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Title

Using rammed earth mixed with recycled aggregate as a construction material

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“Earth turns to gold in the hands of the wise”

Rumi

12th century Persian poet and mystic

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Acronyms

MDD: Maximum Dry Density

NA: Natural Aggregate

RA: Recycled Aggregate

OMC: Optimum Moisture Content

RCA: Recycled Concrete Aggregate

UCS: Unconfined Compressive Strength

CDW: Construction and demolition wastes

GERD: Spanish Guild of Demolition Waste Recycling Entities

Abstract

The importance and recognition of sustainability is growing within the construction industry. Traditional rammed earth has many benefits in terms of sustainability. For this reason, this ancient building method is regaining popularity. Also, the conservation of natural resources as well as the reduction of waste generation is an important aspect of sustainability. Thus, incorporating recycled aggregates (RA) into rammed earth would greatly contribute sustainable practices in the construction industry and promote the wider use of this building technology.

The overall target of this study is to improve the knowledge of rammed earth structures that incorporate RA and to further the development of future sustainable construction. For this purpose, we used artificial soil with different Recycled Aggregates replacement percentages endeavors, to examine the effect of varying different size of RA particles on the unconfined compressive strength (UCS) of rammed earth and also compare the linear shrinkage between the mixes with natural aggregates (NA) and with RA.

The use of appropriate soil is the key to the success of rammed earth. Therefore the characteristics of the soil are considered important. In the state of the art, we focus on the test methods and explain typical physical properties of rammed earth, production process, compaction of the rammed earth and methods used for construction.

Initially the grading and the particles fractions for our artificial soil from natural aggregate was chosen and then after finding the optimum moisture content for rammed earth with natural aggregate we start replacing RA in different percentage instead of bigger particles (gravel and sand) in our samples .Some samples were tested for unconfined compressive strength after 7days and the other after 28 days.

The results of unconfined compressive tests in this experiment indicate that rammed earth mixes with RA have acceptable strength and their compressive strength were fairly lower than natural aggregates. All batches have strengths exceeding 2 MPa and thus can be used in rammed earth construction.

The addition of RA in this study does not lead into a decrease in characteristic UCS, and in general, especially when the coarser natural aggregate (gravel) replaced by coarse recycled aggregates.

Finally in this study, the results of linear shrinkage test were approving the recommendations and were acceptable.

In regards to rammed earth incorporating RA, this study focused in most part on the effect that RA has on the compressive strength and shrinkage of rammed earth. The effect of RA on other properties of rammed earth should also be examined. Other properties such as durability, erosion resistance and thermal conductivity may be affected by the addition of RA and should be study in future.

1. Introduction

1.1. General aspects and motivations

Earth is one of the oldest and most widespread construction materials on our planet. For the past centuries overshadowed by architecture of fossil fuel area, earth construction is slowly regaining its status and becoming integral part of “green thinking”. For architects and engineers re-examination of earth construction under 21st century conditions opens new horizon to challenges and innovations.

Rammed earth is a construction method used primarily to build solid walls by compacting subsoil, sometimes stabilised with cement or other binders, in progressive layers inside temporary formwork [1].

Rammed earth is hardly a modern building technology. However, as it mentioned above more recently, public awareness in regards to sustainable living, has initiated a renewed interest in earth as an alternative building material.

Application of earth as a building material has numerous advantages:

Sustainability

According to basic building material environmental classification by NIBE, various forms of earthen materials have the lowest environmental cost [2].

Comparing rammed earth to alternative building materials as concrete and brick masonry, its embodied energy is significantly lower.

	Rammed earth unstabilized	Rammed earth stabilized (4 -12% cement)	Concrete portland cement	Brick masonry standard
Embodied energy, MJ/kg	~ 0.02	0.14 - 0.42	1 - 1.3	20.5 - 29.3

Figure 1: Embodied energy of rammed earth compared to concrete and brick

Microclimate Regulation

Earth has excellent abilities to maintain stable interior air humidity level and thermal mass potential superior to that of most alternative building materials [2].

Rammed earth keeps interior humidity between 40 and 60 percent where walls containing clay are exposed to an internal space, the ideal range for asthma sufferers and for the storage of susceptible items such as books and artwork.

However, it causes risk of condensation, therefore, when applied as exterior wall especially in climatic zones with high interior/ exterior temperature differences, special attention must be paid to moisture transport calculations in order to prevent dew point within the earth construction.

Although rammed earth has tremendous thermal mass and holds and releases heat slowly, it is not a good insulator. For colder climates, rammed earth walls can be insulated with a panel of recycled Styrofoam

Sound Insulation

Rammed earth is a good sound insulator. Being a dense and porous material, earth is used as sound isolative material in facilities with increased sound intensity as concert halls and recording studios.

In addition, rammed earth has excellent sound reverberation characteristics. It does not generate the harsh echoes characteristic of many conventional wall materials [2].

Aesthetics

Visually rammed earth is true building material. Its color represents soil characteristics of particular geographical region varying from red to bright orange, yellowish, grey and fawn-colored.

The horizontal lines on the surface of rammed earth wall reveal its construction method.

Earth can also be adjusted to wide spectrum of visual requirements. A number of color pigments can be added as well as surface texturing may become a field of creative expression [2].

Figure 2: Natural rammed earth color and texture variations

It is a commonly reported fact that around half of all global CO_2 emissions can be attributed to the construction, and more importantly the operation, of buildings. Advantages of rammed earth construction include decreasing the reliance on unsustainable resources, reduction in embodied energy levels and the potential to decrease transportation costs if insitu materials are used.

Recent popularity has resulted in many people varying traditional rammed earth construction.

A variation of traditional rammed earth construction is to incorporate recycled aggregates (RA) into the compacted material, either partially or completely. If RA is incorporated into traditional rammed earth, there will be extra benefits in working towards addressing the problems caused by the increasing amount of waste generated by society while natural resources continue to diminish.

On one hand, there is critical shortage of natural aggregates (NA) for production of new building materials, whilst on the other the hand enormous amounts of demolished produced from deteriorated and obsolete structures creates severe ecological and environmental problems [37]. To minimize this waste generated from construction activities, recycling the wastes generated is one of the best methods to conserve the environment.

1.2. Objectives

This study aims to further the knowledge of rammed earth incorporating RA. An experimental program consisting of rammed earth made using natural aggregates (NA) with different RA replacement percentages endeavors to examine the effect of varying RA percentages and particles size on the unconfined compressive strength (UCS) of rammed earth and also compare the linear shrinkage between rammed earth with NA and with RA.

The overall target is to improve the knowledge of rammed earth structures that incorporate RA and to further the development of future construction guidelines and open a new horizon of using RA in construction.

Two testing groups were created, one with only natural aggregates, the other one with both natural aggregate and different amount of recycled aggregates. Within each group, cylindrical samples with different RA replacement percentages were constructed and the unconfined compressive strengths of each determined.

1.3. Thesis structure

For most building designers, rammed earth is an unfamiliar material and construction technique [1].therefor, in this study the second chapter is dedicated to a complete state of the art.

In Chapter 3, a survey of literature relevant to recycled aggregates is presented. And then chapter 4 presents the experimental design, describing the materials used in the experiments and the mixes that were tested as part of this project. This chapter also includes the testing procedure and observations made during the experimental phase of this work and descriptions of the experimental procedures and the used equipment.

The results of the experiments are presented and discussed in Chapter 5. With reference to these results, Chapter 6 presents the conclusions of this study, as well as making a number of recommendations for future work.

2. State of the art

2.1 Introduction

Earth can be used for construction in many ways. However, there are a few undesirable properties such as loss of strength when saturated with water, erosion due to wind or driving rain and poor dimensional stability [11]. Therefore Modern rammed earths appeared in which binders were added, such as cement, hydraulic or calcium lime or chemical admixtures. They are called ‘‘stabilized rammed earth’’. The main advantage of stabilizing the rammed earth is to increase its durability (with respect to water attack) and mechanical performance (compressive strength) also reduces shrink and swell, and provides waterproofing qualities. Hence , stabilised rammed earth is a precisely controlled mixture of gravel, clay, sand, and a binder which is carefully proportioned, mixed to the correct moisture content, and then machine-compacted in removable formwork to yield a dense, hard, stone-like wall[4].

Here we try to prepare the state of the art of rammed earth construction looking over journal web sites and thesis, scientific reports and other articles.

The use of appropriate soil is the key to the success of rammed earth. Therefore the characteristics of soils considered important, we try to outlines the test methods and mention typical physical properties of rammed earth. Production process and compaction of rammed earth construction and methods used for compaction in laboratory and in the site are also considered in this state of the art. In counties some physical and mechanical properties like density, compressive strength and optimum moister are cited. And then earth weathering resistance and durability. At the end there are studies about some real cases and in order to understand the role played by earth as a building material and its possibilities for use and its costs, there is an overview of the building regulatory system in different parts of the word.

2.2 Natural Rammed Earth

In rammed earth construction organic matter content should be avoided, as this may lead to high shrinkage and possible biodeterioration as well as increasing susceptibility to insect attack. Organic material also interferes with action of stabilizers such as cement [5].

In order to increase the mechanical strength and weathering resistance of soil it is advantageous to minimize the voids ratio in order to increase the contact between soil particles. Theoretically soils with no voids can be achieved if the soil particles are entirely spherical and their distribution follows the Fuller Formula below:

$p = 100(d/D)^n$

Where: p is the proportion of grains of a given diameter, d is the diameter of grains for a given value of p, D is the largest grain diameter, n is the grading coefficient.

When the grains are entirely spherical then n is equal to 0.5. However, in earth construction a value of n between 0.20 and 0.25 is more appropriate depending on grain shape. In reality it is virtually impossible to find natural soils that match such an ideal distribution [5].

There are four main particle types in sub-soil and these fragments range in size from coarse gravel through to fine gravel(sand), silt and finally to clay. The relative proportions of these constituents play an important role in the performance of the material [1]. Gravel provides the inert skeleton or matrix and together with sand enhances the weather resistance of the exposed faces. Clays, which are quite different from the other constituents swell when wetted and shrink as they dry out [9].

The British Standard grading limits are:

- Gravel, 60 mm to 2 mm
- Sand, 2.00mm to 0.06mm
- Silt, 0.06mm to 0.002mm
- Clay, less than 0.002mm [5]

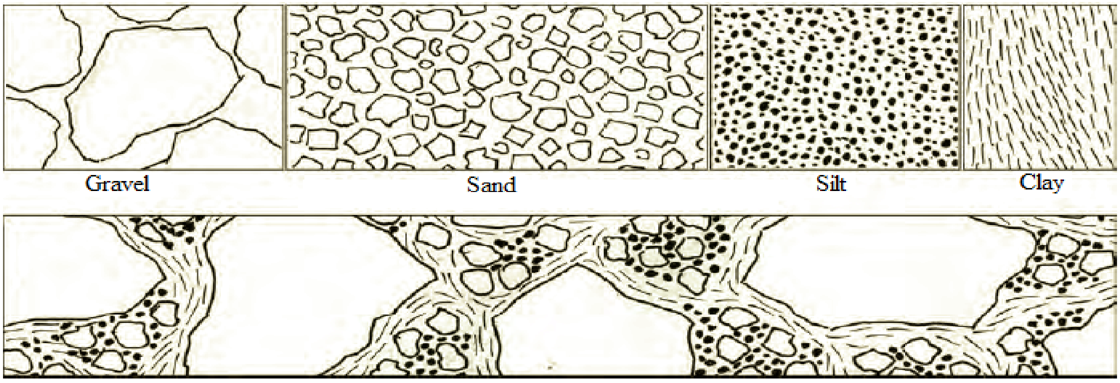


Figure 3: Structure of soil components for rammed earth application (top) and role in final product (bottom)

A wide variety of sub-soils have been used for natural rammed earth buildings, with the exception of uniform coarse sands and gravels with no fines or cementing agents. Ideally the soil should have high sand/gravel content, with some silt. For unsterilized rammed earth, the clay content should be sufficient for compaction and to bind effectively together all other fractions without excessive shrinkage on drying. 8–15% clay fraction is usually suitable for most rammed earth soils.

According to Norton [6], any material coarser than 5-10mm should be sieved out. Previous experimental work indicates that increasing gravel size reduces the compressive strength of rammed earth; however more research is warranted to define grading for rammed earth, especially maximum gravel size and proportions.

There is some agreement on the limits between the main soil elements. The minimum percentage of combined clay and silt should be between 20%-25% while the maximum between

30%-35%. Similarly, the minimum percentage of sand should be between 50%-55% while the maximum is between 70%-75%. In total, proposals tend to converge towards a 30%-70% balance between clay/silt and sand proportions [5].
In the absence of suitable natural deposits, controlled engineered mixtures of gravel, sand, silt, and clay may be manufactured for rammed earth. The limestone aggregates in the soil were angular with an estimated crushing strength, based on parent material, between 20 and 30 N/mm2 [7].

2.3 Cement Stabilized Rammed Earth

2.3.1 Materials: soil type and binder

Stabilized rammed earth is a form of rammed earth that uses sub soils combined with stabilizing agents to improve the materials physical characteristics. Soils for cement stabilized rammed earth tend to have proportionally higher sand and gravel content and correspondingly lower fines content. For example, a soil suitable for Cement stabilization should have a significant sand content.
The composition of soils in different parts of the world varies considerably due to the origin and the climatic conditions or due to our objectives in construction site and laboratory samples. For instance some studies indicates the uses of laterite soils and clayey soils for cement stabilized soil and here , some other materials that can be used for making stabilized rammed earth are described ,such as :limestone, artificial soil and recycled concrete aggregates(RCA).

2.3.1.1 Soil Type

Limestone

As it mentioned by (Ciancio D. Gibbing J) [8], it is important to state that the most used mix in the presented experimental investigation is made of crushed limestone. It is crushed limestone with 13 mm and 19 mm, lateritic gravel mix with 19 mm nominal maximum aggregate size (The crushed limestone has negligible or zero clay content). It is also recommended, that the soils shall not contain particles larger than 38 mm in diameter [11].
There are some concerns about the porosity of limestone [1], but limestone is often stabilised with 6-10% cement and used in rammed earth construction. Rammed earth incorporating limestone is similar to traditional rammed earth with the exception that limestone aggregates are used instead of natural subsoil resulting in a finish that is typically much finer than that of rammed earth [9].

Artificial Soil

In the study realized by M. Yaqub [9], was decided to create an artificial soil so that the results can be repeated. Further advantages of using an artificial soil include the fact that the proportions of the soil constituents were known and could be controlled. The artificial soil was created using kaolin clay, silica flour, clean sand and 10mm blue aggregate. The mix proportions used are detailed in: clay 10%, sand 50%, silica flour 20%, gavel 20% [9].

Recycled Concrete Aggregates

Recently in the study of M. Yaqub [9], Recycled concrete aggregates were incorporated in varying proportions into the rammed earth mixes. These aggregates were derived from the processing of concrete that had already been used in construction [9]. Whilst it would have been of value to ascertain the source of the aggregates, due to the abundance of concrete demolition and recycling undergone to produce the aggregates tracing the source would have been significantly difficult as the materials are to be mixed together when processed.

A portion of the material of the RCA had a particle size greater than 19mm. Particles of this size are not suited to the Modified Proctor test. Additionally it was thought that excessively large particles could result an issues in terms of compaction. Thus, it was decided that the RCA should be sieved and any particles greater than 19mm should be discarded. Upon inspection of the aggregates, it was also found that there was some foreign matter such as leaves, wood particles, crushed brick and steel wire present within the RCA. In the preparation for the material for testing, any visible contaminants were removed from the RCA whilst the material was being sieved [9].

2.3.1.2 Binder

In rammed earth construction, Portland cement is the most common stabilizing agent used. Cement is typically proportioned to between 4% and 15% of the mixture, with the majority of mixes being between 6% and 10% cement stabilized.

There are various advantages when using cement as a stabilizer: The use of cement in rammed earth mixes has derived out of a need to improve wet strength and erosion resistance in very exposed walls. With the addition of cement wet compressive strength resistance improve significantly, so it could increase the overall factor of safety, resistance to water-borne deterioration and general durability and robustness. Soil samples gain strength from the formation of a cement gel matrix that binds together the soil particles. High levels of cement stabilization improve the surface coating and reduce erosion.

Additionally, the presence of cement has a considerable influence in improving the resistance of soils vulnerable to frost attack [9]. Cement stabilization increases the elastic modulus of the material from 1.89 GPa for unsterilized soil to 2.51 GPa for 10% cement stabilized soil [10].

However, the advantages of using cement stabilization must be carefully weighed against the environmental impact, as cement is a major contributor to global CO2 emissions [9]. And also since cement is a relatively costly material, the determination of minimum percentages required for strength and durability is important.

Fine-grained soils respond most favorably to the addition of lime, and for clay sand or clayey soils, lime stabilization is just as effective as cement or perhaps more. The greatest effectiveness of cement in comparison to other stabilizers is with low clay content soils such as sands, sandy and silty soils, and clay soils of low to medium plasticity. These soils respond well to the addition of a minimum of 2–2.5% cement [11].

Although asphalt was used in some experiments, this stabilizer has been shown to have no effect on stabilized strength, and should be regarded only as water proofer when used with cement and/or lime [12].Less popular stabilizers are soda water glass, animal products, plant products (linseed oil, cooked starch, plant juices) and various artificial stabilizers (synthetic resins, paraffin and waxes) [2].

Also in the recent study realizing in northern Portugal, in order to try to mitigate the environmental impact, they have been developing an alternative stabilisation solution, which consists in the addition of a geopolymeric binder obtained from the alkaline activation of fly ash [13].

2.3.2 Soil Properties

In this part the most important properties of soil for rammed earth is determined .Here is the list of tests that we can do in laboratory to determine soil properties: [2]

- Particle size analysis (UNE 103101:95)
- Particle size analysis of soils by sedimentation fi ne (UNE 103102:95)
- Determination of Atterberg limits (UNE 103103:94, and 103104:93)
- Determining the linear shrinkage value.
- Determining the type of clay for the potential expansiveness and for selecting more appropriate stabilizer.
- Determination of an oxidizable organic material by the method of ground potassium permanganate (UNE 103204/93)
- Determination of soluble salt content of a soil. (UNE 103205:2006)
- Modified Proctor-test (UNE 103501:94)
- Unconfined Compressive strength test (305:90 NLT).

2.3.2.1 Density and water content

Earthen material is very sensitive to water that affect its density. It is well understood that density changes in the wall from point to point .In reality, the dry density decreased continuously from top to bottom within a layer. A small variation in density can produce a significant difference in strength. Therefore, achieving a value as high as possible for dry density is considered important since density is related to strength and durability [11].

The dry density of rammed earth is normally between 1.8 and 2.2 kg/m3 the main factors controlling dry density are particle-size distribution and the corresponding optimum moisture content [14].

The optimum moisture content (OMC) for rammed earth soils is critical in order to achieve maximum dry density (MDD) through dynamic compaction, which is thought to be indexed to the strength and durability of the material. If too little water is present, then the soil cannot achieve the same level of compaction due to the greater degree of friction between the soil particles. If too much water is present, then capillary water occupies the soil pore spaces, reducing the level of achievable compaction and incising the level of porosity when the wall has dried. Therefore, at the OMC, the soil becomes sufficiently workable as the soil particles to become closely packed that most of the air is expelled. For most soils when the moisture content is less than the OMC, the soil is more difficult to compact. Beyond the OMC, most soils are not as dense under a given effort because the water interferes with the close packing of the soil particles [9].

By New Zealand Standard (NZS 4298: 1998 w1x), states that for rammed earth production the moisture content should never be less than 3% below OMC or 5% above it [14]. The optimum water content is about 9.5–11.0%. With these moisture contents, a dry density is about 20 kN/m^3 [11].

There is a simple test that can be used to check the approximate moisture content called drop test: A ball is made in the palm using a small sample of soil and then it is dropped on to a floor from about 1.0 m height. If it breaks into 4–5 pieces, the moisture content is satisfactory. If it crumbles away, the soil is too dry or if it stays as one pat, it is too wet [15].

Other tests in order to achieve maximum density are both the ‘standard’ and ‘modified’ Proctor tests. A soil sample of known moisture content is compacted in a 1 litter cylindrical mould. Compaction is carried out in 3 or 5 layers of equal thickness by a dropping weight falling 27 times on each layer from 300mm or 450mm. When the cylinder is ready the wet weight is recorded and then the sample is left to dry. At least 5 specimens at various moisture contents are prepared the same way and their wet weights are recorded. When the samples dry, the moisture content and dry densities are calculated and plotted on a graph. From the resultant curve, it is possible to determine the optimum moisture content for which the soil experiences its maximum dry density for a given compactive effort [5].

2.3.2.2. Unconfined compressive strength

Compressive strength represents a basic quality control measure for rammed earth [1].For this control we should put the samples off rammed earth into a compression testing device. They are then loaded in uniform uniaxial compression until failure.

Unconfined compressive strengths were calculated from the sample failure load using

$$\sigma_c = \frac{P}{A}$$

Where: c is the compressive strength, P is the maximum applied load and A is the loaded surface area. It is assumed that the surface area does not change during testing and that the material behaves elastically [14], so that calculated value is the unconfined compressive strength.

2.3.2.3 Plasticity and shrinkage

Linear shrinkage (LS) is the percentage decrease in the length of a bar of soil dried from the liquid limit, and it is assessed on a distribution sample. And the plasticity index (PI) is a measure of the plasticity of a soil. The plasticity index is the size of the range of water contents where the soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit (PI = LL-PL).

Measures of plasticity and shrinkage reflect both the constituent particle make up of a soil, and how the soil responds to moisture. These variables reflect both textural and moisture effects, they are likely to closely influence the physical processes involved in compaction and stabilization, which would explain their effectiveness at indicating soil suitability for stabilization [11]. In addition to compressive strength, the shrinkage of stabilized soil should also be a considered as an outcome of stabilization, given the potential for weakening of earth walls caused by shrinkage or tensile cracking.

Shrinkage depends on the proportion and type of clay selected. Various clay types in pure form can shrink as little as 4% or as much as 25%.The most preferable clay minerals in rammed earth application are Kaoline and Illite [2].The degree of shrinkage on curing of stabilized soil also depends on stabilizer content, soil type, water content, degree of compaction with rammers, and curing speed. The linear shrinkage of stabilized soil decreases with increasing levels of cement and lime, and therefore the potential for cracking is reduced by using these stabilizers. Finally, the temperature and humidity of ambient air is important. Comparing to other materials as baked brick and concrete, rammed earth dries very fast, emphasizing the risk of cracking. Drying time can be slowed down by increasing environmental air humidity and preventing from direct sunshine.

Shrinkage cracks should be considered inevitable in soil-cement stabilization, and are generally from 3–6 mm wide at a spacing of 3–6 m. shrinkage cracks in rammed earth walls should not be longer than 75 mm, nor wider than 3 mm, nor deeper than 5 mm. Therefore, the soil and stabilizer used should be able to meet these shrinkage criteria [12].

The data show that LS is slightly more efficient at discriminating stabilization success in the good category, but that PI is better at identifying the poor samples. If LS value is good, then fair or poor values of the other variables are able to be tolerated without compromising stabilization success.

	Australia standards 2002	New Zealand standards, 1998	Scotland Scottish Executive, 2001
Maximum permissible linear shrinkage	< 2.5%	0.05%	3%

Figure 4: Rammed earth linear shrinkage according to various building codes and standards

Figure 5: Consequences of major shrinkage

Figure 6: Clay cracks

2.4 Laboratory Rammed Earth production process

2.4.1 Mixing

Soil homogeneity is crucial factor determining compaction level and thus materials mechanic properties .Therefore, in order to ensure the homogeneity of the soil used in rammed earth construction adequate mixing is essential. Additionally, in rammed earth construction mixing is an important process as it ensures the even distribution of moisture content within the soil matrix. In the construction of the samples it is possible to use cement mixer, as the vertical axis mixer is more suited to mixing large volumes of material. The dry components can be mixed thoroughly before water was added. The dry mixes can thoroughly mixed in a tray, using mixing irons. Percentage of water should added and then the soil can mixed thoroughly again.

2.4.2 Ramming

The samples have been rammed using a jackhammer and applying equivalent compaction energy per volume used in the Modified Compaction test to achieve consistency in density and compaction effort for all samples [5].

Compaction is the process of mechanically densifying a soil by pressing the soil particles together into intimate contact and expelling air from the soil. More or less compaction can be used depending upon soil type, and the main factors controlling dry density are particle-size distribution and the corresponding optimum moisture content [14].

For instance to reflect on-site construction technique, samples can be rammed using a Bosch jackhammer or manual hand rammer, as it would best replicate the type and nature of compaction forces that the soil would be subjected to in commercial rammed earth wall production. It is important that the material be compacted in layers of suitable depth and subject to sufficient compactive effort.

As compaction effort is important, in the sample construction process it is essential that during ramming body weight is not applied whilst ramming the sample. If bodyweight is applied, by leaning onto the mechanical rammer the results will be influenced, as each sample will be subjected to different compaction energy [9].

2.4.3 Curing

The formwork can be stripped from all samples after couple of days. The compacted material must be cured properly, avoiding rapid dry out which could lead to extensive shrinkage cracking and loss of strength ,They can wrapped in plastic sheets for a couple of days and then left to cure inside the laboratory in ambient conditions. As recommended by New Zealand Standards (2008) all samples should cured at least 28 days before testing [5].

2.4.4 Samples

The laboratory-based production of rammed earth samples should reflect the on-site construction technique of rammed earth walls for test results to be meaningful and transposable [14].

The specimens can be either cylinders or prisms (including cubes) Specimens are capped using hardboard, plaster or similar material. A summary of the required specimen details for compression strength testing according to various standards around the world is presented in table 1. [5]

Table 1: Recommended design values for characteristic unconfined compressive strength

Reference	Specimen details					
	Cylinder		Prism			Minimum number of specimen required
	Diameter (mm)	Height (mm)	Height (mm)	Length (mm)	Width (mm)	
Bulletin 5; Earth-wall construction , CSIRO	150	110	150	150	1.3x h	5
Standards Australia, 2002	150	300	N/A	N/A	N/A	1 sample for every 25-100 m2
New Mexico adobe & rammed earth building code (Tibbets,2001)	N/A	N/A	102	102	102	N/S
NZS	N/A	N/A	N/S	N/S	2x h	5

There are different types of moulds such as plastic hinged mould and the robust steel mould for making specimens. All moulds should be oiled and brushed clean prior to ramming, allowing for easier removal.

For UCS testing it is required to have smooth level and even surface ends so that compressive forces are uniformly distributed over the full area of the sample. Furthermore, the preparation of specimen ends is important as eccentric and concentrated loads caused by ridges on the base or top of the sample would give misrepresentative test results, as the applied force would be concentrated through particular points [9]. Grinding flat the end surfaces of the samples, using thick soft plywood blocks, thick layers of dental plaster or Teflon sheets are some boundary conditions to achieve different smooth levels of surface. Also there is definitively a slenderness effect in the compressive strength of samples tested with ground flat ends against the steel plates [8].

After being oven dried for at least 24 hours in a 100-105°C oven, it is important to ensure that the samples are cooled in a way that ensured that they did not reabsorb any moisture from the atmosphere.

2.5 Recommended Soils and Stabilizer Treatments

The soil selection scheme involves relating UCS criterion success rates to values of natural soil properties in order to discriminate between soils that are favourable or unfavourable, respectively, for stabilization, in the study(realized by Steve Burroughs 2010) [12]. The two textural variables measured were % sand (0.075–2.36 mm aperture sieves) and % clay-silt (< 0.075 mm aperture sieve), with all material >19 mm being discarded prior. The clay and silt fractions were combined in order that size distributions could be obtained by sieve analysis alone and the practical applicability of the results widened. Each soil property was used in a series of trials to identify the most efficient discriminators between samples that were successfully stabilized and those that failed the 2 MPa UCS criterions.

As you can see in figure 7, on the basis of the discrimination trials, the optimized discrimination process comprises two stages. The first stage of soil selection uses LS to discriminate three classes of soil. The classes have different UCS success rates: 29% for soils with LS > 11.0 (the first class); 69% for soils with LS = 6.0–11.0 (the second class); and 93% for soils with LS < 6.0 (the third class). Soils in the first class are unsuitable for stabilization and should be discarded as candidates for stabilization without further testing. In the second stage of soil discrimination/selection, the second and third classes of soil are tested for sand content (Stage 2a) and clay-silt content (Stage 2b), respectively [12].

In the second stage of soil selection, the second class of soils is tested for sand content, producing two categories. The category with sand content < 64% has a success rate of 86% and is favourable for stabilization. In contrast, the category with sand content ≥ 64% (success rate 56%) is unfavourable for stabilization and such soils should be discarded as candidates for stabilization. For the third class of soils, clay-silt content is tested. For these soils, three categories are identified: soils with clay-silt content ≤ 20% have a stabilization success rate of 89%; soils with clay-silt-content 21–35% have a success rate of 100%; and soils with clay-silt content > 35% have a success rate of 80%. Although the third class of soils itself has an overall success rate of 93%, soils in that class containing clay-silt content > 35% probably lie on the margin of favourability for stabilization, both in terms of achievable strength and with respect to shrinkage/cracking during curing [12].

The soil selection scheme depicted in figure 8 shows that soil suitability for stabilization can be assessed accurately using LS as the initial discriminating soil property and then using either sand (0.075–2.36 mm particles) or clay-silt (<0.075 mm particles) content as a second discriminator depending on the value of LS. The effectiveness of LS as the primary discriminator may be because the property reflects both the textural characteristics of the soil and how the soil responds to moisture, both of which influence the mechanical properties of the stabilized material (Burroughs, 2006) [12], [11].

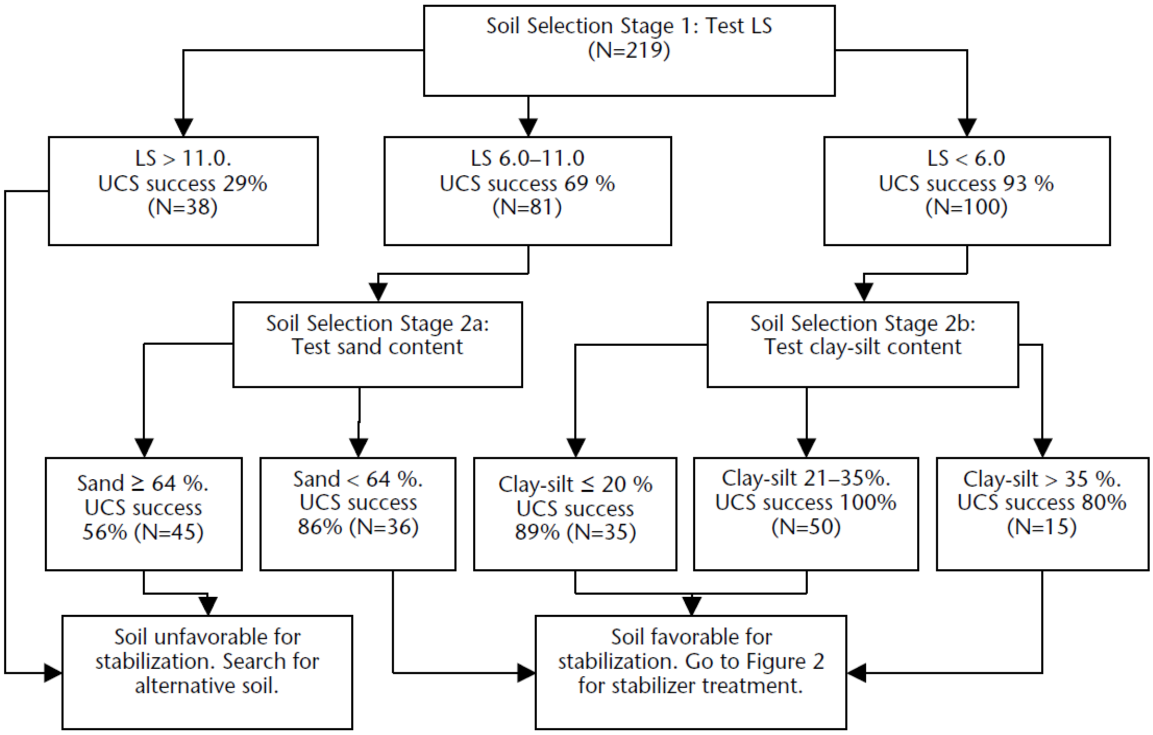


Figure 7: Recommended practical stepwise procedure for determining soil favorability for stabilization based on testing soil properties. (Here stabilization success is the percentage of samples with UCS≥ 2 MPa) [12]

The two best categories of soil are those with LS < 6.0 and clay-silt ≤ 20% or with LS < 6.0 and clay-silt 21–35.In situations where there is a requirement for a higher strength criterion (e.g. 2.5 MPa), two options could be available. The first option would involve confining soil selection to those soils with LS < 6.0 and clay-silt ≤ 35% (combining the two best favourable soil categories), for which the success rate is 70% for a 2.5 MPa criterion. The second option would be to increase the percentage of stabilizer used in any of the favourable soil categories. In general terms, to achieve an increase in strength of 0.5 MPa, the amount of cement stabilizer needed is about 1% and for lime is about 2% [12].

The results of Akpokodje [36] indicate the amount of cement to use to achieve a satisfactory stabilized earth shrinkage value given the LS of the natural soil. As lime is more effective than cement at reducing shrinkage, lime should therefore be used for soils with higher natural shrinkage [12].

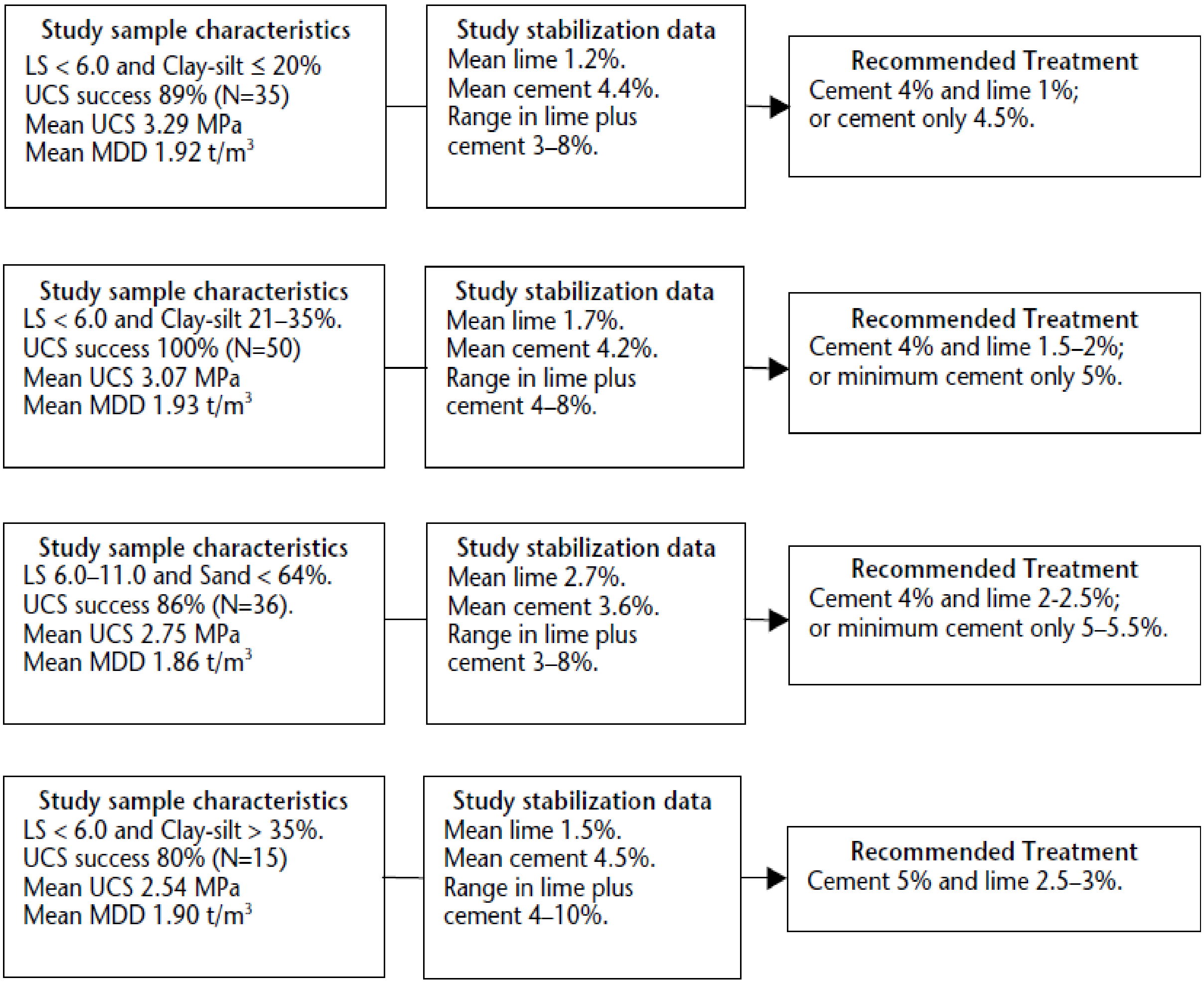


Figure 8: Stabilizer treatment summaries and recommendations for the four categories of soils deemed favorable for stabilization. (UCS success is the percentage of samples with UCS ≥ 2 MPa) [12]

Table 2: Summery of stabilized rammed earth design, selected from different document

	Percentage value							
					5			
Documents*	1	2	3	4	Sandy	hard literate	clayey	6
Grading								
Gravel fraction	45-80%	45-75%	30%		32.20%	56%	50.50%	13-62%
Sand fraction			45%	>33%	59.40%	29.60%	30.40%	30-70%
Clay and Silt fraction	15-30%	10-30%	13%	<30%	8.40%	14.40%	19.10%	21-35%
Atterberg limits								
Liquid limit (LL)	45%	35-45%	49%	<40%				≤35%
Plastic limit (PL)			25%	12<LP<20				16-19%
Plasticity index (PI)	2-30%	15-30%	24%	6_22%				<15%
Linear shrinkage (LS)	0-5%							<6%
Optimum moisture content			12.50%	10-14%	9-11%	9-11%	9-11%	
Maximum dry density (kg/m^3)			1.85			2.03	1.82	
Compressive strength								
N/mm^2			2,46		2.47*	2.03*	1.82*	≥ 2.0

1-Recommendations for soil suitability from Rammed earth, design and construction guidelines (Walker et al, 2005) [1].
2-Recommendations for soil suitability from Handbook 195 (Walker et al, 2002)
3- Properties of the selected soil comply with general published recommendations for rammed earth construction [7].
4- Recommendation for soil selection for rammed earth following IETcc [16].
5- Particle size distribution of soil types. (Case study in Sri Lanka)[3].
6-Recommendations concerning "Good" Value Ranges of Soil Properties for Stabilization. (Defined as ≥80% of Samples Successfully Pass 2 MPa Criterion)[11].

* With the cement content of 6%.

2.6 Mechanical properties

2.6.1 Compressive strength

Rammed earth has relatively good strength in compression but generally poor strength in shear and tension, especially when it is moist. Evaluation of compressive strength values of rammed earth, concrete and brick masonry is shown in figure9.

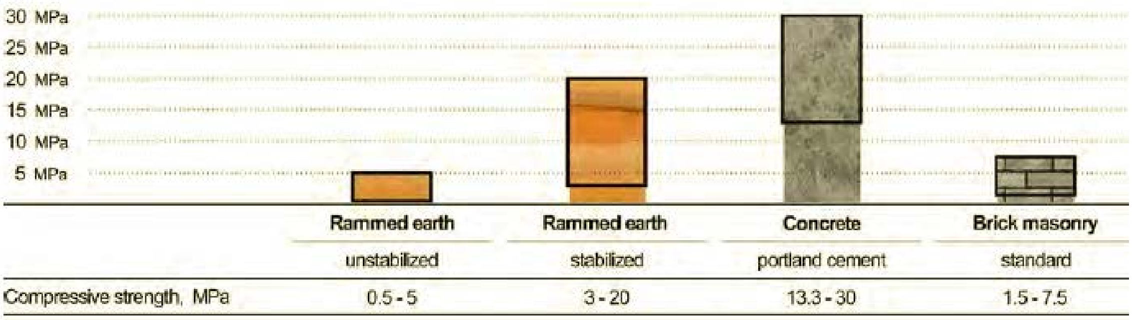


Figure 9: Characteristic compressive strength values of rammed earth, concrete and brick masonry

The mechanical strength of a soil is very much dependent on the voids ratio of the soil after ramming, cohesive strength of fines content, aggregate strength and moisture condition during testing. Density of the soil is a very important factor for the strength of the soil. Therefore, in the same way that it is difficult to give a specific value for the density, it is impossible to predict an exact value for the mechanical strength of a soil based on any kind of description with no prior testing.

Building Codes call for a characteristic compressive strength of not less than 2 MPa which rammed earth walls exceed.

A detailed study carried out at University of Bath [3], indicates that the compressive strength of about 1.0–3.0 N/ mm2 can be obtained with unsterilized rammed earth.

In unsterilized rammed earth the absence of mortar joints make the failure of rammed earth is more of a crushing failure than a tensile failure. Therefore, rammed earth is less likely to give an adequate warning in the form of vertical cracks. Hence, it is recommended to use an adequate factor of safety against failure. Therefore they should have an overall factor of safety of 5 or more [3].

For cement stabilized rammed earth walls, the strength increase with cement percentage.

For sufficient compressive strength of stabilized rammed earth, the compressive force applied on a rammed earth section should be less than or equal to the product of the slenderness and eccentricity reduction factor times the compressive capacity of the section [7]. Therefore, wall panel dimensions were determined so that slenderness effects will not be predominant.

There is a type of rammed wall in Australia [4] that standard 300mm walls can be built as load bearing constructions for up to four stories high, but can be designed to go up to ten stories if required.

According to a recent study (by Ciancio D. Gibbing J) [8], it is shown that in certain cases the mechanical behaviors of concrete and cement-stabilized rammed earth are similar. The obtained results of this study also indicate that the strength of cored specimens is always lower than that of molded specimens. There is a significant difference in the strength of molded and cored samples. Hence the design compressive strength fc should be taken as fcored ≤ fc ≤ fmolded. In this experience the Cement-stabilized rammed earth achieves compressive strength higher than 5 MPa [8].

2.6.2 Elastic module

The elastic modulus of rammed earth will be in the range of 0.5 kN/mm2. This can be used to determine the shortening of rammed earth walls in load-bearing construction when adjacent walls are loaded differently [3].

2.6.3 Anisotropic

Since rammed earth construction is carried out by stacking layers of rammed earth, it is possible that the rammed earth material is anisotropic. According to the experiment of Hall H, Djerbib Y [17], it is presented the first study of this anisotropy, carried out on two scales. The first is the scale of Representative Volume Elements (RVEs) of the rammed earth material, with dimensions close to those of the walls on site, manufactured and tested in the laboratory. The second is the microscopic scale, for which tests were carried out on equivalent Compressed Earth Blocks (CEBs).

The compressive strengths, elasticity moduli and failure moduli are similar in both directions of the material: perpendicular and parallel to the layers. The sum of these results allows us to propose the hypothesis that the rammed earth material is an isotropic material of the first order, if the layers remain adherent to each other.

On the scale of the representative rammed earth samples (RVEs), the anisotropy of this material was studied by using uniaxial compression tests in two directions, both perpendicular and parallel to the layers. Unloading–reloading cycles were added to study the non-elastic behaviour of this material. These tests gave similar results in both directions tested for this material, for compressive strength, failure modulus and the elasticity moduli in the case of preload greater than 0.2 MPa. In case of preload smaller than 0.2 MPa, the difference between the elasticity moduli in two directions is from 5% to 25%. All of these results enable us to initiate the hypothesis that rammed earth is an isotropic material of the first order if the layers remain adherent to each other. These results have justified the successful application of the hypothesis of an isotropic material on the macroscopic scale (in situ rammed earth walls on small deformation) [17].

2.7 Durability

Thousands of rammed earth buildings constructed centuries ago are still giving excellent service in France, Algeria, Morocco, Central America, China, and the Middle East. In Australia there are many rammed earth buildings over 100 years old still in use, therefore earth construction could be consider as durable kind of construction.

Durability in the context of earth construction means the ability of the structure and all its elements to withstand the destructive action of weathering and other actions without degradation to the expected service life. Rain and frost are the most destructive natural actions causing erosion and deterioration of the earthen elements. Accidental abrasion is also a significant agent of deterioration.

2.7.1 Erosion

It is proven that long lasting rain may cause deformations or an erosion of materials outer surface. According to durability tests in France where under climatic conditions of 1000 mm annual rainfall rammed earth specimens were exposed for a period of 20 years, they indicate clear signs of erosion in unprotected areas exceeding 6mm. The erosion measurement depth was 5% of wall (In the case of the rammed earth wall stabilized with 5% (by dry weight) of natural hydraulic lime). Therefore, the stabilization enables to not use any plaster to protect the walls. In the case of the unsterilized rammed earth walls, the erosion measurement was about 1.6% wall thickness, which led to an extrapolated lifetime longer than 60 years. This shows, a potential for the use of unsterilized rammed earth in this kind of climate [18].

According to Heathcote [19], the ratio of wet to dry strength is an indicator of durability of earth wall components. The ratio of wet to dry strength of 0.33–0.50 may be regarded as suitable depending on the severity of the rainfall.

2.7.2 Capillary

Moisture absorption due to capillary suction depends on density and surface smoothness. The particle-size distribution of the soil is also critical in determining the rate at which moisture may ingress due to capillary suction.

When the mass of the binder fraction in a suitable soil is less than 10% of the total soil mass, it would appear that the rate of moisture ingress, due to capillary suction, in rammed earth is significantly increased. It is hypothesised, therefore, that through granular stabilization the rate of capillary moisture ingress in rammed earth can be controlled [20].

2.7.3 Suction

Since the material in rammed earth is initially compacted and then allowed to dry it will be unsaturated, where the soil particles are surrounded by air in addition to water. It is widely accepted that unsaturated soils achieve a component of strength through suction.

As soils dry, so suction increases, and consequently there is an increase in apparent cohesion and hence strength. The contribution to strength from suction in sandy clay reduces as the degree of saturation reduces. So, although suction increases as the soil dries out, the contribution to strength reaches a peak and then drops away. The apparent cohesion is therefore expected to peak between the two limits of zero water content and saturation.

Evaporation of pore water is affected by the relative humidity of the pore air compared with that of the adjacent air outside the wall. In practice, drying of the walls will continue until the pore air humidity equals the humidity of the surrounding air.

Therefore, suction is a source of strength in unsterilized rammed earth, and that the strength increases as water content reduces.

Walls left to dry after construction, in a suitable climate, can be expected to develop very large suctions in the remaining pore water, and hence develop considerable strength over time [21].

2.7.4 Durability tests

The Geelong drip test is a simple assessment test in which water droplets are allowed to impact onto the surface of the test specimen. Initially developed for adobe mud blocks the test can be adopted for rammed earth as well, using specimens 300 x 300 x 125mm thick. Each specimen is inclined at 27_ from the horizontal and water is released through a 16mm wide sponge cloth and allowed to fall 400mm in droplets. One hundred milliliters of water should be released within 20 to 60 minutes of the test commencing and the sample performance is measured in terms of pitting depth and depth of moisture penetration. According to some normative, failure of the specimen occurs when the pitting depth is greater than 15mm or the depth of moisture penetration is greater than 120mm.

The spray test has been more widely accepted. The specimens are subject to a continuous jet of water spay at 50kPa pressure for 60min or until a specimen has completely eroded through, whichever occurs first. The 50mm spray nozzle is 470mm away from the sample and the exposed soil area is bound by an impermeable shield, leaving uncovered a circular section of either 150mm or 70mm diameter. The water spray is temporarily stopped every 15min to allow measurements of the depth of erosion with a 10mm diameter flat-ended rod. The maximum depth is taken as the rate of erosion for the whole specimen. Failure of the specimen also occurs when the depth of erosion or the depth of moisture penetration is greater than 120mm.

The main test procedure used to assess freeze-thaw durability of rammed requires subjecting rammed earth samples to 12 cycles of freezing and thawing whilst the specimens remain saturated. After thawing specimens are subjected to abrasion by a wire brush to remove loosened material. The percentage of mass loss at the end of the test is calculated and if the weight losses are less than the values indicated by the standard used the specimen is considered adequate to produce a durable rammed earth wall. Suitability criteria exist only for soil cement typically varies between 5 and 14% [5].

2.7.5 Moisture Protection For more Durability

Stabilization

The most common rammed earth protection against water impact is by adding cement. A cement gel matrix that binds together the soil particles has not only a positive impact on materials strength and durability in dry state, but unlike clay it maintains strength also in humid state preventing erosion and weakening. [5].

An alternative technique to improve rammed earth water resistance especially for soil mixtures with low clay content is by adding bitumen. Bitumen is either dissolved in water with an emulsifier such as naphtha, paraffin oil or petroleum.

Coating

According to the New Mexico building code, for example, stabilized rammed earth structures can be left opened to the environment, but if unstabilized must be covered with mud or Portland cement plaster. More resistant, however, is lime plaster typically consisting of 1 part hydraulic lime and 3 to 4 parts sand. Practice shows that plaster is usually applied in 5 – 30 mm thick layer. Coating might also be done with paining.

Figure 10: Painted rammed earth building

Avoiding Contact with Moist Surfaces

To prevent capillary suction it is essential to ensure excellent insulation between rammed earth elements and moist building parts as foundation. Earth surfaces should also be separated from moist interiors as shower and kitchen areas. Similar hydro insulation requirements exist if building with most of other materials as well.

Footings and Roof Overhangs

It is essential to maintain protection from direct rainwater and splashing water. In areas, where wind speed is highly predictable (typically dominating from one direction and low from others) large roof overhangs or covered terraces towards the windy side could be enough to protect building from direct rainwater impact . Splashing water impact can be avoided by a concrete footing.

Figure 11: Moisture protection by overhanging roof. Center of Gravity Foundation Hall in Jemez Springs, New Mexico (2003) [2]

Figure 12: Protective concrete footing [2]

Exterior walls must be designed to avoid dew point occurrence within the rammed earth layer. Scientific measurements indicate that most preferable exterior wall type in cold climates therefore is insulated from outside and optionally with ventilated cavity. Condensate thus appears on either external side of the insulation or within the cavity and is handled without harming rammed earth structure.

2.8 Production process and compaction

The compaction is performed using a water content considered optimum. Providing the highest dry density for fixed compaction energy. This process is called the dry method, since the water content is about 10%, while a paste (the case of adobes) should have a water content of about 25%.The construction process is not dissimilar to building a sandcastle. Earth is collected, its consistency checked, and organic matter that will decompose is removed. Unwanted particles (usually rocks larger than 20mm) are separated from other aggregates by sieving. In occasions when excavated soil contains large cohesive aggregations (sand clods, clay clusters) they are fragmented to the level of initial particles to ensure materials looseness. Next, formwork is brought in; this is the frame into which the earth is, quite literally, rammed layer by layer, either manually or by pneumatic rammers. The earth begins to cure straight away and continues to do so for months or years, depending on the local climate. Without baking, the wall is complete and the process can be repeated [22].

The rammed earth is composed of several layers of earth roughly 15 cm thick, poured into a formwork (wooden or metal), and rammed with a rammer (manual or pneumatic). After compaction, each layer is 8–10 cm thick. This procedure is repeated until completion of the wall [4].

To avoid the top layer of the molded sample to be far less compacted than the layers below, it is recommended the use of a collar [8].

Figure 13: A vertical technique has also been popular for ages, where by after a course is completed, the side panel is raised and the next higher layer is added and the process goes on till the entire height of the wall is completed

Figure 14: Today, lightweight, stackable steel frames are popular

Compaction can be given using a steel rammer. Construction can be carried out with steel slip forms. Or a special vertically sliding formwork system, this system slides between corner and middle columns constructed with interlocking cement stabilized soil blocks, it is often suggested that formwork is a significant labour intensive activity consuming about 50% of the site time for erecting, aligning, checking, striping, cleaning, moving and storing of the formwork. This system eliminates most of these activities since once in place, the formwork can slide continuously. The corner and middle columns can be erected rapidly with interlocking cement stabilized soil blocks manufactured with either hydraulically or manually operated machines. The slip formed wall will have the same thickness as the block work. This operation can be further improved with a mechanical rammer instead of a manually operated rammer. However, for countries with lower labour costs, manual rammer could be a better solution [3].

It is also reported that mechanical stabilization by dynamic compaction appear to give better results as compared with static or vibro-static compaction.

Once the soil is compacted well, the formwork is slipped upwards for the next lift of the wall using the long screws available.

Shrinkage of cement stabilized soil increases rapidly during first four days and at latter ages the increase is very slow. Hence, curing for the first four days is very important in reducing drying shrinkage and cracking. Sand particles reduce the shrinkage as it opposes the shrinkage movement [10].

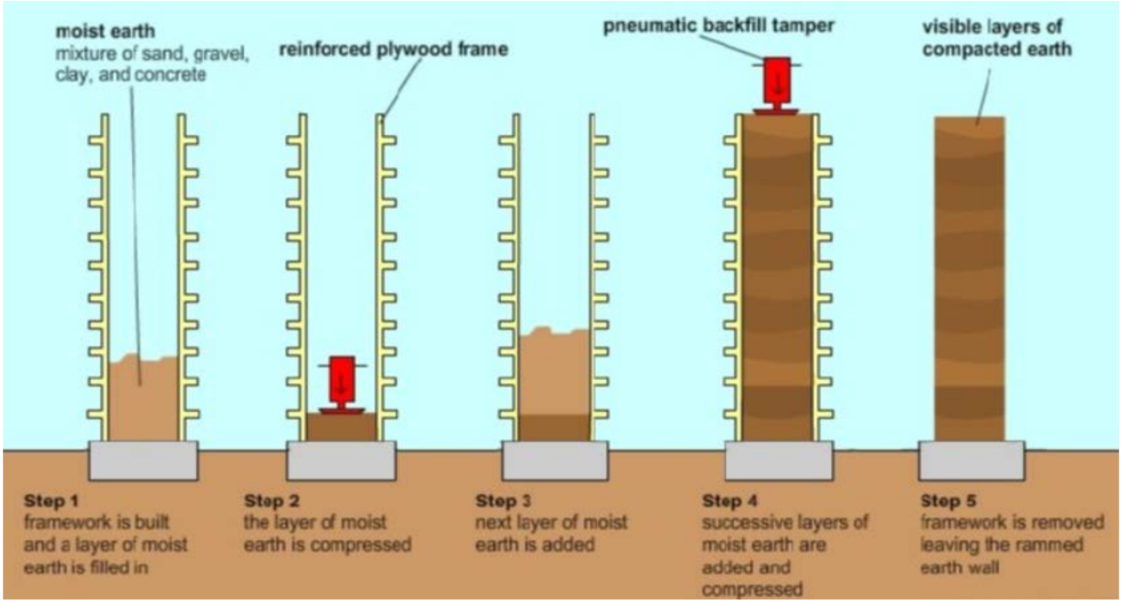


Figure 15: Compacting rammed earth

The process is time consuming and repetitious, but rewarding. And now with power tampers, the job is a bit less demanding. A newly tamped section of wall is so solid that, if desired, the forms can be removed immediately. If wire-brushing is needed after the forms are removed, to even out the framework edge imprints or to add texture, it must be done in the first hour after the form is removed, for the wall dries to the touch quickly, yet will not be fully dried throughout for months. Exposed walls may need to be sealed to prevent water damage if the walls will be exposed to heavy rain.

Figure 16: Rammers used to construct rammed earth walls. Slip form moulds and wood used for wall construction

In the case of rammed earth or stone masonry, the thickness of the wall is at least 50 cm to ensure correct hydrothermal behavior. With such thicknesses, the compression safety factors are around 10 [23].The existing building codes and standards provide guidelines for minimum wall thickness, maximum wall height as well as wall thickness/height ratio. Some of the values differ significantly and are represented in following table 3:

Table 3: Wall thickness for rammed earth in different standards

Refrence	**Thikness of wall**	
	Internal	External
Standards Austalia (2002)	125 mm	200 mm
New Mexico Code (Tibbets,2001)	305 mm	457 mm
New Zealand Code (NZS 4297;1998,1998)	250 mm	
Zimabwe Code (SAZS 724:2001,2001)	300 mm	

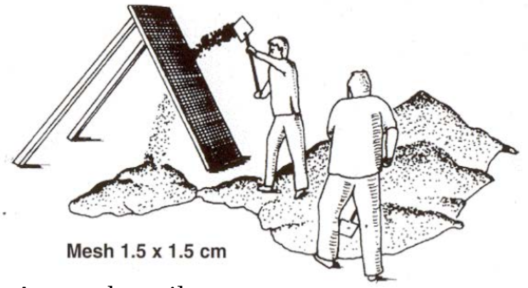
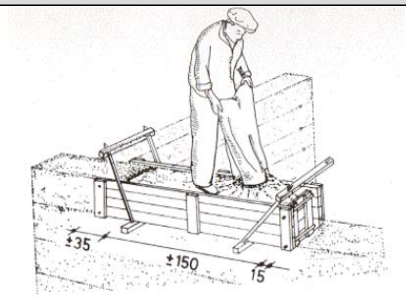
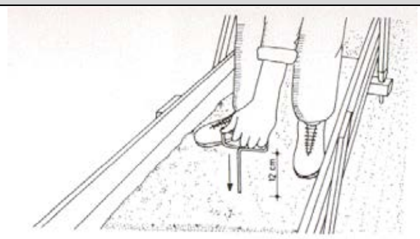
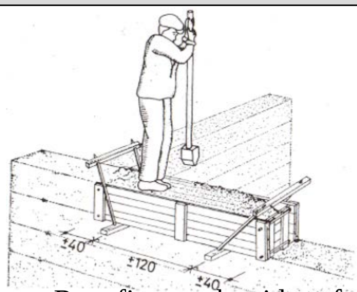
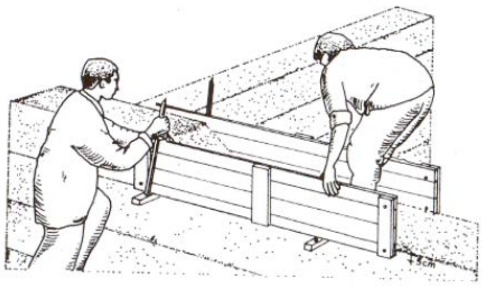
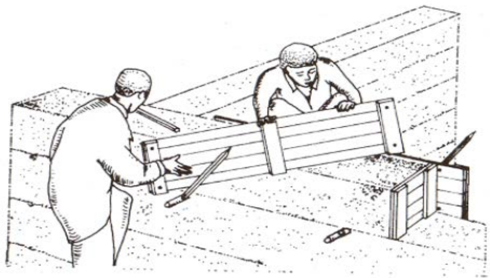
1.Saving the soil	5.Pouring the soil in the form
 • Aerate the soil • Remove lumps, stones and pebbles	 • The soil present must be loosened and slightly humid • Pour layers of only 12 cm thickness
2.Measuiring the components	**6.Checking the layer thickness**
 • Measure all components(soli ,sand, stabilizer) • Fill the containers with accuracy, as per specifications	 • Before ramming, use a layer gauge (Φ6mm MS rod) to check the thickness of the loose soil • Leave evenly the layer (add or remove some soil)
3.Mixing the components	**7.Ramming**
 • Pour in order ,soil, sand and stabilizer • First mix dry,2 times • Add water and mix wet,2 times	 • Ram first on the sides of the panels, and then in the center • Ram the loose soil till you hear a clear sharp sound
4.Setting up the form	**8.Removing the panels**
 • Check with the plumb line that panels are vertical	 • Immediately after finishing the ramming, dismantle the form and proceed further in the same way • Never keep a form in place over night

Figure 17: Rammed earth production step by step

2.8.1 Recommendations for on-site earth compaction

The recommendations concerning on-site compaction presented here are based on defining the forces involved in on-site compaction in order to ensure that equivalence with laboratory test compaction can be achieved. The two most widely used methods of determining the response of a soil to compaction as they mentioned before (section 2.3.2) are the standard Proctor and modified Proctor tests. These tests involve dropping a rammer of specified weight from a specified height onto a cylinder of soil of specified volume and therefore we can determine and the values for OMC and MDD. Various professional organizations concerned with standards for compaction, for example AASHTO (American Association of State Highway and Transportation Officials) and SAA (Standards Association of Australia), each have their own versions of these tests that differ slightly in the dimensions of the apparatus and experimental techniques used (Table 4). However, the result in all cases is that the compactive effort (quantum of energy) applied to the material is the same: for the standard Proctor test, the compactive effort is 596 kN/m2 and is 2703 kN/m2 for the modified Proctor test [12].

Table 4: Test specifications for standard and modified Proctor compaction tests for SAA (1977) and AASHTO

	SAA test specifications (Tests AS 1289.E1.1 and 1289.E2.1)		AASHTO test Specifications (Tests T-99 and T-180)	
Variable	Standard	Modified	Standard	Modified
Weight of rammer (kg)	2,7	4,9	2,5	4,55
Hight of drop (m)	0,300	0,450	0,305	0,457
Number of drops (total)	75	125	75	125
Internal diameter of cylinder (m)	0,1050	0,1050	0,1016	0,1016
Lenght of cylinder (m)	0,1155	0,1155	0,1164	0,1164
Number of soil layers	3		3	5
Volume of soil compacted (m^3)	0,001000	0,001000	0,0009444	0,0009444
Compactive effort (kN/m^2)	596	2703	596	2703

It is necessary to calculate the compactive effort of on-site ramming conditions to control that laboratory and the files campactation are similar [12].

It is clear that considerably more physical exertion needs to be expended by a laborer lifting and thrusting a rammer to compact the soil to a degree equivalent to the modified proctor test than for the standard proctor situation. Therefore, the manpower available for the on-site compaction phase may be a consideration when deciding which laboratory test (proctor or modified proctor) of the moisture-density relationship for determining values of MDD-OMC should be used to simulate on-site compaction conditions for manual ramming (Figure 18).

Pneumatic rammers used for compacting earth walls have a pneumatic force exerted; it is likely that the compactive effort of on-site pneumatic ramming is more comparable to the value of the laboratory modified Proctor test than to that of the standard Proctor test. However, it is clear that the anticipated amount/style of pneumatic ramming should be a consideration in relating laboratory-based stabilization experiments to on-site compaction conditions [12].

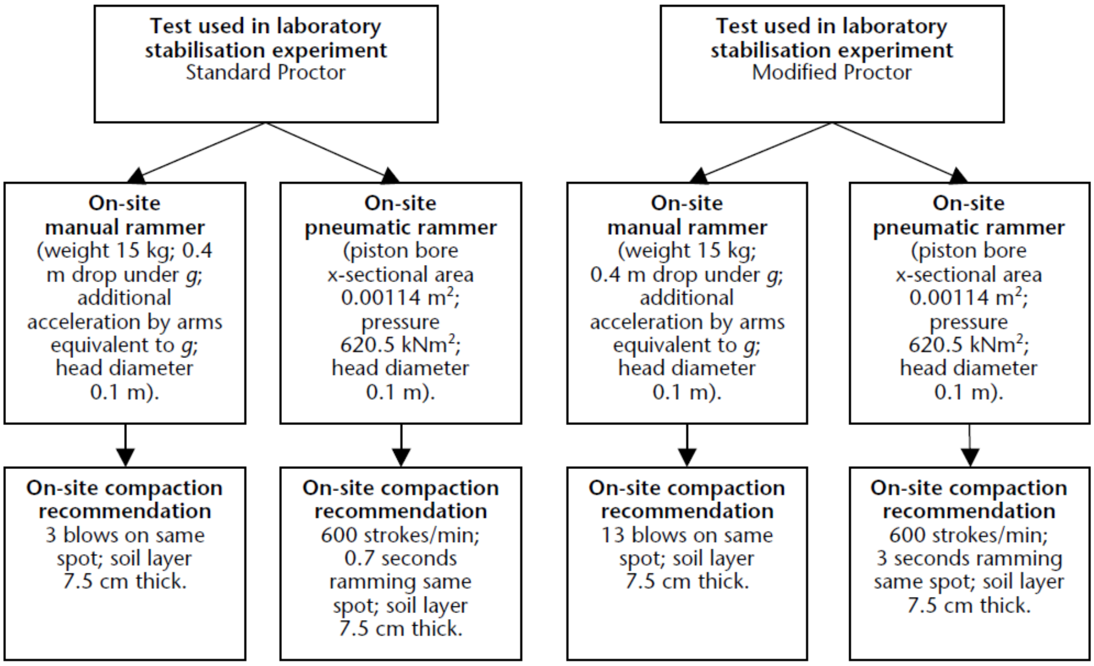


Figure 18: Recommendations for on-site compaction considering both the compaction test used in the corresponding laboratory experiment and the rammer (manual or pneumatic) used on-site

During on-site compaction, the moisture content of the earth-stabilizer mixture must be closely monitored and maintained at or near the OMC, in order that the MDD can be achieved. This is important so that walls with the highest possible densities can be constructed. An associated point that has not been covered in the literature is that the optimum moisture content from a strength perspective may be greater than the OMC associated with MDD as assessed from laboratory compaction tests, on the basis that cement and lime stabilizers require moisture for chemical activation and strength development. However, producing an earth-stabilizer mixture wetter than OMC to account for the use of water by stabilizers would reduce the compactable density of the resulting rammed earth, given the usual moisture-density relationship of a soil under compaction which would in turn reduce strength. Given that the nature of the play-off between these two competing influences on strength is currently unknown, compaction of rammed earth should proceed at the OMC as determined for MDD in laboratory tests.

However, although laboratory tests are used to establish values of OMC and MDD, it is recognized that the MDD may not necessarily be achieved in actual on-site construction conditions. Therefore construction densities could be specified as a percentage (e.g., ≥ 95%) of the modified proctor laboratory-measured MDD, to allow for the moisture content of the mixture slightly exceeding or falling below the OMC. The maximum percentage deviation from OMC that would allow a ≥ 95% specification to be achieved would depend on the moisture-density relationship under compaction of the particular soil being used.

2.8.2 Precaution Activities for Shrinkage and Cracking

Additives

As clay is the component responsible for shrinkage, rammed earth deformations can be significantly minimized by reducing clay content and compensating it with stabilizing binder such as cement. Experiments prove that 5% clay replacement with cement can reduce linear shrinkage more than 10 times.

Shrinkage can also be reduced by adding fibers such as straw, wood, and sisal or bamboo fibers. By increasing the binding force they reduce the risk of cracks. According to Australian Standards, the ideal soil for fiber stabilization should have a plasticity index between 15% and 35% with the liquid limit from 30% to 50%.

Control Joints

Material shrinkage without cracking is possible by separating larger rammed earth parts with control joints.

Elastic Ties and Anchors

Various building parts with diverse shrinkage values usually need to be integrated within a single building system. As for example, rammed earth walls may be connected to additional supporting systems or, more typically, contain doors and windows. In building practice a number of elastic connections exist to avoid gaps or tension between them the various building parts.

Repairing Cracks

In rammed earth walls unsightly shrinkage cracks can be repaired by pointing or filling with dampened soil of similar characteristics, color, grading and plasticity. Surfaces of the crack must be moistened to ensure adhesion and the fill mixture has as little linear shrinkage as possible [36].Structural cracks should be fixed only when the deformation process has stopped.

Figure 19: Repairing rammed earth

Figure 20: Aesthetics of repaired element

2.8.3 Industrialization of formworks and ramming systems

The newest innovation in the field of rammed earth is the introduction of prefabricated elements. When local excavation and ramming aren't possible in dense in urban environments, the solution is to make a long walls of rammed earth in a factory [22].

In general, rammed earth as a construction technique needs an intense amount of work and ability. In this sense, the industrialization in the production of rammed walls would rationalize the costs of labour and execution times, as well as provide improvements in areas such as earth and water metering, control of quality of execution, in particular the degree of compaction and, of course, the final finish.

Prefabrication allows the integration of electrical and air conditioning installations, increasing the qualities of the earth.

Prefabrication is a step towards the modernization of earth construction, which has inherent a strong added value of sustainability on which is tried to open new ways to facilitate its use in building and as a part of the architectural design [24].

Figure 21: Prefabrication of the rammed earth

One of the difficulties in rammed earth prefabricated pieces is transportation, since the lack of ductility of the material requires packaging conditions, storage, loading, unloading and transfer more careful of which for example require the prefabricated concrete

The plasticity of the material let the easy fill and finish of the joints between prefabricated reamed earth pieces by placing a thin base of clay mass that acts fixing the different parts. Depending on the solicitations can pose additional anchorage systems. The vertical joints are often filled with lime mortar base.

The features detailed above, by the solubility of the rammed earth are optimal for filling work and sealing leaks. After the assembly stage are sprayed with water boards, which are filled with wet original material and reinforced with wood.

Prefabrication of the rammed earth is a process of rediscovering and re-teach this technology which is helped its survival in modern construction and equip it with new added values such as sustainability.

Since 1997, in Austria two companies have built and placed more than 600 pieces of rammed earth [24].

2.9 Improving Structural Performance

Stabilization

Significant improvements in materials performance can be achieved with stabilization. Supplementing the typical earth mixture with 5-8% cement (or 8-12% lime) the compressive strength can be increased up to 18 MPa (fig. 34) that is not far from the typical value of 25 MPa for concrete

Though obviously stabilization is one of the most promising and commonly implemented method in both increasing materials strength and durability.

Reinforcement

Supplementing rammed earth structures with reinforcing elements has been known for centuries. Initially by simply improving earthen elements with wooden bars, nowadays rammed earth can be engineered to achieve reasonably high strengths and be reinforced in a similar manner to concrete. Extensive application of reinforcement though can make compaction process technically complicated and result in incomplete densifying of the soil. Excessive vertical reinforcement can also cause cracking problems. Due to this reason disposition of reinforcement bars is rather different as in concrete.

Materials used to reinforce earth walls include threaded stainless or uncoated or also galvanized carbon steel bar and mesh, steel wire, fiber reinforced plastic, bamboo, timber, concrete, and polypropylene geotextile grid material.

Figure 22: Using reinforcement in rammed earth construction

Lintels and Bond Beams

Rammed earth application requires strict precaution activities to avoid highly stressed areas. Therefore larger openings (usually above 1 meter) must be covered with lintels.

In order to equalize load distribution by floor slabs (especially in case of wooden beams or trusses) perimetrial bond beams are highly implemented.

Figure 23: Concrete bond beams. Chronometry Tower, Zurich [2]

Framework

Applying additional structural system is well known building practice. Centuries ago it was common to combine rammed earth walls with wooden frame taking most of the compressive load. Nowadays constructive frames are made also of metal and concrete. Frame can be designed to take the entire load and keep rammed earth only as infill material though it is much more rational to have frame only as a support and therefore make use of compressive potential of earth.

Geometry

Several design aspects should be considered when aiming for maximum performance like the shape, wall thickness or the corners.

Tension and shear stresses can be minimized following the theory in structural mechanics of optimum shapes. Also reducing wall thickness for higher floors is another historically well-known method of optimizing buildings constructive performance applied also for concrete and masonry structures.

Rammed earth laboratory tests show surprisingly explicit relationship between compressive strength and shape of the tested specimen. With identical soil composition, moisture level and compaction energy, the overall performance of cylinders is more than twice as high as prismatic elements. This can be explained by specifics of compaction process when it is technically rather impossible to achieve perfect compaction in corners with a pneumatic rammer. Differences are not that dramatic for samples of larger dimensions since the amount of poorly compressed areas is constant for depending in rammer diameter. Though corners are usually first to fail anyway and thus are preferably to be rounded or designed in angle of 45˚.

Figure 24: Preferable angle construction method

2.10 Applications or real cases

There are several factors for using rammed earth: cultural, social, economic, etc. But the main reason comes from the principle of using available local materials. In the past years, rammed earth has returned to the limelight as human and environmental health has become key concerns. Today, more than one third of the world's population live in building made of the earth and, from Lutyens to Gaudí, many of the world's best-known architects have experimented with it.

The first application of rammed earth construction technique dates back to 5000 BC when in Assyria and China it was used in foundation and wall construction. Soon, after it spread out along dry climatic zones of Africa, Asia and Europe. Initially the formwork was made from wood and ramming done by hand with a ramming pole, as it is still the practice in developing countries with cheap labour [2].

Figure 25: Ancient Indian rammed earth

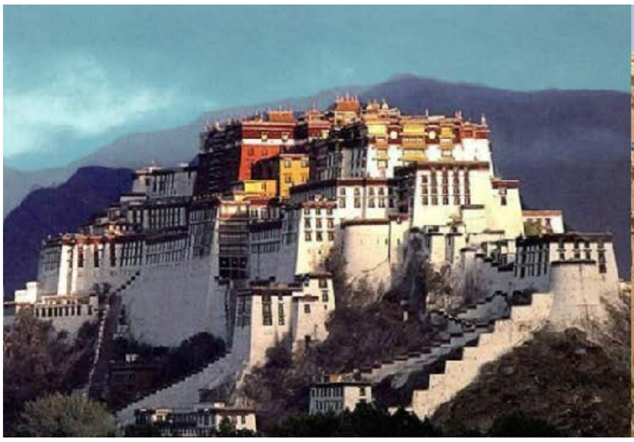


Figure 26: The Pokhara in Tibet is an earth rammed structure. Rammed earth has been popular in Nepal and Tibet for thousands of years. Plaster is a popular finishing technique

Figure 27: The entire village of AitBenhaddou, Morocco is rammed earth

In modern country Modern soil processing and improvement tools available for in situ implementation are able to ensure materials preparation fast, easy and with high degree of precision, providing consistency of the output close to that of manufactured building materials. Relatively mediocre strength and tense constraints set by building codes result in common perception of rammed earth as a construction technique for low-rise buildings, not more than 2 floors high. Obviously this conflicts with nowadays architectural reality of global urbanization and intensification [2]. However, certain structures such as foundations for buildings, ceilings and bridges are not possible in earth [22].

Figure 28: Rammed earth building in Weinberg, Germany (1826) [2]

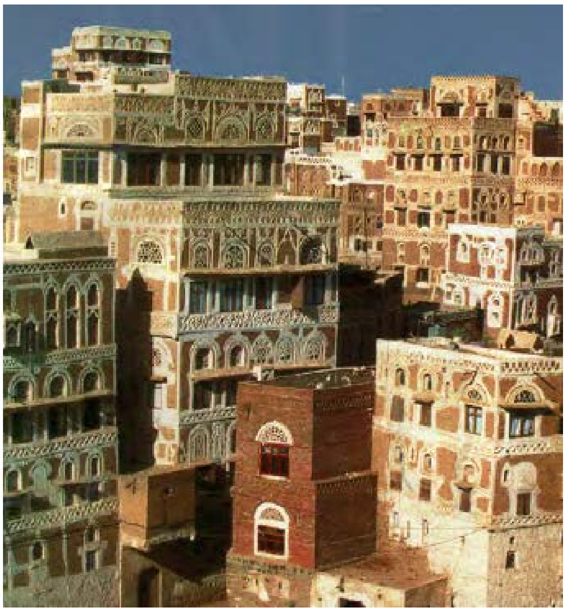


Figure 29: Earth architecture in Sanaa, Yemen

Worldwide, more than forty percent of the population lives in earth built structures [25]. The modern rammed earth buildings are approximately 20% of the new-build market in Australia [14].

Although walls can be from 200mm to over 1000mm, the optimum thickness is 300mm thick

In Australia the highest single rammed earth wall is 9 metres high, while a four-storey resort/hotel is the overall tallest modern rammed earth building. About 10 stories would be the highest that rammed earth walls could be built in a modern setting. Double and triple storey houses are built with 300mm thick, load bearing rammed earth walls.

The termite-resistant, non-toxic, fireproof technique of rammed earth is good to build walls, benches, supports, columns and thick blocks which can then be layered like bricks with mud slurry between. Rammed earth using rebar, wood or bamboo reinforcement should be employed in earthquake prone areas.

Figure 30: Earth House in Victoria, Australia was constructed in rammed earth using local crushed rock. The massive walls keep the winds at bay

Figure 31**:** Desert Cultural Centre in the South Okanagan Valley in British Columbia, Canada. Successive layers of differently colored local soils were placed into the 600mm wide formwork and a pneumatically powered tamper was used to compress each layer to about 50 percent of its untamped height. The technique results in a physically strong, durable wall with excellent thermal qualities, heating up slowly during the day and releasing heat in the cool evenings

Figure 32: The most renowned rammed earth architect and builder.Mooloolaba. Australia

Figure 33: Rammed earth home. Sydney. Australia

In Europe, the energy crisis of the late 1970s led to increasing awareness of the scarcity and foreseeable exhaustion of the planet's energy resources. Many architects and other agents involved in the construction sector and research advocated reclaiming traditional building materials and techniques, in an attempt to find an acceptable balance between the functional and aesthetic demands of current construction and the parameters of bioclimatic architecture [26].

Since the early eighties, in France the builder Nicolas Meunier made rammed earth wall panels, and M. Rauch in his workshop, adapted construction equipment for mixing and soil elevation., soil applied by mechanical projection, among other innovations. They allow building with earth in contemporary constructive approaches and improve the prospects of its economic competitiveness; however the rammed earth construction is still a limited option for luxury architecture [26].

2.10.1 Rammed earth in Spain (current examples)

In Spain during the last few years, a growing interest has been appearing too in earth as a modern construction material for being considered a sustainable material. Some of the reasons for this are the manufacture energy savings compared to clay bricks, the less cement used compared to concrete blocks, the transport savings if soil comes from the construction site or vicinity, and the natural appearance and colors that help buildings integrate into the landscape.

One of the main problems that new earth buildings have to face is the lack of skilled people, at all levels, from architects to builders. In spite of the fact that earth construction was very popular some decades ago in Spain, today it is almost forgotten [16].

While in industrialized countries rammed earth construction under the current parameters is initiated in the early eighties of the last century, in Spain it didn't realize until mid-90s.

20 years ago the book (The rammed earth: millenarian constructive technique) [27] was published, a work written in Catalan which tried to bring architecture attention to raw earth, and the technique of the rammed earth particularly. Revealing this ancient method of building walls, their main characteristics and their future potential use in construction. Since the edition of the mentioned book and also the more recent book (Arquitecturas de Tapia) [28], from the same author, all kinds of research have appeared, throughout the Spanish geography, especially in Cataluña [26].

Further down some of the most important architectures of rammed earth, made in Spain in recent years are presented.

Indoor Swimming Pool, Toro, Zamora

The project, conducted by the (Vier Arquitectos S.L), has been awarded with the first prize of the call for Sustainable Construction Awards of Castilla and Leon (2005-2006). The work was completed in late 2010.

The front walls of the entrance, the dressing room and pool enclosure are stabilized rammed earth walls with white cement, hydrated lime and with the addition of gravel. Walls with 60 cm wide are the skin of the building; give it a strong personality and bringing again the historical tradition of earth construction in the region [26].

Figure 34: Indoor Swimming Pool, Toro, Zamora, Spain

Fontanilles House

The rammed earth is mostly present in the walls of outdoor spaces of the plot, and in the body of the attractive fireplace, visible from the outside of the house.

The walls have 45 cm width. In construction of the garden walls a pneumatic compactor and metal frames were used but for the fireplace compaction they used manual and traditional wooden frame [26].

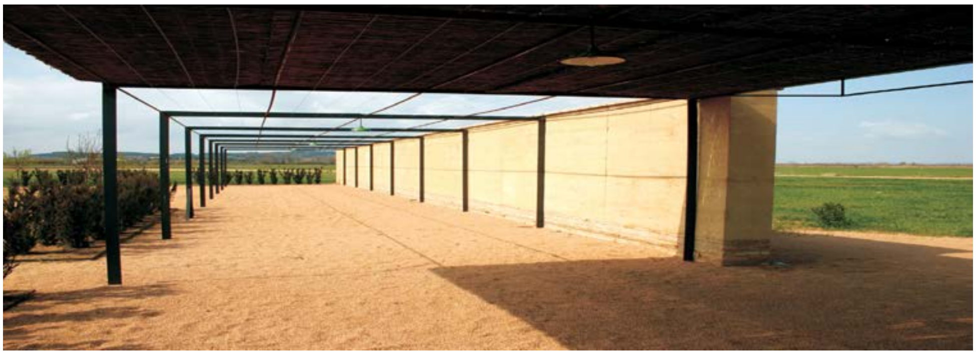


Figure 35: Fontanilles House, garden

Nursery School in Santa Eulalia de Rončana (Barcelona)

This school for children from 0 to 3 years old completed in 2010, was built with compressed earth blocks (CEB) and rammed earth.

Multipurpose salon and dining room, with the surface of 70 m2, have been built with rammed earth walls with 40 cm thickness. The responsible architects for the project were Gabriel Barbeta, Esteban Navarrete, Laura Barbera and Jordi Caminero.

In order to reduce the significant shrinkage of the earth, observed in laboratory tests, wood fibers were added for expanding perlite to improve the thermal insulation and white cement as a stabilizer were applied. The exterior walls are protected with silicone resin, and interior walls with the application of potassium silicate, to improve their response to water action and mechanical erosion [31].

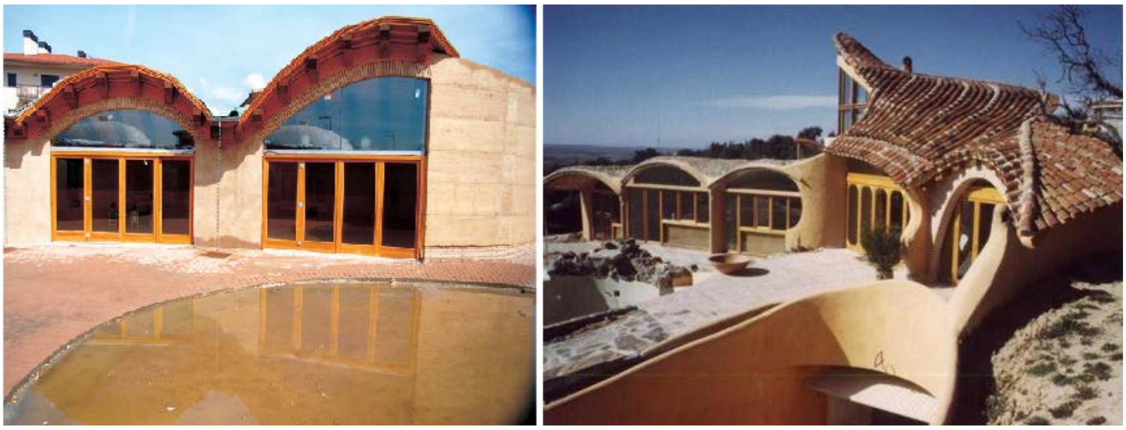


Figure 36: Nursery School in Santa Eulalia de Rončana (Barcelona)

2.11 The cost of rammed earth construction worldwide

The cost of building with rammed earth varies, not only with complexity of design but also with local context. Building with rammed earth is relatively labor intensive. This means it is a cheaper alternative to modern materials in developing nations where wages are low, but comparatively expensive in the industrialized world where mechanization is preferred [22].Also the cost depends on natural soil resources of each individual site. It may vary from perfectly suitable to extreme insufficiency of some rammed earth components. Obviously anything to be imported increases costs, moreover considering that rammed earthworks operate with large material amounts [2].

In Australia, rammed earth constructions tend to be relatively expensive. Luigi Rosselli, an Australian architect known for his work with rammed earth, says the cost of a load-bearing wall built to a high standard with the necessary finishes would be about US$421 per square meter in double brick, $737 in rammed earth, $789 in concrete and $947 in stone[22].

In the UK: Scotland's Central Research Unit undertook a study in 2001, which estimated that there were 500,000 inhabited earth buildings in the UK; earth was the principal material used in Scottish construction until the 18th century. Rowland Keable has extensive experience working with rammed earth in the UK and found that the cost can vary hugely. It begins at zero cost for a self-build community project. In general, he estimates a cost of $250 per sq m for a wall in rammed earth, nearer $790 for double-brick.

In Bangladesh Simple Action for the Environment constructed a rural home from rammed earth in 2011. Each sq foot of wall cost $0.34 to build. It would have cost $0.62 with brickwork.

Stabilized and insulated rammed earth, as offered by construction firm Sirewall, costs 12 per cent more than the stick-frame alternative, according to the company's own figures. A 3,500 sq ft property would cost $1,565,754 to build with Sirewall but $1,375,758 using stick frame, it says [22].

2.12 International standards

This part is a brief overview of current national reference documents and codes for rammed earth from around the world. Structural design regulations for earth buildings are few and generally follow rules developed for masonry construction, often without modification .Over the past fifty years a number of standards and national reference documents have been published in Australia, Germany, New Zealand, Spain, USA and Zimbabwe. Perhaps not surprisingly many of these countries have led the modern revival of rammed earth construction. The combined experience outlined in these national documents expresses the current state-of-the-art in rammed earth construction around the world. At present, the most well-known structural design standard for earth building has been developed in New Zealand _NZS 1998_ [7]. And in terms of

European guidelines, Earth Building UK recently won a European bid to develop shared training standards for rammed earth construction [22].

Australia

Australia was one the earliest countries to develop a national design and construction reference document for adobe, pressed block and rammed earth building, Bulletin 5 (Middleton, 1952).

As of the most recent documents ,The Australian Earth Building Handbook was published by Standards Australia in August 2002.The handbook sets out the principles of accepted good practice and recommended design guidelines for lightly loaded, primarily single and two story buildings, constructed using stabilized and unsterilized unbaked earthen walls and floors. Although this is still an advisory document, it takes the process towards standardization a step further towards a full Standard.

In 2001 the Earth Building Association of Australia published a draft document outlining the organization’s proposed alternative design guidelines for adobe and rammed earth construction (Earth Building Association of Australia, 2001). The proposed draft guidelines include guidance on appropriate materials and methods for evaluation. Design guidance for rammed earth includes footings, damp proof courses, openings; wall slenderness limits, lintels, joints, and recommended details for connections. To date the document remains a draft proposal [5].

It is important to note that neither is specifically written for stabilized rammed earth. The Bulletin 5 does not specify quantitative criteria for the suitability of soils. The two major tests recommended to determine the suitability are the unconfined compressive strength test and the accelerated erosion test. The Handbook 195 specifies grading and plasticity properties of soils suitable for rammed earth, but the maximum gravel size is not specified and appropriate clay types are not mentioned. The circumstances under which cement should be used and the amount of it are not well indicated. HB195 describes in details the experimental procedure to measure strength and durability parameters, but it does not give any indication of values that can be deemed satisfactory [29].

New Zealand

In New Zealand the design of unfired earthen wall building materials (adobe, pressed brick, poured earth and rammed earth), with or without chemical stabilization, is governed by three separate codes published in 1998 by Standards New Zealand:

- __ NZS 4297:1998, New Zealand Standard. Engineering Design of Earth Buildings. Standard New Zealand, Wellington, New Zealand;
- __ NZS 4298:1998, New Zealand Standard. Materials and Workmanship for Earth Buildings. Standard New Zealand, Wellington, New Zealand.
- __ NZS 4299:1998, New Zealand Standard. Earth Buildings Not Requiring Specific Design. Standard New Zealand, Wellington, New Zealand.

NZS 4297:1998 sets out structural design methods for earth walls up to a maximum height of 6.5m (irrespective of thickness). For taller walls more specialized structural engineering advice should be sought. The standard sets the performance criteria for durability, strength, shrinkage and thermal and fire insulation of earth elements. Guidance is provided with regards to ultimate limit and serviceability state design for flexure, with or without axial load, and shear. Finally reinforcement and anchorage details are provided along with details on the requirements for the design of the foundation.

NZS 4299:1998 is limited to earth walls with maximum height of 3.3m or less depending on earthquake zone factor. Buildings designed using this standard should have ground floor plan not exceeding 600m2 for single story buildings or 300m2 per floor for 2 storey buildings. The maximum floor live load should not exceed 1.5kN/m2 with some further minor restrictions regarding the building layout and the foundations also apply. The standard provides standard solutions for the design of walls, structural diaphragms, footings, bond beams and lintels, control joints and openings and fixings. However if any of the conditions stated above is not fulfilled the design should be carried out in accordance with NZS 4297:1998.

NZS 4298:1998 applies to both NZS 4297:1998 and NZS 4299:1998 and sets the requirements for the materials and workmanship when designing earthen elements with soil/cement mixtures less that 15% by weight. The standard provides the general requirements with regards to materials selection and testing, reinforcement and bracing details, control joints, surface finish and quality control. Furthermore, additional requirements relating to the methods of construction are presented [5].

Spain

Earth building in Spain has been used from ancient times. We can find examples in almost all parts of the country, but in the central area it is especially easy to find examples in any small town. Usual systems employed in Spain were adobe and rammed earth walls, followed by wattle and daub walls. Some national and international meetings about earth building have been organized in Spain [16].

In 1992, the Ministry of Transportation and Public Works of Spain published a guidance document for the design and construction of earthen structures (Ministerio de ObrasPúblicas y Transportes, 1992). The document has five main sections and the main focus is on rammed earth, although references and comparisons with adobe techniques are given.

The first section of the document is a general historical account of rammed earth and adobe. Section two is about details the design principles for earth walls, mainly for compression, tension and buckling. The third section examines the construction methods for rammed earth. The formwork used is detailed, the ramming methods demonstrated and the ideal construction sequence is explained. Finally, the construction of earth wall footings and corners is elaborated. The last section provides guidance on quality control measures in order to ensure compliance of the constructed earth walls with the design specifications. The guidance involves information on material testing, additives, reinforcement, formwork and general construction tolerances [5].

Germany

West Germany was one of the first countries in the world to draw up standards for earthen construction. Documents covering earthen construction, including rammed earth, were published between 1947 and 1956 (Houben&Guillaud, 1994).

The LehmbauRegeln was published in 1999. Though lacking the status of a national

DIN standard the LehmbauRegeln provide a national reference document that has subsequently been referenced in the building control regulations of some regional governments. Chapter one sets out the general requirements of earthen construction, while chapter two specifies the types of suitable soil for earth construction and the appropriate selection tests. The third chapter concentrates on describing the various earth wall construction methods (including rammed earth, cob and light straw clay) and materials for the specific application, while the next chapter details the design procedures for each of these methods. In addition, details of the design of vaults, non-load-bearing walls, ceiling joists and rendering are also provided. Chapter five presents some earth properties such as density, thermal insulation, permeability and sound absorption. Chapter six touches upon contractual issues whilst the last chapter presents a glossary of the terns used either within the document or more broadly in earthen construction [5].

Zimbabwe

The Zimbabwe Standard Code of Practice for Rammed Earth Structures was published in 2001 (SAZS 724:2001). Prepared by technical committee the standard however includes additional material, including reference to the accelerated spray erosion test presented in Bulletin 5 (Middleton, 1987) and NZS 4298 (1998).The standard consists of six sections plus appendices. The first section details materials specifications, section two the formwork requirements, and section three the provisions regarding the design of footings for earth buildings. The fourth section details the design of the superstructure with the main focus on the compressive strength, water absorption and weather erosion of the earthen walls, including details for visual inspection. The fifth section concentrates on the structural stability of the walls whilst the final section gives guidance on the detailing and finishes of the earthen elements. Finally, the Appendices include detailed information on material testing [5].

USA

The US State of New Mexico has its own building code for adobe and rammed earth (New Mexico Building Code, 1991). The building code provides some very limited guidance on soil suitability and moisture content, and sets out requirements for formwork, methods of construction, testing and curing of rammed earth [5].

Table 5: Selected standards and regulations and their content [32]

Country	Standards/ Norms	application field	Soil Selection	Product Requirements	Test	Fabrication	Construction	Design
Australia	Bulletin 5,CSIRO 1952	requirements and capabilities of rammed earth construction						
	Standards Australia, 2002	Guidelines for design, construction, maintenance and durability of rammed earth building. quality control	x	x	x	x	X	x
New Zealand	NZS 4297:1998	Structural design and durability of earth buildings.					X	x
	NZS 4298:1998	Characterization of materials and construction specifications for raw soil. Test procedures.	x	x	x	x	X	
	NZS 4299:1999	Design and construction requirements for adobe, compressed blocks or rammed earth that they don't need specific design.					X	x
Spain	UNE 41410	Design and construction of earthen structures and rammed earth building tests.		x	x		X	x
Germany	DIN Lehmbau Regeln 1999	Guidelines for design, rammed earth building tests, specifies the types of suitable soil. Construction methods and materials for the specific application.	x	x	x		X	x
Zimbabwe	SAZS 724:2001	Guidelines for design, construction and rammed earth building tests.	x	x	x		X	x
USA	NMAC 14.7.4,2004	Building Regulations.	x	x	x	x		x
	ASTM E2392 M-10	Guide for building systems with soil.	x		x	x	X	x
India	IS 13827 :1993	Requirements and tests for earth blocks used in construction in general. Tests procedures.		x			X	

3. Recycled Aggregate (RA)

3.1 Introduction

Construction debris resulting from construction and demolition work constitutes a large proportion of solid-waste. For years, landfill sites have been a convenient solution to construction and demolition wastes (CDW) [9].Nowadays, the importance of sustainability is on the rise within the construction industry. As a result, there is an increased consideration of the recycling of construction and demolition waste. This is in line with key environmental policies: waste prevention, material reuse and recycling, energy recovery from waste, saving primary sources and avoiding landfill to the extent possible [9].

The European Union produces approximately 200–300 million tons per year of construction and demolition waste, roughly equivalent to 0.5–1 ton per capita per year [9]. Many European countries and their regional governments have established rules and procedures according to EU guidelines to encourage the reuse of CDW materials in new applications [30].

According to the Spanish Guild of Demolition Waste Recycling Entities (GERD), Spain produced an overall 37.5 million tons of CDW in 2006. In Spanish case, 15 million of CDW (40%) was properly processed at treatment plants. The remaining 22.5 million (60%) were placed in landfill sites. The production of recycled aggregates by treatment plants was 5 million (13.3% recycling rate) [30].

Recycled aggregate from processing construction and demolition waste are mostly composed of concrete, unbound aggregates, ceramic particles and a low amount of other materials considered as impurities. These pollutants were of several kinds, such as asphalt, gypsum, clay, plastic, wood and glass [30].

3.2 Classification

Recycled aggregate, depending on the nature of the original waste, can be classified as: recycled concrete aggregate; recycled ceramic aggregate or mixed recycled aggregate [31].

Recycled concrete aggregate: Arid obtained from crushing and processing waste Portland cement clinker concrete and natural aggregates in recycling plants. The compositional differences can be significant depending on the ratio of residue present in the mortar. It can provide a content of 80% of processed concrete and having a density greater than 2100 Kg/m3 [31].

Recycled ceramic aggregate: Arid obtained from processing waste with predominant presence of ceramic material. 85% of this aggregate should have a density greater than 1600 Kg/m^3 to avoid excessively porous and lightweight materials. Recycled ceramic aggregates have impurities, particularly wood, plaster or glass [31].

Mixed recycled aggregate: Mixed recycled aggregates are those which contain concrete and other recycled stone materials of different nature than concrete, including ceramic material.

As an aggregate it shall contain the percentage of dry concrete higher than 50% with a density greater than 2100 kg/m3 and no more than 50% of different recycled stone materials, including ceramic with the dry density greater than 1600 kg/m3 [31].

It is also possible to characterize recycled aggregate according to their particle size in three groups of: Course aggregate, fine aggregate and graded aggregate.

3.3 Technical regulations

Table 6 shows the different requirements for each control parameter of some international standards. We can see that many regulations have different values depending on the type of recycled aggregate [31].

Table 6: Specifications for recycled aggregates according to different standards

Requirements	Japan			Belgian		Germany				UK		Australia	Spain
	Type 1	Type2	Type 3	GBSB I	GBSB II	Type 1	Type2	Type3	Type4	RCA	RA		
Dry density (kg/m3)	≥2200	≥2200	≥2200	≥1600	≥2100	≥2200	≥2200	≥1800	≥1500			≥2100	
Absorption (%)	≤ 3	≤ 5	≤ 7	≤ 18	≤ 9	≤ 10	≤ 15	≤ 20				≤ 10	≤7
Content material density<2200kg/m^3 (%)					≤ 10								
Content material density<1800kg/m^3 (%)				≤ 10	≤ 1								
Content material density<1000kg/m^3 (%)				≤ 1	≤ 0.5					≤1	≤1		≤1
External material content (metal, glass)%				≤ 1	≤1					≤1	≤1	≤ 2	≤1
Crushing index											≤30		
Organic material content (%)				≤ 0.5	≤ 0.5								
Fines content (<0.063mm) %				≤ 5	≤ 3	≤ 4	≤ 4	≤ 4	≤ 5	≤3			
Lost by cleaning (%)	≤ 1	≤ 1	≤ 1								≤1		
Frost resistance (%)	≤ 12	≤ 12											
Sand content (<4mm) %													≤5
Sulfate content (SO3)%				≤ 1	≤ 1					≤1	≤1		≤0.8
Chloride content (%)				≤ 0.06	≤ 0.06	≤ 0.04	≤ 0.04	≤ 0.15	≤ 0.15				≤0.05
Asphalt content (%)							≤ 1	≤ 1		≤5	≤10		≤1
Ceramic Material content (%)				≤ 100			≤ 30	≤ 80		≤100	≤100		≤5

3.4 Physical properties (Density and absorption)

Particle size influences density and water absorption of aggregates.

Density also depends on the different proportions of materials in recycled aggregate. Smaller fractions present higher density and higher amount of ceramic particles generates lower density [30]. Crushed clay brick decrease the density because of larger porosity. This crushed has a lower density than natural crushed stones [32].

Generally the densities of coarse and fine RA are 2120~2430 kg/m3 and 1970~2140 kg/m3 respectively [32].

Smaller fractions shows lower water absorption and higher amount of ceramic particles present higher water absorption [30].

Absorption shows a major difference between natural and recycled concrete aggregates. Absorption of recycled coarse and fine aggregate may be 7 and 10 times higher than natural coarse and fine aggregate respectively. It is because of low natural aggregate content, rough surface texture with angular particle. Wood chips significantly increased the water absorption of the paving block and waste glass does not have water absorption capacity [32].

3.5 Application

More recently, the interest in using alternative materials such as secondary raw materials or former waste material in construction has grown continuously. Recycling materials allows for higher efficiency throughout the life cycle of materials and is consistent with environmental protection trends. At the end of its life cycle, a material becomes waste, which can then be transformed into a new material to make new products or to be used in structural applications. Effective recycling is using a waste material to produce a new material of similar characteristics, thereby achieving higher efficiency in its life cycle [9].

Recycled aggregates can use as material treated with hydraulic binders in prefabricated concrete, mass concrete and roller compacted concrete [33].

Many researchers have studied how to use recycled aggregates in structural materials, typical current applications of RA include: [9]

- General bulk fill
- Fill in drainage projects
- Sub-base or base material in road construction
- Partial replacement (30%) for natural aggregate in concrete for sidewalks, kerbs and gutters
- Structural concrete (with mix adjustment, inferior permeability and shrinkage properties)

Recycled aggregates have various applications in the area of road construction and road maintenance. Its use is widespread as unbound bases, sub bases, esplanades and fillers; they have been used in more than 16 different types of applications (highways, roads, services, developments, gardens, and other). [33]

It is important to consider that the production process design of recycled aggregates for use in structures, for example, is different from that required by the process for production of recycled aggregates used in solid fillers or for road sub bases. [33]

In this thesis, we will study the incorporation of recycled aggregate with rammed earth to reach a new and better compacted material.

4. Experimental procedure

In this experimental program we used artificial soil with different Recycled Aggregates (RA) replacement percentages endeavors, to examine the effect of varying different size of RA particles on the unconfined compressive strength (UCS) of rammed earth and other characterizations. The overall target is to improve the knowledge of rammed earth structures that incorporate RA and to further the development of future sustainable construction.

Initially we should choose the grading and the particles fractions for our artificial soil from natural aggregate base on the recommendations in state of the art .After finding the optimum moisture content for rammed earth with natural aggregate we start replacing RA in different percentage instead of bigger particles (gravel and sand) in our samples .Therefore, we will have specimen that they don't have any RA and gradually the one that the sand and gravel are replaced completely by RA.

Additionally in RA, we should consider that large particles could result an issues in terms of compaction. Thus, the RA should be sieved and any particles greater than 19mm should be discarded.

4.1. Testing Program

4.1.1 Material used

Natural aggregates

Four kind of natural aggregate with different grading and particle size were used in this testing program. Gravel10/20, gravel4/10, sand 0/4 and sand 0/2 are the natural aggregates from coarser to finer particles respectively. Characteristics of all natural aggregates used in the manufacture of rammed earth are determined in the following table 7 and graph:

Table 7: Grading of natural aggregates used in rammed earth

Sieves UNE-EN 933-2	% weight			
mm	Sand 0-2	Sand 0-4	Gravel 4-10	Gravel 10-20
22,4	100	100	100	100
20	100	100	100	93
16	100	100	100	42,8
12,5	100	100	99,7	12,4
8	100	100	76,4	2,1
5,6	100	99,4	22,0	1,5
4	100	98,4	3,3	-
2	100	83,2	-	-
1	71,3	54,6	0,3	0,9
0,5	37,5	34	-	-
0,25	19,8	20,9	-	-
0,125	9	12,1	-	-
0,063	1,20	5,4	0,1	0,3

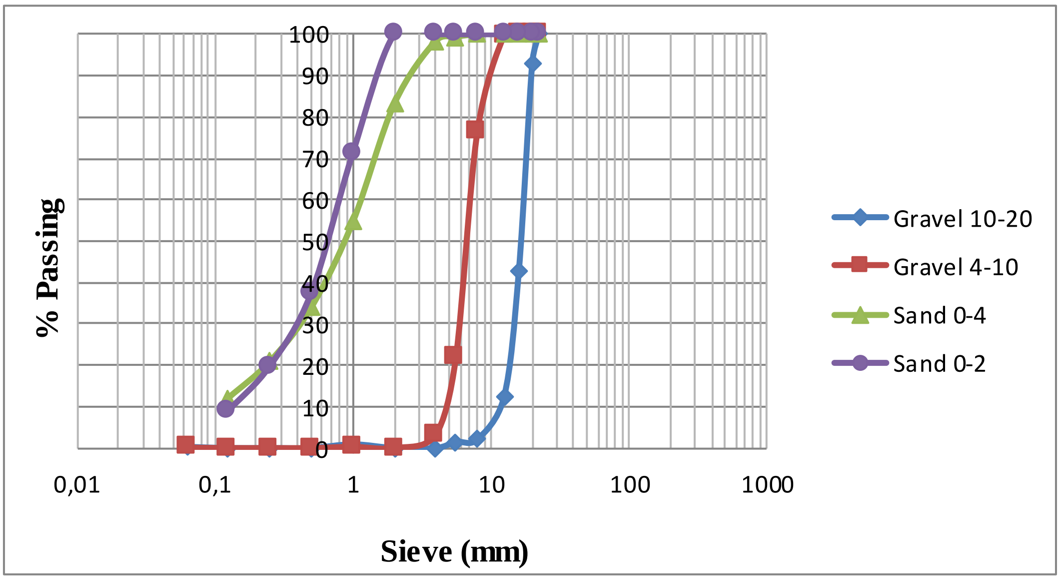


Figure 37: Grading distribution of natural aggregates

In Figure above you can see the particle size curved of natural aggregates used. The particle sizes of all natural aggregates are suitable for using in the manufacture of rammed earth.

In the table below, the physical properties of gravels and sands are shown. However, they may vary each time that we produce rammed earth.

Table 8: Physical properties of natural aggregates

Properties	Gravel 12/20mm	Gravel 5/12mm	Sand 0/5mm	Sand 0/2mm
Apparent density(g/cm3)	2,6	2,69	2,78	
Dry density (g/cm3)	2,61	2,61	2,64	
Saturated density (g/cm3)	2,61	2,61	2,69	2,65
Absorption (%)	0,45	1,3	1,7	0,4

As fine particles we used a mix of silt and clay with physical and chemical properties which is determined in the following tables:

Table 9: Major chemical compounds of the mix of silt and clay

	Percentage (%)
SiO2 total	60,2
Al2O3	14,8
Fe2O3	5,38
CaO	1,65
MgO	1,24
Na2O	1,52
K2O	4,12
Loss on ignition at 1000 ° C	6,54

Table 10: Physical properties of the mix of silt and clay

Liquid limit (LL)	40,1
Plastic limit (PL)	20,6
Plasticity Index (PI)	19,5

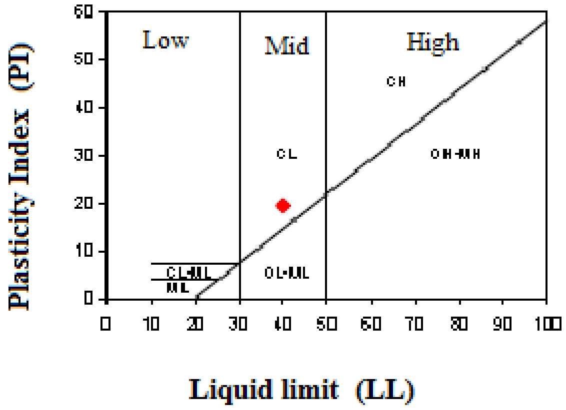


Figure 38: Plasticity graph of fine particles (silt and clay)

Figure 39: Natural aggregates

Recycled aggregates

Three kind of recycled aggregate from two different sites (Les Franqueses, Montoliu) were used in the test: ceramic gravel 5/12.5, ceramic sand 0/5and recycles sand 0/2. As you can observe in the table below two of them are recycled ceramic aggregate. Their properties and component are shown in the table 11. Their defined characteristics are based on corresponded standards.

Table 11: Classification and characterization of recycled aggregate

Properties		Ceramics (%)	Concrete (%)	Natural aggregates (%)	Gypsum (%)	(Other particle glass, wood) etc.)(%)	Fine contents (<0,063mm) (%)	Sand contents (<4mm) (%)	Dry density (kg/m3)	Absorption (%)	Index of slab	Index of Los Angeles
Site		UNE-EN 933-11					EN 933-2	EN 933-1	UNE-EN 1097-6		EN 933 -3	EN 1097-2
Les Franqueses	Sand 0/2mm						6,62		2010	13,1		
Montoliu	Ceramic sand 0/5mm						9,05		1850	16,15		
	Ceramic gravel 5/12,5mm	67	22	10	0,7	0,1	0,85	3	1800	16,45	12	19

Table 12: Grading of recycled aggregates used in rammed earth

Sieves UNE-EN 933-2	% weight		
mm	Sand 0-2 (Les Franqueses)	Ceramic Sand 0-5 (Montoliu)	Ceramic Gravel 5-12,5 (Montoliu)
22,4	100	100	100
20	100	100	100
16	100	100	100
12,5	100	100	91
8	100	100	49,7
5,6	100	99,4	14,8
4	100	84,29	3,4
2	85,22	54,27	1,79
1	58,76	37,65	1,61
0,5	38,72	22,54	1,54
0,25	22,83	11,35	1,45
0,125	11,97	4,12	0,5
0,063	6,90	0,39	0,5

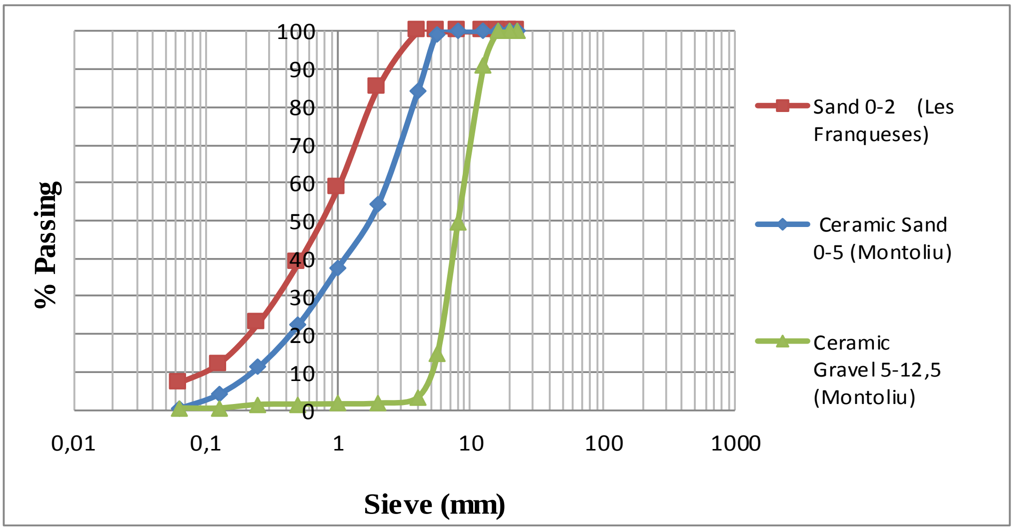


Figure 40: Grading distribution of recycled aggregates

Cement

In the tables below different characteristics of cement, CEM I 42.5 R, used in this experiment are shown.

Table 13: Cement characterization

	Percentage (%)
SiO2	19,16
Al2O3	5,04
Fe2O3	3,56
CaO	62,90
SO3	3,54
MgO	1,66
Na2O	0,15
K2O	0,75
P.F.	3,25
Total	**100**
R.I.	
CaCO3	
CaO free	1,01
Colures	
Sulfurous	
Humidity	0,36

Modules and Components	
L.S.F	101,6
L.C.F	100,0
M.S.	2,23
M.A.	1,42
C3S	61,41
C2S	8,62
C3A	7,33
C4AF	10,82
C4AF+C2F	
CA	
C12A7	
C2F	
AL/Ca	
Fe2O3/Fe3T	
Color	
Na2O equiv.	0,64

Pure Paste	
Mixing water	133
Penet. probe	33
Indicial setting	85
End setting	140
Exp needles	0
Mortar	
Settlement	161
Finesse cement	
Blaine	3462
3µm	
32µm	
45µm	
63µm	
D10	
D50	
D90	

4.1.2 Mix proportions

To determine the effect that the RA has on the compressive strength of rammed earth two testing groups were established. The first testing group has been constructed using artificial soil mixture with only natural aggregate with different densifications, and the second testing group was mixed of different percentage of natural aggregate with recycled aggregate as they shown in table 14.

Table 14: Testing groups

	Batch	Cement %	Gravel 10/20 %	Gravel 4/10mm %	Sand 0/4mm %	Sand 0/2mm %	Clay & Silt %
Natural Aggregate group	N1	5	23	12	39	10	11
	N2	5		35	39	10	11
	N3	5		30	39	10	16
	N4	8		30	39	7	16

	Batch	Cement %	Gravel 4/10mm %	Sand 0/4mm %	Sand 0/2mm %	Clay & Silt %	Recycled ceramic Gravel 5-12,5 (Montoliu) %	Recycled ceramic Sand 0-5 (Montoliu %	Recycled sand 0-2 (Les Franqueses) %
Recycled Aggregate group	R1	8		32	14	16	30		
	R2	5		35	14	16	30		
	R3	8	30			19		29	14
	R4	8		16		19	27	16	14
	R5	8	13,5	16	7	19	13,5	16	7

The first group is with natural aggregate that we have four mixes (N1, N2, and N3and N4) with different dosage percentage.

The applicability of Recycled aggregates (RA) is analyzed in the second group of testing. First, R1 and R2 earth mixtures were produced with 100% of RA in substitution of Natural Graves with 8% and 5% of cement, respectively. The R3 mixture were produced using 100% of Recycled sand in substitution of two different sizes of natural sands. The mixture R4 was produced using 100% of coarse recycled aggregate, 100% of 0/2mm fraction recycled sand and natural sand with 0/4 mm fraction. The last mixture, R5, was produced using 50% of recycled coarse aggregate and 50% of recycled fine aggregate in substitution of natural aggregates. The silt, clay and cement percentages used are shown in the table 14.

4.1.3 Grading

Aggregate grading is defined as relation between size of standard sieve and total amount passing through this sieve. There are different type of ideal curves for optimum grading that worked out on the basis of particles experiments and theatrical calculations like bolomey and fuller curves. The grading curve should follow the equation of Fuller and bolomey to provide good aggregate packing and the best properties.

These curves (fuller and bolomey) normally use for concrete production .however, in this study they used to compare with rammed earth mix grading curves to have an idea to reach the optimum grading .because different studies indicate the importance of a well graded soil for rammed earth to ensure that different particle sizes are packed cohesively and closely in the matrix.

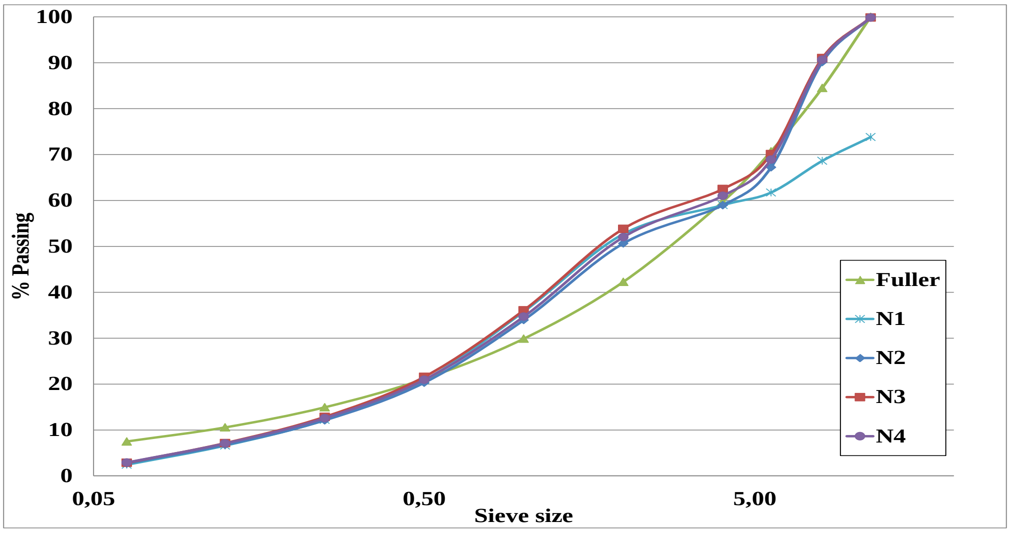


Figure 41: Natural aggregate mix grading comparing with fuller

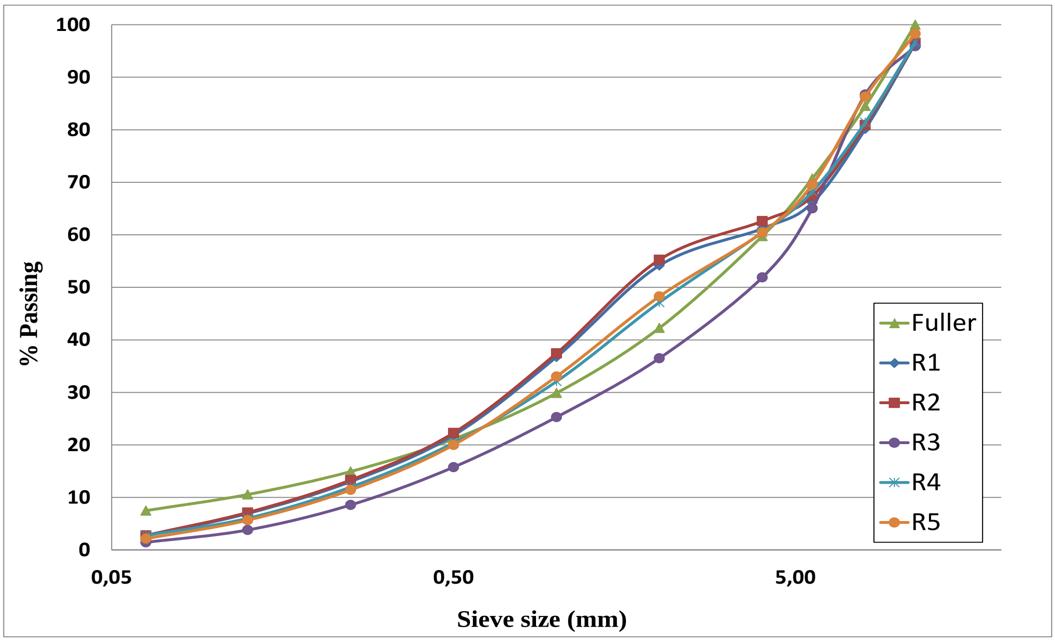


Figure 42: Recycled aggregate mix grading comparing with fuller

4.1.4 Optimum moisture content

Samples were prepared with 6kg mixes for each batch. A 6kg sample was found to be of a sufficient quantity to yield a compacted volume in excess of the cylindrical mould used. All of the batches were cement stabilized. Firstly the dry components were mixed in advance and then the water was added into the mixes gradually.

Cylindrical steel mould with a detachable base plate and collar was used in the laboratory. This mould is with 152mm diameter and of a height of 177mm with the collar and 130 mm without collar (2.35 liter) fitted. The cylinder was oiled and brushed clean prior to ramming, allowing for easier removal.

Figure 43: Cylindrical steel mould with base plate and detachable

The mould, collar and base plate were then assembled and placed on the foundation. Loose, moist soil was placed into the mould in 3 equal layers and compacted with the Bosch jackhammer, it was checked that the compacted height of the sample in the mould is 1/3 of batch high each time.

Upon removing the specimen from the mould, the moisture content was determined. Samples were oven dried in a 101˚C oven until the mass of the sample appeared to be constant. From this, the moisture content and dry density could be obtained.

Figure 44: Samples in oven 101˚C

Table 15: Modified proctor test details

Water added: 7%				Sample weight	
Dosification	Material persantage without water	Material persantage with water	Mass (kg)	Wet	Dry
Sand 0/2 mm	7%	6,51	0,3906	5410,5	5083,6
Sand 0/4 mm	39%	36,27	2,1762		
Grava4/10 mm	30%	27,9	1,674		
Silt & Clay	16%	14,88	0,8928		
Cement	8%	7,44	0,4464		
Water		7	0,42		
Water added: 8%				Sample weight	
Dosification	Material persantage without water	Material persantage with water	Mass	Wet	Dry
Sand 0/2 mm	7%	6,44	0,3864	5526,5	5152,9
Sand 0/4 mm	39%	35,88	2,1528		
Grava4/10 mm	30%	27,6	1,656		
Silt & Clay	16%	14,72	0,8832		
Cement	8%	7,36	0,4416		
Water		8	0,48		
Water added: 8,5%				Sample weight	
Dosification	Material persantage without water	Material persantage with water	Mass	Wet	Dry
Sand 0/2 mm	7%	6,405	0,3843	5469,7	5058,7
Sand 0/4 mm	39%	35,685	2,1411		
Grava4/10 mm	30%	27,45	1,647		
Silt & Clay	16%	14,64	0,8784		
Cement	8%	7,32	0,4392		
Water		8,5	0,51		
Water added: 9%				Sample weight	
Dosification	Material persantage without water	Material persantage with water	Mass	Wet	Dry
Sand 0/2 mm	7%	6,37	0,3822	5427,5	4999,4
Sand 0/4 mm	39%	35,49	2,1294		
Grava4/10 mm	30%	27,3	1,638		
Silt & Clay	16%	14,56	0,8736		
Cement	8%	7,28	0,4368		
Water		9	0,54		

⇩

Table 16: Modified proctor test result

Water added	7	8	8,5	9	
Wet Mass of Soil	5410,5	**5526,5**	5469,7	5427,5	g
Wet Density	2,29	**2,34**	2,32	2,30	kg/dm3
Dry Mass of Soil	5083,6	**5152,9**	5058,7	4999,4	g
Moisture Content	6,43	**7,25**	8,12	8,56	%
Dry Density	2,15	**2,17**	2,13	2,10	kg/dm3

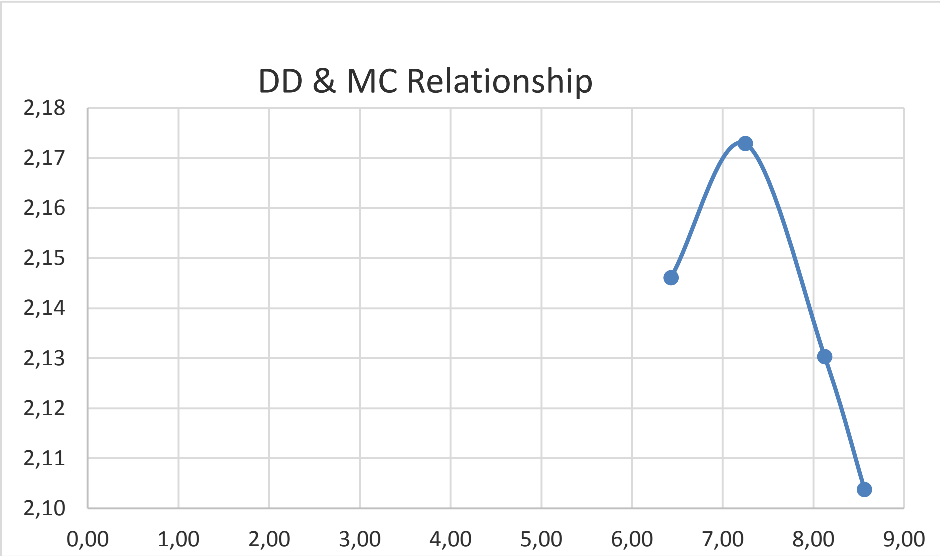


Figure 45: Dry density & moister content relationship curve for finding the OMC

4.1.5 Production process

With the OMC testing, the water content that gave the maximum dry density was determined. However, simply adding this quantity would lead to excessive amounts of water being added to the mix. Thus, the water was added gradually to ensure that the mixture did not become too wet. Walker & Standards Australia (2002) recommends that drop tests be done regularly during mix preparation to determine the optimum moisture content of a soil. The drop test was undertaken by dropping a handful of moist soil from shoulder height, at an arm's length onto firm ground. The manner in which the ball breaks upon impact is used to determine whether the mix is at its OMC. If the soil ball breaks into too many pieces, or disintegrates completely upon impact the moisture content is less than optimum. In the case, that the soil remains flattened in one piece then the moisture content is greater than the optimum amount, or if this result persists for a range of moisture contents, the clay content is too high for rammed earth. If the soil breaks into a few, roughly even sized pieces, the moisture content is considered optimal (Walker & Standards Australia 2002).

Figure 46: Drop Test

Whilst undertaking the drop test some doubt also arose on the applicability of the test for materials with a high RA content. For these batches, it was difficult form the mix into a ball and the appearance of the mix drop from a height did not appear to change significantly with the addition of extra water. This made it difficult to ascertain whether the mix was in fact at its OMC.

For all the rammed earth mixes, this procedure was undertaken on at least four different samples (a,b,c,d in appendix). Water was added in 1 or 0.5 percent increments, so that a range of moisture contents were compacted and weighed. And then for reaching to optimum moisture content it was checked with drop test.

The dry mixes for just one patch were thoroughly mixed in a tray, manually and then a percentage of water was added and then the soil was mixed thoroughly again. However for more speed in filling three batches, all the material were weighted and were mixed in a mixer.

Figure 47: Mixer

Figure 48: Mixing manually

Recycled coarse and fine aggregates have high water absorption capacity and in order to control the absorbed water at production process, the recycled coarse aggregates were used with high moisture content. The recycled fine aggregates were used dried; the water absorbed was added at production process.

Figure 49: Milwaukee Jackhammer and the circular ramming

To undertake the compaction, all samples were rammed using a Milwaukee jackhammer that has a 10kg steel rammer with the electrical potential between 700-900 W. A circular steel plate was used as it suited the sample geometry. All samples were rammed within 20 minutes of the addition of water to the mix, according the (NLT-310/90) standard.

After the ramming it was tried to achieve a flat surface on the top of the samples in the mixes. Upon compaction of the final layer it was found that the aggregates would protrude outwards slightly, leaving an uneven finish on the surface. These protrusions had to be removed, filled with fines and compacted for a small period of time to leave a flat final surface.

Figure 50: Achieving flat surface

The compacted material must be cured properly, thus, all samples were left to cure in a laboratory environment. Samples were dried in plastic bags that were sealed completely.

Figure 51: 3 Specimen of rammed earth with natural aggregate

Figure 52: Specimen with recycled aggregate

4.2. Determination of dry density (Physical properties)

The dry density of each of the samples was determined by weighing each of the samples before they compression test. The volume of the samples was easily determined as the sample heights had been measured using calipers and the diameter was known to be 152mm. With both the mass and volume measurements, the bulk density of each of the samples could be determined.

The density calculated is in fact an estimation based on the mass divided by the volume of the cylinder. This volume does not take into account the presence of the indents on the surface of the cylinder.

Figure 53: Weighting the dry sample before compression

4.3 Compression tests (Mechanical properties)

It was decided to do the compression test for two samples in 7 days and for other two after 28 days .Unconfined compression tests were conducted in the Laboratory using the compression machine with a loading capacity of 3000 kN.

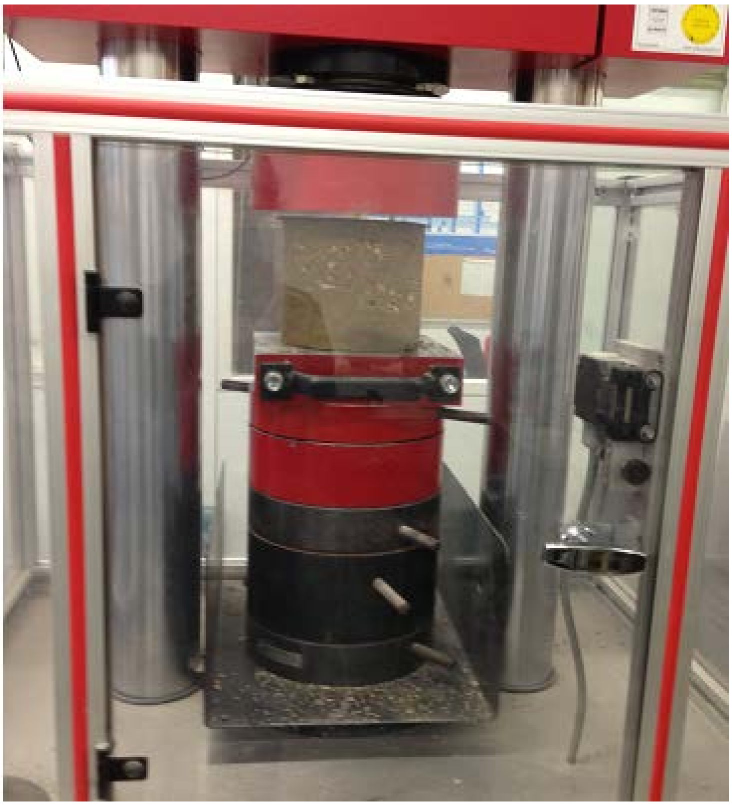


Figure 54: Compression machine with a loading capacity of 3000

4.4. Linear shrinkage test

The shrinkage strain was the parameter which obtained from the experimental program on two different groups of soil, one is the artificial soil with natural aggregate (N4), and the other one is recycled aggregate mix with the highest amount of RA (R4).

Figure 55: The long mould for linear

This test is prepared according to the procedure of the disturbed soil preparation samples, for testing initially the mixtures were prepared and mixed by the mixer machine and then 18% of water was added to the mix until the mass becomes a thick homogeneous paste.

Two steel moulds which has 60 cm length, 15 cm height and width (60x15x15), were cleaned and oiled inside for using in this test. Then the mixes with so much plasticity were poured to the moulds. All air bubbles were removed from each sample by lightly tapping the base of the mould, slightly overfill the mould and then level off the excess material with the spatula, at the end all soil adhering to the rim of the mould was removed.

The specimens were allowed to dry at laboratory temperature for about one week.

Figure 56: Linear shrinkage test samples in the first day

Figure 57: Linear shrinkage test samples after one week

For calculating the linear shrinkage percentage the following formula was used:

$$LS(\%) = \frac{L_s}{L} x\, 100$$

Where:

L = Length of the mould (mm)

Ls = Longitudinal shrinkage of the specimen (mm)

5. Analysis of results and Discussion

The results and analysis of the experiments are presented in this chapter. Firstly the summery of average result is presented in the table (the details of this experiment results are shown in appendix), followed by the graphs and discussions about the results of OMC, dry density and unconfined compressive strength. Then the result of linear shrinkage test is presented and at the end the sample characteristic is analyzed.

Table 17: Summary of results (Average value)

	Batch	Cement %	OMC %	Dry density (kg/m3)		USC (Mpa)	
				7 Days	28 Days	7 Days	28 Days
Natural Aggregate	N1	5	6,5	2,35	2,3	5,63	8
	N2	5	6,5	2,37	2,32	4,99	7,37
	N3	5	7	2,27	2,19	5,67	7,02
	N4	8	7,5	2,29	2,23	5,9	9,03
Recycled Aggregate	R1	8	8	2,18	2,04	5,2	8,22
	R2	5	7	2,17	2	4,15	5,43
	R3	8	6	2,08	1,99	4,89	6,74
	R4	8	6	2,01	1,90	4,15	7,29
	R5	8	7	2,11	2,01	4,78	6,98

5.1 Maximum dry density and OMC and water content

The dry density of each sample was estimated. The density is estimated based on the mass divided by the volume of the cylinder (Appendix). It can be seen that there is some variation in the densities of samples within the same batch (a,b,c,d in appendix). The density of the sample will depend on the compaction effort applied and the relative proportions of the materials.

The effect of the RA content on the density of the rammed earth samples can be ascertained more clearly, when the average density for each batch is determined (table 17).In RA mixes increases, dry density (MDD) is lower than NA mixes. This is because the RA used in the mixes had lower density than the natural aggregates. Also it is normal that dry density of 28 days samples be lower than 7days samples because of losing more water.

Also in can observe in table 17 that in rammed earth mixes with RA the dry density is lower when fine recycled aggregates (sands) is used in the mixes rather than when coarser recycled aggregate (gravel)is consumed.

For both the natural aggregate mixes and RA mixes, the OMC increased by incrementing of the cement percentage. This is because the specific surface of cement is higher; consequently the adsorbed water by cement is also higher.

The less moisture content could be due to evaporation of water in the mixing stages. Conversely, in the case that the moisture content is greater than that added, it shows that the materials in the mix had some existing water content.

5.2 Unconfined compressive strength

It is clear that the presence of RA does not have negative affect on the strength of rammed earth. All samples in this study have a UCS greater than 2 MPa which is the minimum strength. Thus all mixes can be used in rammed earth construction. Moreover, it can be seen that there is some variation in the UCS of samples within the same batch (appendix).

In testing groups, the strengths ranged from maximum of 9.03 MPa (sample N4) to minimum of 5.43 MPa (sample R2).

N4 is the only mix of natural aggregates with 8 % of cement which has the lowest strength growths within 7 days. Nevertheless, it reaches to the highest strength after 28 days.

R1 has the highest USC among the other recycled aggregate mixes that could be because of its good grading and enough fine particles.

R2 is the only mix in recycled aggregates with 5 % of cement which has the lowest USC in 28 days (5.43 Mpa) However, it has reached to its highest percentage of USC increment in 7 days compared to the other recycled aggregates samples (figure 59) .

R4 with USC of 7.29 has the biggest strength increment from 7 days to 28 days with the highest percentage of recycled aggregate.

As result we can get to this point that the higher percentage of cements Leeds to slower growth of strength. Also, the rise of compressive strength from 7 days to 28 days was fairly higher in rammed earth produced with recycled aggregates, except when the recycled aggregates had a high amount of ceramics as their component (R4 with 46% of recycled ceramic aggregates).

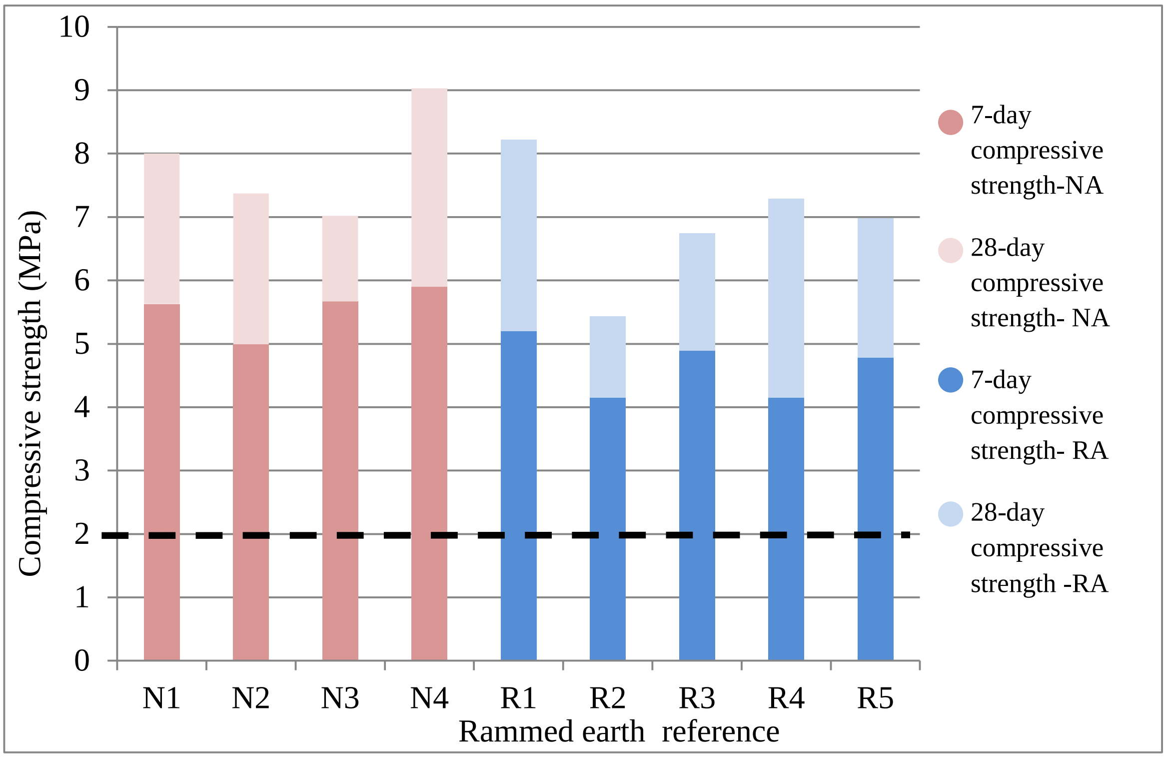


Figure 58: Compressive strength t of rammed earth groups

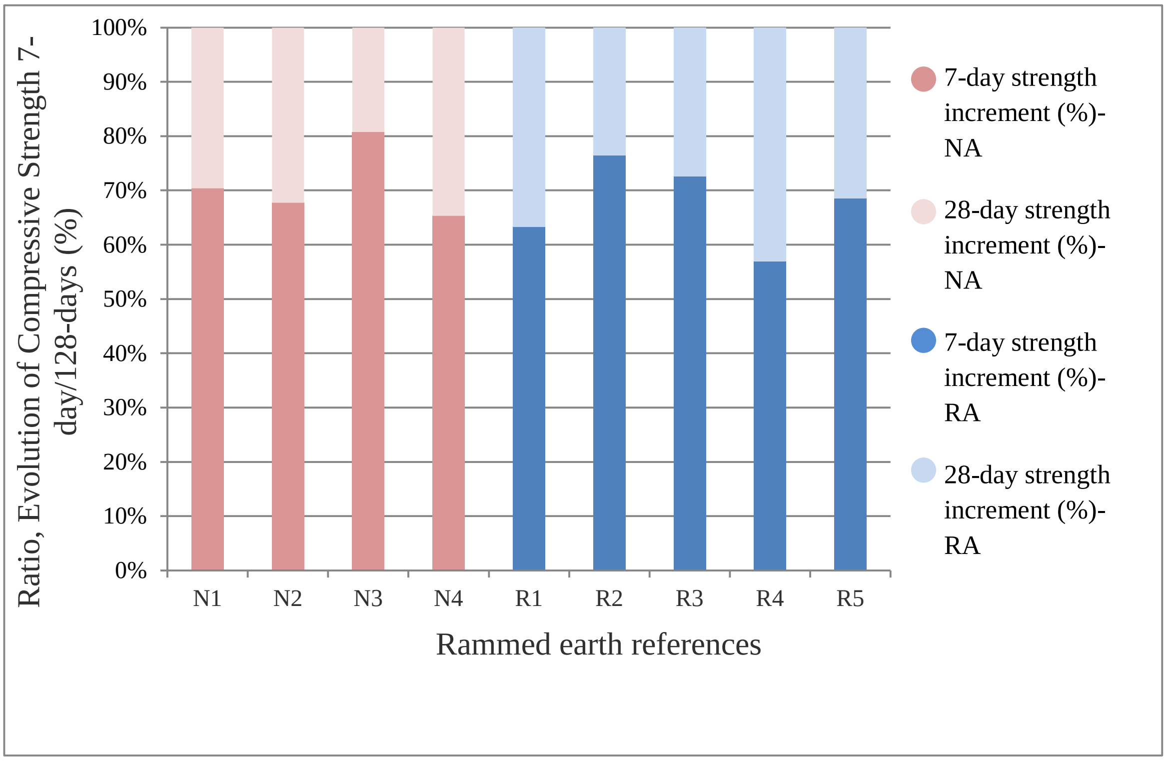


Figure 59: Comparison between the strength increments of rammed earth groups from 7 day to 28

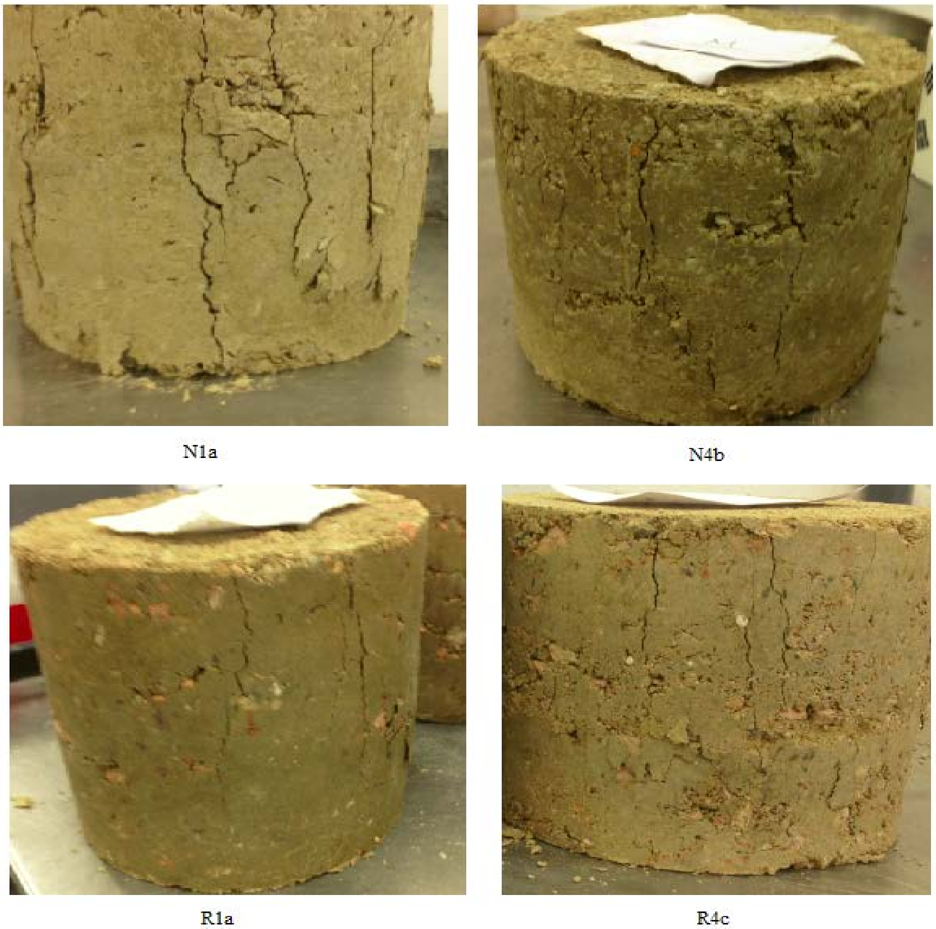


Figure 60: Some samples after compressive strength test. Natural aggregate samples (Top), Recycled aggregate samples (Bottom)

5.2.1 Correlation between density and strength

In rammed earth, density is thought to be linked to strength and durability properties [14]. Densification (by ramming) brings the particles of the soil into more intimate contact. Therefore, achieving high densities will generally provide high frictional strength in rammed earth, although the two variables are not perfectly related [12]. Whilst the calculated densities may be somewhat inaccurate due to the uneven texture of the cylindrical sample.

5.2.2 Effect of particles size on strength

One factor that should be considered in the analysis, is the effect that incorporating RA on the particle size distribution of the mix. Particle size grading was compared by the ideal curve of fuller in (section 4.1.3).

The recycled ceramic aggregates (table 12) used for this experiment consisted of larger particles in comparison with NA (table 7). When the percentages of large particles increase in the mixes, the samples appear to have more voids .The presence of these voids on the surface of the sample is because of fewer fines in mesh between the larger particles.

In fact, in rammed earth construction some researchers have recommended that any material coarser than 5-10mm be sieved out. Previous experimental work has also indicated that increasing gravel size reduces the compressive strength of rammed earth cylinders. The presence of larger particles, without fines is detrimental. It is important to minimize the voids ratio in order to increase the contact between soil particles.

On the other hand, a recent the study in Basque Country (Northern Spain) [34], shows that the ceramic fraction in recycled aggregates generate greater amounts of ceramic fines which has a favorable effect on the process of consolidation of the granular material because, in the presence of water, fine particles of a ceramic nature induce pozzolanic reactions .

According to the very recent study [35], the recycled fine aggregates modify the fresh and hardened concrete properties due to their high absorption capacity. This could be true also for rammed earth.

5.2.3 Effect of contaminants on strength

As the material is recycled, the foreign items could be incorporated into the mix and this could potentially have a great effect on the strength of the samples. As the RA content increases, the likelihood of introducing contaminants into the rammed earth mix also increases. In the RA, foreign matter such as wood chips, glass and gypsum was existed in a very small amount within the aggregates (Refer to table 11). Although utmost care was taken in the preparation and sorting of the RA, all foreign material was not removed.

The presence of contaminants is detrimental to rammed earth as soil homogeneity is important in rammed earth construction for structural integrity [5]. Organic material interferes with action of cement stabilization. This may result in the sample failing at lower strengths. Furthermore, soil homogeneity is important in rammed earth construction in order to ensure minimum localized failure [5].

However as it is shown in table 11 contaminations in the RA used in this test were low and there was a good adherence between the particles of RA with NA and cement in the mix (figure 61).

Figure 61: Adherence between particles

5.3 Linear shrinkage results

The table below indicates linear shrinkage with acceptable results, because the shrinkage in both mixes (natural and recycled aggregate mixes) is less than 0.6%.As it was mentioned before in the state of art it is recommendable to use the soil for rammed earth with the shrinkage less than 0.6% [17] (section 2.5). However, it can observe that the linear shrinkage in the mix with recycled aggregates is bigger.

Table 18: Linear shrinkage test results

	L (cm)	Ls (cm)	LS (%)
N	60	0,2	0,33
R	60	0,25	0,42

Figure 62: Linear shrinkage test samples after 28 days. RA sample (left), NA sample (right)

5.4 Sample characteristics

The RA added to the mix has a clear effect on the appearance of the samples .In rammed earth construction the colour and texture of the rammed earth is depend on the earth and aggregate used in the mix. In the samples with RA content, a significant number of indents can be seen on the surface in the sample.

On the rammed earth samples with NA, the surface is smoother.

Figure 63: Recycled aggregate Sample

Figure 64: Natural aggregate sample

6. Conclusion

Despite the major amount of studies published in the last 60 years, the current knowledge and understanding of rammed earth material properties and design procedures are still far less than other civil engineering materials like steel, concrete and timber.

Lack of professional experience in designing and building with earth, cause several objective aspects like: Inconsistent materials nature, moisture sensitivity, possible shrinkage and cracking and construction may be slow and expensive.

Rammed earth building technology need to be reconsidered in a way to increase construction speed and to be cost effective.

Due to the shortage of natural resources, increasing demand for raw materials, and problems caused by construction and demolition waste sites, investigating new applications for recycled aggregates has become a major field of study in civil engineering. The use of RA in rammed earth highly contributes to the goals of sustainability as it discussed above, aiding with the conservation of resources through recycling and reducing the consumption of raw materials. By improving sustainability, the cost and negative impact of current consumption on future society is significantly reduced.

The results of unconfined compressive tests in this experiment indicate that rammed earth mixes with RA have acceptable strength. In this study, all batches have strengths exceeding 2 MPa and thus can be used in rammed earth construction.

The addition of RA in this study does not lead into a decrease in characteristic UCS, and in general, they did not show a very lower strength than rammed earth with natural aggregates, especially when the coarser natural aggregate (gravel) replaced by coarse recycled aggregates.

In rammed earth mixes with RA the dry density is lower when fine recycled aggregates is used in the mixes rather than when coarser recycled aggregate is consumed.

Most likely, the material strength is related closely to the grading of the mix. This study emphasizes that, for rammed earth, a well-graded soil is essential to ensure that particles are packed cohesively and closely in the matrix.

However, the strength also is very much dependent on the quality and characteristics of the RA (which will vary from site to site), and the contaminations content that they may have. Testing is essential to determine if mixes incorporating the recycled aggregates are adequate. In this study the RA used wet and saturated.

Finally in this study, although the linear shrinkage of recycled aggregate mix was higher than natural aggregate mix, the results were approving the recommendations and were acceptable.

6.1 Recommendation for future researches

Some doubts and problems in the study may be attributed to the lack of recognized standards and codes of practice in many countries. The lack of standards and codes of practice limits the further development and wider use of earthen construction [5].

The experiments carried out emphasized issues regarding the addition of the optimum water content into the mixes. Whilst the OMC can be determined in the lab using the Modified Proctor Test and can be adjusted to account for the cement reaction, during the construction process we used drop test to ensure that the correct amount of water was added to the mix. However, the applicability of the standard drop test is questionable.

The experiments conducted also highlighted issues regarding sample preparation for unconfined compressive tests. Ensuring the smooth and level sample ends required for the tests was difficult to achieve. In future studies it is essential that an effort be made to ensure that there are sufficient fines both in the first and last compaction layer. This will guarantee that sample ends are smooth and level as the fines can mesh in between the larger particles so that there are no indents or protrusions on the sample ends.

It is also recommended that, due to the inherent variability associated with recycled materials, 5 cylinders be tested rather than 4, allowing for a greater range of results. A greater number of samples will increase the ease with which outliers (that exhibit much higher or lower strengths) can be identified.

During the compaction, the jack hammer was fixed and immovable .Therefore, some parts of samples were not compacted adequately. This problem should be solve for next studies with the movable hammer

Also it is recommended to do the compression test for some samples after 2 months, because there are some studies which indicate that the rammed earth reaches to its highest strength after 60 days.

In regards to rammed earth incorporating RA, this study focused in most part on the effect that RA has on the compressive strength and shrinkage of rammed earth. The effect of RA on other properties of rammed earth should also be examined. Other properties such as durability, erosion resistance and thermal conductivity may be affected by the addition of RA.

Appendix

	Batch	OMC %	Wet mass (gr)	Dry mass (gr)	Water content %	Wet density (kg/m3)	Dry density (kg/m3)
Natural Aggregate	N1a	6,5	5629,2	5511,3	2,14	2,39	2,34
	N1b	6,5	5610,3	5581,4	0,52	2,38	2,37
	N1c	6,5	5669,4	5400,8	4,97	2,40	2,29
	N1d	6,5	5649,3	5439,9	3,85	2,39	2,31
	N2a	6,5	5683,5	5600	1,49	2,41	2,37
	N2b	6,5	5519,8	5478,2	0,76	2,34	2,32
	N3a	7	5430,9	5318,2	2,12	2,30	2,25
	N3b	7	5497,1	5392,4	1,94	2,33	2,29
	N3c	7	5414,1	5187	4,38	2,30	2,20
	N3d	7	5369	5137,1	4,51	2,28	2,18
	N4a	7,5	5482	5395,2	1,61	2,32	2,29
	N4b	7,5	5455,4	5394,3	1,13	2,31	2,29
	N4c	7,5	5431,5	5269,3	3,08	2,30	2,23
	N4d	7,5	5437,3	5276,3	3,05	2,30	2,24
Recycled Aggregate	R1a	8	5170,4	5137,3	0,64	2,19	2,18
	R1b	8	5201,7	5147,2	1,06	2,21	2,18
	R1c	8	5097	4795,7	6,28	2,16	2,03
	R1d	8	5105,2	4860	5,05	2,16	2,06
	R2a	7	5140,7	5116,9	0,47	2,18	2,17
	R2b	7	5191,7	5110	1,60	2,20	2,17
	R2c	7	4957,3	4695,8	5,57	2,10	1,99
	R2d	7	5054,7	4744,3	6,54	2,14	2,01
	R3a	6	5009,9	4908,8	2,06	2,12	2,08
	R3b	6	5079,3	4918,5	3,27	2,15	2,09
	R3c	6	5024,2	4716	6,54	2,13	2,00
	R3d	6	4985,6	4663,1	6,92	2,11	1,98
	R4a	6	4794,6	4676,4	2,53	2,03	1,98
	R4b	6	4928,6	4826,4	2,12	2,09	2,05
	R4c	6	4899,5	4539,3	7,94	2,08	1,92
	R4d	6	4821,5	4467,5	7,92	2,04	1,89
	R5a	7	5058,6	4891,7	3,41	2,14	2,07
	R5b	7	5184,8	5065,5	2,36	2,20	2,15
	R5c	7	5047,7	4823,4	4,65	2,14	2,04
	R5d	7	5017,7	4687,5	7,04	2,13	1,99

		Days before compression	USC (Mpa)
Natural Aggregate	N1a	7	6,53
	N1b	7	4,73
	N1c	28	8,72
	N1d	28	7,28
	N2a	7	4,99
	N2b	28	7,37
	N3a	7	5,49
	N3b	7	5,86
	N3c	28	7,16
	N3d	28	6,89
	N4a	7	6,24
	N4b	7	5,56
	N4c	28	9,83
	N4d	28	8,24
Recycled Aggregate	R1a	7	5,4
	R1b	7	5
	R1c	28	9,41
	R1d	28	7,04
	R2a	7	4,34
	R2b	7	3,96
	R2c	28	5,19
	R2d	28	5,67
	R3a	7	5,22
	R3b	7	4,56
	R3c	28	7,21
	R3d	28	6,27
	R4a	7	4
	R4b	7	4,31
	R4c	28	7,1
	R4d	28	7,48
	R5a	7	4,4
	R5b	7	5,16
	R5c	28	7,6
	R5d	28	6,37

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