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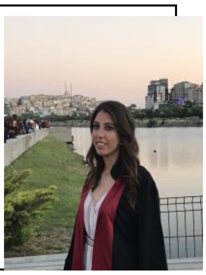
Designing a Sustainable Workflow for the Fabrication of Biologically Improved Rammed Earth Blocks



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ABSTRACT

This paper presents the intermediate results of an interdisciplinary research project that aims to improve earth materials with biological additives and develop a design and fabrication system for prefabricated rammed-earth blocks. In the first phase of the research project, a series of laboratory tests are conducted. Earth is stabilized with microorganisms and waste plant additives in order to improve its physical and mechanical properties. Within the context of laboratory tests, three plant waste-incorporated mixes and three bacteria-incorporated mixes are produced. Bacteria and plant wastes are selected considering the goals of the project as being sustainable and harmless to human health while supporting various performances such as lightweight blocks or durability issues. The physical and mechanical properties such as compressive strength, shrinkage and thermal conductivity of the new mixtures are determined. The second phase of the research project covers the methods to integrate the developed earth mixes into the factory production system and manage a sustainable design-fabrication system for biologically improved rammed earth blocks and panels. The production process will be planned in such a way that the least energy is consumed with the least damage to the environment. It is planned to carry out a life cycle assessment (LCA) starting from the obtaining raw material stage including all additives; transportation of the raw materials to the fabrication area, production step of the rammed-earth blocks with the newly proposed material, transportation step of the rammed-earth blocks to the construction site, construction stage, usage, decomposing or recycling stages of blocks at the end of their useful life. With the LCA, the design-production process will be examined in terms of having a sustainable workflow and environmental factors and effects on human health.
Keywords: Rammed-earth, Biomaterials, Sustainability, Prefabrication, Life Cycle Assessment

1 INTRODUCTION

To improve the mechanical and physical properties of earthen building elements, earth has been supported with different stabilization methods and various additives have been applied [1,10,12] throughout the history. The most commonly used stabilization method is a mixture of earth and straw usually used as adobe bricks, in our country. This method is generally used in rural areas and low-rise buildings because it requires intensive labor, long application time and periodic maintenance after application. Işık, complies with the principles of adobe brick and gypsum adobe brick masonry construction materials, which are suitable for sustainability and human health; she has shown its use by applying it in many individual structures and housing settlements with rapid casting in situ or rapid block production on site [7,23]. Various material mixtures, stabilization methods, on-site production, or factory production methods are being explored to increase the use

of earthen structures in the city, which have significant potential for sustainable cities and healthy buildings[16]. In the research of additives, cement, fly ash, fibers, vegetable waste, etc., contributions are examples. Cement-added rammed-earth shows high performance in terms of strength, but the use of cement is not suitable in terms of environmental effects [6,7,8,9,13]. ALKER mixture, which was founded by Kafescioglu [8] and the Earth Research Group at ITU, consists of a mixture of earth, gypsum, lime and water, having a similar strength to cement-added rammed-earth mixtures [6,7,8,9,13].
Within the scope of the BIRE-PAN research project (*), the mechanical and physical properties of a typical ALKER mixture were compared with new recipes containing different types of plant additives and microorganisms. Within the scope of the project, the properties of the proposed plant and microorganism-added earth mixtures were determined by several tests . A new mixture (BIRE) to be proposed within the scope of the project will be produced and definite properties will be enhanced with several additives considering the designed building blocks and the design-production system (BIRE-PAN) , blocks, panel and mold prototypes to be made at the factory.

2 BIRE:EARTH MIX DESIGN, TESTING METHODS AND PERFORMANCE

In this study, the production of a sustainable earth mix design with enhanced properties was aimed. Within this context, several waste plant additives and microorganisms are used. Several rammed earth mixes were produced, using locally available earth and waste plants. The plant additives such as ground peanut shell (GPS), ground sunflower stem (GSS) and corn husk (CH) pieces are used to enhance physical and thermal properties. On the other hand, bacteria are used to improve the mechanical properties of the earth mixes through biomineralization [5]. Three types of bacteria, *bacillus subtilis, sporosarcina pasteurii, and bacillus subtilis subsp. subtilis,* are tested in rammed earth and gypsum+lime stabilized rammed earth mixes and the compressive strength performance was compared.

The earth sample was collected from a depth between 0.5 and 1.5 m from Kemerburgaz, Istanbul. Table 1 shows the properties of the earth used.

Table 1. Properties of the earth.

Property	Parameters	Details
Atterberg limits	Liquid limit, W_L	36%
	Plastic limit, P_L	18%
	Plasticity index, I_P	18%
Proctor test	Optimum moisture content (OMC)	18%
	Maximum dry density (MDD)	17.3 kN/m^3

In all mixes, alpha gypsum and CL 80S type air lime were used as physicochemical stabilizers to enhance the mechanical properties. Ground sunflower stem (grains lower than 1 mm), ground peanut shell (grains lower than 0.85 mm) and corn husk having 2-3 cm long and 0.5 cm width were used as plant waste additives (Fig. 1).

(a) (b) (c)
Figure 1. (a) Ground peanut shell, (b) ground sunflower stem, (c) corn husk pieces.

A total of five mixes (Table 2) were produced to determine the physical, thermophysical properties, and compressive strength of the mixes. Gypsum and lime were used 10% and 5% by weight of the earth, respectively. The water ratio was kept at 0.25; however, due to high water absorption capacity values of GSS and GPS water ratio increased to 0.28 in those mixes. Plant additives were incorporated by the volume of the mixes. The mixes were coded depending on the plant additives used; *RE* refers to rammed earth, while *SRE* refers to gypsum+lime stabilized mixes.

Table 2. Mix proportions of plant additives-incorporated mixes.

Mixes	**Binders (%)**		**Plant additives (%)**			**Water (%)**
	Lime	**Gypsum**	**GSS**	**GPS**	**CH**	
RE	-	-	-	-	-	25
SRE	5	10	-	-	-	25
SRE-GSS	5	10	5	-	-	28
SRE-GPS	5	10	-	5	-	28
SRE-CH	5	10	-	-	1	25

Bacteria-incorporated mixes are designated with their commercial numbers, which 6051, 11859 and 23857 define *bacillus subtilis, sporosarcina pasteurii, and bacillus subtilis subsp. subtilis,* respectively (Table 3). The mixes were coded depending on the bacteria used; *RE* refers to rammed earth while *SRE* refers to gypsum+lime-stabilized mixes.

Table 3. Mix proportions of bacteria-incorporated mixes.

Mixes	**Binders (%)**		**Bacteria (OD_{600})**			**Water (%)**
	Lime	**Gypsum**	**6051**	**11859**	**23857**	
RE	-	-	-	-	-	25
RE-6051	-	-	3,250	-	-	
RE-11859	-	-	-	4,010	-	
RE-23857	-	-	-	-	1,803	
SRE	5	10	-	-	-	
SRE-6051	5	10	2,475	-	-	
SRE-11859	5	10	-		-	
SRE-23857	5	10	-	3.702	2,262	

6051:Bacillus subtilis, 11859: Bacillus pasteurii, 23857: Bacillus subtilis subsp. subtilis

A wooden hammer was used for compacting the samples manually. Rammed earth cube specimens with a size of 50 × 50 ×50 mm were produced for compressive strength measurements on the 7th, 28th, and 90 days. The thermal conductivity of the mixes are determined on rectangular prisms having dimensions of 80 × 40 ×160 mm. Also, drying shrinkage was determined on 40×40×160 mm beam samples.

It was observed that lime and gypsum addition enhanced compressive strength for both early and further ages. Waste plant additives caused a reduction in compressive strength as expected; it was prominent in GSS-added mixes, while CH-added mixes presented only a slight decrement (Fig. 2). On the other hand, plant additives caused lower shrinkage and thermal conductivity values (Figs. 3 and 4). It can be deduced that waste plant additives, GSS, GPS, and CH, can be regarded as a good potential to obtain lower shrinkage and thermal conductivity values in rammed earth materials; however, possible reduction in the compressive strength should be considered.

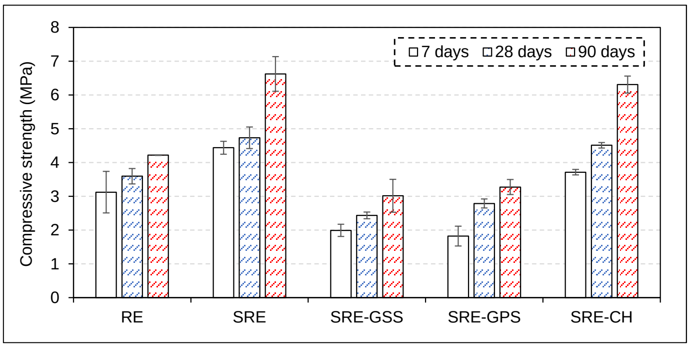

Figure 2. Compressive strength values of rammed earth and plant additives-incorporated mixes.

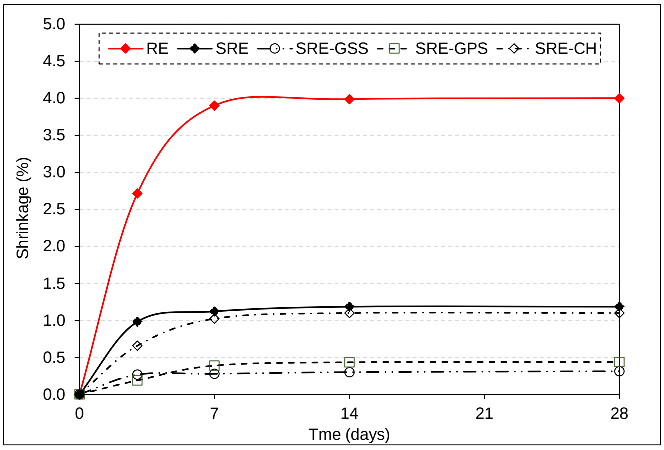

Figure 3. Shrinkage values of rammed earth and plant additives-incorporated mixes.

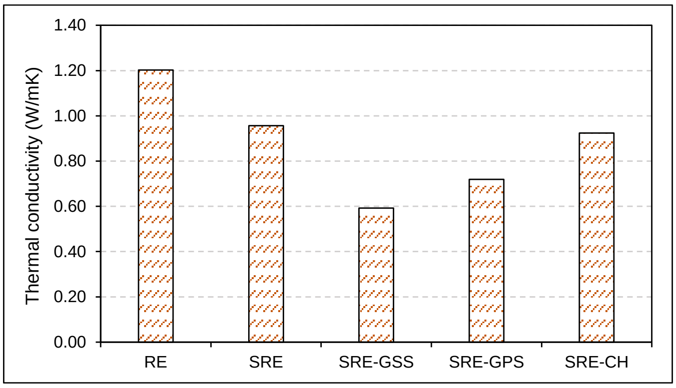

Figure 4. Thermal conductivity values of rammed earth and plant additives-incorporated mixes.

The compressive strength test results of bacteria-incorporated mixes are given in Figs 5 and 6 and it was observed that those mixes presented promising results in terms of compressive strength in the case of gypsum and lime stabilization was applied (Fig. 6). The maximum strength values obtained in the bacillus subtilis incorporated mixes reached higher than 8 MPa at 28 days, representing two times higher values than the reference mix (Fig. 6). 28 days strength values increased significantly compared to the reference stabilized mixes and 7 days results, representing the possible calcite formation which occurs over time [11,15,16]

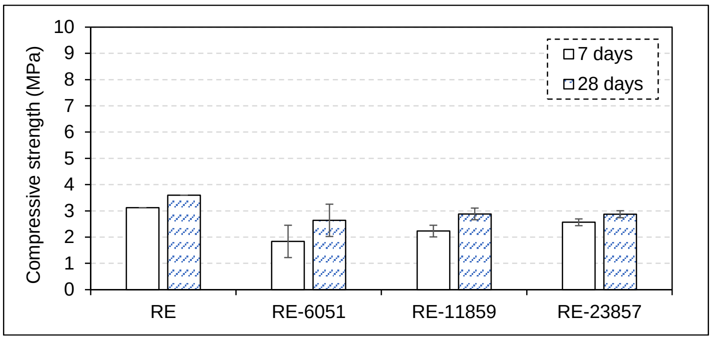

Figure 5. Compressive strength values of bacteria-incorporated mixes.

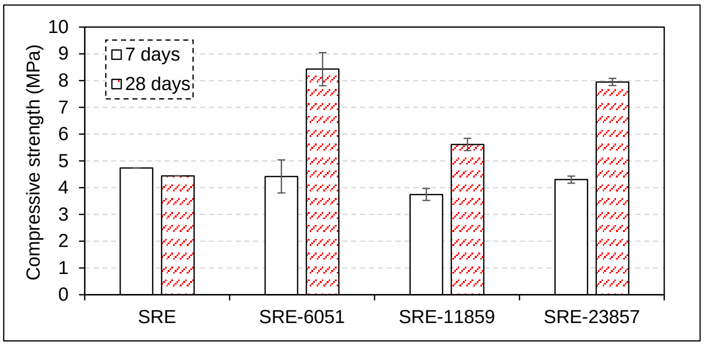

Figure 6. Compressive strength values of stabilized bacteria-incorporated mixes.

3 BIRE-PAN DESIGN AN FABRICATION SYSTEM: DESIGN GUIDE FOR PREFABRICATED RAMMED-EARTH BLOCKS

From the architectural point of view, it is observed that computational techniques enable explorations in earthen block forms and molding techniques. However, these explorations require material research and standardization issues for factory production. As a result of this research project, a context-sensitive design system will be defined as a design guide. This design system will be composed of BIRE blocks that create various types of walls. With the help of material studies and geometric explorations, the performances of these wall types will be evaluated via prototypes[3].

The design system, will be developed using parametric modeling languages included in CAD software. This technology will enable the exploration of design alternatives. The design process of BIRE-PAN's block and panels exhibit major parameters such as lightness, structural strength, and permeability. In general, masonry systems are based on a component-based design logic, which incorporates the combination of basic units into more complex and specialized building components. The design system, which is still under development, will configure these parameters to create a system of solid-void combinations for various functional needs (e.g. wet areas, living spaces, public spaces). It is expected to include not only solid but also semi-permeable wall instances (Fig. 7).

An important issue that should be taken into account in design is that the proposed block/panel systems should have similar deformation characteristics to the load resisting frames of the structure. As an initial phase, the blocks are designed as partition or separation wall systems. Although partition walls are not expected to resist the forces acting on the structure directly, they should have sufficient flexibility to be able to deform together with the beam/column frame they are constructed in.

In general, conventional wall systems are known to have high rigidity but low strength. Shear failure, which is usually observed in the form of X-shaped cracks, is a typical damage pattern caused by insufficient strength. Similarly, if not designed appropriately, due to their high rigidity, walls may also limit the deformation of the columns resulting in a very severe structural problem known as "short column."

Therefore, in order to provide the required flexibility, the blocks are designed in several horizontal layers that can slide over each other in case of an earthquake. The unique shape of the blocks generates a geometric interlocking mechanism for the blocks within the same layer, whereas sliding planes between different layers allow relative deformation and prevent excessive shear stresses due to the increased rigidity.

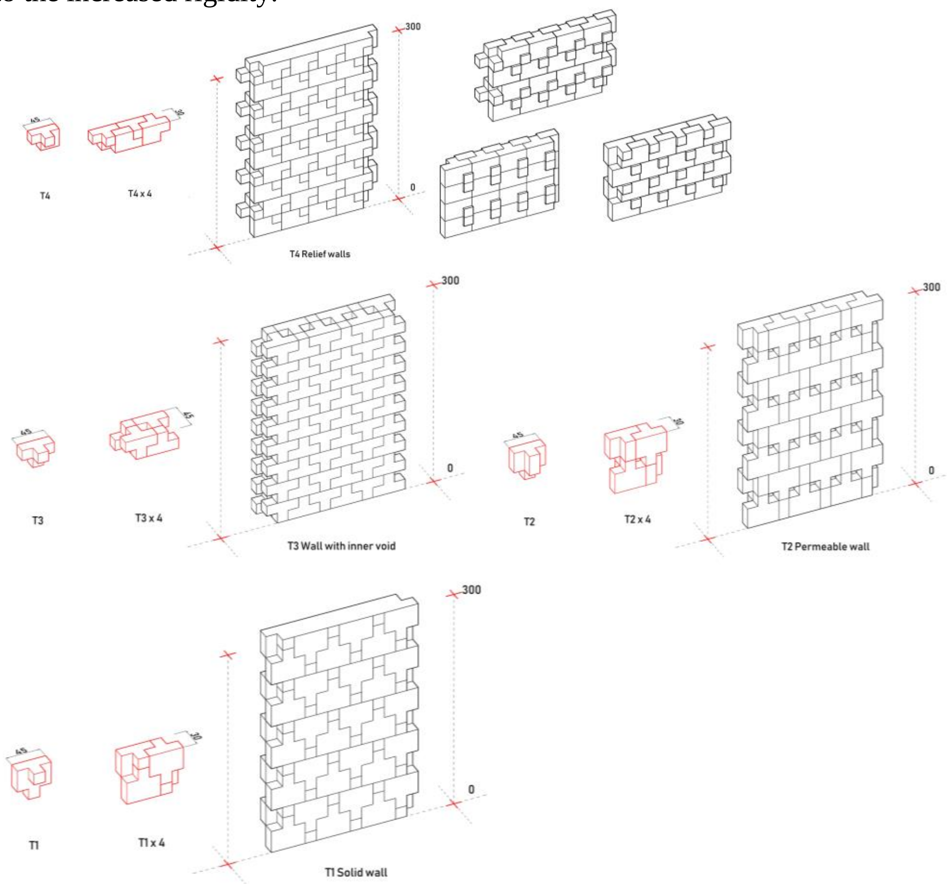

Figure 7. Initial sketches for the design system of BIRE-PAN based on various types of walls composed of prefabricated rammed-earth blocks

4 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a system developed for examining and calculating the environmental impacts of products in their processes from production to disposal. LCA is developing and using assessment tools and databases on a local and global scale in different countries. [2,14,19,20] LCA analyses the phases of raw material obtaining, transportation, production of the product, transportation-distribution, application of the product to the structure, use-maintenance-repair, completion of the life of the product and recycling or decomposed processes. It covers the processes of making an inventory of the energy, water, other raw materials and natural resources used in these processes, as well as the environmental impacts that arise with it, and the systematic and comparative evaluation of the results. The life cycle for structures; material-product production, building production, use and destruction and recycling are examined in 4 basic phases[19,20]. Especially LCA studies for building materials, some phases of the life cycle are taken into consideration instead of the whole. System limits are expressed as; cradle-to-grave (processes from raw material extraction to product destruction); cradle-to-cradle (processes from raw material extraction to raw materials recycling), cradle-to-gate (processes from raw material extraction to factory exit), gate-to-gate (processes between factory entry and exit)[14].
There are few studies within the scope of LCA research for earth material. The reason for this is that different results are obtained for the earth of each region, and a standard is hard to be

established, as issues such as local land use, climate and geography differentiations. The lack of standards prevents definitive results in this area. However, certain parameters can be determined, and a conclusion can be reached through mandatory tests for each earth in line with these parameters. [2,14]Martin Rauch set up Erden Factory for the production of the earthen building components in the factory. They built various components such as rammed-earth blocks or walls produced at the factory [9,21,22]. When the cradle-to-grave life cycle of the building material is examined for the earth material, it completes its life cycle when it is left to the nature after its decomposed, as long as no additives are made to the earth material [Fig.8], [21,22].

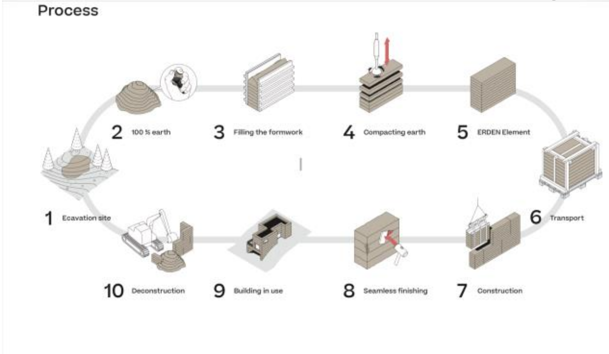

Figure 8. Martin Rauch-Erden Factory Rammed-Earth Fabrication Process.

Within the scope of the BIRE-PAN research project, it is aimed to produce rammed-earth blocks and panels in the factory and to build a prototype space with the recipe obtained as a result of earth construction material research and design processes. It is planned to make an evaluation of the design-production processes in terms of LCA as the guide for design-fabrication process. It is aimed to create a life-cycle evaluation in which raw material obtaining, samples prepared in the laboratory environment, tests, block/panel design processes, production in the factory, prototype structure construction processes generate data. Although cradle-to-grave and cradle-to-cradle inspections will not be possible during the project period, it is expected that there will be an opportunity to examine building materials in terms of 3 of the 4 main phases of LCA assessment.
Witihin the context of the BIRE-PAN research project; Investigation of earth building material in terms of LCA will be realised via an ongoing graduate thesis; within the scope of cradle-to-gate; raw material procurement, laboratory tests, design processes and evaluation of the stages of starting production at the factory.
While making LCA investigations for the production of building materials, it is seen that the most energy consumption and carbon emissions occur during the production phase of the material in the process called cradle to grave. In the whole life cycle of a material; it is similar from the production of the simplest pure material to the production of composite materials that contain many different elements. For composite materials, it consumes a lot of energy not only in the production phase but also in the recycling phases. As well as producing composite material, separating the material into its smallest component, raw material, also causes energy consumption. Since the mixture of alker is created with the additive of gypsum and lime, it can be thought that it is actually a composite material. For this reason, it is necessary to separate all the additives in the material when it is aimed to reuse or decompose the raw materials by recycling when the material ends its useful life. The energy spent in this process; it is much more than additive-free or earth materials containing natural additives. Natural additive materials; can be directly mixed with nature in the processes of destruction after its destruction.

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