Performance Characteristics of Enhanced Soil Blocks: A Quantitative Review

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Abstract

Several studies have focused on improving the properties of soil blocks/bricks due to perceived and real strength and durability limitations. A review of 56 published studies is presented on the effect of stabilization on the performance characteristics of soil blocks. The review found that few studies have been conducted on durability properties of enhanced soil blocks as compared with physico-mechanical properties. Fibre-enhanced soil blocks tended to have peak performance with an optimal content that achieved maximum performance. The maximum performance improvement was generally less than a doubling of the strength of the soil without the fibres. Binders showed a continual improvement with greater concentrations, so much greater improvements can be obtained if the economic and social costs can be justified. Both fibres and binders have variable performance on water absorption with both reductions and increases possible. Generally, both fibre and binder inclusion in soil blocks enhance the performance characteristics of the blocks. Binders are typically more effective on a mass-fraction basis. However the supply of fibres is usually at a lower cost and a reduced environmental impact, and therefore may have a better performance on a per-cost or per-impact basis.

Keywords: bricks, building materials, earth construction, enhanced soil blocks, performance

Introduction

Soil block construction involves compressing a damp mixture of unprocessed earth that has suitable proportions of gravel, sand, silt and clay (sometimes with an added stabiliser) into a mould, creating individual blocks for construction of structures. Earth is one of the oldest building materials and has been used in the construction of shelters for thousands of years, and

presently about one-third of the world's population continue to live in earthen buildings (UN Habitat, 2008). Earth is a cheap, environmentally friendly, socially accepted, easy to work with and abundantly available building material (Binici, Aksogan, & Shah, 2005; Quagliarini & Lenci, 2010), and this has called for a renewed interest over the past few years. It has largely been used for wall construction in buildings globally, predominantly in less developed countries (Ren & Kagi, 1995), due to its social and economic benefits (Arumala & Gondal, 2007). Environmental benefits of earthen structures include reduced pollution, embodied energy, carbon dioxide emissions, regulation of humidity and possible re-use of the earthen material (Lawrence, Heath & Walker, 2008).

In addition, earth provides a cool room temperature due to its thermal insulation properties (Arumala & Gondal, 2007). However, earth construction suffers from shrinkage, cracking, low strength, lack of durability and dimensional stability for building construction, so improvement of these properties would be beneficial to its users (Walker, 1995; Bahar, Benazzoug, & Kenai, 2004; Danso, 2013; Harper, 2011; Riza, Rahman, & Zaidi, 2011). In view of the above, several studies have focused on improving, stabilising, reinforcing or enhancing the properties of soil blocks or bricks in terms of strength, shrinkage, thermal conductivity, and durability in order to improve the material and make it socially acceptable.

A number of studies (Delgado & Guerrero, 2006, 2007; Hejazi, Sheikhzadeh, Abtahi, & Zadhoush, 2012; Pacheco-Torgal & Jalali, 2012) have reviewed the volume of literature in the enhancement, stabilisation or reinforcement of soil blocks or bricks for construction purposes. One study (Hejazi et al., 2012) reviewed the history, benefits, application; and possible executive problems of using different types of natural and/or synthetic fibres in soil reinforcement. Another study (Pacheco-Torgal & Jalali, 2012) reviewed some of the environmental benefits associated with earth construction including an overview about its past and present. It also included a review of economic issues, non-renewable resource consumption, waste generation, energy consumption, carbon dioxide emissions and indoor air quality. In addition (Delgado & Guerrero, 2007) offered a useful global view of the different approaches, contributing to the production of a new standard, which was the main purpose of their review. The study (Delgado & Guerrero, 2006) also reviewed the state of use of the earth building in Spain. It presented researching organisations, modern projects carried out and the existing manufacturers for compressed earth

blocks, and also examine a pair of non-regulatory guides that could act as national reference documents.

There is a significant quantity of literature on the performance of enhanced soil blocks, but at present there is no overview of the data from these studies. There remains a need to quantitatively analyse the data in these published works in order to reveal the scale and trend of their results. It should serve as a useful first-stop for those unfamiliar with the wide literature in the field and as a useful synthesis of results for researchers needing performance data for determining economic viability, environmental impact or technical feasibility of enhanced earth block construction in-general before proceeding to more detailed experimentation and analysis of their particular soil. The range of data can also serve as an indication of expected performance ranges for experimenters to compare with their own results. This paper, therefore, reviews the existing published works on the effect of stabilisers (fibres and binders) on the technical performance of soil blocks or bricks using the performance measures of compressive strength, flexural and tensile strength and water absorption.

Methodology

The review adopted a quantitative approach. Numerical data from a number of previous studies' results were extracted and analysed to ascertain the effectiveness of stabilisation methods used. Fifty-six studies in all were consulted and useful data were found in twenty-five studies. Two broad categories of enhancement were analysed, fibres and binders. The fibres studied in the literature cover a broad range of natural and artificial fibres and were primarily obtained from agricultural and industrial residues. The binders include cement, lime, various polymers and other materials that either react with the soil or set into a crystal lattice after contact with water.

A wide range of tests exist for determining the technical performance of soil blocks. Authors decide on the types of test to conduct based on the focus of their study and sometimes the availability of test equipment. To compare data from the studies, their results were charted using a common format as a series of scatter diagrams as shown in Figure 1. The abscissa of the chart is the concentration of stabilisation used, consistently expressed as a mass fraction. In cases where authors expressed concentration in other units, such as volume fraction or as a part of a wider mix description, this was converted. The ordinate is the performance measure of interest expressed in constant units which depended on the performance measure. For each chart a

regression line was drawn which could be one of two types. In cases where a clear maxima is indicated, a second order polynomial curve was fitted the data and the value corresponding to the maximum point on the curve was obtained. In cases where there was a simple trend upwards or downwards a simple linear fit was performed. The effectiveness of the stabilisation method in the region measured can be expressed in terms of the performance measure per mass of stabilisation added (e.g. MPa per % added). It should be noted that it is very likely that many stabilisation techniques will have a maximum performance at some concentration, so the effectiveness found can only be considered valid in the region studied.

Soil is a very non-homogenous material and therefore stabilisation is not the only factor that affects block performance. Compaction energy, soil characteristics such as particle size distribution and Atterberg limits, moisture content, drying regimen and other factors also have a large impact. As a result of this, a wide variation in unstabilised performance is expected and a subsequent range in stabilised performance. This review attempts to reduce this effect by reporting results in terms of additional performance achieved by the stabiliser rather than fractional improvement.

Figure 1: Scatter plot charts showing the trend values of the data

Stabilisation Methods

The literature review found fifty-six studies which have investigated the use of stabilisation techniques and their effects. Table 1 outlines these stabilisation methods. Stabilisation of soil is the method of adding additional materials to the natural soil/earth in order to enhance its strength and/or other properties for the purpose of construction. According to Houben & Guillaud (1994), stabilising soil “implies the modification of the properties of the soil-water-air system in order to obtain lasting properties which are compatible with a particular application...”. Minke (2009) extends this, stating that the aim of stabilisation is to increase the strength and durability properties of soil blocks for better resistance to applied load and weather. These improvements are made possible by incorporating into the soil other materials such as fibres and binders that will address some of the weaknesses (Ngowi, 1997). There are several ways of stabilising earth, which can be grouped by reinforcement (fibres and other waste), binders (cement, lime and other additives) and combination of the methods.

Table 1: Soil block/brick stabilisation methods

Reference	Fibres	Binders
Quagliarini & Lenci (2010)	Straw	
Yetgin, Cavdar, & Cavdar (2008)	Straw	
Piattoni et, Quagliarini, & Lenci (2011)	Straw	
Bouhicha, Aouissi, & Kenai (2005)	Chopped barley straw	
Maher & Ho (1994)	Polystyrene fibre, glass and softwood pulp	
Elenga, Mabiala, Ahouet, Goma-Maniongui, & Dirras (2011)	Polyethylene waste nets	
Akbulut, Arasan, & Kalkan (2007)	Scrap tire rubber fibre, polyethylene fibre and Polypropylene fibre	
Yalley & Kwan (2008)	Plastic fibre and palm fibres	
Turgut & Yesilata (2008)	Crumb rubber	
Kumar, Walia, & Mohar (2006)	Polyester fibre	
Ghavami, Filho, & Barbosac (1999)	Sisal fibre and coconut fibre	
Gaw & Zamora (2011)	Coconut fibre and coir fibre	
Demir (2006)	Processed waste tea residue	
Kavas (2006)	Boron waste	
Aymerich, Fenu, & Meloni (2012)	Sheep wool fibre	
Sen & Reddy (2011)	Sisal, Coir, Jute and hemp	

Millogo, Morel, Aubert & Ghavami (2014)	Hibiscus cannabinus fibre	
Harper (2011)		Ground granulated blast furnace slag and pulverised fly ash
Degirmenci (2008)		Waste phosphogypsum and natural gypsum
Kouakou & Morel (2009)		Argillaceous minerals
Guetala, Houari, Mezghiche, & Chebili (2002)		Lime
Millogo, Hajjaji, & Ouedraog (2008)		Lime
Muntohar (2011)		Lime and rice husk ash
Reddy & Lokras (1998)		Lime
Reddy & Hubli (2002)		Lime and fly ash
Heathcote (1995)		Cement
Heathcote (2002)		Cement
Montgomery (2002)		Cement
Bahar, Benazzoug, & S. Kenai (2004)		Cement
Millogo & Morel (2012)		Cement
Reddy, Lal & Rao (2007)		Cement
Walker (1995)		Cement
Walker & Stace (1997)		Cement
Walker (2004)		Cement
Morel, Pkla & Walker (2007)		Cement
Gooding & Thomas (1997)		Cement
Alavez-Ramirez, Montes-Garcia, Martinez-Reyes, Altamirano-Juarez, & Gochi-Ponce (2012)		cement, lime and sugar cane bagasse ash
Hossain & Mol (2011)		Cement kiln dust and volcanic ash
Ngowi (1997)		Cement, lime, cow-dung and bitumen
Oti, Kinuthia, & Bai (2009)		Cement and lime
Hossain, Lachemi, & Easa (2007)		Cement, lime and volcanic ash
Atzeni, Pia, Sanna, & Spanu (2008)		Hydraulic cements, lime and organic polymers
Burroughs (2006)		Cement, lime and asphalt
Oti & Kinuthia (2012)		Cement and lime
Binici et al. (2005)	Straw, plastic fibres and polystyrene fibre	Cement
Arumala & Gondal (2007)	Kenaf fibre	Cement
Juárez, Guevara, Valdez, & Durán-Herrera (2010)	Lechuguilla natural fibre	Cement
Vilane (2010)	Sawdust	Cement, molasses and cow-dung
Chan (2011)	Pineapple leaves fibre and oil palm fruit bunch fibre	Cement
Ismail & Yaacob (2011)	Oil palm empty fruit bunches fibre	Cement
Medjo Eko, Offa, Ngatcha, & Minsili (2012)	Salvaged steel fibres from used tyres	Cement
Obonyo, Exelbirt & Baskaran (2010)	Coconut fibre	Cement and lime

Cai, Shi, Ng, & Tang (2006)	Polypropylene	Lime
(Villamizar, Araque, Reyes, & Silva, 2012)	Cassava peels	Coal combustion waste
(Galán-Marín, Rivera-Gómez, & Petric, 2010)	Sheep wool fibre	Alginate
(Achenza & Fenu, 2006)	Seaweed fibres and	Natural polymers

Seventeen Studies stabilised soil blocks or bricks with fibres and other industrial and agricultural by-products. This method has being followed since ancient times, for instance, in ancient Egypt, straw and horsehair were added to mud bricks, while straw mats were used as reinforcement in early Chinese and Japanese housing construction (Li, 2002). The inclusion of soil blocks with waste fibres has structural (improvement of strength and durability properties), economic (low-cost) and environmental (reduction of carbon dioxide and pollution) benefits. Thus, instead of disposing of waste in manner that can pollute the air, it is used in blocks for the purpose of increasing the strength and durability properties of the blocks as well as making them affordable. In the view of Al-Sakkaf (2009), constructing buildings that are durable and low-cost is a need and essential particularly for those in low income bracket. This is important because low-cost housing is described as dwelling units whose total housing costs for either rented or purchased units are deemed affordable to those that have a median household income (Bhatta & Basudeb, 2010), as well as those in the low income bracket.

Twenty-seven studies followed the method that stabilized soil blocks or bricks with only binders. This method is not known only in the stabilisation of soil blocks but also applicable in conventional building materials like concrete and mortar. Cement and lime have proved that they are effective binding agents, but their manufacturing process tend to have long term detrimental effect on the health of people and environment. They also require high energy consumption for production. The energy requirement to produce unstabilised adobe blocks is only 5 kWh/m³, it is about 1000 kWh/m³ for fired bricks and 400-500 kWh/m³ for concrete (Al-Sakkaf, 2009). The production of Portland cement (PC) contributes significantly to anthropogenic CO₂ emissions in the atmosphere (Kinuthia & Mofor, 2010). Therefore, the partial or total replacement of PC is critical to the achievement of sustainable development of infrastructure. As the construction industry is becoming increasingly focused on sustainability, there is the need for alternate building materials that are environmentally friendly and consume less energy (UN Habitat, 2011).

For further enhancement, twelve studies combined fibres and binders. Though most of the studies succeed in demonstrating greater improvement, there are still concerns about the manufacturing process of the binder component which can reduce the environmental differential between unfired and fired blocks as well as increasing the cost of producing housing.

Properties and test methods

From Table 2, the focus of previous studies can be categorised in three ways which are physical properties, mechanical properties and durability properties. A fourth category which is also important is combinations of these properties. These categorisations were made based on the types of test conducted in the previous studies which are detailed in Table 2.

Physical properties are properties other than mechanical properties that depend on the physics of the material, including density, porosity, shrinkage, water absorption, moisture content and thermal expansion. None of the studies focused only on physical properties, though they were often combined with mechanical properties as a comparison. This is because; physical property tests are often simple to carry out in the field and may sometimes be used to imply mechanical properties without the need for more complex mechanical testing.

Mechanical properties are those material properties that measure a material's reaction to applied force, such as tensile strength, compressive strength, flexural strength, modulus of elasticity and efflorescence. Eleven studies focused only on mechanical properties. Mechanical properties have been widely studied because it is felt that the perceived limitations of soil blocks are due to problems in mechanical properties.

Durability properties are the properties of a material that resist weathering action, chemical attack, and abrasion. Durability tests attempt to measure the bond holding particles within the wall under the action of simulated erosive forces (Heathcote, 1995). Five studies focused only on durability and in all only eleven studies included durability testing in their work. Those studies also use a wide range of techniques and performance measures that make comparison difficult. This is an indication that durability has seen little research work; however, it is an important test, particularly for high rainfall areas where erosion, blown dust and wear of the soil particles could be critical.

Table 2: Types of Test Conducted by Previous Studies

Reference	Physical Properties						Mechanical Properties					Durability Properties				
	Density	Porosity	Water Absorption	Moisture Absorption	Dry Shrinkage	Thermal	Compressive	Tensile /Mod. of Rap	Flexural	Modulus of	Efflorescence	First/Post-cured	Freeze Thaw	Wire brush/Abrasion	Drip	Spray
Achenza & Fenu (2006)	✓	✓	✓				✓								✓	
Akbulut et al. (2007)							✓									
Alavez-Ramirez et al. (2012)							✓		✓							
Arumala & Gondal (2007)	✓		✓	✓			✓	✓								
Atzeni et al. (2008)		✓			✓		✓							✓		
Aymerich et al. (2012)												✓				
Bahar et al. (2004)			✓		✓		✓	✓								
Binici et al. (2005)	✓		✓				✓									
Bouhicha et al. (2005)					✓		✓		✓							
Burroughs (2006)							✓									
Cai et al. (2006)	✓			✓	✓		✓									
Chan (2011)	✓		✓				✓			✓	✓					
Degirmenci (2008)					✓		✓		✓							
Demir (2006)	✓	✓	✓		✓		✓									
Elenga et al. (2011)	✓			✓	✓		✓		✓	✓						
Galán-Marín et al. (2010)	✓						✓									
Ghavami et al (1999)			✓				✓	✓								
Gaw & Zamora (2011)					✓		✓									
Gooding & Thomas (1997)	✓						✓									
Guettala et al. (2002)													✓			
Harper (2011)			✓				✓									
Heathcote (1995)															✓	✓
Heathcote (2002)																✓
Hossain et al. (2007)	✓		✓	✓	✓		✓	✓		✓						
Hossain & Mol (2011)	✓		✓		✓		✓	✓		✓						
Ismail & Yaacob (2011)	✓		✓				✓									
Juárez et al. (2010)	✓				✓		✓	✓				✓				
Kavas (2006)			✓		✓		✓									
Kouakou & Morel (2009)		✓			✓		✓									
Kumar et al. (2006)	✓						✓									
Maher & Ho (1994)							✓	✓	✓							
Medjo Eko et al. (2012)	✓						✓	✓	✓							
Millogo et al. (2008)			✓				✓		✓							
Millogo & Morel (2012)			✓				✓		✓							
Millogo et al. (2014)						✓	✓		✓					✓		✓
Montgomery (2002)	✓						✓									
Morel et al. (2007)	✓						✓		✓							
Muntohar (2011)			✓				✓	✓	✓							
Ngowi (1997)	✓		✓				✓							✓		
Obonyo et al. (2010)																✓
Oti et al. (2009)							✓									
Oti & Kinuthia (2012)							✓									
Piattoni et al. (2011)							✓			✓						
Quagliarini & Lenci (2010)							✓			✓						
Reddy & Lokras (1998)							✓									
Reddy & Hubli (2002)							✓									
Reddy et al. (2007)			✓				✓		✓							
Sen & Reddy (2011)	✓		✓	✓			✓	✓		✓						
Vilane (2010)							✓									
Villamizar et al. (2012)			✓				✓		✓							
Walker (1995)	✓				✓		✓	✓								
Walker & Stace (1997)	✓		✓		✓		✓									
Walker (2004)							✓	✓						✓		✓

Reference	Physical Properties						Mechanical Properties					Durability Properties				
	Density	Porosity	Water Absorption	Moisture coefficient	Dry Shrinkage	Thermal	Compressive	Tensile /Mod. of Rap	Flexural	Modulus of	Efflorescence	First/Post-cure	Freeze Thaw	Wire brush/Abrasion	Drip	Spray
Yalley & Kwan (2008)						✓	✓									
Yetgin et al. (2008)	✓	✓	✓				✓									
Total	22	5	21	5	15	2	50	12	13	7	1	2	1	4	2	5
	70						83					14				

Thirty-four studies combined at least two properties while five studies combined physical, mechanical and durability. This is becoming popular because it offers researchers a variety of tests to investigate the broader properties of enhanced soil blocks.

Results

Compressive Strength

Twenty-three of the studies conducted compressive strength tests on stabilised soil blocks/bricks and their results are presented in Table 3 (with fibres) and Table 4 (with binders). The Turkish standard code for the compressive strength of unfired clay brick is 1 MPa (Turkish Standard (TS 704), 1983, 1985), while Houben & Guillaud (1994) recommended at least 2 MPa for cement stabilised blocks.

Table 3: Compressive Strength (with Fibre)

Abscissa is mass fraction (%), ordinate is compressive strength (MPa)

Reference	Fibre	Range of Mass fractions (%)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max Strength (MPa)	Compressive strength (MPa)
Piattoni et al. (2011)	Straw	0.025 – 0.075	0.056 – 2.4	-	8.29	
Bouhicha et al. (2005)	Chopped barley straw	1.5 – 3.3	n/a	4.1	5.6	

Akbulut et al. (2007)	Tire rubber	1 - 5	n/a	0.09	0.18	
Akbulut et al. (2007)	Polyethylene	0.1 – 0.5	n/a	0.09	0.14	
Cai et al. (2006)	Polypropylene	0.05 – 0.25	0.15 – 0.45	0.66*	0.88	
Demir (2006)	Processed waste tea residue	2.5 – 5.0	0.82	3.5	7.6	
Ismail & Yaacob (2011)	Oil palm empty fruit bunch	0.06 – 0.3	-2.86	10.22*	10.65	
Villamizar et al. (2012)	Cassava peels	0 - 5	0.036	1.97	2.15	
Millogo et al. (2014)	Hibiscus cannabinus	0.2 - 0.8	n/a	2.45	2.9	
Arumala & Gondal (2007)	Kenaf	0 - 5	0.02	1.2	1.3	

* "Unstabilised" strength is with a binder, but no fibre. Binder content is kept constant

Table 3 shows nine studies that conducted compressive strength tests with various fibres as the enhancement agent. The results show the three types of trend. 1, a slope with a positive gradient indicating an increase in compressive strength with additional fibres, 2, a slope with a negative gradient indicating a falling strength with additional fibres and 3, a rise to a maxima followed by a fall. The gradients, cover a wide range with a minimum of -2.86 MPa per % added, a maximum

of 2.4 MPa per % added and a median of 0.8 MPa per % added. Five of the studies (Arumala & Gondal, 2007; Cai et al., 2006; Demir, 2006; Piattoni et al., 2011; Villamizar et al., 2012) obtained a positive gradient, while (Ismail & Yaacob, 2011) obtained a negative trend. The balance of the papers (Akbulut et al., 2007; Bouhicha et al., 2005; Millogo et al., 2014) show a definite optimum fibre content. This content varies between 0.1% and 5% with a median of 1.0%. Fibres initially work by increasing the bond between the particles both by friction on the fibre and by tying them together with loops. The fibres have a greater tensile strength than the surrounding soil matrix and therefore impart a greater cohesion and strength (Cai, et al, 2006; Millogo et al., 2014). The effect peaks at some concentration and then fibres begin to bunch together (Ismail & Yaacob, 2011) and lose cohesion with the soil (Medjo Eko et al, 2012) and also break-up the soil matrix (Millogo et al., 2014) causing the soil-fibre composite to weaken. It is likely that those studies that found a consistently rising strength have yet to achieve the peak. Of the studies that did not include a binder as well as fibres, the lowest optimum found was 0.14 MPa which is well under the recommendations, and the highest from soil stabilised by only fibre was 8.29 MPa. Soils alone varied from 0.09 MPa to 5.15 MPa and the improvement due to fibres alone ranged from 0.04 MPa to 1.17 MPa with a median of 0.43 MPa. Interestingly, the improvement followed the soil strength very well with the exception of Ismail & Yaacob (2011). Pearson's coefficient is $r = 0.8$ without Ismail & Yaacob but only $r = 0.09$ with it. This demonstrates the importance of the soil matrix for the effectiveness of fibre reinforcement. As the soil matrix is so important, the fractional improvement obtained with fibres was found to be in a quite narrow range (4% to 117% with a median of 26%).

Table 4 presents the result of compressive strength tests of soil blocks enhanced with different types of binder from seventeen published studies.

Table 4: Compressive Strength (with Binder)

Abscissa is mass fraction (%), ordinate is compressive strength (MPa)

Reference	Binder	% Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Compressive strength (MPa)
Achenza & Fenu (2006)	natural polymer	0 - 10	0.19	2.5*	4.4	

Medjo Eko et al. (2012)	Cement	4 – 10	1.23	0.5*	11.6
Arumala & Gondal (2007)	Cement	0 - 5	0.12	1.2	1.8
Bahar et al. (2004)	Cement	4 - 20	0.086 – 0.27	1.6	6.5
Millogo & Morel (2012)	Cement	4 – 12	0.31 – 0.35	2.5	6.4
Guettella 1997, cited by Morel et al. (2007)	Cement	2.5 - 15	0.96	5.1	20
Walker, 2000, cited by Morel et al. (2007)	Cement	2.5 - 10	0.48	0.9	5.7
Walker & Stace (1997)	Cement	5 - 15	0.45 – 0.77	-	9.4
Gooding & Thomas (1997)	Cement	3 - 11	0.20 – 0.43	-	4.4
Alavez-Ramirez et al. (2012)	Cement	0 – 10	2.29	0.64	23.5
Burroughs (2006)	Cement	2 – 6	0.48	-	4.01

Hossain & Mol (2011)	Cement kiln dust	2 – 20	0.28	0.1	6.01
Burroughs (2006)	Lime	2 – 6	0.28	-	3.03
Alavez-Ramirez et al. (2012)	Lime	0 – 10	1.59	0.64	16.5
Cai et al. (2006)	Lime	2.0 – 8.0	n/a	-	0.88
Millogo et al. (2008)	Lime	2 - 12	0.076	2.4	3.6
Reddy & Hubli (2002)	Lime	6 - 18	0.1 – 0.26	-	3.3
Alavez-Ramirez et al. (2012)	Lime + bagasse ash	0 – 20	1.03	0.64	21.3
Hossain & Mol (2011)	Volcanic ash	5 – 20	0.15	0.1	3.1
Villamizar et al. (2012)	Coal combustion waste	5 – 10	n/a	1.97	3.31
Galán-Marín et al. (2010)	Alginate	0 - 19.75	0.070-0.078	2.23	4.44

Degimenci (2008)	Gypsum	5 -25	0.13 – 0.16	1.0	4.6	
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* “Unstabilised” strength is with fibres, but no binder. Fibre content is kept constant.

The results indicate that the vast majority of the studies had a positive gradient indicating that an increase in binder results in an increase in compressive strength. This increase ranged from 0.07 MPa per % added to 2.29 MPa per % added with a median of 0.28 MPa per % added. In terms of compressive strength improvement, Portland cement is the most successful binder but also the most variable (range = 0.09 – 2.29 MPa/%, median = 0.54 MPa/%). Portland cement has the advantage of reacting with water forming various strong and rigid hydrates which fill spaces and bind particles together independent of reactions with the soil (Bahar et al., 2004; Millogo & Morel, 2012). Though pozzolanic reactions with clays in the soil will occur, they play a small part in strength formation (Millogo & Morel, 2012) and are smaller than the disadvantages associated with clay in the soil (Walker & Stace, 1997). This is followed by materials relying on pozzolanic reactions such as volcanic ash (0.15 MPa/%) and cement kiln dust (0.28 MPa/%) and lime. Finally, materials that set around the particles rather than react with them such as gypsum (0.16 MPa/%) and then polymers (Alginate – 0.08 MPa/%). As many binder reactions do not appear to level off in the regions studied, maximum strength is likely to be an economic or environmental rather than technical constraint, however as an indication of scale within the region of the studies analysed which range from 1% to 20%, the maximum compressive strength recorded was 21 MPa of which 20 MPa was improvement from the cement binder at a 10% mass fraction. An exception to this trend was lime which relies on pozzolanic reactions with clays (Millogo et al, 2008). Once clays are all reacted, the lime simply forms a filler material which is porous and weak (Reddy & Hubli, 2002; Muntohar, 2011). The optimum concentration of lime, therefore is dependent on the clay content of the soil but varies between 1.5% and 14% in the studies including lime as a binder. The performance of the binders was relatively insensitive to initial strength of the soil and the range of fractional improvement was from 50% to 5900%, though there is no reason to assume that this couldn’t be improved upon if it were desirable to do so. As the use of binders enhances the strength of the soil matrix by increased cohesion between particles, their use also should also aid the pull-out performance of fibres and therefore the performance of fibre stabilised blocks. Four studies combined fibres and binders, however the

results were, in fact quite similar to those for soil without binders. The median improvement for fibres in a binder-stabilised soil was 0.22 MPa, whereas the medium improvement for natural soils was 0.33 MPa. It is likely that other factors such as compression and clay content have contributed as much to fibre effectiveness as binder content.

Water Absorption

Ten studies conducted a water absorption test. Of these, eight were stabilised through a binder and two through fibres. The results of the studies are presented in Table 5.

Table 5: Water Absorption

Abscissa is mass fraction (%), ordinate is Water absorption (% by mass)

Reference	Fibre	Binder	% Fibre/Binder (Range)	Slope (%/%)	Unstabilised absorption (%)	Min. absorption (%)	Water absorption (%)
Villamizar et al. (2012)	Cassava peel		0 - 5	-0.64	30.2	27
Ismail & Yaacob (2011)	Oil palm empty fruit bunch		0.06 – 0.3	6.33	14.7*	14.7
Millogo & Morel (2012)		Cement	2 - 12	0.22	28.5	23.5
Bahar et al. (2004)		Cement	2 - 15	0.35	-	13.68
Bahar et al. (2004)		Cement	5 - 10	-0.77 -- 0.92	14.29	2.71
Ngowi (1997)		Cement	5 - 15	-0.26	-	6.85

Reddy et al. (2007)		Cement	4 – 8	0.05 – 0.18	-	14.66	
Walker & Stace (1997)		Cement	5 – 10	0.08 – 0.30	-	13.1	
Hossain & Mol (2011)		Cement kiln dust	2 - 20	-0.53	20.7	7.5	
Ngowi (1997)		Lime	5 - 15	0.04	-	8.52	
Millogo et al. (2008)		Lime	2 - 12	-0.89	29	19	
Villamizar et al. (2012)		Coal combustion waste	5 – 10	0.045	30.2	28.7	
Hossain & Mol (2011)		Volcanic ash	5 – 20	-0.58	20.7	8.5	

* “Unstabilised” contains none of the stabilisation of interest, but contains other stabilisers which are kept constant throughout.

The results for binders indicate variable and fairly neutral water absorption with additional binders. The range recorded was -0.89 % additional absorption for each % of increase in binder (%/%) to 0.35 %/%% with a median of 0.02 %/%% with half the papers reporting an increase and half a decrease. Explanations about the decrease in absorption are that the binder fills the void between particles reducing porosity, but no explanations about increased absorption were offered in the literature. There were few studies of fibres that included water absorption. A number of wider studies attempted to soak a block without binders in water and, predictably, found that it

quickly disintegrated, so the available studies were restricted to blocks with a combination of binders and fibres. One study (Villamizar et al., 2012) recorded a slight reduction in water absorption with fibres (-0.64 %/%) and the other (Ismail & Yaacob, 2011) a significant increase (6.33 %/%). It is likely that in-general, fibres will increase water absorption as the absorbent nature of fibres creates pathway through soil blocks, thereby allowing more water absorption (Ghavami et al, 1999)

Flexural and Tensile Strength

Ten studies conducted flexural strength test of enhanced soil blocks. The results are presented in Table 6.

Table 6: Flexural and Tensile Strength

Abscissa is mass fraction (%), ordinate is Flexural or tensile strength (MPa)

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Flexural strength (MPa)
Millogo et al. (2014)	Hibiscus cannabinus		0.8	n/a	0.52	1.12
Villamizar et al. (2012)	Cassava peel		5	-0.032	0.64*	0.64
Medjo Eko et al. (2012) [†]	Salvaged steel fibres		1.7 – 2.7	n/a	-	0.63
Alavez-Ramirez et al. (2012)		cement	0 - 10	0.19	0.11	1.96
Medjo Eko et al. (2012)		cement	4.0 – 10.0	0.23	0.5*	2.6
Millogo &		Cement	2 - 12	0.093 –	0.5	1.7	

Morel (2012)				0.11			
Bahar et al. (2004) [†]		Cement	4 - 20	0.039	0.24	1.1	
Walker (2004) [†]		Cement	2.5 - 10	0.17 – 0.23	1.37	3.58	
Millogo et al. (2008)		Lime	2 - 12	0.04	0.48	0.92	
Alavez-Ramirez et al. (2012)		Lime	0 - 10	0.1	0.11	1.12	
Alavez-Ramirez et al. (2012)		Lime + bagash	0 - 20	0.06	0.11	1.4	
Galán-Marín et al. (2010)		Alginate	0.0 - 19.75	-0.003 – 0.018	1.05*	1.45	
Degimenci (2008)		Gypsum	5 - 25	0.033 – 0.042	0.6	1.7	
Villamizar et al. (2012)		Coal combustion waste	5 – 10	n/a	0.64	0.76	

* “Unstabilised” contains none of the stabilisation of interest, but contains other stabilisers which are kept constant throughout.

[†] Tensile strength

The result show a very similar trend of results to compressive strength, with binders showing a generally rising flexural strength with increased concentration and fibres showing a maximum value. There were very few studies with fibres and so the maxima recorded must be considered as tentative. Millogo et al. (2014) report a maximum of 1.12 MPa, an improvement of 0.6 MPa which compares to an improvement of 0.45 MPa for compressive strength from the same study, so the ratio of flexural to compressive strength improvement ($\sigma_{f,max}/\sigma_{c,max}$) is 133%.

Conversely, Villamizar et al., (2012) reported a reduction in flexural strength, however these results are based on only two points, one with fibers and one without and so is unlikely to represent an optimum fibre content. The median overall strength achieved was 0.6 MPa, 22% of the median compressive strength achieved with fibres. A notable feature of fibres in both tension and compression is that the failure is more gradual, acting more like a ductile than a brittle material (Cai et al. 2006). This is ascribed to the fibres changing large cracks to many microcracks which hold the soil particles together (Medjo Eko et al., 2012) and form a bridge after the soil has cracked (Aymerich et al., 2012). It has also been proposed that fibres act to reduce the propagation of cracks in the soil matrix (Millogo et al., 2014).

More studies were available involving a range of binders. The maximum recorded flexural strength improvement was 2.2 MPa 11% of the maximum compressive strength improvement, however as with compressive strength, this is likely to be a socioeconomic choice. More relevant for a binder is the rate of improvement. The maximum change is 0.24 MPa/% which is 10% of the maximum rate of improvement for compressive strength. The median change of strength imparted by a binder is 0.1 MPa/% and the median ratio of flexural to compressive strength change was 25%. The hierarchy of binders was also similar to that found for compressive strength with cement displaying the highest and most variable improvement (range = 0.003 – 0.24 MPa/%, median = 0.10 MPa/%). Next, Pozzolanic additives and lime (range = 0.04 – 0.1 MPa/%, median = 0.06 MPa/%) and then other non-reactive materials such as Gypsum (0.042 MPa/%) and Alginate (0.018 MPa/%). One study of a pozzolanic material (Villamizar et al., 2012) showed a clear optimal concentration and another with lime (Millogo & Morel, 2012) showed a weak optimum.

Conclusions

Based on the review of the performance characteristics of enhanced soil blocks or bricks, the following concluding remarks can be made:

1. Few studies focused on improving the durability property of enhanced soil blocks which is one of the major problems with earthen construction, while the majority of the previous studies were found testing for physical and mechanical properties.
2. Studies that enhanced the soil blocks or bricks with fibres mostly recorded an increase in compressive strength until an optimum was reached at a median strength of 0.43 MPa above the unstabilised soil strength, and then further fibres reduced the strength of the block. This optimum varied, but was in the very low percentages with a median value of 1%. The effectiveness of fibres was also very dependent on the soil matrix and can be considered to be capable of improving the strength of a block by up to 117%, but more likely to be in the region of 20 – 50%. The addition of binders generally continually increased the strength of the block with a median improvement of 0.28 MPa per % added with the exception of lime which relies on reactions with clay and therefore has an optimal concentration which depends on the clay content. It is likely that other materials relying on pozzolanic reactions would have a similar peak, however this was not shown in the studies found.
3. Flexural strength displays very similar behaviour to compressive strength, but based on only a couple of studies, fibres appear to have a proportionally better performance. Fibres also make the blocks fail more gradually which may be important for earthquake prone areas. As with compressive strength, the addition of binders generally improves flexural strength, however materials which rely on pozzolanic reactions don't display as pronounced a defined maxima as with compressive strength.
4. The inclusion of stabilisers has a very variable effect on water absorption with as many studies reporting an increased absorption as a decreased absorption. This is contrary to received wisdom which states that binders should reduce water ingress and fibres should increase it.

The review concludes that, in general, fibre and binder inclusion in soil blocks enhances the performance characteristics of the blocks. This paper reviewed the existing published works on the effect of stabilisation on the performance characteristics of soil blocks. Binders are, in

general more effective on a mass-fraction basis, however, the supply of fibres is usually at a lower cost and a reduced environmental impact, and therefore may have a better performance on a per-cost or per-impact basis. The performance data presented in this paper should help determine if this is the case where cost and impact data can be locally determined.

According to Reddy (2004) there is a need for optimum utilization of available energy resources and raw materials to produce simple, energy efficient, environment friendly and sustainable building alternatives and techniques to satisfy the increasing demand for buildings. Earth is affordable and available and would be appropriated in the case of low cost house construction in many countries (Zami & Lee, 2011). While it may be desirable that policy makers incorporate earth construction in their housing policy to provide decent accommodation for their people, especially in areas where housing deficits are high, there is still a considerable negative perception to earth as a building material. Continued work is needed to convince them of earth's strength and durability (Heathcoat, 1995). The present review suggests that the strength properties of soil blocks have been enhanced as indicated in the previous studies. This implies that some of the problems associated with earth construction faced by users or occupants can be addressed with the careful inclusion of fibres and binders. Knowledge of the abilities of these additives may build confidence in the users of earth construction and reduce the negative impression that earth is an inferior material for constructing houses. Further, the quantitative data presented should help policy makers and planners make reasoned choices when specifying materials for building.

The major drawback of earth as construction material is the durability especially when in contact with water. However, few studies have been conducted on durability properties whereas most of the studies are geared towards physico-mechanical properties. Ideally, it will be more beneficial if researchers and practitioners devote good percentage of their research into improving the durability properties of enhanced soil blocks. This implies that researchers and practitioners need to know the right content of fibre to be used for stabilising soil blocks and also check the amount of binders to be used in order not to erase the sustainable aspect of earthen construction.

This paper reviewed existing published studies on the effect of stabilisation on the performance characteristics of soil blocks. However, there are numerous other factors that can affect the engineering properties of a soil block. The methodology used may also consider other factors

such as formation pressure, soil selection, curing or drying methods and optimum water content. The results may further be compared to determine critical factors and interactions. The current study focused on enhanced soil blocks, however the methodology applied can also be employed to review the performance characteristics of rammed earth construction from its published literature. In addition, future studies may consider delving into critical analysis of stabilizers or additives that are more sustainable to help practitioners make decision on which of them to use.

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