Performance Assessment of Alternative Composite Earth Wall Panels

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(Abstract)

The American Society of Heating, Refrigerating and Air conditioning Engineers suggests that the building sector represents over 30 percent of our national energy consumption (Parsons, R., 2001). Embodied energy in components of building construction can represent as much as five to ten years of operating energy. Building materials such as concrete, steel and glass require significant amounts of energy for production, and therefore are important when calculating embodied energy in buildings (Keable, 2007; Rypkema, 2007). Because of the relatively large area and volume of related components, the building enclosure system represents a major factor when calculating embodied energy. Alternative materials could be incorporated by adapting traditional and vernacular building approaches to today's standards, for example, compressing soil blocks for use as external walls in buildings that can be applicable to almost any climate including rainforests and cold climates. As an alternative to high-embodied energy materials used for enclosure systems, compacted earth-based enclosure systems may be a viable option, particularly if developed and applied as a pre-manufactured modular system. This study seeks to both quantitatively and qualitatively explore the potential development of earth-based building curtain wall systems. Using modified ASTM test protocols for building enclosure systems and components, alternative earth-based panels were compared. The results suggest that earth-based panels may be a viable option for curtain wall systems but its performance is highly dependent on the composition of the panels. The results of the tests are summarized.

Dedications

To my dearest friend *Minal, and my family*

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I would like to formally thank:

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Chapter 1.0: Introduction

1.1 Background

Energy consuming activities, such as driving or industrial manufacturing, typically rely on fossil fuels and are major sources of greenhouse gas emissions. One of the largest sources of greenhouse gas emissions and energy consumption in the US and around the globe is building. Architects must recognize that it is of utmost importance to address and be aware of energy flow in buildings from the initial phase of design. Construction and maintenance of buildings account for nearly half of all the greenhouse gas emissions and energy consumed in the US each year. Globally, the percentage is even greater, and architects can play a significant role in turning down the global thermostat. With about 5 billion square feet of new construction and 5 billion square feet of renovation taking place in the U.S. each year, the potential for reducing energy consumption and carbon dioxide emissions is enormous (U.S.EPA, 2009). Buildings can be designed to require less than half the energy of today's average U.S. building, with no additional cost (Mazria, E., 2004). One of the ways to accomplish this is by optimizing material selection and its efficient use. The embodied energy of construction can be equal to ten years or more of building use and operation and consequently architects should not only be concerned with energy efficiency but also with the energy contained in the construction of buildings (Milne, G., & Reardon, Chris. 2010).

1.1.1 Embodied energy

Embodied energy can be defined as the energy consumed during the construction and production of a building, for example, acquiring natural resources for building products. It includes mining, manufacturing materials and equipment, transportation of materials and administrative functions. Research shows that Embodied energy can be equivalent to many years of operational energy (Rypkema, D. D, 2007). Materials used for building have unseen adverse environmental impacts. The impacts can be examined using the Life cycle assessment (LCA) approach. LCA evaluates the environmental impact of material or product through every step of its life, from acquiring raw materials to manufacture, transport, storage, installation, maintenance, disposal or recycling. LCA can generate results for resource depletion, energy and water use, greenhouse emissions and waste generation (Milne, G., & Reardon, Chris. 2010). Construction techniques and materials should be developed in such a way that they have low embodied energy and can be reused or recycled rather than discarded to the landfill (Rael, R. 2000; habitat.org, 2011).

1.1.2 Rammed earth

Rammed earth construction is a process of compressing a damp mixture that is composed of suitable proportions of sand, gravel and clay (sometimes with an added stabilizer). Rammed earth structures are beneficial for building because they can utilize locally available materials with little embodied energy and no harmful waste (Boyer, L. L., 1982; Kapfinger, O., 2001).

Some of the benefits of using rammed earth construction are as follows:

Earthen walls act as good thermal mass (Bengtsson, L. P., and Whitaker, J. H., 1986), offering extra protection from the natural elements; it is also associated with additional energy savings, along with providing substantial privacy. The USDA observed that rammed earth structures last indefinitely and could be built for no more than two-thirds the cost of standard frame houses. It is also affordable to build with, as the materials are inexpensive or free (M. C. Betts, and T. A. H. Miller, 1937). Termites don't infest rammed earth walls; the material is reusable and biodegradable. Furthermore, the reduction of air infiltration within an earth shelter can be highly profitable (Boyer, L. L., 1982).

Rammed earth construction can have potential problems related to the following:

The Rammed Earth panel can have water seepage problems, internal condensation, bad acoustics, and poor indoor air quality. The quality of the final product cannot be completely predicted. The method of construction is labor intensive and may require special equipment and craftsman. Earth sheltering is heavier construction than conventional building techniques, and many construction companies have limited or no experience with earth sheltered construction. Comprehensive compaction of the surface is necessary or the weaker portions of construction can sag causing uneven settlements. This flaw is prominently evident both visually as well as structurally (Cassell, Robert O, 2001; M. C. Betts, and T. A. H. Miller, 1937).

1.1.3 Prefabricated panelized wall systems

Manufacturers are reinventing the process of building construction using assembly line automation and prefabricated panels made from a wide variety of materials. The installed panels form a structural envelope that eliminates the need for conventional framing, provides integral insulation, and can be assembled swiftly with lesser skilled laborers. These advantages have spurred production and the introduction of a thermally efficient structural method of light construction to a broad market. Rammed earth wall construction systems have a few drawbacks when compared to panelized wall systems (Toro, W. M., et al. 2007; NAHBRC. 2005).

Table 1.1: The Table describes the distinction in properties between the panelized systems versus the Rammed earth wall construction system (NAHBRC., 2005)

Panelized wall system	**Rammed earth wall construction**
Variety of materials can be incorporated into the panel systems	It is self-standing, thus requiring materials with sufficient mass and density.
The panels are lightweight, and can be designed to resist earthquakes, high wind pressures, debris impact, moisture, and insect infestation.	Rammed earth is a heavy weight construction; it needs structural bearing to resist earthquakes, high winds, and the impacts of weathering vary with materials.
Insulated panels provide better overall air tightness and thermal performance.	Provides better thermal performance, problems with poor indoor air quality and infiltration.
Panels can be produced in an automated factory environment, using computer-controlled equipment that transfers panel-cutting instructions directly from digital CAD (computer aided design) drawings. The resulting components are precisely engineered and easy to inspect for quality control. Once the panels are shipped to the jobsite, they can be quickly assembled, speeding the onsite construction nedule and allowing homes to be placed under roof more quickly.	Construction is labor intensive and may require special equipment and skilled craftsman.
The fixing mechanism of the panel onto the framework is so simple that it can be easily replaced.	Aging causes failure of the structure. It is difficult to get the same finish when repairing portions of a wall. Regular maintenance is necessary throughout the lifespan of the structure.
Panelized wall systems are available in standardized sizes and thickness.	They have to be built up as per structural and material specifications. Thus, precise sizing is difficult.

Given the environmental benefits of earth construction and the advantages of panelized systems, the intention of this research is to explore the development and application of an earth-based wall panel system. Depending on the behavior of the independent variable binders, it can be suggested that earth can be used in combination with other recyclables to form an efficient external wall panel comprising most of the advantages of the latest panelized wall system such as fiber cement siding (Smith, T., 2002).

1.2 Problem statement

Based on the initial review of rammed earth systems as an alternative composite wall panel, some problems are identified:

- Is it possible to build sustainable, exterior earth wall panels?

The current data available on rammed earth construction is limited to only building load bearing walls, and there is limited research based on using rammed earth for building external wall panels.

- Can binding agents such as clay and cellulose based binding agents or recyclable material such as fly ash provide similar or better stabilizing properties as compared to cement?

The information that is available is limited to some known stabilizers that are associated with high-embodied energy, and non-renewable materials such as cement.

- Is it possible to build a renewable composite panel having lower embodied energy as compared to cement stabilized earth panels?

Earth has not been explored as much as cement for building construction.

- Can an earth panel fulfill all or most of the performance criteria required for weathering, durability, while being aesthetically appealing?
- Can the earth panel resist higher loads compared to cement-stabilized panel?
- Can the earth panel sustain high humidity conditions?
- Does the earth panel require lower effort to build when compared with cement stabilized earth panels?

1.3 Hypotheses

Renewable composite earth wall panel composed of binders such as clay, cellulose-based adhesives and fly ash perform better than cement stabilized earth panel in terms of durability, aesthetically as well as fulfilling most of the weatherability issues (chelseabuildingproducts.com, 2011).

1.4 Research objectives

The research was conducted to fulfill the objectives given below:

- To adapt traditional and vernacular building approaches to today's standard.
- To observe its performance with respect to weather cycling, durability, and issues related to moisture ingress, expansion and contraction.
- To understand the properties and characteristics of an increasing number of materials including rammed earth or clay, cellulose-based adhesives and fly ash.

This research project is a feasibility study of composite earth wall panels. The research addresses the problems observed while building earth panel and to test their performance in comparison to cement stabilized rammed earth panel. The earth panel was designed to be rapidly renewable. The incorporation of this panel within the existing building system is achieved by substituting products. The system or processes involved in installation will remain unaffected.

1.5 Assumptions considered for the preparation of a typical test panel

The research employs an experimental set of procedures grounded on a set of underlying assumptions that include the following.

1.5.1 Assumptions for justification of proposal for application of renewable composite panel

A few assumptions as mentioned below were made with respect to the application of the proposed panel required for the justification for applicability of the composite panel; this would also help narrow the scope of the research.

- Accommodate installation of the proposed panels in areas belonging to third world nations where labor is relatively unskilled and affordable, and the panel building process and installation could be easily adopted with minimal effort.
- Accommodate installation of the panel in places with weather conditions favorable for earth construction, such as in places having hot and dry climates. Earth construction is prevalent in places like Spain, deserts of Iran and Iraq, and third world nations like those in Africa and South East Asian countries (Boyer, L. L., 1982; Maniatidis, V., and Walker, P., 2003).
- Design modular panels that they can be easily mass-produced.
- Conduct the research using experimental test procedures adapted from the American Society for Testing and Materials (ASTM) standards.
- Establish research results and findings from the preparation procedure and tests conducted on the panels were with respect to qualitative analysis.
- Treat the panels tested in the research as a representation of typical panelized systems.

1.5.2 Assumptions associated with findings and results

The test procedures were based on the following considerations.

The panels are usually tested using the American Society for Testing and Materials (ASTM) test standards, but due to lack of funds and equipment the panels were tested using available equipments by applying selected procedures from the ASTM standard. It is assumed that if the panel is successful using these modified procedures then further detailed research would be carried out using the actual ASTM procedures as a future research possibility.

The adapted test procedures evaluate the following performance criteria:

1. Crumble test
2. Scratch test
3. Test for sustainability of Natural binders
4. Load test
5. Weight test

6. Water pressure test

The Jar Test on the sample of dry earth used for this study was conducted to determine the proportions of sand, gravel, and clay/silt present in the soil composition and was assumed to be similar for all panels.

1.6 Limitations of the research

The scope of building and testing the composite earth wall panels was limited due to a few constraints that are described below:

Only one sample associated with each variable was built and tested. This was due to a lack of mechanical compaction tools and time constraints. The earth was gathered from excavated land on a local construction site instead of using preprocessed earth from sources such as local brick manufacturers. The size of the panel was fixed. All of the panels were 1feet x 1feet cross-sectional dimension and 1 ½ inch thickness. The panels were air-dried and could not be heated at controlled temperatures due to the constraint of one sample for each variable. The panels were naturally air-dried and there were no fixed controls to measure temperature difference or humidity levels of the air. The panels were not tested to address issues related to fire resistance, freeze and thaw, or issues related to capillary suction of moisture.

Thus, the primary motivation in conducting this research project was to introduce an exploratory investigation of the feasibility of composite rammed earth panel in contemporary building construction.

1.7 The research method

The organization of the thesis is based on the following procedural flow chart:

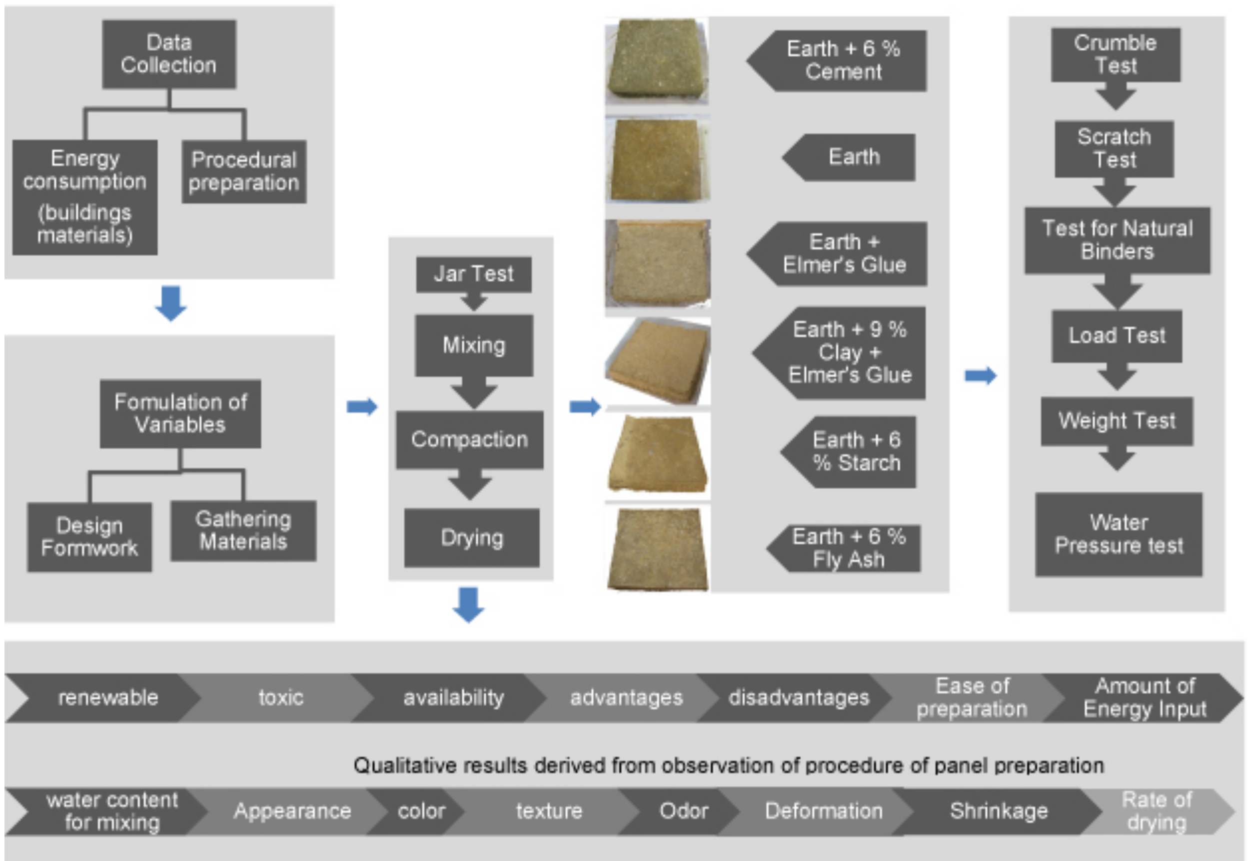


Figure 1: Flow chart defining the research organization

Chapter 2.0: Literature Review and Background studies

This chapter presents the background and current state of knowledge related to earth construction, the material properties of the composite panels, appropriate soil composition for earth construction and the methods of compaction. This background information helped establish the procedures for the production of the panels. The material properties also helped determine the performance mandates and the test procedures. The background information helped potential benefits of the panels and possible directions for building.

2.1 Earth construction

Construction, demolition and remodeling typically produce significant volumes of waste. According to the U.S. Environmental Protection Agency study, the waste generated during U.S. residential renovations during 1996 added up to more than 31 million tons (U.S.EPA., 2003). This waste is typically hauled to landfills with resulting concerns for environmental degradation. This suggests a need to:

- Adapt traditional and vernacular building approaches to today's standards for performance, comfort, durability and safety.
- Use materials with low embodied energy; avoid any toxic or energy intensive stabilizers such as asphalt or cement (Rael, R. 2000).
- Conduct tests on compressed soil blocks for use as external walls in buildings that can be applicable to almost any climate including rainforests and cold climates.

2.2 Earth shelters

Following the energy crisis and the oil embargo of 1973, a back to land movement emerged which referred to a North American social phenomenon of the 1960s and 1970s characterized by migration of people from cities to rural areas. There was a surge of interest in earth shelter and underground home construction in an effort toward self-sufficient living (Boyer, L. L., 1982). Today the more progressed and technically superior standardized materials like steel and cement dominate the demand for earth construction, however, the drawbacks of using these materials are that they are extremely energy intensive and have very high-embodied energy.

Rammed Earth Construction is a method of building with unfired earth. The building method has been used for over 11,000 years (Boyer, L. L., 1982). The construction and techniques vary regionally and locally as per people's need, resources available and climate. Earth building is labor intensive, but requires very little energy use for processing and curing, and it can be recycled and is generally renewable (EBAA., 2006). However, the shortcoming of earth construction is that it must be protected from the rain, making it less viable for external use in places that have high rainfall rates (Bengtsson, L. P., and Whitaker, J. H., 1986; EBAA., 2006).

2.3 Stabilization

Stabilization is required to improve soil properties, strengthen, and provide resistance to water.
There are two types of additives: The first increases the strength and reduces moisture absorption. While the second reduces moisture absorption and moisture movement, but does not appreciably increase strength. It should also be noted that composites are usually preferred due to the following reasons:

- Produce resistance to heat, chemical wear and corrosion
- Have high structural strength, cost effective and are lightweight
- Provide toughness (impact strength), mechanical stiffness
- Cause less public inconvenience
- Require lower long-term maintenance, and replacement costs

Stabilization is required to eliminate the changes in volume that often occurs in soil as it absorbs and discharges water. For certain types of soil under ideal conditions, it is possible to compact the soil enough to resist moisture absorption and thus reduce its tendency to expand in volume even without stabilization. Stabilized rammed earth is made of an aggregate and a binder; the binder activates on the addition of water and facilitates particle movement. The aggregate is in the form of small gravel, sand, silt, and clay. Many materials may be used for soil stabilization (Maniatidis, V., and Walker, P., 2003; Bengtsson, L. P., and Whitaker, J. H., 1986). Binders commonly used for earth construction are:

- Sand or clay
- Portland cement
- Lime
- Bitumen
- Pozzolanas (e.g., fly ash, rice husk ash, volcanic ash)
- Natural fibers (e.g., grass, straw, sisal, sawdust)
- Sodium silicate (water-glass)

- Commercial soil stabilizers (for roads)
- Resins
- Whey
- Molasses
- Gypsum
- Cow dung (Bengtsson, L. P., and Whitaker, J. H., 1986)

Adding sand to soils that contain too much clay and clay to soils that are too sandy helps improve the consistency of the mixture. By doing so, the strength and cohesion of the sandy soil is increased while moisture movement of a clay soil is reduced. High clay content soil must be pulverized before mixing with sandy soil. Portland cement greatly improves the compressive strength and imperviousness and may also reduce moisture movement, especially when used with sandy soils (Bengtsson, L. P., and Whitaker, J. H., 1986).

Cement is used to improve wet strength and erosion resistance in exposed walls. Organic content like humus, and plant matter such as straw, can hinder the binding properties of cement so they should not be used unless dyed, with no chance of later deterioration (Maniatidis, V., and Walker, P., 2003).

Disadvantages of using cement as a stabilizer include: The permeability of moist soils is lost as the earth's ability to allow passage of moisture through the soil mass is lost. The production of cement involves harmful environmental emissions, reducing the opportunity to recycle. Cement stabilization is ineffective on clay rich soils. Cement instantaneously reacts with moisture content and should be used immediately within two hours. If the soil - cement mix hardens before molding, it is useless and must be discarded. A soil-cement block requires curing of at least seven days under moist or damp conditions (Maniatidis, V., and Walker, P., 2003).

2.3.1 Moisture content for cement stabilized earth works

The percentage of water added to the soil for cement stabilization should be equal to the difference between the optimum moisture content and the moisture content of the soil, plus an additional 2% in order to account for evaporation that normally occurs during processing.

Using non-hydraulic lime or slaked lime as a stabilizer for clay or silt mixes often proves to be better. Lime decreases moisture movement and permeability by reaction with the clay to form strong bonds between the particles. Such mixtures would need around 4 to 14% lime content. Lime breaks down lumps and makes it easier to work with soils. Curing at high temperatures makes the cementing molecules stronger and that should be an advantage in the tropical locations. The curing time is longer than soil-cement. If a soil is composed of too much clay for cement stabilization or too little for Lime, then combining Lime with cement stabilization works best. Lime will make the soil easier to work with and the cement will increase the strength. Equal parts of lime and cement are typically used. Mixing the dry soil with lime first, makes the soil more workable. Blocks are cured for at least 7 days under moist conditions. Using Natural fibers to a ratio of about 4%, greatly reduces moisture movement, but also makes dry earth blocks weaker and more permeable to water. Sodium silicate or water glass is used as a waterproofing agent to coat the outside of earthen blocks (Bengtsson, L. P., and Whitaker, J. H., 1986).

2.4 Fiber stabilization

Fiber stabilization helps improve the thermal performance, bending and tensile strength of soil. Natural fibers include straw, sisal fibers and timber. According to the Commonwealth of Australia (Milne, G., and Reardon, Chris, 2010), the ideal soil for fiber stabilization should have a plasticity index between 15% and 35%, and liquid limit from 30% to 50%. One disadvantage of fiber stabilization is that the compressive strength of soils decreases as the straw content increases (Kapfinger, O., 2001; Maniatidis, V., and Walker, P., 2003).

2.5 Readily available materials

Rammed earth – Widely available and can be collected from a variety of sources such as brick manufacturing, agricultural soil waste and excavated soil from construction sites.
Clay – Silt is available from dredging ports, dams, and is often locally available. Unprocessed clay was excavated from a local construction site for testing the proposed panels.

2.6 Problems related to material properties

The material compositions of the various test panels will influence performance.

2.6.1 Earth

The advantages of the material earth are as follows: high strength, chemically resistant, high compressive loading, cheaper than cement (Keable, 2007).

The disadvantages of earth are as follows: relatively high density, bulky by weight and cumbersome to handle. Highly porous and permeable to water-this makes it more difficult for installation as an external wall panel. Low resistance to water penetration resulting in crumbling and structural failure (Bengtsson,

L. P., and Whitaker, J. H., 1986). Very high shrinkage / swelling ratio resulting in major structural cracks when exposed to changing weather conditions (Bengtsson, L. P., and Whitaker, J. H., 1986; Maniatidis, V., and Walker, P., 2003). Low resistance to abrasion and requires frequent repairs and maintenance when used in building construction (Bengtsson, L. P., and Whitaker, J. H., 1986). Unlike cement that gains strength with addition of aggregate or fibers due to strong bonding and compressive properties, earth performs unpredictably in combination with an aggregate or fiber.

Workability of soil with respect to earth construction

The variety of soils is infinite. Not every soil is suitable for earth construction. The soil sample needs to be analyzed in laboratories for workability. It involves processing the soil, separation of gravel into varying sizes and verifying the soil composition. The quality of the aggregate is usually based on compressibility, granular composition, compressibility, plasticity, cohesive properties, and the hydrothermal properties. The quality of the natural binder that is the silt and clay influences the soil behavior. Therefore, it is difficult to give any fixed rule or procedure. There is a need to extract only useful clay or soil from the batch of materials; soil stabilization is needed for rammed earth.

2.6.2 Clay

With experience in working with clay it is noticed that using clay has the following benefits: it can be compressed to produce thinner cross-sections. When properly dried, the clay provides good strength. The surface of clay can be engraved.

The disadvantages of clay are as follows: the cross-section is brittle, can rupture suddenly under a heavy load or due to improper handling. Appropriate viscosity is needed to increase porosity and to reduce shrinkage; slow drying under controlled temperature can reduce deformation caused while drying or firing. The material properties that affect the strength of panels made of clay on preparation are its quality, viscosity, yield strength, stress, setting time, temperature, mechanical properties, modulus of elasticity, creep, shrinkage due to surrounding conditions, and resistance to freezing/thawing chloride.

Workability

Adding certain plasticizers to the clay mixture may reduce the brittleness of the panel. Panels made of clay can be retained as green ware in which case the clay slabs are sun dried or artificially air dried maintaining its green strength; drying permits rapid dehydration because heat enables water to migrate more easily from the inner depth to the surfaces of the panel. The panels are usually fired in a kiln. The process of firing helps crystallize the clay molecules to form strong bonds, but the firing process changes the chemical composition of the material; thus, it would be difficult to disintegrate the resultant material composition to its original state. The firing process is energy intensive and is accompanied by the emission of green house gases.

2.6.3 Natural water-soluble binding agents

The selection of an appropriate binding agent that would work when combined with earth includes National Casein, molasses and Elmer's glue (Woolley, T., et al. 1997).

The glues manufactured from soya, blood albumen, casein, and animal products have lower toxicity compared to their synthetic counterparts and petrochemical based products. The synthetic counterparts consume large amounts of energy for manufacturing. Natural glues are mainly suitable for internal use, so their application is limited (Woolley, T., and Kimmins, S., 2000).

Binders are added to provide sufficient strength to the "green" body (unfired compact) to permit handling or other operations prior to densification. The binders provide lubrication. The selection of an appropriate binder depends on a number of variables, including green strength needed, ease of machining, compatibility with the ceramic powder, and nature of the consolidation process (Richerson D. W., 1992). The effects of the additives include:

- To allow the powder particles to slide past each other to rearrange in the closest possible packing.
- To minimize friction and allow all regions of the compact to receive equivalent pressure.

The hardness and deformation characteristics of organic binders vary with temperature, humidity, and other factors. Many of these materials go through a ductile-brittle transition and behave in a brittle fashion below the transition and in a ductile fashion above the transition. The temperature at which the ductile-brittle transition occurs is referred to as the glass transition temperature.

Organic binders decompose during high temperature densification. This process involves the emission of toxic gases. Some binders leave carbon residue especially if fired under lower temperatures. Organic binders burn at lower temperatures and result in minimal contamination, whereas inorganic binders fuse to become a part of the composition. The water-soluble binders may disintegrate when exposed to outdoor weather conditions. To overcome this, the panel can be coated with a layer of high performing renewable resource based eco waterproofing (Richerson D. W., 1992).

2.7 Factors for rammed earth construction

The factors that affect the successful application of rammed earth systems are as follows:

2.7.1 Soil selection

The soil conditions that are considered appropriate for earth construction include: red colored soils should be preferred. Variation in aggregate color causes non-uniform finishes and this is not acceptable. The soil mix should be free of any organic matter as it may cause undue shrinkage, biodegradation or susceptibility to insect attack. Also, organic material can be a concern as it could diminish the effectiveness of stabilizers such as cement (Delgado, M. C. J., and Guerrero, I. C., 2007; Maniatidis, V., and Walker, P., 2003).

2.7.2 Soils inappropriate for construction

The soil conditions that are considered as inappropriate for earth construction include: those that have higher concentration of clays, organic silts, and gravel. Furthermore, Soils containing organic matter are prone to rot or breakdown. While soils having higher concentration of moisture will impair the strength of the wall panel. Additionally, soils containing large aggregate particles will impair the strength or homogenous nature of the wall (Delgado, M. C. J., and Guerrero, I. C., 2007; Maniatidis, V., and Walker, P., 2003).

2.7.3 Plasticity index

The plasticity index is an indicator if the soil has high clay content and active clay minerals and if higher shrinkage is likely to occur when the earth dries (Maniatidis, V., and Walker, P., 2003). The plasticity index of soil is defined as the liquid limit minus the plastic limit. The liquid limit (LL) is the water content, in percent by weight, at which a soil ceases to behave as a liquid and begins to exhibit plastic behavior. The plastic limit (PL) is the minimum amount of water content required to make soil plastic. Both the liquid limit and the plasticity index are affected by the amount of clay, and the type of clay minerals present. A goal for effective earth construction is to have minimum moisture in a mixture of clay, silt, and sand/gravel (Delgado, M. C. J., and Guerrero, I. C., 2007; Bengtsson, L. P., and Whitaker, J. H., 1986).

2.7.4 Mold

A temporary support system used during soil compaction is a mold. It should have sufficient strength, stiffness and stability to resist pressures, placement of the soil, and dismantling. A favorable mold is one that can be removed almost immediately after compaction, enabling much faster re-use. Selecting the right type of molding system for each application is important, since usually the time spent for setting, aligning and stripping the forms is greater than the time spent transporting and compacting the earth. Problems related to the transportation of soil from the mixing area into the mold depend on the type of mold used. The task of transporting soil mix for building panels in mold is a tedious task (Maniatidis, V., and Walker, P., 2003).

2.7.5 Methods of compaction

The different types of compaction methods that are being applied for practice are as follows:

2.7.5.1 Manual compaction

It is a traditional method of compacting soil using instruments such as a hand tamper. A hand tamper is usually made of wood or steel with a thick heavy base and a handle (Rael, R. 2000; Maniatidis, V., and Walker, P., 2003).

2.7.5.2 Pneumatic compaction

Manual ramming is typically time consuming, thus mechanical compaction is more preferred, as it requires half the time for compaction. Mechanical impact rammers usually operate with compressed air and function by repeated pressure lifts and drops of the striker head of the rammer. For ideal impact, the rammer should have a long stroke, moderate speed and weight to make it safe, and a slender tamper. For these reasons high-speed jack hammers and petrol driven hammers might not be suitable (Maniatidis, V., and Walker, P., 2003).

2.7.5.3 Types of compaction mechanisms

The machines used for compaction into earth blocks have advantages over traditional methods of compaction. The advantage of using this machine is that the soil is compressed to very high densities. The machines are capable of producing many panels in a short period of time that are uniform in density, shape and overall dimensions. Machines in use today include both manually and mechanically operated methods to compress the soil into bricks. One of the major limitations of using manually operated machines is that they are slow and one is limited in how much force that can be applied to the bricks. The hydraulic ram used for compressing the soil and automated conveyors used for delivering panels from the machine to the work area provide higher levels of production capacity and quality to the process. Panels made by using machines are more consistent in strength and dimension (Maniatidis, V., and Walker, P., 2003; Graham C. W., and Burt R., 2001).

An example of a compaction machine is the AECT Impact 2001 Compressed Soil Block Machine. This is a small, trailer-mounted machine that comes with either a 6.5 horsepower gasoline or 7.0 horsepower diesel engine; they are available as either manually or automatically operated. This machine can produce 230 - 300 blocks per hour in a variety of dimensions (Graham C. W., and Burt R., 2001).

2.7.6 The Moisture penetration

Inclement weather conditions significantly influence programming and progress of rammed earth works. Optimum soil moisture during compaction and subsequent drying is essential for the success. The panels need sufficient protection from wet weather and frost. Porous materials are permeable to moisture because they contain a network of open channels. A channel with a nominal diameter of 5 mm or above is classified as porous whereas a channel with a nominal diameter of less than this value is classed as a capillary or a micro-pore. One of the major problems with rammed earth systems is Capillary action. Voids within the rammed earth matrix are likely to be extremely small. The height of capillary rise is inversely proportional to the diameter of the pore or capillary; these ultra-tiny spaces have tremendous capillary action potential. In the right conditions the sponge effect caused by this suction can result in a great deal of water to flow within the voids of the wall, and in un-stabilized rammed earth can cause slaking and deterioration in short periods of time (Hunter, W., 2006). Using stabilized rammed earth, the structural effects are much less marked, but moisture flow occurs none the less. The effects of moisture penetration are less when the external wall is highly finished. Thus, rammed earth construction is popular and performs well in warm, dry climates where the problems of moisture ingress are comparatively low (Hall, M., and Djerbib, Y, 2004).

2.8 Variables

The final array of samples prepared for testing was selected based on the following:

A. Base agent

1. Earth

B. Binding agent

1. Portland cement
2. Matrix having no binding agent

3. Water soluble natural synthetic adhesive

4. Clay

5. Fly Ash

C. The Proportion of Water Content

1. Add water to increase bonding strength of the base agent

2. Based on the variables, six panels were considered:

[Panel-1] Earth + 6% cement stabilizer

[Panel-2] Earth + without stabilizer

[Panel-3] Earth + Elmer's glue

[Panel-4] Earth + 9% Clay and Elmer's glue

[Panel-5] Earth + 6% Starch

[Panel-6] Earth + 6% Fly Ash

2.9 The Pros and cons of using multiple stabilizers

The stabilizers were selected based on renewability and binding properties. Each of the materials produces certain advantages and disadvantages to the soil matrix, thus these properties will need to be determined before constructing the panels to control the ill effects of the excessive proportions of these materials.

2.9.1 Portland cement as a stabilizer [Panel-1]

Composition: Mixture of limestone and clay is heated in a kiln from 1400 to 1600 degrees centigrade (2550 to 2990 F). Cement is highly energy intensive. The production costs are 20 to 30% of the total energy costs. Global demand for cement is ever increasing; it is predicted to grow 4.7 percent annually and it may rise to 2.8 billion metric tons by the year 2010 (primaryinfo.com, 2008a; Keable, 2007).

Advantages

When properly cured, the compressive strength is enhanced along with reducing moisture ingress. Use of cement as a stabilizer has added advantages when used in a sandy admixture, as it shall elevate the binding properties of the panel. It can better withstand external weather conditions. Cement can be recycled and reused, but the strength of the panel made from recycled cement cannot be compared to that of panels made of fresh cement.

Disadvantages

Cement has high-embodied energy. Due to the rapid initial drying period, the compressive strength reduces. In order to get stronger panels, curing the panel must retard the initial drying. In this case, the panel consumes more water than the other samples. The production of cement involves emission of environmentally harmful gases such as carbon dioxide. It is not renewable. It is typically dumped in landfills, adding to the non-degradable waste (Smith, T., 2002). If the cement stabilized earth panel is not cured sufficiently, the panel may have a weaker cross-section than an un-stabilized rammed earth panel. When cement is mixed with earth and water, it produces harmful fumes that are accompanied with pungent odors. The cement imparts an unattractive, dull color and rough texture to the surface of the rammed earth panel (Keable, 2007).

2.9.2 Elmer's glue as a stabilizer [Panel-3]

Elmer's glue was originally manufactured by Borden Cooperation that took over the Casein Cooperation of America, the leading manufacturer of glues made from casein, a milk by-product. Latter Borden introduced the first non-food consumer producer Casco Glue, in 1932. Elmer's glue was first introduced in 1947 under the brand name Cascorez. Sales did not take off until 1951. Later, it was repackaged in the form of Elmer's glue. The brand was a non-toxic based glue, but due to the unreasonable price, over time it was replaced with polymer based poly-vinyl acetate (PVAC) (Borden, 2009). The two products have similar binding properties, thus for the purpose of testing a renewable panel, the Elmer's glue (PVAC) is considered a renewable alternative to the milk-based Borden Glue, and this is a water based binding agent (naturalhandyman.com, 2011)

Casein is a predominant phospho-protein made by clotting milk, proteases and coagulated protein. It is a salt of calcium. Casein is precipitated by acids and by rennet enzymes. Proteolytic enzymes are typically obtained from the stomachs of calves (Rao, et al. 1998). Casein contains a fairly high number of proline peptides; it is relatively hydrophobic in nature (Dalgleish D. G., 1998). It is used in the manufacture of adhesives, protective coatings, and plastics (Ccmr.cornell.edu, 1998).

Advantages

It can be successfully applied to glue wood products. The process provides insight into the behavior of Elmer's glue in combination with earth. The greener casein based option to Elmer's glue when used in combination with earth would be completely renewable. It doesn't have a distinct color, thus retaining the original color of earth. Wood adhesives usually have dry shear strengths that exceed the strength of the wood itself.

Disadvantages

Excessive water is required to obtain a suitable damp mixture composed of Elmer's glue and earth. This may result in low panel strength. The glue tends to dry rapidly; this might be a problem while mixing. The Elmer's glue has high dry shear strength hence strong bonds are formed when earth and Elmer's glue are mixed together. It tends to dry rapidly and the dispersed nature of the earth granular particles causes lumps of dried mix. This lumpy soil mix is difficult to work with or takes time for compaction; additionally, excessive moisture may cause loss of binding properties. Pressurized mixing and mechanized compaction methods may help panels gain much more strength. It is noted that exposure to water-soaking stresses, epoxy bonds weaken more rapidly causing wood failure (Galganski, R. A., 1998).

2.8.3 Clay as a stabilizer [Panel-4]

It is a naturally occurring fine-grained mineral that shows plasticity over a range of water content. On firing in a kiln, a physical and chemical reaction occurs, converting the clay into a ceramic material. The clay appears in varying colors from dull gray to a deep orange-red. The clay exhibits properties that are relatively impermeable to water (Akgün, H., and Wallace R.B., 2005).

Advantages

Clay is impermeable to water. It has better binding properties than fine-grained earth particles. Furthermore, it is easy to make thinner sections. It is easy to carve and make various shapes and sizes. It can be reclaimed and reused. The green clay can be disposed of easily (Akgün, H., and Wallace R.B., 2005).

Disadvantages

It is brittle when dried and thus during production phase the panels would have to dry slowly under cover. If exposed immediately on forming, it could dry rapidly, causing uneven drying, shrinkage, forming cracks on the surface of the panel. It should be noted that the moisture within the section should be completely dry. The clay panels tend to have bubbles and voids that need to be wedged to gain optimum strength. On heating at higher temperatures, the weak sections tend to break. The clay content in the earth used for making a panel is best when it is between 15 and 25%. If the clay content exceeds this it may cause shrinkage and a stabilizer will need to be added to make the earth workable. The clay and earth dry at different rates causing a problem as the layer of clay may shrink and spalling occurs (Maniatidis, V., and Walker, P., 2003; Akgün, H., and Wallace R.B., 2005).

2.9.4 Cornstarch as a stabilizer [Panel-4]

Cornstarch is a starch of maize grain (corn), extracted from the white heart of the corn kernel. The composition of cornstarch has approximately 25% amylose and 75% amylopectin. Cornstarch is used as a binder for food (Schnepf, R., and Yacobucci, B. D., 2013; starch.dk, 2006; mahalo.com 2007).

Advantages

Cornstarch is one of the better alternatives used as an environmentally friendly product. It is a natural binding agent available in products such as Arrowroot, collagen, modified starch, natural gums, Soy, linseed oil and Sago. The addition of starch to the earth will make the sample workable, and easy to ram the lifts. The panel will be comparatively easy to build than an un-stabilized panel (Schnepf, R., and Yacobucci, B. D., 2013; starch.dk, 2006; mahalo.com 2007).

Disadvantages

The process of production of Cornstarch involves fermenting and washing; which require large amounts of water. More energy is required for production and the panel comparatively takes longer to dry. There is a large demand for cornstarch as it is a widely used food product, an environmentally friendly alternative to plastic and polymer based products, and is also used as feedstock for animals. Incentives are provided by US government authorities to encourage use of biodegradable products and for research in this particular area. Corn production for bio-fuels is slowly replacing food-based agriculture. Thus this may cause a shortage of food supply, and increase price. Furthermore, the panel may not be able to withstand weathering especially when exposed to moisture (Schnepf, R., and Yacobucci, B. D., 2013; starch.dk, 2006; mahalo.com 2007).

2.9.5 Fly ash as a stabilizer [Panel-6]

Fly ash is a residue derived from the combustion of powdered coal in electric generating plants. It is an incombustible material present in coal fused to form a glassy, amorphous structure. The amount of carbon content is judged by the coloration of the fly ash. The lighter color indicates lower carbon content, while the darker shade indicates very high carbon content (primaryinfo.com, 2008b; Pflughoeft-Hassett D. F., et al. 2000).

Advantages

Fly ash acts as a barrier against corrosion by reducing the permeability that reduces the rate of moisture ingress. In combination with cement, fly ash acts as a good stabilizer for soils having higher clay content. Furthermore, fly ash improves tensile strength. The finer grained particles of fly ash make compaction easy. A small percent of fly ash to the earth mix does not affect the color or the appearance as compared to that of an un-stabilized rammed earth panel.

Disadvantages

The fly ash market is limited due to proximity of power generation plants to the place of manufacture or installation. The fly ash used for stabilizing should be free from carbon content, as it tends to reduce the binding strength properties of the sample. Separation of carbon in fly ash is a tedious procedure, for this research the fly ash was applied without undergoing separation of carbon content. Fly ash is not a renewable option for a stabilizer, while making the panel non-degradable, although it could be broken down into fine-grained particles and recycled. Fly ash is usually used in combination with cement stabilizer. For this research, fly ash was used as a stabilizer without addition of cement (Pflughoeft-Hassett D. F., et al. 2000). When the panel is applied for external use, the dark colored fly ash can increase solar absorption. Buildings where such panels are installed may lose the Leadership in Energy and Environmental Design (LEED) credit for reducing heat island effect.

This chapter summarizes the current state of knowledge related to issues of construction, composition and performance of earth-based wall systems. This knowledge was applied to the selection and design of the research methods.

Chapter 3.0 Methodology

This chapter describes the research methods used to evaluate the performance of the alternative wall panels. Additionally the chapter also briefly explains the procedures adopted for the preparation of the test panels, and variable parameters. Some of the important factors that needed to be established before preparing the samples were as follows:

- To determine the availability of the materials like earth and water.
- To determine the availability of tools that could be used for compaction and mixing.
- To determine a suitable drying condition
- To design an efficient system for a mold that can be utilized to its optimum extent to build multiple test panels over the period of the project.

The process was adaptive in that while conducting onsite preparation of the panel some of the planned procedures were modified. One of the major reasons for these changes was associated with the time required for compaction and drying of the panels during the initial phase of deriving methods for construction.

3.1 Research procedures

The research is divided into the following sequential stages:

1. Background information
2. Preliminary procedures
3. Design of mold
4. Panel Preparation Procedures
5. Panel test procedures
5. General observation findings
8. Findings and results from the tests conducted
9. Conclusions and Future possibilities

Each of the topics is further explained as five basic subgroups as given below. Although loosely based on quantitative ASTM standard procedures, due to time and equipment constraints the approach is primarily qualitative and interpretive. The research procedures are primarily experimental with the construction and testing of alternative panels.

3.2 Background Information

Background information was collected and organized from literature for construction methods and materials commonly used in earth construction. This became foundational to establishing ranges and boundaries for the panel alternatives.

3.3 Preliminary procedures

Prior to the mold construction and panel preparation the following preliminary procedures required to be accomplished:

- Identify appropriate space for conducting the study. The construction of the panel and the tests were conducted at the Building Research and Demonstration Facility (RDF) at Virginia Tech.
- Identify and collect tools and equipment. To collect timber boards for constructing the molds required for casting the panels, the tools such as the trowel for mixing and the wooden tamper head required for compacting.
- Identify the soil source and collect soil. The soil was gathered from the excavated land of a local construction site at Smith Landings, an off campus housing for Virginia Tech.
- Apply Jar test to determine the composition of the soil.

Table 3.1: Stages of Jar test

Step 1 (soil settlement after 5 minutes)	Step 2 (soil settlement after 24 hours)
	

Jar test (field test) – The composition of soil is made up of four elements; sand, gravel, silt, and just enough clay to act as a binder to assist soil compaction. Material coarser than 5-10 mm should be sieved and removed, as increasing gravel size can reduce the compressive strength of the rammed earth sections. Optimum Levels of materials required in soil compaction are as follows:

Clay/silt and sand proportion = 30%-70% (Berglund, 1986, Easton, 1996),
Minimum combined clay = 20%-25%
Maximum combined clay = 30%-35%
Minimum sand = 50%-55%
Maximum sand = 70%-75%

Soil that requires cement stabilization must have higher proportions of sand and gravel content. It is preferable that the proportion of sand was around to 75% with less than 25% clay (Maniatidis, V., and Walker, P., 2003). The Jar test was carried out in the following steps (Graham C. W., and Burt R., 2001):

1. A glass jar was filled half to its volume with pulverized dry dirt used for making the test samples.
2. Next the jar was filled with clean water leaving an inch gap from the top. A pinch of salt was added to the water, to prompt the sedimentation process.
3. Using a spatula the water, soil and salt was thoroughly mixed.
4. After a gap of 5 minutes the dispersed dirt particles partially settled out of the water at the bottom of the jar. The settled particles are typically composed of gravel and fine sand and this section was demarcated as (T1).
5. After approximately 24 hours, a second reading (T2) was taken, where fine gravel, sand and silt settled out of the water.
6. A third reading (T3) was marked, where the clay particles finally settled completely out of water.

The percentage of the ingredients of the soil were calculated using the folumula established in the works of Galganski, R. A., (1998) and Maniatidis, V., and Walker, P., (2003):
T1 = depth of sand, T3 - T2 = depth of clay, T2 - T1 = depth of depth of silt
Each of these depths are divided by T3 and then multiplied by 100
T1 = Gravel = 0.5inch = (0.5/3.0625)*100= 16.326%
(ii.) T2 = 2.3125 inch
(iii.) T3 = 3.0625 inch
(iv.) T3 – T2 = Clay / Silt = 0.75inch = (0.75/3.0625)*100 = 24.48%

T2 – T1 = Sand = 1.8125 inch = (1.8125/3.0625)*100 = 59.18%

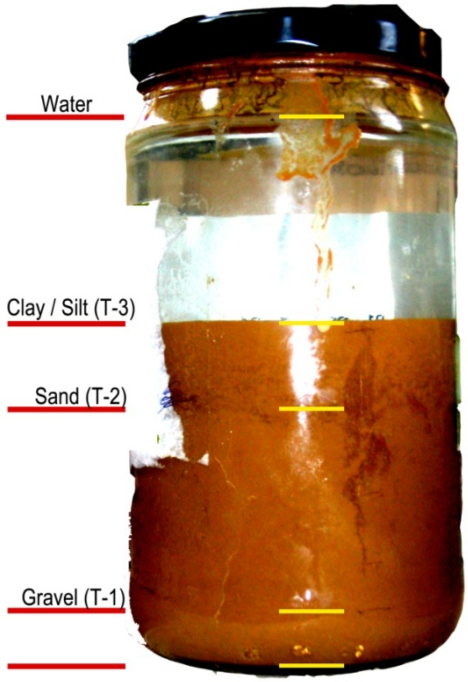


Figure 3.1: Image of the Jar test performed on the soil sample

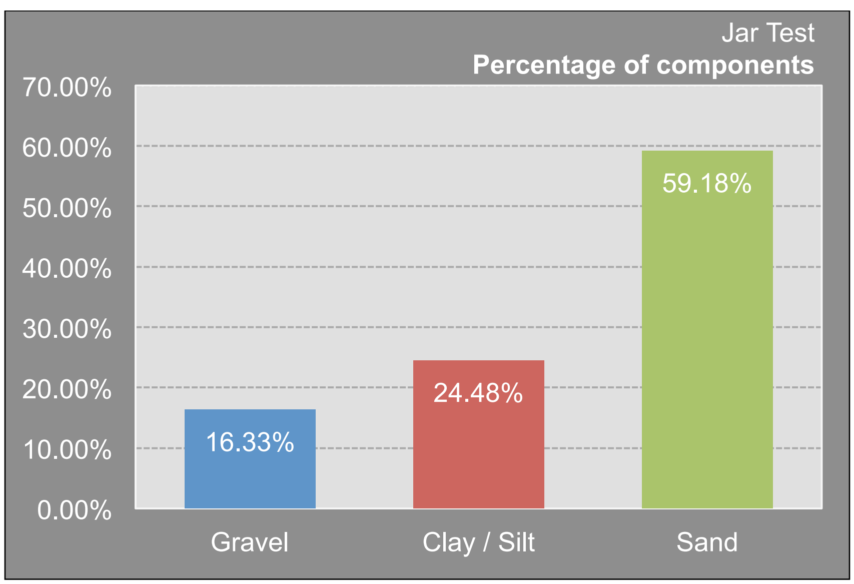


Figure 3.2: Chart with estimates of levels of clay, sand and gravel in the soil composition

3.4 Panel construction

This section explains the procedures used for panel production. Preparation time for each of the test samples varied mostly due to the following: the availability of material and the effort required in the process of pulverizing large earth pieces to fine granular particles and mixing. The amount of water needed to make the optimum damp mixture for compaction. Obtaining efficiency and ease of using the framework for building panels. The number of lifts needed to compress the granular particles, effort and energy required during the compaction of the entire panel. Constraints on weather conditions during the phase of drying of the panel, for example lower humidity levels are suitable for earth building while exposure to extreme weather conditions may affect the preparation process. Another consideration to be notes is that some panel properties are such that they dry unevenly, so for the panel to dry completely it would take longer than usual

3.4.1 Underlying sssumptions

The methods and materials that were used when constructing the test panels were based on a number of underlying assumptions that included the following:

- Built the composite panels using materials that were locally available in abundance.
- Considered volumetric percentages of materials to measure the proportion of the composites.
- Built all the panels at a fixed size of 1foot x 1foot cross-sectional dimension with thickness not more than 1 ½ inches.
- Built the base mold in such a way that it could be reused in future.
- Dried panels using a natural air-drying process to protect it from direct exposure to sunlight, rainfall, or inclement weather conditions.
- Considered varying rates of drying time for each alternative composite to achieve a consistent level of moisture.

3.4.2 Panel compositions

Based on the assumption that the proposed panel is environmentally friendly, it should have lower embodied energy, contain more reclaimed or renewable materials, and have similar stabilizing properties as that of the base case cement stabilized rammed earth panel. Thus the matrix of the variable used for the project is given below. As a rough guide, sandy soils need 5 to 10% cement for stabilization, silt based soils 10 to 12.5% and clayey soils 12.5 to 15%. Based on this study, the percent of cement as the base case independent variable is maintained to the low value of 6 % of the volumetric earth dry mix, the other renewable and recyclable test variables are also maintained at 6 %. For the Panel-4, the behavior of a natural binder in clay rich earth had to be tested; considering this, the proportion of 9% reclaimed clay was used for the research. The workability of the panels was determined using a few simple tests and comparing the results with the base case. Tables 3.2 and 3.3 have details on the samples used for preparing the panels.

Table 3.2: Matrix defining the proportion of variable test sample for the research project

(Panel-1) Base Case	
Material	**Volume (%)**
Subsoil	94
Portland Cement	6
Water (Optimum)	
(Panel-2) Design Case	
Subsoil	100
Water (Optimum)	
(Panel-3) Design Case	
Subsoil	100
Elmer's glue (Optimum)	
Water (to make the Elmer's glue workable)	
(Panel-4) Design Case	
Subsoil	91%
Reclaimed Clay	9%
Elmer's glue (Optimum)	
Water (to make the Elmer's glue workable)	
(Panel-5) Design Case	
Subsoil	94%
Cornstarch	6%
Water (Optimum)	
(Panel-6) Design Case	
Subsoil	94%
Fly Ash (Slag)	6%
Water (Optimum)	

Table 3.3: Details of independent variable components used for preparation of Panel

1. Moist Earth ready to be cast into Mold	Recycled Clay - 6% Manufacturer - Highwater Clays, Product #: 306 Brown firing clay
2. Portland Cement - 6% Manufacturer – Quikrete	3. Argo 100% pure Cornstarch - 6% Argo Gourmet Ltd.
4. Elmer's Wood Glue Carpenter's interior wood glue	5. Slag: Fly Ash - 6% from local power plant

3.4.3 Sizing the test panels

The size of the test panels was based on the following factors: as the proposed panel was built to be part of a panelized wall system, all panels were assumed as equal cross-sectional dimension and thickness, and they were similar in weight. The dimensions of the panels were 1foot x 1foot since most panelized systems are designed in modular increments of one foot. The size is such that it is most convenient to handle.

Conventional rammed earth blocks are usually 6 inches to 8 inches in thickness, and used for carrying structural loads. The intent of the new panels was to install them as part of a panelized system, with a thickness suitable for easy handling and with a thickness not more than about 1 ½ inches.

3.4.4 Design and preparation of the panel mold

This molding process was convenient and was altered to suit the research requirements based on the size of the panels. The criteria that were considered while preparing the mold are as follows: the molds were designed in such a way that it could be repeatedly used over future projects. Furthermore, the entire assembly could be easily dismantled with minimal effort, without affecting the panel cross-section during disassembly (Kapfinger, O., 2001).

Considering the above factors the mold was assembled from separate frame pieces predetermined in size with holes drilled toward the ends to fix the hex bolts tightly for securing the panels. Figure 3.3 shows the figures of the design of the mold and typical procedure adapted for preparing the test panels.

Figure 3.3: Procedure and design of panel mold Kapfinger, O. 2001)

Additional Procedures

The reusability of the mold was the main criteria for the design of the mold assembly. With this in mind the additional procedures included: a ply-board with larger dimensions than the assembly formed the base for the mold. Furthermore, the ply-board was used like a tray for handling the assembly with minimal disturbance to the panel during preparation and maneuvering of the panel to the place of drying or storing. The baseboard was covered with a plastic sheet before placing the wooden frame for compaction as shown in Figure 3.4. The panel was compacted on the surface of the plastic. The intention of using plastic below the panel was to allow the panel to be picked off the base tray. The plastic also helped provide a smooth exterior finish for the base of the earth panel. Finally the wooden frames were tightly fixed using the hex bolts. Before pouring in the first layer of the earth mixture, Murphy's wood soap (vegetable based) was applied to the inner surface and sides of the mold to prevent earth from adhering to the wooden frames. The application of the wood soap does not affect the panel. The application is intended for ease of separation of the panel from the sides and edges of the mold.

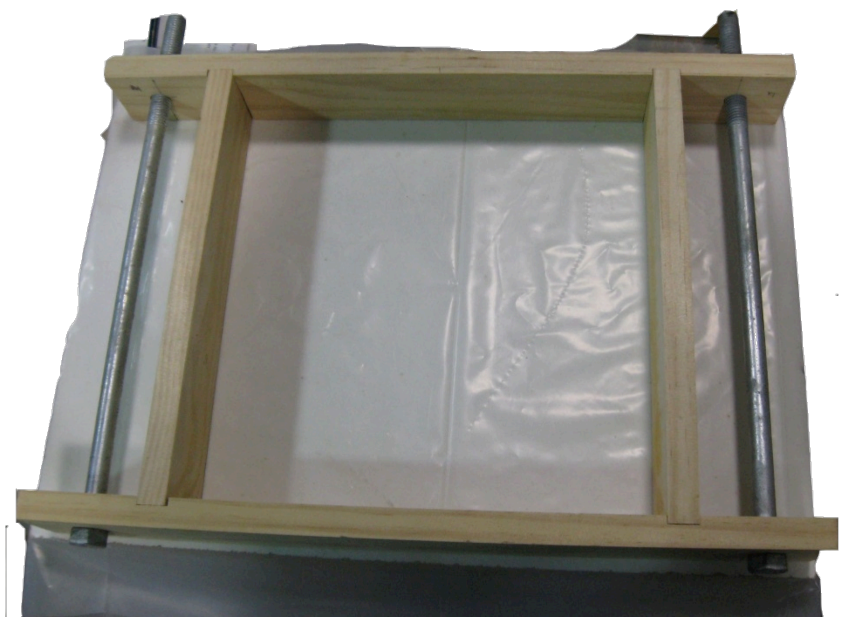


Figure 3.4: Adaptability of mold design

The frames sizes are as follows:

Length of the frame

Frame 1 & 2 = 1foot 8inches

Frame 3 & 4 = 1foot 1inch

Cross sectional dimension of frame

= 1inch x 2-½inches

One of the major shortcomings in the design of the mold was that the straight sides made compaction of the edges difficult, causing weaker edges. Test samples such as Panel-3 (a combination of earth and

Elmer's glue) required use of a plastic cover and application of wood soap onto the frames to prevent glue-laden earth from sticking to the frames.

3.4.5 Material availability: Earth

Composition of the soil is an important consideration for preparation of the test panels. Soil was collected from a nearby construction site. The construction authorities mentioned an excavated location that had the desired soil composition and consistency. The gathered soil represented the local soil available in the region (Maniatidis, V., and Walker, P., 2003).

3.4.6 Determining the required quantity of earth

A mix and measure container with a maximum capacity of 5 gallons was used to prepare the earth mixture. For 1 foot x 1 foot x 1-½ inch panels, the required amount of earth was approximately 6.34 quarts. A measuring jar is used to determine the right quantity of stabilizer in comparison to the volumetric percent of earth. One part was equal to a jar full of the stabilizer. Twenty-three parts of a jar made up a single panel measuring 1 foot x 1 foot x 1-½ inch.

The equation adapted to measure 6% of stabilizer is given below:

6% x 23 parts = 1.38 parts.

3.4.7 Steps followed for panel production

The procedures for preparation of the panels included sorting, mixing, drop test, compaction, layering, drying and storing. The details of each step are described below:

1. Soil Screening: Soil particles larger than recommended limits of 10-20mm should be removed. Gravel larger than this create problems associated with an increase in the likelihood of surface finish problems such as boniness, especially around corners and edges. The gravel particles were sorted and separated from the soil before pulverization (Maniatidis, V., and Walker, P., 2003).

2. Pulverization: Pulverization is a process of breaking down dry clayey or chalky, cohesive soil aggregates; the dry earth is a hard mass and needs to be broken down to attain a consistent blend when mixed with sand or other additives, prior to the wetting, mixing and compacting (Maniatidis, V., and Walker, P., 2003).

3. Mixing: Mixing is an important step to achieve homogeneity of the soil. Mixing helps ensure distribution of moisture within the soil matrix. For optimum results, the soil should undergo screening, pulverizing and mixing as one continuous process. The best equipment to blend and add moisture is to

use the portable concrete batch plant, which is a combination of belt conveyor and paddle auger to blend soil and add moisture. However, this process can be very expensive and has limited practical use. For small projects, a small garden cultivator could be used for mixing. For larger quantities of soil, the quickest way of mixing is with a skilled operator using a bucket-tractor. The dry elements like the earth and the admixture shall be thoroughly mixed to form a homogeneous mix of the components (Maniatidis, V., and Walker, P., 2003). Sprinkling water helped obtain a sufficiently moist mixture required for compaction (Maniatidis, V., and Walker, P., 2003; EBAA., 2006).

4. Drop Test: Density of rammed earth blocks is dependent on soil type and moisture content during compaction. In order to achieve maximum density, the soil should have optimum moisture content, appropriate for compaction (Maniatidis, V., and Walker, P., 2003). The Drop test is helpful for finding approximate moisture levels. The test is based on compacting a fistful of mixture in one's hand and dropping it from an outstretched arm onto the ground. Separation into three to four large clumps of soil is optimum. Separation into more pieces suggests that the mixture is too dry; fewer pieces indicate that the mixture is too wet (EBAA., 2006).

5. Soil Compaction: The test panels were constructed in layers of compacted soil. Depth of each layer varies depending on the effort required for compaction and soil type. Initially a manual compaction approach was followed. These days, power generated earth presses are available, such as the pneumatic, vibrating plate and sheep's foot roller compactors. This would reduce the requirement of manpower to a large extent, and it will be easier to produce panels of desired mix.

For the research, manual compaction methods were adapted. Soil is added in layers, each being compacted before the next is added. Compaction involved striking the dampened earth in molds with a wooden mallet. The goal was to compact each lift, or layer, to half of its original depth (EBAA., 2006). The intensity required for each lift of the tamper differed from one test block to another. The compaction of the base layer was difficult; but, compaction of consecutive layers was easier. On acquiring the desired height, the topmost layer was covered with a plastic sheet for around five to seven days under controlled room temperature to allow for measured drying. The panel shrinks due to evaporation of water, thus the framework of the mold was easily disassembled.

6. Drying: The panels were allowed to dry in the open, while being protected with plastic sheeting to avoid direct exposure to dampness, harsh sunlight and inclement weather conditions. There is a gap of

around 2 feet for free air movement between the panel and the plastic cover. The panels were placed on baseboards raised on precast concrete blocks such that the base is raised above the ground to protect it from dust, and avoid direct contact with the ground. The panels were left to dry for a period of around three to four weeks depending on the type of panel and humidity level of the air.

7. Storing: Panels are stored under controlled temperature for a week after air drying before the tests for stability and effects of moisture ingress were applied.

Tools needed for preparation of Panel

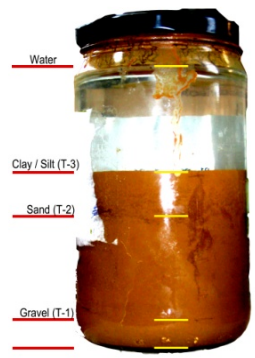
Excavated Earth from construction site

Step 1. Coarser Earth Particles

Step 2. Fine Earth after Pulverizing

Step 3. Drop Test

Step 4. Jar Test 25%-Clay 60%-Sand 15%-Gravel



Step 5. Earth compaction in Mold

Step 6. Rammed Earth Panel in Mold

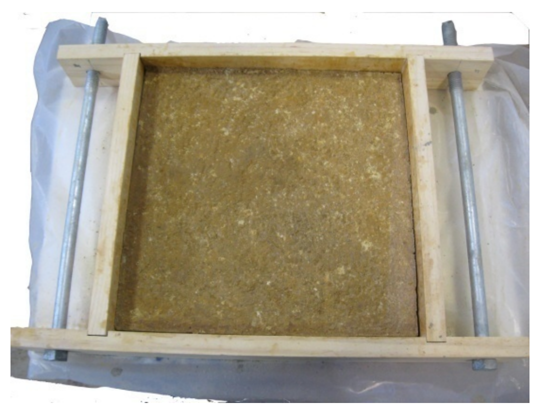


Figure 3.5: Method used for panel production

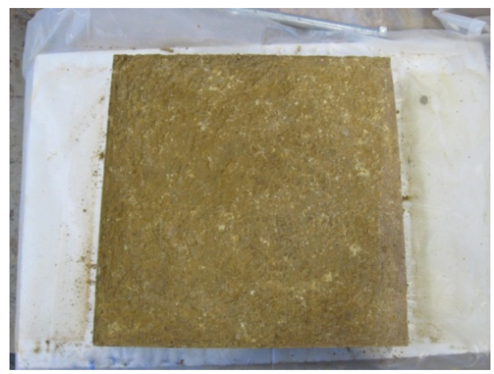
Step 7. Dismantling mold	Step 8. Panel covered with plastic with air gap
	
Step 9. Panel kept for drying	Step 10. Earth Panel ready for use
	

Figure 3.6: Panel preparation procedure

3.5 Performance testing procedures

The Panelized wall systems are tested using the ASTM performance standards applicable for composite panels. However, due to the lack of available testing equipment and considering that the research aimed at finding an appropriate renewable panel, the ASTM standards were modified. Thus, the parameters to test the feasibility of the proposed panels were defined by the qualitative analysis approach. The initial step of literature review involved determining test procedures that could be adapted.

3.5.1 Test procedures

The panels that survived the process of compaction in the test molds were subjected to various stability tests that approximate the related ASTM procedures. As per these considerations it was possible to build one panel for each of the six variable samples; the results were based on the qualitative analysis between the six variable samples built. The tests were designed to determine factors such as structural strength, self-weight properties, toughness (impact strength), mechanical stiffness, and the resistance to corrosion.

3.5.2 Experimental test methods

The following test procedures are explained in detail. The tests are carried out in the same order as stated below. The procedure for conducting these tests is discussed in detail below.

The crumble test

The scratch test

The load test

The weight test

The water pressure test

3.5.2.1 Crumble test

The alternative panels were tested for brittleness and compressive strength by crumbling the panel by twisting, turning, and applying manual force. The expected outcome was that panels with a weaker section would crumble immediately on application of minimal force while the comparatively strong panels would require more force or would not crumble during the test.

Assumptions

Deformation occurring in the center of the panel was considered a failure. Since the results were not measurable, the test was conducted on the basis of qualitative analysis by observing the comparative failure. The results are a graphically representation of failure analysis as per volumetric percent of the respective sample.

3.5.2.2 Scratch test

The scratch test was applied on the panels to determine the surface toughness. The test procedure followed continuous scoring on the surface with a pointed tool such as a fork or a knife. The approach includes calculating the percentage weight of the material scored off in comparison to the initial self-weight of the panel. Anticipated results are that the panels having comparatively strong surface properties would not be affected by the action of scoring, while the panels having a weaker cross-section would show the defects due to scoring immediately.

Assumptions

Deformation occurring in the center of the panel was considered as failure.

Since the results were not measurable, the test was based on qualitative analysis by observing the comparative failure. The results are a graphical representation of failure analysis as per volumetric percent of the respective sample.

3.5.2.3 Load test

A load test was used to evaluate the maximum load carrying capacity of the alternative panels compared to its self-weight. This test was also helpful for determining the strength and patterns of failure in the panels (Maniatidis, V., and Walker, P., 2003).

Figure 3.7: Image of Load test setup

The assumptions followed while applying the Load test are as follows: the test was designed to attain total failure. A quantitative test procedure with measurable values was adopted to compare between the panels. The test helped evaluate the compressive and the relative tensile strength properties of the panel. It was important to study the failure of the panel due to loading. The panel was not loaded directly to avoid the situation when the bricks fall directly onto the panel, thus shattering the panel completely making it difficult to determine the actual failure mechanism.

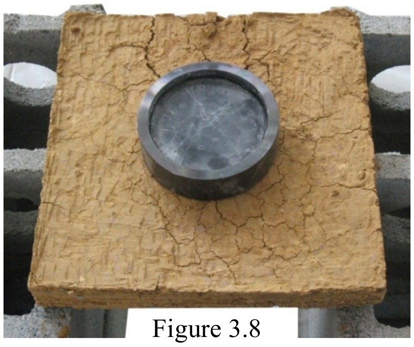


Figure 3.8

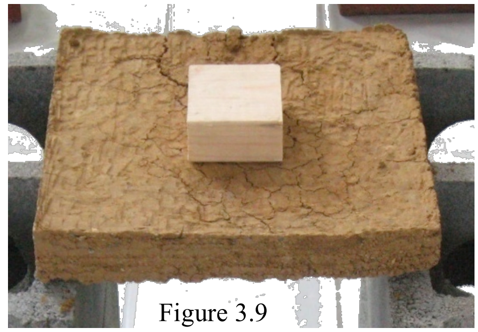


Figure 3.9

Figure 3.8: option-1, Image showing method of loading to allow for point load to distribute load centrally
Figure 3.9: option-1, Image showing method of loading to allow for point load to distribute load centrally

In addition to quantitative analysis, the value of the panel was gauged using qualitative method, where the failed fragments were inspected. Finally, two large pieces of each panel were retained for the weight and water pressure tests. The panels that appeared weaker due to their layer separation and cracking were tested for failure before the other panels. This helped determine if the initial prediction of deformation during the preparation phase held true.

Figure 3.10

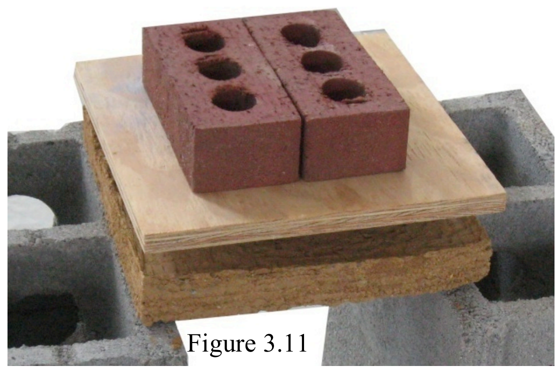


Figure 3.11

Figure 3.10: Image of Universal Dial Weighing scale (Accu-Weigh)
Figure 3.11: Image showing typical loading method used for the research project

Load test is used to evaluate the maximum load carrying capacity of a panel when compared to its self-weight. After analyzing the studies conducted by Maniatidis, V., and Walker, P., (2003), and Richerson D. W. (1992) the procedure adopted for the load test was as follows:

The self-weight of the test samples was measured using a weighing machine with the unit of measure as pounds. The two parallel edges of the panel were supported on concrete blocks. A dead load (a solid weight) weighing 4.5 pound was placed centrally on the panel. A wooden board of the dimension 1 foot x 1 foot was then placed on top to help distribute point load uniformly, the load was in the form of cored bricks weighing four pounds each. The panels were loaded until they failed; this test helped in determining the loading capacity and compressive strength properties of the panel.

Anticipated results: The panel with weaker cross-sections unable to withstand heavier loads. This test was important as it predicted the durability of the panel. The test further helped determine the failure patterns for example, if the panel failed at the edge or due to point load at the center. The edge failure suggested insufficient compaction or that it had a weaker section and that it required more energy for production.

Tests to determine feasibility of using natural binders

The weight and the water pressure tests were conducted to determine if the presence of natural water-soluble synthetic polymers causes disintegration under the influence of inclement weather conditions.

3.5.2.4 Weight test

Previous investigations by Maniatidis, and Walker, (2003), Pflughoeft-Hassett, et al. (2000) and Delgado, and Guerrero, (2007) helped formulate the weight test for this study. The weight test was carried out by immersing the samples under water for half an hour or until the sample had completely eroded, whichever occurred first. A weighing machine was used to measure the rate of disintegration. The result of the weight test was determined using quantitative test analysis procedures with measurable values of the disintegrated panels. A failure limit of the final weight of the panel being more than 1.5 times that of its self-weight was assumed. The test helped determine the amount of moisture that was absorbed by the panel, and the rate of disintegration; which helped predict the saturation levels of the panel samples. Panels with higher resultant weight were more porous, while lower values were more stable and compact (Maniatidis, V., and Walker, P., 2003; EBAA., 2006).

Anticipated results: Higher values of resultant weight show that the panel is porous, while if the values are lower, then the panels are comparatively more stable and compact. Ideally the panel should be of the right consistency and should not be more or less porous than required; it should be just sufficient enough for the panel to breathe.

3.5.2.5 Water pressure test

The test procedures for the weight test was determined using the work of Maniatidis, V., and Walker, P., (2003). In order to conduct the weight test, initially the samples were subjected to a continuous high-pressure jet of water spray for an hour or until the specimen has completely eroded, whichever occurs first. The spray nozzle was located 6 inches away from the sample. The water spray was stopped every 15 min to allow measurements of the depth of erosion with a flat-ended rod. The maximum depth is taken as the rate of erosion of the entire sample. Upon conducting the water pressure test (spray test) if the weight of the test was more than 1.5 times the initial weight of the sample, then it was established that issues related to water ingress may affect the panel performance and viability (Maniatidis, V., and Walker, P., 2003). As a result of the test the weaker samples disintegrated easily with minimal water pressure, suggesting that the panels were unable to fulfill the minimum performance criterion. The more durable panels could withstand this force and remained intact with only minor difference in strength and self-weight (Maniatidis, V., and Walker, P., 2003).

Anticipated results: The weaker samples disintegrate easily with minimal water pressure confirming the panels are incapable of achieving minimum performance. The stronger panels will withstand this force and remain intact with only minor differences in strength and self weight (Maniatidis, V., and Walker, P., 2003).

As per the various test findings, conclusions and future possibilities were formulated in Chapter six.

Chapter 4.0: General Observations

For a panel to have all the properties of being renewable, green, and degradable in nature at the same time, it would be challenging to have excellent properties of stability. The panel was easily biodegradable and could be used as a part of the external façade. Even if the panel is durable and has good compressive strength, it would fail because it won't be able to fulfill all the performance criteria for weather ability issues.

The issues and findings involved in the process of production of the test panels were documented in the form of comparisons and visuals. The discussion shall be based on analyzing the various test samples based on the following factors:

1. Preparation
    - General preparation issues
    - Required effort
    - Energy input
    - Water content
    - Rate of drying
2. Physical characteristics
    - Overall appearance
    - Color
    - Texture
    - Odor
    - Deformation
    - Shrinkage
    - Defects
3. Additional observations
    - Renewable content
    - Toxic content
    - Availability of materials
    - Advantages
    - Disadvantages

4.1 Preparation

Each of the test panels is discussed in detail below.

Table 4.1: Comparative analysis and observing stages of mixing, compaction and drying of samples

(Panel-1) Earth + 6% Portland Cement + Water	Cement is one of the best-known stabilizers. The study involved finding alternatives to replace cement with a renewable and non-toxic binding agent, and the comparisons were made in terms of the factors such as the amount of manpower and water content required for building the panel, and analyzing the sustainability of the panel. The amount of stabilizer (cement) was around 6% by volume of mix. The images depict the characteristic features of the test samples built
	
(Panel-2) Earth + Water	The combination of earth and water is one of the most conventional and traditional methods of preparing rammed earth blocks or building rammed earth structures. The process of pounding larger pieces of dirt was tedious The mix was made up of non-homogeneous composition with a mix of higher proportions of clay, porous or sponge like particles.
	

Table 4.1 continued

(Panel-3) Earth + Elmer's glue mixed + Water	With an intention to find a green and renewable binding agent, Elmer's glue was used; it is an adhesive for natural wood fibers. Its application won't cause harmful emissions that are common with the use of most other glues and adhesion base products. The mix: Since Elmer's glue tends to dry rapidly, the glue needed to be diluted with large quantities of water before mixing with the dry earth mixture to achieve optimum compaction. Dismantling the framework was cumbersome, since the earth laden with Elmer's glue stuck onto the mold.
  	
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	The mixture is composed of reclaimed clay up to 9% by volume of earth Clay is added to determine if the addition of Elmer's glue between the layers further improves the binding strength of the soil sample having high clay content. When water is added to a composition of clay rich earth: clay particles tend to become muddy, due to increase in plasticity index, thus making it difficult to achieve an optimum mixture required for compaction. The proportion of water and earth should be maintained to avoid failure due to improper compaction.
	

Table 4.1 continued

<table>
<tr><td>(Panel-5)
Earth + 6% Cornstarch + Water</td><td colspan="2">6% of Argo based (100% Cornstarch) in powdered form is mixed with the dry granular earth particles.
Cornstarch is a natural water soluble binding agent
Unlike other additives, Cornstarch doesn't interfere with the properties of earth while mixing, compaction and drying.</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>(Panel-6)
Earth + 6% Fly Ash + Water</td><td colspan="2">The dry granular particles of earth and 6% fly ash particles are thoroughly mixed with sufficient water.</td></tr>
<tr><td colspan="3"></td></tr>
</table>

4.1.1 General preparation issues

The issues related to manual construction of the test panels were documented as a comparison between the variable test panels.

Table 4.2: Comparative analysis and observations of each panel while building

(Panel-1) Earth + 6% Portland Cement + Water	Mixing ingredients with water caused the oxidation of cement accompanied with emission of a pungent odor. Cement caused dehydration; the sample needs more water to achieve a suitably damp mixture for compaction. The cement caused the mixture to dry off instantaneously; thus, it required less time for compaction and setting, but it needed twice the amount of water in comparison to a normal rammed earth panel both to obtain a damp mix and for the process of curing. The adverse effects of mixing the contents with bare hands: skin was affected with rashes and became extremely dry and scaly. Edges are sharp. The exterior surface was rough and coarse. The panel appeared non-homogeneous. The patches of cement particles on the surface appeared grayish. Thus, the panel appears to be dark and rubbery in texture. It was a durable test sample.
(Panel-2) Earth + Water	The Mix: The amount of water required for dampening the mixture of earth needs to be optimized. Unlike cement-stabilized panels, using excessive water reduces the strength of the rammed earth panel. Water hinders the process of earth compaction; the water by nature is a good binder. For example, wet paper adheres to any surface it comes in contact with. Similarly, optimum water content is required to give earth its binding properties. The intensity of lifts applied during compaction gives optimum strength to the panel. If the amount of moisture increased, then the earth is unsuitable for compaction, as the mass of moist earth adheres onto the surface of the pounding tool "mallet." Not only this, but the action of pounding tears the rammed earth layer during compaction, thus the earth that had already been rammed and anchored would tear off, making the panel weaker A mixture that is excessively damp tends to dry slowly, while uneven drying causes voids within the panel. When such panels are installed in places where frost is accompanied with high humidity levels, it may cause internal condensation of the panel. Lower temperatures causes the water molecule locked within the cross-section of the panel to freeze. Exposure of the panel to higher temperatures causes expansion; this in turn causes failure due to cracking. The nature of the material is such that the panel won't dry evenly and the content -

Table 4.2 continued

	-toward the edges and corners of the panel dry more rapidly when compared to the central area, resulting in a non-uniform cross-section. This leads to surface cracks at the edges that may cause water seepage problems. The hairline cracks that had appeared on the surface of the panel due to shrinkage vanished when completely dry. The layering was visible towards the edges of the panel. The load test was used to find the optimum binding strengths. This test helped determine the amount of manpower required for compaction of the earth. One of the future research possibilities is to determine if the voids form a capillary-like valve, allowing water to seep within the section of the panel. The water molecules within the gaps don’t dry completely, making weaker cross-sections (Hall, M., and Djerbib, Y, 2004; Correia, J. R., et al. 2006).
(Panel-3) Earth + Elmer's glue mixed + Water	The panels were built using a mixture of Earth and Elmer's glue. The panel was comparatively light. The mixture of earth and Elmer’s glue dry rapidly. Due to uneven drying condition, the sample required 6 to 7 weeks to dry and achieve optimum strength. During the initial phase of drying, hairline cracks appeared on the surface while the edges appeared weaker, but when the panel dried up completely, it attained peak strength. The panel appeared to be golden brown in color; the presence of the hairline cracks may not be appealing but the rear of the panel was clean and thus could be applied as a part of the panelized system. The dry shear strength of Elmer’s glue is larger than earth. Drying is associated with shrinkage. The glue mixed in the earth bonds onto the surface of the frames stretching the panel apart, causing cracks. The edges of the panel chipped off while dismantling the framework. The strong odor of Elmer's glue was prevalent during the process of panel building. The edge condition indicated that the Elmer's glue caused the fine granular particles to bond into clusters.

(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	The clay dries more rapidly than earth, causing undue shrinkage. For the panel to have better strength, the mix should not have more than 15 to 30 % of clay content. A panel built with clay rich mixture needs to dry under controlled temperatures initially to gain maximum strength. At higher temperatures the panel has better strength properties; thus, the panel was kept to dry under a plastic cover so that the panel attains optimum strength. It is evident by appearance of surface fissures that the binding strength of clay was not fully utilized. The exposed part of the panel comprising the top layer and the edges dry more rapidly causing shrinkage, tearing the layers apart from each other.

	The application of Elmer's glue in between the layers was analyzed by adapting the weight test and the water pressure test. The panel is made up of non-homogeneous mixture of clay and earth, the flaw was evident both visually as well as structurally. The panel appeared dull and weak. The initial analysis suggested that the panel might fail to sustain the crumble and the scratch test. The dehydrated panel had natural affinity for water; contact with water made the panel gooey.
(Panel-5) Earth + 6% Cornstarch + Water	The panel was comparatively easy to build. Drying the panel caused surface shrinkage. The starch being water-soluble has natural affinity for water. Exposure to high humidity levels caused undue surface deposits.
(Panel-6) Earth + 6% Fly Ash + Water	Panel appeared dark brown in color, with spots of crystalline carbon particles. Comparatively long drying period. The edges of the panel show distinct uneven settlement.

4.1.2 Required effort

If it takes too much effort to build a panel manually, then mechanized methods need to be adopted. For small-scale application this would not be affordable. If the mixture gets too murky, it might be difficult to compact. The rate of drying may vary as per the properties of materials used. Irregularity in drying may cause weaker panels. The graph below is a qualitative comparison graded in terms of a one to six scale between the variables. The panels were graded based on the assumptions and observations noted while building the panel onsite.

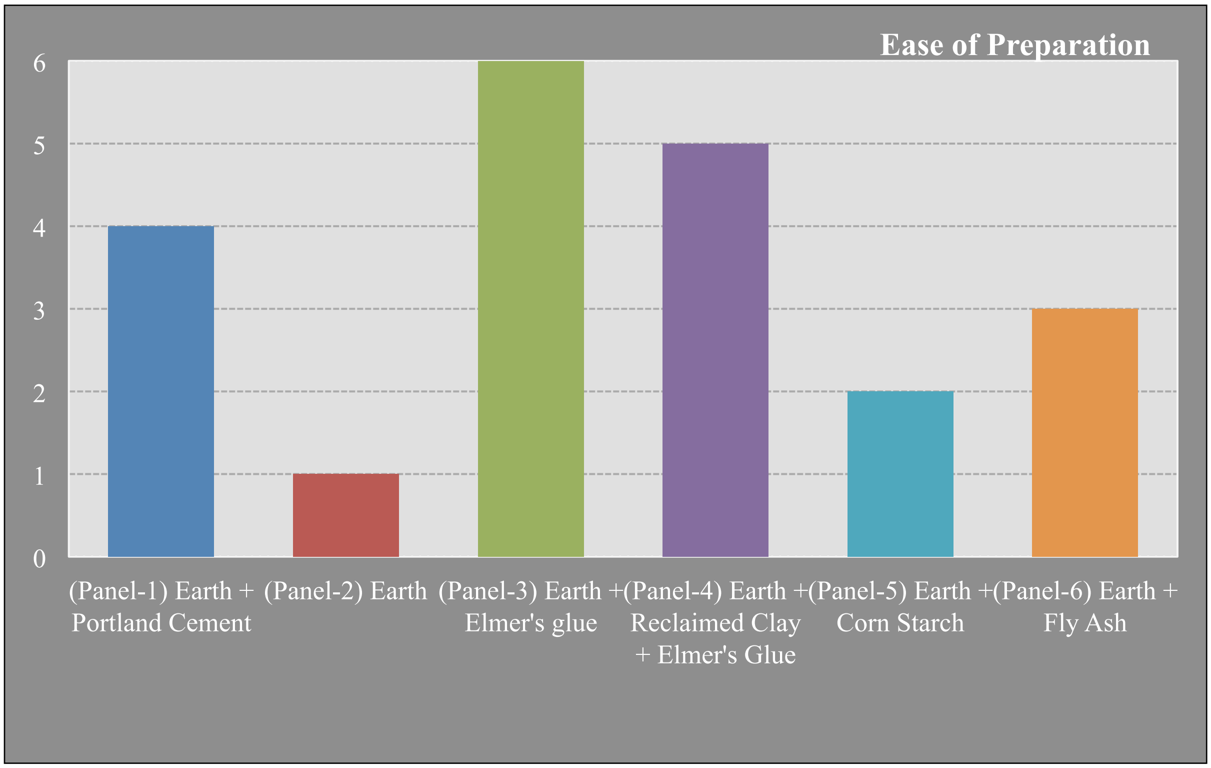


Figure 4.1: Qualitative analysis for ease of preparation of variable sample

The graph above suggests that the un-stabilized earth panel could be built with minimum effort, while it required the most effort to build the panel made up of a mixture of earth and Elmer's glue. The binders starch and fly ash are more compatible when used in combination with the earth mixture.

Table 4.3: Comparative analysis and observing ease of preparation of variable test samples

(Panel-1) Earth + 6% Portland Cement + Water	Controlled addition of water during curing helps ease the production process. Due to the rapid drying nature of cement, mixing with the bare hands can cause excessive dehydration of the skin. It may also cause scaling of the skin and rashes. Utmost care is required during the initial phase of drying; the panel needs to be cured under cover for at least one and half weeks before letting in open air for drying.
(Panel-2) Earth + Water	Panel-2 is one of the easiest to build but care needs to be taken to achieve the optimum water content to the mix. The panel needs to be covered to allow for slow and controlled drying.
(Panel-3) Earth + Elmer's glue mixed + Water	Due to the rapid drying nature of Elmer's glue, it takes much more effort to work with this mixture as it dried even before the mix could be completely compacted. Water needed to be added constantly to maintain the consistency. Proper drying conditions would help attain maximum strength.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Due to excessive clay content, more effort is required to achieve optimum moisture content. The optimum compaction could not be achieved due to the non-uniform mixture with the wet clay content.
(Panel-5) Earth + 6% Cornstarch + Water	Preparation of the panel is easy and quick, due to the addition of fine granular Cornstarch powder. Optimum care was needed during drying.
(Panel-6) Earth + 6% Fly Ash + Water	Preparation of this option was easy, as fly ash doesn't interfere with the workability of the panel.

4.1.3 Energy input

The panels were graded based on the assumptions and observations noted while building the panel onsite. The graph below is a qualitative comparison graded in terms of a one to six scale between the variables. Energy Input was measured using the following factors:

- Production of the base material
- Transportation of the materials
- Ease of mixing materials
- Amount of water needed to make a consistent mixture
- Amount of pressure needed for compaction

- The drying period

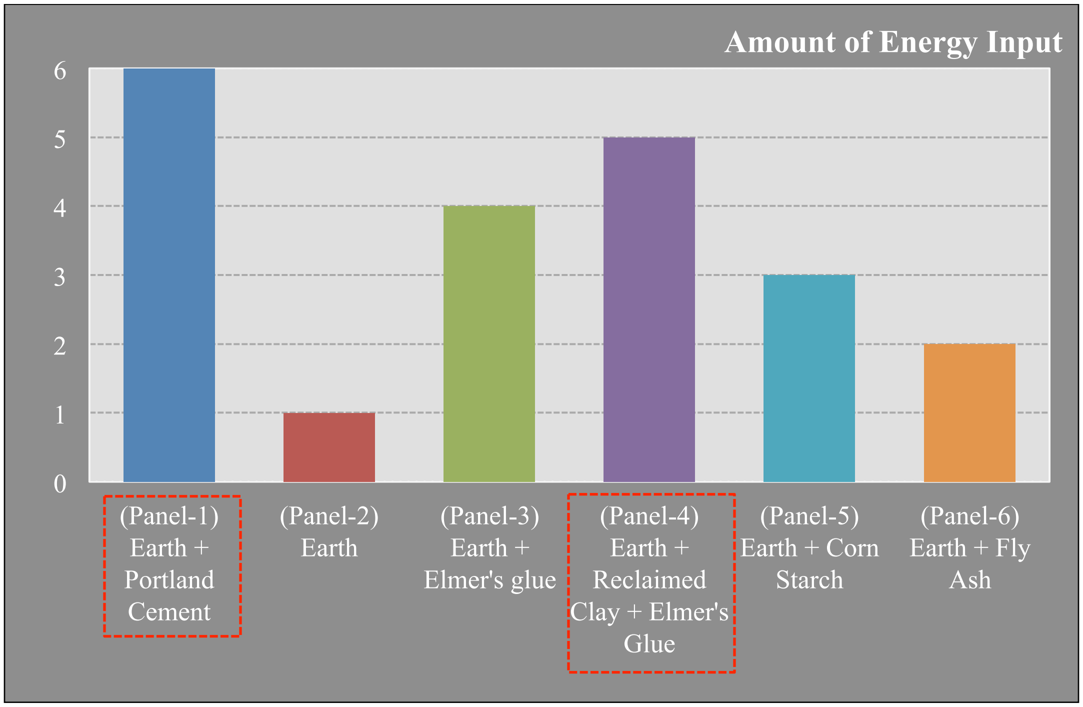


Figure 4.2: Qualitative analysis for amount of energy input for a variable sample

The garph above suggests that Panel-2 required the least energy input since earth is freely available; it required least effort for the preparation and fulfilled most of the measures mentioned above. Panel-1 made of earth and portland cement required the maximum energy input.

Table 4.4: Comparative analysis and observed amount of effort required for building the test samples

(Panel-1) Earth + 6% Portland Cement + Water	The amount of effort required to build the cement stabilized earth panel was considerable large. The embodied energy of cement is high, particularly when considering the transportation costs. The amount of water needed for mixing was high. The drying period was relatively long. It fulfills most of the performance criteria, but the panel does not easily decompose after use.
(Panel-2) Earth + Water	The Earth panel built without stabilization stands out in comparison to the other test samples because it requires less effort and has lower embodied energy.
(Panel-3) Earth + Elmer's glue mixed + Water	Construction of this panel involved considerable effort for mixing and compaction.

(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Construction of this panel involved substantial effort to build the panel. This panel was not very durable.
(Panel-5) Earth + 6% Cornstarch + Water	While it has a low embodied energy and required relatively little effort, the panel would require a waterproofing layer to work well.
(Panel-6) Earth + 6% Fly Ash + Water	The properties of fly ash helped improve the tensile strength and should reduce moisture ingress.

4.1.4 Water content needed for mixing

An optimum amount of water was required to make a consistent mixture that achieves maximum strength. Hence, it was important to keep an account of the amount of water required while mixing. The graph below shows a comparison of water used to prepare the samples of the variables used, which are graded on a one to six scale. The panels were graded based on the assumptions and observations noted while building the panel onsite.

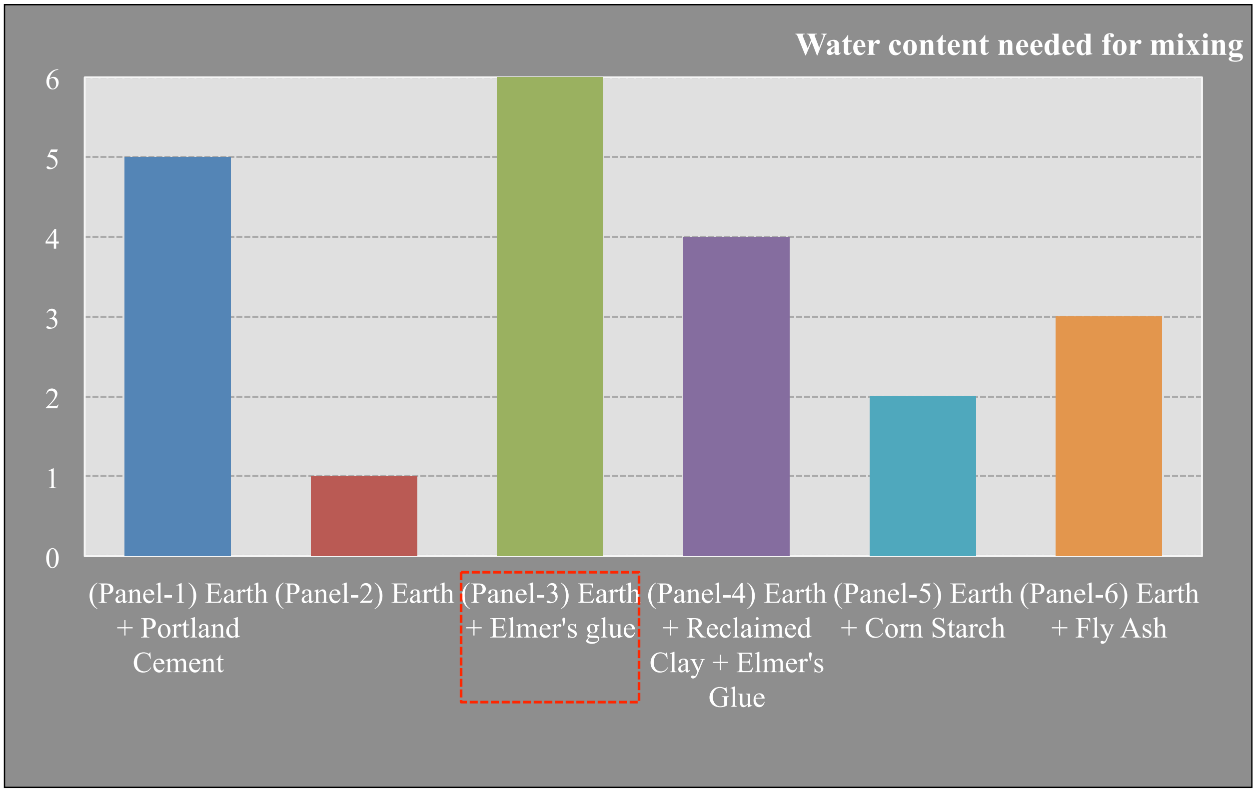


Figure 4.3: Qualitative analysis of water content needed for production of panel

The graph above suggests that panel-2 made of un-stabilized earth comparatively required the least amount of water during the preparation of the panel. Similar trends were observed for effort required to build the panel as well as the amount of the water content. Elmer's glue dries rapidly and requires more water than other panels during the mixing and compaction process.

Table 4.5: Comparative analysis and observed water content required for building the test samples

(Panel-1) Earth + 6% Portland Cement + Water	The production of the panel required comparatively higher quantities of water.

(Panel-2) Earth + Water	The earth panel without stabilizers requires only enough water to dampen the earth for compaction.
(Panel-3) Earth + Elmer's glue mixed + Water	The Elmer's glue tends to dry rapidly; the mix needed more water than the other panels during mixing and compacting.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Since the Elmer's glue was applied without dilution directly between layers, therefore, the water was introduced independent of the Elmer's glue. Water was sprinkled carefully to achieve a consistent mixture of the clay and earth.
(Panel-5) Earth + 6% Cornstarch + Water	The mixture needs careful control of the water content to achieve maximum strength. The Cornstarch being water-soluble did not affect the consistency of the mixture.
(Panel-6) Earth + 6% Fly Ash + Water	Fly ash is not water-soluble, and when added to water, it tends to float. Hence, more water is needed for ease of compaction.

4.1.5 Rate of drying

The time required for drying a test panel was dependent upon the properties of the base materials. The graph below is a qualitative comparison between the variable samples built graded on a scale one to six. The panels were graded based on the assumptions and observations noted while building the panel onsite.

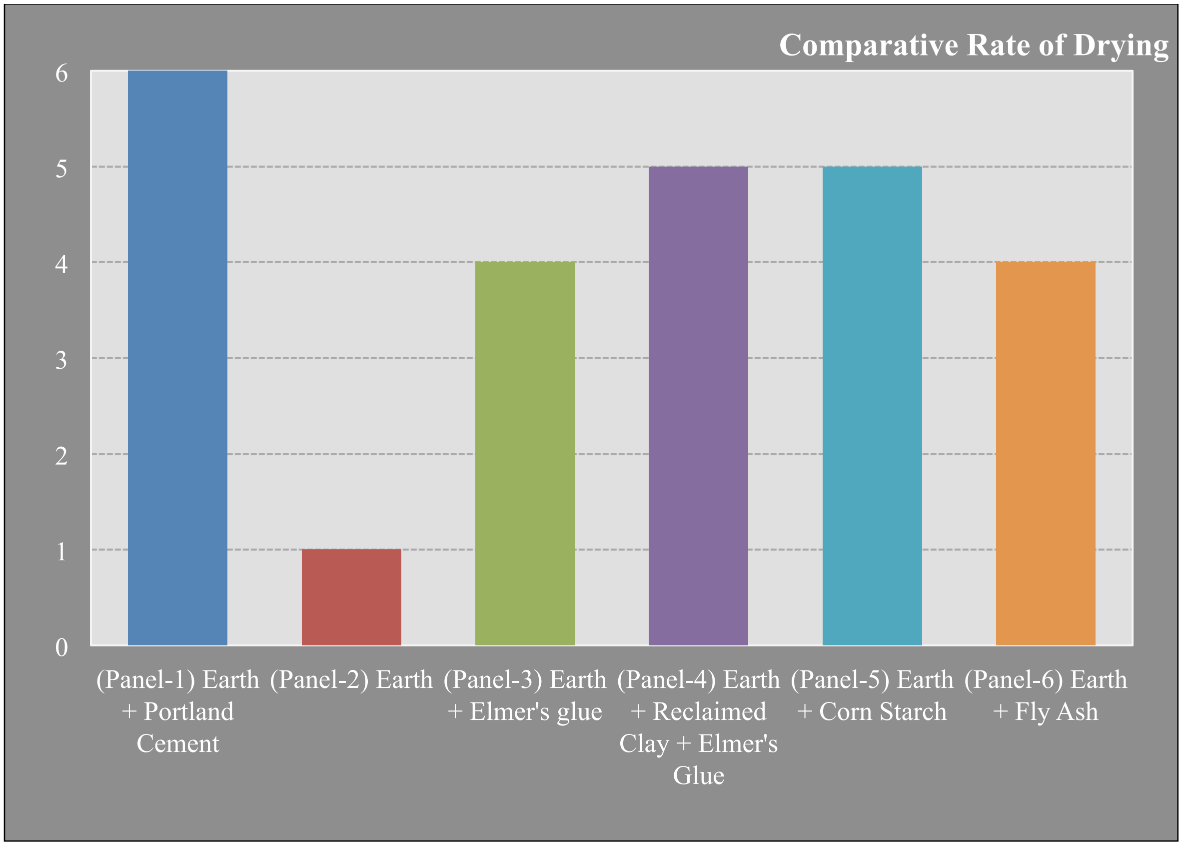


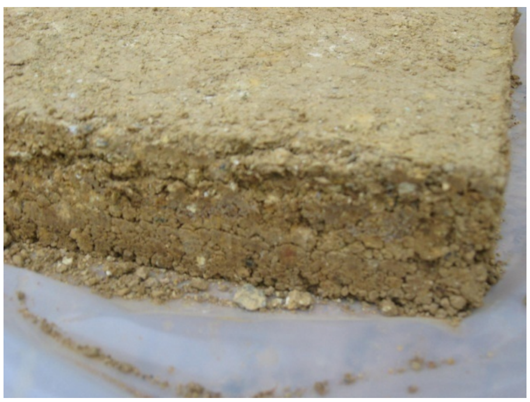
Figure 4.4: Chart emulating Qualitative analysis for Comparative rate of drying at the phase of production

The graph above suggests that panel-1 attains the desirable strength when the panel is cured slowly. Thus, it required the most amount of time to dry and attain strength. The pattern observed in the graph suggests that panel-4 and panel-5 requires more time to dry in comparison to panel-1. One of the major reasons could be the water soluble nature of the binding agents used for increasing the strength of panel-4 and panel-5.

Table 4.6: Comparative analysis and observed rate of drying of test samples during production

(Panel-1) Earth + 6% Portland Cement + Water	In order to achieve the desirable strength, the initial drying period must be slow.
(Panel-2) Earth + Water	The panel dried evenly and at a typical rate, but experienced a very high rate of shrinkage.
(Panel-3) Earth + Elmer's glue mixed + Water	The Elmer's glue seems to trap the moisture present within the cross-sections of the panel, thus the panel dried at a slow rate.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Unusual drying, as the rate of drying for clay differs from that of earth and Elmer's glue. The moisture is trapped between the cross-sections, causing air bubbles.
(Panel-5) Earth + 6% Cornstarch + Water	Both earth and Cornstarch dry at a rapid rate when exposed to moisture. The panel is saturated at higher humidity levels.
(Panel-6) Earth + 6% Fly Ash + Water	The panel made of fly ash and earth dried at a normal rate.

Table 4.7: Edge Condition

(Panel-1) Earth + 6% Portland Cement + Water	(Panel-2) Earth + Water
	
(Panel-3) Earth + Elmer's glue mixed + Water	(Panel-4) Earth + 9% Clay + Water + Elmer's Glue applied between layers
	
(Panel-5) Earth + 6% Cornstarch + Water	(Panel-6) Earth + 6% Fly Ash + Water
	

4.2 Physical characteristics

4.2.1 Overall appearance

The test sample was considered to be a part of the external wall system and thus the appearance of the panel must be taken into account. A panel with blotches, spots, pitting, or irregularities in shape would not be appropriate. Test samples with natural colors typically had a greater appeal. Most of the test panel showed uneven settlement between layers at the edges. However, this was not the guiding factor for determining whether the panel was thought to be weak or would fail during the strength tests. The sides of the framework made it difficult for proper compaction at the edges.

Table 4.8: Comparative analysis and observed properties related to the appearance of the test samples

(Panel-1) Earth + 6% Portland Cement + Water	The panels had consistent cross-sections, little surface shrinkage, and clean edges without uneven settlement. The cement results in grayish coloration making it unattractive when compared to a typical un-stabilized earth panel.
(Panel-2) Earth + Water	The earth panel had consistent cross-sections which was aesthetically appealing
(Panel-3) Earth + Elmer's glue mixed + Water	The surface of the panel is covered with hairline cracks due to uneven shrinkage. The edge finish is even but composed of clumps of earth, making it unattractive. The rear of the panel is free of any deformation. The panel is lightweight. Addition of Elmer's glue tends to enhance the tensile strength.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Appearance is pale and made up of frail cross-sections.
(Panel-5) Earth + 6% Cornstarch + Water	The panel reacts in situations of humidity levels. White patches on the surface reveal the presence of starch. Absence of fungal growth. Uneven settlement of the layers toward the edges.
(Panel-6) Earth + 6% Fly Ash + Water	Crystalline particles of less than 1/8inch were visible on the surface of the panel. The natural color of earth is prominent. Visually appealing.

4.2.2 Color

The color of the panel was another consideration. A panel that appeared dull indicated susceptibility to failure, and was judged to be less appealing.

Table 4.9: Comparative analysis and observed color properties of the test samples

(Panel-1) Earth + 6% Portland Cement + Water	Grayish buff	
(Panel-2) Earth + Water	Golden brown	
(Panel-3) Earth + Elmer's glue mixed + Water	Golden brown	
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Dull dark brown with specks of gray	
(Panel-5) Earth + 6% Cornstarch + Water	Golden brown with white patches of starch deposits	
(Panel-6) Earth + 6% Fly Ash + Water	Grayish brown with specks of black	

4.2.3 Texture

The texture of the panel was another consideration. If the panel is rough to the touch, it may not be appropriate for application as an interior surface.

Table 4.10: Comparative analysis and observed texture properties of variable test samples

(Panel-1) Earth + 6% Portland Cement + Water	Rough, rubbery texture
(Panel-2) Earth + Water	Smooth, clean finish
(Panel-3) Earth + Elmer's glue mixed + Water	Scaly, rough finish
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Dry, parched, barren, easily peeled off with a patchy feel
(Panel-5) Earth + 6% Cornstarch + Water	Even, crackled feel

4.2.4 Odor

A panel that emanates odor is undesirable and could indicate emission of harmful gases.

Table 4.11: Comparative analysis and observed odors or emissions

(Panel-1) Earth + 6% Portland Cement + Water	Preparation of the panel was accompanied with release of pungent odors and gaseous emissions, but after drying in the open, the odor is reduced considerably.
(Panel-2) Earth + Water	Earth panel is odor free.
(Panel-3) Earth + Elmer's glue mixed + Water	The panel is accompanied with strong odors of the Elmer's glue, but after drying, the odor diminished.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	When clay is immersed in water for a long time, it emanates pungent odors; the panel is odor free after drying.
(Panel-5) Earth + 6% Cornstarch + Water	Cornstarch is odor free.
(Panel-6) Earth + 6% Fly Ash + Water	There is no observed odor associated with fly ash.

4.2.5 Deformation caused during preparation and drying

The initial analysis also involved observing surface deformations. The graph below is a comparison of the percent volume between the six variable samples built. The initial deformation during the drying process was observed and measured in terms of the panel's volume. This could help anticipate the possible failure on application of the load or when exposed to water.

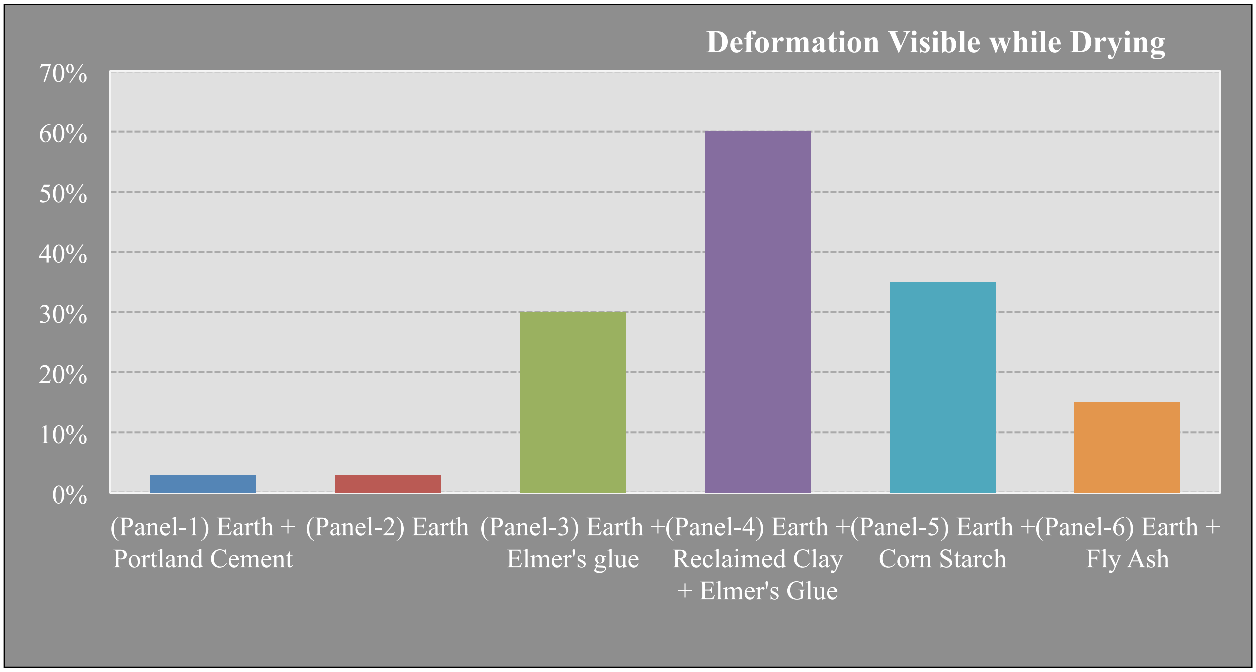


Figure 4.5: Comparative analysis of deformation visible during drying phase of production

The graph suggests that most of the initial deformation is observed in panel-4, which is composed of earth, reclaimed clay and Elmer's glue. This could be due to the combination of the materials having varying rates of drying and adhesion properties.

Table 4.12: Comparative analysis and observed deformation of the test samples during production

(Panel-1) Earth + 6% Portland Cement + Water	The panel had a stable structure, with minimum defects caused during the preparation and drying process.
(Panel-2) Earth + Water	The panel appears to have a stable structure, with minimum defects caused during the preparation and drying process.
(Panel-3) Earth + Elmer's glue mixed + Water	It was impossible to compact the earth mixture without addition of water. Even after the addition of water, the moist dirt dried before the layer could be fully compacted. The Elmer's glue and earth mixture adheres to the wood framework; the edges of the panel had to be struck with a hammer tool to separate it from the framework,

	consequently a portion of the edge chipped off. Improper drying led to stretching of the panel, causing multiple surface fissures. Once the panel was separated from the framework, the panel regained strength and demonstrated a strong interface between layers.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	The soil used for the panels was rich in clay content. Excessive clay hampers the soil interface, thus the mixing process was difficult. The compacting was tedious and the optimum pressure could not be applied. The moist clay adhered to the mallet tearing layers of the compacted earth. Clay has a resiliency and, therefore, deformation or folds will show immediately after the panel is completely dry. The addition of Elmer's glue between the layers didn't help to eliminate this problem.
(Panel-5) Earth + 6% Cornstarch + Water	Outdoor weathering conditions caused surface cracks. White patches of starch deposits were visible on the surface.

Table 4.13: Edge and Corner Detail

(Panel-1) Earth + 6% Portland Cement + Water	(Panel-2) Earth + Water
	
(Panel-3) Earth + Elmer's glue mixed + Water	(Panel-4) Earth + 9% Clay + Water + Elmer's Glue applied between layers
	
(Panel-5) Earth + 6% Cornstarch + Water	(Panel-6) Earth + 6% Fly Ash + Water
	

4.2.6 Panel shrinkage

Observing the shrinkage property of the panels during the forming phase helped to anticipate the failure pattern during the experimental tests. The shrinkage was observed to be dependent on the amount of moisture content, the clay content, and the material properties. For example, when a material like earth is mixed with Elmer's glue, the built panel shrunk in all directions, causing uneven surface conditions. Higher rate of shrinkage indicates failure to sustain weather cycling (Maniatidis, V., and Walker, P., 2003). It also indicates that the panel may experience problems related to water seepage, internal condensation and low resistance to wear. Improper compacting causes uncontrollable shrinkage. The graph below is a qualitative comparison between the six samples built graded on a scale of one to six. The panels were graded based on the assumptions and observations noted while building the panel onsite.

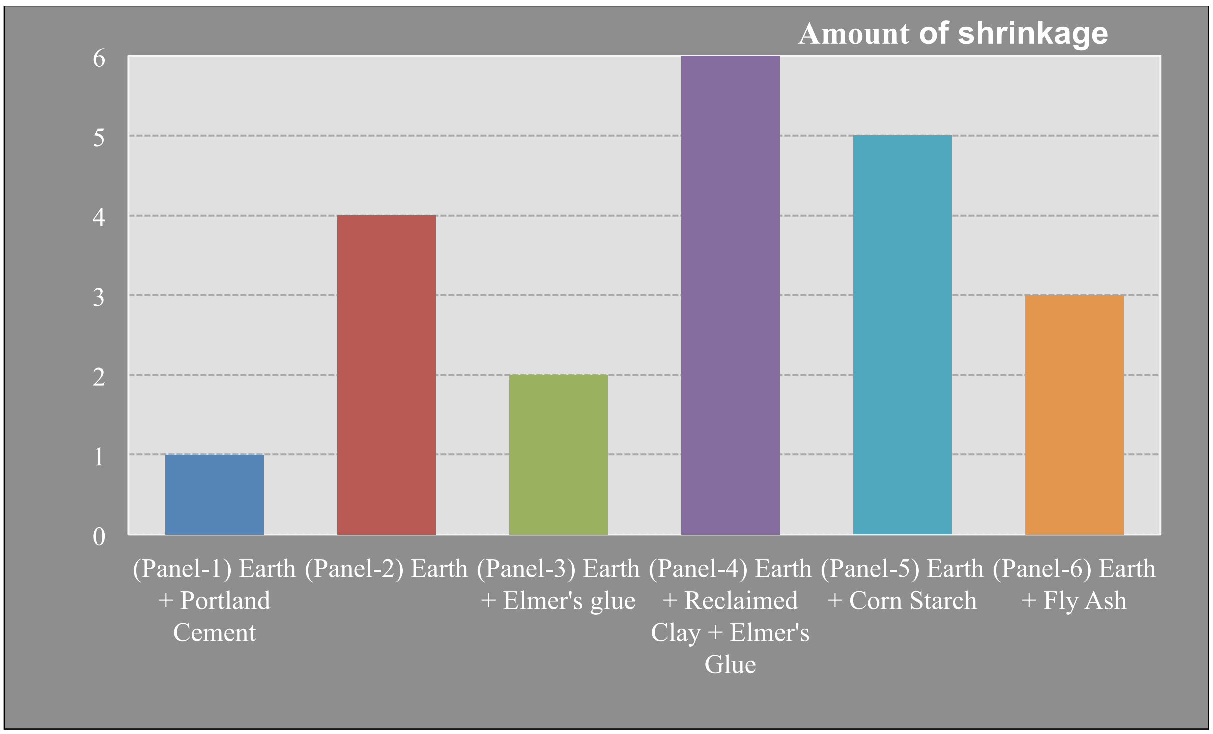


Figure 4.6: Qualitative analysis of amount of shirkage during production of panel

The graph rates panel-4 composed of earth, reclaimed clay and the Elmer's glue mixture as the panel having maximum shrinkage, while panel-1 composed of Earth and Portland cement, was more successful and had a low rate of shrinkage.

Table 4.13: Comparative analysis and observed shrinkage of test samples during production

(Panel-1) Earth + 6% Portland Cement + Water	With proper curing (initial drying is slow) and the appropriate water content levels, the panel shrinks evenly without surface cracks or uneven settlement between layers.

(Panel-2) Earth + Water	Desired compaction achieved, requires lower water content. It dries evenly, but the size of panel shrinks considerably.
(Panel-3) Earth + Elmer's glue mixed + Water	The panel shrinks unevenly in all directions. On drying the panel achieves maximum strength.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Uneven shrinkage of the panel.
(Panel-5) Earth + 6% Cornstarch + Water	The panel tends to dry very slowly. Since Cornstarch is water soluble, it tends to saturate easily at high humidity levels and it is not easy to achieve complete drying. The shrinkage causes surface fissures.
(Panel-6) Earth + 6% Fly Ash + Water	The panel shrinks evenly on drying.

Table 4.15: Surface finish of panel on drying

(Panel-1) Earth + 6% Portland Cement	(Panel-2) Earth + Water
	
(Panel-3) Earth + Elmer’s glue mixed + Water	(Panel-4) Earth + 9% Clay + Water + Elmer’s Glue applied between layers
	
(Panel-5) Earth + 6% Cornstarch + Water	(Panel-6) Earth + 6% Fly Ash + Water
	

4.2.7 Defects observed during preparation

It was very important to know when deformation occurred to determine the reasons for the failure of a given panel.

Table 4.14: Comparative analysis and observed defects of test samples during production

(Panel-1) Earth + 6% Portland Cement + Water	No defects were observed during compacting or the drying process.
(Panel-2) Earth + Water	No defects were observed during compacting or the drying process.
(Panel-3) Earth + Elmer's glue mixed + Water	Measurable defects were observed during the mixing, compacting and drying process.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Measurable defects were observed during the mixing, compacting and drying process.
(Panel-5) Earth + 6% Cornstarch + Water	Measurable defects were observed during the drying process.
(Panel-6) Earth + 6% Fly Ash + Water	Measurable defects were observed during the drying process.

4.2.8 Views explaining the defects observed in the panels

(Panel-1) Earth + 6% Portland cement + Water

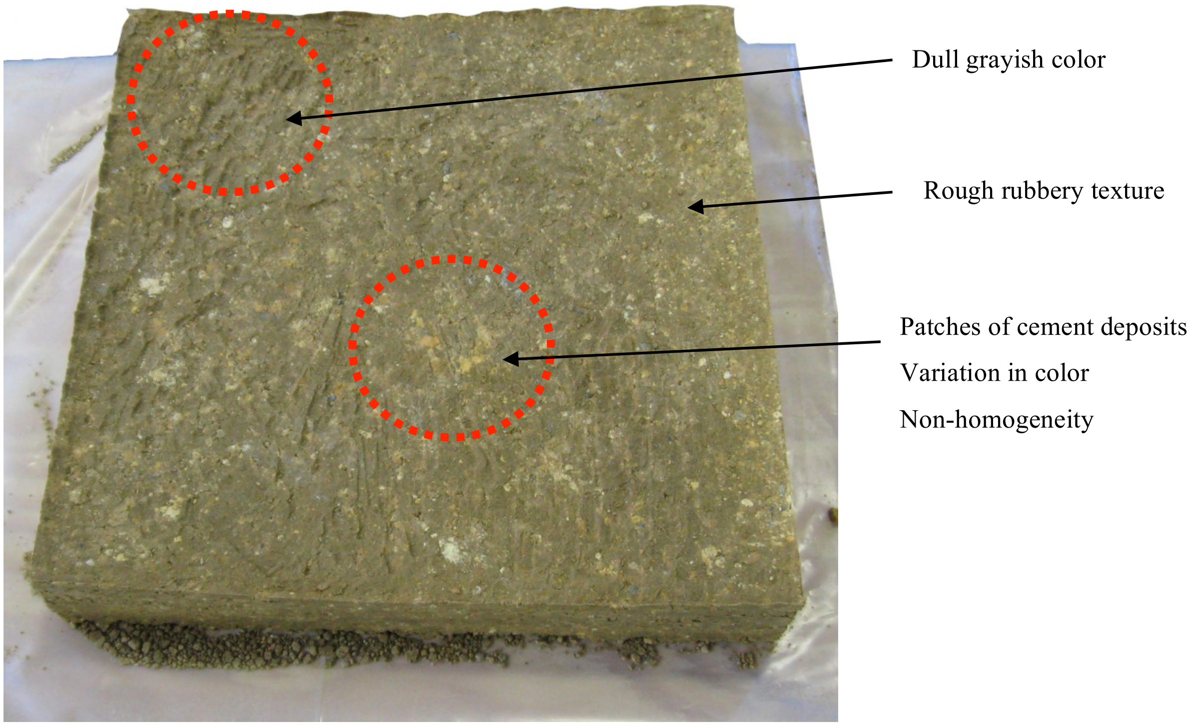


Figure 4.7: Planner view of (Panel-1) Earth + Cement

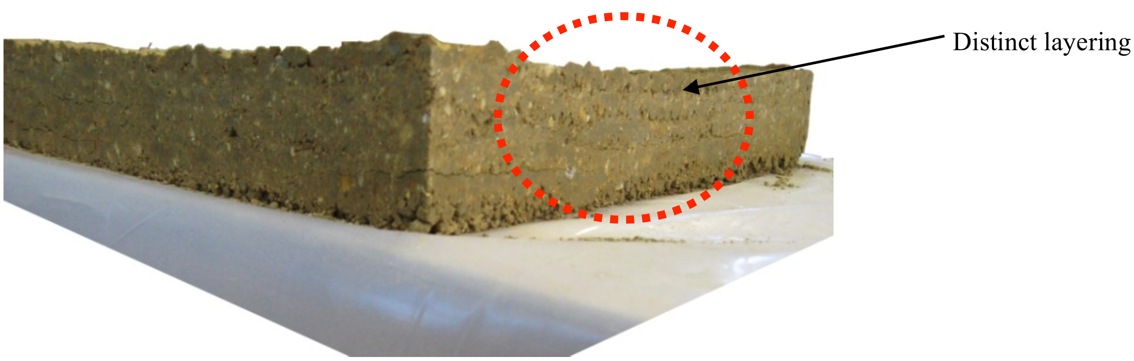


Figure 4.8: Corner detail of (Panel-1) Earth + Cement

(Panel-2) Earth + Water

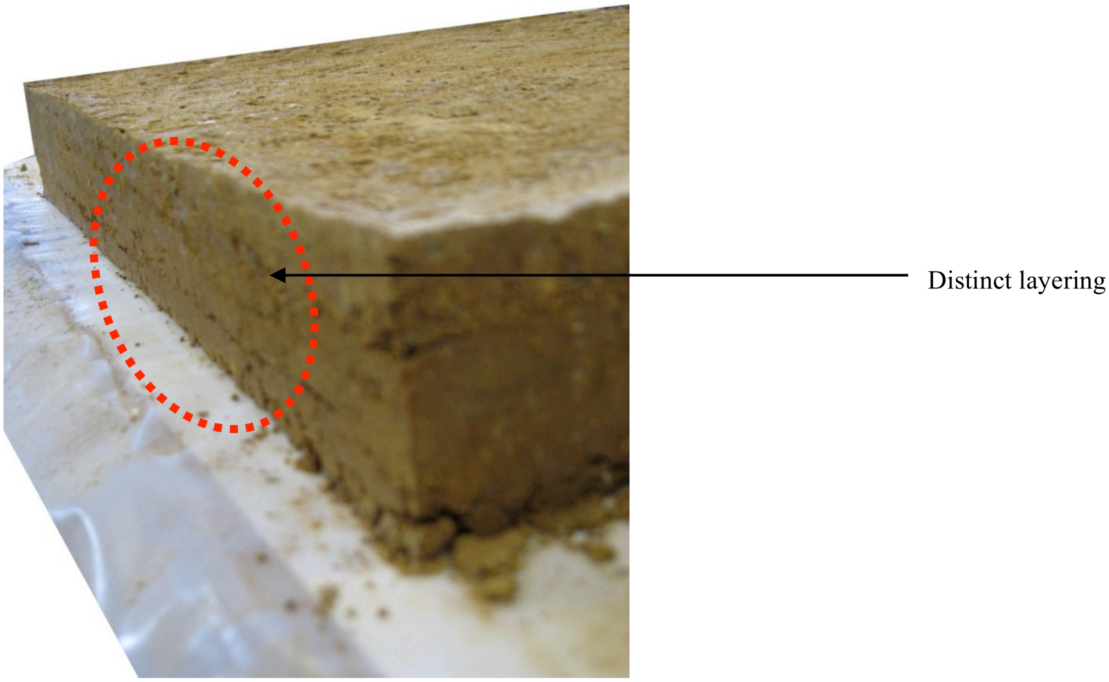


Figure 4.9: Edge detail (Panel-2) Earth

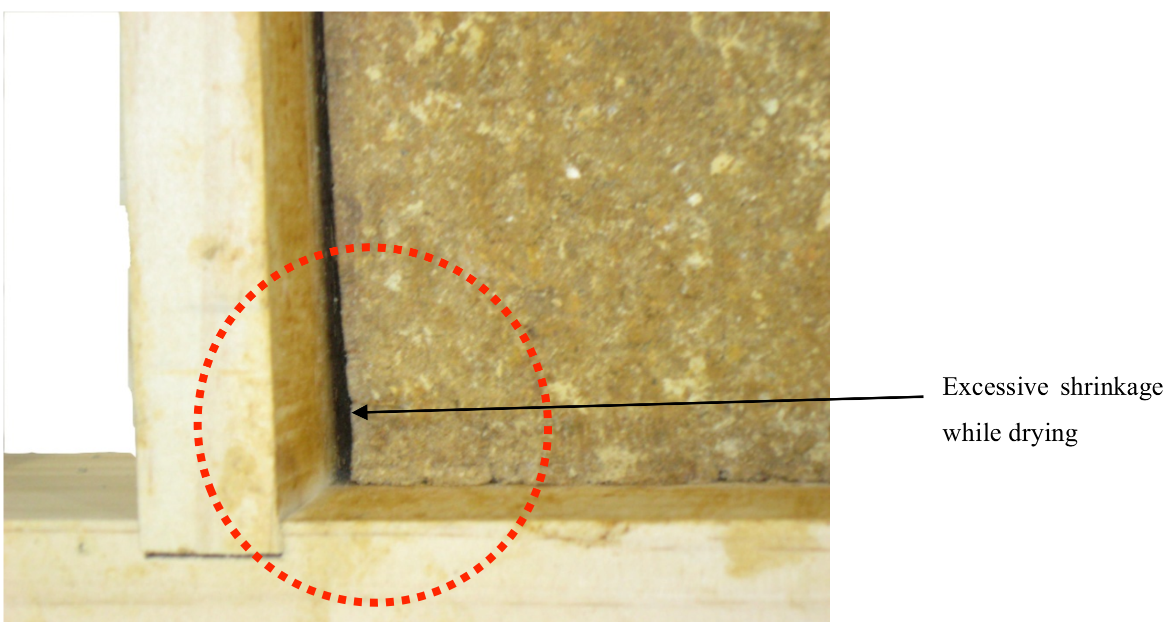


Figure 4.10: Shrinkage observed while drying (Panel-2) Earth

(Panel-3) Earth + Elmer's glue mixed + Water

Figure 4.11: Edge detail (Panel-3) Earth + Elmer’s glue

Figure 4.12; Earth stuck on to mold (Panel-3) Earth + Elmer’s glue

(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers

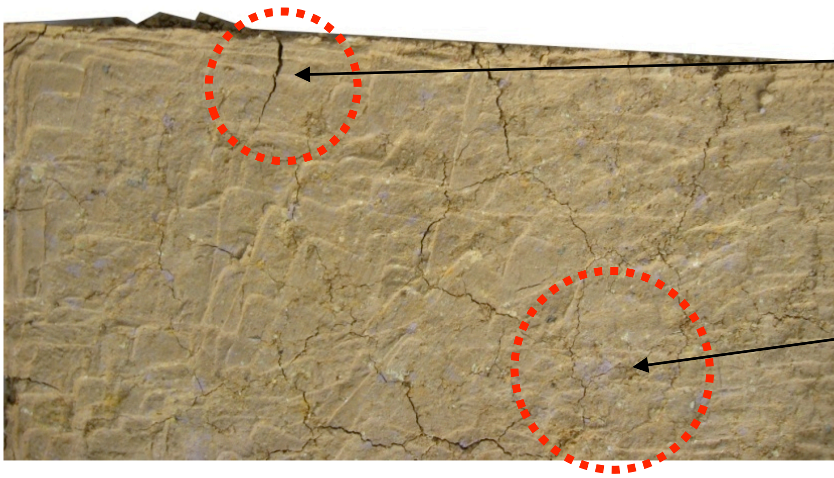


Figure 4.13: Surface cracks on Panel-4 Earth + Elmer’s glue + Clay

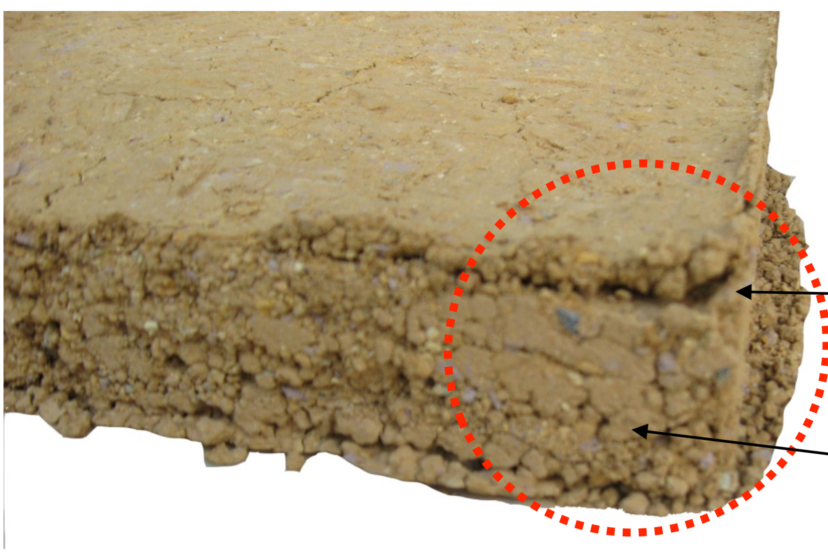


Figure 4.14: Corner detail Panel-4 Earth + Elmer’s glue + Clay

(Panel-5) Earth + 6% Cornstarch + Water

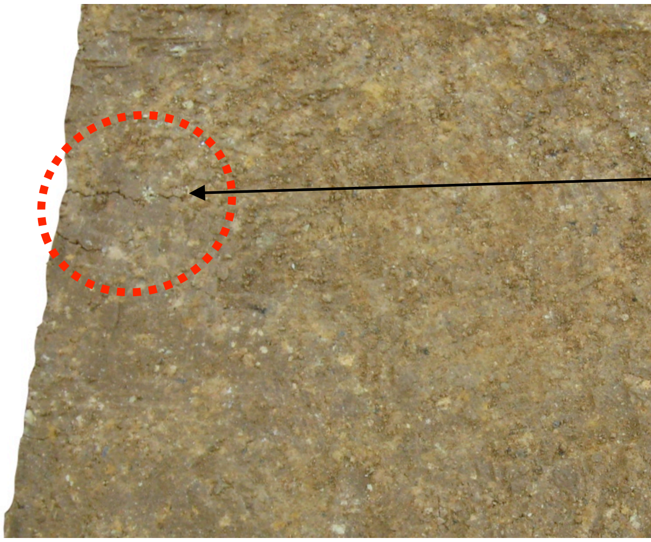
Patches of starch deposits

Figure 4.15: Planner surface of (Panel-5) Earth + Cornstarch

Improper compaction condition at the edges

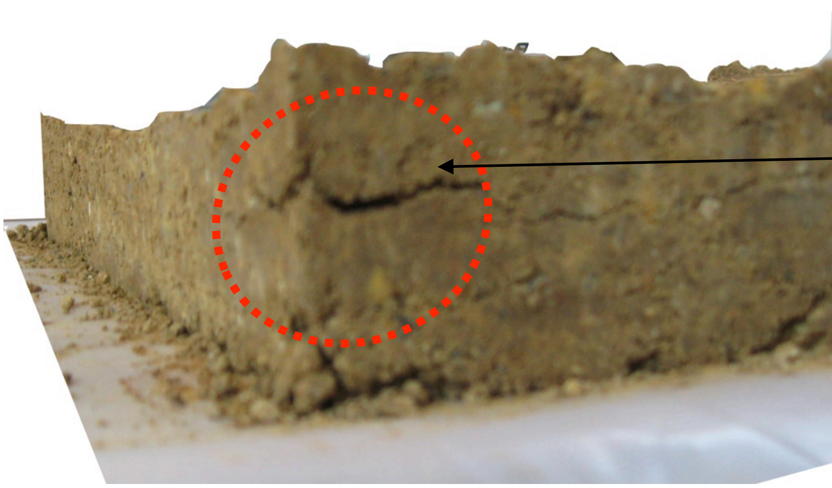
Figure 4.16: Corner Detail for (Panel-5) Earth + Cornstarch

(Panel-6) Earth + 6% Fly Ash + Water



Irregular cracks appear during drying, panel was fine during compaction

Figure 4.17: Planner surface of (Panel-6) Earth + Fly Ash



Layers spread apart during drying; otherwise it seems like an even section

Figure 4.18: Corner detail of (Panel-6) Earth + Fly Ash

4.3 Additional observations

4.3.1 Renewable content

A goal of the thesis was to produce a panel that would be completely renewable and non-toxic while complying with the performance mandates. The intent of the project was to reduce the use of components like cement with high-embodied energy and encourage the application of greener alternatives. Table 4.15 below is a comparison between the panels in terms of the renewability of the materials used. Figure 4.7 is a comparison in percent volume of the renewable content for the six samples. The measurements were based on observations noted by the author during the construction of the panels.

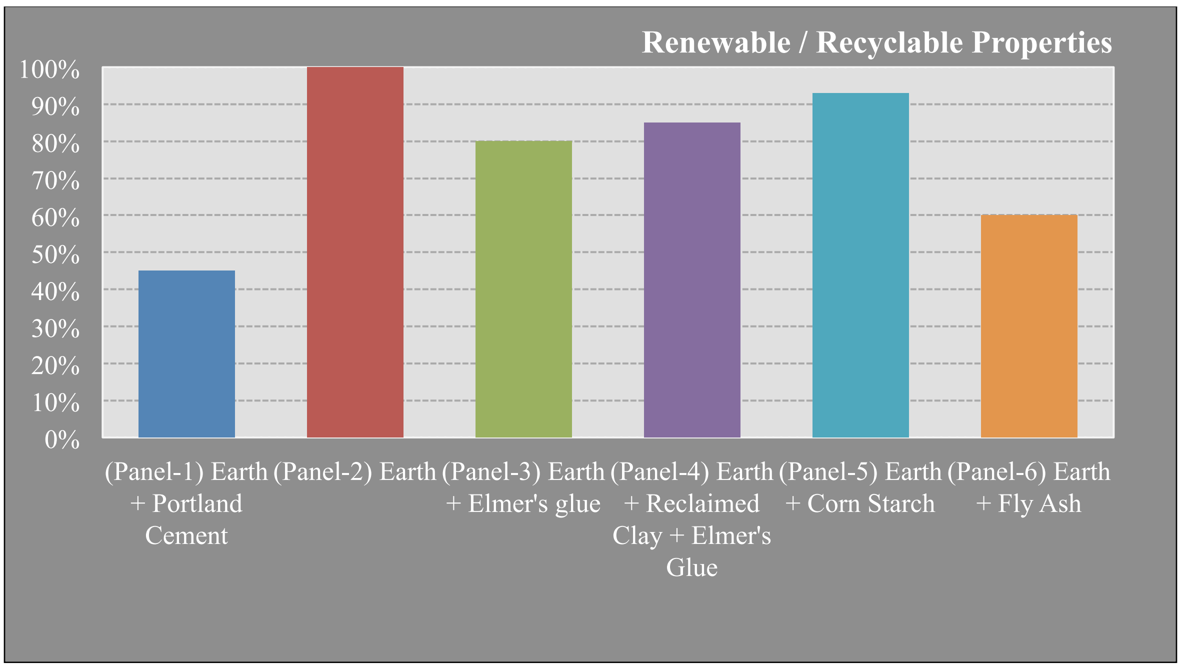


Figure 4.19: Comparative analysis for Renewable materials content for the alternative samples

The graph suggests high percentage of renewability for each panel type. Considering Earth is naturally available panel-1 shows maximum percent renewability, while the renewable properties of the cement and fly ash are low so the panel-1 and the panel-6 have lower values.

Table 4.15: Comparative analysis for renewable material content for the samples

(Panel-1) Earth + 6% Portland Cement + Water	Due to the addition of Portland cement, the panel cannot be considered renewable. The panel won't decompose on disposal. The segregation of components on mixing is difficult and not feasible.

(Panel-2) Earth + Water	The panel is completely renewable. The components can be reused to build similar panels.
(Panel-3) Earth + Elmer's glue mixed + Water	The Elmer's glue used for the study was a polyvinyl acetate emulsion (PVAC). A greener version of Elmer's glue having similar binding properties is commercially available. This new product is composed of milk based Casein. Considering that Elmer’s glue is a water soluble binding agent, it should easily decompose when disposed. The segregation of the primary components should be easy.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layer	All the components should easily disintegrate when disposed.
(Panel-5) Earth + 6% Cornstarch + Water	Cornstarch is a natural derivative binding agent for the panel. The Starch has water soluble properties thus the panel should completely disintegrate. The components could be reused to build similar panels.
(Panel-6) Earth + 6% Fly Ash + Water	The Fly Ash used is a slag, a byproduct of combustion for the power generation plant at Virginia Tech. It is recyclable, but not considered renewable. The segregation of fly ash and Earth was believed to be difficult.

4.3.2 Toxic material content

The amount of the toxicity measured in terms of the percent volume of the panel. The graph below is a qualitative comparison in percent volume between the six samples built.

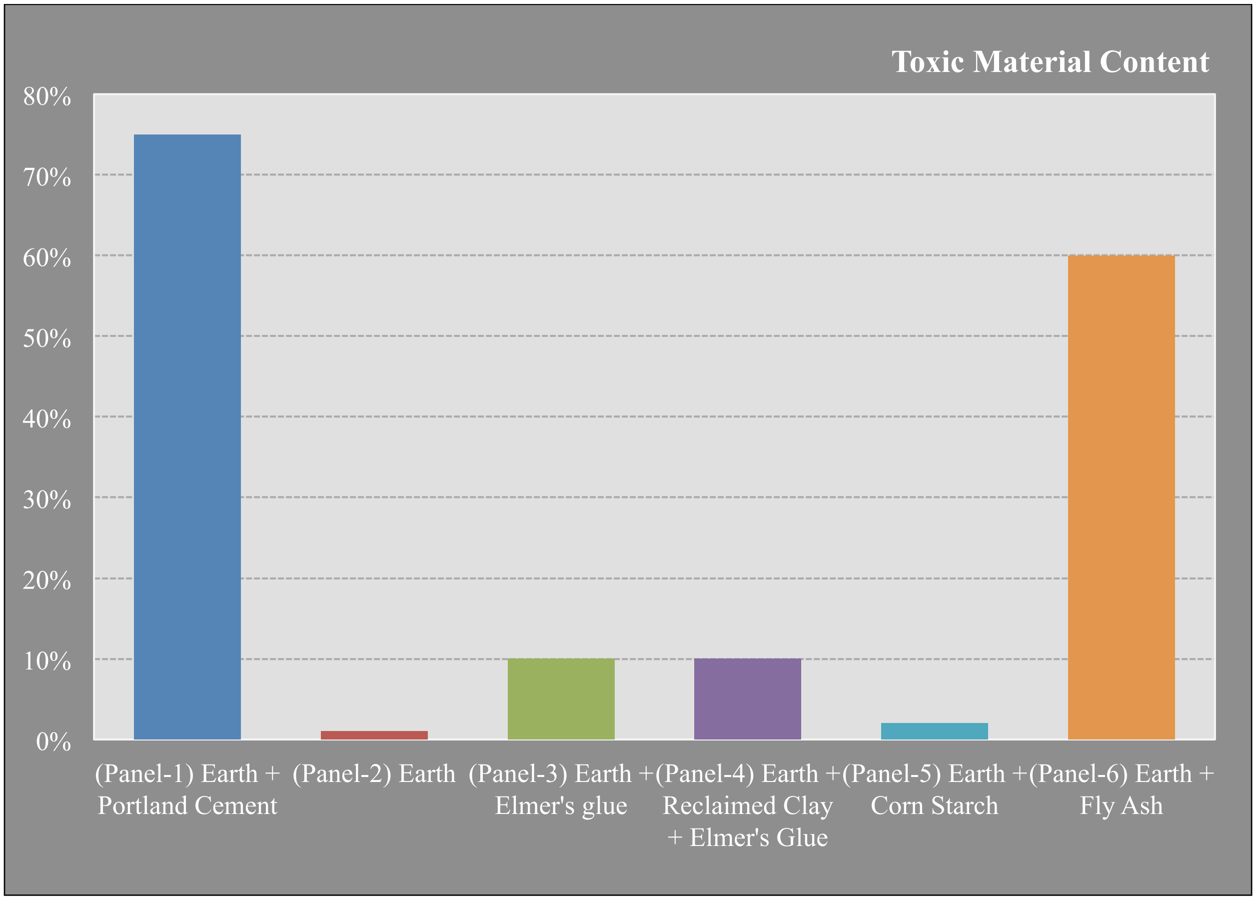


Figure 4.20: Comparative analysis for Toxic content for the test sample

The graph suggests panel-1 composed of the binding component Portland cement contained around 75% of toxic content, while panel-2 composed of earth and water had the lowest toxic content.

Table 4.16: Comparative analysis for Toxic content properties of the test samples

(Panel-1) Earth + 6% Portland Cement + Water	Cement is composed of silicates, aluminates of lime, tricalcium silicate, dicalcium silicate, tricalcium aluminate, tetracalcium and aluminoferrite. The cement industry is considered a major source of pollution due to the emission of dust and particulate matter at various stages of manufacturing cement. Cement dust is toxic in nature; the pollution begins at various stages of raw material grinding, coal mills, rotary kilns (dry & wet), clinker cooling, finished grinding, storage silos and packaging.
(Panel-2) Earth + Water	Earth excavated from construction sites rarely has toxic content. However, if the earth is reclaimed from a Brownfield or farmlands, petrochemical pesticides may be present.
(Panel-3) Earth + Elmer's glue mixed + Water	The Elmer's glue used for this project was a polyvinyl acetate emulsion synthetic polymer. The polymers are hard, brittle, and have high molecular weight, high tensile strength, and set rapidly. The Elmer’s glue has excellent adhesion properties when used for cellulosic substrates, ceramics, concrete, and glass. The Elmer’s glue is readily available as an adhesive and coating agents; it is relatively low cost. The panel could be made of naturally occurring polymeric materials such as starch and casein, or cellulose derivatives such as hydroxyethyl cellulose, methyl cellulose and carboxymethyl cellulose.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	In its green state, clay is free of toxins; however, breathing in clay dust can be harmful to the respiratory system. A protective mask must be used to cover the mouth and nose to avoid direct exposure.
(Panel-5) Earth + 6% Cornstarch + Water	Cornstarch has no known toxic content. It is water-soluble binding agent that is completely biodegradable.
(Panel-6) Earth + 6% Fly Ash + Water	Fly ash is a residual of coal power generation plants. The workers exposed to fly ash in the industry are prone to respiratory diseases.

4.3.3 Availability of materials

The factors that affect the availability of materials are associated with the cost involved in the extraction. Transportation of the associated products to the location of construction from the location of manufacturing, the construction technology, and the availability of materials affect the potential for widespread application. The intent of the research was to work with local materials that are naturally abundant, or reuse materials such as reclaimed clay and byproducts like fly ash.

Table 4.17: Comparative analysis and observed availability of the test samples

(Panel-1) Earth + 6% Portland Cement + Water	Portland cement is a widely used construction material, and is available in abundance.
(Panel-2) Earth + Water	Soil is a naturally abundant material, but not all soil types may be suitable for earth building. The applicability of the soil type depends on the proportions of sand and clay, thus earth construction is preferred in regions having hot and dry climate (Rael, R. 2000; Kapfinger, 2001).
(Panel-3) Earth + Elmer's glue mixed + Water	Elmer's glue is commonly used as an adhesive for wood products; it can be prepared using milk based products such as casein and starch. It is a widely available material in the market. The glue is affordable.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Clay is probably as abundant as earth. Reclaimed clay products can be obtained from ceramic landfills.
(Panel-5) Earth + 6% Cornstarch + Water	Cornstarch is a derivative of the kernel of the corn stock. Due to abundant use of Cornstarch not only for food products but also to produce renewable materials like plastics and PLAs, there is a high demand for Cornstarch. With wide scale applications of Cornstarch, there is a probability of un-affordability and unavailability of the material. But there are various natural binders with similar properties that can replace Cornstarch (Richerson D. W., 1992).
(Panel-6) Earth + 6% Fly Ash + Water	Fly ash is a residual by-product of coal combustion needed to generate electricity in power generation plants. Power generation plants may not be located everywhere, but due to large scale productions of electricity, this coal residual can be available in abundance.

4.3.4 Advantages

The materials with relevant characteristics are combined during this process. Certain features may be more dominant than others, and this section explains if the materials improved or depreciated the panel's stability.

Table 4.18: Comparative analysis and observed advantages of the test samples

(Panel-1) Earth + 6% Portland Cement + Water	The advantage of using cement to stabilize the rammed earth panel was that it helped achieve stability, and solved most of the issues concerned to moisture ingress, and weather cycling. The panel had recyclable properties.
(Panel-2) Earth + Water	The panel was aesthetically more appealing and attractive. It was easy to build, install, and produce these panels on a mass scale. The panel is affordable, completely renewable and biodegradable.
(Panel-3) Earth + Elmer's glue mixed + Water	Panel-3 could replace the toxic and high embodied cement stabilizer. The panels made using Elmer's glue as an adhesive can be mass produced. It is affordable, renewable, and biodegradable. The Elmer's glue has excellent dry sheer strength properties.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	To build panels using soils with very high levels of clay content, natural stabilizing agents like Elmer's glue was used.
(Panel-5) Earth + 6% Cornstarch + Water	It is affordable, renewable and completely biodegradable in nature. This panel is well suited in areas predominantly hot and dry.
(Panel-6) Earth + 6% Fly Ash + Water	Fly ash has excellent tensile properties and can be used successfully in combination with a renewable material like earth.

4.3.5 Disadvantages

The reasons for which the test panels failed to gain complete strength are stated below.

Table 4.19: Comparative analysis and observed disadvantages of the test samples

(Panel-1) Earth + 6% Portland Cement + Water	Portland cement is toxic and nonrenewable.
(Panel-2) Earth + Water	Panels built of earth cannot sustain in places having high humidity. The panel cannot sustain in places predominantly cold and under wet conditions. To build a panel without adding a stabilizer, it is important that the material composition contains appropriate amounts of sand, clay and gravel, or it fails to

	fulfill the performance criteria.
(Panel-3) Earth + Elmer's glue mixed + Water	The Elmer’s glue is a water soluble binding agent and thus it may not survive when installed as a part of the external panelized system. Due to the self-expansion property of Elmer’s glue, it loses dry shear strength when in contact with water.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Excess of clay content tends to damage the physical cross-section of the panel. The panel fails to sustain under moist conditions due to the issues concerning water ingress.
(Panel-5) Earth + 6% Cornstarch + Water	Due to the water soluble nature of Cornstarch, the panel may fail to sustain in extreme cold and wet seasons. Due to the large scale demand of Cornstarch, it is a commodity that may not be readily available.
(Panel-6) Earth + 6% Fly Ash + Water	Fly ash is a nonrenewable material. For best results, at least 15% of fly ash should be mixed with cement. To avoid failure of the panel, the fly ash free from carbon content should be used as a stabilizer.

Chapter 5.0: Findings and Results

Based on the results of the suitable experimental tests conducted on the external wall panels, the most workable and appropriate wall panel was determined. The research demanded that the successfully built test panel satisfy most of the performance criteria, of being aesthetically attractive, built with minimum effort and energy requirements. On the basis of these results, future research and opportunities are suggested in the next chapter. The following tests were conducted on the test panel:

- Crumble Test
- Scratch test
- Load test
- Weight test
- Water pressure test

In this chapter, the test panels are comparatively analyzed on the basis of the above mentioned experimental test performance. The testing program was designed such that the panels would fulfill these minimum requirements:

- To determine if the panel was appropriate as an external wall panel system
- To determine if the test panels was able to sustain inclement weather conditions
- To determine the behavior of the panel in highly humid conditions
- To estimate the load carrying capacity of the panel in comparison to its self weight
- To calculate and estimate fracture toughness properties and the flaw specific structural analysis

The results are presented as a comparison between the samples in the form of visuals and charts. The figure 5.1 presents the visual comparison of the test panels

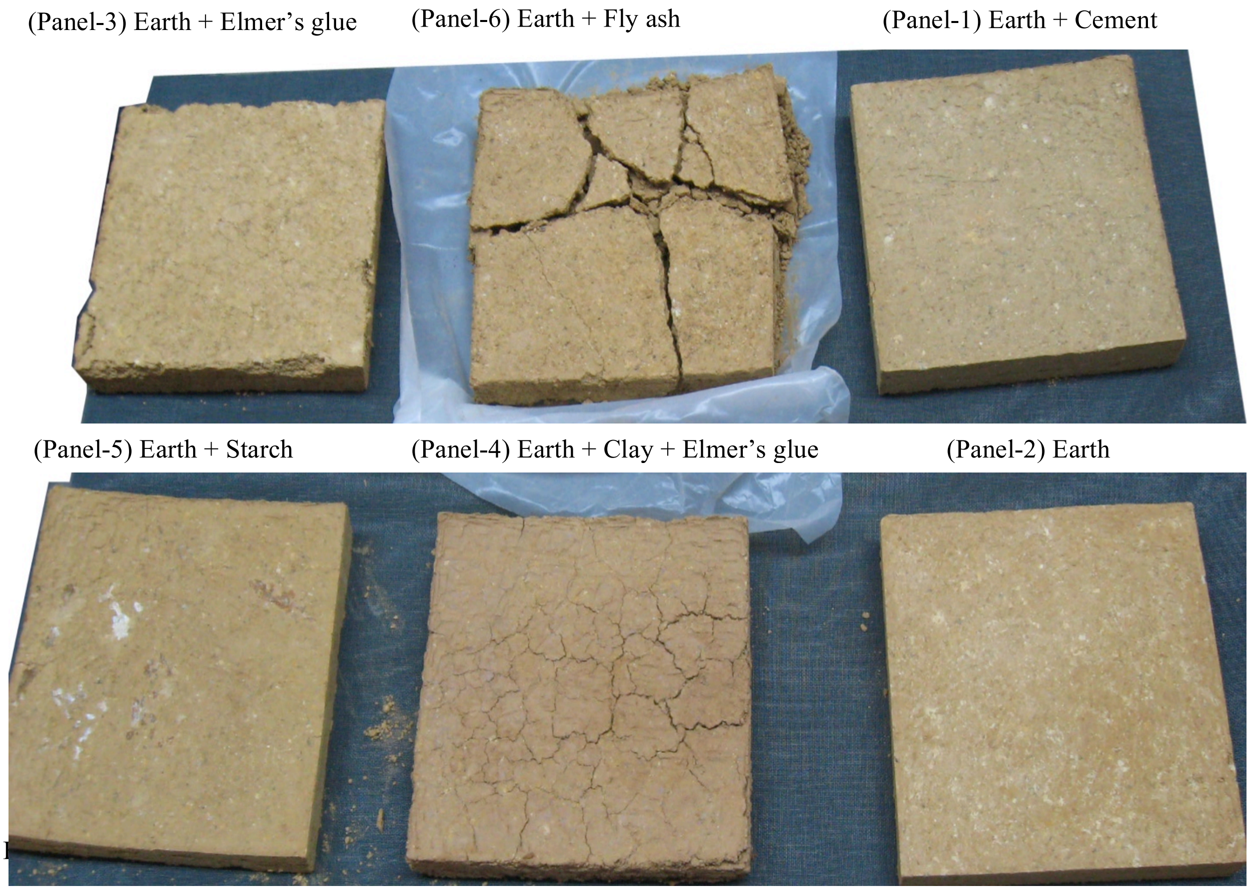


Figure 5.1: Comparison between the samples in the form of visual

5.1 Crumble test

The crumble test was a qualitative test analysis procedure. The testing program for conducting the crumble test is explained in detail in the second chapter, “Methodology.” The result of applying the crumble test on each panel is discussed in detail below:

(Panel-1) Earth + 6% Portland cement + Water

The twisting and turning of the panel doesn’t cause measurable defects, but due to the brittleness, edge defects like chipping and fragmentation of earth was observed; the cross-section of the panel was stable.

(Panel-2) Earth + Water

The cross-section of the panel was stable and the application of the test caused the least deformation.

(Panel-3) Earth + Elmer's glue mixed + Water

The panel remained unaffected on application of the crumble test. The edges remained intact.

(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers

The panel had a fragile cross-section; the observations suggested that the panel may not be able to sustain the experimental tests for fulfilling the performance criteria. The results of the crumble test showed that only the edges and corners cracked due to the uneven drying, while the panel appeared to have a stable cross-section.

(Panel-5) Earth + 6% Cornstarch + Water

The panel remained unaffected on the application of the crumble test. Minor deformations were observed closer to the edges. The edges corrode and disintegrate into fine powder like dust.

(Panel-6) Earth + 6% Fly Ash + Water

The panel could not withstand the crumble tests.

Observations:

The slightest pressure caused the panel to crumble and break into a large number of pieces. The panel was soft and could be easily cut with a knife with low binding strength. The panel failed both across as well as in between the layers.

Figure 5.2

Figure 5.3

Figure 5.2 and Figure 5.3: Structure of the failed fragments of Panel-6 Earth+ Fly ash

The reasons for the cause of the failure patterns as follows: the panel showed low compressive strength capacity; it was unable to withstand minor pressures and loading. Fly ash enhanced the tensile strength properties of the panel, but the high clay content led to ineffectiveness of the panel. The panel would have sustained the experimental tests if cement were added to the mixture in addition to fly ash, as cement has excellent compressive strength properties. Fly ash improved the consistency of the mix. The fly ash used for the research project was black in color. The darker shade of fly ash suggested high concentration of carbon content. Carbon tends to reduce the compressive strength properties. Hence a carbon free fly ash should be preferred when combined with the earth mixture.

Possible solution to improve the stability is the addition of Cement or similar sustainable and renewable stabilizing agent. An example of that is Elmer's glue which when added improved compressive strength. The chart below is a qualitative comparison of the percent failure of the panels in terms of its volume. The results are determined based on observing the behavior of each panel on application of the crumble test.

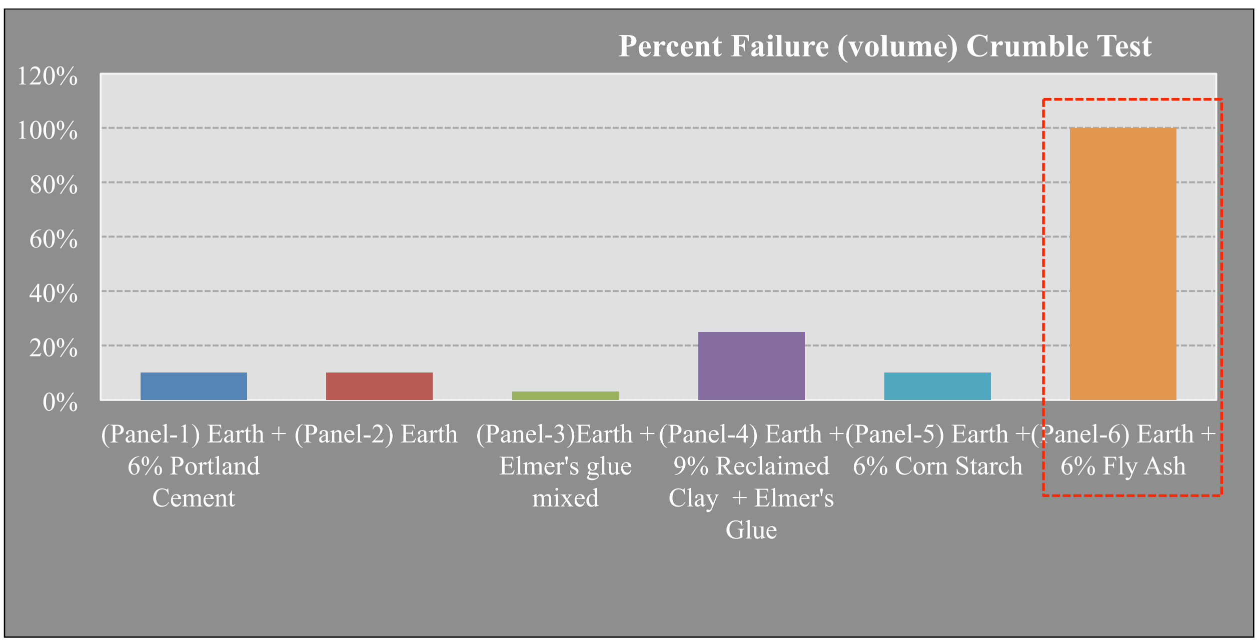


Figure 5.4: Chart of Qualitative analysis of Percent Failure (Volume) Crumble test

The results in the above chart show that panel-3 made of earth and Elmer's glue resulted in low deformations and panel-6 failed completely on application of the crumble test.

5.2 Scratch test

The test program for conducting the scratch test is explicitly explained in the second chapter, "Methodology." The scratch test was conducted as a qualitative test analysis procedure. The results of applying the parameters of the scratch test are discussed below:

(Panel-1) Earth + 6% Portland cement + Water

The result showed that continuous scoring on the surface with a pointed instrument does not affect the panel. The panel was able to withstand minor abrasions and scratches made with a knife.

(Panel-2) Earth + Water

The result showed that continuous scoring on the surface with a pointed instrument did not affect the panel. The panel was able to withstand minor abrasions and scratches made using a knife.

(Panel-3) Earth + Elmer's glue mixed + Water

The panel remained unaffected even after scoring the surface of the panel with a hammer and pointed axe like tool. Figure 5.2 shows that the panel was unaffected and marked minor indentations were observed. This indicated that the panel was not brittle and would not be affected by the scratch test. The panel had a strong configuration.

Figure 5.5: Image showing effects of ramming a hammer on the Panel-3 made of Earth + Elmer's glue

(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers

The panel was fragile, and the cracked and scaly top layers were scored off without effort, but the panel was strong and could withstand the continuous scoring below the top layer suggesting that the panel was able to fulfill the performance criteria for the Scratch test.

Figure 5.6: Image showing intensity of cracks on the surface of Panel-4 Earth + Clay + Elmer's glue

(Panel-5) Earth + 6% Cornstarch + Water

The panel was unaffected by the Scratch test.

(Panel-6) Earth + 6% Fly Ash + Water

The panel was soft and could be sliced easily. It failed even before the Scratch test could be applied.

The chart below is a qualitative comparison of the percent failure of the panels in terms of its volume. The results are determined based on observing the behavior of each panel on application of the scratch test.

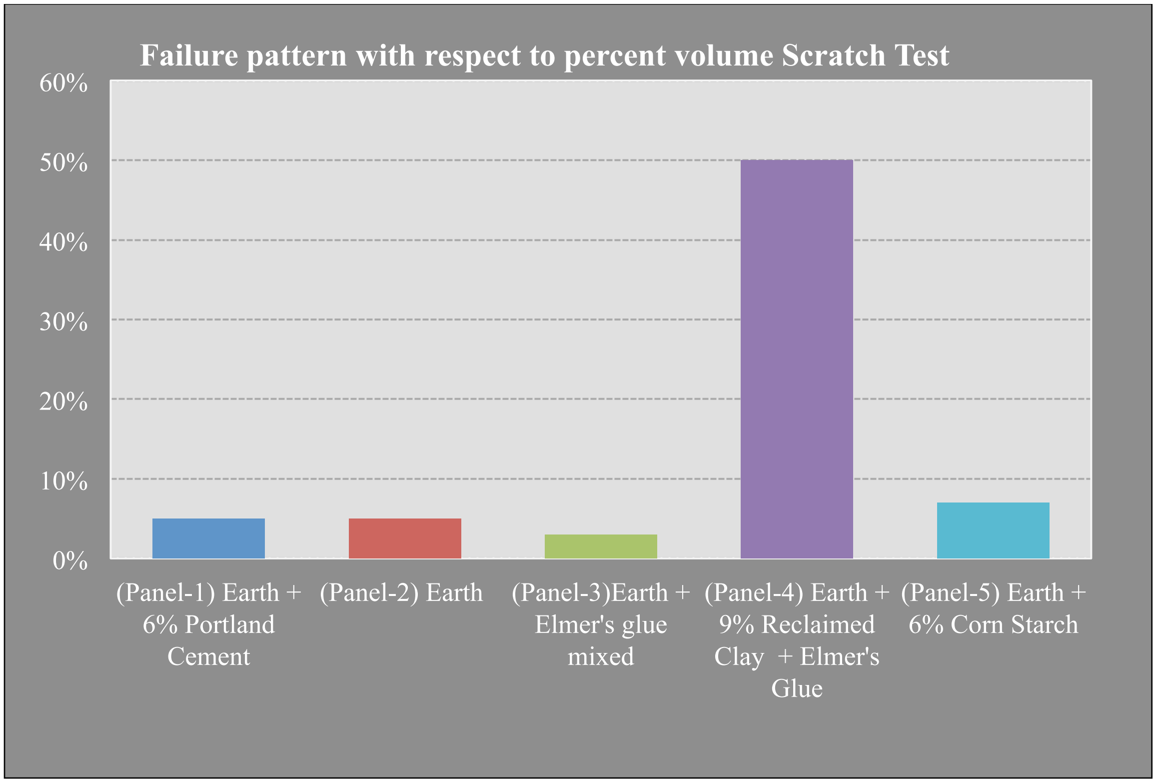


Figure 5.7: Chart of Qualitative analysis of Percent Failure (Volume) Scratch test

The results for the scratch test show that panel-4 made of earth, reclaimed clay and Elmer's glue was the most affected on the application of the scratch test, while panel-3 made of earth and Elmer's glue remained unaffected.

5.3 Load test

The testing program for conducting the load test is explained in detail in the second chapter, "Methodology." The load test was assumed as an experimental test analysis method with measureable values to determine the result, but the final result for the load test is represented as a qualitative test analysis in terms of percent volume of the maximum load carrying capacities in comparison to the self weight of the panel in pounds. The results of applying the parameters of the load test on each panel are discussed below:

The intention of conducting this test was to determine factors such as fracture, toughness, critical crack size, geometry of the failed fragments, loading rates, and the possible influence of material property. The results were presented in the form of failure assessment visuals; this test also confirmed the initial findings of the general observations that were noted during the phase of preparation, for example, to test if the stable crack extension precedes instability on applying the load test. This test also was useful to determine if geometric variables such as grain size and specimen thickness are statistically significant on the dynamic strain rate (Maniatidis, V., and Walker, P., 2003). The chart below shows the measure of the weighted panels in terms of the unit pound.

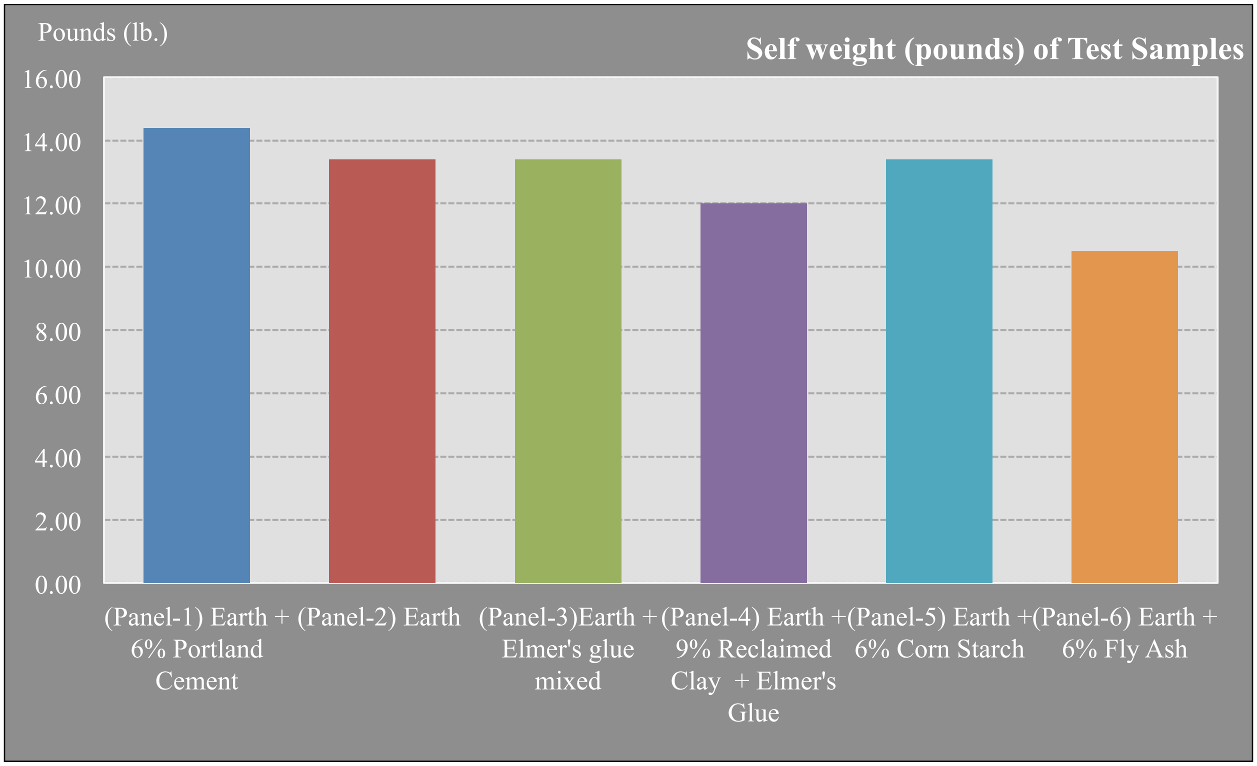


Figure 5.8: Chart showing comparative self weights in pounds of the variable test panels

<u>(Panel-1) Earth + 6% Portland cement + Water</u>

Self-weight of Panel (Pounds) = 14.4 lb. (Pounds)

The panel weighed more in comparison to the other built panels.

The maximum load bearing capacity (bricks loaded x average self weight) = (26 x 4) lb. + weight 4.5 lb. = 108.5 lb.

Conclusion:

The maximum load bearing capacity was much lower than the expectation. Studies show that the cement stabilized earth panels has better compressive strength and should be capable of carrying larger loads, and even though this stabilized earth panel weighed almost one pound more than Panel-2, yet the observation shows that the un-stabilized earth panel outperformed and had much more carrying capacity when compared to its self weight. Additionally, the crack formation pattern in Figure 5.4 below indicates a shear failure. It was assumed for the research project that all the test panels must be 1½ inch thick, while the weight of the panel was considered as a variable based on the material property. Considering this assumption and qualitatively analyzing the panels, the cement stabilized earth panel with self weight equivalent to the other samples would carry lower loads than the other equivalents.

Point of failure

The panel failed along the central axis parallel to the edge of the supports. The observation showed the panel split apart into large uneven fragments. The panel achieved maximum loading capacity before failing.

Cross-section of the panel

The panel was structurally weak and failed at the intersection between consecutive layers implying that the panel dried rapidly before achieving sufficient compaction, causing lower bonding strength. The panel should be cured with sufficient amount of water to achieve complete strength.

Table 5.1: Stages of loading and failure for Panel-1 Cement + Earth

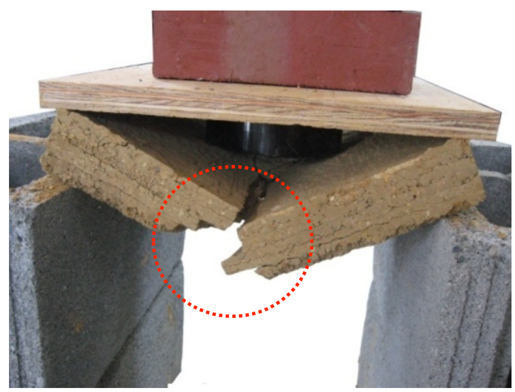
 Step 1	 Step 2
26 cored bricks loaded  Step 3	 De-bonding of layers Step 4
Step 5 	Step 6 

Figure 5.9: Image showing fragmented portions after applying Load test on Panel-1 Earth + Cement

Suggestions

The high clay content present in the soil mixture must have been responsible for reducing the binding strength of the cement stabilizer. Complete strength may be achieved on introducing a suitable proportion of sand to the soil composition. The panel should to be cured for at-least 7 days under cover. The failure of the panel along the central axis was due to fracture; the edge failure may be due to shear, as the panel failed between layers suggesting the critical cracks preceded the fracture failure.

(Panel-2) Earth + Water

Self-weight of Panel (Pounds) = 13.4lb.

The weight of the panel is consistent.

Total no. of bricks loaded. = 23

Maximum load carrying capacity (Pounds) = 92 lb.

Conclusions

The panel satisfied the performance criteria for the load test. The panel carried more load and showed better toughness and compressive strength properties when compared to the base case option "the cement stabilized Rammed Earth panel".

Point of failure

The panel was loaded till the point that it could bear the capacity, and then failed instantaneously; this behavior showed that the panel was extremely brittle with low tensile strength properties. Panel failed along three points; the first two were along the edge parallel to the supports. This behavior suggested that the edges of the panel were weak, and required greater compaction. The panel also displayed poor shear strength properties. The soil used in the mixture contained high clay content. The second point of failure was along the central axis of the panel; the panel failed due to the impact of hitting the ground and then split into two parts. The panel would withstand higher loads with higher compaction and a better soil composition.

Figure 5.10: Image showing fragmented portions after applying Load test on Panel-2 Earth

Table 5.2: Stages of loading and failure for Panel-2 Earth

 Step 1	 Step 2
 Step 3	23 cored bricks loaded  Step 4
 Step 5	 Step 7

Suggestions

The addition of sand to this composition may supersede the brittleness caused due to the excess clay content. Adding sufficient water and maintaining the moisture content while compacting the panel would increase the strength. Maintaining proportions of gravel content helps maintain stability and decreases the risk of failure due to poor bonding.

<u>(Panel-3) Earth + Elmer's glue mixed + Water</u>

Self-weight of Panel = 13.4lb.

The weight of the panel is consistent.

Total no. of bricks carried by the panel = 40 and more bricks + 4.5lb.

Maximum load bearing capacity = more than 164.5lb.

Conclusions

The wood adhesive such as Elmer's glue has a dry shear strength that exceeds the strength of the earth; thus, the panel carried larger loads. The panel successfully fulfilled the performance criteria for the load test. But after a point, further loading had to be stopped, as the bricks loaded on top of each other became unstable and any further loading caused the bricks to sway. This could have caused the loads to fall directly over the test panel. The load types were not changed, assuming all panels would be consistently loaded at a fixed rate.

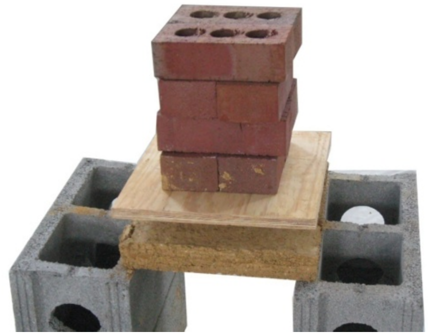
Point of failure

A distinct crack was observed on the bottom of the panel along the central axis after applying the load test, but the panel was very strong and was capable of carrying more loading before it could have failed completely. The application of the weight and the water pressure test helped determine the consequences of exposing the panel to humid conditions.

Cross-section of the panel

The cross-section of the panel had a good interconnected section.

Table 5.3: Stages of loading and failure for Panel-3 Elmer's glue + Earth

 Step 1	 Step 2
 Step 3	 Step 4

Suggestions

The strong binding strength of the Elmer's glue helped the panel gain complete compressive strength and toughness, but using better compaction techniques such as mechanical compaction methods would be more useful.

<u>(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers</u>

Self-weight of Panel (Pounds) = 12lb.

The panel weighed less due to the presence of higher proportions of clay and Elmer's glues which have lower mass.

Total no. of bricks loaded. = 16

Maximum load bearing capacity (Pounds) = 64lb.

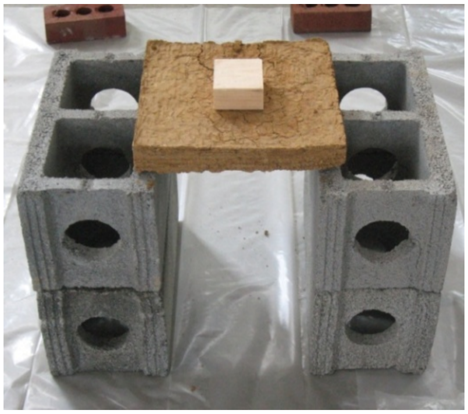
Conclusions

Initial observations indicated that the panel may be weak, but the results of the load test showed that the panel had significant potential to survive as it displayed good compressive strength and toughness properties. The self-weight of the panel was 12 pounds, but it had better load bearing capacity compared to the base case panel. The experiment shows that improved soil composition may improve the compressive strength properties.

Point of failure

The panel failed along the central axis parallel to the supports, thus indicating that the panel was loaded to the point that the panel failed. The panel had good tensile strength and better elasticity. The panel did not fail instantly; there was a visible time lag between the maximum loading condition and total failure. It can be established that this was due to the dry shear strength property of Elmer's glue, and thus the failure occurred due to de-bonding fractures. The initial deformation occurred at the edge perpendicular to the support and this crack line extended along the axis on complete failure.

Table 5.4: Stages of loading and failure for Panel-4 Clay + Elmer's glue + Earth

 Step 1	 Step 2
 Step 3	 Step 4
 Step 5	 Step 6

Cross-section of the panel

The panel failed along the central axis. The configuration of the shattered fragments indicated that this panel was more stable than the panels built using the starch or the fly ash additive. The bonding between the layers remained intact, thus showing that the panel had achieved complete compaction. The properties of clay and Elmer's glue improved the surface binding strength. The panel split into two parts; this observation showed that the panel failed only after it was loaded with maximum carrying capacity. In comparison to the carrying capacity, the panel is light in weight. The addition of Elmer's glue improved the binding properties of the clay-rich soil mixture.

Figure 5.11: Image of fragmented portions after applying Load test on Panel-4 Earth + Clay + Elmer's glue

Suggestions

Introducing stabilizers capable of improving the shear strength properties could enhance binding properties. Adding lime and cement would also enhance the above properties.

<u>(Panel-5) Earth + 6% Cornstarch + Water</u>

Self-weight of Panel (Pounds) = 13.4lb.

The weight of the panel was consistent.

Total no. of bricks loaded. = 11

Maximum loading that the panel resisted (Pounds) = 44lb.

Conclusions

The panel demonstrated poor compression. The panel showed traces of wetness due to poor drying conditions. Considering that all the components of the panel were water soluble, the panel demonstrated high affinity for moisture. This may be one of the major reasons for the fact that the panel could not achieve complete strength. Addition of starch improved the consistency of the soil, and this helped ease the mixing and compaction process.

Point of failure

The panel failed instantaneously along the central axis and shattered in large pieces.

Cross-section of the panel

The panel lost the adhesion between the adjacent layers, thus the panel demonstrated low shear strength.

Suggestions

Introduce materials that would help accelerate the drying process

Table 5.5: Stages of loading and failure for Panel-5 Starch + Earth

 Step 1	 Step 2
 Step 3	 Step 3

Figure 5.12: Image showing fragmented portions after applying Load test on Panel-5 Earth + Starch

<u>(Panel-6) Earth + 6% Fly Ash + Water</u>

Self-weight of Panel (Pounds) = 10.5lb.

The panel was light in weight. The panel disintegrated before the panel could be weighed. It was difficult to weigh the shattered fragments of the panel. The panel may have weighed almost as much as the other panels considering the proportion of the soil mixture used for all the panels were similar. The panel was unable to carry its own weight and thus it failed to satisfy the criteria for load test.

Suggestions

Combining cement or a natural binding agent with good compressive strength properties would help strengthen the panel.

5.3.1 Comparison of results

As a result of the load test analysis, it was concluded that the Earth + Elmer's glue mixed + Water (Panel-3) demonstrated excellent load bearing capacity and it supersedes the load bearing capacity of the base case Earth + Cement + Water (Panel-1). Furthermore, the Earth + Water (Panel-2) outperformed the base case panel. Additionally the Earth + Reclaimed Clay + Water + Elmer's Glue (Panel-4) demonstrated good compressive as well as tensile strength properties. It does not fail instantaneously. The panels were rated based on the load carrying capacity and the final results are represented in a graphical format as shown in Figure 5.14. It can be seen that the final results don't follow the slope in the graph in Figure

5.13 that represents the maximum loading capacity for the tested panels. The major reason for this discrepancy is that even though the design case (panel-2) had lower load bearing capacity than the base case (panel-1), in comparison to its self-weights, panel-2 weighed considerably lower than panel-1; hence, when viewed as a relation between carrying capacity and self weight, qualitatively panel-2 was rated to be of higher grade compared to panel-1. The qualitative analysis helped illustrate the possible scope of improvement.

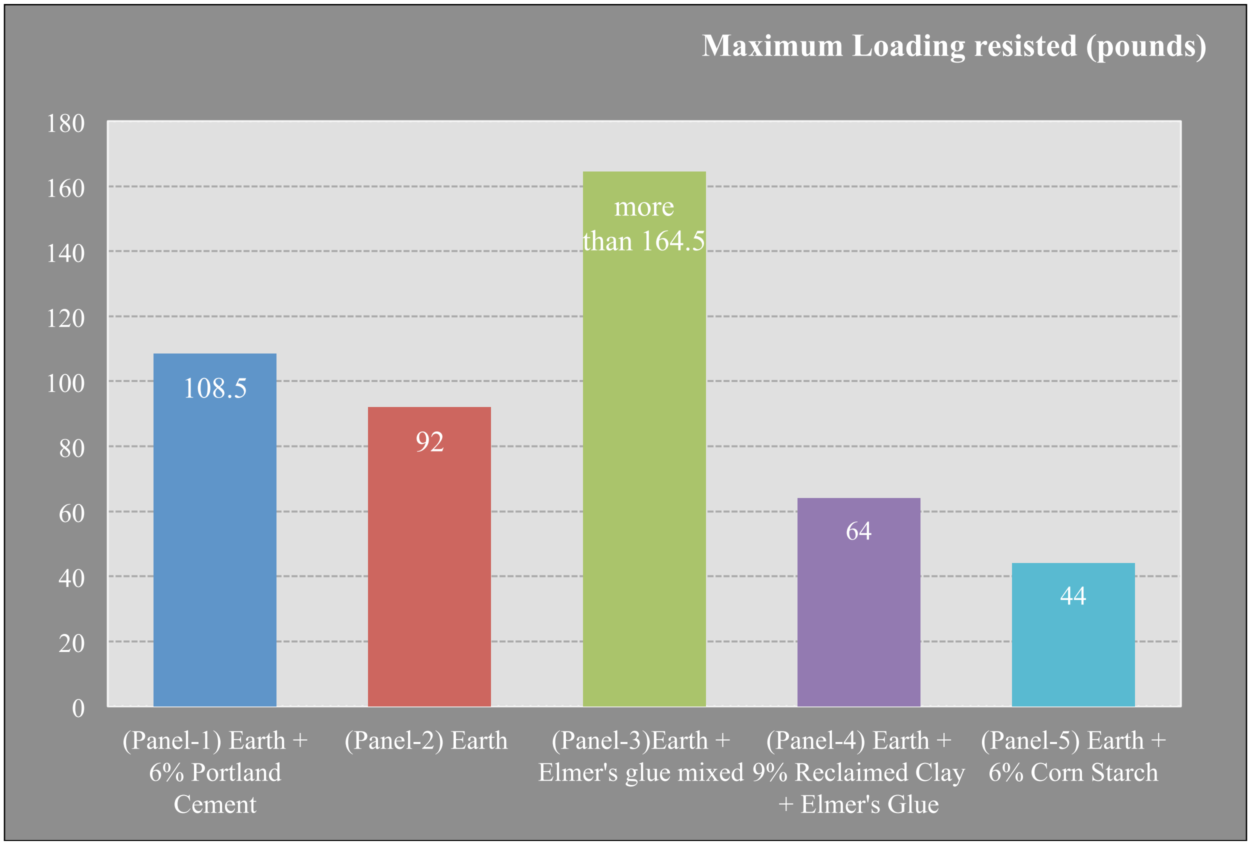


Figure 5.13: Chart showing the comparison of load carrying capacity of variable panel for the project

Figure 5.14 is a comparison of the load bearing capacity measured in pounds for the five panels. The results on the graph suggest that panel-3 composed of Earth and Elmer's glue has the maximum load bearing capacity followed by panel-1 composed of Earth and 6% Portland cement. Panel-6 composed of Earth and Fly Ash is not considered in this graph as it failed to survive the initial test parameters. Thus, panel-5 composed of Earth and 6% Corn Starch has the lowest load bearing capacity.

Figure 5.14 is a chart, which is a qualitative comparison to grade the panels for maximum load carrying capacity. The final results to determine the panel capable of bearing the maximum load was based on criteria such as the amount of shrinkage observed during the drying period, the self-weight of the panel and the maximum load resisted with respect to its self-weight.

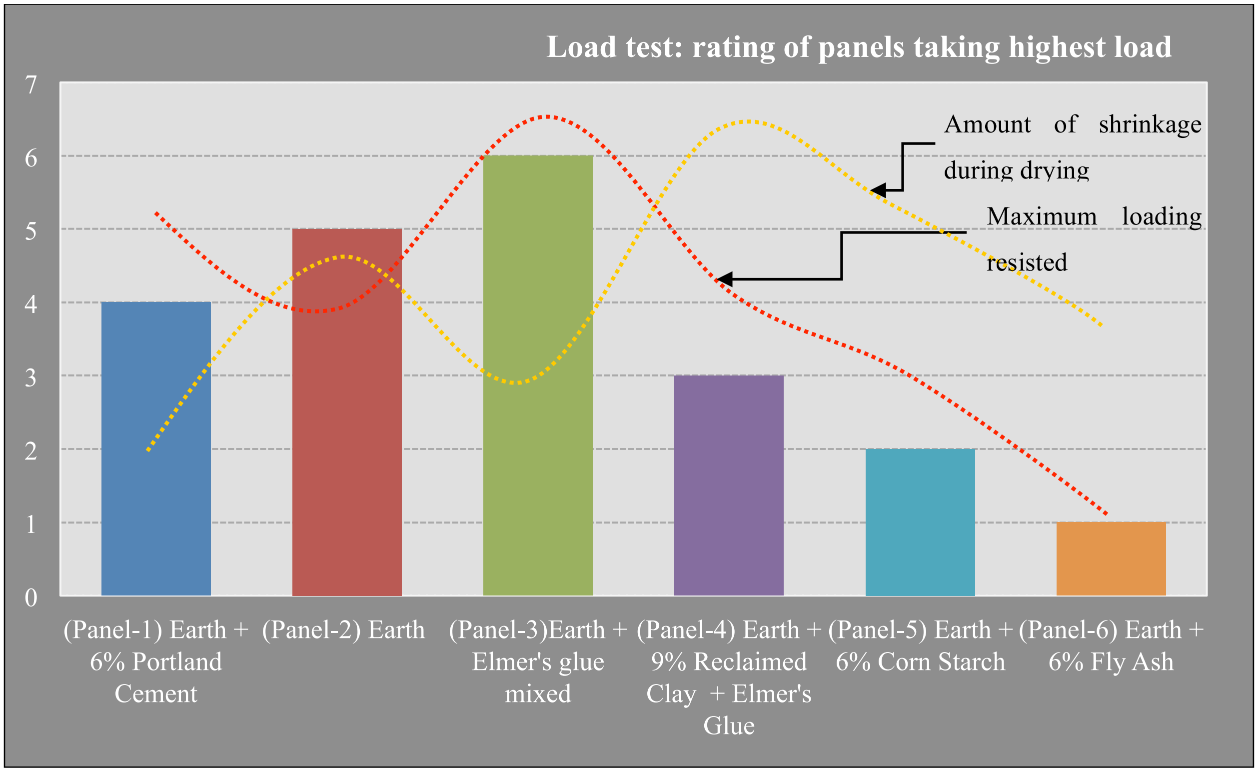


Figure 5.14: Chart of comparative Qualitative analysis of Load test results for panel carrying maximum load

Thus, the result of the chart in Figure 5.14 suggests that panel-3 composed of Earth and Elmer's glue had better load carrying capacities, while panel-2 composed of Earth and 6% Portland cement was graded lower than panel-2 composed of Earth.

5.4 Test for sustainability of natural binders

As mentioned in the earlier chapter "Methodology," the test for sustainability of natural binders was based on the weight and the water pressure tests. In the assumptions, the test for sustainability of the natural binders was a qualitative test analysis procedure. Thus, the results for applying the parameters of these tests shall be discussed below:

Usually in circumstances when the cement stabilizer is used, the properties of cement become dominant. The addition of cement makes the panel impervious to water. Most of the issues related to weather cycling are caused due to moisture ingress and deterioration over time. Water seeps through the cement-stabilized earthen panel in a similar way as it does for the un-stabilized rammed earth panel. But, cement stabilized earth panel has the ability to retain the original compressive strength properties on drying, and this efficacy is attained when the panel is properly compacted. The amount of clay content in the mixture is controlled and the curing period is maintained. Usually over time the external panels suffers from issues such as spalling and corrosion. The issues related to water ingress can be offset with proper compaction, proper waterproofing techniques and the external finish of the panel. Furthermore, the panel surface when installed as a part of the external wall system should be protected from direct contact with moisture; for example, putting a canopy over the external wall protects the panel from the rains.

Additionally the panels made with water-soluble agents as components may deteriorate to produce fungal growth under high humidity levels. When the panels are built using Clay and Elmer's glue, the affinity for water increases making the panel extremely gooey and paste like when soaked in water; the properties of clay are such that it behaved like a sponge and absorbed excessive amount of water, after which failure occurred instantaneously. If the panel is dried sufficiently, the panel shrinks and can no longer take its original form; the panel also looses more than half the binding strength gained during compaction. This result in irregularities, loss of inherent material properties and shrinkage issues. Uncontrolled temperature differences cause undue heating of the panel; the temperature difference may occur due to the heat island effect. To overcome this issue, the insulating properties of the panel system must be improved. The results for the tests conducted are explained in the proceeding section.

5.5 Weight test

The testing program for conducting the Weight test is explained in detail in the second chapter, "Methodology." The Weight test was conducted as an experimental test analysis method and the measured values helped determine the results. However, the final result is presented as a qualitative comparison of the test panels in terms of percent weight. The application of the test was intended to determine stability of the panel in humid conditions; it also helps determine the strength of the panel affected by issues related to moisture ingress. The outcome of the experiment was captured in the form of pictures, to help documentation.

These figures illustrate the failure assessment of the tested panels; the experimental tests confirmed the initial observations made during the production of the test panels. For example, the tests helped gauge if the stable crack extension that occurred due to shrinkage during drying was responsible for the failure of the panel as it would not be able to withstand extreme humid conditions. The experimental test also helped us to determine if the geometric variables such as grain size and specimen thickness affected the sustainability of the panel in harsh weather conditions. The procedure of conducting the Weight test is explained in detail in the second chapter. Table 5.6 below is a comparative matrix representing the weight of the panel during the experiment. The panel that fulfills the performance criteria for the Weight test conformed to the comparative matrix and each panel was analyzed for failure assessment.

Table 5.6: Comparative Matrix analysis of sample weight study before and after the weight test

Weight Test	Initial self-weight (I) Pounds lb.	Weight of panel after immersion (F) Pounds lb.	Resultant weight (R) = I-F (Pounds lb.)
(Panel-1) Earth + 6% Portland Cement + Water	0.9	1.03	-0.13
(Panel-2) Earth + Water	1.85	Disintegrates completely	
(Panel-3)Earth + Elmer's glue mixed + Water	13.4	11	2.4
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	6.2	2.5	3.7
(Panel-5) Earth + 6% Cornstarch + Water	1	Disintegrates completely	

<u>(Panel-1) Earth + 6% Portland cement + Water</u>

The final weight on immersion was less than 1.5 times the initial weight condition. Since the panel fulfilled the basic performance criteria for the weight test, the cement content in the mixture prevented moisture ingress. The panel was stable with no signs of disintegration even after immersion. Issues related to moisture ingress do not affect the cement stabilized earth panel and it is capable of retaining its original properties even in extremely moist conditions. Achieving the complete curing period replenishes the panel helping it to achieve complete strength and survive in excessively cold and humid conditions (Maniatidis, V., and Walker, P., 2003). The panel satisfied the criteria for the weight test successfully.


Figure 5.15: Image of conducting weight test on Panel-1 Earth + Cement

(Panel-2) Earth + Water

In less than an hour of immersing the panel in water, the panel completely disintegrated. The panel was composed of a porous substructure; this enabled moisture ingress. For commercial application, panel-2 would require sufficient surface waterproofing to help sustain extreme humid conditions.

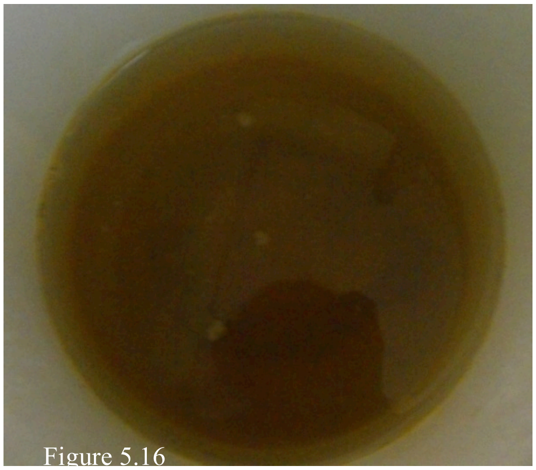


Figure 5.16: Image of conducting weight test on Panel-2 Earth, immersion of panel in a water bath
Figure 5.17: Image of conducting weight test on Panel-2 Earth, disintegrated fragment after half hour

Suggestions

To add stabilizers to the mixture to help improve waterproofing properties of the panel

(Panel-3) Earth + Elmer's glue mixed + Water

The panel successfully fulfilled the performance criteria for the load test, but it failed to sustain the weight test. The result of applying the load test on the panel causes a high rate of disintegration. The Elmer's glue has dry shear strength, which was lost on soaking the panel in water; the binding properties were lost severely affecting the panel's configuration. According to the initial observations, it appeared as though the panel could withstand higher humidity levels when exposed to moist conditions.

Future research opportunities: To determine if the panel could retain its original strength after undergoing a weight test. This test would help to determine the rate of reduction in the compressive strength property of the panel.

Figure 5.18: Image of result of weight test Panel-3 Earth + Elmer’s glue, disintegrated fragment after ½ hour

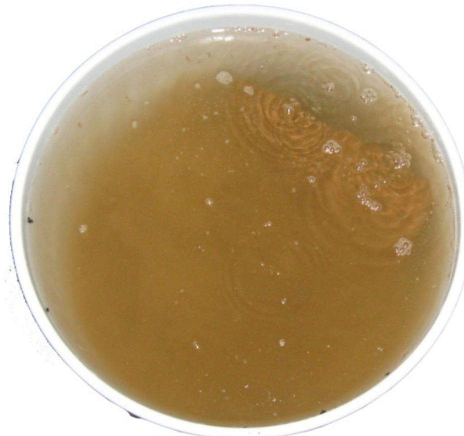
Suggestions

Use of suitable waterproofing agents would improve the imperviousness of the panel.

(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers

The frail appearances of the panel indicate that the panel may not be able to sustain the experimental tests conducted for the research. However, when the tests were conducted on the panel, it performed exceptionally well. But, it was not sufficient to prove that the panel had a good strength retaining capacity. Excess of clay content caused a higher rate of shrinkage. When the panel was put out to dry, some of the uneven and weaker portions of the panel crumbled off; this completely modified the original substructure of the panel. Thus, it can be concluded that if the product were used as an external wall system, the panel could easily disintegrate. Since the panel was renewable containing negligible toxic elements, it can either be discarded easily or reused.

Table 5.7: Stages for weight test failure observed for Panel-4 Clay + Elmer's glue + Earth

Step 1	Step 2
	
Step 3	Step 4
	

(Panel-5) Earth + 6% Cornstarch + Water

The panel failed and disintegrated completely on immersion in less than half an hour. The initial observations indicated that the panel was capable of fulfilling most of the experimental tests; starch was introduced as a binding agent based on the assumption that starch would be a good solution for a natural binding agent in comparison to any toxic stabilizing binding agents. But after the weight test was conducted on this panel, it was confirmed that in fact the addition of starch weakened the panel and reduced the compressive strength properties, while demonstrating lower resistance to issues related to inclement weather conditions.

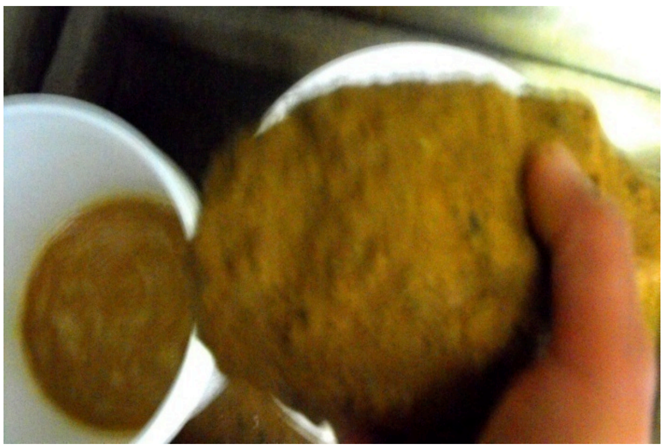


Figure 5.19: Image of results of weight test on Panel-4 Earth + Starch, disintegrated fragment after ½ hour

Conclusions:

Figure 5.20 qualitatively compares the rate of disintegration of the six panels after application of the weight test; the results are demonstrated in terms of percent weight.

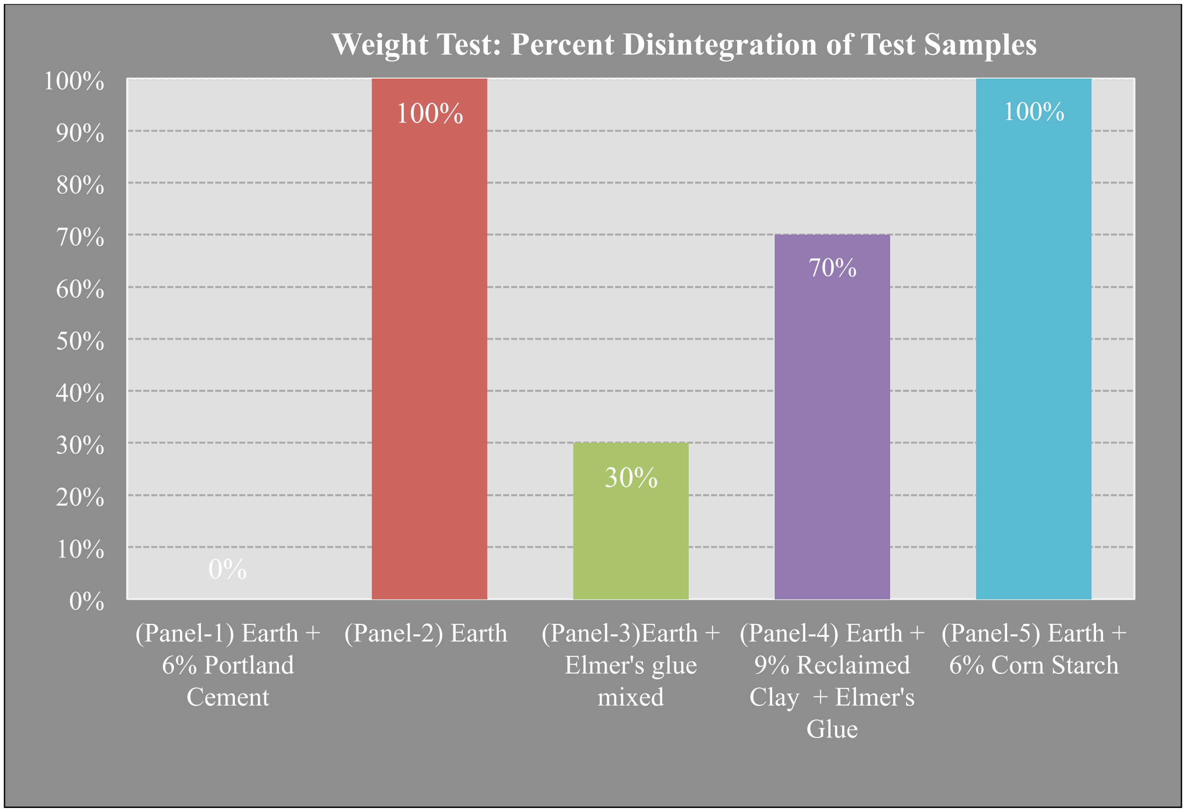


Figure 5.20: Chart with Qualitative analysis of Percent Failure (Volume) Weight test

The result from the graph suggests that panel-1 shows no sign of failure on application of the weight test. Panel-2 and panel-5 completely failed on immersion in water. As a result of the above analysis, it can be concluded that the cement stabilized earth panel outperformed the performance criteria for the weight test. The conclusion further established from this experiment is that panels built with earth, as a component should be protected from direct exposure to extreme moist conditions. The earth panels should be built in combination with materials that improve the waterproofing properties, or materials that are similar to cement that can help make the panel impervious to water. If the waterproofing properties of panel-4 were improved, then the panel made using a natural binder such as Elmer's glue could sustain extreme climate and bear the wear and tear.

5.6 Water pressure test

The testing program for conducting the water pressure test is explained in detail in the second chapter "Methodology." The Water pressure test was conducted as an experimental test analysis method with measured values that helped determine the results. However, the final result is presented as a qualitative comparison between the test panels in terms of percent weight.

The intent of the test was to determine performance of the built panel on application of continuous pressure and the amount of material erosion from the panel's surface due to moisture ingress. The result is presented in the form of figures that illustrate the failure assessment of the tested panels; the test confirmed the initial observations made during the production of the test panels. For example, the test helped establish if the stable crack extension due to shrinkage of the panel caused failure to withstand the wet situations. As per the procedure, the initial self-weight of each variable panel was noted as an initial reading. Table 5.2 below is a comparative matrix of the tested panels listing the values for initial self-weight (I) under normal condition. F is the final weight of the panel after immersion in a water bath for at least half an hour and R is the resultant weight, which is the difference between the initial and final weight. All results shall conform to these readings and each panel was analyzed for failure.

Table 5.8: Comparative Matrix analysis of sample weight study before and after the weight test

Water pressure Test	Initial self weight (I) of Panel (Pounds)	Weight of panel after passing thru water pressure test (F) in pounds.	Resultant weight (R) = I-F
(Panel-1) Earth + 6% Portland Cement + Water	2	2.4	-0.4
(Panel-2) Earth + Water	3	Disintegrated completely	
(Panel-3)Earth + Elmer's glue mixed + Water	11	10.7	1.7
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	5.5	3.5	2
(Panel-5) Earth + 6% Cornstarch + Water	2.9	Disintegrated completely	

The failure pattern observed for the water pressure test was similar to that of weight test.

<u>(Panel-1) Earth + 6% Portland cement + Water</u>

The test panel remained unaffected under the application of the water pressure test. The panel gained 0.4 pounds of weight after the application of the water pressure test. Since this increase is not significant to cause failure, it was concluded that proper curing during the initial drying phase helps the panel gain optimum compressive strength and capable of successfully withstanding higher rates of water pressure and situations of high humidity levels.

(Panel-2) Earth + Water

The panel failed to withstand the water pressure test. It completely disintegrated under high water pressure. The documentation of the final weight was not possible due to the fragmentation of the disintegrated particles in water.

(Panel-3) Earth + Elmer's glue mixed + Water

Though the sample failed to sustain the weight test, the panel was able to withstand the surface erosion on application of high pressures. The mixture composed of Elmer's glue and earth tends to expand due to excessive absorption of moisture, which suggests that the panel is susceptible to failure and is prone to conditions of bacterial growth on drying.

The future possibility is to determine the effect of the water pressure test on the panel prepared with similar composition, pressure compacted and fired to higher temperatures.

Figure 5.21 and Figure 5.22: Image of results of water pressure test on Panel-3 Earth + Elmer's Glue, disintegrated fragment after ½ hour continuous water pressure

(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers

The panel did not disintegrate completely under high water pressure; the clay and the Elmer's glue combination worked well with further possibilities of maintaining the proportion of clay content to around 15 to 20 % of the earth composition. To avoid failure of the panel under excessive water pressure, the built panel could be fired at higher temperatures, thus causing the Elmer's glue to fuse onto the clay particles to form a ceramic crystalline structure.

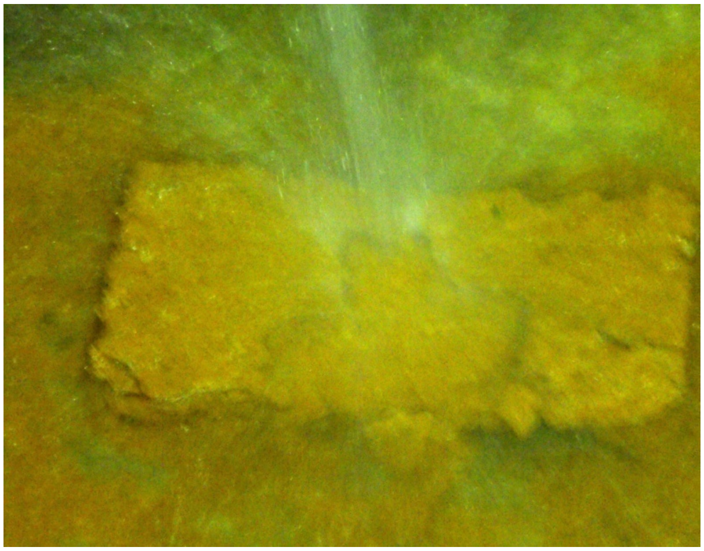



Figure 5.23 and Figure 5.24: Image of results of water pressure test on Panel-3 Earth + Elmer's Glue + Clay, disintegrated fragment after ½ hour continuous water pressure

(Panel-5) Earth + 6% Cornstarch + Water

The built panel could not sustain itself to the high rate of water pressures and disintegrated completely.

The final result for the water pressure test is presented as a comparative distinction chart between the built panels, with the x-axis denoting the classification of the variable test panels and the y axis denoting the percent weight of the individual panel. Figure 5.9 is a qualitative representation approximating the final results as a depiction of the above observations.

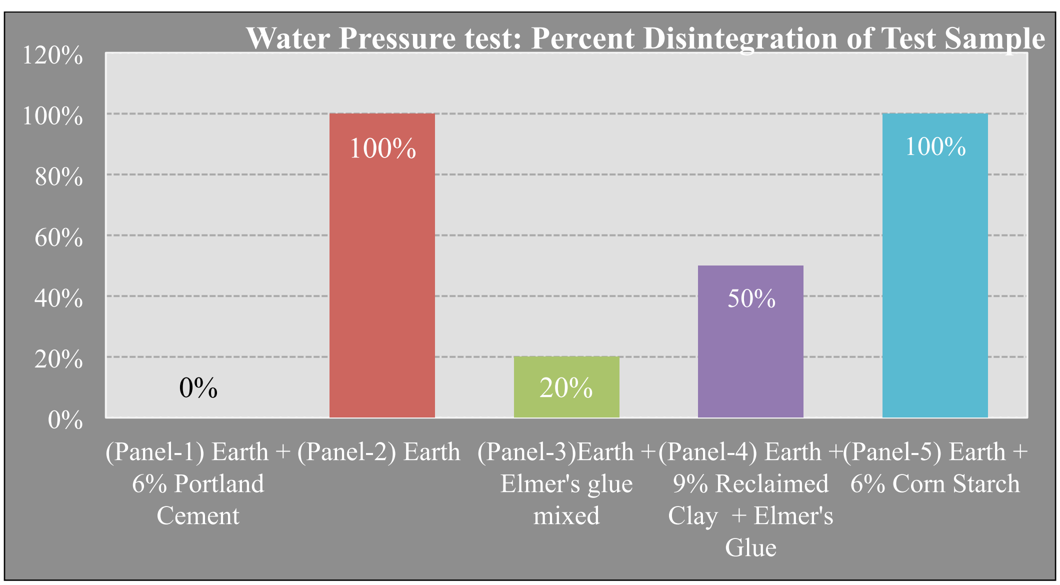


Figure 5.25: Chart with Qualitative analysis of Percent Failure (Volume) Water pressure test

5.7 Final results

The final task was to determine the results for the most efficient test panel based on the factors that included the initial observations made during the panel building; analyzing the ease of preparation; low energy requirements; the physical attributes such as appearance, odor and color and the experimental tests conducted during the research process. A matrix was prepared with the individual observations and experimental tests along the column, with their result for each in terms of the best case, worst case and the test sample with the potential to fulfill the performance criteria with few improvements.

The panel that had a maximum potential to survive and that satisfied most of the performance criteria was considered as a reasonable solution for a renewable external wall panel. The cumulative charts explaining the performance of each test panel is shown in Figure 5.26 and Figure 5.27. Based on this comparative study, the final result for an optimum alternative to renewable composite external wall panel was determined.

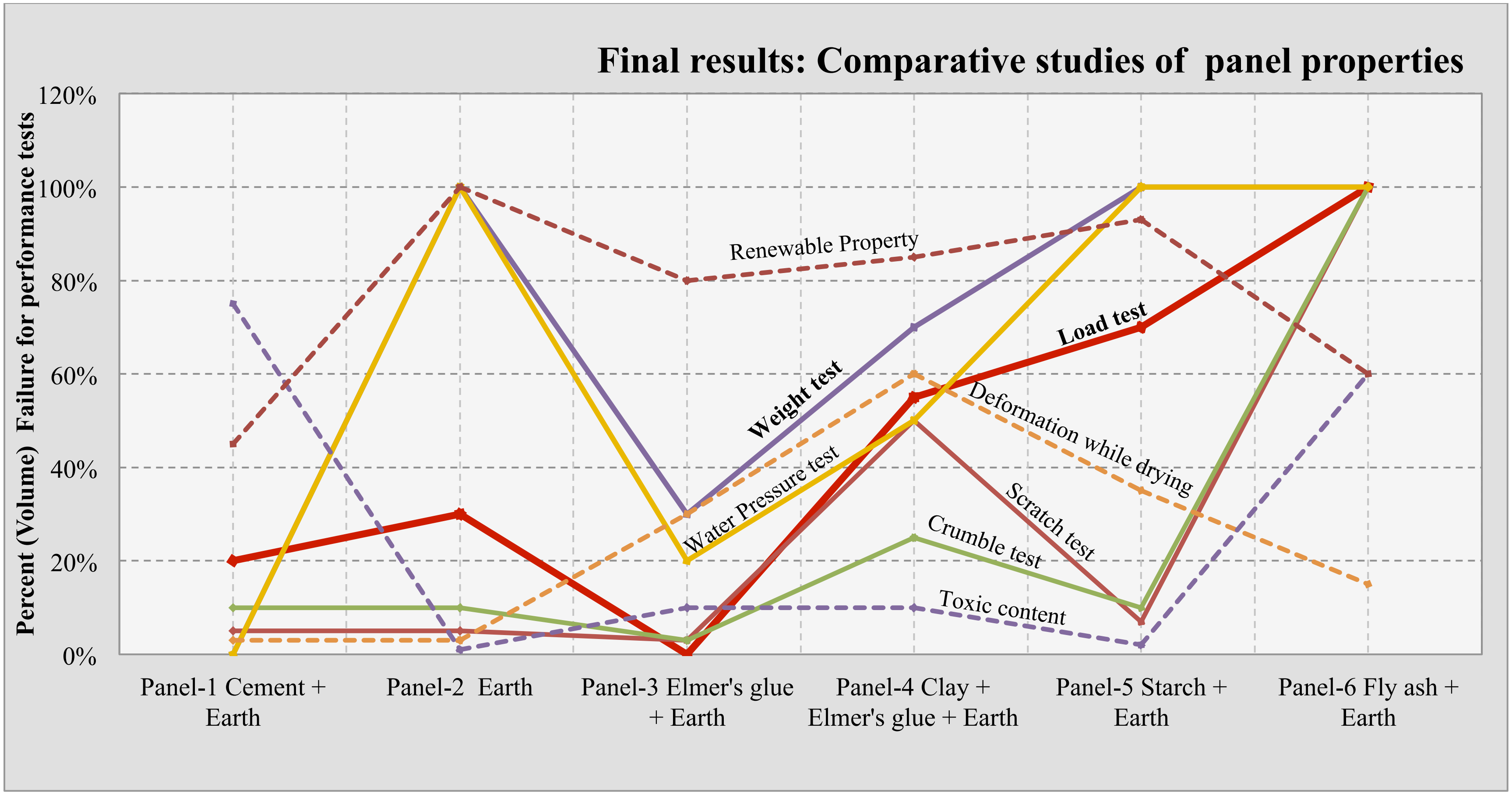


Figure 5.26: Cumulative Failure analysis using the chart

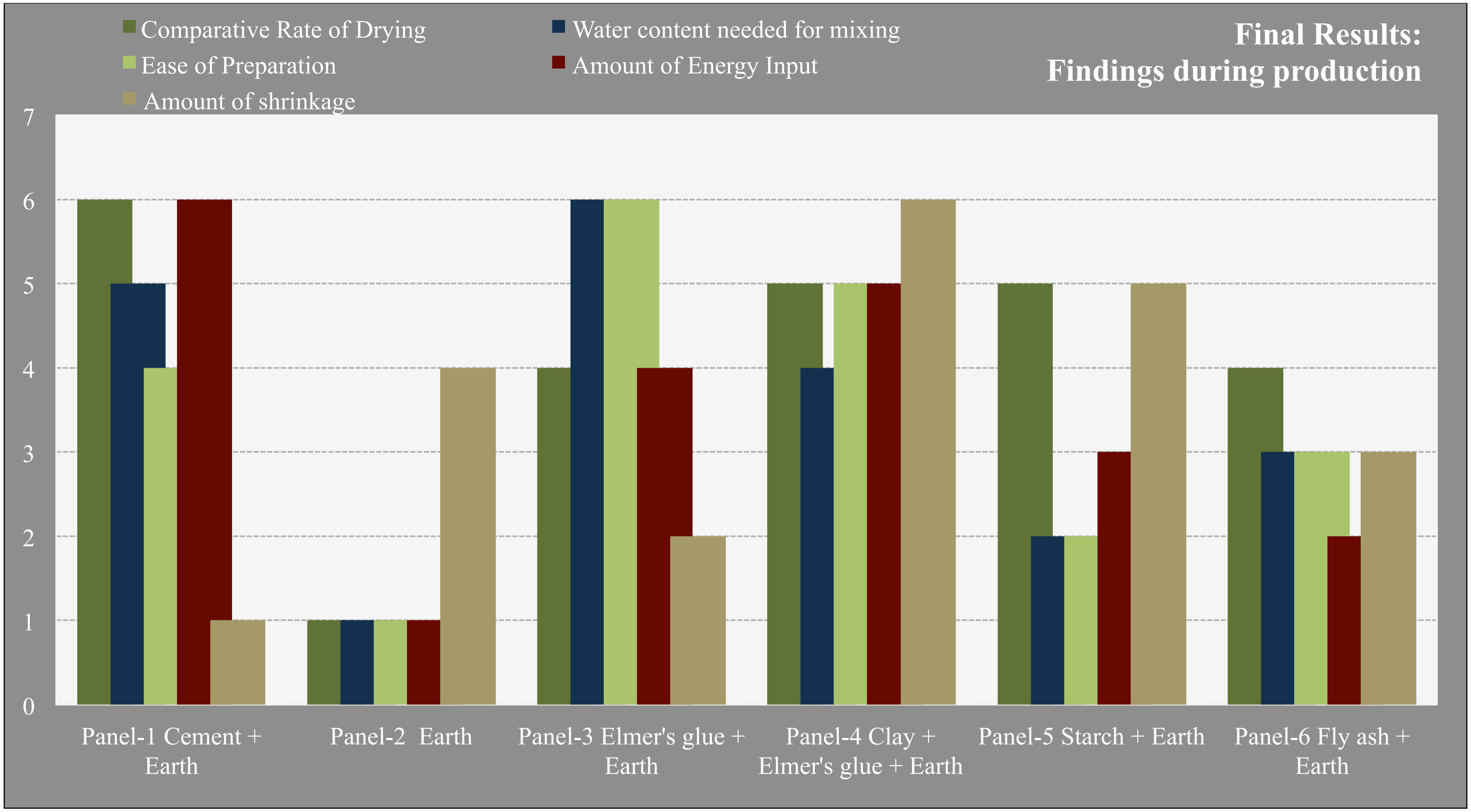


Figure 5.27: Cumulative comparison of the variable sample properties observed during production of panel using the chart

5.7.1 Final result (quantitative approach)

Figure 5.28 is a chart illustrating the most appropriate renewable composite fulfilling most of the performance criteria tested. The chart is a comparison of the proposed renewable panel with respect to the design case cement stabilized earth panel. According the chart, the cement stabilized earth panel performed poorly, not satisfying the requirements for a renewable panel. However, the addition of cement into the earth matrix was a great solution to withstand issues related to water ingress. Most of the proposed renewable panels failed to perform under the influence of moisture. Thus, finding an appropriate natural water-soluble binding agent capable of solving issues related to water ingress would be important. However, quantitatively the panel that satisfied most of the performance mandates observed in this research was the un-stabilized earth panel (Panel-2). The panel built using Earth and Elmer's glue was the second best alternative; it showed excellent properties of dry shear strength and had the capacity to carry huge loads. But both the panels failed the tests that were required to test the performance with respect to weather cycling and moisture ingress. It would be difficult to install these panels as part of the external panelized system, unless green and sustainable water proofing solutions or better alternative binding agents that can withstand issues related to moisture are used as a finishing layer for the renewable panel.

The final result for renewable composite wall panel illustrated in Figure 5.29 was determined based on the number of tests and workability criteria; that is how well the panel had performed overall during the research process. This conclusion was established without assigning the importance of the test or consideration of weighted test requirements that was relevant to fulfill the criteria to be installed as an external wall panel.

Table 5.9: Cumulative results for variable panels satisfying performance mandates

Performance criteria	**Best case (B)**	**Last case (Failed)**	**Potential research**
Renewable Properties	Panel-2 Earth	Panel-1 Cement + Earth	Panel-5 Starch + Earth
Toxic Content	Panel-2 Earth	Panel-1 Cement + Earth	Panel-5 Starch + Earth
Ease of Preparation	Panel-2 Earth	Panel-3 Elmer's glue + Earth	Panel-3 Elmer's glue + Earth
Amount of Energy Input	Panel-2 Earth	Panel-1 Cement + Earth	Panel-5 Starch + Earth
Water content needed for mixing	Panel-2 Earth	Panel-3 Elmer's glue + Earth	Panel-5 Starch + Earth
Appearance	Panel-2 Earth	Panel-1 Cement + Earth	Panel-3 Elmer's glue + Earth
Color	Panel-2 Earth	Panel-1 Cement + Earth	Panel-3 Elmer's glue + Earth
Texture	Panel-2 Earth	Panel-1 Cement + Earth	Panel-5 Starch + Earth
Odor	Panel-2 Earth	Panel-1 Cement + Earth	Panel-5 Starch + Earth
Deformation caused during preparation and drying	Panel-2 Earth	Panel-4 Clay + Elmer's glue + Earth	Panel-3 Elmer's glue + Earth
Shrinkage of Panels	Panel-1 Cement + Earth	Panel-4 Clay + Elmer's glue + Earth	Panel-3 Elmer's glue + Earth
Rate of drying	Panel-2 Earth	Panel-1 Cement + Earth	Panel-3 Elmer's glue + Earth
Defects observed during preparation	Panel-2 Earth	Panel-4 Clay + Elmer's glue + Earth	Panel-1 Cement + Earth
Crumble test	Panel-3 Elmer's glue + Earth	Panel-6 Fly ash + Earth	Panel-2 Earth
Scratch test	Panel-3 Elmer's glue + Earth	Panel-4 Clay + Elmer's glue + Earth	Panel-2 Earth
Test for sustainability of Natural binders	Panel-1 Cement + Earth	Panel-4 Clay + Elmer's glue + Earth	Panel-3 Elmer's glue + Earth
Load test	Panel-3 Elmer's glue + Earth	Panel-5 Starch + Earth	Panel-2 Earth
Weight test	Panel-1 Cement + Earth	Panel-5 Starch + Earth	Panel-3 Elmer's glue + Earth
Water pressure test	Panel-1 Cement + Earth	Panel-5 Starch + Earth	Panel-3 Elmer's glue + Earth

Table 5.10: Final results determined from the Cumulative study from Table 5.9

Panel	Best case (B)	Last case (Failed)	Potential solution with future research (P)	Total points achieved (B-F+P)	Legend
Panel-1 Cement + Earth	4	8	1	-3	
Panel-2 Earth	12	0	3	15	
Panel-3 Elmer's glue + Earth	3	2	9	10	
Panel-4 Clay + Elmer's glue + Earth	0	5	0	-5	
Panel-5 Starch + Earth	0	3	6	3	
Panel-6 Fly ash + Earth	0	1	0	-1	

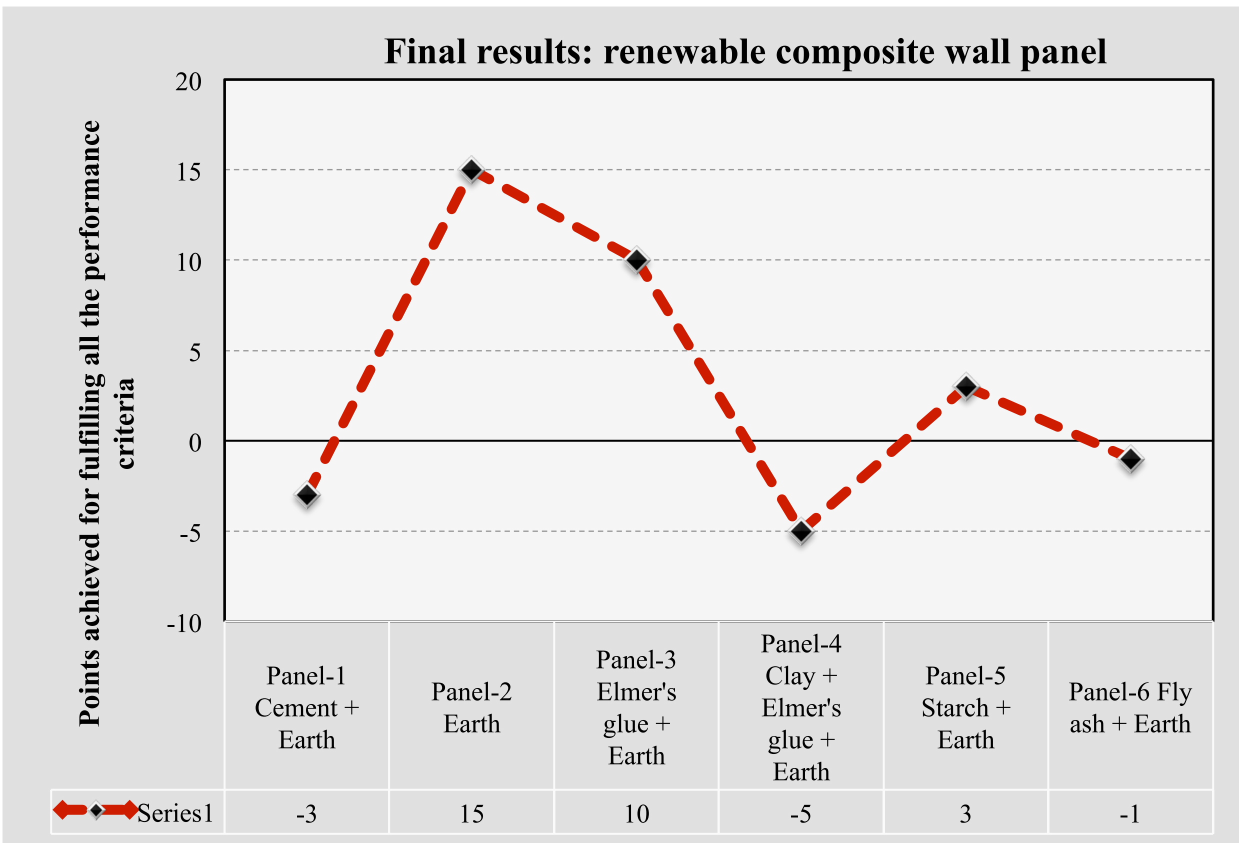


Figure 5.28: Final result for renewable wall panel

5.7.2 Final result (qualitative approach)

The quantitative approach for finding the result established that Un-stabilized Earth panel (Panel-2) could be a successful renewable composite external wall panel, considering that it fulfilled most of the performance criteria for being renewable in nature, aesthetically appealing, stable load bearing capacities and having low embodied energy compared to the other test panels. However, the major criteria for applying earth as a part of the external wall panel should be the weather and wear resistance, corrosion proof, and that it should sustain even extreme climatic conditions. Finally, the renewable panel that satisfied or had a potential to fulfill the weight and water pressure test, with most of the criteria required for this research Panel-3 was studied to be Elmer's glue + Earth. The solutions to improve the individual test panels are suggested below.

Panel-1 Cement + Earth

The efficacy of the panel could be improved by maintaining the curing period, the proportion of cement to earth ratio, and improving the appearance and texture of the panel prepared for installation as an external wall panel.

Panel-2 Earth

The panel showed exceptional properties in terms of embodied energy, ease of preparation, and the load bearing capacities were satisfactory; however, the panel failed to fulfill the performance criteria for the weight and the water pressure test. The efficacy of the panel could be improved by introducing an appropriate natural waterproofing layer to the external surface. An interesting future research possibility would be to introduce a waterproofing layer made using small proportions of vegetable fat or protein.

Panel-3 Elmer's glue + Earth

The panel was extremely strong and had the capacity to carry large loads. However, the panel could not sustain under water, as it lost all its dry shear strength properties. Applying a waterproofing layer to the surface of the panel would help sustain under water.

Panel-4 Clay + Elmer's glue + Earth

The proportion of Clay content should be reduced to around 15 to 20 % of the proportion of the material Earth.

Panel-5 Starch + Earth

The addition of starch reduced the strength of the panel, so a better solution to starch could be to use soy based additives or some natural gum such as lignin that would increase the strength of the panel, and a waterproofing layer could be added to the surface of the panel prepared with this composition.

Panel-6 Fly ash + Earth

Use Carbon free Fly ash to increase the tensile strength properties. Introduce cement or a natural binding agent with similar properties to enhance the strength and water resisting properties of the panel.

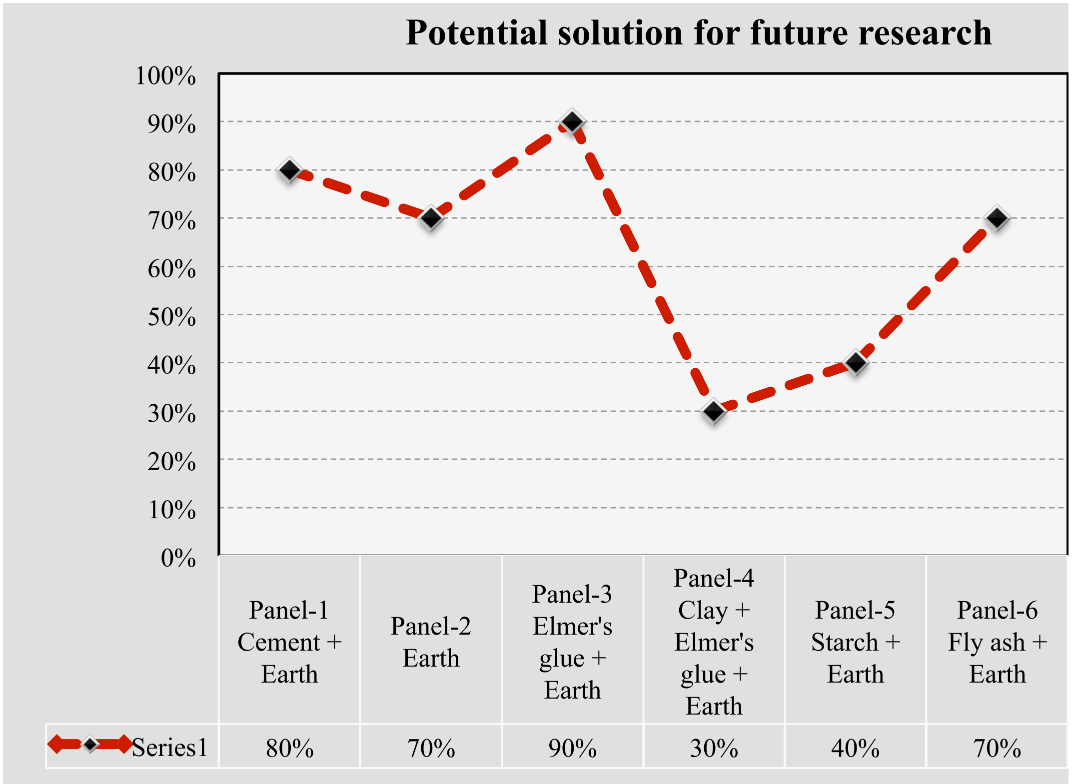


Figure 5.29: Final result as per qualitative analysis for a renewable wall panel

Chapter six illustrates the Conclusions of applying renewable panel as a part of the external panelized system and the various future research possibilities that could be adapted based on the guidelines of this research.

Chapter 6.0: Conclusions and Future research possibilities

The findings of this research are not only going to benefit society, but also pave the path for future research to be conducted so that the realms of the knowledge could be increased. The first part of this chapter deals with the conclusions and impacts of the research on the society and the second part of this chapter deals with prospects of future research.

6.1 Conclusions of using renewable composite external wall panel

Depending on the behavior of the independent variable binders used, earth panel could be installed as an efficient external wall panel comprising most of the advantages of the latest panelized wall system such as fiber cement siding. The proposed panel could be manufactured on a mass scale to be incorporated as a part of a sustainable building system. The study reinforces previous findings that it composite earth helps construct better, affordable and readily available environmentally efficient technologies for building the earth panels (Bengtsson, L. P., and Whitaker, J. H., 1986). Reuse of panels with recyclable value enables recyclability of the wall panels. The assembly line systems have better scope for easy replacement, low maintenance requirements, long lasting.

6.2 Future research possibilities

Based on the tests that were applied on the built panels for this project, further research possibilities were established. This section elaborates on details about other test procedures that can be applied to determine the efficiency of an external wall panel along with feasible solutions to withstand issues related to water ingress needs. Thus, the various research possibilities are mentioned below.

6.2.1 Alternatives

This section provides an overview of the alternative method for the application of the test panels. It would be a challenge to incorporate fibers such as hay, straw, sawdust, corn scales, hair strands and recyclable carpet fiber to reinforce the test sample, and to determine the effect of this addition on the properties of tensile strength (Augarde, et al. 2004).

Table 6.1: Comparative analysis and observing alternatives to improve the performance of test sample

(Panel-1) Earth + 6% Portland Cement + Water	Alternative for cement: lime, bitumen, gypsum (plaster of Paris). Addition of sand would increase efficiency of cement stabilization.
(Panel-2) Earth + Water	The earth composition used for building the test panel was composed of 25% of clay content. Addition of sand into the mix would reduce shrinkage due to excessive clay content.
(Panel-3) Earth + Elmer's glue mixed + Water	Alternatives for Elmer's glue: milk based casein, molasses, soy based glue.
(Panel-4) Earth + 9% Reclaimed Clay + Water + Elmer's Glue applied between layers	Alternatives for clay: Finely crushed particles of fired clay, ceramic waste from landfill, cow dung.
(Panel-5) Earth + 6% Cornstarch + Water	Alternatives for Cornstarch: Arrowroot, Collagen, Modified Starch, Natural gums, Soy, linseed oil, Sago.
(Panel-6) Earth + 6% Fly Ash + Water	Alternatives for Fly ash: Volcanic ash, rice husk ash.

6.2.2 Future research possibilities

Some of the future research possibilities are proposed below:

- To measure the effect of type of compaction methods with respect to stability.
- To measure the efficiency of the panel while varying the proportions of binding agents.
- To measure the tensile strength for the panel, on introducing renewable or recyclable fiber particles to the soil composition.
- To measure the efficiency of the panel on varying the sizes of the panel.
- To measure stability of the panel in humid conditions on introduction of varying proportions of renewable or recyclable water proofing agents.
- To measure the efficiency while varying thickness of the panel.

6.2.3 Future possibility to find an appropriate variable test sample

Based on this research the following variables were proposed.

A composite material pattern is made up of two constituent elements, the matrix and the reinforcement material. At least one variety of each type is necessary. Thus, the variable possibilities are as follows

A. The Base Agent

Earth – varying percentages

This is the primary variable agent.

B. The Binding Agent

1. Matrix having no binding agent

Portland cement - varying percentages

Fly ash – varying percentage

Water-soluble natural synthetic adhesive - varying percentages

To vary the material such that it increases the efficiency and compressive strength of the base agent. To find if doing so will increase the stability of the panel? To find if the panel built with natural binding agents as a component sustain the natural weather conditions?

C. The Reinforcement

Carpet

Ceramic waste

To establish if adding fibers increase the strength and plasticity of the composite panel? Does firing of the panel change the chemical properties of the composition? To determine the behavior of the panel built using carpet fiber with the earth matrix.

D. The Proportion of Water Content

To add water in such a way that it increases self-bonding property of the Base agent.

E. The Technique of drying

Sun dried or compressed

Fired

To evaluate optimum temperature at which the binding agent will not disintegrate. Furthermore, to create a matrix of variables into five basic groups: the base, the reinforcement i.e. fiber material, the binding agent, proportion of water, and the technique of drying. To study the addition of reinforcement member like recycled carpet fiber to the existing composition of samples. The proceeding section introduces carpet as reinforcing material and its benefits.

6.2.4 Carpet

The introduction of the reinforcement into the matrix helps improve the tensile strength properties of the panel and hold onto the bonded particles to perform well when subjected to impact loads. The behavior of carpet as a reinforcing agent is discussed below.

1. It has a life expectancy of about 8 years. In the U.S., 1.8 million tons of carpet ends up in landfills annually. It is one of the least recycled materials.
2. The construction waste like concrete slabs or steel reinforcement is reused from waste or landfill for new construction (Rypkema, D. D, 2007; habitat.org, 2011). But the major concern is to reuse the carpeted flooring; there is significantly more wastage and loss of money from this product due to no reuse value, and thus it gets dumped in the landfill.
3. Usually carpet cannot be easily biodegraded, but there are some varieties of renewable carpet fiber that can be sheared from the carpet backing to be used for various purposes (Sferrazza, R. A., et al. 1996).
4. This material has no practical application after it is used once, unless recyclable carpet fiber is used.
5. The organizations like the Radford fiber corporation, the DOE Assets management and support services groups at Washington DC work on acquisition, installation, removal, and recycling of carpet and related services. For testing of proposed panel to use the recycled carpet available from a demolition site (habitat.org, 2011)

6. The recyclable fiber from the backing can be sheared off and reused to make carpet.

7. The carpet fiber could be used as a reinforcing agent by mixing the fiber and the soil composition to prepare an earth panel. To test if an addition of fiber to the sample of earth would increase or reduce the strength; it is believed that the fiber would enhance the tensile strength properties of the panel. It would be a worth studying if the carpet fiber can be reused along with the backing material which otherwise always finds its way to the landfill (McNally M., 2007).

6.3 Future possibilities for testing performance mandates

As an extension to the research project, evaluate the use of a stabilizer like cement in comparison to all the other options when air-dried or heating with varying proportions of each variable. Some of the tests were not applied on the panel considering that the research was in its initial phase of preparation and applying all the test procedures to such renewable earth panel was not possible due to lack of access to appropriate testing apparatus

The freeze and thaw test: The wet earth panel that has attained maximum saturation shall undergo a series of freeze and thaw experiments, maintaining temperature difference of around 40 degrees using equipment like a freezer and oven with varying degrees of humidity level to see how the panel performs on being installed in extreme climatic conditions. The resulting deformation with respect to percent weight is measured (Correia, J. R., et al. 2006).

Life cycle assessment: To judge the energy usage and results of the process of making a composite wall panel using recyclable materials. Computer simulation using the software for Life Cycle Analysis will be undertaken to find embodied energy and life cycle cost analysis of the new panel with these alternative materials.

If the panel sustains the initial test procedures, a detailed study using the American Society for Testing and Materials (ASTM) test procedures standards to test the performance criteria of the panel can carried on (Correia, J. R., et al. 2006). The following (ASTM) standards applicable are as follows:

1. ASTM E – 72-05

Standard Test Method of conducting strength tests of panels for building construction.

2. ASTM E – 2127-01a (2006)

Standard Methods of static load test for combined tensile and transverse load resistance of paneled wall systems in building construction.

3. ASTM E – 2099-00

Standard practice for the specification and evaluation of pre – construction laboratory mockups of exterior wall systems

4. ASTM C 1201 – 91 (2003)

Standard test methods to test structural performance of exterior dimension stone cladding systems by uniform static air pressure difference.

5. ASTM C – 217-94 (2004)

Standard test method for weather resistance of slate

6. ASTM E – 84-06a

Standard Test method for surface burning characteristics of building materials

Energy modeling: Use of a simulation tool like Energy Plus to predict the fairly accurate behavior of the composite in its built-form to base the initial inputs of composite proportions, and the following effects on the performance criteria.

Mechanical testing: The panels could be mechanically tested in a laboratory facility for tensile strength, toughness, and shear strength, stability, weight, stiffness, and fatigue life.

Water test: Effects of solar radiation, thermal expansion, evaporation of water from the surface, wear resistance, corrosion resistance, and temperature depending factors, spalling.

Chapter 7: Reference

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7.1 Useful websites

http://www.aseg.net

http://www.craterre.archi.fr

http://www.earthbuilding.org.nz

http://www.hahaha.com.au/rammed.earth

http://www.ramderth.com

http://www.rammed-earth.info

http://www.earth-auroville.com/index.php?nav=menu&pg=rawmaterial&id1=3