Developments of Rammed Earth Walling Technology

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Abstract *— Earth building technology has traditionally originated with putting up shelters using pure earth mixed with water applying in the way of cob, adobe, rammed earth and wattle-and-daub in most part of the world. The technology has been rapidly developed during last few years as the results of researches conducted throughout the world to satisfy the requirement of affordability and sustainability. The process of the developments for rammed earth technology was studied by collecting fifty research papers published during the period from 2003 to 2016. It is found that 72% of them were for the development in the forms of compressed blocks, bricks or rammed earth where rammed earth investigations were conducted by the highly reputed countries of science and technology aiming for the development of the properties of rammed earth for better design and construction to suit to the requirement of the proposed work.*

Keywords *— Earth building, Rammed earth, Affordability, Sustainability.*

I. INTRODUCTION

At early stage of civilization in most parts of the world, earth was used for shelters and other related constructions needed for humans for their day to day activities. Other related earth constructions could be identified as roads, temples, churche, mosques, irrigation tanks, irrigation dams and canals. Most of these structures lasted for long periods and some of them are still standing today. Pure earth which was freely available nearby was used for these constructions and people built them in ecological and economical ways with attractive features by adopting simple methods of construction. The methods adopted were the forms of adobe, cob, rammed earth (RE) and earth bags where same earth could be easily used with minimum energy.

With industrial revolution and development of production techniques, use of earth for housing has been declined and new technologies have been introduced. Brickwork and cement block work came to the building industry as an alternative walling material which needs additional resources such as cement, sand, energy and more labour to build the wall completely to satisfy its requirements. Uses of these alternative materials are costly today due to the increase of prices of resources.

RE technology is yet being applied for putting up walls for buildings. It enables to protect the environment without harnessing the resources and providing a healthy durable home with thermal comfort. Because of these reasons, studies have been conducted continuously to investigate the properties of RE and to find its development to suit to the proposed work. Fifty research papers were studied to investigate the developments for the RE walling technology throughout the world.

II. OBJECTIVES

Objectives of this research are to refer the published papers on earth building and investigate the development on RE technology for walling of buildings.

III. LITERATURE REVIEW

A. *Earth Building Technology*

Earth technology has a very long history covering most part of the world. Part of Great Wall of China was begun over 5000 years ago and archaeological evidence shows the existence of entire cities built of earth, such as Jericho and Babylon, some 10,000 years old [1]. Some of the traditional methods of earth construction are adobe block or lumps built up into walls, wattle and daub, Cob and rammed earth. The first recorded earth building technique was adobe, unfired mud bricks containing straw [2]. Adobe mud brick houses dating from 8,000 to 6,000 BC have been discovered in Russian Turkestan [3]. It was a sun-dried earth block for which sufficient content of clay was in soil to provide a better bonding. Some countries used chopped straw to avoid cracks due to the presence of clay in soil. Mud mortar or lime mortar was used when laying adobe blocks. Cob was used for constructing originally cottage type houses by taking mixture of earth and water. Sandy soil mixed with straw is the usual composition adopted to form lumps or cobs. They were placed in rows by throwing or stamping on the previous layers and finish good by trimming rough surfaces or providing render with mud paste. RE technique dating from 5000 BC have been discovered in Assyria [3] as another earth building technique which was made placing wet earth layer by layer in a temporary timber mould and compacted using suitable tamper till it gets sufficient compaction. Many world Heritage sites contained structures constructed from RE. Examples include Buddhist

monasteries, Muslim fortresses dating from the 18th century throughout Spain and North Africa. Major centres of RE construction include North Africa, Australasia, regions of North and South America, China and Europe, including France, Germany and Spain [4].

Earth has been identified as one of the environmental friendly, locally available and cheapest construction material and it has gained acceptable name due to the prolong applications with lasting quality. Over one third of the world's population live in houses built from earth, and over 70% of the earth's landmass is either pure clay or laterite [1]. Earth is a natural resource which requires no energy to produce and provide the natural comforts, humidity and durability. Because of these qualities, earth building technology was widely spread all over the world and there were more than 600 historic earth buildings in New Zealand started in 1980s [5]. New Zealand established relevant earth building codes in 1998 which could gain considerable attention internationally. With this initiation, numerous scientific experiments has been continuously conducted over the world to encourage the builders. As a result, builders are able to construct buildings as expected and it was noted that number of modern earth buildings have been erected in the last few decades in New Zealand [5].

B. Earth Buildings in Sri Lanka

During the colonial period and thereafter many buildings in Sri Lanka were built with adobe and rammed earth in movable form. National Building Research Organization conducted island wide survey in 1984 on rural housing and found that earth, burnt clay bricks and Kabook were used for superstructure walls of rural houses by 61.8%, 16.2% and 4.15% respectively. Most of houses made with earth were mainly based on wattle and daub (50.4%), RE (8.4%) and adobe (4.6%) confined to certain area of the island [6]. As other countries, it can be stated that earth was the main raw material used in Sri Lanka for housing till 1984. With the development of earth building in other countries, Cinver ram earth bricks had come to the industry for constructing walls of single storey houses and later this was further developed to compressed earth bricks or blocks (CEB).

C. Development of Rammed Earth Technology

Under the literature review adobe and RE were continuously developed by considering the mechanical properties of the earth. As the result of study from very traditional RE buildings, it was found that physical composition of RE was strong and hard to penetrate and it was an early form of concrete just before the invention of Portland cement [7]. It was noted that many studies were based on stabilized techniques, compressive strength, particle size distribution and compaction of RE. As the result, stabilized earth bricks (SEB) and stabilized rammed earth (SRE) came to the building industry. Large numbers of structures constructed with RE last more than fifty years and proved that RE is a durable construction material. SRE can be used as a direct replacement of other walling materials such as concrete block and fired bricks [8]. Cement was investigated as a good stabilizer for earth building technique due to its good binding property and high strength [9], [12].

Thermal performance of RE has been investigated and found that in summer, uninsulated and insulated RE houses had the similar performance but in winter, RE house tends to be 5 degrees cooler than the insulated RE house. Inner and outer wall climate conditions have been tested using full scale wall panels and recorded that after five days of exposure there were no evidence of moisture penetration and internal condensation [10]. New Zealand research has indicated that monolithic earth walls perform better under earthquake conditions than walls made of separate brick or block [4].

D. Cement Stabilized Rammed Earth (CSRE)

Cement stabilized rammed earth (CSRE) is a mixture of soil, Portland cement and water. Through mechanical or manual compaction and cement hydration the mixture hardens with soil particles bonding together to form a dense mass. Successful use of CSRE for walls can be seen in Australia, USA, Europe, Asia and many other countries [11]. The basic control factors for satisfactory achievement in cement stabilization are selection of good soil, adequate cement content, proper moisture content and adequate compaction. Selection of soil for CSRE technology is taken into grant and maintained less than 30% clay content while performing the research activities on load bearing walls. On site soil has been selected through jar test as jar test has proved accurate results in previous experimental works. The composition of 5-20% gravel, 45-60% sand, 20-35% silt and clay has been recommended for better performance of wall construction. Composition can be checked by performing jar test [12]. Testing program has revealed that the best category of soil are those with linear shrinkage (LS) < 6.0 and clay and silt content $\leq 20\%$ or with LS < 6.0 and clay and silt content 21 – 35%. These two categories have shown the highest stabilization success [13].

CSRE load bearing walls were designed and constructed in two storey house in Sri Lanka [14] using steel-slip form mould for the purpose of dissemination the technology as affordable housing method. The amount of cement required will depend on grading and other soil characteristics. Presence of clay generally impedes effectiveness of cement stabilization and, therefore should be generally minimized [4]. Cement is typically used in proportions between 6% and 10%. Increased cement content improves strength and erosion resistance. Maximum compressive strength of 3.71 N/mm^2, 2.82 N/mm^2 and

2.29 N/mm^2 have been obtained for sandy, kabok and clay soils respectively with 10% of cement by volume [12]. Study programme on "compressive strength and elastic properties of stabilized rammed earth and masonry" conducted by Reddy and Kumar [11] has revealed that compressive strength of cement stabilized rammed earth is sensitive to the moisture content of the specimen at the time of testing and showed wet strength is about 60% of dry strength.

Structural design is necessary when constructing any structure for safe construction to conform to the relevant standards. Walker [8] has described the structural design and guidelines for building rammed earth walls for one or two storey based on limiting geometry and axial compressive stress. British Standard (BS) 5628: Part 1-2005 covers masonry design which can be applied when designing load bearing walls for buildings [14]. Structural and energy performance of CSRE can be enhanced further by introducing rigid insulation and steel reinforcements to the CSRE constructions [15]. Further, the research on fiber-reinforced CSRE construction revealed that soil-cement-fiber mixture could improve the safety of RE during failure and collapse. Design of two types of shear reinforcement was studied through full scale RE walls to improve the structural performance of RE [16]. With the recent trend forwarding sustainable construction and green building concepts, building with earthen materials is becoming more and more popular in the world. Developments recommended so far for constructing RE has to be applied when constructing earth buildings to demonstrate the acceptability of RE technology.

IV. ANALYSIS AND RESULTS

A. Summary of Research Papers

Fifty research papers during the period of 2003 to 2016 based on earth building was searched from internet and studied the development made on earth walling technology.

TABLE I

SUMMARY OF RESEARCH PAPERS

Studied Papers	Papers	
	Nos.	%
total research papers surveyed	50	
papers from 2003 to 2009	23	46
papers from 2010 to 2016	27	54

Surveyed papers during first seven years and last seven years of the evaluated period are 46% and 54%.

B. Type of Earth Building Technology

Surveyed research papers were separated according to the type of earth building technology focused for the developments.

TABLE II

TYPE OF EARTH BUILDING TECHNOLOGY

	Earth Building Technology	Papers	
		Nos.	%
1	general earth building technology – cob, adobe, compressed earth blocks, rammed earth, earth bags	14	28
2	only compressed earth bricks / blocks	14	28
3	only rammed earth	22	44

With reference to the summary of the research papers, it is found that 72% of the papers were directly focused to the enhancement of compressed earth blocks and RE technology and may be the reason of present interest throughout the world. Information requires for both compressed earth blocks and the RE has been continuously provided throughout the last 14 years to assist and encourage for the proper application of earth technology for buildings.

C. Method of Investigations

It was found that the research investigations were based on laboratory experiments, information collected from practical applications and from existing RE buildings. Most of the countries which are highly recognized for science and technology have been engaged in studying RE technology. Summary of this findings are in Table III below.

TABLE III

METHOD OF INVESTIGATION

	Method of Investigation	Papers		Countries
		Nos.	%	
1	laboratory experiments	17	74	U.K, U.S, Australia, New Zealand, India, France, Romania, Canada, Sri Lanka
2	practical applications	5	22	
3	existing RE buildings	1	4	
	Total	23		

It is noted that 74% of the papers were based on laboratory experiment and 22% from practical applications. Papers were separated the way of carrying out the investigation to understand the developments of RE technology. When studying the above 23 papers, it was noted that more studies were related to SRE technique.

TABLE IV

RAMMED EARTH TECHNOLOGY

Earth Technique	Laboratory Experiments	Practical Applications	Existing RE Buildings
SRE	11	3	0
non- SRE	6	2	1

Out of the total 23 papers, 14 relates to SRE and 9 for RE. It is found that cement was introduced as a stabilizer in more studies. SRE papers were then separated to CSRE and use of other types of stabilizer.

TABLE V

STABILIZING RAMMED EARTH

Earth technique	Laboratory Experiments	Practical Applications
CSRE	7	2
other stabilizers	4	1

D. Development of RE Technology

Information presented in the above 14 papers were taken into account to identify the investigation areas for the proposed developments.

TABLE VI

AREA OF INVESTIGATION IN RE TECHNOLOGY

Laboratory Experiments		Practical Applications	
Investigated Area	**No. Papers**	**Investigated Area**	**No. Papers**
soil type	4	Method of design	1
stabilization	4	construction	1
Density	4	energy saving	1
moisture content	3	cost efficiency	1
compaction	2	Insulation	1
Strength	12	thermal performance	2
strain bearing capacity	1		
Durability	1		
Erosion	1		
Humidity	2		
Insulation	2		
Shrinkages	2		
incorporation with RCC	1		

Most of the results of the studies were based on laboratory experiments. Therefore well proved and very useful information are now available to carry out rammed earth construction successfully. Little information is available from the studies carried out under practical applications. Information collected was described in Table VII and VIII below. Studied papers and their numbers were given in the annexure.

TABLE VII

FINDINGS FOR CSRE AND SRE (LABORATORY TESTING)

Investigated area	Paper No.	Findings
soil type particle size distribution compressive strength moisture contents compaction	9	1. Minimum cement requirements for CSRE with different types of soils to achieve specific compressive strength.
	20	2. Wet strength is about 60% of dry strength. CSRE has high compressive strength and large strain bearing capacity (1.5 – 2%).
	32	3. Satisfactory compressive strength of CSRE with 5% cement stabilizer. Minimum 5 mm mineral insulation for economical and ecological rammed earth exterior walls.
	36	4. Satisfactory compressive strength of CSRE with 5% cement stabilizer for casting wall junctions along with density and compaction ratios.
	37	5. Rigid insulation and reinforcing steel to enhance the structural requirements of CSRE walls.
	41	6. Use of cement and synthetic plastic fiber additives to increase the strength parameters of RE wall. Soil-cement-fiber mixture could improve the safety of RE buildings during failure or collapse.
	44	7. Mechanical properties of soil are essential to improve the compressive strength of earth. Two types of shear reinforcements were designed as the results of full scale two rammed earth walls.
	46	8. With the addition of stabilizer RHA, maximum dry density of RE reduced. Compressive values decreased with subsequent addition of RHA to its maximum at 5% RHA. Addition of cement or lime is required for stabilizing RE.
soil stabilization compressive strength shrinkage Durability	9	1. Cement stabilizer from 5% to 10% was applied to show respective compressive strengths of different types of soils (gravel, sandy and clay).
	49	2. Suitability of local soil for RE construction by optimizing stabilizer. Compressive strength, drying shrinkage and durability were found.
energy, humidity and condensation	6 24	1. No evidence for moisture penetration. Negligible risk of internal condensation 2. SRE walls have potential to reduce the energy demand for humidification.

TABLE VIII

FINDINGS FOR CSRE AND SRE (PRACTICAL APPLICATIONS)

Investigated Area	Paper No.	Findings
efficient construction method cost effectiveness	5	1. Use of steel slip-form for casting SRE and cost analysis to demonstrate cost effectiveness
design and construction of load bearing RE wall	7 48	1. Temporary moulds for casting SRE by using "Stabilform" to suit to the design. Structural design detail for SRE along with structural and non-structural properties of SRE. Improvements have been made with steel reinforcements suitably. 2. Design and construction of load bearing walls of two storey house using CSRE. Cost effectiveness was demonstrated using actual expenditure for this construction.
Thermal performance Insulation Energy saving	7	1. SRE walls have low thermal resistivity and have a very high capacity to store heat energy by absorbing due to their high density. SRE wall can be designed to install internal dry lining or timber stud walling including insulation bats.

The above findings have clearly proved that stabilized rammed earth is a strong, durable, environmental friendly and cost effective material for putting up load bearing walls of buildings. Structural analysing of SRE walls, strength, safety and other properties can be further enhanced by analysing the results obtained from the scientific experiments. Studies done through practical applications of RE demonstrate the way of carrying out structural design and method of construction by addressing erection of temporary moulds, soil preparation, mixing, placing and compacting.

There are possibilities to construct rammed earth buildings as a modern technology, without any stabilizer indicated in the Tables IX and X below.

TABLE IX

FINDINGS NON-STABILIZED RE (EXISTING BUILDINGS)

Investigated Area	Paper No.	Findings
strong and hard to penetrate	16	The physical composition of rammed earth, strong and hard to penetrate. Based on the analysis, methods of repair are specified. Rammed earth has, in the past, been referred to as concrete and has verified its comparable durability to concrete.

Studies have been shown that, non-stabilized RE is a very strong, hard and durable material similar to concrete prior to Portland cement came to the building industry. Repairs in existing RE work can be made in a specific manner using local soils. Laboratory experiments and practical applications has support to develop the qualities such as compressive strength, compaction, thermal performance and energy saving of RE by considering physical and mechanical properties of soil. The respective results were given in Table X below.

TABLE X

FINDINGS FOR NON-STABILIZED RAMMED EARTH (LABORATORY TESTING AND PRACTICAL APPLICATIONS)

Investigated area	Paper No.	Findings
strength density moisture content elastic modulus	1 8 21 35 45	1. Different type of soil recipes to satisfy compressive strength and proctor compaction. 2. Rammed earth can be modeled using the Mohr-Coulomb failure criterion. Layered nature of rammed earth is to be taken into account when building the model. 3. Improving qualities of RE using properties of soil. 4. Prefabricated system is faster for wall construction. Insulated material can be incorporated into RE. 5. Slight increase in the moisture content of dry RE is not followed sudden drop in wall strength.
Soil type, moisture content Shrinkage and erosion	42	1. Soil particle size distribution criteria does not alone necessarily mean suitability of soil for RE.
Thermal performance Insulation Energy saving	12 17	1. RE building needs more energy for heating. Relatively high infiltration rate lead to cool internal temperature in the winter and in summer, air exchange is very low to cool the building daytime. 2. In summer, the uninsulated rammed earth houses have similar performance to the insulated RE house. In winter, the rammed earth house tends to be around 5 degrees cooler than the insulated rammed earth house

V. CONCLUSIONS

Rammed earth is one of the earth building technologies originated from 5000 BC and presently it is used as one of the alternative material for putting up load bearing walls of buildings. It is found that earth building technology has been continuously developed in most parts of the world performing investigations through laboratory experiments and practical experiences. Only little findings are available from the studies carried out using existing RE buildings. Reasons for these developments are mainly due to its valuable qualities such as strength, durability, thermal performance, energy saving and cost effectiveness. Structural properties and non-structural properties of RE has been developed by adding cement as stabilizer where quantity of stabilizer can be determined with respect to the expected compressive strength. Well proved information is now available either to design and construct rammed earth walls for buildings or improve the qualities further to address insulation performances by taking pre fabrication units or to enhance the structural properties by inserting steel reinforcements.

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ANNEXURE

Surveyed papers related to rammed earth technology (23 Papers)

Paper No.	Title	Author / Authors	Year	Country	Type	Method of Study	Findings
1	Rammed earth sample production: context, recommendations and Consistency	Matthew Hall &, Youcef Djerbib	Nov. 2003	U.K.	RE	Laboratory testing.	The variation in dry density due to soil type did not appear to be directly related to the characteristic unconfined compressive strength of RE.
5	Development of an efficient construction technique for rammed earth	Kamaladasa N. and Jayasinghe C.	2005	Sri Lanka	RE	Practical application.	Economy of CSRE and use of steel slip-form as efficient method of construction.
6	Assessing the environmental performance of stabilised rammed earth walls using a climatic simulation chamber	Matthew R. Hall	Aug. 2005	U.K.	RE	Testing of full scale SRE walls.	No significant increase in humidity. Negligible risk of internal or interstitial condensation.
7	Stabilized rammed earth wall construction – Now available in the UK	Matthew Hall	Sep. 2005	U.K.	RE	Practical application along with theoretical details on SRE.	SRE can be used for any low or medium rise masonry wall structure.
8	Analysis of Historic Rammed Earth construction	P. A. Jaquin, C. E. Augarde & C. M. Gerrard	2006	India	RE	Finite element modeling and Laboratory experiment	Strength parameters respect to nature of the layers of RE.
9	Compressive strength characteristics of cement stabized rammed earth walls	C. Jayasinghe and N. Kamaladasa	2006	Sri Lanka	RE	Laboratory testing.	Compressive strength of CSRE. For different types of soil.
12	Energy use and thermal comfort in a rammed earth office building	P. Taylor, R.J. Fuller and M.B. Luther	May 2007	Australia	RE	Practical application. Questionnaire survey.	Too hot in summer and too cold in winter. Rammed earth building used more energy for heating.
16	"Rammed earth architecture's journey to the high hills of Santee and its role as an early concrete.	Jessica Golebiowski	May 2009	U.S.	RE	Surveyed in very traditional rammed earth buildings at high *hills of Santee*	RE strong and hard to penetrate and early forms of concrete..
17	Analysis of indoor performance of houses using rammed earth walls	Veronica Soebarto	Jul. 2009	Australia	RE	Investigation of thermal performance in RE houses.	In summer, the uninsulated RE houses have similar performance to the insulated RE. In winter, RE tends to be around 5 degrees cooler than the insulated RE.
20	Compressive strength and elastic properties of stabilized rammed earth and masonry,	Reddy, B. V. V. & Kumar, P. P.	2009	India	RE	Laboratory testing.	The wet strength is about 60% of dry strength. RE shows 20-30% higher compressive strength when compared to the strength of REB masonry. CSRE shows large strain bearing capacity (1.5-2%).
21	The strength of unstabilized rammed earth materials	Jaquin P.A., Augarde C.E., Gallipoli D. and Toll D.G.	2009	France	RE	Laboratory testing.	Application of soil mechanics for the improvement of RE.
24	Hygrothermal analysis of a stabilized rammed earth test building in the UK.	David Allinson and Matthew Hall	Jun.2010	U.K.	RE	Using computer simulation hygrothermal analysis software	SRE wall have potential to reduce the energy demand for humidification / dehumidification plant.

Paper No.	Title	Author / Authors	Year	Country	Type	Method of Study	Findings
32	The use of cement stabilized rammed earth for building a vernacular modern house	Gabriela-Teodora Ciurileanu and Ildiko Bucur Horvath	Mar.2012	Romania	RE	Laboratory testing.	Compressive strength is achieved with 5% cement stabilizer. A minimum of 5 mm mineral insulation has to be added for economic and ecological rammed earth exterior wall.
35	Modular Building Using Rammed Earth	Gabriela T. C iurileanu & Ildiko Bucur Horvath	Sep.2012	Romania	RE	Laboratory testing.	Application of modular building principles, while using natural materials as wood, rammed earth and straw as building materials
36	Load bearing Rammed Earth Wall construction with Pre-cast Earth Wall Junctions	Jayasinghe C & Kandamby G.W.T.C	2012	Sri Lanka	RE	Laboratory testing.	Wall junctions can be made with CSRE
37	A report of contemporary of rammed earth construction and research in North America	Bly Windstorm	Jan. 2013	U. S.	RE	Laboratory testing.	Contemporary SRE builds upon traditional RE and incorporates rigid insulation and reinforcing steel, enhancing the structural and energy performance.
41	Rammed earth: Fiber-reinforced, cement stabilized.	Eric Walter Simenson	Nov.2013	U.S.	RE	Laboratory testing.	Use of cement and synthetic plastic fiber additives to improve the strength of rammed earth walls. It is appeared that the soil-cement-fiber mixture could improve the safety of rammed earth buildings during failure or collapse.
42	Advances on the assessment of soil suitability for rammed earth	Daniela Ciancio, Paul Jaquin and Peter Walker	2013	UK	RE	Laboratory testing.	A soil particle size distribution criterion is not alone necessary for the suitability of soil for RE.
44	Case Study characterizing material properties of cement-stabilized rammed earth to construct sustainable insulated walls.	Rishi Gupta	2014	Canada	RE	Testing of full scale RE wall and mechanical properties.	Obtained high compressive strength and two types of shear reinforcement designs were also studied.
45	Effect of moisture content on the mechanical characteristics of rammed earth	Quoc Baobui, Jean Claude Morel, Stephane Hans and Peter Walker	Mar.2014	UK	RE	Laboratory testing.	Slight increase in the moisture content of dry rammed earth is not followed sudden drop in wall strength.
46	STABILIZATION OF RAMMED EARTH	Mihir vora , Ankit patel, , Mohammad Soyab Shaikh	Apr.2014	India	RE	Laboratory testing.	Increase in RHA percentage with increase in the Optimum Moisture Content (OMC) and reduction in the Maximum Dry Density (MDD) and addition of RHA to its maximum at 5%. The deterioration is increases with increasing in RHA content. Addition of cement or lime is required for stabilization of rammed earth.
48	Two storey cement stabilized rammed earth house – Case study	G.W.T.C. Kandamby	Oct.2015	Sri Lanka	RE	Practical application	CSRE can be used for load bearing walls of two storey house. Cost effectiveness.
49	A study on stabilized rammed earth for sustainable construction	Abhirami Suresh and K.B. Anand	Dec.2016	India	RE	Laboratory testing.	Optimizing stabilizer, mixing water, compressive strength characteristics, drying shrinkage and durability.