

Determining Material Characteristics of “Rammed Earth” Using Non Destructive
Test Methods for Structural Design

by

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Bachelor of Engineering, Mehran University of Engineering & Technology, 2011

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Supervisory Committee

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Bachelor of Engineering, Mehran University of Engineering & Technology, Jamshoro,
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Abstract

Rammed earth is an ancient construction material which has recently regained the attention of the stakeholders involved in the maintenance of older buildings and design of new buildings according to the rules of modern sustainable architecture. The homogeneity and stability of the construction are enhanced through mixing with an additive and compaction of the mix inside a removable formwork. Control or assessment of the material properties is essential for the accurate design or assessment of a structure, in particular for cases of poor fundamental understanding of the structural behavior, like rammed earth. Moreover, the obvious need for limiting pre-assessment intervention, especially for historic rammed earth buildings, has given rise to the importance of non-destructive testing for the determination of material features. This thesis proposes to treat cement-stabilized rammed earth similarly to concrete or natural rock for determining its compressive strength and quality through non-destructive testing techniques. The tested specimens were fabricated by adding industrial waste additives such as Fly ash & Metakaolin with cement-stabilized soil. Then, three rounds of non-destructive evaluations using the Rebound Hammer Test and the Ultra Sonic Pulse Velocity Test were performed on specimens exposed to wetting-drying cycles and ambient conditions in a time laps of one month and one year for wall to evaluate the effect of environmental conditions and time on the material characteristics. Compression testing of cylinders up to failure was also performed to assess the compressive strength of rammed earth and to benchmark the results of non-destructive tests. Moreover, different mix designs were selected to evaluate the impact of adding industrial waste additives in the material characteristic.

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Nomenclature

RE= Rammed Earth

P= Maximum load at which the specimen failed (N)

A= Area

L = Length of the specimen (mm)

R= Rebound Number Nm

UPV= Ultra Sonic Pulse Velocity

MPa= Mega Pascal (N/mm^2)

Fly Ash= Industrial Waste Additive

MetaKaolin= Industrial Waste Additive

V = pulse velocity (km/s)

L = path length (cm)

T = transit time (μs)

Mix 1 = No Removal of Cement

Mix 2= 15% Removal of Cement & Addition of 7.5% Fly Ash & Meta Kaolin.

Schmidt Test= Rebound Hammer test

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Dedication

To my Parents, Wife & Naeem Bhai

1 Introduction

1.1 Motivation and Problem statement

Rammed Earth (RE) (also called “Pisé de Terre” in French, “Taipa” in Portuguese and “Tapial” in Spanish) is a composite material that is often used for the construction of foundations, floors, and walls using as basis earth, adequate proportions of sand or clay and/or an additive that plays the role of stabilizer for the construction. Ancient construction involved mainly the use of lime or animal blood as additive, while in modern times cement is the main additive used in construction. The manufacturing process involves mixing/ramming the above-mentioned materials and compacting the mixture into a mold usually made of plywood, similarly to a modern reinforced concrete structure. The use of earth is an ancient technology for the construction of structures that dates back to construction of Great Wall of China [1].

One of the main advantages of this construction technique is that the earth used for the construction is most times available in the region, therefore reducing significantly the material transportation costs from distant locations, which reduces CO₂ emissions that contribute to global warming [2] and therefore contributing to sustainable construction. This is the reason for which this construction technique has regained the attention of modern architecture. Other advantages include the construction simplicity, durability and thermal insulation. Its susceptibility to water damage if inadequately maintained is the main disadvantage of this material.

In North America SIREWALL system is an excellent example of use of RE materials with rebar and additives such as lime. SIREWALL system is using rigid insulation in the wall center for enhanced thermal efficiency and comfort [2].

Construction using RE is rather popular in regions all over the world. SIREWALL has an excellent project history in completing such projects in many countries under different environmental conditions. One can state indicatively the following successful projects:

- New Delhi Boutique Hotel (Construction was performed under temperatures ranging from 5 C to 49 C).
- NK'Mip Desert Cultural Centre (Largest Insulated RE Wall in the World- Length = 80m, Height = 5.5m and thickness = 0.6 m).
- Brinton Museum (Construction was performed under temperatures of -35 F with frequent strong winds) [2]

Consisting 10% cement by volume in RE wall requires 75% lower production energy than a steel- framed wall [3].

However, the strength of RE materials, their long-term durability under various environmental conditions, and change in properties when constructed using different additives are not well understood and additional research in this field is needed.

In order to get better insight on the material behavior of RE and assess its adequacy as construction technique, tests on different RE specimens and walls were conducted. The main focus was on the influence of different material compositions on compressive strength of the material.

RE is becoming again a popular material for construction because of the use of local materials, less CO₂ emissions and generally lower environmental impact compared to other construction materials such as reinforced concrete and structural steel. However the material properties and structural behavior of RE walls are not fully understood yet [4]. Thor A. Tandy, P.Eng, C.Eng, Struct.Eng MStructE, FEC, UNISOL Engineering Ltd, identified these challenges and provided funding to UVic research team to study the characteristics of RE materials which including compressive and flexural strength, as well as the influence of the boundary conditions offered by different ramming heads.

12 Objectives

In the framework of the present thesis, three different specimen types were fabricated by adding a predefined percentage of industrial waste additives (Fly Ash / Metakaolin) and cement to study the impact of different exposure conditions (i.e. wetting-drying cycles and ambient state) on the material properties. To this end, two types of Non Destructive Tests were carried out: a) Rebound Hammer Test and b) Ultrasonic Pulse Velocity Test.

The experimental study was complemented by uniaxial compression tests on cylinders up to failure.

Moreover, the influence of the boundary conditions offered using different ramming heads is investigated, as well as the impact of the mix design in the measured material characteristics.

1.3 Literature review

In ancient buildings and construction, lime was the main component used to provide strength and durability to the material. This technique is still used in rural and remote areas where people use soil that is available in the proximity for housing construction. Example of such projects includes the volunteer work of the author in the construction of a single-room shelter for people affected by floods in Pakistan in 2010, which are still in very good condition. This project was funded by the International Organization of Migration (IOM). This organization highly recommends construction of shelters by adding lime to soil available in the proximity.

Up to date, monitoring of the condition of rammed earth materials was mostly performed on relatively old structures, while no recent structure has been evaluated during the last 10 years. The literature review presented herein is not to cover the entire research studies on rammed earth structures but to give an overview of works focusing on non-destructive techniques for strength and quality evaluation of existing rammed earth structures or structural components (e.g. walls). The key aspects and findings of each work are presented in what follows.

Liang performed non-destructive tests on five Hakka RE buildings in the Fujian province of China, constructed between 1662 and 1706 [12]. The use of lime renders these buildings significantly robust serving as perfect example of RE longevity. The compressive strength of the specimen containing high amount of lime was observed to be higher compared to the specimen with limited amount of lime. Rebound Hammer Test UPV Test was also performed on the same buildings and was found that UPV gives more accurate results with regard to the actual strength properties of the buildings [12].

Kailey and Gupta conducted non-destructive tests on the seven years old First Peoples House Building at the University of Victoria, which is constructed of RE material. This was the first reported study that was performed in the climate region of British Columbia, Canada [5]. In the framework of the same study the thermal envelope of two RE walls of the same building was analyzed through thermal imaging and the compressive strength of each wall was determined using the Rebound Hammer, these rammed earth walls were exposed to 7 years of natural weathering in a wet climate [5]. It was found that Wall#2 experiences higher exposure to winds than Wall#1. It was also found that Wall#2 exhibits more strength reduction and surface Extreme than Wall#1. The outcomes from the Rebound Hammer Test and high Thermal Imaging affirmed the speculation for quality decay, yet did not support surface weakening. More experiments and testing methods were suggested by the author for determining the surface Extreme of the material [5].

2 Experimental Work

2.1 Specimen properties

The tested specimens included rammed earth walls, cylinders and prisms. This section describes some key aspects of the tested specimens, including geometric properties, material composition and manufacturing process. All specimens were manufactured by either bore diameter 6" Rammers or 3" Rammers as shown in Fig 1:



Figure 1 - Rammed Earth Rammers 3" & 6" [13]

In cylinders and prisms, industrial waste additives i.e. fly-ash and metakaolin were added due to the fact that these were proven additives in last few decades for greater workability of the concrete and their usage can improve strength, segregation and ease of pumping in the case of concrete

2.1.1 Wall

Figure 2 shows an axonometric view of typical rammed earth wall of the present campaign. Each wall has dimensions 4' x 8' x 9" (height x length x thickness) and is divided into two equal sections.

- 3 Inch Head
- 6 Inch Head

For the construction of the walls, a rammer head of 3" is used on one section and a rammer head of 6" is used on the other section. Each rammed earth wall was constructed by ramming through mixing of selected aggregates, addition of the required amount of water and ramming the mix between strong wood panels often called formwork or mold.

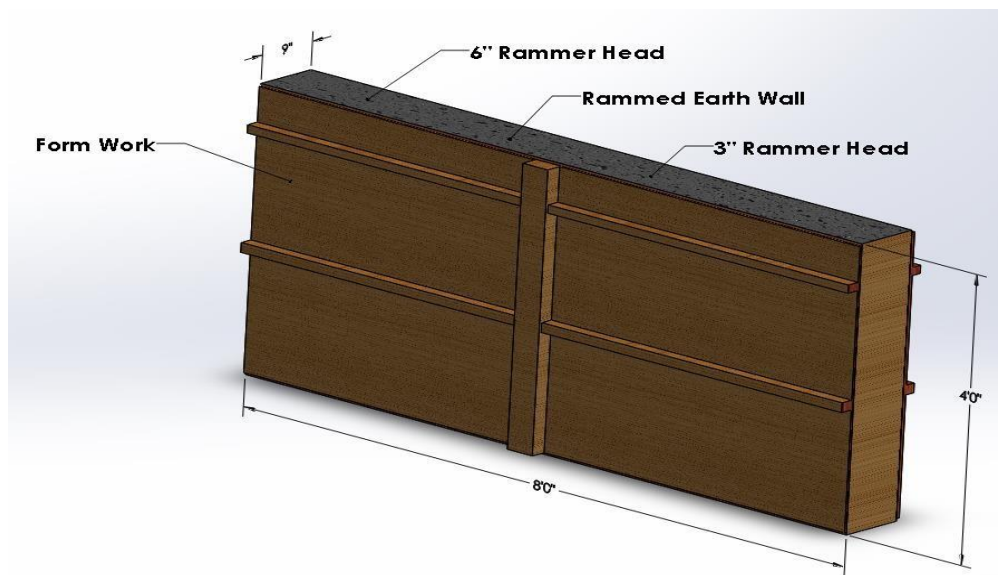


Figure 2 - Rammed earth wall

The composition of the ideal soil for Rammed Earth wall is indicated below:

- 23% coarse sand
- 30 % fine sand
- 32% silt
- 15% clay
- 10% water by mass

Other two main ingredients are cement and gravels. And ratio for all three ingredients should Be 20:4:1 (Soil: Gravels: Cement)

2.1.2 Cylinders

In total, nine cylinders were fabricated using RE material with dimensions of 6" \varnothing \times 12" each one, as shown in Figure 3. Cylinders composed of two different mix designs were

Fabricated maintaining the volume of each cylinder constant and equal to 339.29 cubic inches as per ASTM C192. All cylinders were fabricated using 3" rammer head.

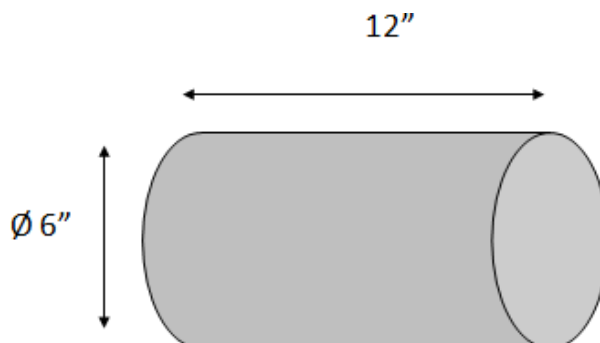


Figure 3 - Cylinder dimensions

Three cylinders were kept outside in ambient conditions extracted to investigate the influence of environmental conditions on the compressive strength while the remaining six cylinders were exposed to wetting and drying cycles as shown in Table 1. These cylinders were fabricated using two different mixes, mix 1 and mix 2, as follows:

1. Mix 1: No replacement of cement by additives
2. Mix 2: 15% removal of cement and addition of 7.5% of Metakaolin and Fly ash each.

Cylinders			
Wetting & Drying Cycle		Ambient Environment (-2 °C to 19 °C)	
Mix 1	Mix 2	Mix 1	Mix 2
<ul style="list-style-type: none"> • Sample A • Sample B • Sample C • Sample D 	<ul style="list-style-type: none"> • Sample A • Sample B 	<ul style="list-style-type: none"> • Sample A 	<ul style="list-style-type: none"> • Sample A • Sample B

Table 1 - Cylinder Specimen Division

Four samples from Mix 1 and two samples from Mix 2 of cylinders were exposed to continuous wetting and ambient environment cycles. Pump with motor and timer was arranged to check the continuity of exposure of the samples as shown in Figure 4. All cylinders were made by using 3” rammer head.



Figure 4 - Cylinders exposed to wetting and drying cycles

2.1.3 Prisms

Five samples of prisms were made from the same two mixes as of cylinders. Each Prism had dimensions 6” × 6”×21” as prescribed by the ASTM C805/C805M standard as shown in Fig 4.

All specimens were exposed to wetting and ambient environment cycle over the same period of time and setup as of cylinders. The samples are categorized as shown in below:

- (1) Mix 1- Sample A
- (2) Mix 1- Sample B
- (1) Mix 2- Sample A
- (2) Mix 2- Sample B
- (3) Mix 2- Sample C

Reinforcement bars were used in a construction of these specimen to see behavior of material under an influence of rebar as shown in Fig 5.



Figure 5 - Formwork of prisms including the rebar that is positioned

2.2 Loading procedure

This section presents the loading procedure followed during the non-destructive for both adopted techniques, i.e. the Rebound Hammer Test and the Ultra-Sonic Pulse Velocity Test. For each method, the measurement principle is presented first, followed by some information that is specific to the application on the specimens treated in the framework of this thesis.

2.2.1 Rebound Hammer Test

Schmidt Hammer or Rebound Hammer or Swiss Hammer is used to measure the elastic properties or strength of materials such as rock or concrete surface but also surface hardness the material and penetration resistance. In this experimental study, the ASTM C805/C805M standard is used to determine the surface strength of rammed earth specimens as they have similar properties to concrete. Proceq Schmidt Hammer Model N is used throughout this work.

Figure 6 shows a typical rebound hammer as well as its conversion curve which is then used to convert the rebound value R to strength in MPa.

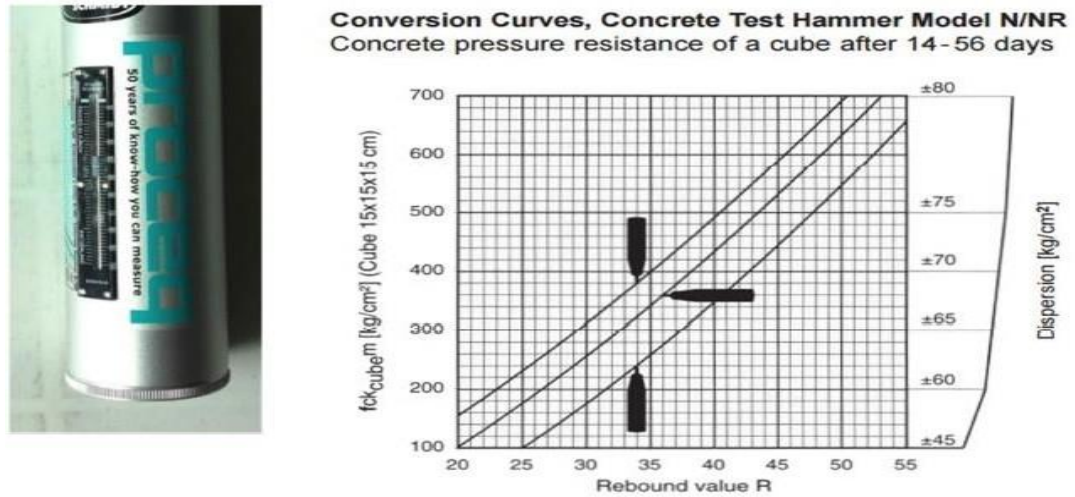


Figure 6 - Rebound hammer with conversion curve [6]

Figure 7 outlines the principle of use of the rebound hammer step by step. The spring stacked mass has a settled measure of vitality bestowed to it by extending the spring to a settled position. This is accomplished by squeezing the plunger against the surface of the tested material. Upon discharge, the mass bounces back from the plunger, is still in contact with the material surface and the separation underwent by the mass is communicated as the rate of the underlying augmentation of spring which is called Rebound Number R. This number is used in combination with the conversion table of the equipment in order to calculate the strength in MPa [7].

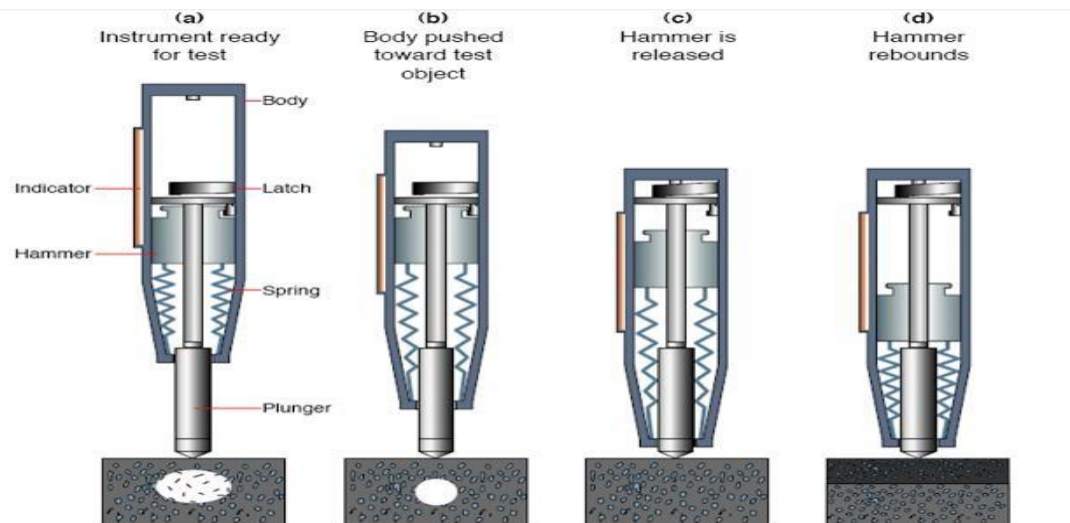


Figure 7 - Principle of rebound hammer [7]

The following subsections discuss specific features with regard to the application of the rebound hammer test to rammed earth walls, cylinders and prisms. The geometric properties of each specimen are briefly recalled while emphasis is given to the location of reading points and frequency of measurements.

2.2.1.1 Rebound Hammer Test

The fabricated RE wall is separated into two segments as far as ramming head utilized, however each segment is additionally partitioned into three sub-segments for the simplicity of separating test range amid the entire section as shown in Fig 8. 116 Points were taken from each section of the wall for the Rebound Hammer Test as per ASTM C805/C805M which allows least separation between test points to be no less than 1 Inch for Rebound Hammer/Schmidt Test.

Three readings were taken within a period of one month to evaluate the change in surface quality on both wall segments. Another set of readings was taken after one year to re-evaluate the wall characteristics to see if any Extreme had taken place when exposed to actual outdoor conditions in Victoria.



Figure 8 - Rammed earth wall reading points: a) schematic plan and b) actual wall specimen

To evaluate the boundary effect created due to lack of proper reach of ramming heads of 3" & 6", average corner point readings on both sections are compared with the readings of middle section of the wall for both rammer sizes.

2.2.1.2 Cylinders

The cylinders that were fabricated and tested within this research had dimensions 6" x 12" (diameter x height). Three sets of readings were recorded on all cylindrical specimens that were exposed to wetting and drying cycles as well as in ambient conditions over the interval of one month. Five points at the top face and the bottom face of each cylinder were taken as shown in Figure 9.

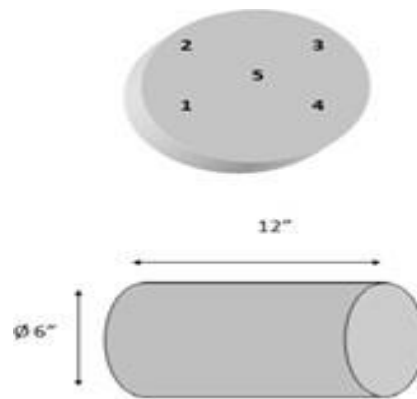


Figure 9 - Rebound hammer points on cylindrical specimen

After each set of readings, the obtained results were compared to evaluate the fluctuation of material characteristics between specimens with different material composition and under different environmental conditions.

2.2.1.3 Prisms

Each prism had dimensions 6" x 6" x 21" (width x height x length). Three sets of readings were recorded on each prism under wetting and drying cycles over the interval of one month. Nine points on each prism were taken at the top face of the prism as shown in Fig 10.

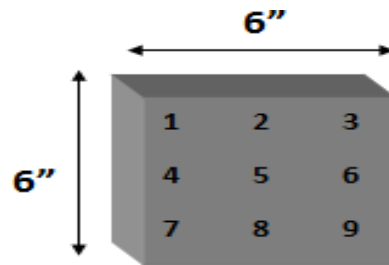


Figure 10 - Rebound hammer reading points on a typical prism specimen

The results of tests with different mix designs were compared with each other to evaluate the change in material properties as well as the influence of the aforementioned parameter.

2.2.2 Ultra-Sonic Pulse Velocity (UPV) Test

Determination of the pulse velocity inside a material can serve as an indicator of the material quality and strength. The pulse velocity reading mainly depends on the density and the elastic properties of the material under investigation [8]. The test consists in sending an ultra-sonic pulse wave and measuring the necessary time for the pulse to pass through the considered specimen/member. This is the basic principle of this device. Lower velocities ($<3\text{Km/sec}$) indicate lack of continuity (e.g. high void ratio or cracking) while higher velocities ($>4\text{ Km/sec}$) indicate material homogeneity and good overall quality. In the present study Pundit Lab UPV equipment was used for determining the ultra-sonic pulse velocity of each rammed earth specimen.

Figure 11 shows the UPV equipment with set standards of pulse velocity on concrete to determine its quality. Since the rammed earth material treated in this thesis contains cement as stabilizer, the same equipment can be used on rammed earth specimens following the same principles as for concrete specimens.



Figure 11 - UPV equipment and quality ranges [8]

The ultra-sonic pulse velocity (UPV) is calculated by dividing the path length, i.e. the length of the member/specimen under consideration, by the time of arrival:

$$V = L/T$$

Where V = pulse velocity (km/s), L = path length (cm), T = transit time (μs) [9].

There are three different methods for determining the pulse velocity through the use of the UPV equipment, as depicted in Figure 14:

Direct Method

Indirect Method

Semi-direct Method

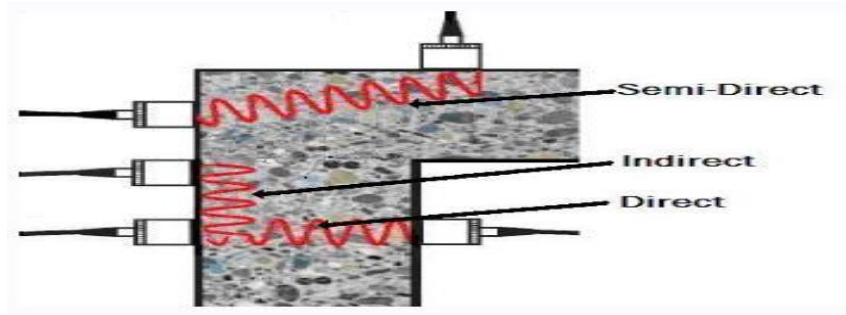


Figure 12 - Ultra-sonic pulse velocity methods [8]

The following subsections discuss more detailed information with regard to the application of UPV methods on the rammed earth specimens tested within this project. Information concerning the geometric properties can be found in the previous section and, therefore, are not presented in what follows. The emphasis is drawn on the location of reading points and the adopted method.

2.2.2.1 Wall

As shown in Figure 13, the same pattern of reading points was used for both the ultra-sonic pulse velocity test and the rebound hammer test, to allow for easier comparison between the two techniques. Each wall is divided into two main areas in the vertical direction: a) one area that is hammered by 6" hammer and b) another that is hammered by 3" hammer. Three UPV test readings were recorded on 12 points through use of the "direct method" on both wall sections within one month and the average speed is obtained for each section after the test. Same set of readings is taken again after one year to see change in material characteristics.

ASTM C 597 Standard has been followed throughout this experiment on specimen and UPV test limits lengths to around 50-mm least and 15-m most extreme.

<u>Zone A- "6"</u>			<u>Zone A-1 -3"</u>		
1	2	3	1	2	3
<u>Zone B- 6"</u>			<u>Zone B- 1-3"</u>		
1	2	3	1	2	3
<u>Zone C- 6"</u>			<u>Zone C-1 3"</u>		
1	2	3	1	2	3
4	5	6	4	5	6

Figure 13 - Pattern of reading points for ultra-sonic pulse velocity tests on walls

2.2.2.2 Cylinders



Figure 14 - Application of the UPV method to cylinders [10]

On all specimen under wetting and drying cycles and in ambient condition, direct UPV method is used where transducers are placed on both ends of cylinder to compute the pulse velocity, as shown in Figure 14.

2.2.2.3 Prisms

For Ultrasonic pulse velocity test, all prism specimen are divided into three main zones that are denoted as A, B and C (see Fig. 15). In each zone, ten UPV records were obtained through use of the “**direct**” UPV method as shown in Figure 17. This method was selected in order to investigate the influence of the reinforcing bars on the prism.

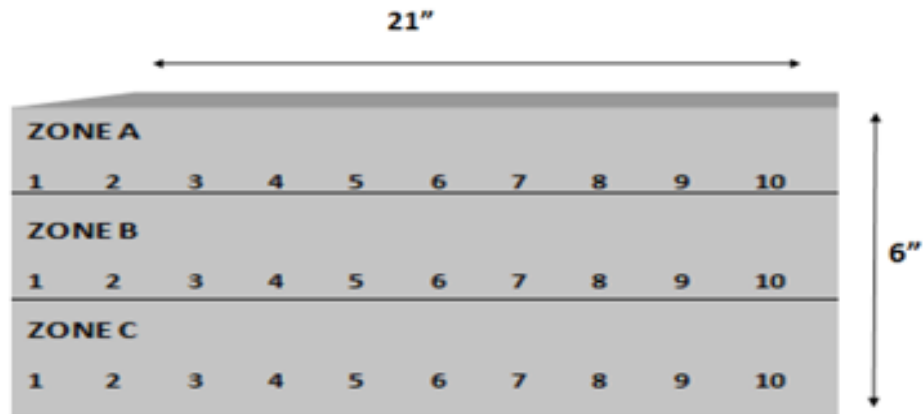


Figure 15 - UPV reading points on prism

3 Test Results and Discussion

This chapter presents and discusses the results of the experiments carried out within the framework of this dissertation. The present work aims at increasing the current knowledge of rammed earth as construction material. For this reason, the result presentation moves from the experiment of the largest scale (i.e. wall) to the experiment of an intermediate scale (i.e. prism) and finally to the experiment of the smallest scale, I.e. the cylinder, that is the most common test unit used to describe the material behavior for structural engineering. Section 3.1 focuses on the observed behavior of rammed earth wall, while section 3.2 gives an overview of the obtained results from tests on rammed earth prisms. Section 3.3 focuses on the response of rammed earth cylinders determined through both destructive and non-destructive techniques. The test results presented in the first two sections are based on the non-destructive techniques presented in the previous chapter.

3.1 Rammed earth wall

This section presents the results of non-destructive tests on the fabricated rammed earth wall to evaluate the influence of ramming head size, time effects and boundary effects on the material strength. Subsection 3.1.1 presents the results using the Rebound Hammer, while subsection 3.1.2 presents the results using the Ultra-sonic Pulse Velocity Test. Finally, subsection 3.1.3 presents the synthesis from the measurements described above and discusses the results.

3.1.1 Rebound Hammer Results

Four sets of Rebound Hammer/Schmidt readings were taken on the wall at different points as discussed previously. The effectiveness of the ramming technique during construction was assessed through comparison of the available Rebound Hammer measurements at the wall edges and the middle section, as illustrated in Figure 16.

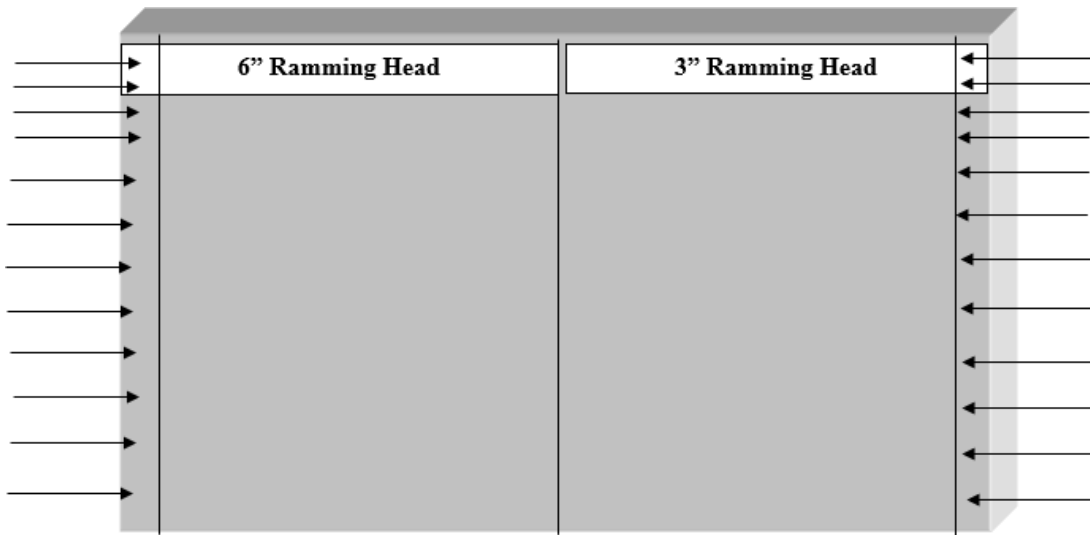


Figure 16 - Edge readings against middle section readings for the RE wall

To allow for easier comparison between readings taken at various time intervals after fabrication, an average value of each set of readings is shown below in Figure 17. The same figure distinguishes between the measurements taken at the part of the wall where a 3" and a 6" ramming head were applied to evaluate the influence of the ramming head size on the surface strength of the material.

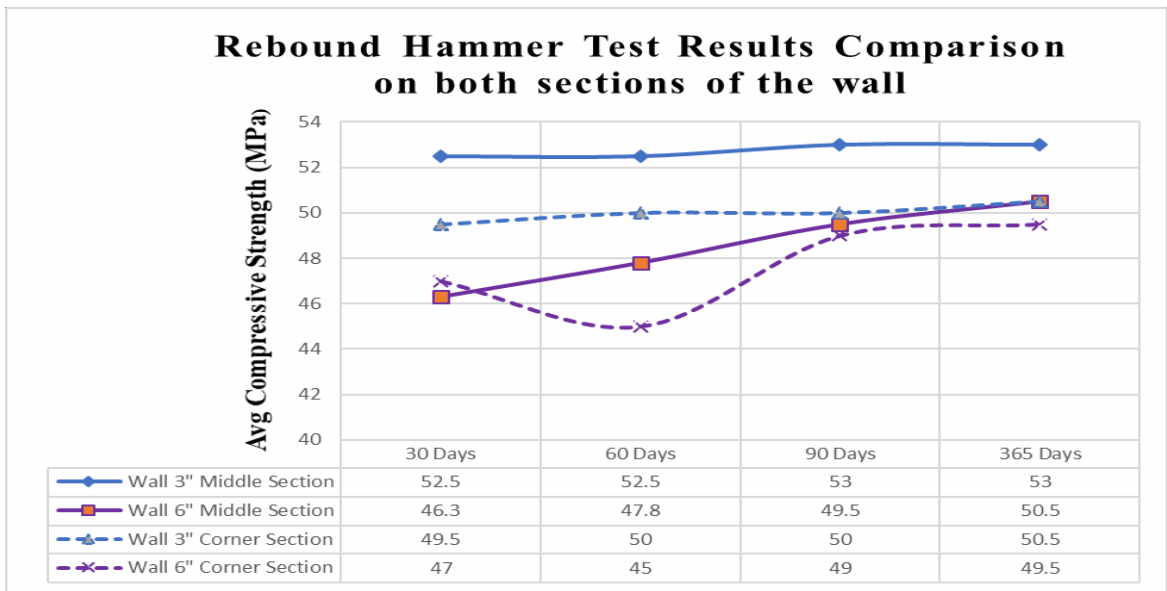


Figure 17 - Rebound Hammer test results on the rammed earth wall

The results shows that use of 3” ramming head confers higher compressive strength of the surface compared to 6” ramming head. This can be attributed to the fact that a smaller ramming head applies the same force to a smaller area, resulting in higher applied pressure and therefore to better compaction of the material from very early stages. For both ramming head sizes the resistance increases with time. The increase of strength with time is, though, more rapid for the 6” ramming head than for the 3” ramming head. At future stages, since the void ratio of the wall rammed with a larger head is expected to be higher, the space that is available for the cement to expand is also higher and the increase of strength becomes more rapid.

With regard to the influence of the boundaries on the surface strength of the material, result comparison between edges and middle part of the wall shows that the ramming process resulted in slightly smaller resistance at the wall compared to the middle section for both ramming head sizes that were used. This is probably due to the fact that less pressure was applied close to the boundaries of the wall. Overall, such variability of rammed earth material characteristics is too expected in actual construction practice.

3.1.2 Ultra-sonic Pulse Velocity results

In order to get better understanding of the influence of ramming head size and time on the overall quality of the material, including the inner part of wall section, measurements using Ultra-sonic Pulse Velocity equipment were performed. Table 2 shows the results from ultra-sonic pulse velocity tests for both ramming head sizes that were adopted for the rammed earth wall. The same results are illustrated in Figure 18.

Test Time Interval	Pulse Speed (m/s) on 6" Ramming Head	Pulse Speed (m/s) on 3" Ramming Head
30 Days	4271	4226
60 Days	4339	4325
90 Days	4354	4349
365 Days	3046	2907

Table 2 - Rammed Earth Wall UPV Results

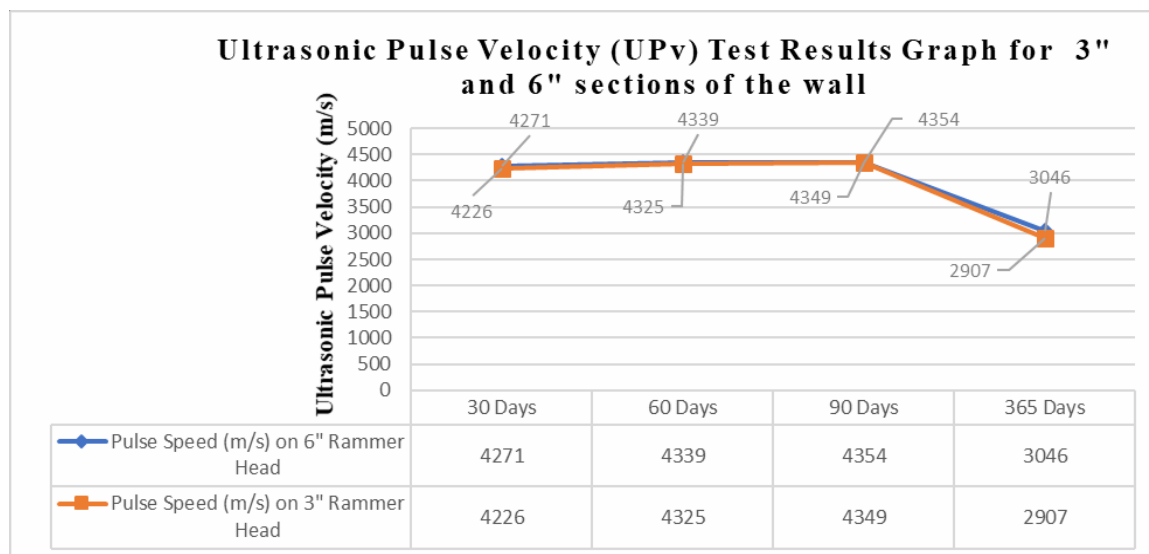


Figure 18 - Measured pulse speed for the tested Rammed Earth Wall for 3" and 6" ramming heads as function of age

For the first three readings, pulse velocity for the wall was rather high and similar for both ramming head sections of the wall, however a significant drop in pulse velocity is noted when the same test was repeated one year later, as can be observed in Figure 18.

3.1.3 Discussion of the results

In general, the test results on rammed earth wall show that an increase of the material age leads to higher surface strength and material quality. This behavior is anticipated for every material that contains cement (e.g. concrete) because cement obtains resistance gradually with time.

Increase of the ramming head size increases significantly the surface strength of the rammed earth wall but does not appear to have any particular impact on the overall quality of the material. The implication of such finding is rather interesting if rammed earth is to be used in an aggressive environment, i.e. near the sea. For this purpose, tests in an aggressive environment and subjected to wetting-drying cycles should be performed in order to evaluate the influence of environmental conditions on the surface strength of the material. This is done in one of the following sections using rammed earth cylinders.

32 Rammed earth prisms

The present section shows and analyze the results of non-destructive tests on a series of five rammed earth prisms to evaluate the influence of mix design, environmental conditions and time effects. Subsection 3.2.1 gives the results using the Rebound Hammer, while subsection 3.2.2 presents the results using the Ultra-sonic Pulse Velocity Test. Finally, subsection 3.2.3 presents a critical analysis of the obtained measurements.

3.2.1 Rebound Hammer Results

For all five specimen that were exposed to timed wetting and drying cycles the Rebound Hammer test was conducted three times with an interval of 30 days. All specimens were fabricated of Mix 1 and Mix 2 and then tested. Two different mixes were selected to investigate the influence of the presence of additives in the mix composition as follows:

- Mix-1: No replacement of cement
- Mix-2: replacement of 15% of cement and addition of 7.5% of Metakaolin and 7.5% Fly ash (Industrial Waste Additive).

Note: All prisms were exposed to wetting & drying cycle.

Mix Design	Rebound Hammer Test Results for Prisms Fabricated with Mix 1 & 2					
	Individual Strength (MPa) 30 Days	Individual Strength (MPa) 60 Days	Individual Strength (MPa) 90 Days	Avg. Strength (MPa) 30 Days	Avg. Strength (MPa) 60 Days	Avg. Strength (MPa) 90 Days
Mix 1	18	22	22.5	17.5	20.5	21.75
	17	19	21			
Mix 2	16	18.5	18.5	16.5	19.5	21.5
	16.5	19.5	19.5			
	16.5	19.5	21.5			

Table 3 - Rebound Hammer results for prisms fabricated with Mix 1 & 2

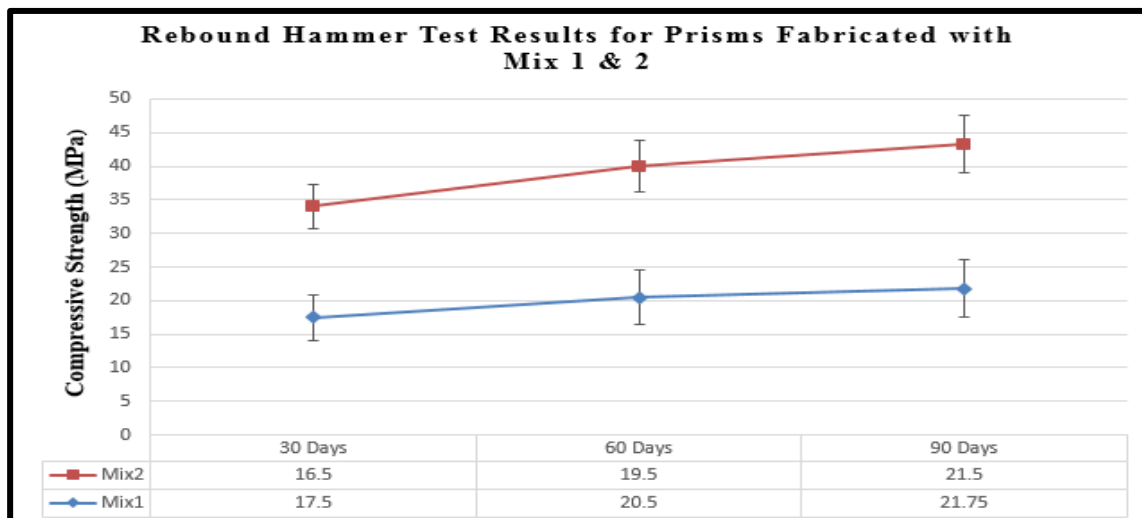


Figure 19 - Rebound Hammer results graph for prisms fabricated with Mix 1 & 2

Rebound Hammer test results suggest that for both mixes the surface strength increases with time. It is also shown that the mix design does not influence the measured surface strength to a significant degree.

3.2.2 Ultra-sonic Pulse Velocity Results

In order to get better understanding of the influence of the mix design and the age on the overall quality of the material, including the inner part of the prisms, measurements using Ultra-sonic Pulse Velocity equipment were performed. Table 4 shows the results from ultra-sonic pulse velocity tests for both adopted mixes that were adopted for the rammed earth prisms. The same results are illustrated in Figure 20.

Mix Design	Ultrasonic Pulse Velocity (UPV) Test Results for Prisms Fabricated with Mix 1 & 2					
	Individual UPV(m/s) 30 Days	Individual UPV(m/s) 60 Days	Individual UPV(m/s) 90 Days	Avg. UPV (m/s) 30 Days	Avg. UPV (m/s) 60 Days	Avg. UPV (m/s) 90 Days
Mix 1	4188	4236	4302	4150	4173	4223
	4111	4110	4145			
Mix 2	4188	4236	4302	4150	4176	4223
	4111	4116	4145			

Table 4 - Measured pulse speed for the tested Rammed Earth prisms fabricated using Mix- 1 & 2 as function of age

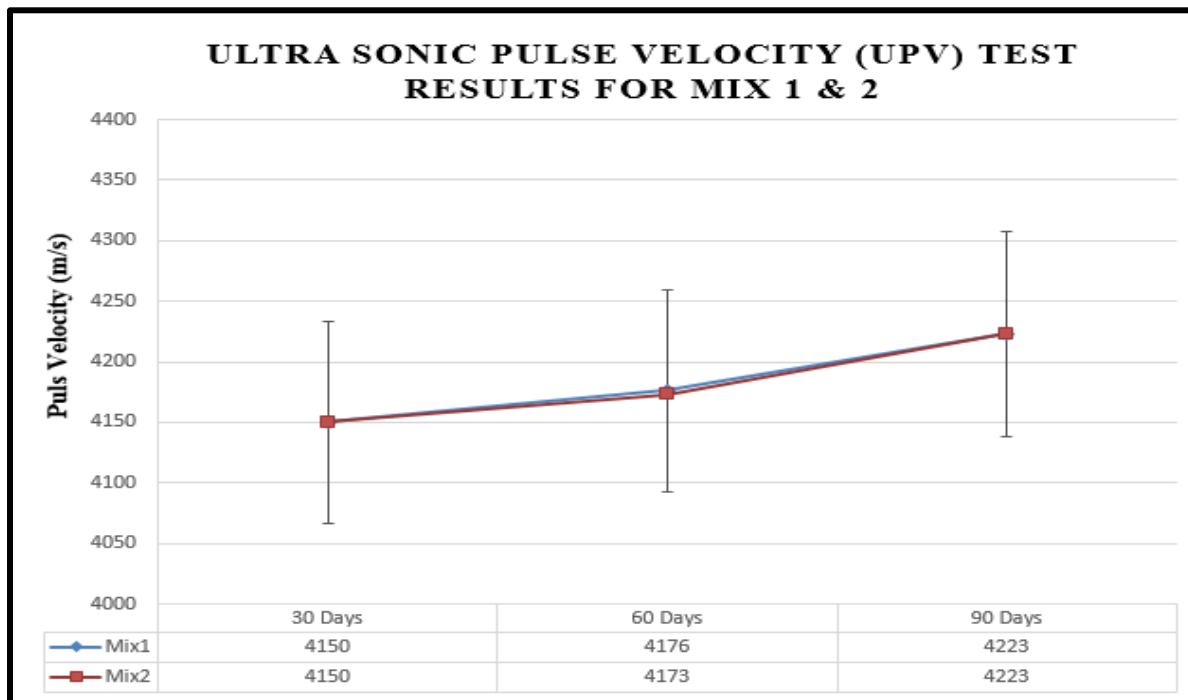


Figure 20 - Measured pulse speed for the tested Rammed Earth prisms fabricated using Mix-1 & 2

Overall, it can be observed that the material quality of the tested rammed earth prisms is rather high and increases for increasing material age. With regard to the influence of mix design on the material quality, it is demonstrated that addition of industrial waste additives instead of cement increases the quality of rammed earth, particularly as function of the specimen age.

3.2.3 Discussion on the results

It is confirmed, similarly to non-destructive tests on the rammed earth wall, that an increase of the material age results in higher surface strength and material quality, which is expected for cement-based materials. For prisms with partial replacement of cement by industrial waste additives the increase of material quality is more pronounced than for prisms without behavior concrete replacement. This shows the beneficial role of additives when designing the composition of rammed earth.

Regarding the influence of the mix design, it is shown that substitution of 15% cement by 7.5% fly ash and 7.5% Metakaolin leads to higher material quality but no marked effect is shown for the surface strength.

Finally, with regard to the influence of the adopted experiment scale, it is shown that for rammed earth prisms the measured surface compressive strength is approximately two times lower than the one measured on the rammed earth wall. This might be due to the fact that prisms were subjected to wetting-drying cycles while the wall was not. On the other hand, the overall material quality, determined through Ultra-sonic Pulse Velocity tests, does not appear to be affected by the experiment scale.

33 Rammed earth cylinders

This section presents the results of destructive and non-destructive tests on the fabricated rammed earth cylinders to evaluate the influence of material age and boundary effects on the material strength. Subsection 3.3.1 presents the results using the Rebound Hammer, while subsection 3.3.2 presents the results using the Ultra-sonic Pulse Velocity Test. Subsection 3.3.3 presents the results of compression tests on cylinders up to failure to

Calculate the uniaxial compressive strength of the specimens using the destructive technique for cement-based material. Finally, subsection 3.3.4 presents the synthesis from the measurements described above and discusses the results.

3.3.1 Rebound Hammer Results

In total nine cylindrical specimens were fabricated of Mix 1 and Mix 2 and then tested. Out of Mix-1 and Mix-2 different samples were extracted to investigate the influence of environmental conditions on the compressive strength. Two environmental conditions were selected: a) ambient environment and b) wetting-drying cycles. Four samples of Mix 1 and two samples of Mix 2 were extracted for testing under wetting-drying cycles, while for ambient conditions one sample is extracted per mix.

Rebound Hammer test results on cylinders fabricated with Mix-1 under wetting-drying cycles are shown in Table 5 and Figure 21.

Mix Design	Rebound Hammer Test Results for Cylinders Fabricated with Mix 1 & 2 (Under Wetting & Drying Cycle)					
	Individual Strength (MPa) 30 Days	Individual Strength (MPa) 60 Days	Individual Strength (MPa) 90 Days	Avg. Strength (MPa) 30 Days	Avg. Strength (MPa) 60 Days	Avg. Strength (MPa) 90 Days
Mix 1	25	25.5	29	25.75	29	32
	35	44	46			
	20	22.5	26			
	23	23.5	27.2			
Mix 2	31	33	41.5	31	32.5	37.5
	31	32	33.5			

Table 5 - Rebound Hammer Test Results- Mix 1 & 2 - Wetting & Drying Cycles

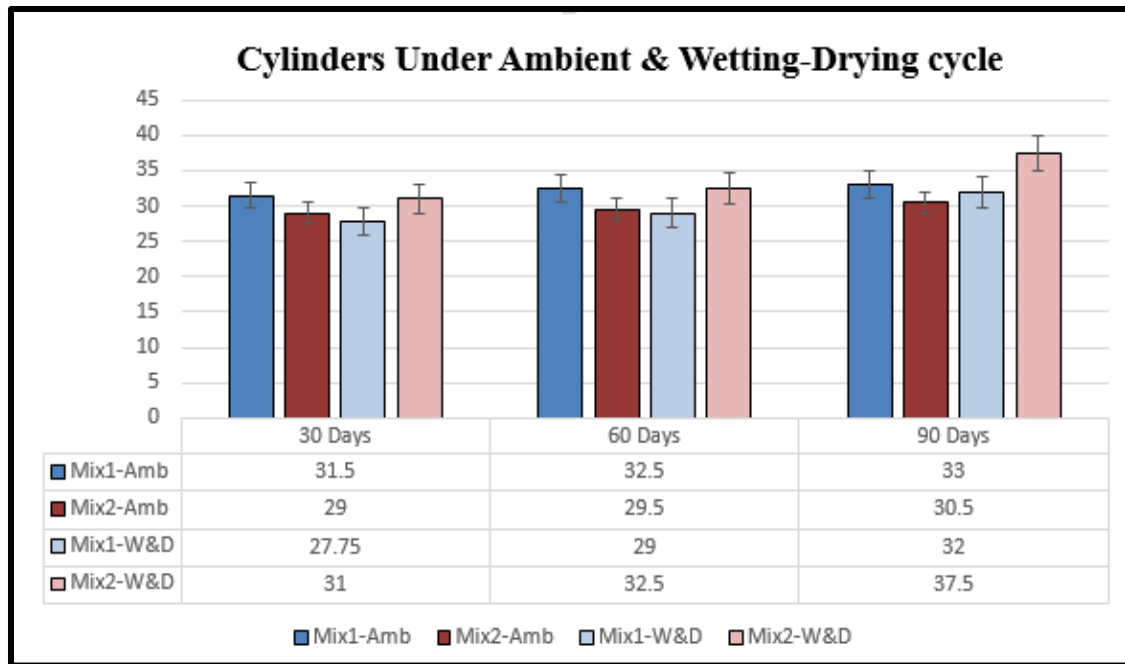


Figure 21 - Rebound Hammer Test Results- Mix 1 & 2 - Wetting & Drying Cycles

It was observed that the reference cylinders, i.e. without removal of cement and replacement by additives, had an average compressive strength of 20-25 MPa right after casting (first set of readings). However, after 60 days of wetting and drying cycles, the cylindrical samples showed higher strength compared to first set of readings but was less marked after 90 days of curing.

Regarding the cylindrical samples fabricated with Mix-2, i.e. with replacement of 15% of cement by 7.5% of Metakaolin and 7.5% of Fly ash, the tests indicated higher compressive strength compared to the reference cylinders, as shown in Table 5 and Figure 21.

The average compressive strength for Mix 2 samples remained close to 30-32 MPa, however no significant change has been witnessed over the interval of time (30-90 Days).

Cylinders under Ambient conditions

Two Specimen of Mix-2 and one specimen of Mix 1 were exposed to ambient condition where temperature was 6 °C to 14 °C. Results are presented in tabulated form in Figure 21 above.

Concerning the influence of the environmental conditions, it is interesting to note that Mix 2 samples showed similar average compressive strength under both ambient conditions and under wetting and drying cycles, while for Mix 1 samples alternated wetting and drying resulted in reduced strength compared to ambient environmental conditions. From the rebound hammer testing, it is concluded that specimens of Mix 2 in which 15% additives were used showed higher compressive strengths under different conditions. Strength increase with time has been observed on all tested specimens.

3.3.2 Ultrasonic Pulse Velocity Test Results

Table 6 & Figure 23 shows ultra-sonic pulse velocity test results of rammed earth cylinders with Mix 1 subjected to wetting and drying cycles.

Mix Design	Ultrasonic Pulse Velocity (UPV) Test Results for Cylinders Fabricated with Mix 1 & 2-Wetting & Drying Cycle					
	Individual UPV(m/s) 30 Days	Individual UPV(m/s) 60 Days	Individual UPV(m/s) 90 Days	Individual UPV(m/s) 30 Days	Individual UPV(m/s) 60 Days	Individual UPV(m/s) 90 Days
Mix 1	4510	4198	4380	4437	4298	4391
	4257	4320	4477			
	4510	4477	4198			
	4471	4198	4510			
Mix 2	4613	4358	4444	4528	4358	4366
	4444	4358	4287			

Table 6 - UPV Results on cylinders fabricated with Mix-1 & 2 under Wetting & Drying Cycle

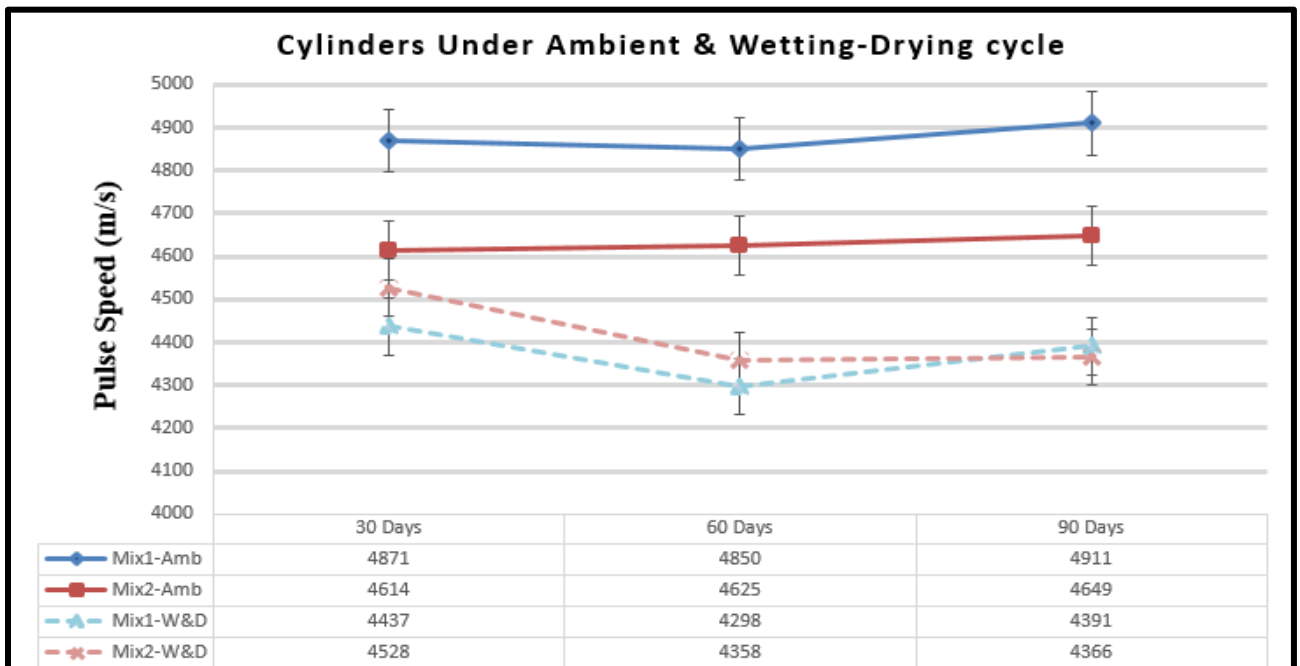


Figure 23 - Mix 1 Cylinders UPV Test Result for cylinders under ambient conditions and Wetting & Drying Cycles

Pulse velocity was found to be rather high for all tested samples of Mix-1, with an average velocity of 4300 m/s).

Pulse velocity was found to be slightly higher for cylinders fabricated with Mix-2 (Avg= 4400 m/s) compared to cylinders with Mix-1 (Avg= 4300 m/s). Hence, it is evident that under Extreme conditions, the quality of the rammed earth cylinders does not appear to be affected by the mix design over the period of time studied here.

Cylinders under Ambient Conditions

Figure 23 presents the Ultra-sonic Pulse Velocity results for the tested cylinders under ambient conditions. Comparison with the measured values under wetting-drying cycles indicates that there is a slight Extreme (by approximately 9%) of the material quality when the cylinders are exposed to wetting and drying cycles for 90 days. It would be interesting to expose cylinders to wetting-drying cycles for longer intervals.

3.3.3 Uniaxial compression test results up to failure

In order to obtain better understanding of the material behavior of rammed earth up to failure, uniaxial tests were conducted on cylinders, similarly to concrete specimens. The

aim of this test series was to check the observation from the non-destructive tests shown earlier in this thesis and compare them with the most classic testing method for determining the compressive strength of a material. The testing was performed on a Forney Machine in accordance with the ASTM C39 Standard. The compressive strength (measured in units of stress) is calculated based on the applied load P , which is typically monitored using a load cell, divided by the area of the cylinder A , that is known in advance.

Tables 7 and 8 present the results on cylinders subjected to wetting-drying cycles and ambient conditions, respectively.

Mix-1	Applied Load (N)	Compressive Strength (MPa)
Sample A	706000	38.73
Sample B	840000	46.11
Sample C	663000	36.39
Sample D	672000	37.28
Mix-2	Applied Load (N)	Compressive Strength (MPa)
Sample A	589000	32.3
Sample B	627000	34.4

Table 7 - Test Results for cylinders subjected to uniaxial compression up to failure under wetting-drying cycles

Mix-1	Applied Load (N)	Compressive Strength (MPa)
Sample A		29
Mix-2	Applied Load (N)	Compressive Strength (MPa)
Sample A	677000	37.16
Sample B	631000	34.65

Table 8 - Table 8: Test Results for cylinders subjected to uniaxial compression up to failure under ambient conditions

As general comment, one can state that the measured uniaxial compressive strength for rammed earth are of the same order of magnitude as for concrete. This indicates that rammed earth can be a reliable material for modern construction of commercial structures, i.e. for compressive strengths varying from 17 MPa to 28 MPa [11]. It can also be observed that under ambient conditions substitution of 15% cement by 7.5% fly ash and 7.5% Metakaolin (Mix-2) leads to an increase of the compressive strength by up to 28%. It can be seen that for Mix-2 the measured compressive strengths under wetting-drying cycles were slightly lower than ones under ambient conditions, with the difference being small. Interestingly, for Mix-1, for which no cement removal occurred, alternated wetting and drying of the specimens resulted in increase of the compressive strength by up to 34%.

3.3.4 Discussion of the results

The cylinder tests confirm what was previously shown using the wall and the prisms, i.e. that an increase of the material age results in higher surface strength. This behavior is expected for cement-based materials. For the material quality, the UPV test results did not show any marked trend compared to prisms. This is attributed by the author to the fact that material imperfections influence to a higher degree cylinders than prisms due to their smaller size.

It is also shown that the uniaxial compressive strength is generally higher than the surface strength of cylinders. This is expected since the core of the cylinder has better confinement than the surface of rammed earth. The measured values are though close to each other.

For the influence of the environmental conditions, use of fly ash and Metakaolin (Mix-2) in the mix renders the effect of wetting-drying less pronounced on the surface strength than for cylinders without fly ash and Metakaolin, for which the surface strength decreases under wetting-drying cycles compared to ambient conditions.

Regarding the influence of the mix design, it is shown that substitution of 15% cement by 7.5% fly ash and 7.5% does not affect the material quality significantly. The measured

Values are high for all specimens indicating that rammed earth is a material with very good quality. Under ambient conditions, the compressive strength is higher for the cylinders for which cement substitution occurred compared to cylinders with no cement removal. On the other hand, for cylinders subjected to wetting-drying cycles, partial substitution of cement resulted in decrease of the compressive strength.

Finally, with regard to the influence of the adopted experiment scale, it is shown that rammed earth cylinders have higher surface strength than rammed earth prisms but lower than the measured surface compressive strength of the rammed earth wall. This is probably due to the fact that the material behavior measured on two-dimensional members, such as a wall, is probably influenced by the second direction and ends to be higher than the compressive surface strength on specimens aimed to reproduce the uniaxial behavior of the material.

4 Conclusion

This chapter presents the conclusions of the experimental study conducted on rammed earth specimens in the framework of this thesis. The main focus was drawn on the impact of using different ramming heads, adding additives to rammed earth as well as the influence the environmental conditions on the compressive strength, surface strength and material quality. The main points are presented in the following:

- It is concluded that the surface strength (obtained using the Rebound Hammer) of the rammed earth increases with time. This behavior is anticipated for cement-based materials. The material quality (obtained using Ultra-sonic velocity tests) is satisfactory and shows small dependency on the material age.
- It is also shown that the uniaxial compressive strength determined through cylinder compression testing up to failure might not be representative of the surface strength of the material, potentially leading to unsafe design.
- The ramming process becomes more effective both in terms of compressive strength and quality. Use of a head with smaller Diameter provides enhanced compaction of the material (higher density, smaller void ratio) and therefore higher compressive strength compared to a ramming head with larger width.
- Partial substitution of cement by industrial waste additives led to higher surface strength and ultrasonic pulse velocity compared to samples in which no removal of cement took place. Compression tests on cylinders showed the same trend (i.e. strength increase) when subjected to ambient conditions but when subjected to wetting-drying cycles, cement removal led strength decrease. This findings suggest that adding industrial waste additives might not be the most adequate option under Extreme conditions.
- Alternated wetting and drying results in increase of the compressive strength for specimens that contain larger cement quantity, while for specimens with partial cement substitution by industrial waste additives no marked effect is observed. Moreover, the surface strength of specimens with industrial waste additives

reduces when subjected to wetting-drying cycles when compared with ambient conditions curing.

- For the measuring capabilities of the adopted non-destructive techniques, the Rebound/ Schmidt Hammer gives results that are in accordance with the destructive compression tests for specimens where no significant difference between surface strength and core strength is expected. Ultra-sonic Pulse Velocity tests give more qualitative measurements that become more questionable for structural members and should therefore be supported by quantitative measurements.

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Figure 8 <http://www.xraymachines.info/article/482531631/rebound-hammer-test/>

Figure 11 <http://www.pcte.com.au/pundit-lab-ultrasonic-tester>

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Figure 1 <http://rammedearthconsulting.com/rammed-earth-rammers.htm>