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B. V. Venkatarama Reddy
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Pete Walker *Editors*

Earthen Dwellings and Structures

Current Status in their Adoption

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Preface

The word Earth has many interpretations; as a planet that sustains all life and ecosystems, terrestrially it is the land mass we live on; as a material resource, it represents the complex mixture of clay, sand, minerals and nutrients that sustains agriculture, subterranean biodiversity and human civilisations; and spiritually, it goes full circle to establish our primal oneness with the planet. To all native civilisations, the earth is all encompassing and revered spiritually; to all modern civilisations, the earth supports all the ecosystem services that drives development, industrialisation and economic growth. Through millennia, the earth has served to house civilisations across the world, in nearly all climates and terrains, and has sustained the ravages of time as a durable and sustainable building material. In modern interpretations, the earth carries a nearly zero-carbon footprint, negligible life-cycle impact and complete recyclability with no end of life (disposal). It is accessible in its diversity to nearly all civilisations across the world, where unique construction techniques have evolved from cob wall, wattle and daub, to modern rammed earth building technologies.

However, never in recorded history have we faced with the challenges to sustainability such as now, with buildings driving more than half of global energy and resource consumption and CO_2 emissions. Modern pursuits, driven by high energy efficiency in buildings, are also proving to be counterintuitive with rebound effects yielding an exponentially higher net-energy consumption, rather than energy saving. Recent reports on measures to mitigate climate change have revealed the need to reduce building energy and resource footprint by half in the coming decades, if global warming temperatures are to be kept below 2 °C.

It is but timely that earthen constructions are revisited for their potential to meet the growing demand for modern housing, relieve the increasing burden of urbanisation, and as an alternative material which is environmentally benign, renewable, globally accessible and affordable. Scientific research needs to step in to reinforce modern faith on the durability, structural performance, climate responsiveness and best building practices in the adoption of earthen construction to suit modern lifestyles. Researchers working on various facets of earthen construction, ranging from its cultural heritage to climatic and structural performance, are few and scattered. The current volume is a compilation of well-written diverse articles, with earth being the common connecting theme, from researchers worldwide exploring the earth for sustainable construction.

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This book is an important outcome of the International Symposium of Earthen Structures 2018 (ISES 2018). The prime mover for organising ISES 2018 has been the UK-India collaborative (UKIERI) project (UKIERI 2016-17-063) on developing earth-based building products utilising solid wastes. On behalf of the organisers, we take immense pride in expressing our gratitude for the generous financial assistance from the UKIERI scheme.

Special thanks also to Springer for taking this up as an edited publication and making it accessible worldwide.

B. V. Venkatarama Reddy
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Introduction

Earthen Structures

The earliest attempts by humans to build shelters included the use of earth/soil along with twigs/leaves and branches as basic building materials. More than a third of humanity dwells in earthen buildings even in today's twenty-first-century super modern world. Earthen structures are more climatically suited, environmentally benign, accessible and affordable to all and provide a very primal cultural connection with nature. This is valid, despite the diversity in culture, soil and natural conditions and climatic conditions. Civilisations have thrived in earthen construction even in extremes of climatic conditions. The earth that is accessible to diverse geographical locations is in itself diverse in its characteristics and represents a material that is inherently durable given their availability and occurrences despite millennia of climatic exposure and weathering. In our current pursuit of sustainable development, earthen structures hold enormous relevance and potential in providing solutions for environmentally friendly buildings that are energy efficient, comfortable, durable and recoverable/recyclable. The earth in the native cultures is associated with poverty, deprivation and underdevelopment, which in modern civilisations is associated with abundance, choice and wealth. Given the incessant demand for housing, earth holds immense potential as a sustainable material for the larger share of human society. Native cultures have always found a spiritual connection with the earth as a supporter of life (and dwellings). They have also developed a natural physiological resilience to withstand wider climatic variabilities moderated within earthen dwellings. The indoor air quality in naturally ventilated earthen dwellings is generally healthier than that found in conditioned buildings. Their acoustic performance is also superior to that of modern building materials. The design of earthen dwellings is generally organic with spatial inclusiveness that fosters greater social interaction in comparison with modern conditioned dwellings that tend to adopt a compartmentalised layout that inhibits social interaction. Faith in the appropriateness of earth as a climate responsive, durable and environmentally friendly building material needs to be restored, by revisiting them based on modern scientific scrutiny and the subsequent generation of codes and best practices.

Lack of tested earth-based construction practices, rapid urbanisation, changing lifestyles and increased adoption of (energy-intensive) modern construction materials have led to a steep decline in the adoption of traditional/vernacular earthen structures. Modern architecture is characterised by dwellings that are not climatically responsive, adopt exotic energy-intensive materials and rely heavily on (fossil fuel) energy for operation and maintenance. The inhabitants exhibit much lower physiological resilience to climatic variabilities, being completely habituated (and vulnerable) to artificially conditioned indoor environments.

Vernacular dwellings typically carry a low embodied energy less than 2 GJ/m^2, while modern dwelling can exceed 8 GJ/m^2. Consequently, operational energy (for comfortable indoor environments) is barely 1 GJ/household/year for vernacular dwellings and can exceed 30 GJ/household/year for modern dwellings. Accounting for modern transitions in vernacular dwellings (that house nearly 2 billion in China and India), the implication on resource and energy demand for housing is worrisome. These transitions, if not regulated appropriately, can further exasperate sustainability at the global scale, which is already threatened by energy- and resource-intensive lifestyles of industrialised regions. Materials derived from the earth, that are easily accessible, have the potential to provide for sustainable dwelling alternatives and dampen the otherwise insatiable reliance on energy-intensive materials (and lifestyle).

In the past, a variety of earth-based technologies and techniques have been adopted for building construction. Adobe masonry, cob walls, rammed earth, natural fibre-reinforced earth, wattle and daub, etc., are few of the traditional methods used for earthen construction. Limitations in the widespread adoption of earth-based techniques for buildings include lack of standardised engineering methodologies, loss of traditional (undocumented) skill and wisdom, poor seismic resistance, lack of strength upon saturation, poor resistance against rain impact, uncertified products, lack of sustained R&D efforts, insufficient education and training, poor regulatory mechanisms and the perceived stigma of poverty associated with earthen construction. Fortunately, interest in traditional and modern methods of earthen structures has been steadily growing as more sustainable and healthier buildings are sought globally. There is considerable interest in the adoption of earth-based materials such as stabilised earth blocks, rammed earth, fibre-reinforced earthen materials, cob walls and earthen mortars. Currently, there are focused R&D efforts in the areas of earthen materials, thermal performance of such materials and buildings, durability studies, standardisation of earthen building products, seismic response of earthen structural systems, knowledge dissemination, education and teaching, across the world.

The edited book is an amalgamation of diverse and interconnected topics on earthen structures, derived from peer-reviewed papers submitted to the International Symposium on Earthen Structures (ISES 2018). The book provides an in-depth analysis on various aspects of earthen structures, with science-based technical content on materials and technologies, structural design and seismic performance, durability, seismic response, climatic response, hygrothermal performance and durability, design and codes, architecture, heritage and conservation and technology dissemination. The book will be useful to architects, engineers, scientists, teaching professionals, construction professionals and students, providing a useful document on the current status and knowledge of earthen structures.

Part I
Earthen Materials and Technology

Chapter 1
Studies on Geopolymer-Based Earthen Compacts

R. K. Preethi and B. V. Venkatarama Reddy

1.1 Introduction

Geopolymer mechanism involves the silicates and aluminates in the presence of alkali to undergo the process of geopolymerisation. Geopolymer products are originated by poly-condensation of aluminosilicates with alkali-activating metals yielding polymeric Si–O–Al bonds (Davidovits 1999; Duxson et al. 2007; Provis 2014). Earlier geopolymer was named as "Gruntosilikat" and "Gruntocement-geocement" (Gluchovskij 1959). Sodium hydroxide (NaOH) or potassium hydroxide (KOH) along with sodium silicate solution is used as an alkali activator solution in preparing geopolymer products (Davidovits 1988, 1994). Hardening process of the geopolymers in the presence of alkali metals takes place at the temperatures between 25 and 90 °C. Curing the geopolymer specimens beyond 90 °C results in the dehydration which will lead to the formation of cracks in the specimens (Hardjito et al. 2003; Khale 2007; Rovnanik 2010; Heah and Kamarudin 2011; Slaty et al. 2013).

Cement is the most commonly and widely used binder material in the construction industry. To reduce the consumption of cement in the building industry, alkali-activated products (Geopolymers) are emerging as alternative binder materials. Replacing Portland cement with geopolymer binder as an alternative in the conventional concrete has been attempted (Rangan 2008a, b, 2009; Hardjito 2004; Kunal Kupawade Patil and Allouche 2013). Geopolymer binders are energy efficient as they result in reduced carbon emission (Mclellan et al. 2011).

In the manufacturing process of clay bricks, clay is subjected to high temperature (1000–1400 °C) where the clay mineral changes from its natural form to a stable form

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called mullite (Grim and Bradley 1940). Burnt clay bricks possess high embodied energy (Reddy and Jagadish 2003; Praseeda et al. 2015). Production of masonry units using Portland cement, autoclaving or firing at higher temperature results in higher amount of energy consumption and carbon emissions. Alkali activation of natural clays and natural soils is an alternative method in the manufacturing process of masonry units (Munoz et al. 2015; Maskell et al. 2014). The current study is focused on exploring geopolymer binder using natural soil and clay minerals for the manufacture of masonry units.

1.2 Scope of the Study and Experimental Programme

The scope of the present study included the utilisation of geopolymer binders in the manufacturing process of masonry units. The earlier studies have indicated the benefit of using the geopolymer binders in manufacturing the masonry units. An attempt was made to examine the wet compressive strength of the alkali-activated earthen compacts in the presence of ground granulated blast-furnace slag (GGBS) and fly ash materials, with various molar concentrations of NaOH solution.

Different mix proportions were considered for casting the specimens. One set of specimens were cast by varying the clay content in the mix. Additional source of silica and alumina materials such as GGBS and fly ash was also used in casting the specimens. Second set of specimens were cast using GGBS and fly ash with fixed

Table 1.1 Details of the experimental programme

Materials	Clay (%)	GGBS or fly ash (%)	NaOH		
			8 M	10 M	12 M
Kaolinite/ Montmorillonite mineral	10	0	√	√	√
	15	0	√	√	√
	20	0	√	√	√
		4	√	√	√
		8	√	√	√
		12	√	√	√
		15	√	√	√
Red soil	20	0	√	√	√
	30	0	√	√	√
		5	√	√	√
		10	√	√	√
		15	√	√	√
		30	√	√	√
	41	0	√	√	√

clay content in the mix. The experimental programme considered in the study is given in Table 1.1.

1.3 Materials Used in the Study

The materials used in the investigations include locally available soil, river sand, natural clay minerals (kaolinite and montmorillonite), ground granulated blast-furnace slag (GGBS) and fly ash. Laboratory grade sodium hydroxide (NaOH) with 99% purity was used in the study.

The lime reactivity of GGBS and fly ash was tested as per IS: 1727–2004 code guidelines; the results were 9.74 and 2.99 MPa, respectively. Figure 1.1 gives the grain size distribution curves of kaolinite, soil, sand, soil with 20% clay fraction and 20% kaolinite in the mix used. It was difficult to obtain grain size distribution curve for montmorillonite clay mineral using hydrometer analysis. The natural soil has 41% clay fraction (<2 μm) containing predominantly kaolinite clay mineral. Kaolinite clay mineral possesses clay size fraction of 54.69%. The clay fraction (<2 μm) of the soil mix with 20% clay content and that of mix with 20% kaolinite are 18.73 and 10.96%, respectively.

The chemical composition and physical properties of some of the materials used in the study are given in Table 1.2. The elemental composition was determined by energy-dispersive X-ray (EDX) spectroscopy. Silica (Si) and alumina (Al) are the major components present in the materials.

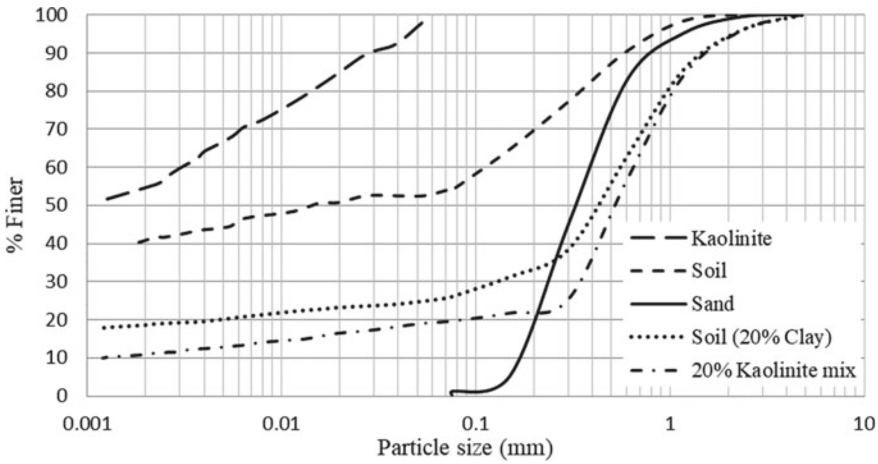

Fig. 1.1 Particle size distribution curve for river sand, natural soil, kaolinite, soil (20% clay fraction) and 20% kaolinite mix

Table 1.2 Chemical composition and physical properties of the materials used in the study

Element	Composition (% by weight)				
	Red soil	Kaolinite	Montmorillonite	GGBS	Fly ash
Al	15.68	22.13	10.79	10.87	20.85
Si	24.56	29.82	20.31	18.31	26.77
Ca	0.32	0.61	0.26	21.61	1.27
Fe	9.28	1.41	2.83	0.48	5.08
Ti	0.8	0.81	2.02	0.41	1.93
K	1.17	0.78	–	0.4	2.08
Mg	0.19	–	1.36	4.41	–
Na	–	–	2.11	–	–
S	0.3	–	–	0.65	–
Physical properties					
Specific gravity	2.68	2.63	2.39	2.91	2.28
Liquid limit	31	37.1	264.0	–	–
Plastic limit	19.48	18.87	158.0	–	–
Shrinkage limit	15.99	15.98	–	–	–

1.4 Casting and Testing Procedure

The effectiveness of geopolymer binders was evaluated through the determination of compressive strength using the cylindrical specimens of size 38 mm diameter and 76 mm height. Sodium hydroxide pellets were dissolved in the distilled water to prepare three different molar concentrations of 8, 10 and 12 M solution. The alkali solution was used after 24 h of its preparation.

1.4.1 Mixing and Casting

The materials were mixed in the dry state to achieve a homogenous mixture; later, the alkali activator solution was added to the dry mix. The moulding moisture content (MMC) (containing alkali and silica) was in the range of 10–15% of the dry mix. MMC depends upon the quantity of clay minerals in the mix. Higher percentage of clay demanded higher MMC to achieve a consistency needed for compaction. Mortar mixer was used in mixing the ingredients for 7 min to obtain the uniform mixture. The dry density of the specimens was controlled and kept at 1.8 g/cc. The cylindrical specimens were cast by compacting the partially saturated mix in a screw press.

1.4.2 Curing and Testing

Specimens after 24 h of casting were cured in an oven at 80 °C for 72 h. Cured specimens were dried in air for 24 h before testing. The specimens were tested for the wet compressive strength by soaking them in water for 48 h prior to the testing.

1.5 Results and Discussions

1.5.1 Alkali-Activated Earthen Compacts

The wet compressive strength of the alkali-activated natural soil (containing kaolinite clay) compacts was determined. The strength results are shown in Fig. 1.2. The figure shows the relationships between strength and clay content of the natural soil with varying molar concentrations of the alkali solution. The relationships show that the wet strength of the specimens increases with the increase in clay content in the mix, irrespective of the molar concentration. The strength and clay content are linearly related. There is about 50% increase in strength as the clay content was increased from 20 to 41%. Higher the clay content in the mix, more amount of reactive silica and alumina available, which resulted in the higher strength. Also, the increase in molarity of the activator solution increased the wet strength of the specimens. High alkali content (>12 M) and higher clay content in the mix result in maximum compressive strength for the soil compacts. The maximum strength obtained was 1.72 MPa with 12 M NaOH solution and with 41% clay fraction in the mix.

An attempt was made to examine the strength of alkali-activated compacts using pure clay minerals. The compacts were prepared using pure clay minerals (kaolinite and montmorillonite) and sand. The percentage of pure clay minerals in the mix was varied between 10 and 20%. Figure 1.3 shows the variation in wet compressive

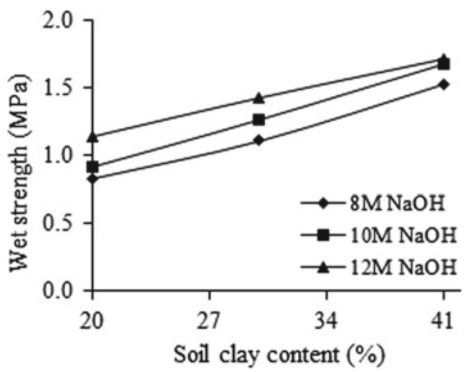

Fig. 1.2 Wet compressive strength of alkali-activated natural soil compacts