Prefabrication and Automation in Rammed Earth Building Construction

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Purpose Rammed earth construction (REC) is an ancient building technique. It has been wildly used globally for thousands of years[1]. However, it has been abandoned and neglected by the mainstream construction industry after the industrial revolution, due to the availability and affordability of mass produced construction material such as bricks and concrete. REC has not been further developed since, meanwhile the potential of this ancient technique has been forgotten, until recently there is an increasing trend among construction industry, which attempts to reduce its carbon footprint and explore new ways of sustainable construction. The purpose of this paper is to examine and explore the existing techniques, materials, and strength, limitation of REC and evaluate the potential of implementation of new technologies throughout the design and build phase. Identify how technology implementation and cross disciplinary strategies would eventually upgrade this ancient building technique to its 21th century standard. **Method** For instance, in China, the government aim to carry out one of the biggest regeneration program in its vast rural areas. The main scheme is to improve rural housing condition and provide adequate new dwellings. In terms of sustainability, REC technique seems the best candidate for this role. Traditional REC has the reputations of labour intensive, time consuming and easily affected by external environment such as rain and wind[2]. This paper will describe possible solutions to overcome those difficulties by examining various on-site and off-site construction technologies that have been adopted by mainstream construction industry, and also emphasis how technology implementation, innovation and alteration would influence REC in terms of efficiency and quality. Additionally, the potential of use rammed earth technique in different terrain, social and economy circumstances. **Results & Discussion** By analysing the differences between traditional REC methods and advanced methods, the author demonstrates the opportunity of optimizing existing techniques in other sectors such as manufacturing and automotive industries (Figure 1). Consequently, this could enhance the productivity and sustainability of advanced REC in the future. However, industrialized production methods might overshadow the nature of rammed earth building technique. Therefore, preserving yet enhancing the traditional techniques is vital.

***Keywords**: Rammed earth construction, automation, prefabrication.*

INTRODUCTION

REC has been widely used throughout the globe for thousands of years, from the ancient Great Wall of China 4000 years ago to the 250 year old Fortified City in the Draa Valley in Morocco. Archaeologist's founding has proven that earth as a building material and technique has inspired our ancestors, and has influenced the way we build. However, after the industrial revolution due to the availability of cheap building materials such as brick, rammed earth has become less popular. After the invention of cermet, concrete became the primary material in modern construction. Rammed earth has slowly abandoned by the industrialized world. Fortunately, this historic building technique still been widely applied in many developing countries today. More than one third of human population still reside in earthen houses[1].

Under the current trend of seeking sustainable construction methods, rammed earth has been rediscovered due to its unique characteristic. Firstly, soil is an ecofriendly natural building material and vastly available. Secondly, it is cost effective; building with rammed earth can dramatically decrease building cost. Last but not least, REC has very small energy consumption. However, there are still indicated many weaknesses, and potential for improvement. Commonly earth will be compacted with manual rammers layer by layer. This is an extremely nerve racking building process. It is not only time consuming, labour intensive but also effected by many external elements such as weather and terrain. Research has

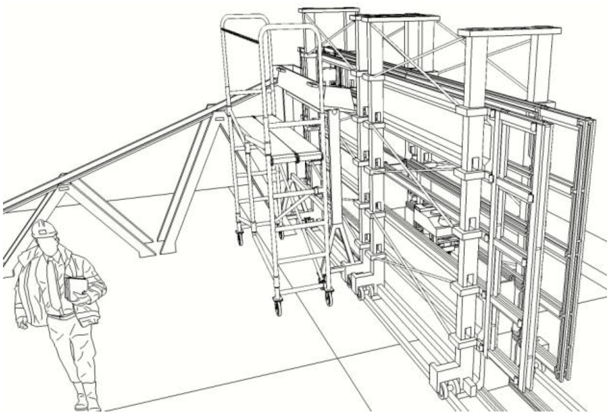

Fig.1. Proposed method

shown that in the private housing sector mechanic tool have been developed and adopted into rammed earth construction, such as flexible design of formworks and pneumatically powered dynamic rammers. This has improved efficiency of the building process. Furthermore, newly developed, advanced earth building techniques demonstrate the value of earth building not only in self-built sectors, but also for construction contractors[1]. Future development and improvement on existing technology is essential, which covers various aspects, as well as challenges, the author will discuss these issues in later stages of the paper. Furthermore, the paper will mainly focuses on REC of single or double storey family dwellings.

CONVENTIONAL REC TECHNIQUE

REC technique is used predominantly for building load bearing walls which require moist earth unloaded into a temporary formwork in layers. Each layer approximately 10-15cm thick and then well compacted by means of ramming. Traditionally, the formwork consisted of two wooden panels on either side of the work space acting as a retaining wall which enable the panel to firmly hold up the soil while ramming is in operation (Figure 2). The formwork will then be disassembled, moved forward and reassembled in the direction of the construction. It will be interlocked by series of spacers which enable

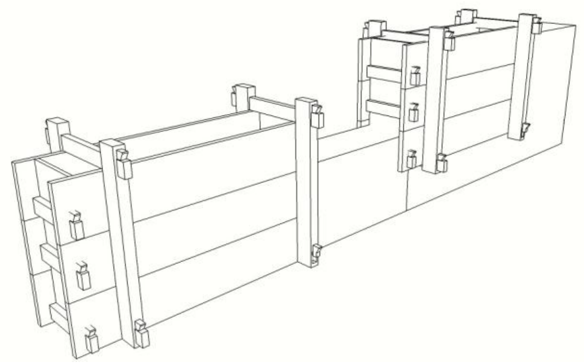

Fig.2. Traditional formwork

the formwork to lock into place and stop the form work expanding outward caused by the force. Compared with adobe masonry construction, rammed earth construction offers more stable ability because of the nature of monolithic structure.

Earth-based materials have shown many sustainable characteristics such as low carbon emissions minimising construction pollution and waste. In many countries, construction industry is one of the major producers of carbon emissions. Within the context of sustainable strategies for reduction of the environmental impact of construction, earth materials have the potential to make a significant contribution. The market for conventional rammed earth buildings is growing rapidly in many parts of the world, especially in Australia where in certain regions it accounts for approximately 20% of the new-build market. The same trend can be also found in the UK, USA, and other Latin America countries[3]. Especially in Australia, REC technology has been improved by many construction firms. Formworks and tools are been upgraded and customized to optimise efficiency. Building codes have been issued to overlook the building standard by local authority. Subsequently, there are specialized firms and skilled workers which would deliver high quality standard building projects. In contrast, in developing nations such as China who are behind the glorious economic growth, there are still many undeveloped regions where people are still suffering from inadequate accommodation.

CHINA RURAL AREA REGENERATION

Recently the Chinese government has introduced an ambitious national programme which aims to regenerate its vast rural area. The main challenge of the programme is to improve and upgrade the rural housing standard but not to compromise with the local environment. In China rural areas are predominately occupied by agriculture land. In many provinces local authority have issued tough regulations to control the use of farm land. As a result, limited subsoil can be excavated. On the other hand there are many remote areas that are not accessible by any means of transportation. Tools and building material can only be delivered by human labour or by animals. It is unfeasible to use heavy machineries and modern construction technique. This might be one of the reasons why the local construction sector was undeveloped. In addition, more and more young people decide to migrate to larger cities in search of economic opportunities; this has led to major demographic shift in Chinese rural population. According to a national report, in the year 2011 China's urban population has exceeded the number of rural dwellers for first time in its history. Less labour is available in its rural region and skilled craftsmen are even in shorter supply. To be able to achieve the goal of regeneration of such vast area, selection of building method choice of building method is essential. REC is inexpensive and relatively low-tech, which has demonstrated many advantages and potentials of fulfill this task.

MATERIAL SELECTION & TREATMENT

Sub-Soil, clay, sand, silt and gravel are the primary materials for REC. Material section and mixing is the first step and the most important step of preparation. But not all soils are suitable for rammed earth construction, only sub-soils. Because top soil consisted of soil mixed with organic remains of plants and animals, structural performance can be affected when it starts to decay. Soil needs to be mixed with right amount of gravel, sand and clay to form desired mixture for wall construction. Each project is different depending on its geological characteristics of the local area; local geological survey and collection of soil sample is recommended. Poor performance of the soil mixture can be optimised by adding stabilizers, such as Portland cement and lime which are commonly used. Yet this method was controversial as the nature of sustainability of rammed earth construction is compromised as the building cannot be recycled when cement stabilizer is added.

According to research from Energy & Environmental Research Center University of North Dakota alternatively coal combustion, fly ash and bottom ash have excellent potential for use in REC. They are more cost effective and environmental friendly. There are no well-established engineering standards available for soil–fly ash or soil–bottom ash mixes. The fly ash industry has established many tests to evaluate the product. There are also numerous standardized tests to evaluate soil characteristics. Although these tests provide a starting point for rammed earth evaluation, many of the tests that are used for soil or fly ash as individual components are not applicable to rammed earth because the nature of the composite is different from that of either component. Standardized tests to evaluate soil–fly ash mixes do exist, but the tests are merely performed to establish appropriateness for roadbeds and fill, not for REC. Consequently, establishing engineering standards for rammed earth is necessary[4].

Conventionally, REC contractors tend to repeatedly use their soil source from the same quarry due to lack of trust of local soil source. Logistic can be costly if materials have to travel across long distance. Time spent during transportation is non-productive and could cost delay on a project. Therefore gathering soil locally can be cost effective, that a local soil database could hold record of local soil data and guideline of local excavation. This solution could be realized by incorporation with local geologists as well as university and research instituted. Data collected can be shared as guide line for local building control authority and local construction contractors. Using evacuated sub-soil from a conventional construction site can be reused rather than landfilled. Removal cost could be split by the construction firm and rammed earth soil provider. The soil will be treated and mixed under the guideline and distributed to REC industry. Reuse evacuated soil could offer minimal construction waste to landfill.

IN-SITU CONSTRUCTION & PREFABRICATION

Panning is the key strategy for in-situ type of construction such as REC which most of construction activities are conducted on-site. Materials and components need to be protected from external influence before assembly. Firstly, material storage can be problematic in an on-site situation as a result of changing characteristics of the weather. For instance in cold climates will produce frost due to the moisture level left in the soil mixture and by contrast in dry climates moisture will quickly evacuate. As a result soil mixture is damaged and can cause delays on-site. Despite the course of climate and location, a fundamental part of in-situ construction is to have prefabricated component materials on site ready for assembly. In REC, structural components can be prefabricated on-site to reduce initial investment. Secondary elements such as internal wall or roof structure can be prefabricated either on or off-site depending on the project. Weatherproof shelters can be used to protect finished components and workers from external elements. In addition, on-site quality control, in terms of controlling soil moisture content and precision of the assembly it is essential to ensure construction quality.

DESIGN FLEXIBILITY & STANDARDIZATION

Industrialisation in building is not new and many buildings are now industrially manufactured. Characteristics of industrial production are mass production, repetition and standardisation, off-site production and machine made production[5]. Post-war housing shows some the characteristic of mass production. Also in Japan there are many examples regards to off-site building production such as Toyota Housing, Sekisui Heim which has demonstrated the advantages of factory made buildings; high precision, high quality, highly customized, and brilliant customer relationship. To be able to adopt the principle of industrial building method, traditional REC technique has to be reconsidered regards the way it has been designed produced and assembled.

Formwork design

Traditionally, formwork for rammed earth construction is similar to formwork used in concrete production; it offers temporary support during compaction process. It must provide strength and stability. Normally formwork will be dismantled and reconnected almost immediately after compaction. It is labour intensive and requires coordination between all site personnel. This assembly of formwork costs a significant part of overall construction time; therefore an efficient formwork system is essential to improve productivity of REC. There are many choices of formworks available on the market. However, to apply those in an extreme terrain became a difficult task due to their weight and size. The suggested solution is that formwork needs to be designed modular, light weight, easy to be cleaned and transport, potentially without using crane or other heavy lifting device. Furthermore due to increased cost of formwork, attempts have been made to develop permanent formwork techniques. Permanent formwork made from thin masonry or brickwork or alternatively timber frame formwork, which became part of the structure after use[6].

Implication for components design

Wall is one of the primary parts of the rammed earth construction which offers load bearing structure of a building. Commonly formwork is used to construct walls. However, it is time consuming and takes experience to manage. Instead of producing entire wall section on foundation slabs, alternatively wall modules can be designed as interlocking parts with special connecting point designs, which smaller or individual formwork can be used. Each module has to offer sufficient stability as monolithic structure so mortar might be used as stabilizer. Size and weight of each module is important issue. Preferably it will be easily carried and assembled by 4-5 people on-site with basic construction equipment. On the other hand, smaller size means building module along with formwork can be transported by trains, trucks, van, or even by a family car (Figure 3).

Standardization

Another core challenge is standardization of REC. Building design requirements need to be regulated, for example, Australia, New Zealand, and USA (New Mexico) have already issued full national building codes regards to construction of rammed earth building. Standardization of the design will allow prefabrication to take place, which can dramatically improve productivity of rammed earth modules and optimise its quality. For example standard component design allows mass production of the component therefore reducing the cost. Implementing the principle of the open-building approach by John Habraken, the base building such as the wall can be constructed with standard modular element to offer a rigid outer shell. In contrast internal walls and fit out of the building need to be designed to be more flexible; prefabricated by timber frame or light steel frame structure, which can be easily disassembled when internal alteration is needed. An open-building approach could offer individuality to a standardized design as the end user is engaged into the design process, therefore the finished building should appear with a high degree of customization but offer a mass produced price, which is in common with automotive industry today.

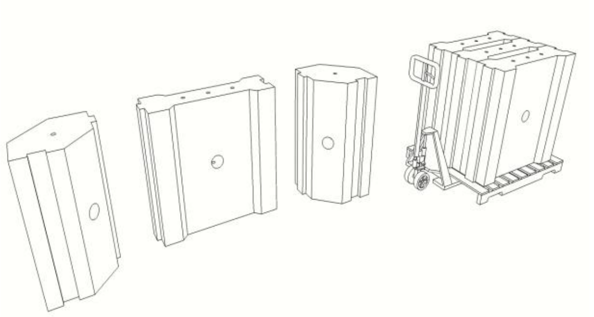

Fig.3. Smaller components design allow easy transportation

TECHNOLOGY IMPLEMENTATION & FLOW OF WORK

The methods and tools already available to help industrialisation in the construction sector to be a step forward are numerous. They vary from robotizing of traditional craftwork to completely new techniques especially designed for application in industrialised construction[7]. Implementations of the correct technologies or methods are essential. In Japan they

Fig.4. Proposed on-site factory

have developed huge numbers of single task robots and automated construction systems. These have demonstrated increased productivity and improved quality of construction. However, this cannot be achieved without the cost of heavy research investment and facilities. The similar approach seems unfeasible to develop REC in developing nations. Subsequently, use low- tech approach seems practical, which will keep the cost low and offer an affordable product. Although it might be low-tech, it does not mean to follow a conventional approach. The attention is to use limited man power, tools with minimal energy consumption to achieve optimised result. An efficient, well organized on-site construction facility will ensure the quality and safety of production. Similar to off-site factory production, distribution of different types of materials and storage of different types of prefabricated components as well as managing division of work forces has to be stressed (Figure 4). If necessary, work tasks can be divided into sequential stages and different level of priority. For instance, Sekisui Heim has established sophisticated production facility. To keep a smooth production flow, the company adopted production sequence which is very close to automotive industry. Tasks and workstations are well divided; components are prefabricated on a sub-line, which running simultaneously with the main line to reduce time losses of the entire production line. Another approach is from Sekisui House, which is a smaller family business who relies on Sekisui Heim's powerful production capability. The company purchase bespoke building design from Sekisui Heim, so no production facility is needed. This is prefect solution for smaller firms. A unique bottom up approach is used to erect the roof, "J-up" jacking system to lift up the roof structure one storey high at once. When the wall frames are secured the jack will repeat the same action again. This not only saves on-site space but also provide a weather proof shelter for the ground work force. These approaches can be modified and implemented for REC.

Mobile factory is a construction concept developed by Manu Build. The concept is container based with the ability to "link" containers together on-site to produce a variable and extendable factory. The container-based factory can be moved by lorry from one site to another whenever and wherever it is needed. The factory has autonomy in energy, management and operational senses. In addition the factory is flexible and provides safe working environments and is reconfigurable for multipurpose on-site activities and materials[8]. Alternatively, the concept can be implemented into REC, which soil can be transported by containers together with formwork and construction equipment. A mobile rammed earth factory can be very flexible despite the influence of the weather and location (Figure 5). Prefabrication of the wall components can even start during the transportation period by using on-board automated system similar to the concept of cement mixer lorry, thus the normally wasted delivery time is now productive.

Preservation of local work force and local business has to be taken into account at an early stage of any project. Rammed earth component prefabrication does not necessarily be off-site factory based. Because of this, most building components can be prefabricated on-site or sub-contracted to a local firm. The building needs to be designed in a way that

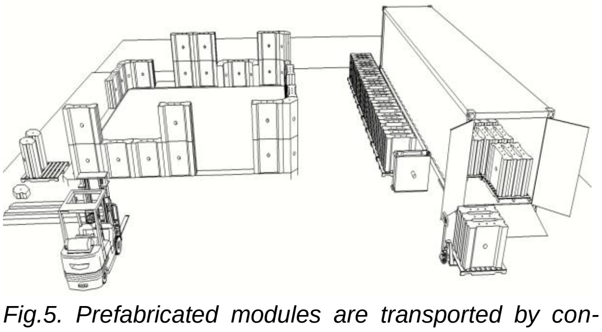

Fig.5. Prefabricated modules are transported by containers

non-skilled workers could erect after short training and guidance by professionals. Because in many cases, especially in China, a rural building site is where villagers come together and work as a team. It offers senses of community and belonging, outsiders normally are not invited. Hence social impact and local custom need to be addressed before construction to ensure all stakeholders can benefit from the development.

SUMMARY

Rammed earth is not currently treated as a standard form of construction method used in the construction industry today. However, it has the potential to be accepted as mainstream construction due to its features of sustainability, customizability and flexibility. To be able to complete with other types of construction, rammed earth construction must preserve its strength and overcome its weakness by technology integration and implementation. The author has mentioned some possibilities of improvement, but there are still many issues unaccounted for, which require more extensive studies and research to accomplish.

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