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Evaluation of Strength Characteristics of Cement-Stabilized Rammed-Earth Material

Abdul Munim Sahito [1*], Rizwan Ali Memon [1], Aneel Kumar [1*], Riaz Bhanbhro [2]

[1] *Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, 76060, Pakistan.*

[2] *Department of Civil Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, 67450, Pakistan.*

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Abstract

The traditional method of rammed-earth construction is seeing a resurgence because of its minimal environmental impact and sustainability. Numerous elements, including soil composition, compaction procedure, stabilization methods, moisture content, and ambient conditions, affect the properties of rammed-earth materials. This research work aims to investigate the strength characteristics of cement-stabilized rammed-earth material. The strength characteristics involve compressive strength and splitting tensile strength. There are four soil types involved in the casting of cement-stabilized rammed-earth, i.e., 0C100S, 10C90S, 20C80S, and 30C70S. The moisture contents used are based on the OMC of Thar Desert sand, i.e., 11.5%, 12.5%, and 13.5%. While the cement contents used are, i.e., 5%, 10%, and 15%. The number of specimens cast is equal to 216. The results of compressive strength and splitting tensile strength tests conclude that strength increases with the increase in cement content; however, the increase in moisture content decreases the magnitude of compressive strength and splitting tensile strength. The increase in clay content up to 20% increases the compressive strength; a further increase in clay content, i.e., 30%, results in a reduction of compressive strength. The splitting tensile strength increases with the increase in clay content. The maximum compressive strength equal to 13.43 MPa is achieved in the specimen, i.e., 20C80S15c, with minimum moisture content used, i.e., OMC-1% (or 11.50%). While the maximum splitting tensile strength achieved is 6.68 MPa of the specimen, i.e., 30C70S15c, with a moisture content of 11.50%.

Keywords: Thar Desert Sand; Sand-Clay Mixture; Cement-Stabilized Rammed-Earth; Mechanical Properties; Rammed-Earth Construction.

1. Introduction

1.1. Introduction to Rammed-earth Material and Construction

Rammed-earth material and construction have been developed since BC and have applications in earthen bunds, embankments, built-in furniture, foundations, floors/roofs, and walls, etc. [1]. Desert soils can be utilized in rammed-earth constructions as an in-situ and low-cost, energy-efficient, and sustainable construction material. Using Thar Desert sand in cement-stabilized rammed-earth as a base material is an amalgamation of in-situ and sustainable material usage. This technique may help the inhabitants of regions where the conventional construction materials are expensive and/or unusual. The infrastructure in Pakistan is built without consideration of extreme temperatures and carbon emissions. Most of the constructed structures in Pakistan are built with concrete that contains cement as a binding material, which is not cost-friendly and also causes a larger carbon footprint in terms of cement manufacturing. This research aims to investigate the strength characteristics of cement-stabilized rammed-earth and to test its suitability for various engineering constructions. Soil is a cost-efficient and locally available material. Rammed earth structure is a system of

* Corresponding author: munim.sahito@admin.muet.edu.pk; aneel.kumar@faculty.muet.edu.pk

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structural walls built with soils that are compacted in layers within a strong formwork. These walls are durable, strong, thermally massive, incombustible, and easy to construct. They are labor-intensive to build exclusive of machinery. It seems a sufficiently strong material to be used for constructing structures and provides sustainable, healthy, durable, and resilient environments in weathering conditions.

A striking mixture of traditional structure methods and contemporary sustainability objectives is rammed earth construction. It all comes down to structure sturdy, visually beautiful, and structurally sound walls with locally accessible earth that has been compacted into layers. By using less cement and other high-energy materials, this approach not only lowers the carbon footprint but also deeply integrates structures with their natural environments. According to research, rammed earth has enormous promise for an environmentally friendly structure [2].

From a structural point of view, Jaquin et al. (2009) [3] investigated the stiffness and strength of rammed earth material. The results comment that by proper understanding and designing of soil engineering, the rammed-earth may achieve advanced engineering milestones without additions of high-profile stabilizers. It is good to highlight the method's capacity to reduce environmental conditioning along with keeping structural integrity.

Considering the durability properties, Reddy et al. (2022) [4] illustrate the environmental conditioning. It states that the erosion prevention of rammed-earth may be improved by longevity, proper finished surface, and compaction methods even if the environmental conditions are extremely worst.

The advantages of using Thar Desert sand in cement-stabilized rammed-earth material are local resource optimization, economic benefit, and cultural resonance. Thar Desert sand consists of exceptional properties that improve the performance of cement-stabilized rammed-earth structures. The improved environmental conditioning includes thermal performance and sustainability after the addition of Thar Desert sand in cement-stabilized rammed-earth.

The challenges and techniques for mitigation are erosion susceptibility and structural integrity. Sand-based wall construction may be more vulnerable to deterioration. The surface can be protected from environmental deterioration by applying protective coatings or natural plasters. It is crucial to make sure the rammed earth complies with construction norms and safety requirements. Designing safe and useful walls is aided by carrying out thorough soil testing and structural assessments.

Research and development opportunities arise when rammed earth structures use sand from the Thar Desert. Furthermore, the personalized mix designs include adapting soil blends to maximize durability and strength while preserving sustainability. Sustainable practices add to further improve the construction's environmental friendliness, consider using kaolinite-dominant clay.

Traditional rammed-earth often lacks sufficient durability and strength for contemporary structural applications, leading to the incorporation of stabilizers such as cement. Cement-stabilized rammed-earth improves mechanical properties while retaining the benefits of rammed-earth construction.

1.2. Motivation and Research Problem

Despite its benefits, cement-stabilized rammed-earth faces challenges in standardization, including variability in long-term performance, optimal cement content, moisture content, and soil composition under different environmental conditions. There is a need for comprehensive research work to establish durability metrics, strength parameters, and reliable mix designs to promote cement-stabilized rammed-earth as a viable alternative to conventional construction material.

1.3. Importance of Cement-Stabilized Rammed-Earth in Construction Over Unstabilized Rammed-Earth

The cement-stabilized rammed-earth is important in construction due to improved strength, ductility, and durability compared to un-stabilized rammed-earth, provides cost-effectiveness and lower embodied energy than conventional construction materials, improves thermal insulation when combined with lightweight aggregates, and is suitable for various structural applications such as foundations, roads, and walls.

Cement-stabilized rammed-earth construction is related to higher embodied carbon emissions, but lower emissions than brick wall-supported structures. It is more cost-effective, improving economic viability and social acceptability in rural areas [5]. The cement-stabilized rammed-earth is essential in the design and analysis of rammed-earth structures, with its modulus influenced by density, cement content, and strength [6]. Compared to typical burnt bricks, which need energy-intensive kilns and contribute to deforestation, the CSRE structure dramatically reduces greenhouse gas emissions [7].

In the Thar Desert's intense heat, rammed earth walls provide exceptional thermal mass, collecting heat during the day and releasing it at night [8]. Improved thermal performance reduces the need for artificial heating and cooling, which saves energy and lowers utility bills [9]. By increasing the rammed earth walls' compressive strength and resistance to erosion, cement-stabilization makes them more resilient to severe weather [10]. Over time, CSRE structures provide a sustainable investment since they require little upkeep and last a long time [11]. For houses in rural and isolated locations, CSRE is a financially feasible alternative due to lower material and transportation costs [12]. Because the

CSRE structure is so straightforward, it may be scaled to effectively meet the housing need [13]. Adopting rammed earth preserves cultural identity while incorporating contemporary technical methods, which is consistent with traditional construction traditions in Pakistan [14]. The desert landscape is complemented by the earthy tones and natural textures of CSRE structures, which improve visual harmony. For the severe desert climate, CSRE is the best option because of its improved thermal performance and structural endurance.

1.4. Problem Statement

The construction industry currently faces significant challenges due to the escalating costs of conventional construction materials, including cement, brick masonry, glass, synthetic fibers, and timber. These materials not only contribute to high project expenditures but also have a substantial environmental impact due to greenhouse gas (GHG) emissions during their manufacturing processes, particularly in the production of Portland cement and fired clay bricks. Additionally, operational structures continue to emit carbon dioxide (CO_2) throughout their lifecycle, further exacerbating their carbon footprint. Cement-stabilized rammed-earth construction offers sustainable characteristics and potential for low-cost construction. Cement-stabilized rammed-earth has improved water absorption, increased compressive strength, and improved compaction characteristics, making it a viable alternative to traditional rammed-earth for load-bearing structures [15].

1.5. Objective of the Study

The objective of this study is to evaluate the optimized percentage of cement-moisture-clay contents for the strength characteristics of rammed-earth material. This study anticipates advancing familiarity with sustainable construction materials and methods appropriate for arid and semi-arid regions by shedding light on the strength behavior of cement-stabilized rammed-earth material.

1.6. Characteristics of the Rammed-Earth Material

The rammed-earth material generally has moderate compressive strength, low tensile and shear strength, good thermal and humidity regulation properties, and its mechanical and physical characteristics, i.e., isotropy, durability, density, and strength. These properties are significantly influenced by parameters, i.e., additives, compaction method, moisture content, and layer adhesion.

Modified rammed-earth improves compressive strength, water stability, and splitting tensile strength by reducing porosity and adding fiber types [16]. Modified rammed-earth (MRE) materials have higher thermal conductivity and specific heat capacity, but may experience slower moisture dissipation, potentially impacting indoor air quality and durability [17]. The stress-strain relationships in rammed-earth can be modelled as a quadratic polynomial, and the stress limit depends on the ratio of the secant modulus to the initial tangent modulus [18].

The dry shear strength is 0.6 to 3.2 MPa, increases with confining pressure and cement content. While wet shear strength, 50% lower than dry values (0.2 to 1.8 MPa), highlighting the moisture sensitivity. Higher cement content, i.e., 15% vs 4%, improves compressive strength and doubles cohesion [19].

Cement-stabilized rammed earth blends the performance improvements offered by contemporary materials engineering with the sustainability and cultural significance of conventional earth structure. For dry areas like the Thar Desert, CSRE is an ideal material because of its qualities, which include improved strength, durability, thermal and acoustic performance, and environmental advantages. Its application can result in stronger structures that satisfy modern construction codes while preserving environmental balance.

1.7. Rammed-Earth Construction Techniques

The cement-stabilized rammed-earth construction improves economic viability, durability, and strength, compared to unstabilized earth, with properties further improved by additives like lightweight aggregates or fibers, but increases carbon emissions and embodied energy with higher cement content, and requires careful consideration of moisture effects, environmental impact, and corrosion protection.

Stabilizers, such as glass fibers, bagasse ash, and cement, can improve the compressive strength and durability of rammed-earth structures, offering potential for sustainability and innovation in architecture and civil engineering practice [20].

Reducing layer height significantly decreases the impact energy in robotic rammed-earth processes, with a minimum number of strokes and ramming frequency needed for sufficient compaction [21]. A novel rammed-earth construction technology, combining recycled or natural materials, can create seismic-resistant buildings with low energy consumption and environmental impact [22].

Plant fibers (date palm fibers or barley straw) can improve rammed-earth strength, particularly in tensile strength, but decrease stiffness, while lime and cement increase it [23].

A moist mixture of subsoil is compressed into a formwork to make solid walls using the sustainable structure technique known as 'rammed earth'. This method uses local resources and has become more relevant in the current era because of its thermal and environmental advantages [9]. Local subsoil with the right ratios of clay, silt, and sand is used in traditional rammed earth construction [24]. Using hand rammers, the soil is compressed after being layered inside wooden formworks [13]. By adding cement, it becomes more durable and mechanically strong, meeting modern structure standards [15]. Particularly in soils with a high clay concentration, lime improves workability and long-term strength [25]. Increased efficiency and consistent density are provided by mechanical tampers and pneumatic rammers [26]. Performance and appropriateness for various environmental situations are improved by engineering the soil mixture [27]. Using locally produced materials encourages sustainability and reduces transportation-related emissions [28]. High thermal mass lowers the need for artificial heating and cooling, which promotes energy efficiency [29]. Significant compressive strength that is appropriate for structural walls may be attained by properly stabilized rammed-earth [30]. Residential constructions in Australia have effectively utilized rammed earth, highlighting both its aesthetic appeal and thermal efficiency [31]. Regional adaptations take into consideration climate and local materials, resulting in a variety of structural techniques [2]. The bonding and particle arrangement in stabilized soils are revealed by methods such as Scanning Electron Microscopy (SEM) [32]. Tensile strength and resistance to cracking are enhanced by the use of natural fibres [33]. Rammed-earth stabilized with recycled materials and local waste maintains its recyclability and mechanical strength, offering a sustainable alternative to traditional cement or lime-based construction methods [34].

1.8. Sustainable Improvement in Rammed-Earth Construction

Refinements in rammed-earth techniques and recycling of excavated soil can achieve ecological sustainability in rammed-earth construction without the use of additives [35]. Rammed-earth construction can play a role in developing sustainable hybrid buildings by incorporating various construction technologies and influencing their overall sustainability [36]. Stabilized rammed-earth with 10% cement and optimum moisture content can improve energy efficiency in buildings [37].

Using local soils promotes sustainability by lowering transportation expenses and emissions [26]. Mechanical and thermal performance can be improved by modifying the composition of the soil, for example, by adding sand from the Thar Desert. Tensile strength is increased and shrinkage cracking is decreased by adding natural fibres such as coconut coir, hemp, or straw [33]. While being environmentally friendly, these biodegradable materials improve structural integrity. Lime is a lower-carbon substitute for cement that enhances workability and durability over time. Compressive strength is increased when lime and clay minerals combine to produce stable compounds [30]. Alkaline solutions are used to activate alumino-silicate minerals to create geopolymers, which are inorganic polymers. Compared to Portland cement, they have much lower carbon emissions while offering superior strength and durability [38]. Prefabricated and modular rammed-earth components save structure time and waste on the job site, increasing productivity and lessening environmental impact [9].

1.9. Factors Affecting the Properties and Behavior of Rammed-earth

The properties and behavior of rammed-earth are mainly affected by the proportions and types of raw materials and stabilizers (such as clay, sand, lime, cement, and fibers), moisture and water content, compaction and layering methods, and environmental factors like weathering and humidity.

The proportions of raw materials and loading rates significantly affect the stress-strain relationships and mechanical properties of rammed-earth [39]. Fiber reinforcement improves the mechanical strength of rammed-earth in both tension and compression, with an optimal content of fibers determined [40]. Modified rammed-earth improves splitting tensile strength, water stability, and compressive strength by adding fiber types or reducing porosity.

Interlayer failure of rammed-earth is mainly caused by the lack of cohesion of the soil at the interlayer interface, with 24% to 45% of the intra-layer cohesion and 33% to 84% of the intra-layer shear strength [41].

1.10. Necessity of Conducting the Current Research and Contribution to the Body of Knowledge

The construction sector uses conventional methods and materials that require a huge amount of energy and emit a huge amount of CO_2. To overcome this issue, the current study adds the knowledge of using natural and sustainable structure construction materials for construction purposes. Furthermore, as per the knowledge of the authors, the optimized percentages of moisture, clay, sand, and cement contents in cement-stabilized rammed-earth have not been worked out yet.

1.11. Novelty of the Current Research Work

The Thar Desert soil is taken as a base material in this experimental study. The time horizon is cross-sectional and based on the region Tharparkar, Sindh (Coordinates: 24°50’45” N69°26’57.2”). The inclusion of Thar Desert soil in rammed earth is carried out to achieve a better material in terms of economically feasible and sustainable construction. The research strategy is experimental, based on laboratory testing of cement-stabilized rammed earth.

The sand-clay mixture is formed as a suitable soil for cement-stabilized rammed-earth. The base material in the cement-stabilized rammed-earth is Thar Desert sand. The clay used is kaolinite dominant clay. The sand-clay-cement-water amalgamation is studied and an optimized contents of each are determine by conducting the compressive strength and splitting tensile strength test.

1.12. Limitations of the Study

This study's concentration on a particular soil type and mixture of geotechnical characteristics is one of its limitations, which might restrict how broadly the findings can be applied to different soil compositions. Furthermore, without taking into account long-term durability under various environmental circumstances like freeze-thaw cycles, erosion, or climatic fluctuations, the study looks at the compressive strength and splitting tensile strength qualities. Your findings would be more applicable to larger settings in cement-stabilized rammed earth structures if future studies were expanded to cover a greater variety of soil types and long-term performance evaluations.

1.13. Sustainable Development Goals

The sustainable development goals, numbers 9, 11, and 13 from the 17 SDGs are addressed. In this research, the risk reduction of environmental impact, housing costs, and infrastructure development is addressed. Carbon footprints (indirectly), the expensive costs of construction (directly), and infrastructure development (directly) are addressed.

2. Materials and Methods for Cement-stabilized Rammed Earth Casting and Testing

2.1. Real-World Rammed-Earth Construction Procedure

The granulation graphs of the materials used are shown in Figure 1. The real-world rammed-earth construction process is illustrated in the flowchart (Figure 2). While the rammed-earth wall after following the procedure is shown in Figure 3.

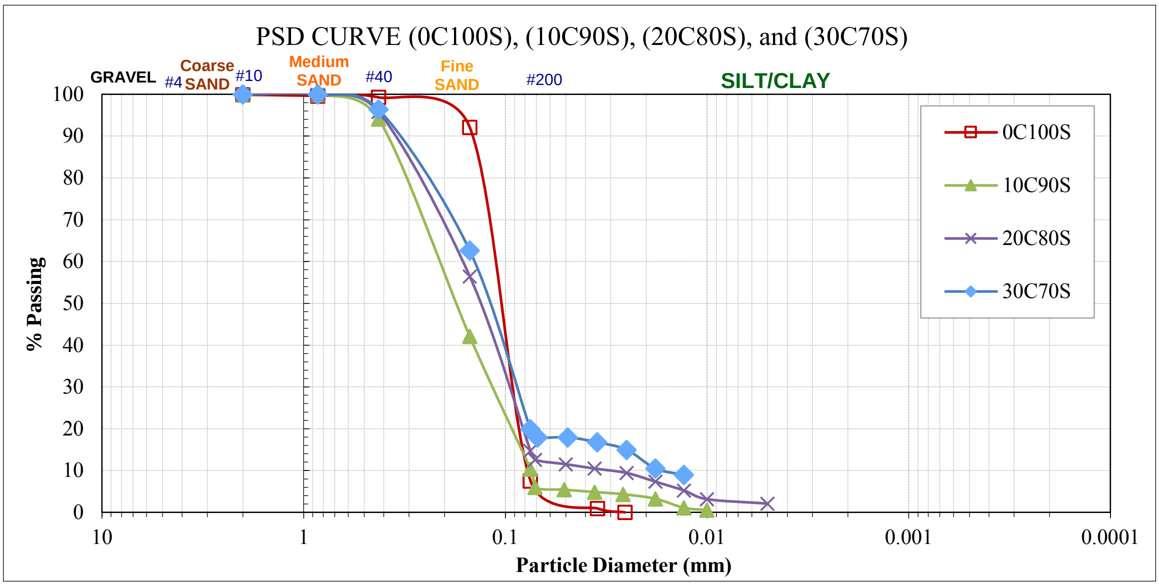

Figure 1. Granulation diagram of the (0C100S), (10C90S), (20C80S), and (30C70S) in rammed-earth

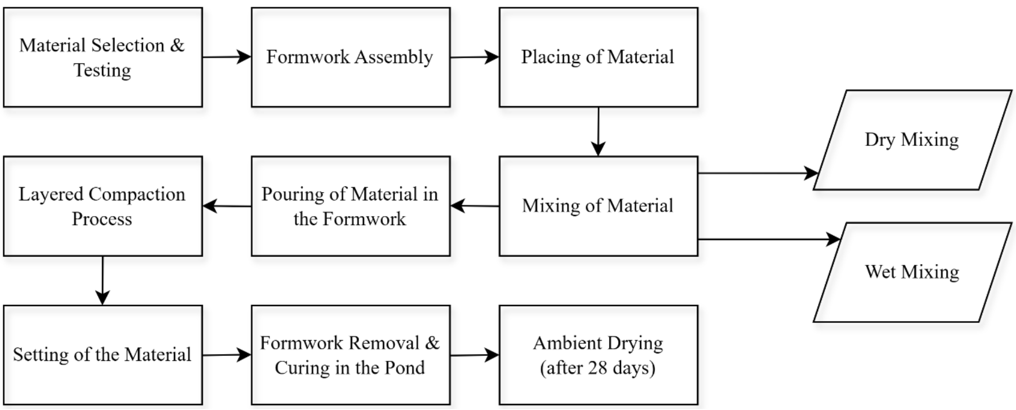

Figure 2. Rammed-earth construction procedure

Figure 3. Rammed-earth wall

2.2. Methodology Flowchart

The workflow of the methodology is summarized in Figure 4.

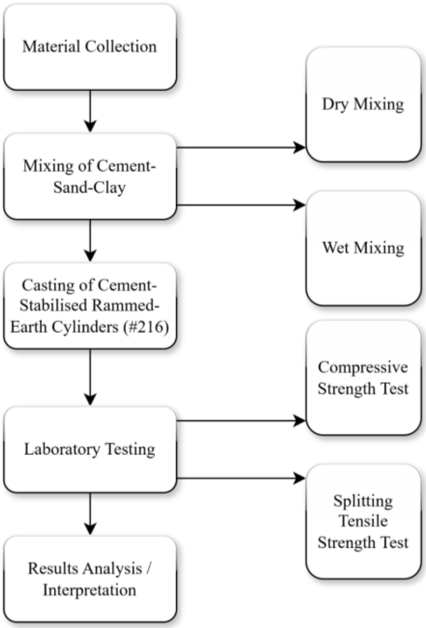

Figure 4. Methodology flowchart

2.3. Theoretical Approach

The theoretical approach is based on principles of rammed-earth-stabilization and strength development. The strength enhancement of cement-stabilized earth is influenced by the cement content, fine content, and water content [42]. Cement is the most efficient stabilizer for enhancing the strength of organically treated soils, with optimal improvement in strength occurring at 9% cement and 7% organic matter [43].

2.4. Thar Desert Sand

The base material used in this experimental investigation is the Thar Desert sand (Figure 5). The cross-sectional time limit is for the region of Tharparkar, Sindh, Pakistan (coordinates: 24°50'45"N69°26'57.2").

Figure 5. Thar Desert sand

2.5. Clay

The clay displayed in Figure 6 was obtained from Al-Manzar, Jamshoro, 25° 26' 9.888" N and 68° 16' 48.612 E. Various proportions of clay content are used with Thar Desert sand for rammed-earth material preparation.

Figure 6. Clay soil

2.6. Ingredients for Cement-Stabilized Rammed-Earth

While preparing the Thar Desert sand-clay combined soil samples for rammed-earth material, four various soils were prepared. Table 1 explains the proportions of the clay and Thar Desert sand soils used to prepare the various soil samples for rammed-earth material. The numbers in the codes, i.e., 0C100S, explain the soil proportions, i.e., 0% clay and 100% Thar Desert sand; likewise, the codes are assigned to other soil samples too.

Table 1. Composition of prepared soil samples

Type of soil	Soil Proportions (% by dry weight of Thar Desert sand)		Code
	Clay (C)	Sand (S)	
Soil-I	30	70	30C70S
Soil-II	20	80	20C80S
Soil-III	10	90	10C90S
Soil-IV	0	100	0C100S

When forming the various sand-clay mixes for various soil types, the Thar Desert sand and clay are mixed in a dry state to achieve a heterogeneous soil.

2.7. Casting of Cement-stabilized Rammed-Earth Cylinders

Casting of cement-stabilized rammed-earth cylinder involves compacting a wet mix of soil in layers into a cylindrical mould or formwork. The following are the steps carried out while casting the cement-stabilized rammed-earth cylinders:

2.7.1. Soil Formation Procedure

Four types of soils are formed for the cement stabilized rammed earth specimens casting. The proportions of the ingredients for the cement-stabilized rammed-earth are illustrated in Table 1.

2.7.2. Dry Blending of Clay and Thar Desert Sand

The sand-clay mix is achieved by hand mixing the Thar Desert sand and clay during the preparation of the various mixes for the various soil types. This blending is carried out to achieve a uniform dry mix used in casting the cement-stabilized rammed-earth specimens using the cylindrical mould, as shown in Figure 7.

Figure 7. Dry hand blending of clay and Thar Desert sand

2.7.3. Dry Blending of Cement in the Sand-Clay Mix

Before adding water, it is crucial to fully mix the dry elements (sand, clay, and cement) throughout the mixing process. The mixture ought to be steady and homogeneous. The cement is blended with the dry sand-clay mix to achieve a uniform dry soil-cement mix for the cement-stabilized rammed earth cylindrical specimen casting (Figure 8). The cement contents used in mixing for the rammed earth specimen casting are illustrated in Table 2.

Figure 8. Dry blending of cement with sand-clay mix

Table 2. Proportion of cement content used in cement-stabilized rammed-earth

Sr. No.	Cement content (% by dry weight of soil)
1	5
2	10
3	15

2.7.4. Soil-to-Cement Mix Ratio

The soil-to-cement (s/c) ratios used are, i.e., 10:0.5, 10:1, and 10:1.5.

2.7.5. Computation of the Compaction Energy for Cylinder Casting Purposes using Modified Proctor Compaction Energy p.

The ASTM D 1557 procedure was carried out while conducting the compaction. The mechanical energy applied per volume of soil by certain mechanical equipment during the compaction process is known as compaction energy. This mechanical energy works to improve the soil's bearing capacity, shear strength, and reduce the permeability while also rearranging the soil particles and decreasing voids. The rammer's weight, height of descent, volume of the mold being used, number of blows, and number of layers receiving each blow all affect the compaction energy or effort. The acceleration due to gravity (g) also plays a role in compaction effort. The compaction method and related details are shown in Table 3.

Table 3. Compaction energy parameters

Compaction Method	Weight of rammed (kg)	Number of blows (N_B)	Height of drop (m)	Number of layers (N_L)	Volume of mould (m^3)
Modified Proctor (ASTM D1557)	4.54	44	0.457	5	0.00165

The mechanical energy applied per volume of soil by certain mechanical equipment during the compaction process is known as compaction energy. This mechanical energy works to improve the soil's bearing capacity, shear strength, and permeability while also rearranging the soil's particles and decreasing voids. The rammer's weight, height of descent, volume of the mould being used, number of blows, and number of layers receiving each blow all affect the compaction energy or effort. Acceleration due to gravity (g) also plays a role. The mathematical expression for the determination of compaction energy is shown in Equation 1, given by Arcement & Wright [44].

$$E = \frac{[W]\times[N_B]\times[H]\times[N_L]\times[g]}{V} \tag{1}$$

where, E is Compaction energy or compaction effort (kJ/m^3), W is Weight of hammer (kg), N_B is Number of blows, H is Height of drop of rammer (m), N_L is Number of layers, V is Volume of mould (m^3), and g is acceleration due to gravity (m/s^2).

Acceleration due to gravity (g) value is constant, i.e., 9.81 m/s^2. Applying (Equation 2) to the parameters given in Table 4, to determine the compaction effort for the modified proctor compaction method for the casting of cement stabilized rammed earth as shown below.

$$E = \frac{[4.54]\times[44]\times[0.457]\times[5]\times[9.81]}{0.00165}$$
$$E = 2713812.24\ \frac{J}{m^3} = 2713.81224\,\frac{kJ}{m^3} \tag{2}$$

Table 4. Coding of material mixes (Mix-19 to Mix-27)

Material	Codes (here; C = Clay, S = Sand, and c = Cement
Mix-19	20C80S5c
Mix-20	20C80S10c
Mix-21	20C80S15c
Mix-22	20C80S5c
Mix-23	20C80S10c
Mix-24	20C80S15c
Mix-25	20C80S5c
Mix-26	20C80S10c
Mix-27	20C80S15c

2.7.6. Casting of Cement-Stabilized Rammed-Earth Cylinders

Recommends the content of cement in the range of 5 to 12% of the mass of soil, considering the increase in compressive strength [15]. Rammed earth is normally stabilized with 7 to 15% cement by soil mass [45]. The researchers, i.e., [26, 46], used the cement contents in the range of 5 to 15%. The curing time is 28 days [47]. The water ponding method is adopted for the curing purpose. The various moisture contents used in this study are shown in are shown in Table 5. The various material mixes are coded as shown in Tables 4, and 6 to 8. The number of cement-stabilized rammed-earth specimens cast is 216 in total.

Table 5. Moisture contents used: recommends the addition of OMC ± 1% to 2% [30]

Sr. No.	Used moisture contents for rammed-earth	
1	OMC-1%	11.50%
2	OMC	12.50%
3	OMC+1%	13.50%

Table 6. Coding of material mixes (Mix-1 to Mix-9)

Material	Codes (here; C = Clay, S = Sand, and c = Cement
Mix-1	0C100S5c
Mix-2	0C100S10c
Mix-3	0C100S15c
Mix-4	0C100S5c
Mix-5	0C100S10c
Mix-6	0C100S15c
Mix-7	0C100S5c
Mix-8	0C100S10c
Mix-9	0C100S15c

Table 7. Coding of material mixes (Mix-10 to Mix-18)

Material	Codes (here; C = Clay, S = Sand, and c = Cement
Mix-10	10C90S5c
Mix-11	10C90S10c
Mix-12	10C90S15c
Mix-13	10C90S5c
Mix-14	10C90S10c
Mix-15	10C90S15c
Mix-16	10C90S5c
Mix-17	10C90S10c
Mix-18	10C90S15c

Table 8. Coding of material mixes (Mix-28 to Mix-36)

Material	Codes (here; C = Clay, S = Sand, and c = Cement
Mix-28	30C70S5c
Mix-29	30C70S10c
Mix-30	30C70S15c
Mix-31	30C70S5c
Mix-32	30C70S10c
Mix-33	30C70S15c
Mix-34	30C70S5c
Mix-35	30C70S10c
Mix-36	30C70S15c

The clay content in soil formation is carried out by considering the research, i.e., [26, 48, 49].

The total number of cement-stabilized rammed-earth specimens cast for testing purposes was equal to 216. The three specimens were cast with the same specimen specification for each test.

2.7.7. Proportions of Cement-Moisture-Clay Contents in Cement-Stabilized Rammed-Earth Cylinders

The proportions of ingredients in each mix prepared for the casting of cement-stabilized rammed-earth cylinders are illustrated in Tables 9 to 12.

Table 9. Details of cement-stabilized rammed-earth mixes (Mix-1 to Mix-9)

Material	Type of soil	Moisture content (% dry weight of soil)	Cement content (% dry weight of sand)
Mix-1	0C100S	11.50%	5
Mix-2	0C100S	11.50%	10
Mix-3	0C100S	11.50%	15
Mix-4	0C100S	12.50%	5
Mix-5	0C100S	12.50%	10
Mix-6	0C100S	12.50%	15
Mix-7	0C100S	13.50%	5
Mix-8	0C100S	13.50%	10
Mix-9	0C100S	13.50%	15

Table 10. Details of cement-stabilized rammed-earth mixes (Mix-10 to Mix-18)

Material	Type of soil	Moisture content (% dry weight of soil)	Cement content (% dry weight of sand)
Mix-10	10C90S	11.50%	5
Mix-11	10C90S	11.50%	10
Mix-12	10C90S	11.50%	15
Mix-13	10C90S	12.50%	5
Mix-14	10C90S	12.50%	10
Mix-15	10C90S	12.50%	15
Mix-16	10C90S	13.50%	5
Mix-17	10C90S	13.50%	10
Mix-18	10C90S	13.50%	15

Table 11. Details of cement-stabilized rammed-earth mixes (Mix-19 to Mix-27)

Material	Type of soil	Moisture content (% dry weight of soil)	Cement content (% dry weight of sand)
Mix-19	20C80S	11.50%	5
Mix-20	20C80S	11.50%	10
Mix-21	20C80S	11.50%	15
Mix-22	20C80S	12.50%	5
Mix-23	20C80S	12.50%	10
Mix-24	20C80S	12.50%	15
Mix-25	20C80S	13.50%	5
Mix-26	20C80S	13.50%	10
Mix-27	20C80S	13.50%	15

Table 12. Details of cement-stabilized rammed-earth mixes (Mix-28 to Mix-36)

Material	Type of soil	Moisture content (% dry weight of soil)	Cement content (% dry weight of sand)
Mix-28	30C70S	11.50%	5
Mix-29	30C70S	11.50%	10
Mix-30	30C70S	11.50%	15
Mix-31	30C70S	12.50%	5
Mix-32	30C70S	12.50%	10
Mix-33	30C70S	12.50%	15
Mix-34	30C70S	13.50%	5
Mix-35	30C70S	13.50%	10
Mix-36	30C70S	13.50%	15

2.7.8. Pouring of Water in the Soil-Cement Mix

The water is thoroughly poured upon the dry mix to achieve a wet condition for wet mixing as shown in Figure 9. The moisture contents used in mixing for the rammed earth specimen casting are shown in Table 13.

Figure 9. Pouring of water in the soil-cement mix

Table 13. Moisture contents used in this study

Sr. No.	Moisture content
1	OMC – 1%
2	OMC
3	OMC + 1%

2.7.9. Preparation of the Wet Mix of Soil-Cement

The strength and longevity of the specimen are influenced by the water-to-cement ratio, which is crucial. While too little water can make the mixture difficult to work with and interfere with the hydration process, too much water can weaken the mixture. A wet mix of soil-cement is formed after pouring water on the materials in a tray and mixing them as shown in Figure 10. This mixing is carried out for an adequate time and effort to achieve uniformity in the composite material.

Figure 10. Wet mixing of soil-cement material

2.7.10. Pouring of the Wet Mix of Soil-Cement in the Cylindrical Mould

The cement-stabilized moist earth is filled into the mould. The layer of cement-stabilized moist earth is compacted Figure 11. The successive layers of cement-stabilized moist earth are added and compacted till the height of the mould is achieved. The wet soil-cement mix is poured into the cylindrical mould of diameter and height equal to, i.e., 0.1016 m (4 in) and 0.2032 m (8 in), respectively, as shown in Figure 12.

Figure 11. Pouring of wet soil-cement mix in the cylindrical mould and compaction in layers

Figure 12. Compacted wet soil-cement mix in the cylindrical mould up to complete height

2.7.11. Ramming of Wet Soil-Cement Mix in the Cylindrical Mould

Pouring of wet-mix of cement and soil in the mould in 5 individual layers of depth equal to 0.04064 m (1.6 in). Then applying compaction effort equal to 2713.81224 kJ/m^3 (44 number of blows) at each layer, as shown in Figure 10. The dimensions of the mould and parameters for layer compaction are shown in Table 14.

Table 14. Parameters of rammed-earth specimen casting

Sr. No.	Parameters		Magnitude or Dimension
1	Depth of each layer		0.04064 m (1.6 in)
2	Cylindrical Mould	Diameter (d)	0.1016 m (4 in)
		Height (h)	0.2032 m (8 in)
		Area (A)	0.00811 m^2 (0.08725 ft^2)
		Volume (V)	0.00165 m^3 (0.05822 ft^3)
3	Number of blows per layer		44
4	Compaction energy		2713.81224 kJ/m^3
5	Number of layers		5
6	Modified Proctor Test Rammer	Weight	4.54 kg (10 lb)
		Free fall height	0.457 m (18 in)

2.7.12. Finishing of Cement-stabilized Rammed-Earth Specimen

The topmost surface of the cylindrical specimen is made smooth and flat to achieve a better surface for testing purposes, as shown in Figure 13.

Figure 13. Finishing of the cement-stabilized rammed-earth specimen in the cylindrical mould

2.7.13. Resting Cement-Stabilized Rammed-Earth in the Cylindrical Mould for 24 Hours

After the pouring and ramming procedure for cement-stabilized rammed earth, the specimen is rested in the cylindrical mould for 24 hours (Figure 14.), so that it can set and become dry to remove it from the mould easily.

Figure 14. Cement-stabilized rammed-earth specimens cast in the cylindrical moulds

2.7.14. Demoulding of Cement-Stabilized Rammed-Earth Specimens from the Cylindrical Moulds

The specimens were demoulded from the cylindrical moulds after 24 hours (Figure 15).

Figure 15. Demoulded cement-stabilized rammed-earth specimens

2.7.15. Labelling of the Cement-Stabilized Rammed-Earth Specimens Before Curing

The labelling on the specimen according to the specifications, i.e., sand content, clay content, cement content, and moisture content, is necessary for future identifications and conducting the test on the known specimen, as shown in Figure 16.

Figure 16. Labelling of cement-stabilized rammed-earth specimens

2.7.16. Curing of the Cement-Stabilized Rammed-Earth for 28 Days

The specimen must be properly cured after mixing, using the curing pond method to develop its strength to the fullest. Curing is the process of keeping the specimen at the proper temperature and moisture content for a predetermined amount of time to give it strength and environmental conditioning. The cylindrical cement-stabilized rammed earth specimens are kept in a curing pond for 28 days to preserve and achieve strength, as shown in Figure 17. The specimens after curing and the ambient drying process are shown in Figure 18.

Figure 17. Curing of cement-stabilized rammed-earth specimens

Figure 18. Cement-stabilized rammed-earth specimens after curing and ambient drying, and before testing

3. Laboratory Testing Procedures

3.1. Compressive Strength Testing on the Cement-stabilized Rammed-earth Cylinders (ASTM C39)

The compressive strength of rammed earth is dictated by factors such as soil type, particle size distribution, amount of compaction, moisture content of the mix and type or amount of stabilizer used. The compressive strength test procedure covers the evaluation of the compressive strength of cement-stabilized rammed-earth using cast cylinders as specimens. This test is conducted using a UTM machine (Figure 19). The testing standard carried out is ASTM C39.

Figure 19. Universal testing machine (UTM at the Department of Civil Engineering, Mehran UET, Jamshoro

The pictorial presentation of cement-stabilized rammed-earth specimens before the application of compressive load is shown in Figure 20. In this test, the specimen is inserted vertically in the Universal Testing Machine (UTM) and the compressive load is applied in Newton (N), as shown in Figure 21.

Figure 20. Cement-stabilized rammed-earth specimens before the compressive strength test

Figure 21. Cement-stabilized rammed-earth specimens under the application of compressive load

3.2. Splitting Tensile Strength Test on the Cement-Stabilized Rammed-Earth Cylinders (ASTM C496)

The easiest method for determining concrete's tensile strength is splitting tensile strength. Due to the difficulty of applying direct traction to this material, diametric compressive stress is typically applied, which indirectly creates traction in the perpendicular direction and ultimately leads to the material's failure [50]. Tensile Strength is one of the most important properties as the structural stresses make the specimen weak to cracking due to tensile stresses. Splitting tensile strength test is an indirect method of determining the tensile strength, and it can be conducted to determine the tensile strength of rammed earth or stabilized rammed earth cylindrical specimens. Marginal differences in ingredient proportioning and moisture content may influence the required strength and structural stability. Cracks may develop due to the brittleness of rammed earth or stabilized rammed earth members. Therefore, it is very important to perform the splitting tensile strength test. A minimum of three specimens must be tested, and the average value is calculated. The cement-stabilized rammed earth specimen is inserted horizontally lengthwise in the Universal Testing Machine (UTM) and the indirect tensile load applied in Newton (N), as shown in Figure 22. The testing standard carried out is ASTM C496.

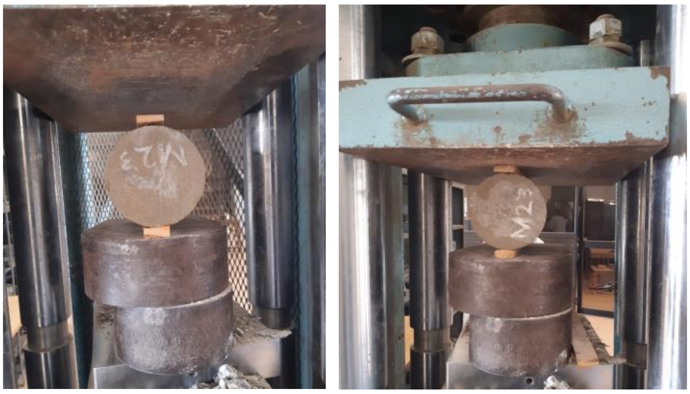

Figure 22. Cement-stabilized rammed-earth specimens under the application of indirect tensile load

4. Results and Discussion

4.1. Compressive Strength of Cement-Stabilized Rammed-Earth Specimens (ASTM C39)

The compressive strength test is conducted after a 28-day curing period of the cylindrical specimen. The specimen is kept vertical in the Universal Testing Machine (UTM) under the application of compressive load. The diameter of the specimen is equal to 0.1016 m (4 in); therefore, the area of the specimen is equal to 0.00810732 m^2 (12.5664 in^2). The compressive force applied to the specimens is in Newtons. The results of the compressive strength test are shown in Table 15, Figure 23, Table 16, Figure 24, Table 17, Figure 25, and Table 18, Figure 26.

Table 15. Results of compressive strength test conducted on cement-stabilized rammed-earth specimens (Mix-1 to Mix-9)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
		17599	8107.32	2.17	
0C100S5c	11.5%	17698	8107.32	2.18	2.19
		18039.8	8107.32	2.23	
		42569	8107.32	5.25	
0C100S10c	11.5%	42776	8107.32	5.28	5.28
		43178	8107.32	5.33	
		60783	8107.32	7.50	
0C100S15c	11.5%	60995	8107.32	7.52	7.52
		61087	8107.32	7.53	
		12913	8107.32	1.59	
0C100S5c	12.5%	12987	8107.32	1.60	1.60
		13118	8107.32	1.62	
		32781	8107.32	4.04	
0C100S10c	12.5%	33129	8107.32	4.09	4.09
		33483	8107.32	4.13	
		57909	8107.32	7.14	
0C100S15c	12.5%	58952	8107.32	7.27	7.23
		58978	8107.32	7.27	
		8594	8107.32	1.06	
0C100S5c	13.5%	9671	8107.32	1.19	1.17
		10117	8107.32	1.25	
		31781	8107.32	3.92	
0C100S10c	13.5%	32139	8107.32	3.96	4.04
		34416	8107.32	4.25	
		57329.5	8107.32	7.07	
0C100S15c	13.5%	57654	8107.32	7.11	7.11
		57812	8107.32	7.13	

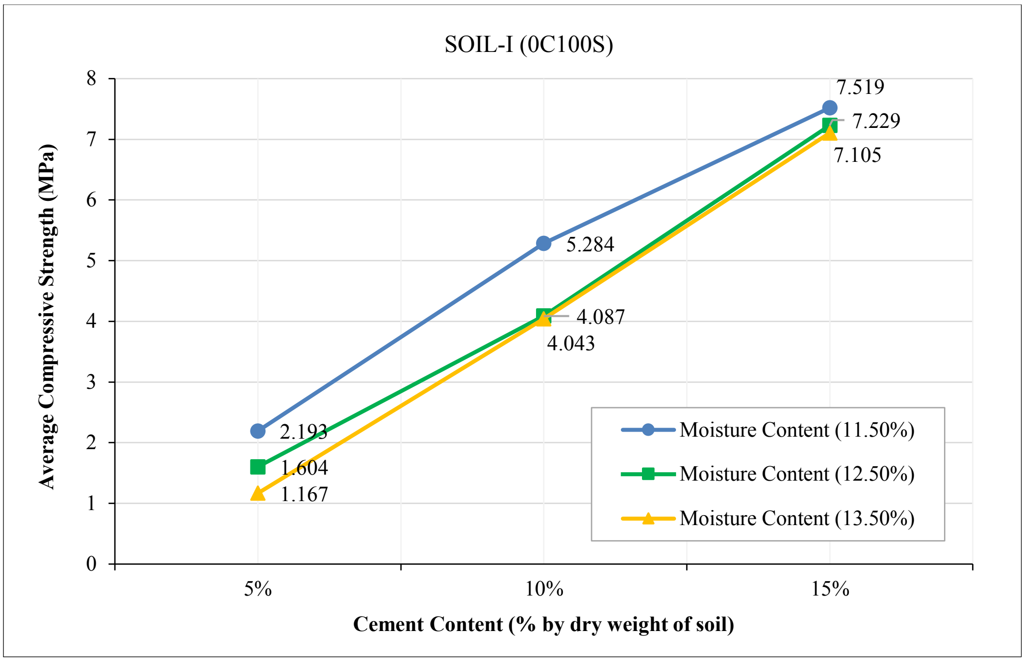

Figure 23. Graphically presenting the results of the ambient dry compressive strength of cement-stabilized rammed-earth cylinders (M-1 to M-9)

Table 16. Results of compressive strength test conducted on cement-stabilized rammed-earth specimens (Mix-10 to Mix-18)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
		18903	8107.32	2.33	
10C90S5c	11.5%	18930	8107.32	2.33	2.37
		19833	8107.32	2.45	
		45704	8107.32	5.64	
10C90S10c	11.5%	45888	8107.32	5.66	5.66
		46009	8107.32	5.67	
		67209	8107.32	8.29	
10C90S15c	11.5%	67207	8107.32	8.29	8.33
		68200	8107.32	8.41	
		17765	8107.32	2.19	
10C90S5c	12.5%	17798	8107.32	2.20	2.21
		18091	8107.32	2.23	
		35590	8107.32	4.39	
10C90S10c	12.5%	36001	8107.32	4.44	4.43
		36103	8107.32	4.45	
		62309	8107.32	7.69	
10C90S15c	12.5%	63908	8107.32	7.88	7.82
		63971	8107.32	7.89	
		15356	8107.32	1.89	
10C90S5c	13.5%	17343	8107.32	2.14	2.06
		17402	8107.32	2.15	
		31254	8107.32	3.86	
10C90S10c	13.5%	35500	8107.32	4.38	4.25
		36501	8107.32	4.50	
		59938	8107.32	7.39	
10C90S15c	13.5%	60032	8107.32	7.40	7.43
		60736	8107.32	7.49	

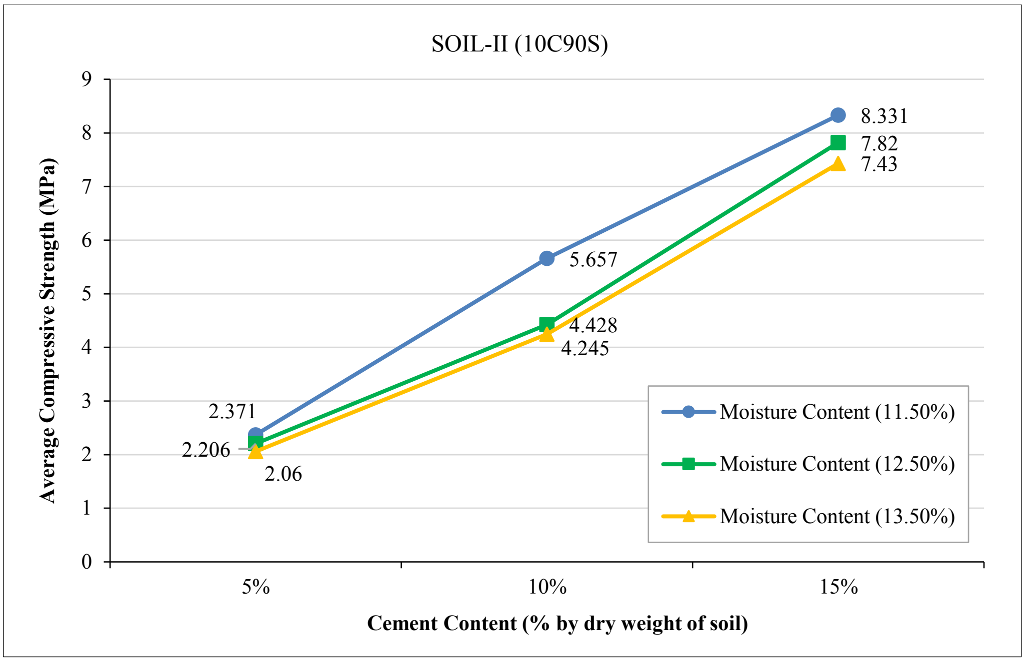

Figure 24. Graphically presenting the results of the ambient dry compressive strength of cement-stabilized rammed-earth cylinders (M-10 to M-18)

Table 17. Results of compressive strength test conducted on cement-stabilized rammed-earth specimens (Mix-19 to Mix-27)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
		42977	8107.32	5.30	
20C80S5c	11.5%	43088	8107.32	5.31	5.31
		43193	8107.32	5.33	
		70910	8107.32	8.75	
20C80S10c	11.5%	75427	8107.32	9.30	9.12
		75503	8107.32	9.31	
		101800	8107.32	12.56	
20C80S15c	11.5%	112100	8107.32	13.83	13.43
		112831	8107.32	13.92	
		40101	8107.32	4.95	
20C80S5c	12.5%	42107	8107.32	5.19	5.11
		42109	8107.32	5.19	
		54560	8107.32	6.73	
20C80S10c	12.5%	55915	8107.32	6.90	7.01
		60103	8107.32	7.41	
		80991	8107.32	9.99	
20C80S15c	12.5%	81829	8107.32	10.09	10.13
		83545	8107.32	10.30	
		38940	8107.32	4.80	
20C80S5c	13.5%	39567	8107.32	4.88	4.87
		39891	8107.32	4.92	
		54109	8107.32	6.67	
20C80S10c	13.5%	54535	8107.32	6.73	6.72
		54831	8107.32	6.76	
		77903	8107.32	9.61	
20C80S15c	13.5%	78786	8107.32	9.72	9.69
		79027	8107.32	9.75	

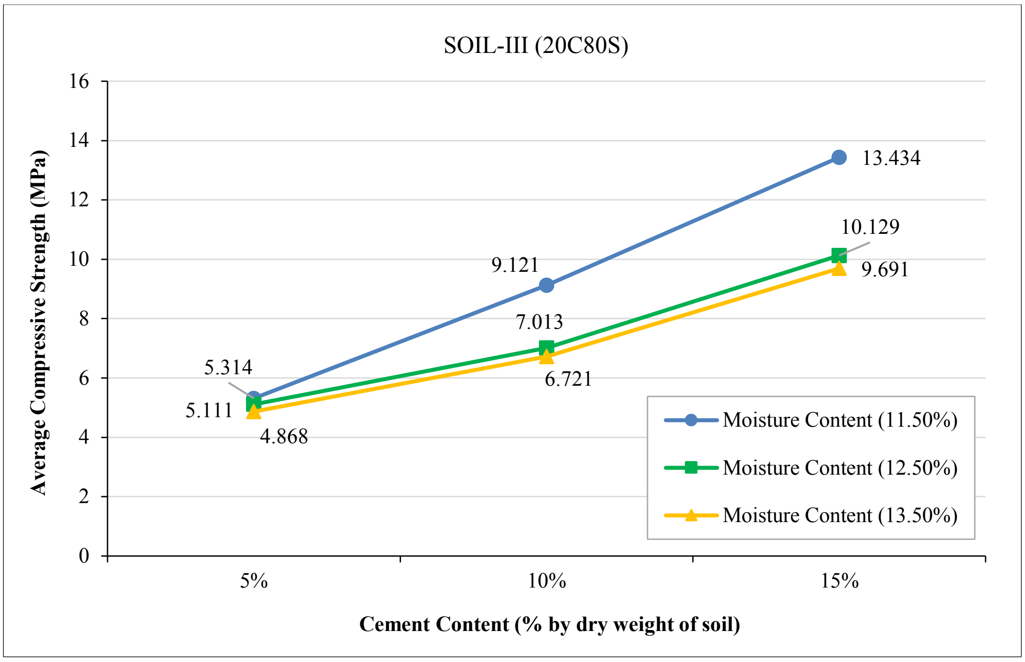

Figure 25. Graphically presenting the results of the ambient dry compressive strength of cement-stabilized rammed-earth cylinders (M-19 to M-27)

Table 18. Results of compressive strength test conducted on cement-stabilized rammed-earth specimens (Mix-28 to Mix-36)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
		40197	8107.32	4.96	
30C70S5c	11.5%	40923	8107.32	5.05	5.03
		41185	8107.32	5.08	
		63102	8107.32	7.78	
30C70S10c	11.5%	63761	8107.32	7.86	7.84
		63795	8107.32	7.87	
		79117	8107.32	9.76	
30C70S15c	11.5%	79552	8107.32	9.81	9.80
		79807	8107.32	9.84	
		38430	8107.32	4.74	
30C70S5c	12.5%	38727	8107.32	4.78	4.77
		38895	8107.32	4.80	
		53577	8107.32	6.61	
30C70S10c	12.5%	53975	8107.32	6.66	6.65
		54107	8107.32	6.67	
		76105	8107.32	9.39	
30C70S15c	12.5%	76369	8107.32	9.42	9.42
		76541	8107.32	9.44	
		31431	8107.32	3.88	
30C70S5c	13.5%	31975	8107.32	3.94	4.00
		33897	8107.32	4.18	
		51973	8107.32	6.41	
30C70S10c	13.5%	52766	8107.32	6.51	6.48
		52970	8107.32	6.53	
		67387	8107.32	8.31	
30C70S15c	13.5%	67428	8107.32	8.32	8.32
		67631	8107.32	8.34	

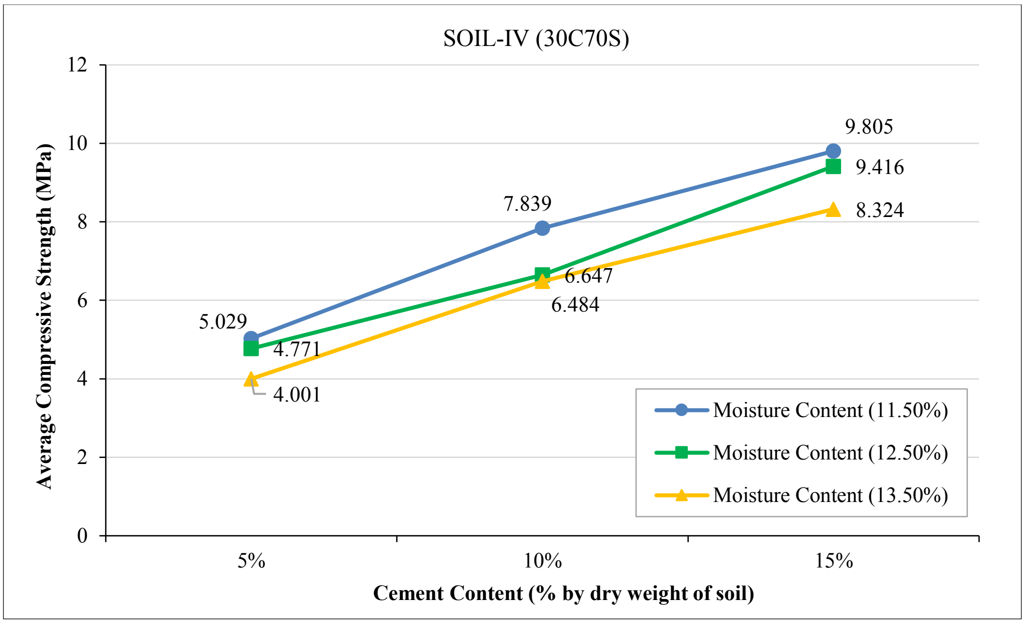

Figure 26. Graphically presenting the results of the ambient dry compressive strength of cement-stabilized rammed-earth cylinders (M-28 to M-36)

Experimental results demonstrate a direct correlation between cement content and compressive strength, with peak strength (13.43 MPa) achieved at 15% cement content. However, increasing moisture content beyond OMC-1% (11.50%) reduces strength due to excess pore water pressure and weakened inter-particle bonding.

Clay content exhibits a non-linear influence: a 20% clay fraction and 80% sand optimizes strength by balancing cohesive (clay) and frictional (sand) properties, while 30% clay induces excessive plasticity, reducing strength. The optimal mix (20C80S15c), comprising 20% clay, 80% sand, and 15% cement at OMC-1% (11.50% moisture), yields the highest compressive strength (13.43 MPa), attributed to efficient cementitious bonding and optimal soil skeleton density, and ultimately the compressive strength.

The compressive strength of cement-stabilized rammed-earth increases significantly over the curing period, with substantial strength gains observed up to 120 days [51]. Adding 5%, 10%, and 15% cement to rammed-earth walls significantly increases their compressive strength compared to conventional blocks [52].

The load distortion characteristics and failure patterns are shown in Figure 27.

Figure 27. Failure patterns/mechanisms of cement-stabilized rammed-earth specimens after the compression failure

Under compressive loading, cement-stabilized rammed-earth cylinders exhibit quasi-brittle failure, characterized by vertical splitting cracks due to inclined shear cracks or Poisson-induced tensile stresses (45° to 60°) from shear localization. Micro-cracks initiate at weak interfacial zones between soil aggregates and cement matrix, coalescing into macro-cracks under progressive loading. Layer delamination may occur if compaction is non-uniform, highlighting interlayer bonding weaknesses. The crack patterns reflect material heterogeneity, cement content, and stress distribution, aligning with Mohr-Coulomb failure criteria for frictional, cohesive materials.

The clay content impacts as the specimen shows a pressing compression, in which a specimen goes under stress-strain kind of phenomenon, and a pressing is observed. For example, when the clay content is 30%, the specimen is pressed layer-on-layer.

4.2. Splitting Tensile Strength of Cement-Stabilized Rammed-Earth Specimens (ASTM C496)

The highest stress a material can withstand before breaking when permitted to be stretched or pulled is known as its tensile strength. This test is conducted after a 28-day curing period. The specimen is kept horizontal in the Universal Testing Machine (UTM) to apply an indirect tensile load to determine the splitting tensile strength of the cylindrical specimen. The diameter of the specimen is equal to 0.1016 m (4 in); therefore, the area of the specimen is equal to 0.00810732 m^2 (12.5664 in^2). The tensile force applied to the specimens is in Newtons. The results of splitting tensile strength tests are shown in Table 19, Figure 28, Table 20, Figure 29, Table 21, Figure 30, and Table 22, and Figure 31.

Table 19. Splitting tensile strength test conducted on cement-stabilized rammed-earth specimens (Mix-1 to Mix-9)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
		6878	8107.32	0.85	
0C100S5c	11.5%	6895.2	8107.32	0.85	0.85
		6902	8107.32	0.85	
		13851	8107.32	1.71	
0C100S10c	11.5%	13907	8107.32	1.72	1.71
		13911	8107.32	1.72	
		28439	8107.32	3.51	
0C100S15c	11.5%	28528	8107.32	3.52	3.52
		28591	8107.32	3.53	
		5897	8107.32	0.73	
0C100S5c	12.5%	5901	8107.32	0.73	0.73
		5961.6	8107.32	0.74	
		11903	8107.32	1.47	
0C100S10c	12.5%	12297	8107.32	1.52	1.50
		12299	8107.32	1.52	
		27460	8107.32	3.39	
0C100S15c	12.5%	27479	8107.32	3.39	3.39
		27482	8107.32	3.39	
		3974.6	8107.32	0.49	
0C100S5c	13.5%	4064.9	8107.32	0.50	0.50
		4155.2	8107.32	0.51	
		9033.2	8107.32	1.11	
0C100S10c	13.5%	9133	8107.32	1.13	1.13
		9304.2	8107.32	1.15	
		21736	8107.32	2.68	
0C100S15c	13.5%	21795.5	8107.32	2.69	2.69
		21973	8107.32	2.71	

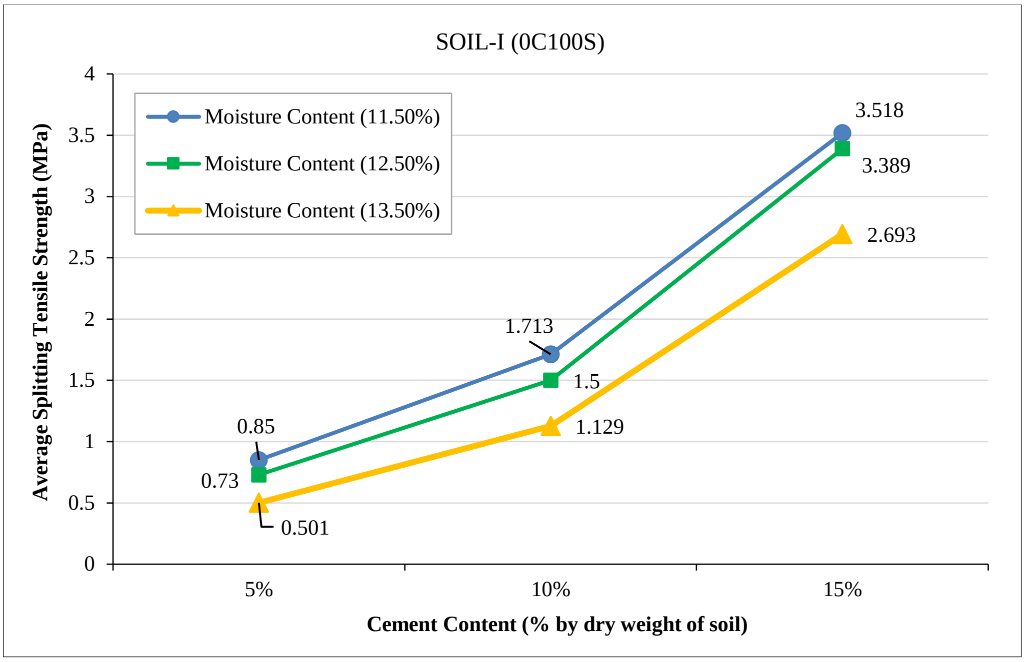

Figure 28. Graphically presenting the results of splitting tensile strength of cement-stabilized rammed-earth cylinders (M-1 to M-9)

Table 20. Splitting tensile strength test conducted on cement-stabilized rammed-earth specimens (Mix-10 to Mix-18)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
10C90S5c	11.5%	7923	8107.32	0.98	0.98
		7959	8107.32	0.98	
		7965	8107.32	0.98	
10C90S10c	11.5%	19060	8107.32	2.35	2.36
		19144	8107.32	2.36	
		19247	8107.32	2.37	
10C90S15c	11.5%	33422	8107.32	4.12	4.13
		33548	8107.32	4.14	
		33596	8107.32	4.14	
10C90S5c	12.5%	7581	8107.32	0.94	0.94
		7635	8107.32	0.94	
		7765	8107.32	0.96	
10C90S10c	12.5%	16996	8107.32	2.10	2.10
		16999	8107.32	2.10	
		17011	8107.32	2.10	
10C90S15c	12.5%	29937	8107.32	3.69	3.70
		29963	8107.32	3.70	
		29970	8107.32	3.70	
10C90S5c	13.5%	7226.5	8107.32	0.89	0.91
		7226.5	8107.32	0.89	
		7698	8107.32	0.95	
10C90S10c	13.5%	15085	8107.32	1.86	1.88
		15192	8107.32	1.87	
		15371	8107.32	1.90	
10C90S15c	13.5%	21893	8107.32	2.70	2.70
		21905	8107.32	2.70	
		21932	8107.32	2.71	

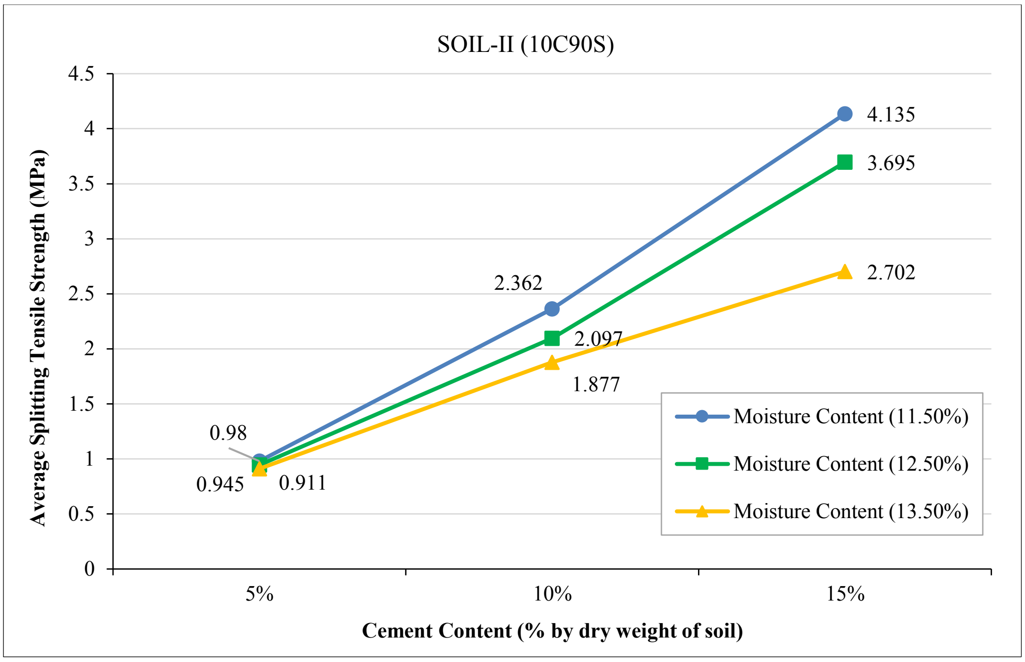

Figure 29. Graphically presenting the results of splitting tensile strength of cement-stabilized rammed-earth cylinders (M-10 to M-18)

Table 21. Splitting tensile strength test conducted on cement-stabilized rammed-earth specimens (Mix-19 to Mix-27)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
		19988	8107.32	2.47	
20C80S5c	11.5%	20571	8107.32	2.54	2.53
		20892	8107.32	2.58	
		35967	8107.32	4.44	
20C80S10c	11.5%	36154	8107.32	4.46	4.49
		36967	8107.32	4.56	
		52985	8107.32	6.54	
20C80S15c	11.5%	53028	8107.32	6.54	6.55
		53417	8107.32	6.59	
		18446	8107.32	2.28	
20C80S5c	12.5%	18988	8107.32	2.34	2.32
		18999	8107.32	2.34	
		31065	8107.32	3.83	
20C80S10c	12.5%	31349	8107.32	3.87	3.87
		31722	8107.32	3.91	
		47809	8107.32	5.90	
20C80S15c	12.5%	47991	8107.32	5.92	5.91
		48029	8107.32	5.92	
		15988	8107.32	1.97	
20C80S5c	13.5%	16571	8107.32	2.04	2.03
		16892	8107.32	2.08	
		30967	8107.32	3.82	
20C80S10c	13.5%	31154	8107.32	3.84	3.87
		31967	8107.32	3.94	
		38700	8107.32	4.77	
20C80S15c	13.5%	38777	8107.32	4.78	4.79
		38927	8107.32	4.80	

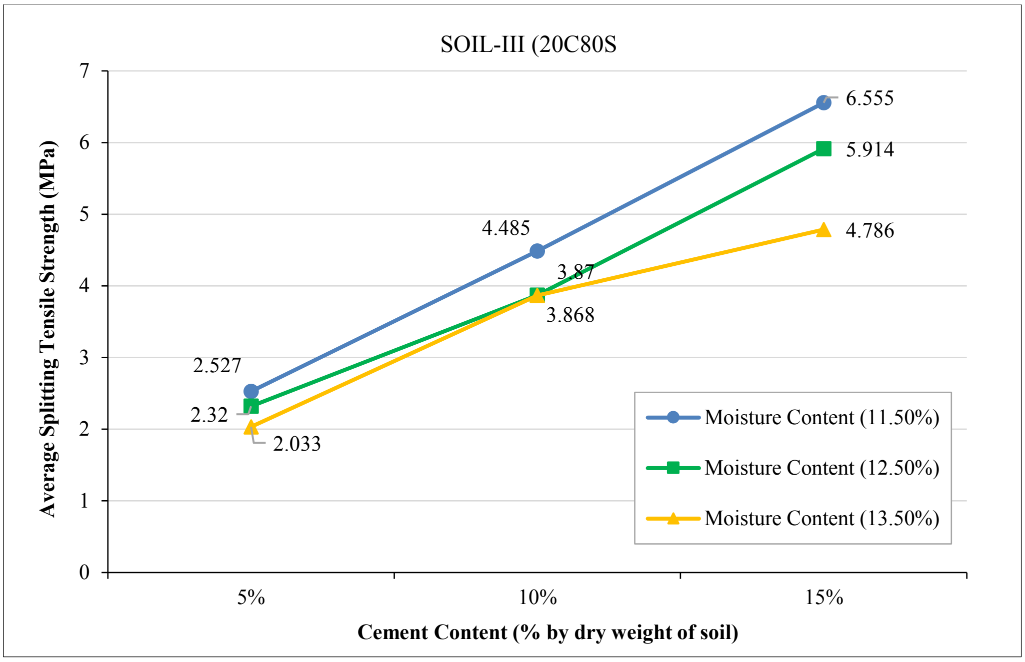

Figure 30. Graphically presenting the results of splitting tensile strength of cement-stabilized rammed-earth cylinders (M-19 to M-27)

Table 22. Splitting tensile strength test conducted on cement-stabilized rammed-earth specimens (Mix-28 to Mix-36)

Material	Moisture content (% dry weight of soil)	Force (N)	Area (mm^2)	Stress, σ (MPa)	σ_{avg} (MPa)
		20994	8107.32	2.59	
30C70S5c	11.5%	21641	8107.32	2.67	2.65
		21736	8107.32	2.68	
		41179	8107.32	5.08	
30C70S10c	11.5%	43107	8107.32	5.32	5.25
		43359	8107.32	5.35	
		53379	8107.32	6.58	
30C70S15c	11.5%	54382	8107.32	6.71	6.68
		54737	8107.32	6.75	
		19873	8107.32	2.45	
30C70S5c	12.5%	20101	8107.32	2.48	2.48
		20368	8107.32	2.51	
		34922	8107.32	4.31	
30C70S10c	12.5%	34993	8107.32	4.32	4.32
		35048	8107.32	4.32	
		49333	8107.32	6.08	
30C70S15c	12.5%	49353	8107.32	6.09	6.10
		49589	8107.32	6.12	
		16529	8107.32	2.04	
30C70S5c	13.5%	16737	8107.32	2.06	2.07
		16959	8107.32	2.09	
		31099	8107.32	3.84	
30C70S10c	13.5%	31280	8107.32	3.86	3.88
		31983	8107.32	3.94	
		47985	8107.32	5.92	
30C70S15c	13.5%	48028	8107.32	5.92	5.94
		48417	8107.32	5.97	

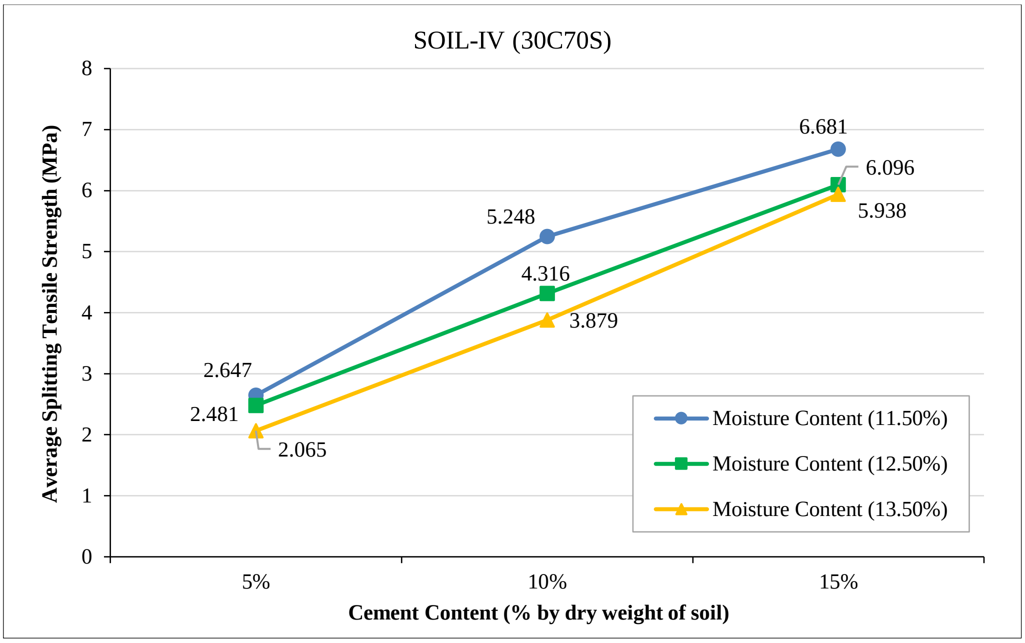

Figure 31. Graphically presenting the results of splitting tensile strength of cement-stabilized rammed-earth cylinders (M-28 to M-36)

Experimental results indicate a positive correlation between cement content and slitting tensile strength, with the peak strength (6.68 MPa) achieved at 15% cement content, significantly higher than specimens with 5% and 10% cement content. Moisture content inversely influences strength, as OMC-1% (11.50%) yields maximum tensile resistance due to optimal particle packing density and reduced lubrication effects, whereas higher moisture levels (OMC, OMC+1%) degrade strength by weakened interfacial bonds.

Clay content exhibits a strength improvement effect, with 30% clay and 70% sand delivering the highest splitting tensile strength, attributed to improved cohesive matrix formation and improved stress distribution. The optimal mix (30C70S15c) comprising 30% clay, 70% sand, 15% cement, and 11.50% moisture, giving superior performance, aligns with microstructural densification and effective cement-clay collaboration.

Higher cement content improves the splitting tensile strength of the cement-stabilized rammed-earth specimen [23, 53]. The tensile strength can be improved by up to 70% by adding textile fibers along with alkali-activated GGBFS geopolymer [54].

The load distortion characteristics and failure patterns are shown in Figure 32.

Figure 32. Failure patterns/mechanisms of cement-stabilized rammed-earth specimens after the tension failure

In case of 5% cement-content, the cement-stabilized rammed-earth cylinders exhibit classic tensile splitting failure characterized by clean, longitudinal cracks perpendicular to the applied load, typical of indirect tensile stress under diametric compression. The cracks propagate through the specimen's midsection, reflecting the material's tensile strength limit and heterogeneous microstructure. Minimal fragmentation indicates brittle yet cohesive failure, consistent with stabilized earth behavior. This pattern confirms the efficacy of the splitting tensile test in assessing tensile capacity critical for structural performance optimization.

As the cement content increases, the cracking mechanism becomes different. The midsection is affected diametrically, and unclean/irregular severe cracking throughout the longitudinal section is observed. The clay content impacts as the specimen shows a pressing compression, in which a specimen goes under stress-strain kind phenomenon and a pressing is observed.

5. Conclusion

It can be observed from the results of the compressive strength test that the magnitudes of compressive strength increase with the increase in cement content. The optimum compressive strength is achieved at 15% cement content. The increase in moisture content decreases the magnitude of compressive strength. The optimum compressive strength is achieved at OMC-1% or 11.50% moisture content. Now with the increase in clay content, i.e., 20%, the optimum compressive strength is achieved. Further increase in clay content, i.e., 30%, reduces the compressive strength of the specimen. Hence, optimum proportions of the materials in the cement-stabilized rammed-earth cylindrical specimen are obtained as, i.e., 20% clay, 80% sand, and 15% cement (20C80S15c), with the minimum moisture content used, i.e., OMC-1% or 11.50%, considering the maximum compressive strength value equal to 13.43 MPa.

It is observed that the splitting tensile strength increases with the increase in cement content. In this study, the maximum cement content used is 15%, which gives the greatest results compared to the other percentages used, i.e., 5% and 10%. The optimum splitting tensile strength is achieved at 15% cement content. Further, it is observed that the minimum moisture content used, i.e., OMC-1% or 11.5% moisture content, gives the greatest splitting tensile strength results compared to the moisture contents, i.e., OMC or 12.5% and OMC+1% or 13.5% moisture content. Hence, it is concluded that the minimum moisture content used gives the maximum splitting tensile strength value. It is observed from the splitting tensile strength test results that the magnitude of splitting tensile strength increases with the increase in clay content. The maximum splitting tensile strength value is equal to 6.68 MPa using 30% clay, 70% sand, and 15% cement (30C70S15c) with OMC-1% or 11.5% moisture content.

Both the parameters, i.e., splitting tensile strength and compressive strength, of cement-stabilized rammed-earth are closely related to the clay content in clay-sand combined soil. Higher clay content within certain limits can improve the tensile strength, while there is an optimal clay content that maximizes the compressive strength in cement-stabilized rammed-earth specimens. Understanding these relationships is essential for optimizing the mechanical properties of rammed earth for sustainable construction. Hence, optimum proportions of the materials in the cement-stabilized rammed-earth cylindrical specimen are obtained as, i.e., 20% clay, 80% sand, and 15% cement (20C80S15c), with the minimum moisture content used, i.e., OMC-1% or 11.50%.

5.1. Future Research Directions

The future work should validate these findings through a full-scale field trials with instrumented rammed-earth walls, integrating non-destructive monitoring to correlated lab-based crack mechanisms with real-world performance under environmental and structural loads. Additionally, long-term durability studies and optimized field compaction protocols should be developed to ensure practical scalability.

6. Declarations

6.1. Author Contributions

Conceptualization, A.M.S., A.K., and R.B.; methodology, A.M.S. and R.A.M.; validation, R.A.M., A.K., and R.B.; formal analysis, A.M.S.; investigation, A.M.S.; data curation, A.M.S.; writing—original draft preparation, A.M.S.; writing—review and editing, A.M.S.; visualization, A.M.S.; supervision, R.A.M., A.K., and R.B.; project administration, A.M.S.; funding acquisition, A.M.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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