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Article

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Application of agro and non-agro waste materials for unfired earth blocks construction: A review

Nusrat Jannat [a,*], Aseel Hussien [a], Badr Abdullah [a], Alison Cotgrave [a]

Built Environment and Sustainable Technologies (BEST) Research Institute, Department of Built Environment, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK

Abstract

The production process of conventional building materials consumes a high amount of energy which has a negative impact on the environment. The use of locally available materials and upgradation of traditional techniques can be a good option for sustainable development. Consequently, earth has attracted the attention of the researchers as a building construction material for its availability and lower environmental impact. On the other hand, in developing countries waste disposal from the agricultural and industrial sectors raises another serious concern. The scientists have introduced such waste additives into the earth matrix to improve its performance. Therefore, the present paper reviews the state-of-the-art of research on the effects of these various agro and non-agro wastes in the production of unfired earth blocks. This study is divided into three sections: The first section outlines the different types of waste materials and earth blocks considered in the selected papers. The second part deals in depth with the test results of the different properties (density, water absorption, compressive strength, flexural strength and thermal conductivity) of unfired earth blocks containing waste materials. The last section analyses and compares the results with the current earth-building construction standards. The literature survey presents that the waste materials have a clear potential to partly replace earth by complying with certain requirements. Moreover, the application of such wastes for the development of building construction materials provides a solution that decreases energy usage as well as contributes to effective waste management. Future research on establishing guidelines and standards for the development and production of these sustainable unfired earth building materials is recommended.

Keywords: Agro waste, Earth block, Non-agro waste, Sustainability, Unfired.

Contents

1. Introduction

Sustainable development in building construction sector has become a major challenge in both developed and developing countries today. Application of locally available materials and techniques in building construction is considered as one of the prospective ways to support sustainable development [1, 2]. Construction and maintenance of modern buildings are commonly believed to consume enormous amounts of energy and release significant greenhouse gas. Currently, the construction sector is consuming 30-40% of total global energy and contributing to produce one-third of the total greenhouse gas emissions [3]. Therefore, the development of new

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[*] Corresponding author.
E-mail: N.Jannat@2019.ljmu.ac.uk

green building materials with better properties is becoming increasingly important [4-6]. Earth is one of the oldest and most traditional construction materials on our world dating back to 8000 B.C. [7]. The construction of earth building is still common in some of the most hazardous regions in the world, such as Africa, Latin America, the Middle East, the Indian subcontinent and other parts of Asia and Southern Europe [Fig. 1]. Statistics from UNCHS show that around 40% of the population of the world lives in buildings made of earth and in developing countries the number is higher [9]. In developing countries, nearly half the population lives in earth dwellings in which at least 30% of the population is in rural areas and others are in urban or suburban areas [10].

Earth is considered as an environmentally friendly choice due to its low carbon emission, low thermal conductivity and good hygroscopic characteristics [11, 12]. However, some of the disadvantages of earth construction are the lack of strength, durability and vulnerability to erosion by rain [13-15]. Unfortunately, due to these drawbacks, the use of earth building materials in the modern construction sector has been ignored over many years [16] and is being extensively replaced by more durable and stronger construction materials such as fired brick and concrete [14, 17, 18]. However, unfired earth masonry provides many advantages compared to traditional fired brick and concrete masonry in terms of environmental impacts. The use of energy-intense processes of conventional fired brick and concrete masonry production leads to high levels of carbon dioxide emissions [19, 20]. The mean energy consumed per tonne of fired brick is calculated at 706 kWh and carbon dioxide emission per tonne is estimated at 0.15 tonne [21]. On the other hand, traditional unfired earth blocks use low-energy materials which can be modified to enhance their properties and strengthened by low-cost natural aggregates with a little additional energy cost [22]. Although it is important to acknowledge the contributions made by modern clay brick manufacturing and other modern earth construction to improve the overall properties of earth structures, it is equally important to consider the environmental effects of these methods. Presently, to meet the requisite comfort standards, earth building construction is also regaining its prominence in industrialised countries and becoming an integral part of “green thinking” [23, 24]. Therefore, comprehensive articles on this issue have been published over the last decades. Many studies have presented that due to the popularity and low cost of earth building materials improving it for large usage would seem to be a technique more likely to succeed than replacing it with new modern materials or using costly and inefficient methods [25-27]. Fibrous materials such as straw have long been used by local home brick manufacturers to improve the strength of mud bricks [28]. However, they were unable to conduct basic experimental research on the optimisation and balance of materials. Hence, researchers have developed various additives and methods to enhance the performances (strength, aggregate stability, thermal conductivity, water absorption, etc.) of unfired earth materials [29-31]. Further experiments in the field of alternative additives to unfired earth materials have recently been focused mainly on agro and non-agro wastes [32, 33].

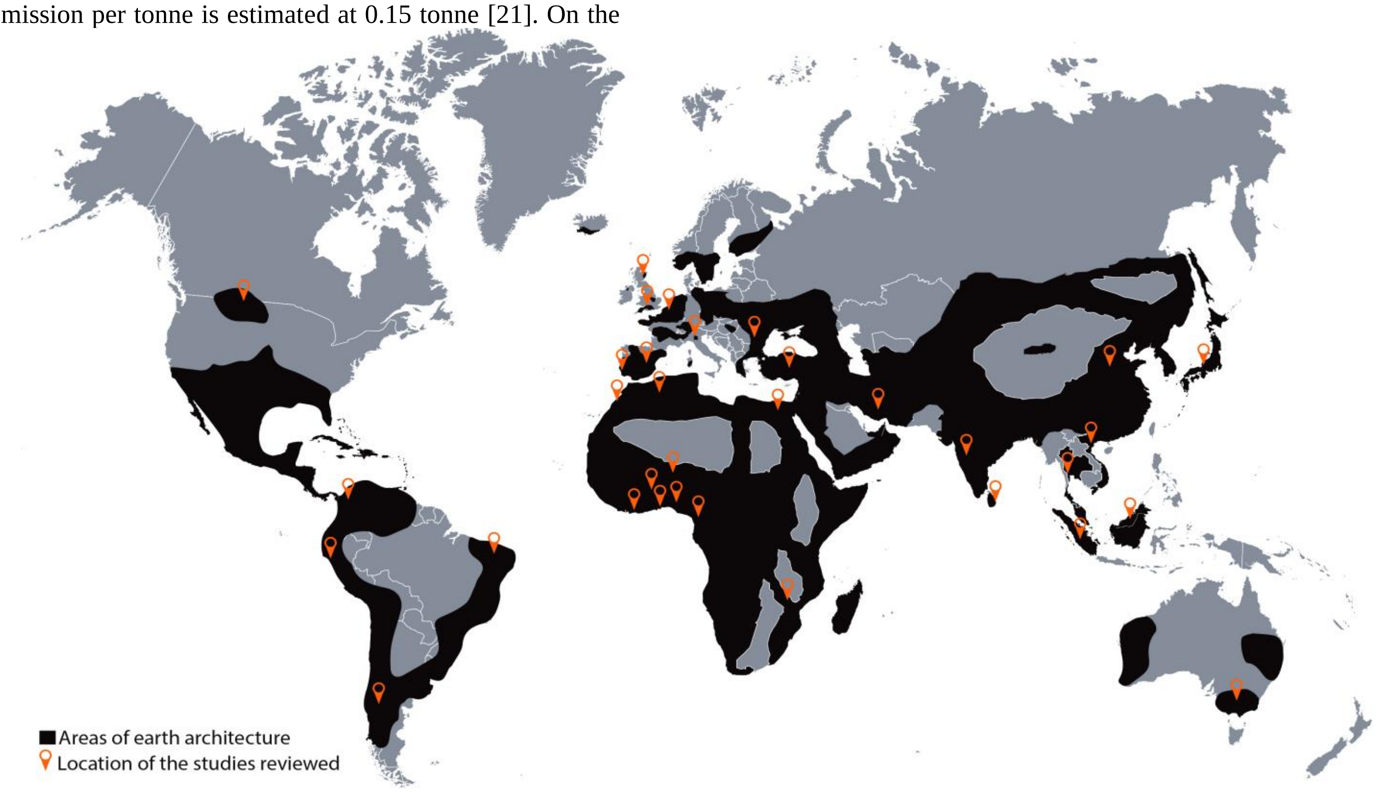


Fig. 1. Areas of earth architecture distribution across the world [8] and location of the studies reviewed in this paper

Industrial or agricultural solid waste management has become one of the most important global environmental concerns. The current estimated global waste generation volume is around 1.3 billion tonnes annually, with an expected annual increase of 2.2 billion tonnes by 2025. [34]. In many developing countries increased large quantities of agro and non-agro wastes are not efficiently managed and utilised which eventually generates a threat to the environment [35-37]. Agricultural wastes are the residues generated from the cultivation and processing of raw agricultural products such as crops, fruits, poultry, dairy products, etc. [38]. On the other hand, materials that are made useless during a production process, such as wastes from the factory, milling and mining activities create non-agro wastes or industrial wastes [39]. Several recent studies have presented that these agro-wastes have a high potential for use in building construction materials on account of their good physico-mechanical properties [40-42] and they are the most environmentally sustainable, economical and energy-efficient materials [43-45]. Also, previous research articles have demonstrated the prospective use of industrial wastes for different construction applications [33, 46, 47]. As alternative material studies are now clearly a priority for decreasing energy consumption and solving waste management problem, several studies have shown that the use of such wastes in the development of unfired earth building materials can meet this environmental challenge [33, 48, 49]. Therefore, researchers have made considerable efforts to partially substitute soil or clay with specific agro and non-agro waste materials to produce sustainable unfired earth blocks.

In consideration of the application of agro and non-agro waste materials, the present paper reviews the use of various wastes in different compositions to develop sustainable unfired earth blocks. The study highlights only five different properties of unfired earth blocks (density, water absorption, compressive strength, flexural strength and thermal conductivity) as these characteristics were tested in most of the previous studies to evaluate their suitability for construction purposes. Also, in contrast to previous review articles [32, 33], this paper outlines the standards used for the experiments and compares the results with the relevant unfired earth blocks standards. Consequently, this review paper will contribute to developing a database to support the manufacturers in the production of unfired earth blocks with different potential agro and non-agro waste materials.

2. Review method

This review paper addresses the current state-of-the-art of developments on the utilisation of various waste materials in the manufacture of unfired earth blocks. The study followed a mixed-method approach collecting and analysing secondary data from several prior studies. A comprehensive systematic search was performed in the Google scholar and Scopus repositories for scholarly contributions from 2000 to 2019. In order to search articles, the following keywords were used: “Unfired earth blocks”, “Agricultural wastes”, “Non-agricultural wastes”, “Industrial wastes”, “Sustainability” and “Earth building code”. A total of 108 journal articles, conference proceedings, book chapters, theses and reports on unfired earth blocks incorporating agro and non-agro waste materials were reviewed of which 87 provided useful information.

This study is divided into three sections: The first part summarises the different types of waste materials and earth blocks considered in the selected papers. The second part addresses in great detail the experiment results of various properties of waste-incorporated unfired earth blocks. Finally, the paper analyses the data concerning current established standards for earth building construction.

3. Previous reviews

A few review studies were conducted on the use of different types of waste materials as clay additives. Two of the studies should be addressed here.

Laborel-Préneron et al. [32] reported the impact of widely used plant aggregates and fibres on the development of unfired earth building materials based on 50 major studies. The study highlighted the details of plant aggregate sources and characteristics as well as the treatments used to improve their performance. Moreover, the compositions and the manufacturing techniques of earth-based composites, for example, earth plasters, earth blocks, rammed earth, cob and wattle and daub were presented. In addition, the paper studied mechanical, durability and hygrothermal performances of the selected plant aggregates and fibre-based composites. The report lacked data on standards for experiments and detailed results on the assays.

Al-Fakih et al. [33] studied physical and mechanical properties of both fired and unfired masonry bricks such as loadbearing and non-load bearing concrete masonry units, concrete building brick, sand lime brick and clay building brick made by adding different organic and inorganic wastes. The paper presented information about the manufacturing method of burnt (firing temperature) and unburnt bricks (cementing method) incorporating waste materials. Moreover, in this study, four major test findings, such as compressive strength, flexural strength, bulk density and water absorption were discussed. However, the research was limited to the information on unfired clay bricks containing wastes since it focused on the development of different masonry brick types.

All papers covered in this review are presented in Table 1 and Table 2. The tables also specify the types of wastes, sources and location of research. It should be noted that certain articles were already included in the aforementioned reviews, but they are more comprehensive here.

4. Review of studies

4.1 Unfired earth blocks

Unfired earth blocks are made of earth materials and also referred to as earth masonry. These blocks are similar to other masonry systems where they are air-dried after manufacturing to minimize shrinkage and improve strength. Unfired earth blocks can be classified into three categories, "adobe blocks," "compressed earth blocks" and "cut blocks" based on the method used to shape the blocks [8].

Adobe blocks-Traditionally, adobe mud blocks are hand-shaped or made in wooden moulds and left to dry under the sun after casting.

Compressed earth blocks-The compressed earth blocks are made using a manual or motorised press. The method includes moistening the soil with water or stabiliser and then pouring it into a compacting steel press for compaction.

Cut blocks-These blocks are made by cutting earth and used like bricks in areas where the soil is cohesive and has carbonate concretions. These examples are typically found in tropical areas where building materials are produced by laterite soils.

Besides these three types of earth block construction, there is another traditional earth construction named rammed earth.

Rammed earth**-** In rammed earth construction, the soil is thoroughly mixed with water and then poured into thin layers. Traditionally each layer is rammed by hand to increase the density. Compressed earth block is considered as a development from traditional rammed earth and adobe blocks construction.

4.2 Wastes characterisation

4.2.1 Agro wastes

All undesirable materials generated by agricultural activities are known as agro wastes. Such wastes may come from plants or animals. Most of the papers reviewed in this study included wastes from plants while only four publications included work on animal origin wastes (sheep wool and pig hair). The plant aggregates/fibres are composed of cellulose, lignocellulose and made up of wood fibre, seed fibre, bast fibre, leaf fibre or grass fibre [50]. They are popular for use in reinforcement because of their lower density compared to other inorganic fibre. On the other hand, the hydrophilic nature of these wastes is one of the barriers to specific applications [51].

4.2.2 Non-agro wastes

Industrial wastes comprise any materials that are made unusable during a production procedure from mills, factories and mines. Some industrial wastes include fly ash, bottom ash, metals, glass, slag, sludge, plastic fibre etc. [52]. Fly ash and bottom ash are the remainders from various combustion processes of solid materials or power plants. Slag is the residue from the metal industry and sludge is produced by the wastewater treatment plant. Construction wastes often come from new buildings, refurbishment or demolition and wastes from the transport industry are created from vehicle repair such as used tyres, for example. Various types of fibre wastes such as glass, polypropylene, polyester, textiles, etc. are also available from different industries.

Table 3 and Table 4 present the studies on the development of unfired earth blocks with various agro and non-agro wastes.

Table 1
Different agro waste additives for the production of unfired earth blocks

Agro-wastes	Source(s)	Countries	References
Straw (Wheat, Barley)	Agricultural by-product (Stalk)	Burkina Faso, China, Egypt, France, Germany, Iran, Italy, Japan, Morocco, Peru, Spain, Turkey	[53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [71], [73], [74], [78], [83], [88], [101]
Lavender straw	By-product of lavender oil production (Stalk)	France	[62]
Fonio straw	Agricultural by-product (Stalk)	Burkina Faso	[63]
Coconut coir	Agricultural by-product (Fruit)	Ghana, India, Indonesia, Sri Lanka, Thailand	[64], [65], [66], [67], [68]
Banana fibre	Agricultural by-product (Pseudo Stem)	Egypt, India	[69], [70]
Hemp fibre	Agricultural by-product (Bast)	Egypt, France, Japan, Romania	[71], [72], [73], [74], [75], [76]
Rice husk	Agricultural by-product (Grain)	Burkina Faso, Indonesia, Iran, Vietnam	[77], [78], [79], [80]
Wood aggregate/fibre	Waste of carpentry product (Trunk, Branch)	Iran, Italy, UK, Zimbabwe	[78], [81], [82], [83]
Sawdust	Sawmill waste (Trunk, Branch)	Nigeria, Turkey	[84], [85], [102]
Sugarcane bagasse	Food industry waste (Stalk)	Brazil, Ghana, Portugal, Sri Lanka	[65], [86], [87]
Corn cob	Agricultural by-product (Grain)	France	[73], [74]
Corn plant fibre	Agricultural by-product (Stem)	Spain	[88]
Corn silk fibre	Agricultural by-product (Grain)	Japan	[89]
Corn husk ash	Agricultural by-product (Stem)	Nigeria	[90]
Cassava peels	Agricultural by-product (Root)	Colombia, Kenya	[91], [92]
Olive waste fibre	Agricultural by-product (Leaf)	Morocco	[101]
Grounded olive stone	Agricultural co-product (Pellets)	Spain	[88]
Pineapple leaf fibre	Agricultural by-product (Leaf)	Malaysia	[94]
Flax fibre	Agricultural by-product (Bast)	Egypt	[72]
Wheat hay fibre	Agricultural by-product (Stalk)	Egypt	[95]
Sisal fibre	Agricultural by-product (Leaf)	Brazil, Kenya	[92], [93]
Fescue	Agricultural by-product (Stalk)	Spain	[88]
Kenaf fibre	Wild plant (Bast)	France, Benin	[96], [97]
Henequen fibre	Agricultural by-product (Leaf)	UK	[98]

Jute	Agricultural by-product (Bast)	Japan	[71]
Date palm fibre	Agricultural by-product (Leaf, Sheath)	Algeria, Morocco	[99], [100], [101]
Palm bark fibre	Agricultural by-product (Bark)	Iran	[78]
Oil palm fruit fibre	Agricultural by-product (Fruit)	Ghana	[65]
Oil palm fruit bunch fibre	Agricultural by-product (Fruit)	Malaysia	[94]
Eucalyptus pulp microfibre	By-product of paper manufacturing (Trunk)	Brazil	[93]
Dawul Kurudu, Pines gum, Bael resin, Jack resin, Agarwood resin, Wood apple resin	Agricultural by-product (Leaf, Fruit, Stem)	Sri Lanka	[87]
Pinus roxburghii fibre, Grewia optiva fibre	Forest waste, Fodder waste	India	[29], [103], [104]
Seaweeds fibre	Alginate extraction by-product (Stem, Frond)	UK, Italy	[105], [106]
Bio-briquette	Agricultural waste product	India	[107]
Processed waste tea	Food industry waste (Leaf)	Turkey	[108]
Tobacco residue	Tobacco industry by-product	Turkey	[84]
Eggshell	Food industry waste	Ghana, Nigeria	[102], [109]
Pig hair	Food industry waste	Chile	[110]
Sheep wool	Textile industry waste	Italy, Morocco, Scotland	[60], [111], [112]

Table 2
Different non-agro waste additives for the production of unfired earth blocks

Non-agro-wastes	Source(s)	Countries	References
Fly ash	By-product of Coal-fired power plant	Canada, China, India, Vietnam	[113], [114], [115], [122]
Granulated blast furnace slag	By-product of iron and steel-making	India, UK	[117], [118], [119], [120]
Bottom ash	By-product of coal-fired power plant	India, Niger	[121], [122]
Polyethylene terephthalate	Shredded waste plastic bottles	Morocco, Nigeria, USA	[123], [124], [125]
Crumb rubber	Recycled industry by-product, transportation waste	Australia, Spain	[88], [126]
Polyurethane	Appliances by-product	Spain	[88]
Salvaged steel fibre	By-product of steel making	Cameroon	[127]
Alumina filler & Coal ash	By-product of aluminium foundry plant	Spain	[128]
Brick dust	Waste from cutting of fired clay bricks	UK	[129]
Magnesium oxide	By-product of mining & industrial company	Spain	[130]
Calcium carbide residue	Residues from industrial gas	Burkina Faso	[80], [131]
Recycled aggregate	Recycled aggregate derived from construction debris	Portugal	[132]
Molybdenum tailing	By-products of the mining industry	China	[133]
Iron mine spoil	By-products of the iron mining industry	India	[134]
KS770, Soda ash	By-product of the locally made black soap	Nigeria	[135]
Glass fibre reinforced Polymer	Waste from water boxes manufacturing company	Brazil	[136]
Ceramic, Concrete waste	Waste from recycling plants	Malaysia, Spain	[137], [138]
Marble dust, Polymer fibre	Waste from marble industry	Turkey	[139]
Plastic fibre, Polystyrene fibre	Waste Plastic, Polystyrene fibre	Turkey	[53]
Waterworks sludge	Waste from water treatment plants	China	[140]

4.3 Unfired earth blocks construction incorporating agro wastes

Binici et al. [53], Vega et al. [54], Ashour et al. [55], Parisi et al. [56], Abanto et al. [57], Türkmen et al. [58], Azhary et al. [59], Statuto et al. [60], Wang et al. [61] evaluated the impact of straw fibre incorporation on the engineering properties of unfired earth bricks. Various percentages and lengths of straw that were incorporated to produce the earth blocks were as follows: 2.5wt% [53], 25 and 33.3vol% [54], 3wt% [55], 0.64wt% [56], 1.5-3.7wt% [57], 1mass% [58], 2-5wt% [59], 3wt% [60], 5, 10 and 15wt% [61]. Fibre length: 2-3mm [61], lower than 10mm [56], 20mm [58, 59], 40mm [55], 50-100mm [54]. The analysis illustrated that the compressive strength, density and thermal conductivity of the unfired samples decreased with the increased amount of straw fibre [55, 57, 59, 61]. From the experiments conducted by Binici et al. [53], average water absorption value was found 36.80% and the lowest thermal conductivity value was recorded for wheat straw at 0.30W/mK (3% fibre), barley straw at 0.31W/mK (3% fibre). Other two studies presented the lowest thermal conductivity value of 0.25W/mK (2.5% fibre) [57] and 0.26W/mK (5%fibre) [59]. Vega et al. [54] showed that maximum compressive strength (3.99MPa for 33.3vol% fibre) was achieved with the highest amount of straw while maximum flexural strength (0.82MPa for 25vol% fibre) was acquired with the lowest fibre content. Wang et al. [61] used cement (10, 15 and 20%) with straw and reported that addition of cement prolonged the curing time, and increased the compressive strength (11.70MPa for 20% cement and 5% fibre). Other studies found optimum compressive strength as 5.80MPa [53], 0.46MPa [56], 4.58MPa [58], 1.86MPa [60]. Parisi et al. [56] measured peak tensile strength as 0.56MPa (0.64% fibre). The density of the specimens ranged between 1544.98

kg/m^3-1827.58kg/m^3 [59], 1400kg/m^3-1470kg/m^3 [58], 1628.70kg/m^3-1766.2kg/m^3 [57], 1357.70kg/m^3-1575.60 kg/m^3 (wheat straw) and 1139.90-1542.50kg/m^3 (barley straw) [56].

Giroudon [62] compared the effects of utilisation of barley and lavender straw (3%, 6% by mass and 10mm) in unfired earth brick production. The test results showed that barley straw improved thermal performance but lowered engineering strength while better durability and fungus growth resistance were achieved with lavender straw. Compressive strength tests were conducted using the same standard followed by Laborel-Préneron et al. [73] and for all the specimens a compressive strength value higher than the minimum requirements of the New Mexico Earthen Building Code (2MPa) [149] and the New Zealand Earth Building standard NZS D4298 (1.30MPa) [151] was recorded. For both types of straw, the maximum compressive strength 3.90MPa (lavender straw) and 3.80MPa (barley straw) were achieved for 6% fibre addition. Thermal conductivity decreased as the percentage of both types of fibre increased and the lowest values were measured as 0.28W/mK (6% lavender straw) and 0.15W/mK (6% barley straw). Moreover, the results indicated that the incorporation of lavender straw improved the dry abrasion resistance while it was reduced by the addition of barley straw.

Ouedraogo et al. [63] investigated the physical, thermal and engineering properties of adobe blocks incorporating fonio straw (0.2, 0.4, 0.6, 0.8, 1.0wt% and a maximum length of 10mm). It can be observed that the association of fonio straw with clay matrix increased water absorption and reduced thermal conductivity. However, the inclusion of small quantities of straw improved the engineering properties of the samples and made them less fragile. The compressive (2.90MPa) and flexural (1.30MPa) strength reached its optimum value at 0.4% and 0.2% fibre content respectively. However, the lowest thermal conductivity value (0.35W/mK) was shown by 1% of fibre sample. The capillarity water absorption coefficient was maximum around 1.82g/m^2/$s^{1/2}$ (0.2% fibre) and minimum around 0.139g/m^2/$s^{1/2}$ (1% fibre). The research concluded that 0.2 to 0.4% of fonio straw could contribute to improving the properties of the adobe blocks.

Khedari et al. [64] analysed the influences of coconut coir fibre (10%, 15% and 20% of reference cement volume) addition in the thermal properties of unfired soil blocks. The test results demonstrated that coconut coir addition to the blocks led to a reduction in density (1754.94kg/m^3 to 1344.60kg/m^3), thermal conductivity (1W/mK to 0.6W/mK) and compressive strength (5.79MPa to 1.50MPa). According to the study, optimum coconut coir ratio was 20% as it showed the best thermal performance.

Danso et al. [65] assessed the suitability of sugarcane bagasse (SB), coconut husk (CH) and oil palm fruit (OP) incorporation in two different types of earth to produce unfired building blocks. Various proportions (0.25, 0.5, 0.75 and 1wt%) and lengths of (50mm, 80mm and 38mm) CH, SB and OP were used to strengthen the earth blocks. The test results exhibited that water absorption increased and dry density decreased with increasing fibre content. Dry density varied from 1772kg/m^3 to 1857kg/m^3, 1790kg/m^3 to 1867kg/m^3 and 1802kg/m^3 to 1889kg/m^3 and water absorption ranged from 9.80-15.30%, 10.40-16.50% and 9.40-14.30% for CH, SB and OP reinforced samples respectively. Moreover, the results showed that there was a significant improvement in compressive (3MPa for CH and 2.80MPa for SB) and tensile strength (0.32MPa for CH and 0.30MPa for SB) by incorporating fibre up to 0.5%. The values continued to drop with the addition of fibre from 0.5% to 1%. On the other hand, OP fibre samples reached the highest compressive (3MPa) and tensile value (0.36MPa) at 0.25% of fibre content. Therefore, the study indicated that 0.5% of the fibres would be ideal for enhancing the strength of unfired earth blocks.

Thanushan et al. [66] incorporated 0.2, 0.4 and 0.6% of mass portions of coconut fibre with unfired soil blocks and presented that fibre addition increased water absorption (215.20kg/m^3 to 293.30kg/m^3). On the other hand, there was a progressive decrease in compressive (2.72MPa to 3.44MPa) and flexural strength (0.87MPa to 0.99MPa). Dry density and wet density of all specimens were more similar with a slight increase from 1765kg/m^3 to 1785kg/m^3 and 2025kg/m^3 to 2060kg/m^3 respectively. Besides, the freeze and thaw test revealed that the compressive strength of the samples decreased by 19% after 12 freezing cycles while for the unreinforced sample it was 33%.

Sangma et al. [67] prepared unfired earth blocks by adding coir fibre (5wt% and 20 to 80mm) and studied its effect on the physical and mechanical properties of the samples. The compressive and tensile strength tests were conducted following the Indian Standard, IS 4332 Part 5 and IS 5816 respectively. The study concluded that the unreinforced sample had lower compressive (1.15MPa) and tensile strength (0.14MPa) than the reinforced ones. The peak compressive and tensile strength were measured as respectively 1.67MPa and 0.56MPa which were 1.45 and 4 times higher than the unreinforced block. In the case of fibre length, samples reinforced with 40mm long coconut fibre displayed the best performance.

Purnomo and Arini [68] conducted experimental studies to investigate the influence of humidity on the physical and mechanical properties of unfired bricks made with treated coconut coir. The samples were developed following the Indonesian Standard SK SNI S-04-1989-F [153] and strength tests were conducted as per the ASTM Designation: C 67–03a [154]. It was found that in wet conditions, the sample with 4% treated and 25mm coir fibre showed better mechanical properties than other samples. Average maximum compressive and bending strength were measured as 3.50MPa and 0.70MPa respectively at 90 days. Moreover, there was a variation in water absorption rate in different humid conditions though the tendency to have a higher absorption rate (30-50%) was in more humid conditions.

Table 3

Overview of research on agricultural waste additives for production of unfired earth blocks

Agro-wastes	Ref.	Content (wt%, vol%) and fibre length (mm)	Unit size (mm)	Soil, sand and clay type	Density (kg/m^3)	Max. Compressive Strength (CS), Flexural Strength (FS) (MPa)	Min. Thermal conductivity (W/mK)	Water absorption (wt%)
Straw (Wheat, Barley)	[53]	2.5%	150×150×150	Clay	undefined	CS-5.80	undefined	36.80%
	[71]	0.5, 1.5, 3% 10, 20, 30 mm	ø 50×100 ø 100×200	Acadama, Bentonite clay, Toyoura sand	820-1110	CS-0.55	undefined	undefined
	[54]	25, 33.3 vol% 50-100 mm	250×120×100	Local soil	1650-1820	CS-3.99 FS-0.82	undefined	undefined
	[55]	1, 3%, 40 mm	240×120×60	Cohesive soil	1357.70-1575.60	undefined	0.30	undefined
	[56]	0.64% <10 mm	100×200×400 40×40×160	Clayey/silty sand	undefined	CS-0.46	undefined	undefined
	[88]	1, 2, 3%	160×40×40	Commercial clay sand	undefined	CS-2.90 FS-0.29	undefined	undefined
	[57]	1.5, 1.8, 2.1, 2.5, 3.7%	45×45×12	Soil, sand	1628.70-1766.20	undefined	0.25	undefined
	[58]	1 mass%, 20 mm	160×40×40	Cohesive soil	1400-1470	CS-4.58	undefined	undefined
	[59]	2, 3, 4, 5%, 20 mm	100×100×22	Local Clay	1544.98-1827.58	undefined	0.26	undefined
	[78]	0.3, 0.6, 0.9% 10-40 mm	220×220×70 ø150×300	Clay, sand and gravel	undefined	CS-8.70	undefined	undefined
	[74]	3, 6%	ø50×20 180×70×35	Quarry fines	1100-1537	undefined	0.14	undefined
	[73]	3, 6% 15 mm	ø50×20 180×70×35	Quarry fines	1315-1519	CS-3.80 FS-1.80	undefined	undefined
	[60]	3%	undefined	Clay	undefined	CS-1.86	undefined	undefined
	[62]	3, 6 mass% 10 mm	ø50×50 150×150×50	Quarry fines	1195-1520	CS-3.80	0.15	undefined
	[83]	<2%, 17-18%	ø40×40	Clayey sandy silt	1180-1790	CS-6	undefined	undefined
	[101]	10, 20, 30 vol%	undefined	Clay	1221.43-1554.35	undefined	0.26	undefined
	[61]	5, 10, 15%, 2-3 mm	50×100×200	River dredging sludge	undefined	CS-11.70	undefined	undefined
Lavender straw	[62]	3, 6 mass% 10 mm	ø50×50 150×150×50	Quarry fines	1585-1772	CS-3.90	0.28	undefined
Fonio straw	[63]	0.2, 0.4, 0.6, 0.8, 1.0% 10 mm	160×40×40	Reddish brown clayey local soil	undefined	CS-2.90 FS-1.30	0.35	undefined
Coconut coir	[64]	10, 15, 20 vol%	125×250×100	Lateritic soil, river sand	1344.60-1754.94	CS-5.79	0.65	undefined
	[65]	0.25, 0.5, 0.75, 1%, 50 mm	290×140×100	Local red, brown soil	1772-1857	CS-3	undefined	9.80-15.30%
	[66]	0.2, 0.4, 0.6 mass%	150 ×150×150 400× 100×100	Local soil	Dry: 1765-1785 Wet: 2025-2060	CS-3.44 FS-0.99	undefined	undefined
	[67]	5%, 20, 40, 60, 80 mm	150×150×150	Local soil	1450-1510	CS-1.67	undefined	undefined
	[68]	4% 250 mm	230×110×55 50×50×50	Soil from hill	undefined	CS-3.50 FS-0.70	undefined	30-50%
Banana fibre	[69]	0.35, 0.175% 25, 50 mm	120×120×90 240×120×90	River soil	2050.36	CS-5.92 FS-0.95	undefined	10-20%
	[70]	1-5% 50,60,70,80,90,100 mm	120×120×90 240×120×90	River soil	1947	CS-6.19 FS-1.02	undefined	undefined
Hemp fibre	[71]	0.5, 1, 2, 3, 4% 10, 30 mm	ø 50×100 ø 100×200	Acadama, Bentonite clay, Toyoura sand	820-1110	undefined	undefined	undefined
	[72]	1%, 3%	160×40×40	Cohesive soil	1060-1700	CS-3.75	undefined	undefined
	[74]	3, 6%	ø50×20 180×70×35	Quarry fines	1271-1591	undefined	0.20	undefined
	[73]	3, 6% 15 mm	ø50×20 180×70×35	Quarry fines	1221-1603	CS-2.40 FS-1.34	undefined	undefined
	[75]	1.5%, 1-5 mm	200×100×50	Illitic soil	2244-2316	undefined	1.27	undefined
	[76]	50, 66, 75 vol%	150×150×30 40×40×160	Earth clay	966-1060	CS-0.94 FS-0.47	0.09	undefined
Rice husk	[77]	5, 10, 15%	230×110×55 600×150×150	Clay soil	undefined	CS-20.70 FS-0.05	undefined	0.80-9.60%
	[78]	0.3, 0.6, 0.9%	220×220×70 ø150×300	Clay, sand, gravel	undefined	CS-4.14	undefined	undefined

	[79]	10, 20, 30, 40, 50%	220×105×60	Natural sand	1930-2075	CS-30.30 FS-6.17	0.68	7.50-10.40%
	[80]	10-40%	140×140×95	Clayey soil	undefined	CS-6.60	undefined	undefined
Wood aggregate/ Wood fibre	[81]	undefined	222.8×105.6×66.9	Conventional Clay	1597	CS-10.50	undefined	undefined
	[78]	0.3, 0.6, 0.9% 10 mm	220×220×70 ø150×300	Clay, sand, gravel	undefined	CS-6.91	undefined	undefined
	[82]	1.5, 3%	225×105×65 ø 60×85	Clayey soil	1600	Dry CS-8.30 Wet CS-1.49	undefined	11-16%
	[83]	<2%, 17-18%, 20 mm	ø 40×40	Clayey sandy silt	1180-1790	CS-6	undefined	undefined
Sawdust	[84]	2.5, 5, 10%	100×75×40	Raw brick clay	undefined	CS-5.10	undefined	undefined
	[85]	4, 8, 12 mass%	285×130×115s	Laterite	undefined	undefined	undefined	2-6%
Sugarcane bagasse	[86]	2, 4, 8%	340×340×110	Sandy earth	undefined	CS-2.89	undefined	11.57-13.79%
	[65]	0.25, 0.5, 0.75, 1%, 80 mm	290×140×100	Local red, brown soil	1790-1867	CS-2.80	undefined	10.40-16.50%
	[87]	5, 10, 15, 20%	undefined	Podzolic soil	1800-1825	CS- 0.50	undefined	10-11.30%
Corn cob	[73]	3, 6% 15 mm	ø50×20 180×70×35	Quarry fines	1754-1878	CS-3.20	undefined	undefined
	[74]	3, 6%	ø50×20 180×70×35	Quarry fines	1565-1671	undefined	0.25	undefined
Corn plant fibre	[88]	1, 2, 3%	160×40×40	Commercial clay Sand	undefined	CS-3.25 FS-0.39	undefined	undefined
Corn silk fibre	[89]	0.25, 0.5, 1%, 10 mm	ø50×100	Silty sand	undefined	CS-9	undefined	undefined
Corn husk ash	[90]	10, 20%	undefined	Local rammed earth	942.50-959.50	undefined	0.48	undefined
Cassava peel	[91]	2.5, 5%	320×80×150	Raw clay from local brick plant	undefined	CS-2.60 FS-0.58	undefined	26.38-29.36%
Cassava powder	[92]	1.5, 2.5, 4, 5 ,7, 10, 15, 20%	undefined	Bautzen clay	1635.31-1781.25	CS-7.36 FS-1.71	undefined	undefined
Olive waste fibre	[101]	10, 20, 30 vol%	undefined	Clay	1398.30-1642.59	undefined	0.40	undefined
Grounded olive stone	[88]	5, 10, 15%	160×40×40	Commercial clay sand	undefined	CS-1.61 FS-0.16	undefined	undefined
Pineapple leaf fibre	[94]	0.25, 0.5, 0.75%, 10 mm	100×50×30	Clay soil	1250-1430	CS-18	undefined	1.10-1.25%
Flax fibre	[72]	1, 3%	160×40×40	Cohesive soil	1080-1700	CS-4.50	undefined	undefined
Wheat hay fibre	[95]	0.5, 1, 1.5% 15-25 mm	test- ø25.4×63.5 ø25×50	Clayey soil	1550-1730	CS-0.50	undefined	undefined
Sisal fibre	[92]	0.25, 0.5, 0.75, 1.0, 1.25% 3-10 mm	160×40×40	Bautzen clay	1738-1895	CS-9.14 FS-1.63	undefined	undefined
	[93]	0.5, 1.0, 2.0%, 10 mm	200×50×15	Ceramic company soil	1700-1740	FS-5.50	undefined	19-20%
Fescue	[88]	1, 2, 3%	160×40×40	Commercial clay sand	undefined	CS-2.88 FS-0.60	undefined	undefined
Kenaf or Hibiscus cannabinus fibre	[96]	0.2, 0.4, 0.8% 30, 60 mm	295×140×100	Lateritic soil	undefined	CS-2.85 FS-1.15	1.30	undefined
	[97]	1.2% 10, 20, 30 mm	40×40×160	Local soil	undefined	CS-6.40 FS-2.75	1	undefined
Henequen fibre	[98]	0.25, 0.5, 0.75, 1.0%	ø50×100	Brick manufacturer clay	1884-1906	CS-5.22	undefined	undefined
Jute	[71]	0.5, 1, 2, 3, 4% 5, 10, 20, 30 mm	ø50×100 ø100×200	Acadama, Bentonite clay, Toyoura sand	820-1110	CS-1.30	undefined	undefined
Date palm fibre	[99], [100]	0.05, 0.10, 0.15, 0.2% 35, 120 mm	100×100×200	Local soil, crushed sand	1892-1930	CS-12.50	0.76	9.50-11.30%
	[101]	10, 20, 30 vol%	undefined	Clay	1218.74-1572.19	undefined	0.28	undefined
Palm bark fibre	[78]	0.3, 0.6, 0.9%	220×220×70 ø150×300	Clay, sand, gravel	undefined	CS-16.53	undefined	undefined
Oil palm fruit fibre	[65]	0.25, 0.5, 0.75, 1%, 38 mm	290×140×100	Local red and brown soil	1802-1889	CS-3	undefined	9.40-14.30%
Oil palm fruit bunch	[94]	0.25, 0.5, 0.75 %, 10 mm	100×50×30	Clay soil	1300-1500	CS-19.50	undefined	1.10-2%

Eucalyptus pulp microfibre	[93]	0.5, 1.0, 2.0% 0.7 mm	200×50×15	Ceramic company soil	1680-1700	FS-4.50	undefined	20-21.25%
Dawul Kurudu	[87]	5, 10, 15, 20%	undefined	Podzolic soil	1800-1850	CS-0.50	undefined	9.50-13.30%
Pines gum	[87]	5, 10, 15, 20%	undefined	Podzolic soil	1925-2052	CS-2.65	undefined	9.30-15%
Bael resin	[87]	5, 10, 15, 20%	undefined	Podzolic soil	undefined	CS-0.13	undefined	undefined
Jack Resin	[87]	5, 10, 15, 20%	undefined	Podzolic soil	undefined	CS-0.24	undefined	undefined
Agarwood	[87]	5, 10, 15, 20%	undefined	Podzolic soil	undefined	CS-0.20	undefined	undefined
Wood apple	[87]	5, 10, 15, 20%	undefined	Podzolic soil	undefined	CS-0.25	undefined	undefined
Pinus roxburghii fibre (PR), Grewia optiva (GO)fibre	[103], [104], [29]	PR-0.5, 1, 1.5, 2%, 30 mm GO-0.5, 1, 2%, 30 mm	ø38×76 190×90×90	Local sand, clay	PR: 1700-1950 GO: 1650-1890	PR:CS-2.25 GO:CS-3	undefined	PR: 2.33-3.62% GO: 2.07-2.67%
Grass	[84]	2.5, 5, 10%	100×75×40	Raw brick clay	undefined	CS-5.15	undefined	undefined
Seaweed fibre	[105]	10%, 10 mm	100×100×100	Quaternary sediment	1720-1810	CS-4.44	undefined	undefined
	[106]	0.1%	160×40×40	Silt loam	1690-2250	CS-1.64 FS-0.95	undefined	undefined
Bio-briquette	[107]	(5,15,25,35,45,55%)	230×100×85	Sand	1170-1470	CS-4.19	0.35	13-25%
Processed waste tea	[108]	2.5, 5 mass%	40×70×100	Clay	undefined	CS-7.60	undefined	undefined
Tobacco residue	[84]	2.5, 5, 10%	100×75×40	Raw brick clay	undefined	CS-4.75	undefined	undefined
Eggshell	[109]	10, 20, 30, 40%	200×100×75	Laterite soil	2001-2044	CS-3.05	undefined	undefined
Eggshell and sawdust ash	[102]	2, 4, 8, 16%	291×138×115	Laterite soil	1489-1749	CS-1.25	undefined	undefined
Pig hair	[110]	0.5, 2% 7, 15, 30 mm	310×105×70	Clayey soil	undefined	CS-1.92 FS-0.49	undefined	undefined
Sheep wool	[111]	0.25, 0.5% 10 mm	160×40×40 40×40×40	Soil from brick manufacturer	1790-1800	CS-4.44 FS-1.45	undefined	undefined
	[60]	3%	undefined	Local clay	undefined	CS- 4.32	undefined	undefined
	[112]	0.25, 0.5, 1% 30-50 mm	160×40×40 100×50×50	Local red clay Illite	undefined	CS-3.04 FS-1.83	0.19	undefined

Mostafa and Uddin [69] [70] studied the mechanical properties of compressed earth blocks by mixing various proportions (1-5wt%) and lengths (25-100mm) of banana fibre. The blocks reinforced with fibre lengths of 60mm and 70mm had the highest compressive (6.58MPa) and bending strength (1.02MPa) than other samples. The compressive strength improved about 68% (70mm) and 71% (60mm) while flexural strength increased by 82% (70mm) and 77% (60mm) over the sample without fibre [70]. Moreover, the water absorption rate of the banana fibre reinforced compressed earth blocks was recorded as an average of 10.60% [69].

Islam and Iwashita [71] utilised the waste jute fibre (0.5, 1, 2, 3, 4wt% and 5, 10, 20, 30mm) and straw fibre (0.5, 1.5, 3wt% and 10, 20 and 30mm) to produce low-cost earthquake resistant adobe blocks. The results presented that a higher amount of fibre in the samples caused the dry density to decrease slightly from 1110kg/m^3 to 820kg/m^3. The results also showed that ductility significantly improved with the addition of 1.5% of straw fibre, although it caused a drop in compressive strength. In the case of samples containing 20mm straw fibre, the toughness seemed to show an increasing rate and for 30mm straw samples, toughness displayed a slightly declining rate after addition of 1.5% fibre. Therefore, to improve the ductility of the adobe, 1.5% straw and 20mm long fibre were recommended as optimum value. The study also found that specimens made of crushed straw had greater compressive strength than specimens that contained whole straw. On the other hand, compressive strength decreased and ductility improved by increasing jute fibre quantity in the samples. The sample with jute fibre reached the highest toughness with 2% and 20mm long fibre. The optimum compressive strength for straw and jute fibre sample was noted as 0.55MPa and 1.30MPa respectively.

Zak et al. [72] investigated the mechanical properties of unfired earth bricks incorporating flax and hemp fibre (1 and 3 mass%). The test findings presented that flax fibre addition did not considerably change the compressive strength of the samples compared to the control sample but the brittle breaking behaviour of the sample decreased. However, in contrast with the control sample hemp fibre inclusion induced a slight reduction in compressive strength of the unfired bricks. The highest compressive strength was attained as 3.75MPa and 4.50MPa for hemp and flax fibre sample respectively at 3% of fibre addition. Samples density was between 1060kg/m^3 and 1700kg/m^3 for hemp fibre and 1080kg/m^3 and 1700kg/m^3 for flax fibre.

Laborel-Préneron, A. et al. [73, 74] utilised 3 and 6wt% of hemp shiv, barley straw and corn cob to produce unfired earth blocks and investigated the mechanical and hygrothermal properties. The average length of 15mm straw fibre was used for bending strength testing. The test results showed that bulk density decreased from 1878kg/m^3-1754kg/m^3, 1603kg/m^3-1221kg/m^3, 1519kg/m^3-1315kg/m^3 and thermal conductivity reduced from 0.26W/mK-0.35W/mK, 0.20W/mK-0.30W/mK, 0.14W/mK-0.28W/mK with the addition of corn cob, hemp shiv and straw fibre respectively [74]. Moreover, compressive and flexural strength also reduced with a higher amount of waste addition except for the straw fibre blended samples where maximum compressive strength (3.80MPa) was found at 6% of fibre addition. Optimum compressive strength of hemp and corn cob samples were recorded as 2.40MPa and 3.20MPa respectively for 3% of fibre content. Furthermore, peak flexural strength (1.80MPa) was achieved by straw mixed sample followed by hemp (1.34MPa) [73]. Based on the test results, it can be concluded that the straw mixed sample displayed the best thermal performance, which reduced the thermal conductivity by 75% compared to the waste-free sample.

Bruno et al. [75] examined the thermal performance of unfired earth brick walls utilising hemp fibre (1.5wt% and 1-5mm). The hemp brick samples were developed in the laboratory by hyper-compacting to 100MPa resulting in a high dry density and bulk density value of 2244kg/m^3 and 2316kg/m^3 respectively. The thermal conductivity value of the individual sample was measured as 1.28W/mK whereas the result from the tested hemp brick wall presented the conductivity value of 1.27W/mK.

Fernea et al. [76] conducted experimental research on the properties of clay building material using hemp and clay binder in a ratio of 1: 1, 2: 1 and 3: 1. From the tests, it was observed that the sample with 1:2 ratio reached the highest density above 1000kg/m^3. At the same time, this composition had an optimum flexural strength value of 0.47MPa. Conversely, a 1:3 ratio sample showed the lowest density close to 966.73kg/m^3 and the highest compressive strength of 0.94MPa. Furthermore, thermal conductivity increased from 0.09-0.18W/mK when the density increased.

Muntohar [77] studied the application of rice husk ash and lime (5, 10, 15wt%) for the manufacture of compressed earth blocks. The results revealed that the ratio of 1:1 rice husk and lime showed the best performance for compressive (20.70MPa) and flexural strength (0.05MPa). As the lime and rice husk ratio increased the water absorption rate decreased significantly from 9.60% to 0.80%. However, water absorption properties of all lime and rick husk blended specimens met the Indonesian Standard SNI 15-2094-2000 [18] for masonry brick.

Oskouei et al. [78] utilised straw (S), rice husk (RH), palm fibre (PF) and wood chips carpentry (WC) in the production of unfired mud bricks with the amount of 0.3, 0.6 and 0.9wt%. The tests demonstrated that the compressive strength of additive samples ranged from 2.67MPa to 16.53MPa and the tensile strength improved from 57% to 281%. The compressive (16.53MPa) and tensile strength (0.16MPa) of palm fibre specimens showed the best performance whereas RH incorporated specimens displayed the lowest compressive (4.14MPa) and tensile strength (0.70MPa). S and WC admixed samples reached a maximum compressive strength of 8.71MPa and 6.91MPa and maximum tensile strength of 0.10MPa and 0.08MPa respectively.

Huynh et al. [79] investigated the effects of rice husk ash (10-50wt%) on the various properties of unfired bricks. A solution of Sodium hydroxide (NaOH) was used as an activator when producing the samples. The study concluded that the strength of the samples improved with curing period and compressive and flexural strength of all samples at 28 days ranged from 16.20 MPa to 30.30MPa and 4.04MPa to 6.17MPa respectively. The highest strength was obtained at 10% of rice husk addition and the strength steadily declined at a higher percentage of ash content. The maximum compressive and flexural strength was respectively 3.5% and 2.7% higher than the values of the control brick sample. Moreover, the rate of water absorption for all specimens was between 7.50% and 10.40%, substantially lower than the 12% maximum limit for the M15 and M20 brick grades. Besides, the bulk density of all samples varied from 1930kg/m^3 to 2090 kg/m^3. Furthermore, oven-dried specimens displayed remarkably lower thermal conductivity (0.68W/mK-1.25W/mK) values than the sun-dried specimens (1.24W/mK-1.68W/mK) in the range of 34 to 82%. The discrepancy was mainly due to the sample temperature variation because generally thermal conductivity decreases with the increase in sample temperature.

P. Nshimiyimana et al. [80] investigated the compressive strength of compressed earth blocks utilising calcium carbide residue (CCR) and rice husk ash (RHA). At the first phase of experiments, different fractions of CCR (0-15wt%) were used to determine the effect of CCR on the samples and its optimum compressive strength. The results showed that due to the pozzolanic interaction between earth particles and the CCR the compressive strength nearly doubled (3.40MPa) for 8%CCR content in comparison to the control sample (1.90MPa). However, more than 8% of CCR addition decreased compressive strength. Therefore, in the second phase, the compressive strength of the samples with more than 8 CCR was further enhanced by the partial replacement of CCR by RHA (10 to 40%). It was observed that in the case of 10% and 15% CCR the optimum RHA replacement was 20% and 30% respectively. The compressive strength was found 5.30MPa for 20%RHA and 6.60MPa for 30%RHA substitution which was respectively twice and three times higher than the only 10% (2.50MPa) and 15%CCR (2.20MPa) sample.

Heath et al. [81], Masuka et al. [82] and Piani, et al. [83] investigated the incorporation of wood fibre/aggregate in the development of unfired earth blocks. Masuka et al. [82] initially prepared four samples of the various ratio of lime (L), coal fly ash (F) and wood aggregate (W) (L: 4-8%, F: 10-16%, W: 1.5-3%). Among all the samples, L-10%, F-10% and W1.5% sample showed a significantly higher compressive strength value of 8.30MPa. Later the study used cement (4% and 10%)

with this mixture to further investigate its impact on the physical and mechanical properties of the samples. Moreover, the author evaluated the water-resistance of the samples using a qualitative scoring system by observing their damage evidence after a shorter immersion period of 2h and 4h. The results revealed that L-10%, F-10% and W-1.5% sample had maximum water resistance by exhibiting negligible and moderate damage. The study concluded that the sample prepared with 10% lime, 10 % fly ash and 4% cement was the most cost-effective composition (based on the cost of raw materials lime and cement) which also fulfilled the engineering specifications as stated in the British standards BS EN772 [156]. Heath et al. [81] found that adding wood fibre to unfired brick resulted in a dry density reduction (1597kg/m^3) of up to 12% than the control sample (1793kg/m^3) and compressive strength was noted as 10.50MPa. Piani et al. [83] utilised wood and straw fibre together (<2%, 17-18% and a maximum length of 20mm) in adobe blocks to examine the compressive strength. The results showed that the density of the samples varied between 1180kg/m^3 to 1790kg/m^3 and maximum compressive strength was attained as 6MPa (<2% fibre).

Demir [84] conducted experiments to develop unfired clay bricks using grass, sawdust and tobacco residues (2.5, 5 and 10wt%). Based on the test results it can be concluded that the compressive strength of the unfired brick samples improved from 3.35MPa to 5.10MPa, 3.10MPa to 4.75MPa and 3.40MPa to 5.15MPa for sawdust, tobacco residue and grass addition respectively.

Fadele and Ata [85] investigated the water absorption properties of compressed earth blocks incorporating sawdust lignin additives and cement. Samples were prepared separately using 4, 8 and 12% by mass of cement and sawdust additives. In contrast to cement-stabilised samples, the sawdust additives mixed samples showed an improvement in the water absorption properties. The water absorption rate was measured high for cement-stabilised samples ranging from 6% to 15%, while it varied between 2% and 6% for sawdust additives.

Lima et al. [86] incorporated sugarcane bagasse ash to the compressed earth blocks (2, 4 and 8wt%) aiming at the application in non-structural masonry elements. The findings presented that, blocks blended with 8% sugarcane bagasse ash and 12% Portland cement had higher compressive (2.89MPa) and tensile strength (0.39MPa) at 28days than the minimum value mentioned by the Brazilian standards (2MPa). Therefore, in the manufacture of non-structural masonry components, this mixer proportion was proposed.

Udawattha et al. [87] evaluated the performance of natural polymer addition (5, 10, 15 and 20wt%) to earth blocks as a stabiliser. Seven natural polymers such as pines resin (PR), dawul kurudu (DK), bael resin (BS), sugarcane bagasse (SB), agarwood resin (AWR), wood apple resin (WAR) and jack resin (JR) were collected from vernacular polymer technologies of Sri Lanka. According to the results DK (0.85-1.17MPa), PR (0.98-1.70MPa) and SB (0.54-0.87MPa) presented the proper compressive strength while BR, WAR, AWR and JR functioned against the block strength. The optimum compressive strength was found as 0.13MPa (20%BR), 0.25MPa (10%WAR), 0.20MPa (5%AWR) and 0.24MPa (15%JR). Moreover, the results showed a decline in sample densities from 1925kg/m^3-2052kg/m^3, 1800kg/m^3-1850kg/m^3, 1800kg/m^3-1825kg/m^3 and a rise in water absorption rates from 9.30-15%, 9.50-13.30% and 10-11.30% with the increasing amount of PR, DK and SB respectively. From the tensile splitting test, it was observed that for PR (2.58MPa for 15%) and DK (0.25MPa for 15%) the tensile strength increased with an increased percentage of polymer whereas for SB maximum value was recorded as 1.75MPa at 5% polymer content.

Serrano et al. [88] studied the feasibility of different by-products wastes as additives in the manufacture of adobe blocks. The additives were categorised into two groups namely fibre (corn plant, fescue and straw of 1–3wt%) and pellet (olive stones of 5–15wt%). The mechanical test results indicated that in the case of fibre admixed samples the best flexural strength behaviour was achieved by fescue admixed samples (0.33MPa-0.60MPa) followed by corn plant (0.25MPa-0.39MPa) and straw (0.15MPa-0.29MPa) while the highest compressive strength was obtained by corn plant (1.98MPa-3.25MPa) followed by straw (2.04MPa–2.90MPa) and fescue (1.93MPa–2.88MPa). On the other hand, pellet adobe samples exhibited compressive and flexural strength varied from 0.98MPa to 1.61MPa and 0.07MPa to 0.16MPa respectively.

Tran et al. [89] experimented on mechanical properties of soil blocks incorporating waste corn silk fibre (0.25, 0.5, and 1wt% and 10mm). The results revealed that the compressive (9MPa) and tensile strength (1.30MPa) reached a peak at 0.5% and 0.25%of fibre content respectively. Further increasing fibre content from this range resulted in a decline or slight increase in strength. Also, the dry unit weight decreased with the addition of fibre and ranged from 13.10kN/m^3 to 12.20kN/m^3. Therefore, the optimum fibre content was proposed as 0.25%-0.5% as it showed around 177% and 88% of improvement in compressive and tensile strength respectively compared to the fibre-free sample.

Batagarawa et al. [90] investigated the potential use of corn husk ash (10 and 20wt%) as a stabiliser for rammed earth to improve the thermophysical properties. The test results exhibited a considerable reduction in thermal conductivity from 0.63W/mK to 0.48W/mK and a slight increase in density from 942.50kg/m^3 to 959.50kg/m^3 with an increasing percentage of corn husk ash. Hence, the study recommended 20% of corn husk ash as the optimum percentage to improve the thermal properties of rammed earth blocks.

Villamizar et al. [91] studied the effects on the strength of compressed earth blocks by incorporating coal-ash (5, 7.5 and 10wt%) and cassava peels (2.5 and 5wt%). The test results showed that the stabilised earth blocks exhibited the highest compressive (3.37MPa) and flexural strength (0.75MPa) for 5% coal ash addition while for 5%

cassava peal incorporated sample the value was 2.21MPa and 0.50MPa respectively. At 2.5% cassava peel and 7.5% coal ash combination, the sample presented compressive strength of 2.60MPa and flexural strength of 0.58MPa. Besides 10% of coal ash sample showed the lowest compressive (1.09MPa) and flexural strength (0.40MPa). Water absorption, however, appeared to decline as cassava peels percentage increased. The average water absorption rate was measured as 30.65% (10% coal ash), 28.64% (5% coal ash), 27.77% (2.5% cassava peel and 7.5% coal ash) and 27.01% (5% cassava peel). The study suggested that the optimum percentage to produce CEB should be 2.5% cassava peel and 7.5% coal ash.

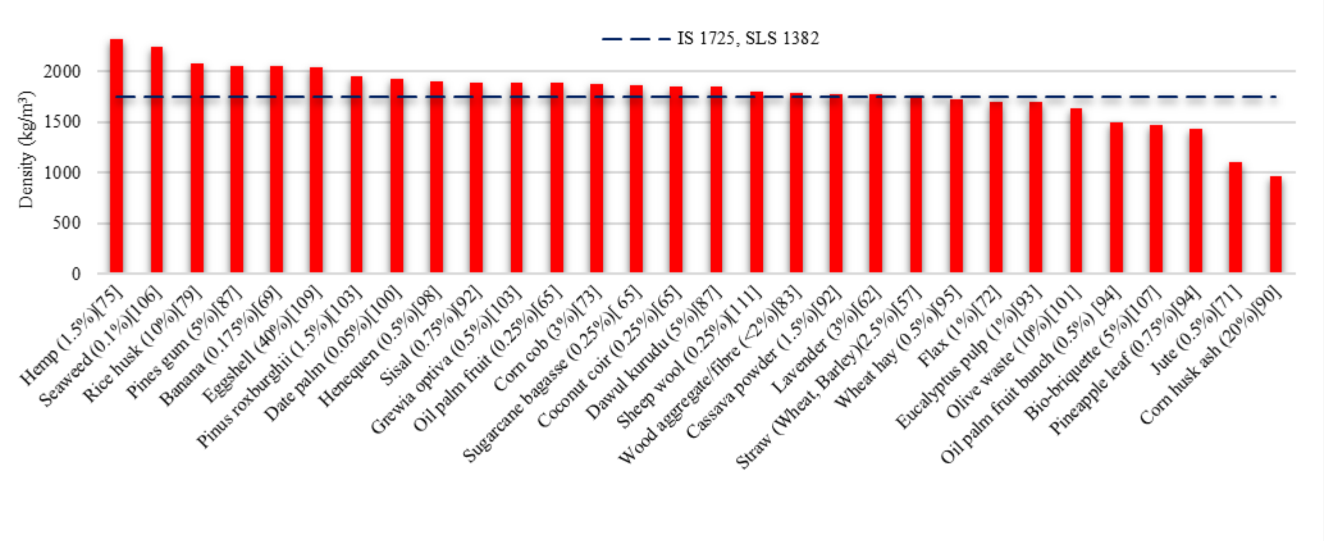


Fig. 2. Density of agro waste-incorporated samples

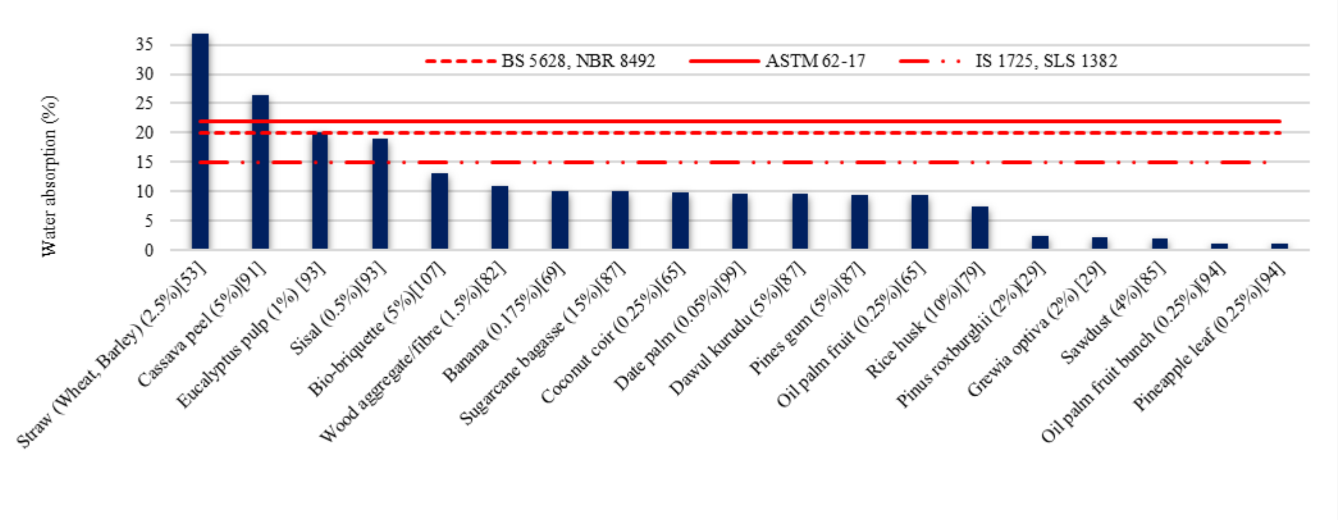


Fig. 3. Water absorption of agro waste-incorporated samples

Namango [92] investigated the different properties of sisal fibre (0.25, 0.5, 0.75, 1.0, 1.25wt% and 10mm) and cassava powder (1.5, 2.5, 4, 5 ,7, 10, 15, 20 wt%) stabilised compressed earth blocks. The test results revealed that for sisal fibre-reinforced blocks optimum flexural (1.63MPa) and compressive strength (9.14MPa) were achieved for 0.75% of sisal which corresponded to a 64.30% and 90.50% improvement in strength compared to the fibre-free block. The density of the sisal reinforced blocks increased to 1895kg/m^3 for 0.75% fibre and subsequently dropped at 1.25% of fibre addition (1738kg/m^3). On the other hand, the samples with cassava powder had compressive strength between 7.36MPa (1.5% cassava) and 4.29 MPa (7% cassava). The trend of flexural strength values was similar to that of the compressive strength and ranged between 0.94MPa and 1.71MPa. The optimum value of compressive and flexural strength of cassava powder blended samples provided a 53.50% and 72.50% strength increase respectively compared to the non-reinforced block.

Ojo et al. [93] investigated the properties of extruded alkali-activated earth building blocks incorporated with sisal (0.5-2vol% and 10mm) and eucalyptus pulp (wood kraft pulp) microfibre (0.5-2vol% and 0.7mm). Sisal fibre admixed samples showed higher improvement in tensile strength (74%) than eucalyptus pulp blended samples (29%) compared to the control sample. Moreover, wastes addition increased density from 1700kg/m^3 to 1740kg/m^3 (sisal), 1680kg/m^3 to 1700kg/m^3 (eucalyptus pulp) and water absorption ranged from 19% to 20% (sisal), 20% to 21.25% (eucalyptus pulp). Sisal fibre reinforced sample had the highest flexural strength (5.50MPa) at 0.5% of fibre content and eucalyptus pulp specimens reached its peak strength (4.5 MPa) at 1% of fibre content.

Chan, [94] studied the performance of clay bricks using oil palm fruit bunch and pineapple leaf fibre (0.25, 0.5, 0.75wt% and 10mm). The results presented that the sample density ranged between 1300-1500kg/m^3 (oil palm), 1250-1430kg/m^3 (pineapple leaf) and the water absorption rate varied between 1.10% to 2% (oil palm), 1.10% to 1.25% (pineapple leaf). The maximum compressive strength was similar and achieved at 0.75% of fibre content for both samples being 19.50MPa (oil palm fibre) and 18MPa (pineapple leaf fibre) which satisfied the minimum strength requirement for conventional brick.

Mohamed [95] studied the properties of clay blocks utilising hay fibre (0.5, 1, 1.5wt% and 15-25mm). The test results indicated that the water absorption, swelling potential, the maximum dry density and shrinkage limit of the samples decreased (up to 1% hay fibre) while the shear strength as well as the tensile strength, increased with the addition of hay fibre. The maximum tensile strength was recorded as 0.07kg/cm^2 (1% hay fibre) which was a 30% increase in strength compared to the fibre-free sample. However, the maximum compressive strength was found as 0.45MPa at 0.5% of fibre.

Millogo et al. [96] examined the prospect of utilising kenaf fibre in the production of pressed adobe blocks (PAB) and Laibi et al. [97] conducted experiments to investigate the influences of different kenaf fibre length on the thermal and engineering properties of compressed earth blocks (CEB). The adobe sample blocks were reinforced with 0.2 to 0.8 wt.% and two different lengths (30, 60mm) of fibres [96] while CEBs were produced using 1.2wt% and three various lengths (10, 20 and 30mm) of fibres [97]. The results showed that for short (30mm) and long (60mm) fibres, compression strength improved respectively by 16% and 8%. Moreover, the addition of 0.2 to 0.6% of 30mm fibres reduced the pore size of the samples. Furthermore, the amount of 0.8wt% of 60mm fibres negatively influenced the compressive strength of the adobe samples [96]. Another study [97] showed maximum compressive and flexural strength as 6.40MPa (20mm) and 2.75MPa (30mm) respectively. The results also indicated that the thermal conductivity reduced when both the fibre length and percentage were raised. Thermal conductivity value was measured as 1.30W/mK (0.8% and 60mm) [96] and 1W/mK (1.2% and 20mm) [97]. Hence, the studies recommended 30mm fibre length of kenaf as suitable for stabilisation of PAB and CEB.

Murillo et al. [98] evaluated the effects of addition of henequen fibre (0.25, 0.5, 0.75 and 1.0 mass%) on engineering properties of unfired earth blocks. The findings indicated that 1% of fibre addition led to a decrease in compressive strength up to 33% and linear shrinkage up to 36% in comparison with the fibre-free sample. The compressive strength and the linear shrinkage of the samples were found respectively between 4.21MPa to 5.22MPa and 4.1% to 3%. However, the lowest density was measured as 1884kg/m^3 (0.75% fibre) and the highest was reported as 1906kg/m^3 (0.5% fibre).

Taallah et al. [99], Taallah and Guettala [100] studied the utilisation of date palm fibre on compressed earth blocks production. Various percentages of cement (5, 6.5 and 8%) and fibre (0.05, 0.10, 0.15, 0.2wt% and 20mm, 35mm) were incorporated to conduct the tests. The results of the experiments exhibited that the better outcome of the dry compressive (12.50MPa) and tensile strength (1.50MPa) were achieved by samples with 0.05% of fibre and 8% cement content. The lowest water absorption (9.50%) and swelling value (0.18%) was also attained with this percentage. However, higher fibre content decreased the thermal conductively (0.80-0.76W/mK) and bulk density (1910-1892kg/m^3) of the specimens.

Lamrani et al. [101] assessed the thermal efficiency of unfired clay masonry bricks combining 10, 20, 30vol% of olive waste fibre [OW], date palm fibre [DPF] and straw [S]. It reported that the addition of S and DPF improved the thermal performance of the samples while OW began to degrade the performance. The density of the samples ranged between 1398.30kg/m^3-1642.59kg/m^3 (OW), 1218.74kg/m^3-1572.19kg/m^3 (DPF) and 1221.43kg/m^3-1554.35kg/m^3 (S). In the case of thermal conductivity, straw fibre reinforced samples performed the best (0.26W/mK), followed by DPF (0.28W/mK) and OW (0.40W/mK) samples.

Ayodele et al [102] utilised sawdust ash and eggshell ash (0, 2, 4, 8 and 16wt%) in the production of lateralised unfired bricks. From the experiment results, it was noticed that the sample with 4% ash had the lowest density (1749 kg/m^3) while 16% ash blended sample had the maximum density (1489kg/m^3). On the other hand, there was a downward trend in the values of compressive strength of the samples as the amount of ash percentage increased and maximum compressive strength reached around 1.25MPa which was achieved at 2% and 4% ash content.

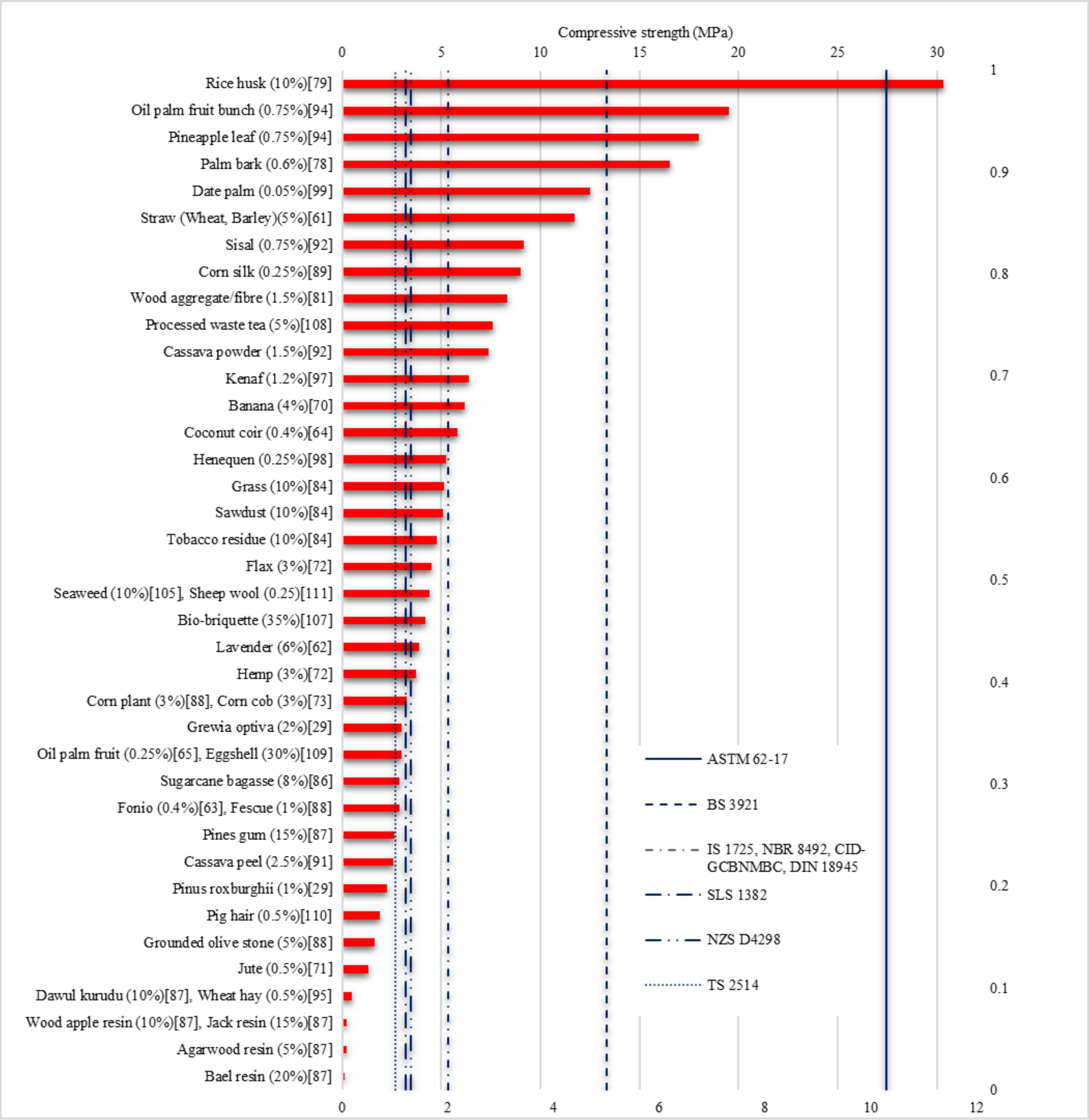


Fig. 4. Compressive strength of agro waste-incorporated samples

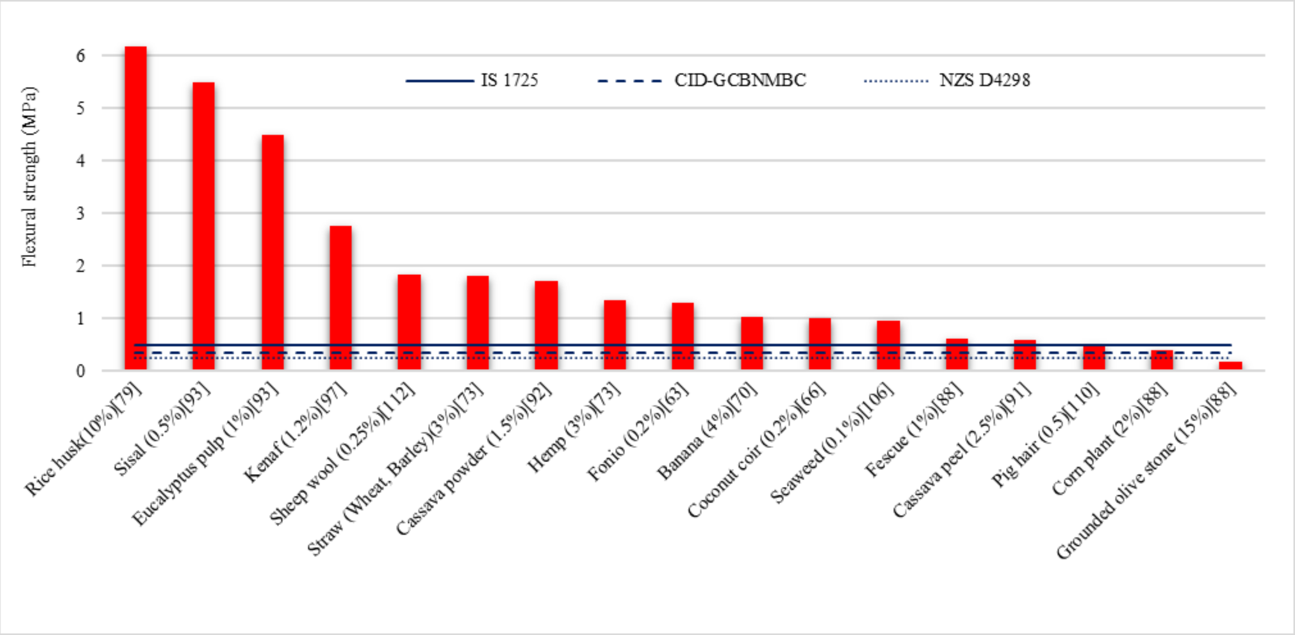


Fig. 5. Flexural strength of agro waste-incorporated samples

Sharma et al. [29, 103, 104] investigated the compressive strength and durability of rural adobe blocks incorporating pinus roxburghii fibre (PR), grewia optiva fibre (GO) in the Indian state of Himachal Pradesh. Different proportions of fibres (0.5, 1, 1.5, 2wt% and 30mm) were used in the sample along with 2.5% cement. The results revealed that GO fibre-mixed samples showed better improvement in durability than PR fibre-mixed samples. GO and PR samples reported 72% and 56% decreased in water absorption respectively, resulting in a proportionate durability increase compared to the control sample. Furthermore, the compressive strength of the sample blocks increased around 94% to 200% for GO and 73% to 137% for PR fibre. Compressive strength value reached its peak at 2.25MPa (1%fibre) and 3MPa (2% fibre) for PR and GO respectively. The water absorption test presented that it ranged from 2.33% to 3.62% for PR and 2.07% to 2.67% for GO samples [29]. The study recommended using 2% GO and 1% PR fibres for earth blocks construction in seismic prone areas.

Achenza and Fenu, [105] and Dove [106] incorporated seaweed fibre additives for unfired clay bricks production. Achenza and Fenu [105] used 10mm long and 10wt% seaweed fibre and natural polymer (beetroots and tomato residues) with soil. Dove [106] utilised 0.1% Scottish seaweeds (Laminaria hyperborean) with silt loam to prepare the blocks. According to the test results density of the samples varied from 1690kg/m^3 to 2250kgm/m^3 [106] and 1720kg/m^3 to 1810kg/m^3 [105]. It was observed that the compressive strength improved (about 75%) with natural polymers addition in the sample and the highest compressive strength was observed as 4.40MPa. The test results also presented a water absorption value of around 2.10gm/cm^2 [105]. On the other hand, Dove [106] presented maximum compressive and flexural strength of 1.64MPa and 0.95MPa respectively.

Sakhare and Ralegaonkar [107] conducted research using bio-briquette ash (BBA) (5–55wt%) for the development of unfired masonry bricks. The findings showed that the density of the samples tended to slowly decrease from 1470kg/m^3 to 1170kg/m^3 as levels of the waste quantity increased. However, the increase in BBA content increased water absorption from 13% to 25%. The compressive strength reached its highest value (4.19MPa) at 35% BBA addition and gradually declined with the increase of BBA. Furthermore, the tests of thermal conductivity showed that the value decreased as BBA increased and the best thermal conductivity value was found (0.35W/mK) for a sample of 45% BBA.

Demir [108] examined the durability and mechanical properties of unfired clay bricks utilising processed waste tea (2.5 and 5% by mass). The results showed that the unit weight of unfired specimens reduced with an increasing waste ratio in mixtures and ranged from 1.52 to 1.70 kg/dm^3. The compressive strength of unfired samples was above 5MPa which corresponded to the Turkish standard [152]. However, the optimum compressive strength was measured as 7.60MPa with 5% waste content. Based on the test results, it can be concluded that a maximum of 5% processed tea waste can be used as an additive in unfired brick manufacturing.

Adogla et al. [109] utilised eggshell powder (10, 20, 30 and 40wt%) to examine their potentiality to substitute soil partially in the production of lateralised unfired compressed bricks. From the density tests, it was noticed that the dry density of the samples increased gradually (2101kg/m^3 to 2044kg/m^3) as the amount of waste increased. On the other hand, compressive strength test findings showed that there was an upward trend in the values of compressive strength of the samples as the amount of ash percentage increased to maximum 30% and after that compressive strength showed a decrease in value. The optimum compressive value was found at 3.05MPa after 6 days of curing.

Araya-Letelier et al. [110] measured the efficacy of using pig hair as reinforcement in adobe (0.5, 2wt% and 7, 15, 30mm). The test results presented a reduction in strength with the incorporation of a higher amount (2%) and long length (15mm and 30mm) of pig hair. After 28 days of curing the average flexural and compressive strength values were found between 0.34MPa to 0.49MPa and 1.20MPa to 2.02MPa respectively. Moreover, incorporation of larger quantities (2%) and higher length (30mm) of wastes minimised the drying shrinkage of the adobe samples. The research recommended 0.5% and 7mm length of pig hair for adobe manufacturing since it exhibited best performances in flexural toughness and drying shrinkage cracking compared to waste-free adobe.

Galán-Marín et al. [111], Statuto et al. [60], Benkhadda and Khaldoun [112] examined the utilisation of sheep wool to reinforce unfired earth blocks. Statuto et al. [60] used 3wt% whereas Galán-Marín et al. [111] and Benkhadda and Khaldoun [112] incorporated 0.25-1wt% of 10-50mm sheep wool and alginate as a natural polymer to produce the blocks. The results reported that density increased with the increasing amount of wool fibre and ranged from 1790kg/m^3 (19.5% alginate and 0.25% wool) to 1800kg/m^3 (19.5% alginate 0.50% wool) [111]. The compressive strength reached its peak at 4.44MPa [111] and 3.04MPa [112] and maximum flexural strength was recorded as 1.45MPa [111] and 1.83MPa [112] with 0.25% sheep wool and 19% alginate content.

4.4 Unfired earth blocks construction incorporating non-agro wastes

Siddiqua and Barreto [113], Gu and Chen [114] and Huynh et al. [115] [116] studied the potential use of fly ash as a stabiliser for unfired earth bricks and rammed earth construction. Siddiqua and Barreto [113] investigated the use of two industrial by-products namely, fly ash (FA) and calcium carbide residue (CCR) as binders in rammed earth construction. Gu and Chen [114] used fly ash, phosphogypsum waste, cement and quicklime for rammed earth compaction. On the other hand, Huynh et al. [115] [116] explored the mechanical strength and thermal characteristics of unfired samples by combining fly ash, fine aggregates and cement. Siddiqua and Barreto [113] used two different compositions of CCR and FA (CCR:FA=40:60, CCR:FA=60:40) with 5 diverse binders (3-15wt%) for the experiments. For both the compositions dry density decreased (1820kg/m^3 to 1796kg/m^3 for CCR: FA=40:60 and (1805kg/m^3 to 1774kg/m^3 for CCR: FA=60:40) with the increase of binder content. The maximum compressive strength was achieved at a 15% binder addition. The peak compressive values were 5.97MPa (CCR: FA=40:60) and 5.82MPa (CCR: FA=60:40) after 60 days of curing. However, 12% binder content and CCR: FA=40:60 was proposed as an optimum percentage since it presented a substantial development of the strength in the samples. Gu and Chen [114] incorporated 5, 10, 15, 20wt% of fly ash with loess, waste phosphogypsum (3, 5, 8, 10wt%), cement (10wt%) and quicklime (2, 4, 6, 8wt%) to produce self-compacting rammed earth. The study showed that flexural and compressive strength improved when the temperature increased at different curing ages. For the sample with mix proportion of 100% loess, 8% cement, 3% quicklime, 5% phosphogypsum and 20% fly ash, the flexural strength improved from 1.31MPa to 2.63MPa at 28 days when temperature increased from 55˚C to 85˚C. Also, the compressive strength increased from 18.20MPa to 23.72MPa for the same mixture in the same condition and both the values met the Chinese national standard GB/T 5101-2003 [155]. Besides, the water absorption rate of the samples varied from 15-25%. The highest softening coefficients for flexural strength (0.9) and compressive strength (0.95) were obtained from the mixture proportion of 100% loess, 20% fly ash, 10% cement, 3% phosphogypsum and 8% quicklime. Huynh et al. [115, 116] developed a novel eco-friendly building brick using different proportions of crushed sand (70, 80, 90 and 100%wt), river sand (10, 20, 30wt%), low-calcium fly ash (10, 15, 20wt%) and ordinary Portland cement (8, 10, 12wt%). From the Scanning electron microscope observation, it was noticed that the density of the samples decreased and water absorption rate increased (around 8-8.5%) with an increasing amount of fly ash. The compressive strength value was found as 4.50MPa (10% fly ash), 5.10MPa (15% fly ash) and 6.03MPa (20% fly ash) which were 36.7%, 17.7%, and 3.4% higher than the control sample. For the ordinary Portland cement content strength was recorded as 4.24MPa (8%) which was further increased by 4.0% and 9.4% with cement content increase to 10% and 12%. respectively.

Oti et al. [117-119] used ground granulated blast furnace slag (5, 5.5, 11, 12wt%), clay, two different types of lime (quicklime and hydraulic lime) and Portland cement to conduct the experiments. The results indicated that lime activated samples performed better than cement activated samples. The dry density of the samples varied from 1790-1800kg/m^3 [118]. The highest compressive strength was obtained as 7.40MPa (lime activated) and 5.50MPa (cement activated) at 90 days curing [117]. Besides, the lime activated samples showed a lower thermal conductivity value (0.37W/mK) than the cement activated sample (0.38W/mK) [119]. At the end of the 90 days, the lime activated samples displayed a lower water absorption rate (17–20%) relative to the cement activated samples (20-22%) [118]. Also, the rate of linear shrinkage of the samples was found to be very low after 28 days curing.

Sekhar and Nayak [120] studied the utilisation of granulated blast furnace slag (GBFS) in the manufacture of compressed earth blocks. Different percentages of waste (5, 15, 25, 35, 45wt% for lithomargic clay and 10, 15, 20, 25, 30wt% for laterite soil) were used in the production of the samples. The results revealed that compressive strength improved and water absorption decreased when cement was added to the mixer (6-12wt% for lithomargic clay and 2-8wt% for laterite). For lithomargic clay blocks, maximum compressive strength was obtained as 5.55MPa (25%GBFS+12%Cement) and for laterite blocks, it was 5.25MPa (20%GBFS+8%Cement). Besides, for all samples, the water absorption values were less than 15%. The study suggested that 20% granulated blast furnace slag, 80% laterite soil and 6% cement are the ideal composition to manufacture unfired earth blocks.

Table 4
Overview of research on non-agricultural waste additives for production of unfired earth blocks

Non-Agro-wastes	Ref.	Content (wt%, vol%) and fibre length (mm)	Unit size (mm)	Soil, sand and clay type	Density (kg/m^3)	Max. Compressive strength (CS), Flexural strength (FS) (MPa)	Min. Thermal conductivity (W/mK)	Water absorption (wt%)
Fly ash	[113]	3, 6, 9, 12, 15%	ø40×80	Natural soil	1796-1820 1774-1805	CS-5.97	undefined	undefined
	[122]	4, 8, 12%	ø150×300 450×300×150	Soil	1800-1850	CS-2.50	undefined	undefined
	[114]	5, 10, 15, 20%	70.7×70.7×70.7 40×40×160	Loess	undefined	CS-23.72 FS-2.63	undefined	15-25%
	[115], [116]	10, 15, 20%	80×80×180	River sand	undefined	CS-6.03	0.78	0.79-8.50%
Granulated blast furnace slag	[117], [118], [119]	5, 5.5, 11, 12%	215×102.5×65 102×102×35	Lower Oxford Clay	1790–1800	CS-7.40	0.37	17-20%
	[120]	Lithomargic:5, 15, 25, 35, 45% Laterite:10, 15, 20, 25, 30%	305×143×105	Laterite soil, Lithomargic clay	undefined	Lithomargic:5.55 Laterite:5.25	undefined	Lithomargic: 12.51-13.90% Laterite: 10.90-12.90%
Bottom ash	[121]	75, 60, 52.5 vol%	140×140×90	Lateritic clayey soil and sand	1200-1600	CS 27	undefined	undefined
	[122]	6, 12, 18%	ø150×300 450×300×150	Soil	1800-1850	CS-2.50	undefined	undefined
Polyethylene terephthalate	[123]	0.2, 0.4, 0.6, 0.8, 1.0%, 54 mm	191×203×121 229×203×121	Local soil	undefined	CS-5.55 FS-1.02	undefined	undefined
	[124]	1, 3, 7%	undefined	Local brown soil	undefined	CS-1.55	undefined	undefined
	[125]	1, 3, 7, 15, 20%	160×40×40	Local clayey soil	1440-1710	CS-4.50	undefined	undefined
Crumb rubber	[88]	5, 10, 15%	160×40×40	Commercial clay Sand	undefined	CS-2.52 FS-0.16	undefined	undefined
	[126]	5, 10, 20%	150×150×150	Quarry products sand, Kaolin clay	2064	CS-10	undefined	7.50-8.75%
Polyurethane	[88]	5, 10, 15%	160×40×40	Commercial clay Sand	undefined	CS-2.62 FS-0.17	undefined	undefined
Salvaged steel fibre	[127]	1.7, 2, 2.7 vol% 20, 35, 50 mm	215×105×55.0	Lateritic soil	undefined	CS-11.60 FS-2.60	undefined	undefined
Alumina filler (AF) and Coal ash (CA)	[128]	AF:16.1, 32.2, 47.82%, CA:7%	125×60×40	Gray Marl clay soil	1540-1840	CS-16	undefined	15-24%
Brick Dust	[129]	5, 10, 15, 20%	ø50×100	Mercia mudstone clay	undefined	CS-2.10	undefined	5.50-8.20%
Magnesium oxide	[130]	3, 6, 9, 12, 15, 18%	ø65×75	Local red clay	2000-1890	CS-9.90	undefined	4.90-14.25%
Calcium carbide residue	[80]	0-15%	140×140×95	Clayey soil	undefined	CS-3.40	undefined	undefined
	[131]	5, 10, 15, 20, 25%	295×140×95 60×40×30	Local Beige clayey soil	1610-1820	undefined	0.47	undefined
Recycled aggregate	[132]	15%	295×140×90 145×140×90	Local soil	1740-1810	CS-5.40 FS-1.19	0.61	13.60-16.50%
Molybdenum tailing	[133]	55, 60, 65, 70, 75%	160×40×40	River sand	undefined	CS-27.35 FS-7.56	undefined	undefined
Iron mine spoil	[134]	30, 40, 50%	230×110×75	Qssuarry Dust	2050	CS-6 FS-1.12	undefined	12.0-18.90%
Soda ash	[135]	4.38,4.56,4.74,4.92 l of water	200×225×75	Lateritic	1160-1410	CS-1.71	undefined	undefined
KS770	[135]	4.38,4.56,4.74,4.92 l of water	200×225×75	Lateritic	1250-1300	CS-1.45	undefined	undefined
Glass fibre reinforced polymer	[136]	2.5, 5.0, 7.5, 10%	300×150×80 600×85×35	Red Latosol, clay	1524-1565	CS-2.05	0.68	12.88-15.76%
Ceramic	[137]	50, 75, 100 %	100×50×40	Laterite	1703.33-	CS-33.60	undefined	17.52-

waste					1774.89			19.52%
	[138]	30%	ø65×75 225×110×60	Grey marl	undefined	CS-12.65	undefined	5.90-19.20%
Concrete waste	[138]	50%	ø65×75 225×110× 60	Grey marl	undefined	CS-12.75	undefined	9-16.90%
Marble dust (MD) and Polymer fibre PF)	[139]	MD-10, 20% PF-0.5, 1, 1.5, 0.2%	50×50×50 40×40×160	Haspolat and Taskent soil	undefined	CS-3.47 FS-1.43	undefined	undefined
Plastic fibre	[53]	2%	150×150×150	Clay	undefined	CS-7.10	undefined	37.60%
Polystyrene fibre	[53]	1%	150×150×150	Clay	undefined	CS-4.90	undefined	33.50%
Waterworks sludge	[140]	20-50%	undefined	Ordinary sand	undefined	CS-30	undefined	undefined

Vinai et al. [121] incorporated bottom ash (52.5, 60, 75vol%) with the various proportions of cement (10-57vol%), sand and lateritic clayey soil for the production of unfired bricks. The test results indicated that the porous microstructure of bottom ash produced very lightweight samples (1200–1600kg/m^3). The uniaxial compressive strength was reported between 4MPa to 27MPa for the maximum amount of cement mixed samples. The study concluded that most economic stabilisation mixture proportion could be 10% cement and 20% laterite which reached around 8MPa of strength.

Raj S. et al. [122] conducted experimental research on the characteristics of rammed earth using two binders, fly ash (FA) (4, 8, 12wt%) and bottom ash (BA) (6, 12, 18wt%). Results showed that unconfined compressive strength significantly improved from 7.13MPa to 17.36MPa when the mixing ratio was 60:40 (BA:FA). Also, the dry density of the samples varied from 1800kg/m^3 to 1850kg/m^3. The study proposed the use of 30% of the binder along with 3% and 6% cement as an activator for the determination of rammed earth properties.

Donkor and Obonyo [123], Akinwumi et al. [124] and Limami et al. [125] investigated the utilisation of polyethylene terephthalate to develop unfired compressed earth blocks. Different proportions of polyethylene terephthalate 1, 3 and 7wt% [124], 0.2, 0.4, 0.6, 0.8wt% with length of 54mm [123] and 1, 3, 7, 15 and 20wt% [125] were mixed to produce the samples. The test results showed that the highest compressive and flexural strength were measured as 5.55MPa and 1.02MPa respectively for 0.4% of waste content [123]. On the other hand, from the test results of Akinwumi et al. [124] and Limami et al. [125], the maximum compressive strength was found to be 1.55MPa and 5.04MPa respectively with 1% of waste incorporation. A growing proportion of the shredded plastic content increased the erosion rate [124] and capillary water absorption coefficient (33.69% to 64.15%) [125] of the samples. According to Donkor and Obonyo [123], mixing of various materials became more difficult and the strength started to drop when the percentage of fibre went over 0.6%. Therefore, the study suggested the optimum range of fibre between 0.4% and 0.6%.

Serrano et al. [88] and Porter et al. [126] evaluated the incorporation of crumb rubber (5-20wt%) to enhance the varies properties of adobe bricks and rammed earth respectively. According to Serrano et al. [88], the optimum compressive and flexural strength values were obtained 2.52MPa (5% crumb rubber) and 0.16MPa (15% crumb rubber) respectively. Porter et al. [126] presented that compressive strength decreased (10MPa to 5.20MPa) as crumb rubber residues increased. On the contrary, the water absorption rate of the samples amplified (7.5% to 8.75%) with an increased amount of waste. Thermal property test was conducted for a sample containing 20% of crumb rubber and specific heat capacity value was measured as 1321J/kgK. Serrano et al. [88] investigated the mechanical properties of adobe bricks combining polyurethane (waste from refrigerators insulation) as additives by using 5-15wt%. The experiment results revealed that flexural and compressive strength varied from 0.17MPa (10% polyurethane) to 0.07MPa (15% polyurethane) and 2.62MPa (5% polyurethane) to 1.23MPa (15% polyurethane) respectively.

Eko et al. [127] explored the utilisation of salvaged steel fibre (1.7, 2, 2.7vol%) from used tires for reinforcement of unfired earth blocks. The fibre lengths used in the experiment were 20, 35, and 50mm with a radius of 1.59mm. The maximum tensile strength was observed as 0.68MPa for 2% fibre reinforced sample. Moreover, the maximum unconfined compressive (11.60MPa) and flexural strength (2.60MPa) were found with the addition of 10% cement. The results concluded that the ideal fibre quantity and essential fibre length were respectively 2% by volume and 35mm for the production of steel fibre reinforced earth blocks.

Miqueleiz [128] utilised alumina filler waste (16.1, 32.2 and 47.82wt%) and coal ash waste (7wt%) as replacement of clay for unfired bricks construction. Two different limes, natural hydraulic lime, calcareous hydrated lime and Portland cement were used in the experiment. The results showed a lower sample density (1500kg/m^3-1840kg/m^3) with increased alumina fillers. Nonetheless, the optimum moisture content value of the samples was between 9% and 14%. A maximum unconfined compressive strength was found at 16.1% waste content (16MPa) and with the increase in waste amount unconfined compressive strength decreased. On the contrary, with the addition of waste, water absorption rate increased from 15% to 24%. The freeze and thaw cycle test revealed that 47.82% waste added sample performed very good but some surface cracks in the samples made with 60% of waste were observed from the beginning to the end of the cycles.

Oti et al. [129] analysed the possibility of utilising brick dust waste (BDW) as a partial replacement (5, 10, 15 and 20wt%) for earth in the production of unfired building materials such as brick and mortar. The primary stabilising agent for the experiment was a lime-activated ground granulated blast furnace slag. The results presented that the replacement of 5-20% clay with BDW led to a significant increase in stabilised mixture strength (around 0.60 to 2.10MPa) which is approximately 250% higher than the control sample. Moreover, the water absorption rate (5.40-8.20%) and linear expansion of the specimens increased as the percentage of waste increased. The linear expansion value of the waste mixed samples was between 0.25% and 0.67% when the three-days curing process was completed but improved to 0.30% to 95% when the fifty-three days was completed. The results of the freeze-thaw stability test showed that weight losses were between 1.20% to 1.60% after the 7th cycle and a significant increase in weight loss of approximately 1.40% to 1.90% for all stabilised test specimens was reported after cycle 28.

Espuelas et al. [130] studied the efficiency of magnesium oxide (3-18%) and calcareous hydrated lime (3-18%) as substitute binders for the development of unfired clay bricks. The results demonstrated that maximum dry density (1980kg/m^3 to 2000kg/m3) and the optimum moisture content slightly increased (12.60% to 15.70%) with the addition of magnesium oxide to the soil. On the other hand, the addition of lime decreased the maximum dry density (1890kg/m^3 to 1800kg/m^3) but caused an increase in the optimum moisture content (13.10 to 18.30%). Maximum compressive strengths for magnesium oxide and calcareous hydrated lime incorporated bricks were reported as 9.90MPa (15% magnesium oxide) and 9.80MPa (6% lime). From the durability point of view, water absorption decreased (14.25% to 4.90% for magnesium oxide and 13.50% to 6.10% for lime) as the doses increased for both additives. A minimum dose of 9% and 6% respectively of magnesium oxide and lime were found as optimum in the case of sample stability.

Moussa at el. [131] investigated the stabilisation effects of 5–25 mass% calcium carbide residue (CCR) and 8 mass% of cement on compressed earth blocks produced from quartz-kaolinite rich earth material. The results exhibited that the inclusion of CCR waste in the earth matrix resulted in a reduction of apparent density (1820kg/m^3 to 1600kg/m^3). Also, the total porosity of the samples rose from 30% to 40% compared to 20% for the non-stabilised sample. At the same time, there was a decreasing trend in thermal conductivity (0.69W/mK to 0.52W/mK) and increasing trend in heat capacity (812J/kg/K to 938J/kg/K) as the amount of CCR residues increased.

Bogas et al. [132] evaluated the possibility of utilising 15wt% of recycled fine aggregates (consisting of fired clay bricks, concrete and cement mortar from construction debris) in the production of compressed earth blocks. The results presented that fresh density of unfired compressed earth blocks incorporated recycle aggregates ranged between 1929kg/m^3 and 2003kg/m^3 whereas dry density varied from 1740kg/m^3 to 1810kg/m^3 depending on the moisture composition. The highest compressive, tensile and flexural strength were recorded as 5.40MPa, 0.61MPa and 1.19MPa respectively. Besides, the water absorption rate ranged from 13.6% to 16.5% and 0.61W/mC was found as the lowest conductivity value.

Zhou et al. [133] incorporated Shang Luo molybdenum tailings (55, 60, 65, 70, 75wt%) to produce unfired bricks. Test results indicated that when 55% of molybdenum tailings was applied to the samples, the compressive and flexural strength were recorded 27.35MPa and 7.56MPa respectively after 28 days which met MU25 requirements [155]. The compressive and bending strength decreased from 20.12MPa to 23.36MPa and 5.36MPa to 6.42MPa respectively, when the molybdenum tailings ratio increased to 60%-70%. Finally, as molybdenum was applied at 75%, the compressive and flexural strength dropped to 15.69MPa and 4.83MPa. Furthermore, the study also examined the consequence of silica powder addition on the properties of unfired samples and the experiments concluded that with the addition of silica powder the mechanical properties of unfired bricks decreased.

Nagaraj and Shreyasvi [134] studied the prospect of using iron mine spoil waste (MSW) (30, 40, 50wt%) in the production of compressed earth blocks using quarry dust, cement and lime. Test results revealed that the optimum waste percentage was 30% as at this amount the compressive (5MPa) and flexural strength (1.12MPa) were found the maximum after 6 months of ageing. However, with an increase in the waste amount water absorption rate declined from 18.9% to 12.0%.

Oladeji and Akinrinde [135] analysed the influences of two chemical additives namely KS770 and soda ash (4.38, 4.56, 4.74, 4.92 l of water) on the different properties of unfired clay bricks. The results reported that soda ash improved the clay brick properties than KS770 additives. However, the addition of soda additive decreased the density (1410kg/m^3 to 1160kg/m^3) and compressive strength (1.71MPa to 1.50MPa) of the unfired brick samples. In comparison, the additive KS770 seemed to improve the moisture content of the samples and thus avoided early setting and hardening. The study suggested an optimum water additive ratio of 1:27 with soda ash to enhance the workability of unfired clay bricks.

Gandia et al. [136] carried out an experimental study on different physical, mechanical and thermal behaviour of adobe blocks strengthened with glass fibre reinforced polymer (GFRP) waste (2.5, 0.5, 7.5, 10wt%). The results showed that as the percentage of GFRP waste increased in the adobe samples, the bulk density (1565kg/m^3-1524kg/m^3) and thermal conductivity (0.79W/mK-0.68W/mK) decreased while compressive strength (1.32MPa to 2.05MPa) and water absorption (12.88% to 15.76%) increased. The study concluded that the optimum mix ratio of GFRP was 10% because it showed a 6%

reduction in bulk density, a 21% reduction in thermal conductivity and a 45% increase in compressive strength.

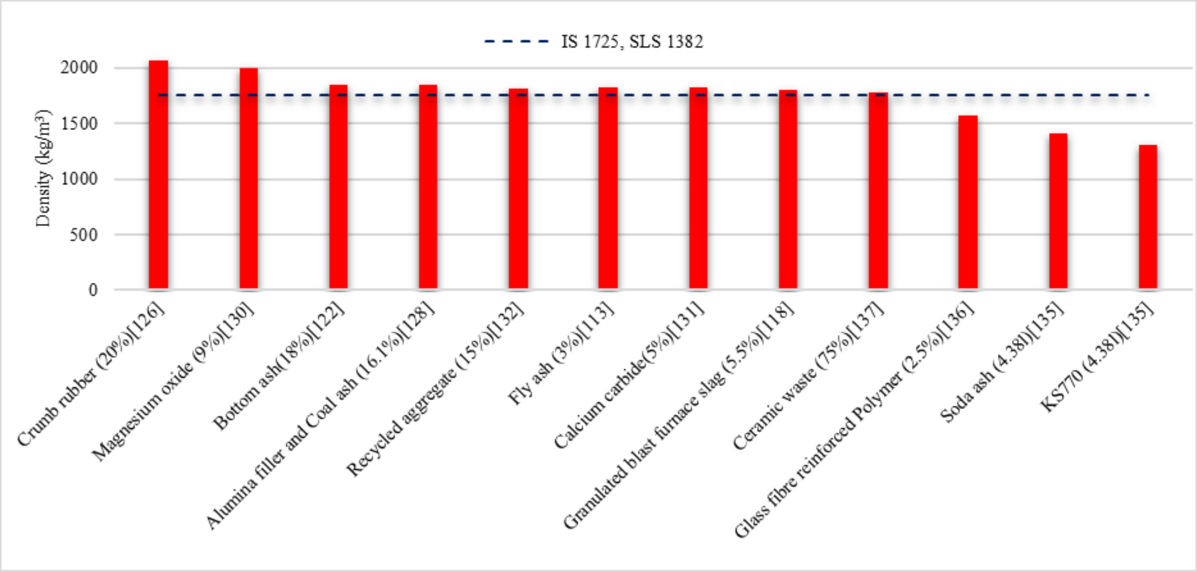


Fig. 6. Density of non-agro waste-incorporated samples

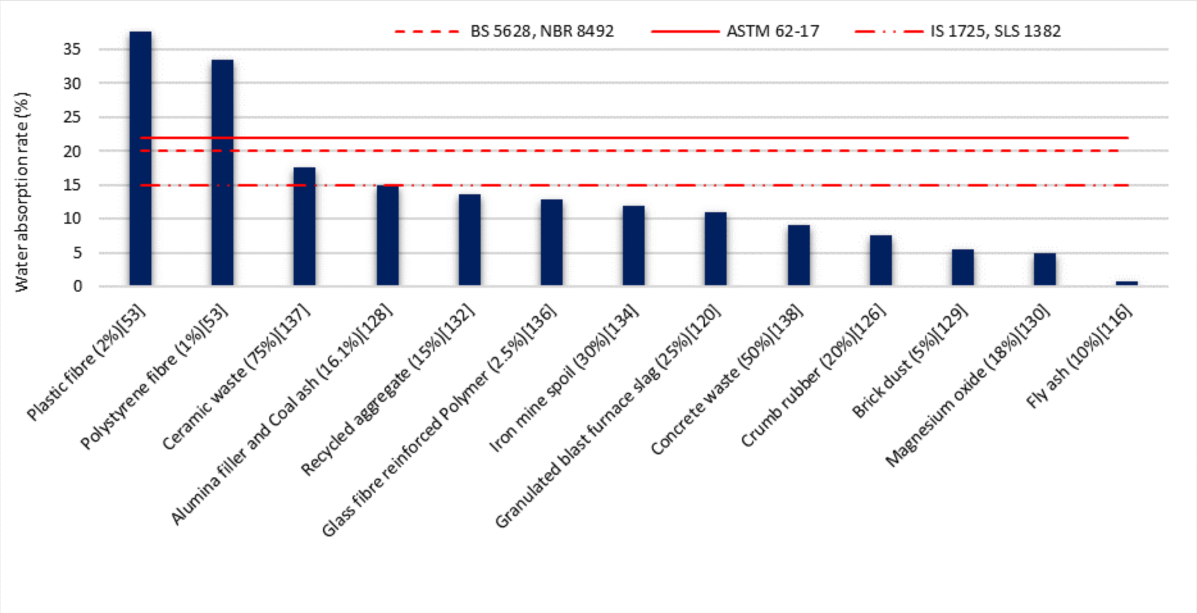


Fig. 7. Water absorption of non-agro waste-incorporated samples

Ali et al. [137] assessed the effects of the addition of ceramic waste (50, 75, 100wt%) in the composition of laterite soil compressed bricks. It reported that 75% of ceramic content had the highest density (1774.89kg/m^3) while the lowest density was (1703.33kg/m^3) found for 100% ceramic content. Moreover, the sample containing 75% of ceramic waste exhibited the best compressive strength with the results of 24.40MPa (7 days curing) and 33.60MPa (28 days curing). However, the compressive strength decreased for both 7 and 28 days above 75% of ceramic waste replacement. Furthermore, 75% of ceramic waste reported the lowest value as 17.20% and 1.63kg/min/m^2 respectively for water absorption test and initial rate absorption test.

Seco et al. [138] utilised the concrete waste (50wt%) and ceramic remains (30wt%) to partially replace the soil in the production of unfired bricks. The study investigated the mechanical properties, water absorption rate and freeze-thaw resistance. In addition, based on Life Cycle Analysis the environmental impacts of the specimens were measured. The samples were manufactured by using grey marl soil from northern Spain and four additives such as ground granulated blast furnace slag, Portland cement, calcareous hydrated lime and natural hydrated lime as binder components. According to the test results, the maximum unconfined compressive strength was witnessed for concrete and ceramic-based bricks respectively 12.65MPa (after 21 days of curing) and 12.65MPa (after

28 days of curing). The ideal binder proportion for both the mixer was 2% calcareous hydrated lime and 8% ground granulated blast furnace slag. In the case of water absorption rate, no major distinction existed between the two bricks blends, but the decrease in water resistance in concrete waste samples was slightly greater than the ceramic waste samples. Water absorption rate varied between 5.90% to 19.20% (ceramic waste) and 9% to 16.90% (concrete waste). However, the test results revealed that bricks mixed with concrete waste performed better than bricks with ceramic waste in freeze-thaw resistance. Finally, the analysis of the life cycle found that the environmental impact of the blended bricks was largely determined by the binder materials in the mixture.

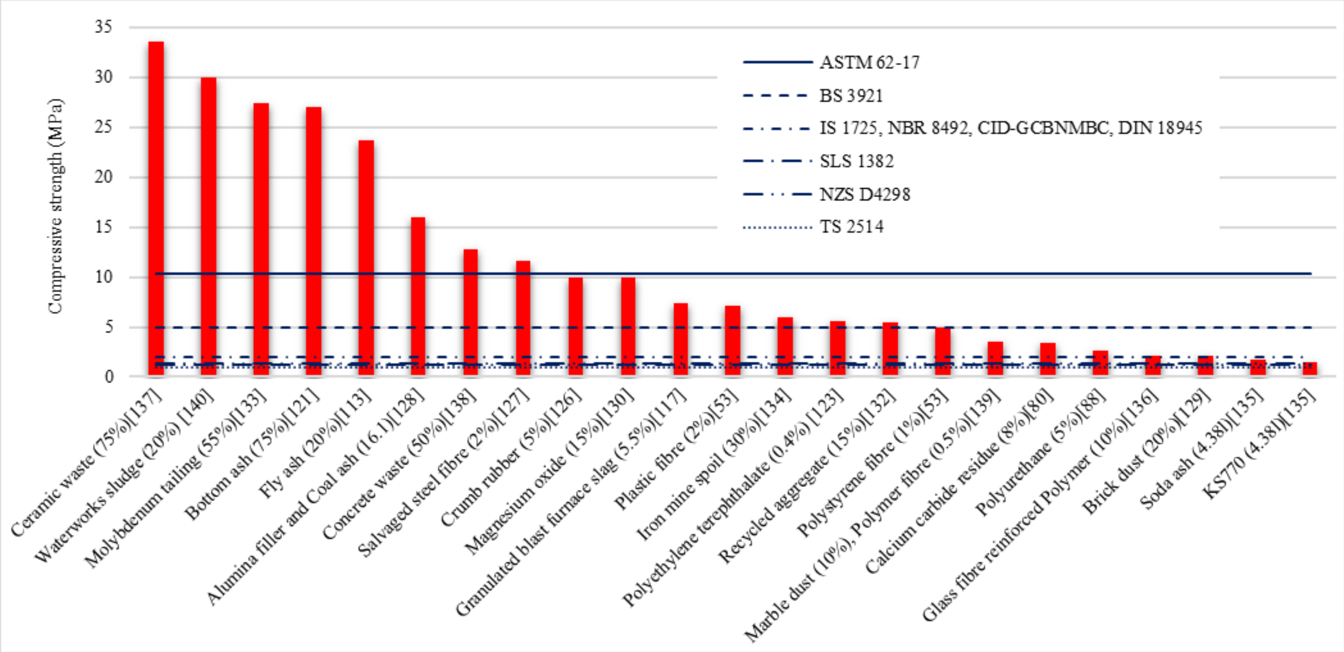


Fig. 8. Compressive strength of non-agro waste-incorporated samples

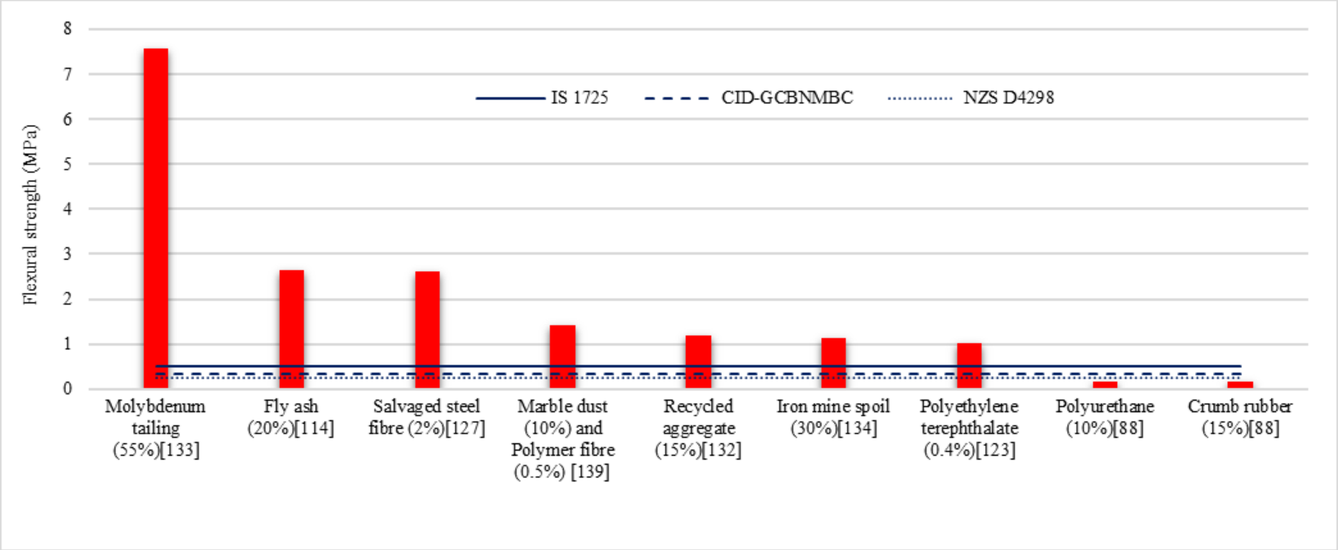


Fig. 9. Flexural strength of non-agro waste-incorporated samples

Balkis [139] investigated the mechanical properties of adobe blocks comprising different amounts of polymer fibre (0.5-2.0wt%) and marble dust waste (10 and 20wt%). This research examined the effects of such wastes on the compressive and bending strength of adobe samples made of two separate soils collected from Taskent and Haspolat regions in Turkey. The findings presented that adobe samples reinforced with polymer fibres enhanced the mechanical properties of the samples. For both soils, the most desirable results were achieved with a ratio of 0.5%

polymer fibre and 10% marble dust since these complied with the minimum strength requirements of Turkish standard for adobe block [152]. The combination had a compressive and flexural strength of 3.47MPa and 1.43MPa respectively.

Binici et al. [53] developed an earthquake-resistant mud brick using two industrial waste materials (polystyrene fibre and plastic fibre). The mud bricks were made by combining clay (50kg), cement (10kg), lime (2kg), gypsum (3kg), basaltic pumice (15kg), polystyrene fibre (0.5kg), plastic fibre (0.1kg) and water (20kg). The produced samples were checked for compressive strength development after different casting days such as 28 days, 72 days and lastly 96 days. The results revealed that the compressive strength (3.70MPa to 7.10MPa) of fibre-reinforced samples exceeded the minimum requirement indicated in Turkish Standard (1MPa) [152]. The ultimate compressive strengths of plastic and polystyrene fibre reinforced samples were obtained respectively 7.10MPa and 4.90MPa at 96 days curing. Moreover, the study concluded that water absorption rate (after 24 h) for plastic fibre reinforced samples was higher (37.60%) than polystyrene fibre reinforced samples (33.50%). In addition, the weight losses for plastic fibre and polystyrene fibre samples were measured as 16.10% and 13.40% respectively by the wetting and drying cycling test (7 days).

Xie et al. [140] investigated the utilisation of waterworks sludge waste (WS) (20-50wt%), fly ash, sodium silicate and feldspar powder as additives in the manufacture of fired and unfired bricks. The maximum compressive strength value for unfired blocks reached a peak of around 30MPa (20wt% WS) and decreased when the WS ratio rose from 20% to 35%. However, in all the cases, compressive strength value stayed above 20MPa. But the permeability coefficient of the unfired bricks was lower than the acceptable value. It happened because the smaller particles of cement managed to fill the gaps formed by the large particles of soil. Also, cement, soil and WS were closely bound together during the hydration process, leaving little gaps.

5. Discussion

Tables 3 and 4 indicate that researchers used different agro and non-agro waste materials in various quantities to produce unfired earth building blocks. Several physical, mechanical and thermal properties were assessed by distinctive tests following the different available standards (see Table 5). As presented by Cid et al. [141] and Schroeder [142] there are some certain universal and regional guidelines established for the unfired earth building construction worldwide. However, the properties mostly specified in different accessible standards include bulk density, water absorption and compressive strength. In Table 6, unfired earth blocks specifications are provided in compliance with the standards and codes. In the following sections, we discuss the results of all tests conducted by various authors of the chosen articles.

5.1 Effects of waste materials on the physical properties of unfired earth blocks

Density and water absorption are two physical properties extensively examined by the authors. The density of the composite material is an important measurement because many other properties including mechanical and thermal properties can be associated with this. Increasing the waste amount in earth samples induces a drop in earth content, which eventually reduces the composite density. The results showed that porosity and water absorption of the samples were inversely related to bulk density [65, 77, 93, 100, 102, 109, 125, 128, 136, 137]. Therefore, more pores of the low-density samples permitted high water flow due to the capillary effect, leading to a higher water absorption coefficient. Also, from the discussions in Section 4.3, it could be generalised that the addition of agro wastes increased water absorption rate because of the hydrophilic nature of lignocellulosic fibres [93]. Fig. 3 and Fig. 7 exhibit the water absorption results from different research work reviewed.

5.1.1 Effects of agro wastes on the density of unfired earth blocks

The density of the samples varied depending on the types of earth materials and fibres used. Danso et al. [65] found that adding coconut husk, sugarcane bagasse and oil palm fruit fibres to the samples led to a decrease in density as fibres had a low density (810kg/m^3 to 500kg/m^3) itself relative to soil density (1780kg/m^3). Thus, increasing fibre content to replace the heavier soil decreased sample density [72, 83, 93, 100]. In the case of powdered materials, Huynh et al. [79] and Namango [92] presented that rice husk ash and cassavas powder addition decreased the density of the samples due to their lower density like the soil used. On the other hand, the result was slightly different for the eggshell ash [102] as the percentage of ash increased to 4% the density of the samples increased. This is because of the very small particles of ash that filled the voids in lateritic soil. Subsequently, the sample density dropped by a rise of 8% and 16% in the amount of ash, since the ash had a lower specific gravity than the laterite. In general, from the Fig. 2 it can be concluded that almost all the waste-incorporated samples complied with the minimum IS 1725 and SLS 1382 criteria (1750kg/m^3) except wheat hay fibre, flax fibre, eucalyptus pulp microfibre, olive waste fibre, oil palm fruit bunch fibre, bio-briquette, pineapple leaf fibre, jute and corn husk ash samples.

5.1.2 Effects of non-agro wastes on the density of unfired earth blocks

In general, the density of the waste blended samples decreased with the addition of waste materials due to the lower specific density of the wastes relative to the earthen particles [131, 135, 113, 128]. However, the density of bottom ash blended samples decreased initially, but additional waste increased the dry density by enhancing the mixture gradation. [122]. In the case of glass fibre reinforced polymer, the porosity of the samples increased due to displacement of the fibres in contact with the soil resulting in lower sample density [136]. Fig. 6 illustrates that only three waste materials (glass fibre reinforced polymer waste, KS770 and soda ash) did not fulfil the minimum requirements of the standards IS 1725 and SLS (1750kg/m^3).

Table 5
Different standards followed by all the reviewed papers

Compressive strength test
American Standard: ASTM C 140-96b [64], ASTM C 109/C 109M [114] [139], ASTM C 618-15, ASTM D698-12e2 [113], ASTM: C 1018 [110], ASTM: C 67-07 [69][108] [123], ASTM D 1633 [89], ASTM D 2166-00e1/06 [91][95][127], ASTM E 11–04 [56]
British Standard: BS 3921:1985 [94][137], BS 1377 [102][135], BS 1924-2: 1990 [129], **European Standard:** EN 196-1 [97], EN 1015-11 [58][72], EN 1926 [56][66], EN 12390-3 [54], EN 83-821-925 [111], BS EN 772-1[65][81][82][83][87], BS EN 771-1:2003 [117], BS EN 1015-11:1999 [106], SR EN 196-1:2016 [76], **French Standard:** XP P 13-901 [63][73][80][99][100], **Spanish Standard:** UNE 103400 [130][138], UNE EN 772-1(2002) [128], UNE-EN 196-1 [88]
Brazilian Standard: NBR 8491, NBR 8492 [86][132][136], **New Mexico Earthen Building Materials Code:** CID-GCBNMBC [62], **Peruvian Standard:** NTE-E.080 [136], **Columbian Standard:** NTC 5324 (2004) [132]
Ghana Standard: GS 297-1 [109], **Moroccan Standard:** NM EN 772-1-2015 [125]
Turkish Standard: TS EN 771-1 (2002), TS 2514, 1977 [84], TS 2514-2515 [139], TS 704, TS 705 [108][124], **Iranian Standard No**. 7 [78]
Indian Standard: IS 4332 [67], IS: 2720-10 [29], IS 3495 : 1992 [107][134], IS:1905-IS:1987, IS:1725-IS:1982, [120] [122], **Malaysian Standard:** MS 76:1972 [94][137], **Indonesian Standard:** SNI 15-2094-2000, **Vietnamese Standard**: TCVN 6477:2011 [79], TCVN 6477-2016 [115][116], **Chinese Standard:** MU15 [133], MU7.5 [61], GB/T 17671-1999 [114], JC/T945-2005 [140], **Japanese Standard:** JIS A1216 [71]
New Zealand Earth Building Standard: NZS 4298 (NZS 1998) [62][73]
Flexural and Tensile strength test
American Standard: ASTM C 67-07 [69], ASTM C1018 [110], ASTM C 1609 [66], ASTM D 1635-00 [91], ASTM C 496 [89], ASTM D 3967-08-16 [87] [95]
British Standard: BS 6073 [73], **European Standard:** EN 83-821-925 [111], EN 196-1 [97], EN 772-6 (2001) [132], EN 12372 [54], EN 1015-11 [56], EN 12390-6 (2009)[132], BS EN 1015-11:1999 [106], BS EN 12390-6 [65] [87], SR EN 196-1:2016 [76], **French Standard:** NF EN 196-1 [73], AFNOR: XP P13-901[63][99][100], **Spanish Standard:** UNE-EN 196-1 [88]
Turkish Standard: TS 2514-2515[139, **Indian Standard:** IS 5816 [67]
Indonesian Standard: SNI 03-6458-2000 [77], Chinese Standard: MU15 [133]
Density test
American Standard: ASTM C 67 [108], ASTM C 134-94 [64], ASTM C 948 [93], ASTM D 6611 [66]
British Standard: BS 1377 [102], BS 6073 [109], **European Standard:** BS EN 771-1 [65], **French Standard:** NF P18-459 [131]
Moroccan Standard: NM EN 772-16, NM 10.1.009-2014 [125]**, Kenyan Standard:** KS 1070:1993 [92]
Indian Standard: IS 3495 (Part I-III): 1992, IS 1077:1992 (d) [107]**, Vietnamese Standard:** TCVN 6355:2009 [79]
Water absorption test
American Standard: ASTM C 67-11 [91], ASTM C 272/C272M-12 [87], ASTM C 948 [93]
British Standard: BS 3921:1985 [94], BS 1377 (1990) [135], BS 3921: 1985 [137], **European Standard:** EN 771-1 [130][138], BS EN 772-11[58][65][85][87], BS EN 771-1 [118][119][129], **French Standard:** AFNOR: XP P13-901 [63][99][100], **Spanish Standard:** UNE EN 771-1(2003) [128], **Portuguese Standard:** LNEC E394 (1994) [132]
Brazilian Standard: NBR 8491, NBR 8492 [86]
Moroccan Standard: NM EN 772-11[125]
Turkish Standard: TS 704, TS 705 [108]
Indian Standard: IS 1077:1992 (d) [107], IS: 1725, 1982, 2013 [29][120][122][134]**, Malaysian Standard:** MS 76:1972 [94][137]**, Vietnamese Standard:** TCVN 6355:2009 [79], TCVN 6477-2016[116]**, Chinese Standard:** GB/T 50082-2009 [114]
Thermal conductivity test
American Standard: ASTM C 1113-99 [55], ASTM C518-91, ASTM C1132-89 [119]
European Standard: BS EN 1745 [119], SR EN 12667:2002 [76], **French Standard:** AFNOR: XP P13-901[63]
Japanese Standard: JIS R 2618 [64]

Table 6
Different Standards Requirements for Clay Masonry and Earth Building

	Standards	Compressive strength (min.)	Flexural strength (min.)	Bulk density (min.)	Water absorption (max. % by weight)
Standards for masonry	American Standard: ASTM 62-17 [143]	Grade SW: 20.7 MPa, Grade MW: 17.2 MPa Grade NW: 10.3 MPa			Grade SW: 17 % Grade MW: 22.0% Grade NW: no limit
	British Standard: BS 3921 [144]	5 MPa			
	BS 5628 [145]				12-20%
Standards for unfired earth blocks	Indian Standard: IS 1725 [146]	Class 20: 20 MPa Class 30: 30 MPa	0.50 MPa	1750 kg/m^3	15%
	Sri Lankan Standard: SLS 1382 [147]	Dry CS- 2.80 MPa Wet CS- 1.20 MPa		1750 kg/m^3	15%
	Brazilian Standard: NBR 8492 [148]	2 MPa		1810 kg/m^3	20%
	New Mexico Earthen Building Code [149]	2.06 MPa	0.35 MPa		
	German Standard: DIN 18945 [150]	Class 2 to Class 6 brick: 2MPa to 6 MPa respectively			
	New Zealand Standard: NZS D4298 [151]	1.30 MPa	0.25 MPa		
	Turkish Standard: TS 2514 [152]	1 MPa			
	SW: Severe weathering, MW: Moderate weathering, NW: Negligible Weathering				

5.1.3 Effects of agro wastes on the water absorption of unfired earth blocks

Out of 58 papers only 19 papers discussed on the water absorption of the waste-incorporated composites. Fig. 3 indicates that the rate of water absorption of straw and cassava peel samples exceeded the requirements stated in the standards whereas bio-briquette, wood aggregate/fibre, banana fibre, sugarcane bagasse, coconut coir, date palm fibre, dawul kurudu, pines gum, oil palm fruit fibre, rice husk, pinus roxburghii fibre, grewia optiva fibre, sawdust, oil palm fruit bunch fibre, pineapple leaf fibre fulfilled all the standards criteria. In addition, eucalyptus pulp microfibre, sisal fibre satisfied the NBR 8492 and BS 5628 standard (20%). Based on the data in Fig. 3 it is evident that the strongest resistance (1.10%) was demonstrated by pineapple leaf fibre and oil palm fruit bunch fibre samples.

5.1.4 Effects of non-agro wastes on the water absorption of unfired earth blocks

Section 4.4 indicates that 14 studies addressed the water absorption rate of the manufactured samples utilising non-agro wastes. It also presents that, the inclusion of various residues in unfired earth blocks amplified the water absorption rate. In some of the cases, however, the rate of water absorption declined with an increase in waste amount as stated by Nagaraj and Shreyasvi [134], Espuelas et al. [130] and Sekhar and Nayak [120]. Fig. 7 illustrates the water absorption rate of non–agro wastes blended samples from all the studies concerning the different standard values. According to the figure, all the samples met the requirements of the standards apart from plastic fibre and polystyrene fibre for which the water absorption rate was higher than the standard requirements of 15-22%. In the case of ceramic waste, it complied with the NBR 8492, BS 5628 (20%) and ASTM 62-17 (22%) requirements.

5.2 Effects of waste materials on the mechanical properties of unfired earth blocks

The key details contained in Table 3, 4 and section 4.3, 4.4 state that the application of waste materials changed the physical, mechanical and thermal properties of unfired earth blocks in different ways. The effects of adding waste to the samples differed by researchers as the performance of the materials depended on the types of the wastes, compaction process of the soil and methods used for testing. For example, with the same soil and the same testing procedure, the addition of different waste materials can accomplish the opposite results. Therefore, there can be no generalisation of the results.

5.2.1 Effects of agro wastes on the compressive and flexural strength of unfired earth blocks

The findings of the different studies in Section 4.3 showed that all most all the researchers examined the compressive strength of the samples. The results indicated that the majority of the waste materials contributed to improving the strength of the specimens. Strength increased due to the isotropic matrix formation between the structure of earth mixture and the all-directional fibre network which resisted particles movements and provided stability. The impacts of fibre length on the mechanical properties of earth blocks were also investigated by some of the authors. Sangma et al. [67] observed that samples of 40mm coconut fibre obtained the highest compressive (1.67MPa) and tensile strength (0.56MPa). However, as the fibre length increased from 40mm to 80mm both compressive (1.13MPa) and tensile strength (0.18MPa) declined. Similarly, the maximum compressive (6.58MPa) and flexural strength (1.02MPa) of banana fibre [70] were assessed for fibre lengths of 60 mm and 70 mm respectively. Besides, whereas shorter kenaf fibres [97] (10 and 20mm) had a positive effect on flexural strength, the best result was achieved with 30mm fibre length. For pig hair [110] the average compressive and flexural strength decreased as the amount and length of pig hair increased. It is due to the cluster generation by the higher fibre length in the mixture which induced poor adhesion between the fibres in the clusters and the earth matrix. In addition, fibre clusters in the matrix functioned as porosity, impacting its average strength. Oskouei et al. [78] showed that non-fibrous rice husk particles decreased the adhesion of clay with other constituents which also reduced the friction of components by separating the soil particles. Hence, the compressive strength decreased as the amount of rice husk increased in the samples. Muntohar [77] explained that the addition of lime and rice husk ash (RHA) increased the compressive strength and reached a maximum value at 1:1 ratio but strength continued to decrease when the ratio increased. In moist condition, lime and RHA consumed water for exothermic reaction and generated cementitious materials (calcium silicate hydrate) which bound the clay particles together, imparting strength to the soil mixture. When the quantities of RHA was higher than the amount of lime in the mixtures, there was an insignificant increase in strength due to the insufficient presence of calcium in the lime–RHA system for the reaction. Besides for higher lime ratio, unreacted lime caused the formation of portlandite which increased the porosity and caused the reduction of mechanical resistance. On the other hand, Udawattha et al. [87] reported that thicker natural polymers (Pine resin, Dawul kurudu, sugarcane resin) created better bonds between soil particles than very lightweight natural polymers (Bael resin, Jack wood resin, Agarwood resin, wood apple resin). Also, in most of the studies, the compressive strength generally improved with the addition of cement or other binders.

The compressive strength findings from several different studies are shown in Fig. 4. The figure displays that the peak compressive strength was achieved by rice husk ash (30.30MPa) waste sample followed by oil palm fruit bunch fibre (19.50MPa) and pineapple leaf fibre (18MPa). On the other hand, natural polymer such as bael resin (0.13MPa), agarwood resin (0.20MPa) and jack resin (0.24MPa) had the lowest values. It can be observed that, dawul kurudu, wheat hay fibre, wood apple resin, jack resin, agarwood resin, bael resin did not satisfy any standard criteria whereas rice husk, oil palm fruit bunch, pineapple leaf fibre, palm fibre, date palm fibre and straw met all the standard requirements. Sisal fibre, wood aggregate/fibre, corn silk fibre, processed waste tea, cassava powder, banana fibre, kenaf fibre, coconut coir, henequen fibre, grass and sawdust waste materials fulfilled the minimum requirements (2MPa) of the New Mexico Earthen Building Code [149], NBR 8492 [148], DIN 18945 [150], IS 1725 [146] and BS 3921 [144] (5MPa) except ASTM 62-17 [143] (10.30MPa). Tobacco residues, flax fibre, seaweeds fibre, sheep wool, bio-briquette, lavender straw, hemp fibre, corn plant fibre, corn cob, oil palm fruit fibre, grewia optiva fibre, eggshell, fonio straw, sugarcane bagasse, fescue, pines gum, cassava peel and pinus roxburghii fibre satisfied the New Mexico Earthen Building Code, NBR 8492, DIN 18945, IS 1725. Nevertheless, grounded olive stones, pig hair and jute compiled with the NZS D4298 [151] (1.30MPa), SLS 1382 [147] (1.20MPa) and TS 2514 [152] (1MPa) standards.

Like compressive strength, flexural strength varied noticeably depending on the references (see Fig. 5). The results presented that flexural strength improved with the addition of waste. But for higher waste content of cassava peel, sisal fibre, pig hair, banana fibre, rice husk and hemp shiv and flexural strength seemed to decrease. Only grounded olive stones had the value (0.16MPa) lower than the standards and all other waste-incorporated samples met the standard requirements of IS 1725 (0.50MPa) [146], New Mexico Earthen Building Code (0.35MPa) [149] and NZS D4298 (0.25MPa) [151]. The highest flexural strength value was achieved by rice husk ash (6.17MPa) followed by sisal fibre (5.50MPa) corresponding to around 11 times higher than IS 1725 standard.

5.2.2 Effects of non-agro wastes on the compressive and flexural strength of unfired earth blocks

Section 4.4 revealed that almost all studies showed an increase in compressive strength with increasing additive percentage. However, additives such as KS770, soda ash, molybdenum tailing, crumb rubber and alumina filler waste showed a decreasing trend in strength as the volume of waste increased. Porter et al. [126] presented that the addition of crumb rubber decreased the compressive strength as it is a softer material which reduced the bulk properties of the mixture. For alumina filler waste [128] increasing waste content resulted in a decrease in strength because of the reduction of cohesion between particles thereby forming an additional internal open structure on the samples. According to Zhou et al. [133], the raw materials (cement, sand and molybdenum tailings) reacted with water and formed $CaO.SiO_2.xH_2O$ (CSH) and $CaO.Al_2O_3.xH_2O$ (CAH). The particles of molybdenum tailing were bonded by CSH and CAH forming skeletal structure and hence the samples attained mechanical strength. However, when the addition of molybdenum was greater, the CSH and CAH were lacking in the samples, as a result, the mechanical strength decreased. It is evident from the Fig. 8 that ceramic waste (highest value of 33.60MPa), waterworks sludge, molybdenum tailings, bottom ash, fly ash, coal ash, alumina filler residues, concrete waste and salvaged steel fibre satisfied all the standard requirements mentioned in Table 6. On the other hand, KS770 (1.45MPa) and soda ash showed the lowest compressive strength (1.71MPa) but met the NZS D4298, SLS 1382 and TS 2514 standard. In addition, polystyrene fibre, marble dust, polymer fibre, calcium carbide residues, polyurethane, glass fibre reinforced polymer and brick dust waste fulfilled the New Mexico Earthen Building Code, NBR 8492, DIN 18945, IS 1725, NZS D4298, SLS 1382 and TS 2514 standard conditions. Other wastes such as crumb rubber, magnesium oxide waste, granulated blast furnace slag, plastic fibre, iron mine spoil waste, polyethylene terephthalate and recycled aggregate complied with all the standards except ASTM 62-17.

Table 4 indicates that only 9 papers out of 29 conducted tests on flexural strength. From the results summarised in Section 4.4, it can be presented that the incorporation of waste materials in the samples had various impacts on the flexural strength. In general, all the additives enhanced the flexural strength with the increase of their doses. From Fig. 9, it can be observed that molybdenum tailing (7.56MPa) followed by fly ash, salvaged steel fibre (2.60MPa) showed higher flexural strength values which were approximately 15 and 5 times greater than the standard IS 1725 (0.50MPa) requirement. Also, marble dust and polymer fibre, recycled aggregate, iron mine spoil waste and polyethylene terephthalate waste achieved the minimum requirements mentioned in Indian standard for Earth Building, New Mexico Earthen Building Code and New Zealand Standard NZS 18945. Contrarily, polyurethane (0.17MPa) and crumb rubber (0.16MPa) indicated value bellow the standards.

5.3 Effects of waste materials on the thermal properties of unfired earth blocks

The influences of agro and non-agro waste materials on the thermal properties of the unfired earth blocks were very rarely studied. Thermal properties were rarely investigated by the selected articles. However total 15 articles [62], [63], [64], [73], [79], [90], [97], [101], [107], [112], [115], [119], [131], [132], [136] measured the thermal conductivity and only 6 articles [90], [101], [115], [119], [126], [131] measured specific heat capacity as well (see Fig. 10 and Fig. 11). Different apparatus was used to measure the conductivity value such as QTM-500 quick thermal conductivity meter [55], EP500 guarded hot plate apparatus [74], TR-1 probe [63] and Fox 200 device with the thermoflux meter [76]. Huynh et al. [79], Oti et al. [119] and Bogas et al. [132] presented that density, void volume and thermal conductivity were correlated. Thermal conductivity decreased with the reduction in density but it had an inverse relation with the void volume of the samples. Overall, the results of the review papers suggested that the thermal efficiency of the unfired earth samples enhanced with the introduction of waste materials.

5.3.1 Effects of agro wastes on the thermal conductivity of unfired earth blocks

Schroeder [142] reported that for earth building materials, the thermal conductivity values ranged from 0.10W/mK to 1.40W/mK for 300kg/m^3 to 2.200kg/m^3 of material density. All the studies reviewed presented that thermal conductivity value decreased with the addition of agro-wastes and ranged between 0.14-1W/mK which complied with the results presented by Schroeder [142]. The straw fibre reinforced sample showed the lowest thermal conductivity value (0.14W/mK) followed by sheep wool (0.19W/mK) and hemp fibre (0.20W/mK) samples. On the other hand, higher conductivity values were recorded for kenaf fibre (1W/mK), rice husk (0.68W/mK) and coconut fibre (0.65W/mK) samples. For other wastes such as fonio straw, date palm, corn husk, corn cob, lavender straw and olive waste the value reached between 0.25-0.50W/mK.

5.3.2 Effects of non-agro wastes on the thermal conductivity of unfired earth blocks

Oti et al. [119] conducted the tests using Laser-comp FOX 200 thermal conductivity meter within the temperature range of 2.5–17.5˚C and Bogas et al. [132] used an ISOMET 2114 portable heat transfer analyser for laboratory data collection and analysis. In all the five cases of the study, it indicated that incorporation of waste materials to the sample blocks enhanced the thermal performance by decreasing the thermal conductivity values. Fig. 11 shows that granulated blast furnace slag (0.37W/mK) blended samples exhibited the best performance followed by calcium carbide residue (0.47W/mK), recycled aggregate (0.61W/mK), glass fibre reinforced polymer waste (0.68W/mK) and fly ash (0.78W/mK).

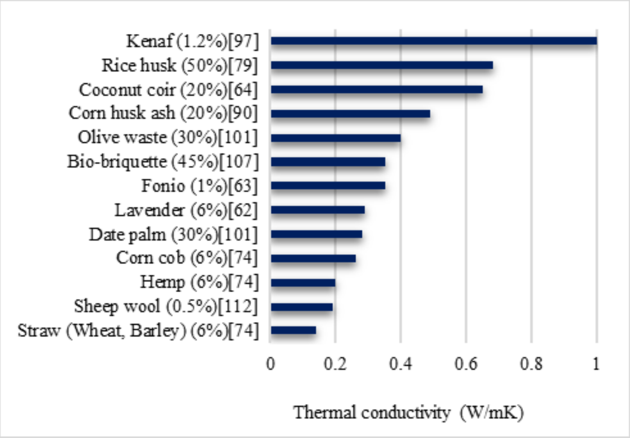


Fig. 10. Thermal conductivity of agro waste-incorporated samples

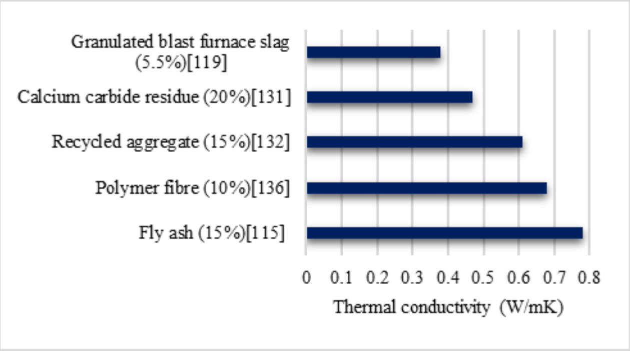
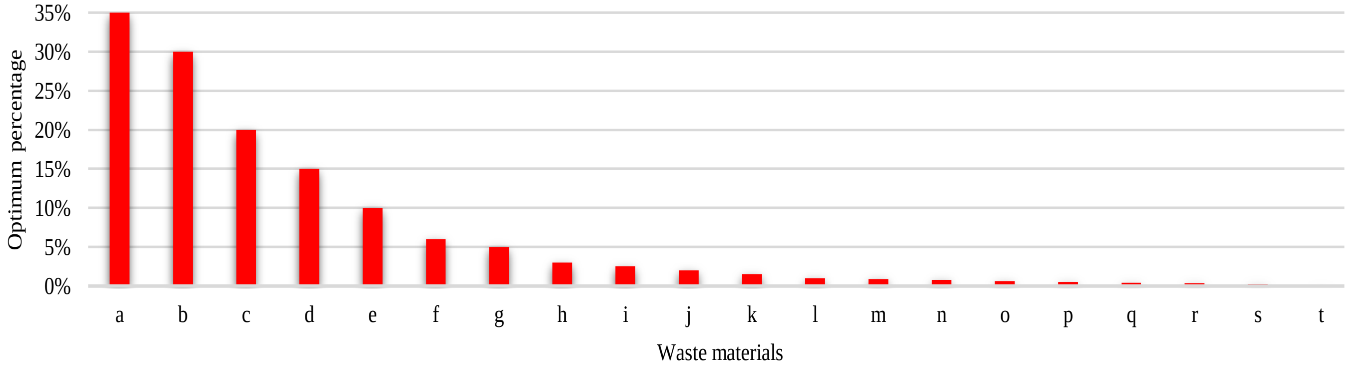


Fig. 11. Thermal conductivity of non- agro waste-incorporated samples



a-Bio-briquette [107], b-Eggshell [109], Olive waste [101], c- Bael resin [87], Corn husk ash [90], d-Sugarcane bagasse, Dawul kurudu, Pines gum, Jack resin [87], e-Sawdust, Tobacco residue, Grass [84], Wood apple resin [87], Seaweed [105], f-Straw (Wheat, Barley), Lavender [62], Corn cob [73], g-Rice husk [77], Agarwood resin [87], Grounded olive stone [88], Processed waste tea [108], h-Hemp, Flax [72], Corn plant [88], i-Cassava peel [91], j-Grewia optiva [29], Jute [71], k-Wood aggregate/fibre [82], Cassava powder [92], l-Pinus roxburghii [29], Fescue [88], Eucalyptus pulp [93], Wheat hay [95], m-Palm bark [78], n-Sisal [92], Oil palm fruit bunch [94], o-Kenaf [96], p-Coconut coir [65], Pig hair [110], q-Fonio [63], r-Banana [69], s-Oil palm fruit [65], Corn silk [89], Pineapple leaf [94], Henequen [98], Sheep wool [111], t-Date palm [99], [100].

Fig. 12. Optimum percentage of different agro wastes

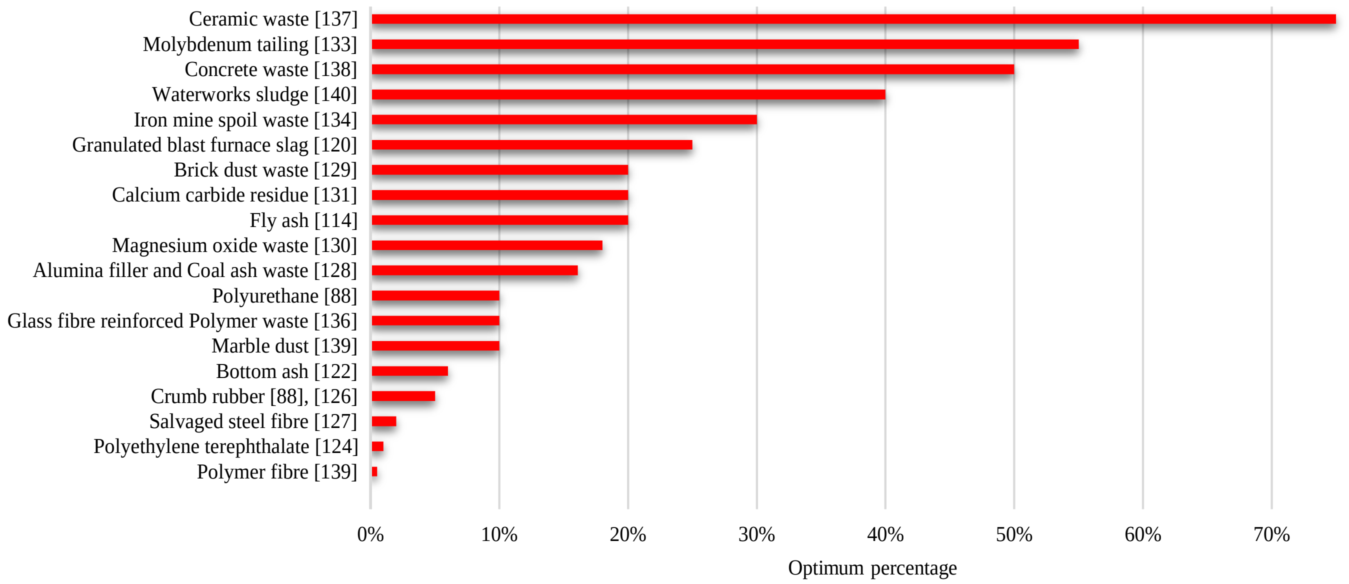


Fig. 13. Optimum percentage of different non- agro wastes

5.4. Optimum percentage of waste materials

Fig. 12 and Fig. 13 show respectively the optimum percentage of agro and non-agro wastes recommended by the several reviewed studies. Among various agro wastes bio-briquette (35%), eggshell powder and olive waste (30%) had a greater optimum percentage followed by corn husk ash and bael resin (20%). Sugarcane bagasse, dawul kurudu, pines gum, jack resin, tobacco residues, grass, wood apple resin, sawdust and seaweeds fibre performed better between 10% to 15%. Moreover, straw, lavender straw, corn cob, rice husk, grounded olive stones, processed waste tea and agarwood resin had a lower percentage (5% to 6%). Other agro wastes blended samples achieved better properties in lower than 5% of the waste quantity.

Fig. 13 reveals that ceramic waste, molybdenum tailing and concrete waste can replace 50% soil effectively whereas waterworks sludge and iron mine spoil waste can substitute 40% and 30% soil respectively. On the other hand, the optimum ratio of granulated blast furnace slag was reported as 25%. Brick dust, calcium carbide waste, magnesium ash and magnesium oxide waste accounted for an optimum proportion of approximately 20%. Also, alumina filler performed better at 16% of doses. Polyurethane, glass fibre reinforced polymer waste and marble dust exhibited the best performance at the same amount (10%). Besides, crumb rubber, polyethylene terephthalate, salvaged steel fibre, polymer fibre had a lower optimum value ranged between 0.50-6%.

6. Conclusion

The following conclusions can be reached based on the review of numerous agro and non-agro-waste materials incorporations into unfired earth blocks production:

Several recent studies widely considered the use of several waste materials for the development of unfired earth blocks construction and concluded that waste materials can help to develop renewable and environmentally friendly building products [138]. Different test methods and standards have been listed and results have been discussed by the types of wastes addition. The literature contains different tests, but the most widely mentioned are density, compressive strength and water absorption. It is also observed that the selected papers rarely mentioned other important properties such as thermal, acoustic and fire resistance of the earth blocks. Since these building material properties are related to human comfort and safety, it may be useful to implement the evaluation of these features in the manufacture of waste-integrated earth building materials [58, 76, 110]. The test results varied according to the types of waste materials (fibre, powder, pellet, polymer etc.), length of fibres and soil composition. Regarding physical properties, a decrease in density and an increase in water absorption was observed with the addition of agro wastes content because of their lightweight and high hydrophilic characteristics. Besides, strength and thermal efficiency enhanced with the addition of waste materials. In most of the cases, the produced waste-incorporated earth blocks were well agreed with the specifications specified in the relevant standards. Moreover, it was concluded as a cost-effective choice for sustainable green building material design [71, 82, 131]. As there are no specific experimental guidelines available to select design parameters for production and property assessment of waste-incorporated earth blocks further research work in the field of establishment of standards is required. In conclusion, as waste management in the developing world raises environmental concerns, utilising these wastes in the building construction sector might be a worthwhile alternative solution for global environmental pollution control.

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