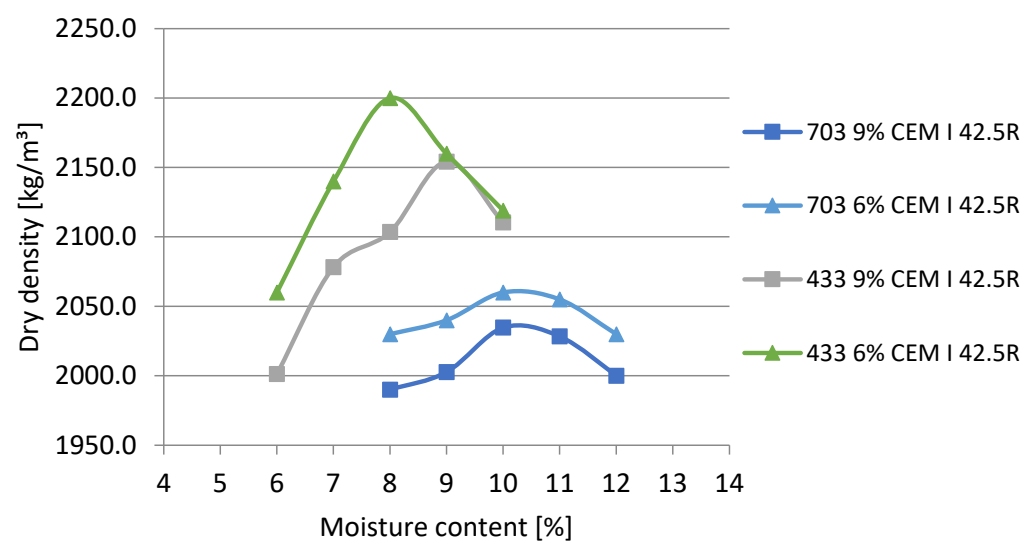


Figure 7. The relationship between dry density and moisture content for different soil mixtures [4].

The properties of CSRE depend on the mineral composition of the soil used, particularly the content of swellable minerals in the clay fraction (Figure 8) [29,30]. Unfortunately, the mineral composition is often overlooked in research about CSRE. The mineral composition of the soil mixtures used in this study is shown in Table 3. Sand and gravel fractions generally consist of quartz and carbonate crumbs. The main differences in mineral content are found in the clay fraction, which was added in the same amount to all mixtures. Therefore, the mineral composition of all mixtures was almost the same.

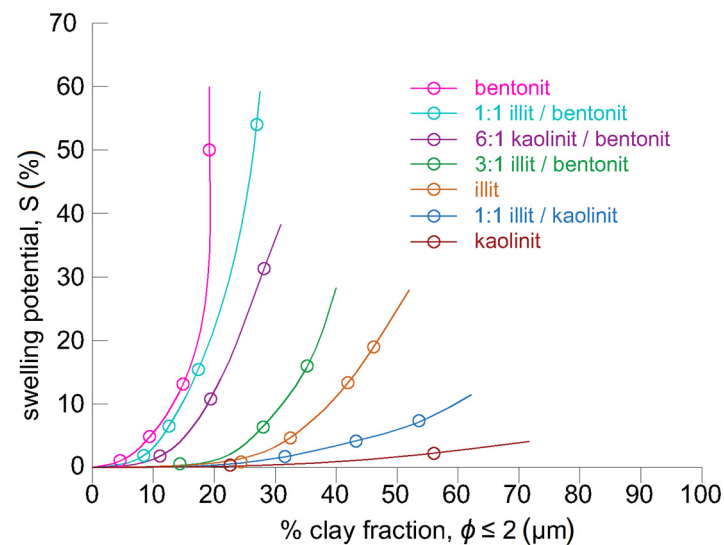


Figure 8. Swelling potential of popular minerals in clay fractions [45].

Table 3. Mineral composition of soil mixtures used in tests.

Soil Mixture	Mineral Composition (%)							Quartz and Carbonate Crumbs
	Beidellite	Kaolinite	Illite	Goethite	Siderite	Carbonates	Organic Substance	
703 433	2.67	2.58	7.86	-	1.8	-	-	85.09

2.2. Specimen Preparation and Compressive Strength Tests

2.2.1. Molded Laboratory Specimens

To investigate the change in compressive strength of CSRE over time, groups of specimens were tested after 1, 14, 28, 56, and 120 days. The specimens were cube-shaped with a side length of 100 mm. The method of their formation was described earlier in the method for determining OMC. The specimens were demolded after 24 h and then cured in conditions of high relative humidity ($95\% \pm 2\%$) and a temperature of $20\text{ }^{\circ}\text{C}$ ($\pm 1\text{ }^{\circ}\text{C}$). Because the surfaces of the specimens were not perfectly smooth, soft fiberboard washers were placed between the specimens and the pressing surface of the testing machine (Figure 9).

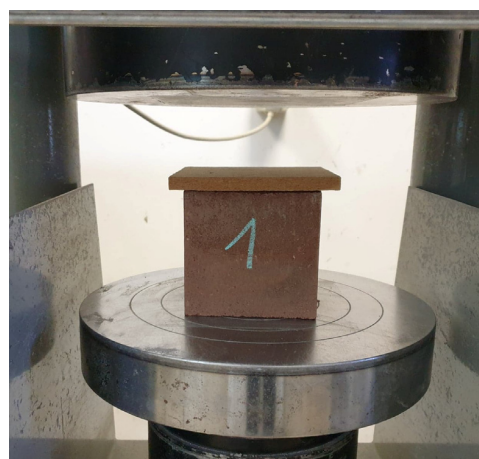


Figure 9. A cubic specimen prepared for compressive strength test.

2.2.2. Cored Specimens Extruded from Wall-Panels

For each series, five small wall-like panels of $200 \times 300 \times 250$ mm were prepared. The elements were rammed in 5 cm layers in a waterproof plywood formwork (Figure 10). Similar techniques are often mentioned in various studies [44–47]. The compacting process consisted of free-lowering the 6.5 kg hand rammer from a height of 30 cm onto the moist layer of soil–cement mixture. The ramming started from one end of the mold, where 10 strokes were made at the very edge, and then moved 5 cm, and another 10 strokes were made. The same compaction energy per unit area of the element was used for mold specimens and wall-panels. When ramming the layers, their volumes were controlled—it was assumed that all the layers of the specimen had to have a similar volume density. After the completion of molding, the specimens were left in forms, tightly wrapped in foil for 24 h, and then demolded. Like the cubic specimens, the wall panels were curing for 120 days. temperature of $20\text{ }^{\circ}\text{C}$ ($\pm 1\text{ }^{\circ}\text{C}$) and relative humidity of 95% ($\pm 2\%$).



Figure 10. (Left) formwork for the specimen. (Right) specimen after forming.

After the curing period, four cylindrical specimens 100 mm in diameter and 100 mm were cut from each wall-panel. Two cylindrical forms were cut with a hole saw. Then each of the molds was cut to the desired height (Figure 11) [48]. Water cutting was not used so as not to change the moisture of the specimens. Specimens were cut and tested in one day. For each series, at least three cored specimens were selected for the compressive strength tests. The comparison between the cored cylindrical specimen and the cubic specimen is shown in Figure 12.



Figure 11. (Left) cutting a cylindrical specimen 100 mm in diameter from a rectangular block. (Right) trimming the specimen to a height of 100 mm [48].



Figure 12. (Left) cored cylindrical specimen. (Right) cubic specimen.

3. Results

The results of the change in compressive strength over time for the cubic specimens from the various soil–cement mixtures are shown in Figure 13. CSRE specimens still show a significant increase in mechanical strength after 28 days of maturation. After 1 day of maturation, the specimens obtained average compressive strengths of 3.30 and 4.07 MPa. This indicates that even after one day, the compressive strength is sufficient to allow the use of cement-stabilized rammed earth as a construction material. The rate of increase in compressive strength decreased over time but remained noticeable. The 120-day period was considered to proceed to the second part of the research, which involved testing the cored specimens. The results of the compressive strength tests for specimens cored from the wall panels cured for 120 days are shown in Table 4, and for the cube-shaped laboratory specimens in Table 5. Trendlines shown are to be treated as an approximation of material behavior, not a final UCS development model.

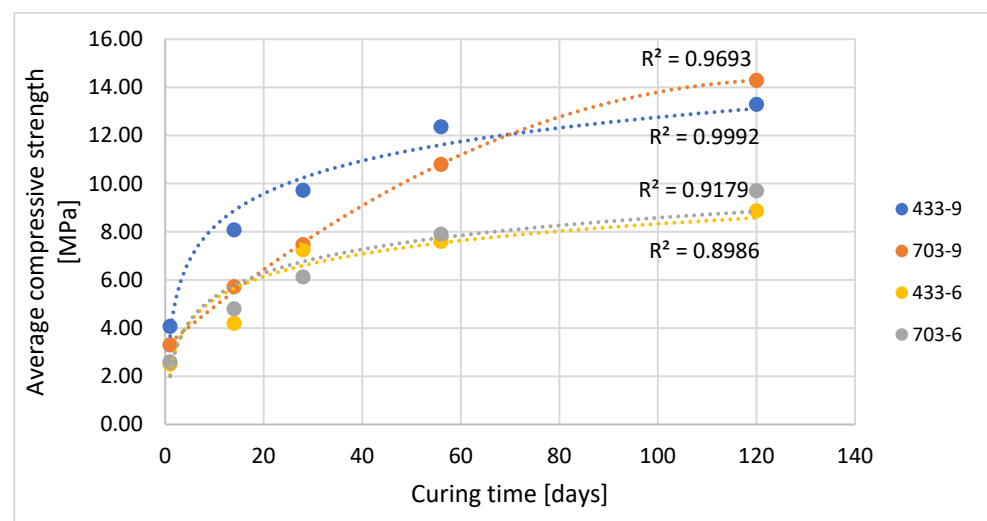


Figure 13. Increase in the average compressive strength of CSRE series over time.

Table 4. Compressive strength of cube specimens in MPa for different CSRE mixtures tested after 120 days.

	703-6	703-9	433-6	433-9
Test results	9.68	13.36	9.44	13.46
Test results	9.97	14.76	8.36	14.77
Test results	9.45	14.76	8.81	13.36
Test results				12.61
Test results				12.24
Mean of tests	9.70	14.29	8.87	13.29
Standard dev.	0.261	0.808	0.542	0.973

Table 5. Compressive strength of cylinder specimens in MPa for different CSRE mixtures cored and tested after 120 days.

	703-6	703-9	433-6	433-9
Test results	10.11	10.77	9.39	13.24
Test results	10.91	13.12	9.40	12.67
Test results	8.95	11.53	8.83	11.51
Test results	8.21	14.28		
Test results	9.98	14.18		
Test results	9.96			
Mean of tests	9.69	12.78	9.21	12.47
Standard dev.	0.955	1.575	0.326	0.882

Prior to the mechanical strength test, the density of groups of specimens with 9% cement that were tested after 120 days was determined, the results of which are shown in Table 6. The difference in the results between all series of samples did not exceed 2.5% and was higher for the cored samples. This may result from different sizes of forms, heights of layers, and curing conditions. However, the differences in density were small in both cases, which can lead to the conclusion that compaction energy was similar in both types of specimens.

Table 6. Density of specimen groups.

Group	Density of Specimens (kg/m ³)	
	Cube	Cored
703-9	2217.7	2274.7
433-9	2242.4	2272.0
703-6	2177.6	2204.6
433-6	2230.5	2259.4

4. Statistical Analysis

4.1. Assessing Means of Two Samples Groups with ANOVA

Comparing the mean values from two or more populations using Analysis of Variance (ANOVA) can provide valuable insights into the differences or similarities between the populations. ANOVA is a statistical method that allows us to determine whether there are statistically significant differences between the means of three or more groups. By conducting an ANOVA analysis, we can gain several key advantages and insights. Identifying Differences: One of the primary benefits of comparing mean values with ANOVA is the ability to determine whether there are significant differences between the populations. By analyzing the variance both within groups and between groups, ANOVA allows us to assess whether the observed differences in means are likely due to random chance or if there is a true effect. This analysis allows for partitioning the total variability in the data into different sources: the variability within groups and the variability between groups.

This breakdown helps us understand how much of the overall variance is due to differences between populations and how much is due to random variation within groups. It is to emphasize that ANOVA results can often be generalized beyond the specific sample studied, providing insights into broader populations or settings. This generalizability is particularly valuable when making inferences or decisions based on the results of the analysis [49–52]. Conducting an ANOVA requires the following four assumptions to be met:

- independence of random variables for each population,
- measurability of variables,
- normality of the distribution of random variables in each population,
- variance homogeneity in all populations.

Independence and measurability of the crush-test are provided. Each crush-test was made for a separate CSRE cube or cylinder. The results—the compressive strengths—were calculated based on the readouts of crushing force from the instrument separately for each sample. To confirm the normal distribution of the compressive strengths in each set of samples, the Shapiro–Wilk tests are done. Homogeneity of variances is verified throughout Levene’s tests [49–51]. The sequence of calculations is presented in Figure 14.

4.1.1. Shapiro–Wilk’s Test

Shapiro–Wilk’s test is very strong, and it is recommended for samples of a low number of cases [49]. It can be found in [51] that it has to be applied if the size of a sample is from 3 to 50. It is decided to use just this test to verify that the compressive strengths have a normal character in each sample. The verified hypotheses are the following:

H_0 —compressive strengths are normally distributed

H_1 —the distribution of compressive strengths is not normal

To verify that test statistics W is calculated based on the following formula:

$$W = \frac{\left[\sum_{i=1}^{n/2} a_{ni} (x_{n-i+1} - x_{(i)}) \right]^2}{\sum_{i=1}^n (x_i - \bar{x})^2}$$

where

x_i —non-ordered values in the sample

$x_{(i)}$ —values in the sample ordered increasingly

$\bar{x}$ —mean value

n —number of values in the sample

$[n/2]$ —total part of the half of the number of crush-tests in a sample

$a_{n,i}$ —tabularized coefficient dependent on n

Then the calculated test statistics W is compared to the theoretical W_{th} value, which is read from the table. This theoretical W_{th} depends on n and the confidence level α . If the following condition is met $W > W_{th}$ there is no reason to reject the hypothesis H_0 (the normal distribution is confirmed). In Statistica 13.1 software (by Tibco), statistics W is calculated and presented together with the value of p . If $p > \alpha$ then also $W > W_{th}$. So, there is no reason to reject the hypothesis H_0 (normal distribution) is confirmed [50].

4.1.2. Levene’s Test

The assumption for this test is that samples have a normal distribution. So, this test is applied after Shapiro–Wilk’s test. It can be confirmed with Levene’s test that the variances of different samples are homogenic. The null hypothesis assumes homogeneity of variances for all analyzed samples.

H_0 —the variances of all samples are homogenic

H_1 —the variance of at least one sample is not homogenic with the variance of other samples

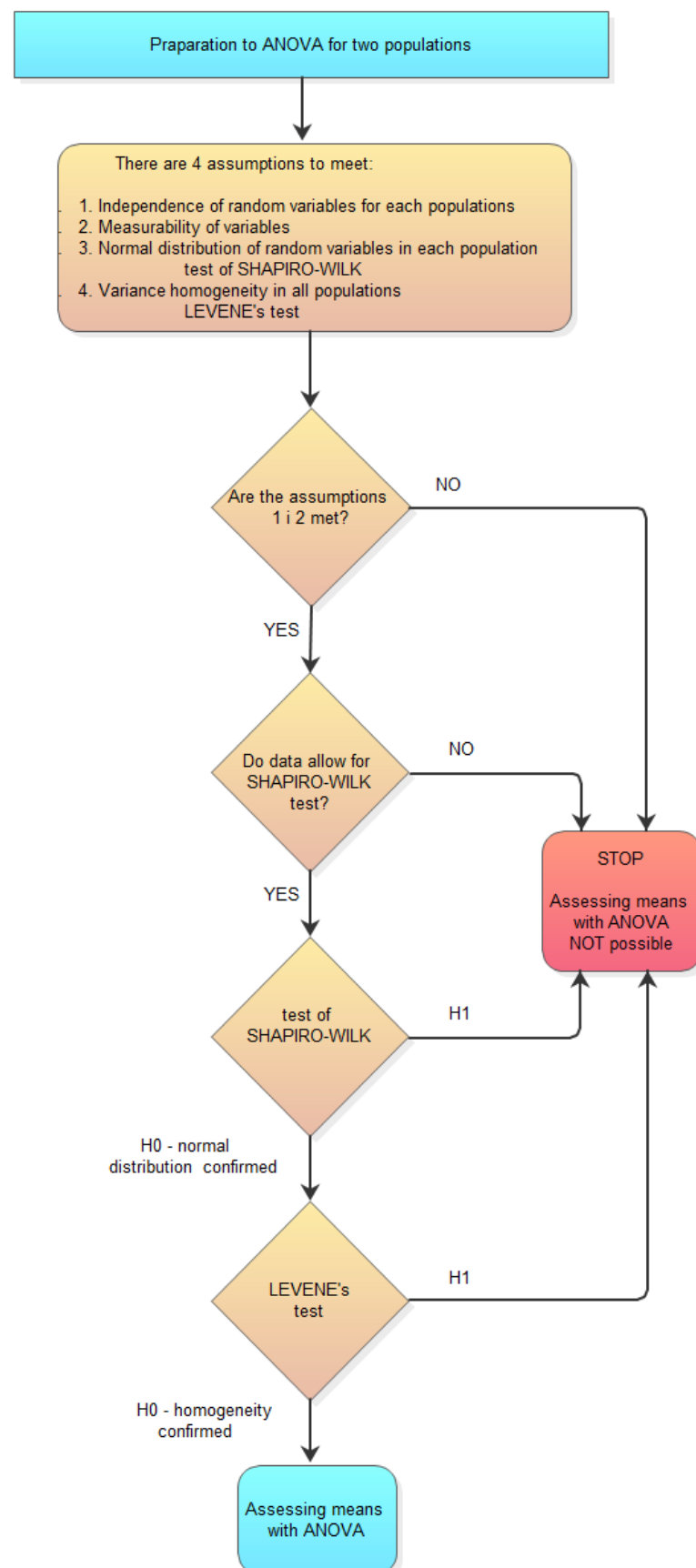


Figure 14. Sequence of calculations leading to ANOVA.

This test is similar to the one-way ANOVA described below, but instead of values that belong to two (or more) samples, the absolute values of the differences between the values and mean in each group are considered. The statistics W for this test is presented in [53] and widely discussed, e.g., in [54,55].

$$W = \frac{n - k}{k - 1} \times \frac{\sum_{i=1}^k n_i (\bar{z}_i - \tilde{z})^2}{\sum_{i=1}^k \sum_{j=1}^{n_i} (z_{ij} - \bar{z}_i)^2}$$

where:

n is the total number of cases in all samples

k is the number of different samples to which the sample cases belong

n_i is the number of cases in i - th samples

and

$$z_{ij} = |x_{ij} - \bar{x}_i|$$

where

x_{ij} is the j - th value in i - th sample

$\bar{x}_i$ is the mean value in i - th sample

$\bar{z}_i$ is the mean value of z_{ij} in i - th sample given by the following formula:

$$\bar{z}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} z_{ij}$$

$\tilde{z}$ is the mean of all z_{ij} given by the formula

$$\tilde{z} = \frac{1}{n} \sum_{i=1}^k \sum_{j=1}^{n_i} z_{ij}$$

As the test statistics W is approximately F distributed it is compared to F value read from Fisher's tables based on confidence level α , and degrees of freedom, i.e., $k - 1$ and $n - k$. The Levene test rejects the null hypothesis (variances of all samples are equal) if $W > F$ value. Similarly to Shapiro-Wilk's test, Statistica software, instead of giving the value of comparison of W to F value returns the p value. If $p < \alpha$ the null hypothesis should be rejected.

4.1.3. Assessing Means of Two Samples with ANOVA

There are two hypotheses in ANOVA:

H_0 – the means of all samples are equal

H_1 – the mean of at least one sample is different from the means of other samples.

These hypotheses are tested with the following procedure based on [49]:

- calculating means $\bar{x}_i$ for each of k samples (for $i = 1, 2, \dots, k$)
- calculating the mean for all samples $\tilde{x}$ (global mean) with the following formula:

$$\tilde{x} = \frac{1}{n} \sum_{i=1}^k \sum_{j=1}^{n_i} x_{ij}$$

where:

$$n = \sum_{i=1}^k n_i$$

n_i is the number of elements in i - th sample

x_{ij} is the value of j - th element in i - th sample

- calculating SS_{btw} i.e., sum of squared deviations of the means (of each sample) from the global mean with the following formula:

$$SS_{btw} = \sum_{i=1}^k (\bar{x} - \bar{x}_i)^2 \times n_i$$

- calculating SS_{tot} i.e., sum of squared deviations of x_{ij} (all values from all samples) from the mean of each sample with the following formula:

$$SS_{tot} = \sum_{i=1}^k \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i)^2$$

- calculating variances two variances: variance between samples named MS_{btw} and variance within the samples named MS_{tot} , with the following formulas:

$$MS_{btw} = \frac{SS_{btw}}{df_{btw}}$$

$$MS_{tot} = \frac{SS_{tot}}{df_{tot}}$$

where degrees of freedom (df_{btw} and df_{tot}) are as follows:

$$df_{btw} = k - 1$$

$$df_{tot} = n - k$$

- calculating the statistics F with the following formula:

$$F = \frac{MS_{btw}}{MS_{tot}}$$

- reading the F_α value from the Fisher's tables. F_α depends on: the assumed confidence level α , df_{btw} , and df_{tot} .

If $F > F_\alpha$ there is no reason to reject the hypothesis H_0 , so it can be stated that the means of the samples are equal. Statistica software returns p value. If $p > \alpha$ there is no reason to reject the hypothesis H_0 . The condition $F > F_\alpha$ is met if and only if the condition $p > \alpha$ is met.

4.2. Results—ANOVA for Mean Comparisons

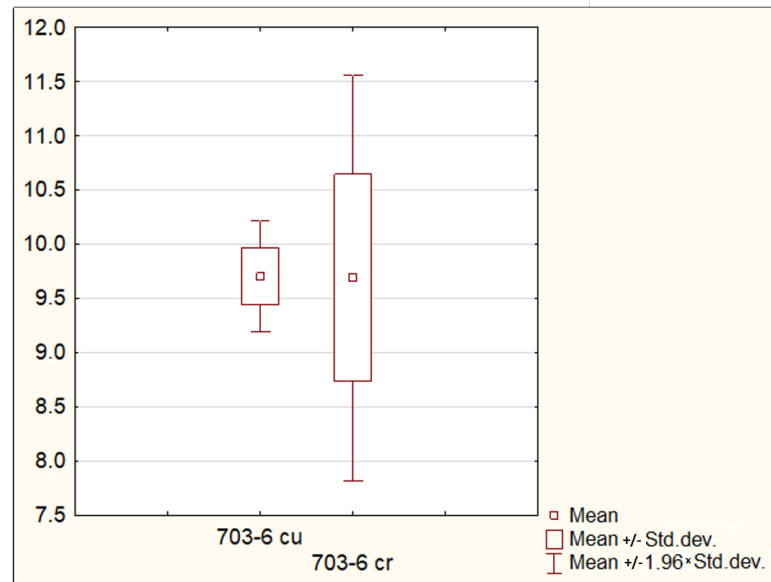
There are four types of CSRE mixtures used. They differ with aggregate composition (marked as 703 and 433) and cement addition (6 or 9%). The samples were of cubic shape (moulded; they are marked as cu) or cored from the wall structure (they are marked as cr). So, labeling the sample "433-9 cu" means that this sample contains values of the compressive strength calculated based on the compressing crush test of cubic specimens prepared from 433 CSRE mixture with 9% cement addition. All the crush tests were carried out 120 days after the day of compacting a fresh mixture (in a mold or in a structure). This article is aimed at a comparison of the compressive strength (calculated based on crush-tests) for cube and cored specimens made of the same type of CSRE mixture.

4.2.1. ANOVA 703-6 cu vs. 703-6 cr

The basic statistics of the 703-6 cu and 703-6 cr samples are presented in Table 7. The comparison of means, the comparison of ranges of means $\pm$ standard deviations, and the comparison of means ± 1.96 times standard deviations for these two samples are presented in Figure 15.

Table 7. Basic statistics of 703-6 cu and 703-6 cr samples.

Soil Mixture	Mean	Standard Deviation	Min	Max	Number of Specimens in a Sample
703-6 cu	9.70000	0.260576	9.45000	9.97000	3
703-6 cr	9.68667	0.954959	8.21000	10.91000	6

**Figure 15.** Comparison of means and standard deviations for 703-6 cu and 703-6 cr samples.

Results of Shapiro–Wilk’s test, i.e., test statistics W and p values are presented in Table 8.

Table 8. Shapiro–Wilk’s test results.

Soil Mixture	Number of Crush Tests	Value W (Shapiro–Wilk Test)	p Value
703-6 cu	3	0.995582	0.872957
703-6 cr	6	0.933756	0.609401

As the p values for both analyzed samples are higher than the assumed confidence level $\alpha = 0.05$, the normal character of the compressive strengths for these two samples is confirmed. Therefore, the homogeneity of the variances can be tested with Levene’s test. The results of that are presented in Table 9.

Table 9. Levene’s test results.

Samples	Levene’s $F(1,df)$	df (Degree of Freedom)	p Value
703-6 cu vs. 703-6 cr	3.26891596	7	0.113544479

As $p = 0.113544479$ is higher than $\alpha = 0.05$ the homogeneity of variances, this is confirmed for the two analyzed samples. Then, the significance of the difference between means can be verified with an ANOVA. To conduct that, the sample 703-6 cu is supplemented with three results that are equal to the mean of the results of the real three crush tests made (to make an equal number of specimens in each sample, i.e., 6). The results of the ANOVA are presented in Table 10.

Table 10. Results of ANOVA for 703-6 cu vs. 703-6 cr.

SS_{btw}	df_{btw}	MS_{btw}	SS_{tot}	df_{tot}	MS_{btw}	F	p
0.000533	1	0.000533	4.695533	10	0.469553	0.001136	0.973778

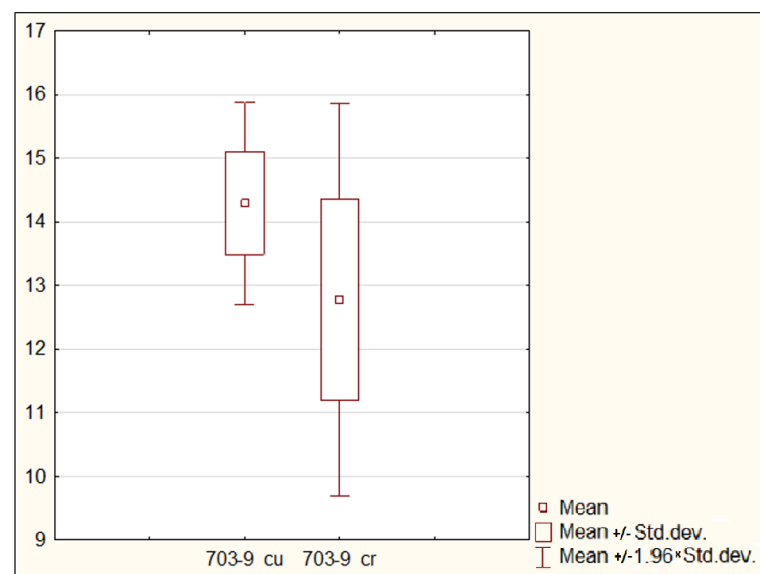
Instead of comparing the value of statistics F (presented in Table 10) to F critical (read from the Fisher table, dependent on confidence level α , and df_{btw} , and df_{tot}), Statistica software gives p value. As $p = 0.973778$ is higher than the assumed confidence level, $\alpha = 0.05$ it can be stated that there is no reason to reject the hypothesis H_0 , and it can be stated that the means of these two samples are equal.

4.2.2. ANOVA 703-9 cu vs. 703-9 cr

The basic statistics of the 703-9 cu and 703-9 cr samples are presented in Table 11. The comparison of means, the comparison of ranges of means $\pm$ standard deviations, and the comparison of means ± 1.96 times standard deviations for these two samples are presented in Figure 16.

Table 11. Basic statistics of 703-9 cu and 703-9 samples.

Soil Mixture	Mean	Standard Deviation	Min	Max	Number of Specimens in a Sample
703-9 cu	14.29333	0.808290	13.36000	14.76000	3
703-9 cr	12.77600	1.575446	10.77000	14.28000	5

**Figure 16.** Comparison of means and standard deviations for 703-9 cu and 703-9 cr samples.

Results of Shapiro–Wilk’s test, i.e., test statistics W and p values are presented in Table 12.

Table 12. Shapiro–Wilk’s test results.

Soil Mixture	Number of Crush Tests	Value W (Shapiro–Wilk Test)	p Value
703-9 cu	3	0.750000	-
703-9 cr	5	0.889965	0.356930

As Shapiro–Wilk’s test has confirmed the normal character only for the 703-9 cr sample, it is not possible to compare the mean of these two samples with an ANOVA. Just two (out of three total) specimens of the 703 cu sample have exactly the same value of the compressive strength (see Table 4), so it is not possible to calculate the p -value for this sample.

4.2.3. ANOVA 433-6 cu vs. 433-6 cr

The basic statistics of the 433-6 cu and 433-6 cr samples are presented in Table 13. The comparison of means, the comparison of ranges of means $\pm$ standard deviations, and the comparison of means $\pm$ 1.96 times standard deviations for these two samples are presented in Figure 17.

Table 13. Basic statistics of 433-6 cu and 433-6 samples.

Soil Mixture	Mean	Standard Deviation	Min	Max	Number of Specimens in a Sample
433-9 cu	8.87000	0.542494	8.36000	9.44000	3
433-9 cr	9.20710	0.326610	8.83000	9.40000	3

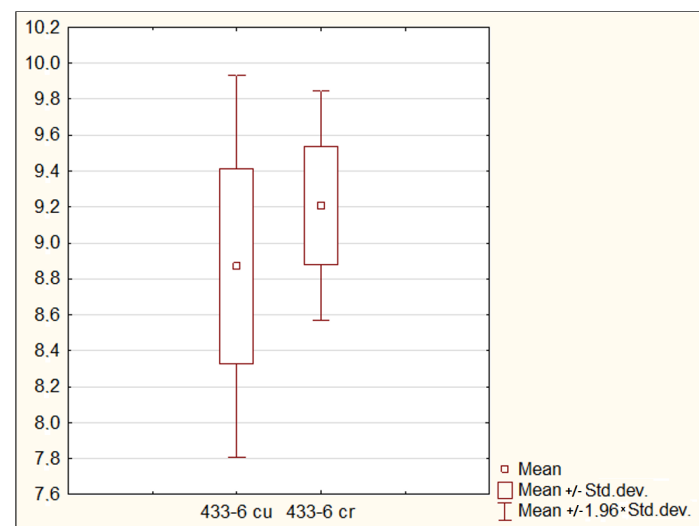


Figure 17. Comparison of means and standard deviations for 433-6 cu and 433-6 cr samples.

Results of Shapiro–Wilk’s test, i.e., test statistics W and p values are presented in Table 14.

Table 14. Shapiro–Wilk’s test results.

Soil Mixture	Number of Crush Tests	Value W (Shapiro–Wilk Test)	p Value
433-6 cu	3	0.990826	0.816787
433-6 cr	3	0.761433	0.025411

As Shapiro–Wilk’s test has confirmed the normal character only for the 433-6 cu sample, it is not possible to compare the mean of these two samples with an ANOVA. The calculated p value for the 433-6 cr sample (0.025411; see Table 14) is much lower than the assumed confidence level $\alpha = 0.05$. The 433-6 cr sample does not have a normal character, which excludes the possibility of ANOVA application.

4.2.4. ANOVA 433-9 cu vs. 433-9 cr

The basic statistics of the 433-6 cu and 433-6 cr samples are presented in Table 15. The comparison of means, the comparison of ranges of means $\pm$ standard deviations, and the comparison of means ± 1.96 times standard deviations for these two samples are presented in Figure 18.

Table 15. Basic statistics of 433-9 cu and 433-9 samples.

Soil Mixture	Mean	Standard Deviation	Min	Max	Number of Specimens in a Sample
433-9 cu	13.28800	0.973278	12.24	14.77	5
433-9 cr	12.47333	0.881608	11.51	13.24	3

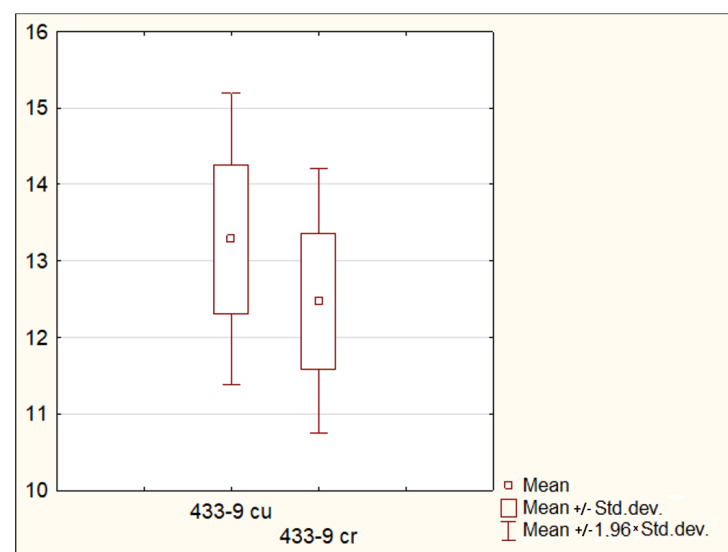


Figure 18. Comparison of means and standard deviations for 433-9 cu and 433-9 cr samples.

Results of Shapiro–Wilk’s test, i.e., test statistics W and p values are presented in Table 16.

Table 16. Shapiro–Wilk’s test results.

Soil Mixture	Number of Crush Tests	Value W (Shapiro–Wilk Test)	p Value
433-9 cu	5	0.939440	0.661979
433-9 cr	3	0.962677	0.628698

The normality of both samples is compared through the Shapiro–Wilk test.

$$p = 0.661979 > \alpha = 0.05$$

$$p = 0.628698 > \alpha = 0.05$$

So, the homogeneity of the variances of these two samples can be tested with the Levene test. The results of that test are presented in Table 17.

Table 17. Levene’s test—results.

Samples	Levene’s $F(1,df)$	df (Degree of Freedom)	p Value
433-9 cu vs. 433-9 cr	0.015156	6	0.906041

As $p = 0.906041$ is higher than $\alpha = 0.05$ the homogeneity of variances, this is confirmed. Then, the significance of the difference between means can be verified with an ANOVA. To conduct that, the set 433-9 cu is supplemented by two results that are equal to the mean of the results of the real three crush tests made (to make an equal number of specimens in each sample, i.e., 5). The results of the ANOVA for 433-9 cu and 433-9 cr samples are presented in Table 18.

Table 18. Results of ANOVA for 433-9 cu vs. 433-9 cr.

SS_{btw}	df_{btw}	MS_{btw}	SS_{tot}	df_{tot}	MS_{btw}	F	p
1.45161	1	1.45161	5.4008	8	0.6751	2.15021478	0.180723

Instead of comparing the value of statistics F (presented in Table 18) to F critical (read from the Fisher table, dependent on confidence level α , and df_{btw} , and df_{tot}), Statistica software gives a p value. As $p = 0.180723$ is higher than the assumed confidence level $\alpha = 0.05$ it can be stated that there is no reason to reject the hypothesis H_0 and the means of these two samples are equal.

4.2.5. Summary of Results

There were four ANOVA analyses assumed to be conducted:

- 703-6 cu vs. 703-6 cr samples
- 703-9 cu vs. 703-9 cr samples
- 433-6 cu vs. 433-6 cr samples
- 433-9 cu vs. 433-9 cr samples

For all of them, a confidence level $\alpha = 0.05$ is assumed. For the sample 703-9 cu, it is not possible to verify the normal character of the compressive strength results with Shapiro–Wilk’s test. For the sample 433-6 cr—according to results of Shapiro = Wilk’s test—the normal character of the sample is not confirmed. So, two of the comparisons, i.e., 703-9 cu vs. 703-9 and 433-6 cu vs. 433-6, cannot be done with ANOVA. The other two comparisons, i.e., 703-6 cu vs. 703-6 and 433-9 cu vs. 433-9, are completed. The ANOVA null hypothesis (the means of the compared sample are equal) is proved for both of these comparisons.

5. Discussion

The popularization of cement-stabilized rammed earth as a building material that is in direct competition with concrete requires the development of standards for determining compressive strength classes similar to those determined for concrete. The obtained results showed that the compressive strength of CSRE specimens should be carried out for a period longer than 28 days, as specified in the standard for concrete EN 206 [31]. The cubic specimens tested after this time obtained a compressive strength equal to 63% to 73% of the strength of 120 day specimens. The nature of the CSRE compressive strength growth curve is much different from that of concrete. It is also noted that after 120 maturing data points, the results of the compressive strength of the core and cubic specimens were similar and differed by less than 1 MPa.

Density over 2200 kg/cubic meter is significantly higher than the minimum tested in other studies [21,42,56], where approximately 1800 kg/cubic meter is the minimal value guaranteeing proper UCS values. It could be an explanation for the vastly higher values of destructive forces measured in this study in compression, as the dependence of UCS on dry density is well documented [57–59].

Comparisons of UCS between cube-shaped and cored specimens of different mixtures of cement-stabilized rammed earth initially may reveal a small advantage in mechanical properties in favor of cube ones. The mean averages for specimens except for 433-6% were higher than their cored counterparts. Ratios for mean UCS vary from 1.001 to 1.119, which represents values from 0.01 to 1.51 MPa in these cases, but analysis of variance

failed to prove that the achieved results are statistically different. Tests conducted on an atypical outlier, that is, a mixture of 433-6%, inversely revealed cored specimens with better mechanical properties, achieving 9.21 MPa of compressive strength.

It seems important to stress that for mixtures with 9% stabilizer, the difference between specimens is visibly more highlighted, reaching 0.82 and 1.51 MPa for 433 and 703 mixtures, respectively. This disparity is reduced in specimens with only 6% of cement, as it reaches only 0.34 MPa for mixture 433 and 0.01 for mixture 703.

The need for safety factors in order to erect CSRE construction in a moderate climate is obvious, as it seems unreasonable to base this technology on in situ, long-lasting testing. The provided analysis made it noticeable that a coefficient factor between cube specimens UCS and cored ones' is not necessary, and tests and research to date failed to find any statistically significant difference between the mean values of the compressive strength for the 433-9 and 703-6 mixtures. As far as the study is concerned, estimating UCS for CSRE within any construction element based on laboratory testing of a mixture specimen is not viable. The confidence interval shown in Figures 19 and 20 defines the range where, with 95% probability, the “real” mean can be located.

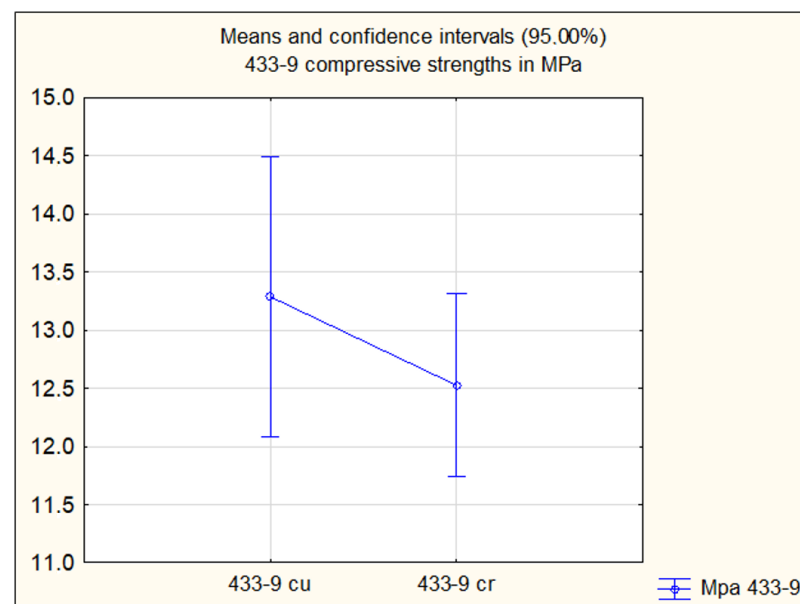


Figure 19. Comparison of means and confidence intervals for 433-9 cu and 433-9 cr samples.

The quotation mark used for “real” means it needs explanation. The mean values presented in these figures are based on the results of the tests. When the normality of the samples is confirmed at the confidence level $\alpha = 0.05$ the confidence intervals can be calculated and presented. This means that if more cube samples are prepared (samples marked as cu in these figures) or more core samples (cr) are drilled off the structure, the mean of the compressive strength, as we can expect, will be within the range stated by the confidence intervals. As discussed in [49], if the graphical representation of confidence intervals overlaps each other (as they do in Figures 19 and 20), it also confirms that the mean values of the compressive strength are indistinguishable between the compared samples.

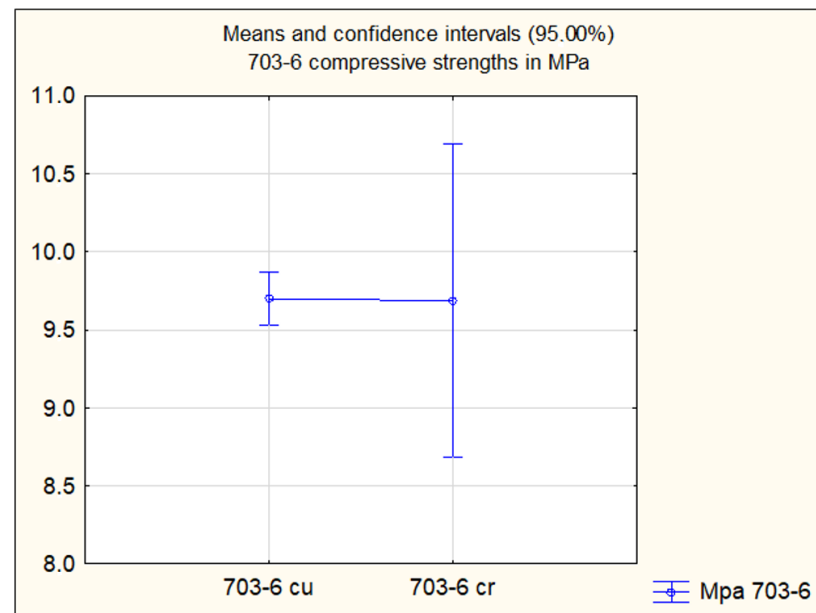


Figure 20. Comparison of means and confidence intervals for 703-6 cu and 703-6 cr samples.

6. Conclusions

In this article, we analyze the compressive strength of cement-stabilized rammed earth (CSRE), comparing results obtained from cubic and cored specimens that underwent a 120-day curing process. These studies, using analysis of variance (ANOVA), provide significant data on the differences and similarities in strength between specimens molded in the laboratory and those extracted directly from structures.

When determining the compressive strength of cement-stabilized rammed earth (CSRE), it is recommended to test specimens after curing for more than 28 days since the mechanical strength of CSRE increases up to 120 days. The conducted analyses revealed that there is no statistically significant difference between the mean UCS of cubic and cored specimens for mixtures 433-9 and 703-6; therefore, no shape coefficient factor is needed to calculate the compressive strength of CSRE elements using laboratory testing. For mixtures 433-6 and 703-9, ANOVA analysis was impossible to conduct as a normal distribution was not proven for two samples. Nevertheless, the similarity in mean UCS may lead to the conclusion that the correlation between these samples is comparable.

To ensure an adequate level of safety for future construction made from CSRE, it is evident that an appropriate safety factor is required. However, determining a statistically validated safety factor will necessitate significantly larger sample sizes. Future research should focus on conducting analogous statistical analyses for 28-day specimens as well as those aged for many years to better understand the long-term development of compressive strength in CSRE. The conducted research indicates that a shape coefficient factor for specimens may not be necessary. Nonetheless, establishing a reliable safety factor for the practical application of rammed earth will require a broader scope of studies.

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