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Optimizing Compressive Strength in Rammed Earth Walls: Correlating Cement Dosage Effects

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Abstract*– In this research, the relationship between "added cement" and "compressive strength of rammed earth walls" was explored using a linear regression model. These walls were constructed using aggregates from Colpa Alta, Huánuco, Peru, and analyzed using bivariate data analysis. The motivation for this study stemmed from the heightened challenges faced by the local populace in constructing confined masonry houses due to increased building material costs triggered by the COVID-19 pandemic. Given these circumstances, rammed earth walls present a more economical alternative to conventional construction, although their structural capacity requires enhancement. For the study, 60 aggregate samples were gathered on-site in compliance with the Peruvian Technical Standard E-080 and categorized into four groups of 15, with cement replacements at 5%, 10%, and 15%. Compressive strength assessments were conducted on these samples, and statistical methods were employed to analyze the results. The outcomes indicated a notable enhancement in compressive strength in the cement-augmented samples compared to traditional rammed earth blocks, establishing a robust correlation between "added cement" and the "compressive strength of rammed earth walls." This correlation and its impact were quantitatively delineated through the developed linear regression model.

***Keywords*-- rammed earth walls, cement, compressive strength, correlation, compressed earth blocks.**

I. INTRODUCTION

The construction of rammed earth houses or compressed earth block (CEB) utilizes clay soil that is compacted with wooden rammers. Roux and Espuna highlight that "vestiges found in the Asian, European, and American continents confirm the use of earth construction techniques for many years" [1]. The widespread adoption of this method is attributed to its low construction costs, which arise from the use of locally available materials and the absence of a need for skilled labor. Additionally, it offers superior thermal and acoustic properties.

According to the most recent population survey by the National Institute of Statistics and Informatics (INEI) in the Huánuco region of Peru, there are 104,930 private residences constructed using adobe or rammed earth, accounting for 55.3% of all private homes in the region [2]. Although the use of noble materials in homes increased by 53.3% in 2017 compared to 2007, there has been a shift towards the confined masonry system. This system offers enhanced structural safety, improved finishes, and greater comfort. However, the implementation of confined masonry is costly due to the materials required and the necessity for professional involvement throughout the construction process, a situation exacerbated by the COVID-19 pandemic. Consequently, a significant portion of the population still prefers the CEB system. In response to this situation, there is a pressing need to augment the compressive strength of traditional CEB by incorporating specific percentages of cement into the locally sourced aggregate. This modification aims to reduce structural failures in walls constructed using this method, thereby enhancing the safety of the local population.

II. BACKGROUND

A meticulous review of pertinent scholarly literature was undertaken to solidify the theoretical framework and elucidate the experimental precedents relevant to our study, thus preparing the ground for subsequent field testing. Among the sources consulted, Samaniego and Sarmiento [3] provided insights into how additives influence the mechanical characteristics, specifically the compressive strength and density, of cement-stabilized rammed earth walls. This necessitates an experimental quantitative analysis. Compressive strength testing of rammed earth yielded a baseline strength of 10.71 kg/cm2. Furthermore, in trials where soil was substituted with cement at increments of 6%, 8%, and 10%, compressive strengths of 7.2 kg/cm2, 10.73 kg/cm2, and 13.47 kg/cm2, respectively, were recorded. Notably, a blend labeled as mixture No. 12, comprising 10% cement, demonstrated superior compressive strength of 29.48 kg/cm2, marking a 22% improvement over stabilized rammed earth with identical cement content and a 175% enhancement relative to traditional rammed earth construction.

Garcia [4] investigated the compressive strength of non-fired masonry by replacing soil with 3%, 6%, 9%, and 12% of Type I Portland cement and lime. The standard adobes exhibited an average compressive strength of 11.3 kg/cm2, whereas samples containing 9% lime and 12% cement showed significantly higher strengths of 63 kg/cm2 and 73.47 kg/cm2, respectively; thus, affirming that the inclusion of cement and lime significantly elevates performance over conventional adobe.

Additionally, the research by Chávez and Medina [5] aimed at fabricating cement-enhanced compacted earth blocks for rural housing construction in the province of San Martín. The design compressive strength of blocks containing 10% cement was observed at 39.02 kg/cm2 at 7 days, escalating to 76.96 kg/cm2 over 14 and 21 days. Comparisons with standard compressed earth blocks (CEB) showed increases of 52.66%, 154.83%, and 252.20% over these respective periods, substantiating that cement augmentation markedly boosts the strength of CEBs.

A. Tapial

The Peruvian Technical Standard E.080 [6] defines rammed earth as a "construction technique that uses wet earth poured into firm molds (boards), to be compacted by layers using wooden mallets or rammers".

B. Rammed earth and formwork unit

Peruvian Technical Standard E.080 [6] regulates that "rammed earth units must have the following dimensions: minimum width: 0.40 m., maximum height: 0.60 m, maximum length: 1.50 m and the minimum thickness of formwork wood must be 20 mm".

C. Aggregate

In this study, the term 'aggregate' refers to the earth utilized in the construction of compressed earth blocks (CEB). The Peruvian Technical Standard E.080 [6] characterizes earth as a construction material comprising four fundamental components: clay, silt, fine sand, and coarse sand

D. Portland Cement Type I

Giraldo and Tobón detail that the primary constituents of this type of cement include beta dicalcium silicate (Ca_3SiO_4), tricalcium silicate (Ca_3SiO_5), along with a composition of 60% lime (CaO) and alumina (Al_2O_3), and Portland clinker. They also note that theories concerning the structure, composition, and formation processes of this cement vary considerably [7]. Sánchez mentions that this particular cement formulation is employed broadly in various construction projects where no specific properties are demanded of the cement [8].

III. METHODOLOGY

The current study adopts a quantitative methodology to investigate the relationship between the amount of cement added and the compressive strength of compacted earth walls. It utilizes mixed methodologies, underscoring the importance of employing diverse methodological approaches in engineering. Such approaches are essential for addressing complex and multidisciplinary challenges effectively. This methodological diversity enriches the understanding of key variables and augments the practical application of the research findings within the civil engineering domain [9].

A. Aggregate Extraction

An optimal source for aggregates necessary for the production of compressed earth blocks (CEB) was identified in the Colpa Alta region of Huánuco, Peru. It was imperative that the soil from this location met the evaluation criteria for clay content to ensure its compatibility with the construction requirements of rammed earth walls as defined by the Peruvian Technical Standard NTP E0.80 [6].

The initial test conducted was the "Clay Ribbon" test. This involved molding a cylinder with a diameter of 12mm from a wet mud sample, which was then manually flattened into a tape approximately 4mm thick. If the tape could be extended to a length between 20cm and 25cm without breaking, this indicated a high clay content, signifying the soil's potential suitability for CEB manufacture.

Following this, the "Dry Resistance" test was applied, where four pellets were formed using minimal water and then allowed to dry over a period of 48 hours, shielded from any moisture and water exposure. Once dried, these pellets were tested for durability by pressing them with fingers. In this specific case, none of the pellets broke or cracked, confirming the aggregate’s suitability as a building material. If any pellets had failed this test, it would have necessitated a retest, and consistent failure would result in the disqualification of the quarry as a material source.

The final test was the "Moisture Content" test, wherein a fist-sized ball of aggregate was compacted strongly and then dropped from a height of 1.10 meters onto a solid surface. The disintegration of the earth ball into more than five pieces indicated the appropriate moisture content, aligning with the standards prescribed in NTP E0.80 [6]. This series of tests confirms the viability of the soil for use in CEB construction within the specified standards.

B. Soil Mechanics Tests

To ascertain the content of clay, silt, and gravel in the extracted aggregate, a granulometric analysis was conducted in accordance with the guidelines of NTP-400.012 [10]. Additionally, the plasticity index (PI) was determined, which is defined by NTP 339.129 [11] as the range of soil moisture content over which the soil exhibits plastic behavior. This value was calculated by first determining the liquid limit (LL) and the plastic limit (LP) and then performing an arithmetic subtraction of these two values in the mentioned order.

The LL, indicative of the moisture content at the transition from liquid to plastic states of the soil, was measured using the Casagrande method. The LP, representing the moisture content at the boundary between plastic and semisolid states, was determined by taking approximately 20 grams of the material used for the LL test. This sample was kneaded and allowed to lose moisture until it could be formed into cylinders of 3.2 mm diameter. The process continued by reducing the cylinder's diameter until it began to crack or crumble, at which point the weight of the material was recorded to calculate the moisture content. This procedure was replicated with another soil sample, and the average moisture content from both tests was used to ascertain the LP.

The PI values, categorized as $IP>20$, $20\geq IP\geq 7$, $7>IP>0$, and $IP=0$, correspond to soils with very high clay content, moderate clay content, low clay content, and no clay content, respectively. This classification aids in evaluating the suitability of the soil for various construction applications, particularly for projects involving the use of compacted earth or rammed earth techniques.

C. Handling and Processing of samples

Following soil mechanics tests, 60 soil samples were segregated into four distinct groups of 15 samples each. One group was retained as the control with no modifications; the remaining three groups were amended by adding 5%, 10%, and 15% of Type I Portland Cement to each group, respectively.

The preparation of the compressed samples was conducted in accordance with the stipulations of NTP E.080 [6]. The samples were shaped in molds measuring 0.1 x 0.1 x 0.15 meters. Each sample was compacted by delivering 10 blows with a 5 kg mallet to ensure uniform density and structure.

To facilitate proper curing, the compressed samples were stored for 28 days in a controlled environment that was shielded from moisture and maintained cool to promote slow drying. This measure was critical to minimize the risk of cracking and ensure optimal material properties, as per the guidelines in NTP E.080 [6]. This curing process is essential for developing the strength and durability required for the intended structural applications of the compressed earth blocks.

D. Compressive Strenght Test

To assess the compressive strength of the ground block samples, breaking stress tests were conducted. These tests involved the application of axial loads or compressive forces to the previously prepared and dosed cubes at a controlled rate until failure was induced. According to the protocol outlined in NTP-339.034 [10], the sample resistance was calculated by dividing the maximum force achieved during the test by the cross-sectional area of the specimen.

It is important to note, as detailed in [6], that the average resistance of the four highest-performing samples out of a set of six cubes must meet or exceed the last observed resistance value. This criterion ensures that the data reflects consistent material performance and reliability in structural applications, providing a robust measure of the material's suitability for construction purposes.

E. Data Analysis and Processing

Upon gathering the data from the compressive strength tests as documented in laboratory records [11], the results were processed using Microsoft Excel to calculate the compressive strength of each sample. For a more comprehensive statistical analysis of the sample data, the SPSS V.26 software was employed. This advanced statistical analysis tool was utilized to determine the measures of central tendency—mean, median, and mode—for each group of samples.

To verify the assumption of normality, which is critical for the application of parametric tests, the Shapiro-Wilk test was conducted. This test is particularly appropriate given the sample size did not exceed 50 units. Following the confirmation of normal distribution, the Student's t-test, a parametric method, was used to compare the means of the different sample groups. This step is crucial for identifying statistically significant differences in compressive strength across the groups, thereby providing insights into the effects of varying Portland Cement concentrations in the soil samples.

IV. RESULTS

In the TABLE I, the compressive strengths obtained from the standard samples are presented, which is formed only by the aggregate.

TABLE I

COMPRESSIVE STRENGTH OF CONVENTIONAL RAMMED EARTH BLOCKS

Conventional rammed earth blocks or standard (sample)	Compression force (Kg)	Area (cm^2)	Compressive strength (Kg/cm^2)
1	2046	102.01	20.06
2	2056	100.00	20.56
3	2038	104.04	19.59
4	2239	100.00	22.39
5	2137	98.01	21.80
6	2120	100.00	21.20
7	2048	98.01	20.90
8	2069	96.04	21.54
9	2139	100.00	21.39
10	2024	102.01	19.84
11	1970	102.01	19.31
12	2146	100.00	21.46
13	2026	102.01	19.86
14	2126	100.00	21.26
15	1988	100.00	19.88

Note: Calculation of compressive strength after division of the compressive force obtained from the test by the cross-sectional area of the sample.

Considering TABLE I, Fig. 1 was elaborated, which shows the behavior of the compressive strength of the blocks. In addition, TABLE II shows the measures of central tendency of the data collected.

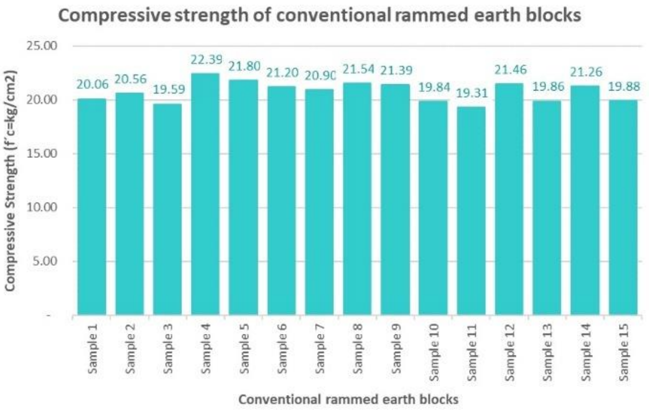


Fig. 1. Graph of the compressive strength of conventional rammed earth blocks [12]

TABLE II
CENTRAL TENDENCY MEASURES OF COMPRESSIVE STRENGTH DATA FROM CONVENTIONAL RAMMED EARTH BLOCKS

Sample number	Valid	15
	Lost	0
Stocking		20.7360
Fashion		19.31$^{\text{to}}$

Note: Average and mode of 15 valid data.

The analysis of compressive strength data for conventional rammed earth blocks at 28 days revealed an average strength of 20.74 kg/cm². Additionally, the altered samples with cement additions of 5%, 10%, and 15% yielded average compressive strengths of 25.27 kg/cm², 30.75 kg/cm², and 39.43 kg/cm², respectively. These values were computed to establish the mean compressive strength for each group and have been systematically presented in TABLE III, juxtaposed with the compression resistance data of the unaltered samples. This comparative display facilitates an evaluation of the impact of cement addition on the structural integrity and compressive capacity of rammed earth blocks.

TABLE III
COMPRESSIVE STRENGTH OF CEMENT EARTH BLOCKS FROM 5% TO 15% WITH RESPECT TO THE DRY WEIGHT OF THE MIXTURE

Sample	Compressive strength of standard samples (Kg/cm^2)	Compressive strength of blocks with 5% cement addition (Kg/cm^2)	Compressive strength of blocks con 10% cement addition (Kg/cm^2)	Compressive strength of blocks with 15% cement addition (Kg/cm^2)
1	20.06	25,18	31,53	39,32
2	20.56	24,58	29,33	37,36
3	19.59	24,88	30,44	37,45
4	22.39	24,90	31,07	39,72
5	21.80	24,93	30,41	38,51
6	21.20	25,26	31,39	39,18
7	20.90	24,01	31,01	38,24
8	21.54	24,63	29,60	42,09
9	21.39	26,43	30,94	39,69
10	19.84	24,23	30,62	40,58
11	19.31	26,55	29,87	39,07
12	21.46	26,74	31,52	40,00
13	19.86	25,24	30,85	41,44
14	21.26	25,47	32,30	39,02
15	19.88	25,96	30,34	39,83

Note: Applied to conventional rammed earth blocks and average compressive strength for rammed earth blocks with 5%, 10% and 15% by weight of Portland cement type.

Considering TABLE III and Fig. 2 showing the behavior of the compressive strength of the blocks compared to the averages of the resistances of the blocks with addition of cement of 5%, 10% and 15%.

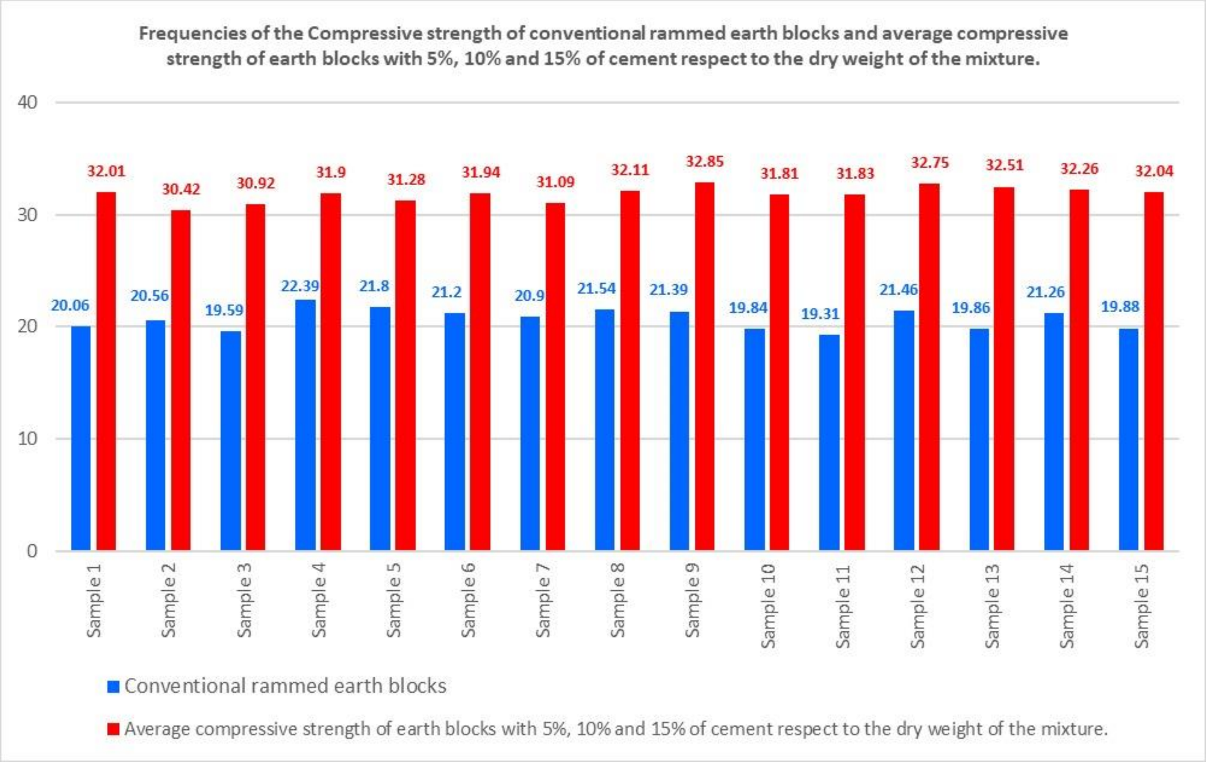


Fig. 2. Graph of frequencies of the compressive strength of conventional rammed earth blocks and average compressive strength of earth blocks with 5%, 10% and 15% of cement respect to the dry weight of the mixture [12]

The figure above clearly demonstrates a significant enhancement in the compressive strength of samples with added cement compared to the standard samples without cement. To further understand the influence of cement on aggregates sourced from Colpa Alta, it is crucial to establish whether the compressive strength data for these samples adhere to a normal distribution. This assessment is fundamental for applying parametric statistical tests, such as the t-test, which assume normality in the data distribution.

The first analytical step involves conducting the Shapiro-Wilk test, which is particularly suitable given that the number of samples is less than 50 ($n<50$). This test will statistically ascertain if the compressive strength values conform to the normality hypothesis. A confirmation of normal distribution allows for the subsequent application of parametric methods to robustly evaluate the impact of cement addition on the compressive strength of the rammed earth blocks.

TABLE IV
Compressive strength normality test

	Shapiro-Wilk		
	Statistical	Gl	Gis.
Compressive strength of conventional rammed earth blocks	0.942	15	0.412
Compressive strength of rammed earth blocks with 5% by weight of cement	0.940	15	0.387
Compressive strength of rammed earth blocks with 10% by weight of cement	0.982	15	0.982
Compressive strength of rammed earth blocks with 15% by weight of cement	0.967	15	0.805

Note: Applied to conventional rammed earth blocks and average compressive strength for rammed earth blocks with 5%, 10% and 15% by weight of Portland cement type.

Upon executing the Shapiro-Wilk test as detailed in TABLE IV, the following p-values were recorded: 0.412 for the compressive strength of the conventional rammed earth blocks, 0.387 for the blocks with a 5% cement addition, 0.982 for the blocks with a 10% cement addition, and 0.805 for the blocks with a 15% cement addition. Given that all p-values exceed the 0.05 threshold, the null hypothesis (H0) that the samples adhere to a normal distribution is accepted for each group analyzed (control, 5%, 10%, and 15% cement additions).

Subsequently, a test for equality of variances, or homoscedasticity, was conducted using the parametric Levene's test as presented in Table V. This test assesses whether the variance within each group of samples is statistically equivalent. The null hypothesis (H0) of Levene's test posits that there are no significant differences in variance among the populations from which the samples were derived, indicating homogeneity of variances across the groups. Conversely, the alternative hypothesis (H1) suggests that there is a significant variance difference between at least one of the group variances compared to the others.

$$H0 : \sigma_1^2 = \sigma_2^2$$
$$H1 : \sigma_1^2 \neq \sigma_2^2$$

If the Levene test results in a statistically significant p-value, falling below the commonly accepted significance threshold of 0.05, the null hypothesis would be rejected. This outcome would lead to the conclusion that the variances among the populations from which the samples are drawn are not equal. Such a finding indicates a heterogeneity of variances across the different groups tested, which has implications for the statistical methods applicable for further analysis of the data.

TABLE V
Compressive strength normality test

	Shapiro-Wilk		
	Statistical	Gl	Gis.
Compressive strength of conventional rammed earth blocks	0.942	15	0.412
Compressive strength of rammed earth blocks with 5% by weight of cement	0.940	15	0.387
Compressive strength of rammed earth blocks with 10% by weight of cement	0.982	15	0.982
Compressive strength of rammed earth blocks with 15% by weight of cement	0.967	15	0.805

Note: Applied to conventional rammed earth blocks and average compressive strength for rammed earth blocks with 5%, 10% and 15% by weight of portland cement type.

As indicated in TABLE V, for all cases, the significance values (p-values) exceed 0.05, thereby satisfying the null hypothesis that the variances among the groups are equivalent. This confirmation allows for the application of the Student's t-test for two independent samples, which assumes homogeneity of variances.

Given that the normality condition for all samples has been established, the Student's t-test was applied, comparing the standard samples against each set of cement-added samples. The null hypothesis (H0) for this test posits that there is no significant difference between the means of the two populations from which the samples are derived. Specifically, it asserts that the difference between the population means is zero (H0: $\mu 1 - \mu 2 = 0$). The alternative hypothesis (H1) contends that there is a nonzero difference between the means (H1: $\mu 1 - \mu 2 \neq 0$). This test is conducted as a two-tailed test.

The results of the Student's t-test, as detailed in TABLE VI, provide statistical evidence on whether the addition of cement significantly affects the compressive strength of the samples compared to the standard samples without cement.

TABLE VI
Test of independent samples

	Levene test	
	F	Gis.
Pattern – 5% cement	0.979	0.331
Pattern – 10% cement	1.409	0.245
Pattern – 15% cement	0.498	0.486

Note: Applied to conventional rammed earth blocks and average compressive strength for rammed earth blocks with 5%, 10% and 15% by weight of portland cement type.

Upon executing the Student's t-test, a p-value approaching zero was obtained, which is below the threshold of 0.05. This result leads to the rejection of the null hypothesis in all cases, affirming that the addition of cement significantly influences the compressive strength of compressed earth blocks (CEB) made with aggregates from Colpa Alta, Huánuco.

To quantitatively assess the extent of influence or the level of correlation between the amount of cement added and the compressive strength of the reinforced earth walls, it is essential to employ multivariate analysis. This approach is particularly pertinent given the variety in the cement content across the samples, with four distinct groups studied: standard, 5% cement, 10% cement, and 15% cement.

Prior to engaging in multivariate analysis, the homogeneity of variances among these groups must be verified. This is typically conducted using the Levene's test, which assesses whether the variance within each group is statistically equivalent. The null hypothesis (H0) for the Levene's test posits that there are no significant differences in variance among the populations from which the samples are derived, indicating homogeneity of variances across the groups. This step is crucial as it ensures the applicability of certain multivariate techniques that assume equal variances across groups.

$$H0 : \sigma_1^2 = \sigma_2^2 = \sigma_3^2 = \sigma_4^2$$

H1: at least one of the measures is different

The TABLE VII shows the results of the Levene test. The significance level p is 0.298 > 0.05, so the null hypothesis is accepted.

TABLE VII
Homogeneity of Variances Test

		Levene statistics	Gl1	Gl2	Gis.
Resistance	Based on the average	1.258	3	56	0.298

Note: Levene test for all four study groups.

The outcomes documented in TABLE VIII are significant as they involve a bivariate analysis between the standard sample and other samples with added cement, all resulting in p-values less than 0.05, affirming the acceptance of the null hypothesis for equality of variances. Subsequent multivariate analysis further confirmed this equality of variances across the groups.

The next analytical step is to employ the Analysis of Variance, commonly referred to as one-factor ANOVA. This statistical method decomposes the total variance observed in the data into two components: variance attributable to the effect of the studied factor (between-group variance) and variance due to random error (within-group variance). The one-factor ANOVA tests the null hypothesis (H0) that all group means are equivalent, suggesting that there are no significant differences among them.

In application, one-factor ANOVA will determine whether the variations in compressive strength observed across the different cement additions (standard, 5%, 10%, and 15%) are statistically significant or merely the result of random variation. A rejection of the null hypothesis in the ANOVA would indicate significant differences in compressive strength across the groups, attributed to the varying percentages of cement added to the CEB samples. This analysis is crucial for understanding the impact of cement content on the structural properties of the blocks, guiding optimization strategies for material formulation in construction applications.

$$H0 : \sigma_1^2 = \sigma_2^2 = \sigma_3^2 = \sigma_4^2$$

In this context, μ1, μ2, μ3, and μ4 denote the mean values for the four investigated groups (pattern, 5% cement, 10% cement, and 15% cement addition). The alternative hypothesis (H1) postulates that a minimum of one population mean differs from the remaining ones:

H1: at least one of the measures is different

Where μ1, μ2, μ 3, μ4 represent the means of the populations of the 4 groups under study (pattern, 5% cement, 10% cement and 15% added cement). TABLE VIII shows the results of the test and the null hypothesis is verified because p

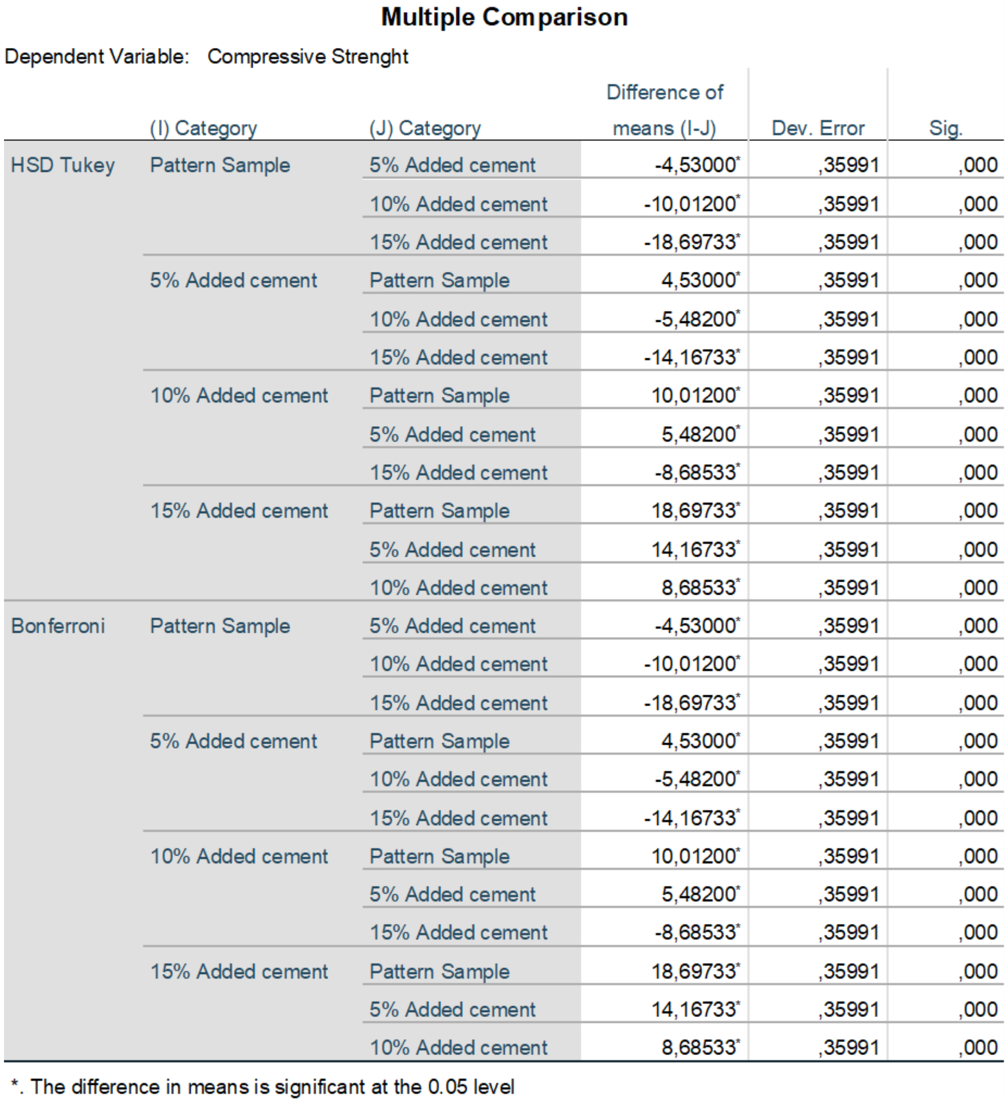
= 1.422E-18 < 0.05. This also reaffirms the bivariate analysis between two samples.

TABLE VIII
One-factor ANOVA test

Sample	Sum of squares	Gl	Quadratic mean	F	Gis.
Between groups	2912.070	3	970,69	999.165	1.422E-48
Within groups	54.404	56	0.972		
Total	2966.474	59	30,44		

Note: The ANOVA test allows us to compare the measurements of the four study groups.

It is important to note that the one-factor ANOVA does not identify which specific groups differ from each other. To determine which groups have different means, the Tukey test and the Bonferroni test, after performing the one-factor ANOVA, were performed to compare results as shown in Figure 3.



Multiple Comparison

Dependent Variable: Compressive Strenght

	(I) Category	(J) Category	Difference of means (I-J)	Dev. Error	Sig.
HSD Tukey	Pattern Sample	5% Added cement	-4,53000*	,35991	,000
		10% Added cement	-10,01200*	,35991	,000
		15% Added cement	-18,69733*	,35991	,000
	5% Added cement	Pattern Sample	4,53000*	,35991	,000
		10% Added cement	-5,48200*	,35991	,000
		15% Added cement	-14,16733*	,35991	,000
	10% Added cement	Pattern Sample	10,01200*	,35991	,000
		5% Added cement	5,48200*	,35991	,000
		15% Added cement	-8,68533*	,35991	,000
	15% Added cement	Pattern Sample	18,69733*	,35991	,000
		5% Added cement	14,16733*	,35991	,000
		10% Added cement	8,68533*	,35991	,000
Bonferroni	Pattern Sample	5% Added cement	-4,53000*	,35991	,000
		10% Added cement	-10,01200*	,35991	,000
		15% Added cement	-18,69733*	,35991	,000
	5% Added cement	Pattern Sample	4,53000*	,35991	,000
		10% Added cement	-5,48200*	,35991	,000
		15% Added cement	-14,16733*	,35991	,000
	10% Added cement	Pattern Sample	10,01200*	,35991	,000
		5% Added cement	5,48200*	,35991	,000
		15% Added cement	-8,68533*	,35991	,000
	15% Added cement	Pattern Sample	18,69733*	,35991	,000
		5% Added cement	14,16733*	,35991	,000
		10% Added cement	8,68533*	,35991	,000

*. The difference in means is significant at the 0.05 level

Fig. 3. Tukey and Bonferroni test results among study groups

The analysis of Figure 3 clearly illustrates a more pronounced influence of 15% cement addition by weight on the compressive strength of reinforced earth walls. However, as indicated in Table IX, there is a larger variance in the results within this study group, a phenomenon not observed in other groups where the deviation is typically smaller than that of the standard group.

This increased variability in the 15% cement addition group could suggest a number of potential issues or variables impacting the consistency of results, such as differences in material properties, mixing procedures, or curing conditions.

Such variability underscores the importance of rigorous quality control measures and standardized procedures in the experimental setup to ensure reliable and reproducible results across all samples and groups.

Understanding these variances is crucial for accurately assessing the impact of cement addition on the structural properties of rammed earth walls. It highlights the need for further investigation into factors that contribute to the inconsistency of results, especially at higher levels of cement addition, to optimize the formulation and application of cement-stabilized earth in construction.

To determine the correlation, the variable "cement addition" can be classified as an ordinal type (0%, 5%, 10% and 15%). When performing this analysis, a correlation factor of 0.968 with Spearman's Rho factor and a significance level of 1.1475E-36<0.05 are identified, so it is considered that there is a "strong" correlation between the variable "cement addition" and "compressive strength.

TABLE IX
DESCRIPTIVE DATA OF SAMPLES

		Resistance	
		Stocking	Standard deviation
Category	Boss	20.74	0.93
	5% Cement	25.27	0.83
	10% Cement	30.75	0.79
	15% Cement	39.43	1.31

Note: The samples were tested with 3 different types of cement percentage

However, it is also convenient to adapt the variable "cement addition" as a quantitative variable (0, 0.05, 0.10 and 0.15) to build a linear regression model.

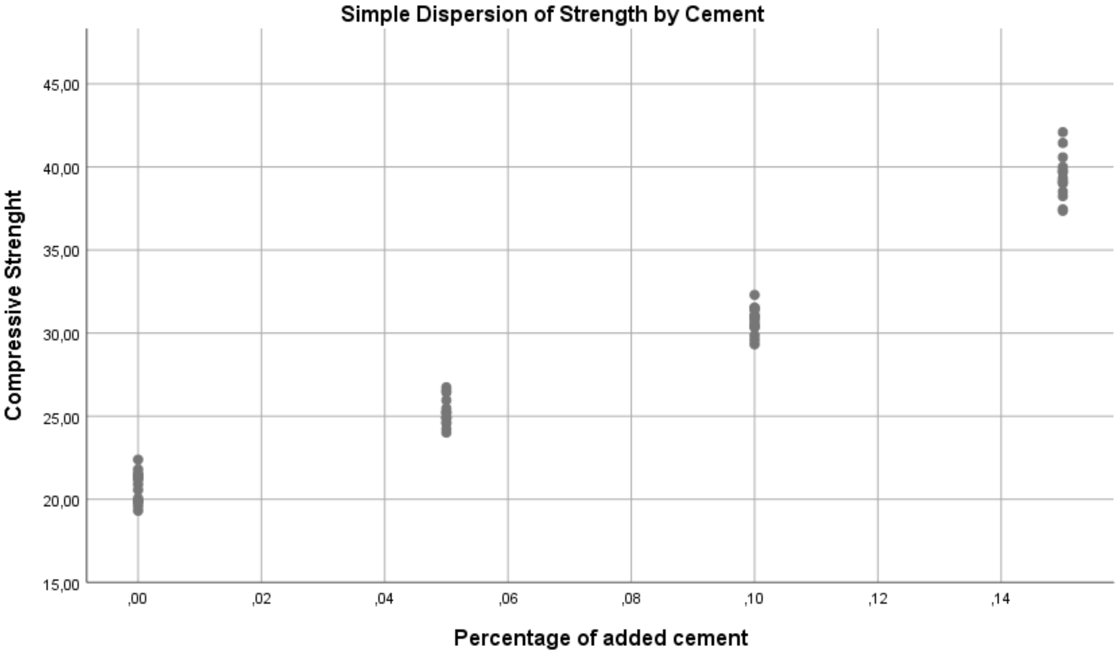


Fig. 4. Scatter plot considering the variables "added cement" and "compressive strength."

When making the determination by Pearson's correlation factor, it is identified that the factor is equivalent to 0.979 with a significance 8.6049E-42 so it is accepted that there is a strong correlation between the variables. With this, we proceed to build the linear regression model. The model equation has the structure shown in (1)

$$Y = \beta_0 + \beta_1 x \quad (1)$$

Where:

β_0:constant y β_1:linear coefficient

TABLE X shows the results of the determined model, where β0 = 19.81 and β1 = 123.418. This means that a minimum average strength of 19.81 kg/cm2 is expected for samples without cement addition and 1.23148 kg/cm2 for each cement addition percentage unit.

TABLE X
DETERMINATION OF THE LINEAR REGRESSION MODEL

		Non-standardized coefficients		Standardized coefficients		
Model		B	Dev. Error	Beta	t	Gis.
1	(Constant)	19,810	,315		62,982	,000
	Cement	123,148	3,362	,979	36,624	,000
Dependent variable: Compressive strength						

The structure of the linear regression model is shown in (2) describing the average compressive strength with the addition of Portland cement type I using High Colpa aggregates in Huánuco is:

$$Y = 19.81 + 123.148x \tag{2}$$

Where:

Y: Compressive strength expected (kg/m2)
X: % cement added (expressed in decimal places)

The R^2 coefficient, a key metric for assessing the goodness of fit in linear regression models, is reported as 0.959. This value indicates that approximately 95.9% of the variance in the "compressive strength" variable is explained by the "cement addition" variable within the context of the regression model. Consequently, only 4.1% of the variability is due to factors not included in the model.

An R^2 value close to 1.0 suggests that the regression model provides a robust representation of the data, capturing a significant portion of the variance in the dependent variable based on the independent variable(s). This high level of explanatory power demonstrates the strong influence of cement addition on the compressive strength of the reinforced earth walls. Figure 5 visually represents this regression model and includes confidence intervals, which offer a graphical depiction of the potential precision of the predicted values and the range within which the true values are likely to fall, given a certain level of confidence. This aids in better understanding the model's reliability and the consistency of cement's impact on compressive strength across different scenarios and data points.

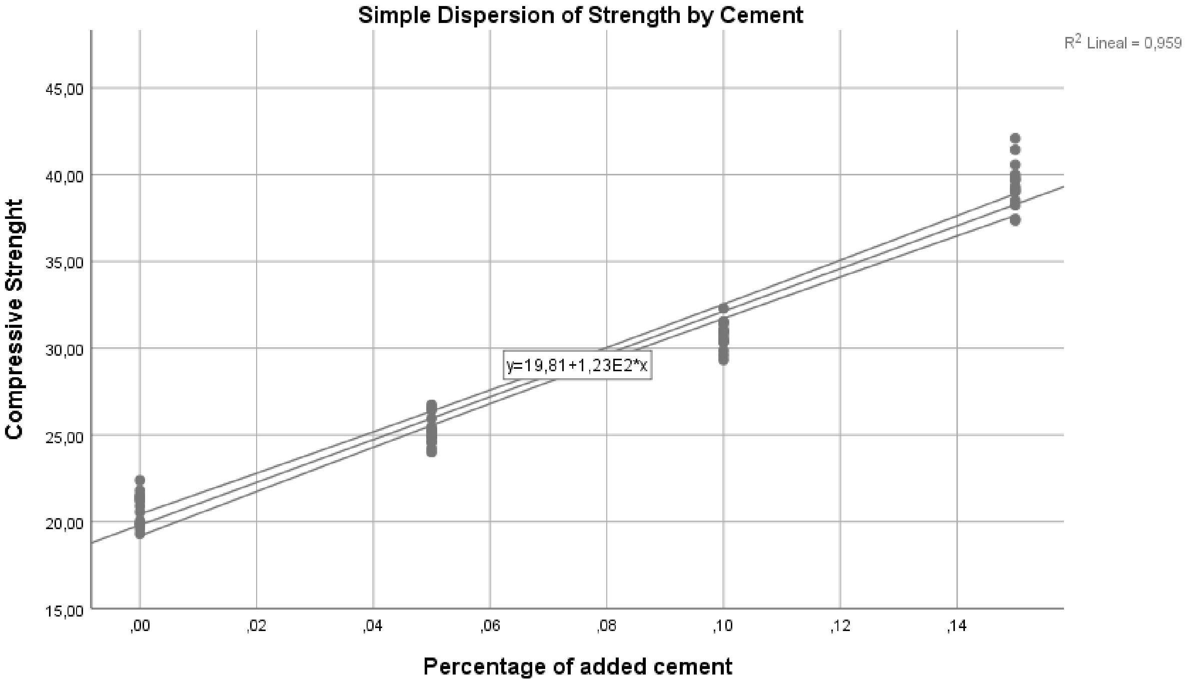


Fig. 5. Linear regression model with confidence intervals

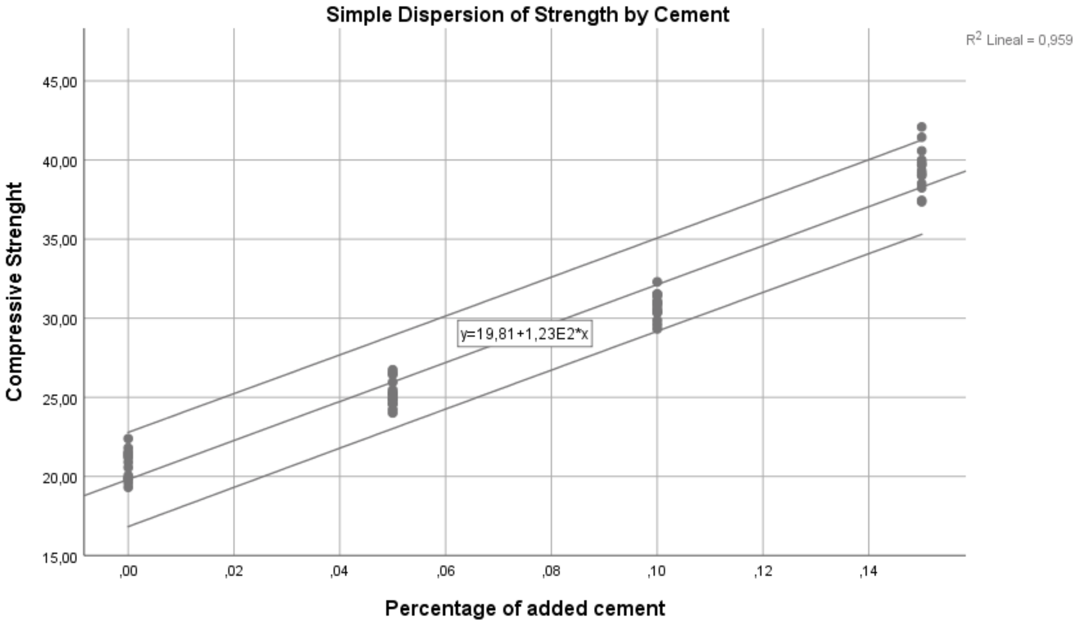


Fig. 6. Linear regression model with prediction intervals

Figure 6 displays the regression model along with prediction intervals, which offer a more conservative estimation method compared to confidence intervals.

V. CONCLUSIONS

The three tests conducted at the Colpa Alta quarry in Huánuco, Peru, for verifying adequate clay content as per [6], were successfully completed as required. The granulometric analysis, liquid limit, and plastic limit tests, referenced in [9] and [10], confirmed that the extracted samples meet the specifications for compressed earth block (CEB) preparation outlined in NTP-E.080 [6].

The stabilization designs incorporating 5%, 10%, and 15% cement demonstrated a clear impact on increasing compressive strength, establishing a robust correlation between the percentage of cement added and the resultant compressive strength. A proportional increase in the average compressive strength of CEBs was observed with higher cement content; thus, more cement in the mix correlates with greater compressive strength.

The derived linear regression model is Y=19.81+123.148x, where “x” represents the percentage of added cement and “Y” denotes the compressive strength of the rammed earth walls in kg/cm2. The results indicated that cement significantly and positively affects the compressive strength of CEBs; notably, samples with a 15% cement addition exhibited the greatest impact, though they also showed the most variability compared to those with 5% and 10% cement content.

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