

Critical review of recent development in fiber reinforced adobe bricks for sustainable construction

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ABSTRACT This paper presents a state-of-the-art review of research on the utilization of fibers (predominantly derived from waste materials) as reinforcement in adobe brick production. Recycling of these wastes provides sustainable construction materials and helps to protect the environment. Specimen preparation and test procedures are outlined. The effects of addition of these wastes on the physical and mechanical properties of adobe bricks as presented in the literature, are investigated. The main results for each additive are presented and discussed. It is concluded that improved adobe brick properties can be expected with the addition of combination of waste additives. The use of waste materials in the construction industry is generally of interest and useful for engineers and designers seeking sustainable solutions in construction. It is also of interest to researchers actively seeking to develop methodical approaches to quantifying, optimising and testing the performance in use of such waste material additives.

KEYWORDS adobe bricks, fibre reinforced bricks, green, sustainable building material, physical and mechanical properties

1 Introduction

Adobe is a composite construction material made of earth mixed with water and organic materials such as straw and dung. It has been used in construction across the world for thousands of years. Adobe continues to present an environmentally sustainable alternative that avoids the use of energy intensive, high carbon content materials. Features of adobe bricks include their availability, low cost, unsophisticated production technique and, in many applications, acceptable physical and mechanical properties. The adequacy and durability of adobe construction is well documented [1–5].

However, adobe has some undesirable properties such as affinity for water, brittle behavior and low compressive and tensile strength compared to other mainstream construction materials [6–9]. Such deficiencies may be overcome by reinforcing the soil mixture with additives or stabilizers. Moreover, the rising demand and popularity for use of sustainable, lightweight and affordable construction materials drives the need to investigate how this can be achieved to benefit the environment while ensuring

compliance with regulatory standards. As a result, the use of additives in adobe bricks has been the focus of many studies. Much of the research in this area is based on the hypothesis that brick properties can be enhanced by the addition of natural and waste materials. In addition, use of such additives in reinforcing construction materials is a practical and valuable solution to the environmental pollution problem.

Recycling waste materials, instead of dumping or burning them, is one of the advantages using waste in brick-making. A number of other advantages are reported in the literature. Some of these include improved strength and durability of the finished product. The inclusion of certain additives creates a network of fibers, which can help to reduce the size of shrinkage cracks and post-cracking tensile strength [10–14]. Likewise, enhanced thermal and acoustic properties of adobe reinforced bricks due to their porous structure have also been investigated [15–17].

Much research has been carried out, but commercial production of improved adobe brick using waste additives remains very limited. The authors of the present paper draw attention to the importance of developing and using green building materials such as adobe bricks made of

readily available local materials. The use of energy-intensive, high carbon content, and very often expensive construction materials can be avoided, for example in the housing sectors worldwide especially in developing countries, where the use of adobe has withstood the test of time.

A wide variety of clay compositions and preparation methods have been used in previous studies to improve the performance of adobe bricks by selectively incorporating waste materials in its production. There is thus a need for production methodology and characterization of raw materials use, including recycled waste additives, and the method of production to be investigated and documented in some detail. The primary objective of the present paper is to assess and present the information that is reported in the literature, to encourage brick makers and researchers to better evaluate the potential for producing improved adobe bricks from selected, widely available waste materials. This study contribute to solving the problem of housing shortage by providing affordable building materials, and relevant to all with an interest in sustainable, affordable construction material development.

2 Previous reviews on utilization of waste additives in adobe bricks production

Over the years, many review papers have been carried out that looked at incorporating different kinds of agricultural and industrial wastes in adobe brick making. Four studies of note are highlighted in this section [18–21].

Bahobail [18] reviewed mud additives that are used in different regions of the world and their effect on adobe brick making and performance. This study presents information about additive addition in improving soil mixture. However, precise details about sample preparation and soil characterization were missing.

Raut et al. [19] investigated recycling of several industrial and agricultural solid wastes in the development of sustainable waste-modified adobe bricks. Size of sample, shaping methods and curing process and tests conducted were discussed. However, the study was limited because the effect of percentage of additive on water absorption (WA) and the compressive strength (CS) of the modified bricks were not presented.

Dondi et al. [20,21] studied the utilization of different waste additives in adobe brick production. Additive content, shaping technique and chemical composition, for each additive, were outlined. In addition, the influence of each additive on linear shrinkage (LS), WA, bending strength (BS), and CS were determined. This study was published in two parts and is one of the early attempts to discuss the recycling of industrial wastes in brick production. Some of this work is mentioned in Refs. [18–21] but is discussed here in greater detail.

Table 1 lists the full body of literature reviewed in this

study, summarizing the types and percentages of additives used, together with the origin /location and publication date of the study. 22 different additives are discussed, based on 45 literature studies from the past 15 years. It is important to note that in most cases the additives used were locally available, inexpensive (or even free), and recycled. This explains their variety, they were thus chosen not only for their composition or properties but more for their abundance.

It can be seen from Table 1 that some additives were only partially investigated. Wool fiber, for example, was the only animal fiber reported in the literature to date, as indicated in Table 1 [23,31]. Moreover, animal fiber such as chicken feather is inexpensive, lightweight, and continuously renewable with excellent compressibility and resilience. It is a global waste product and has good thermal insulation properties [67]. Due to its desirable characteristics, a number of studies looked at the use of fiber from chicken feather in many potential industrial applications such as in textile industry [68], bioplastics [69] and wastewater treatment [70]. However, none have focused on reinforcing adobe bricks with this additive. Research and development trials, to reinforce adobe bricks with chicken feather, are being carried out by the authors and will be reported in the near future.

Another interesting additive presented in Table 1 is sugarcane bagasse. According to Sun et al. [71], the annual production of sugarcane bagasse globally is over 54 million tons. This large amount of sugarcane bagasse, a commonly found waste product in some parts of the world, creates several environmental problems such as land contamination, dust, and air pollution [72]. Sugarcane bagasse has been used in applications ranging from animal feed to paper production [73]. However, due to the low volume usage of these industries, the reduction in the quantity of bagasse waste used is small. Sugarcane bagasse is mainly composed of crystalline silica particles and could be used as a filler in clay brick [33,46,47,61,64]. Studies on the use of sugarcane bagasse in adobe brick production are limited. More comprehensive and detailed research on adobe brick reinforced with sugarcane bagasse is therefore indicated.

Use of chicken feather and sugarcane bagasse have thus been selected for further study by the authors because of their availability across the world, their low cost along with superior properties such as density and strength.

3 Review of developments in reinforced adobe bricks

3.1 Soil characterization

The chemical analysis of soil without additives must be considered as the chemical composition of soil has significant effect on its physical and mechanical properties

Table 1 Literature reviewed on types of fiber additives investigated

ref. no.	additive (wt% age used)	location	date
[22]	waste tea (0%–5%)	Turkey	2006
[23]	sheep's wool (0.25%–0.5%)	UK	2010
[24]	polypropylene fibers (0.2%–1.0%)	USA	2016
[25]	lime-activated ground granulated blastfurnace sag (0%–1.3%) and Portland cement (0%–1.3%)	UK	2009
[26]	hemp fiber (0%–15%)	Romania	2016
[27]	lime (0%–20%)	UK	2008
[28]	sisal fibers 0.5%	France	2004
[29]	oil palm fiber (0.25%–1%)	Malaysia	2017
[30]	polypropylene fibers (0.2%–1.0%)	USA	2015
[31]	wool fibers (2%–3%)	Italy	2012
[32]	pineapple leaves (0.25%–0.75%) and oil palm fruit bunch (0.25%–0.75%)	Malaysia	2011
[33]	coconut (1%), bagasse (1%), and oil palm fibers (1%)	UK	2015
[34]	ground granulated blastfurnace slag (1.5%–3%) and alkaline (lime) (1.5%–3%)	UK	2009
[35]	natural vernacular fibers of <i>Grewia optivia</i> (0.5%–2%) and <i>Pinus roxburghii</i> (0.5%–2%)	India	2015
[36]	<i>Grewia optivia</i> (0%–2%) and <i>Pinus roxburghii</i> (0%–2%)	India	2016
[37]	straw fiber (0%–0.33%)	Italy	2011
[38]	banana fibers (0%–5%)	USA	2016
[39]	<i>Hibiscus cannabinus</i> fibers (0%–0.8%)	France	2014
[40]	rice husk ash (0%–10%)	Indonesia	2011
[41]	straw fibers (0.5%–3%)	Italy	2015
[42]	plastic-fiber (0.1%–0.2%)	India	2015
[43]	quicklime (0%–30%) and portland cement (0%–15%)	Egypt	2013
[44]	sawdust (2.5%–5%)	Romania	2014
[45]	straw (25%–33.3%)	Spain	2011
[46]	sugarcane bagasse (2%–6%)	Brazil	2015
[47]	sugarcane bagasse ash (0%–50%)	Thailand	2013
[48]	date palm fibers (0%–0.2%)	Algeria	2014
[49]	plastic fiber (0.1%), straw (2%), and polystyrene fiber (0.5%)	Turkey	2005
[50]	wheat straw fibers (1%–3%)	Egypt	2015
[51]	date palm fiber (0.05%–0.2%)	Algeria	2016
[52]	straw fibers (0%–0.75%)	Italy	2010
[53]	hemp and flax fibers (0%–3%)	Austria	2016
[54]	wheat straw fibers (0.89%–3.84%)	Turkey	2008
[55]	brick dust waste (5%–20%)	UK	2014
[56]	wood cutting wastes (4%)	Mexico	2016
[57]	plastic fiber (0.2%), straw (2%), and polystyrene fabric (0.6%)	Turkey	2009
[58]	straw (1%) and fly ash (10%)	Turkey	2011
[59]	sugarcane fiber (0%–3%)	USA	2016
[60]	lime (0%–12%)	Burkina Faso	2008
[61]	coconut (0.25%–1%), oil palm (0.25%–1%), and bagasse (0.25%–1%)	UK	2015
[62]	corn plant (1%–3%), fescue (1%–3%), straw (1%–3%), grounded olive stones (1%–3%), rubber crumbs and polyurethane (1%–3%)	Spain	2016
[63]	plastic fibers (0.2%)	Turkey	2007

ref. no.	additive (wt% age used)	location	date
[64]	sugarcane bagasse ash (0%–8%)	Brazil	2012
[65]	lime-activated ground (1.5%–2.6%)	UK	2009
[66]	<i>Pinus roxburghii</i> (0.5%–2%) and <i>Grewia optivia</i> (0.5%–2%)	India	2015

(Continued)

[74,75]. Therefore, this must be established so that the effect of additives can be properly studied. Based on X-ray diffraction (XRD) results obtained from the reviewed papers [22,23,26–28,33,34,39,40,47,48,51,55,57,58,60,63–65], the chemical properties of the soil used in the papers that were considered in Table 1 are summarized in Fig. 1.

XRD analysis shows that there are four main chemical components. The most abundant component is silica (SiO_2) which typically ranges from 50% to 60% by weight (Fig. 1). The porosity of adobe is strongly related to the silica content in the mix. The next most abundant component is alumina (Al_2O_3). At constant pH, strength increases with alumina content, which typically averages at about 10% by weight of the soil composition. Its presence is thought to contribute to improved quality of adobe bricks (Fig. 1).

Another important component observed is ferric oxide (Fe_2O_3), which may often be the cause of efflorescence in adobe. As a result, it is considered good practice to keep the ferric oxide content at less than 10% by weight (Fig. 1). Lastly, the concentration of lime (CaO) can be up to 10% by weight (Fig. 1). Mechanical strength increases with increasing interaction between lime and silica. However, if free lime does not bond with silica, expansion in bricks due to moisture absorption may be developed, which will eventually lead to cracks and failure [74].

It should be noted that most of the papers considered by this work have used soil with acceptable chemical composition by brick manufacturers. Nevertheless, few papers presented low SiO_2 content such as [27,33,51,61] and other showed high concentration of CaO [27,51].

When adobe bricks are reinforced with lime [27]; coconut [33,61] or date palm [51], exhibit problems related to porosity and strength that are expected in the manufacture of adobe bricks from one of these additives at industrial scale.

The chemical composition of soils reported in the literature is shown in Fig. 1, highlighting similarities and differences. The chemical composition of the additives used can vary significantly due to different origins and treatment process of such additives. It is not possible to quantify the chemical composition of every additive because of variability source: this aspect will be the subject of a separate, future investigation.

Particle size (PS) distribution is carried out by shaking the soil samples in a set of descending opening size sieves, and measurement of the cumulative percentage amounts passing through each sieve size [38]. Different soil components will have a significant influence on the binding force, and therefore also on the tensile and compressive strength of adobe bricks [53]. The PS of the soils reported in the literature are presented in Fig. 2.

According to the literature, the following ranges are suitable for earth construction: less than 10% of gravel (grain diameter $d_g > 2.0$ mm); 40%–70% of sand ($0.063 \text{ mm} < d_g < 2.0$ mm); 10%–30% of silt ($0.002 \text{ mm} < d_g < 0.063$ mm) and less than 40% of clay ($d_g < 0.002$ mm) [26,30,33,36–38,40–42,49–54,58,61,63,64].

3.2 Sample preparation

Sample preparation methods can define the physical,

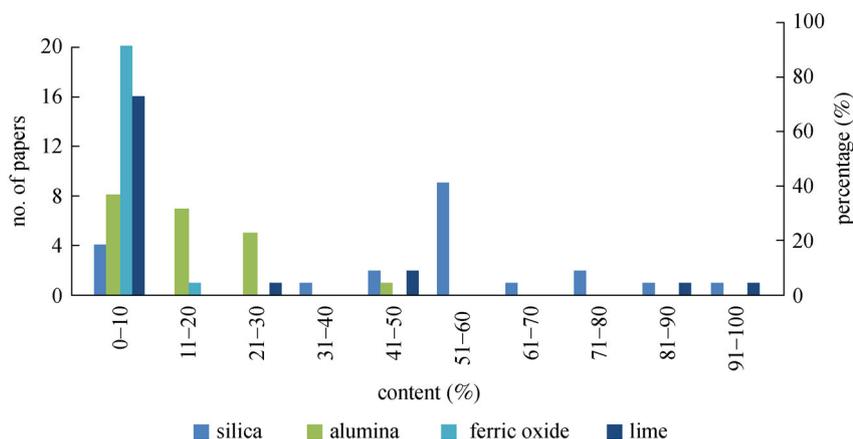


Fig. 1 Chemical analysis of the soil types reviewed in the literature.

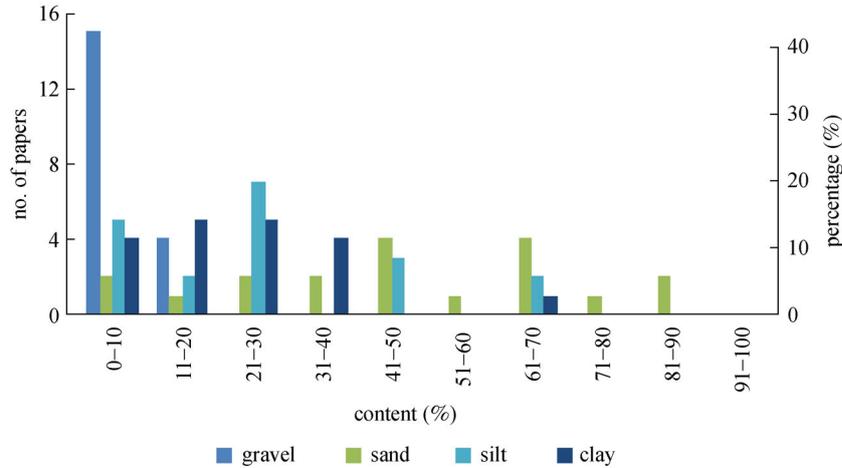


Fig. 2 PS distribution of the soil types reviewed in the literature.

mechanical and thermal properties of adobe bricks. For industrial applications, authors are required to state clearly how samples are developed. A review of literature shows that several adobe-making methodologies were used in the papers that were considered by this work as presented in Fig. 3.

Adobe bricks are generally made from soil, water, and additives. All materials are mixed and sufficient amount of water is added to the mixture for workability purposes. The amount of water is a main factor that can affect the shaping and the drying of the finished bricks, before the clay mixture is shaped using one of the following shaping techniques: pressing, extrusion or molding. The technique chosen for brick shaping, influences the required amount of mixing water to achieve optimum plasticity. Adobe brick manufacture by extrusion generally uses an Archimedes auger. This method is preferred as it delivers lower overall production cost [74].

It should be noted that the pressing force was not reported in studies that employed the pressing method [25,27,32–34,42,50,64], except for Refs.[30,51]. For samples made by molding [23,24,65,66], information about the molding method is not fully described, and less so with the extrusion method [22,55]. For example, pressure data for bricks made by molding is not given although this information is valuable to upscale results to commercial level. This is also important for the brick manufacturer since the volume of mixing water required depends on this pressure.

Finally, the shaped samples are dried at ambient laboratory conditions, and/or in an oven. The drying process can affect the size and volume of the finished product. Uncontrolled dry conditions may produce cracks, deformation on adobe bricks, and/or efflorescence due to the soluble salts contained. Gentle drying at ambient in the laboratory is the most commonly used drying method

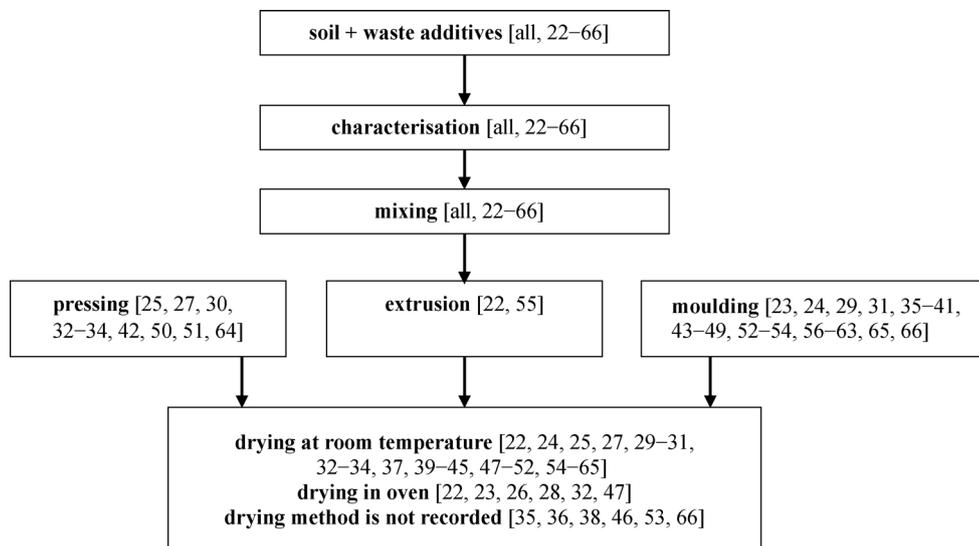


Fig. 3 Brick production methodologies reviewed in the literature.

[24,25,27,29–31,33,34,37,39–45,47–52,54–65] with the temperature ranging between 20°C to 35°C until constant weight is achieved. However, Refs. [23,26,28,32] used oven for drying at temperature reaching up to 105°C. Some researcher used both natural drying and electronic oven [22,32,47], while few researchers did not report their drying methods [38,53]. Drying time and temperature are key factors to retain the resistance of the brick and avoid cracks or fractures.

It is notable that the practice in many countries is for adobe bricks to be mixed, cast or molded, dried and stored outdoors, where the process would be influenced by outdoor air relative humidity, temperature and flow, and exposure to solar radiation. In factory production, on the other hand, the drying process involves several stages of tunnel drying with controlled humidity and temperature requirements.

Procedures for the making of adobe bricks in the papers that have been considered are summarized in Table 2. Shaping techniques, number of samples, size and drying methods are also presented. Various types of brick with different shapes (blocks, cubes, cylindrical, prism shape) were produced in the literature, as summarized in Table 2. Some studies did not report their sample number [24,28,29,31–33,39,43–46,48,62], while others did not mention their sample size [34,50,51]. It is important to note that all the steps followed in the study and development of reinforced adobe bricks are important if one is to replicate and confirm the findings from these studies. Therefore, all information related to sample preparation should be recorded and reported in detail to assure the same results on commercial scale.

It is clear from Table 2 that researchers have tested various waste additives in different proportions and adopted various methodologies to produce adobe bricks, as per the various applicable standards in their countries.

3.3 The testing of samples

Various types of tests have been carried out on adobe bricks to measure their properties for construction purposes as presented in Table 2. The properties of the bricks obtained depend, among other things, on the nature and quantity of the additives added. The authors of these studies have mainly focused on durability, reliability and strength. The most common adobe tests conducted in the papers reviewed were CS, WA, and flexural strength (FS). Based on the results of these tests, bricks can be grouped into different categories according to different material standards. Bulk density (BD) and LS are also required and should be measured to guide the design of suitable molds and tools used in adobe brick production. Characterization of raw materials through XRD, PS, porosity measurement (AP), and scanning electron microscope (SEM) investigations were used to understand how different waste additives affect clay mixtures.

One of the known benefits of adobe construction is its inherent potential to help ensure stable, well controlled indoor environmental conditions (temperature and humidity) in buildings. However, limited research has been carried out to investigate and quantify the thermal conductivity (TC) of adobe [26,29,30,39,47,50,51,60,63]. Only one study touched on the hygroscopic performance of adobe bricks by testing its water suction (WS) [29].

Table 3 summarizes all the tests that have been undertaken in the considered papers, and the standards referenced. It should be noted that some of the additives used include toxic agents such as rice husk ash [40], sugarcane bagasse ash [47,64], fly ash [58], and brick dust waste [55]. In these cases, leaching tests should be carried out to avoid health risk related problems. More research regarding the environmental impact of adobe bricks is required.

4 Discussions

The procedures and tests reported in the papers that were considered have been summarized in Table 3. The adobe brick properties considered by most researchers as required by various standards are BD, water absorption (WS), and CS. The results from these tests will now be evaluated and discussed in detail.

The density of a material is known to strongly correlate with mechanical and thermal properties. Adding additives into the clay mixture decreases the density of the bricks. As bricks are generally heavy and compact, future research must focus on the development of lightweight products, reducing weight and at the same time recycling wastes to obtain the desired result. Too high a reduction in density can, however, lead to structural defects.

Figure 4 shows that BD of adobe bricks incorporating plastic fiber [57] is the lowest (1.26 g/cm³) compared to bricks incorporating other waste materials. BD is clearly reduced when plastic fibers are used in the mix. Adobe bricks created from waste have an average of 1.67 g/cm³. The reported density for a good quality, traditionally made adobe brick is between 1.80 and 2.00 g/cm³. Most of the samples that were tested fall within this range, except for those incorporating 0.20% plastic fiber at 1.26 g/cm³ [57] and 5% sawdust at 1.32 g/cm³ [44].

As expected, brick density falls when the amount of waste additive is increased. The reduction in density was between 7%–9% compared to control samples [61]. The main reason for such a result is the lower waste additives density itself compared to soil, which is heavier.

Adobe bricks with coconut fiber have the highest density of 1.95 g/cm³ [61]. This is evidence of densification, where the presence of waste actually improves sample compaction. No record of adobe BD has been found for some waste additives, including oil balm fiber [29], blast furnace slag [34], *Grewia optivia* (a fiber-rich tree commonly

Table 2 Sample making methodologies from literature

refs. no.	pre-conditioning	mixing water	shaping	no. samples	size (mm)	drying
[22]	sieved (max. size 4.3 mm)	24%–36.5%	by extrusion	10	40 × 70 × 100	at laboratory conditions at 21°C for 72 h and kept in an oven at 105°C
[23]	undefined	0.25%–19.75%	by molding	7	40 × 40 × 160	in an oven at 50°C for 24 h
[24]	undefined	8.0%	by molding	undefined	413 × 102 × 102	in plastic sheets and moist cured for the first 7 days
[25]	sieved (max. size 5 mm)	1.3%–1.8%	by pressure (undefined)	11	215 × 102.5 × 65	in a room temperature of about 20°C ± 2°C for 90 days
[26]	sieved (max. size 2 mm)	0.4%–2%	undefined	3	40 × 40 × 160	in an oven till to constant mass (undefined)
[27]	undefined	25%–40%	by pressure (undefined)	3	ϕ50 × 100	at room temperature of about 20°C + 2°C for 28 days
[28]	sieved (max. size 10 mm)	16.2%	by pressure (undefined)	undefined	100 × 140 × 295	in an oven at 35°C until a constant mass was attained
[29]	dried	undefined	by molding	undefined	210 × 100 × 100	dried for 28 days (undefined)
[30]	sieved (max. size 3.4 mm)	1.32%	by pressure at 1.6 MPa	5	191 × 203 × 121	under plastic sheets for 7 days (undefined)
[31]	sieved (max. size 6.2 mm)	0.18%–0.29%	by molding	undefined	360 × 75 × 75	at room temperature at 20°C for 28 days after demolding
[32]	dried, ground and sieved (max. size 63 μm)	40%	by pressure (undefined)	undefined	100 × 50 × 30	air-dried for 7 days, then transferred to an electric oven at 40°C for 7 days
[33]	sieved (max. size 7.5 mm)	18%	by pressure (undefined)	undefined	290 × 140 × 100	sun-dried at 27°C for 21 days
[34]	undefined	6%	by pressure (undefined)	11	undefined	at room temperature for 20°C ± 2°C
[35]	undefined	12.5%	by molding	216	ϕ38 × 76	undefined
[36]	sieved (max. size 10 mm)	1.4%	by molding	90	ϕ38 × 76	dried and cured for a period of four weeks (undefined)
[37]	sieved (undefined)	undefined	by molding	70	150 × 230 × 130	at Laboratory condition at 25.5°C
[38]	sieved (max. size 4.75 mm)	10%–12%	by molding	35	120 × 120 × 90	undefined
[39]	crushed and sieved (max. size 80 μm)	20%	by molding	undefined	295 × 140 × 100	at room temperature for 22°C until for 3 weeks
[40]	sieved (max. size 0.001 mm)	19%	by molding	12	230 × 110 × 55	at room temperature at ± 30°C (undefined)
[41]	dried and sieved (max. size 100 mm)	27%	by molding	36	40 × 40 × 160	dried under the sun to ensure water removal (undefined)
[42]	sieved (max. size 4000 μm)	14%	by pressure	3	101.5 × 117 × 50	cured under jute bags for 28 days
[43]	sieved (max. size 10 mm)	0.35%–0.5%	by molding	undefined	50 × 50 × 50	at room temperature at 35°C ± 2°C for 90 days
[44]	undefined	15%–25%	by molding	undefined	40 × 40 × 40	kept in natural conditions for 28 days
[45]	sieved (max. size 0.08 mm)	17.1%	by molding	undefined	100 × 120 × 250	spread out on the ground in the open air for 4 weeks
[46]	sieved (max. size 2.78 mm)	0.2%	by molding	undefined	300 × 150 × 80	undefined
[47]	dried, crushed and sieved (max. size 70 μm)	11%–18%	by molding	10	140 × 65 × 40	air-dried at room temperature for 24 h and then oven-dried at 105°C for another 8 h
[48]	crushed and sieved (max. size 2.3 mm)	10%	by molding	undefined	100 × 100 × 200	at laboratory condition at 20°C ± 2°C for 28 days

(Continued)						
refs. no.	pre-conditioning	mixing water	shaping	no. samples	size (mm)	drying
[49]	sieved (max. size 20 mm)	20%	by molding	5	150 × 150 × 150	covered with wet bags and allowed to cure for a week
[50]	dried and sieved (max. size 8 mm)	24%	by pressure (undefined)	63	undefined	at room conditions at 21.7°C for 60 days
[51]	crushed and sieved (max. size 5 mm)	12%	by pressure at 10 MPa	3	undefined	at laboratory condition at 50°C for 24 h
[52]	sieved (max. size 9 mm)	2.45%	by molding	80	310 × 460 × 130	at room condition average at 26°C for least 2 months
[53]	crushed and sieved (max. size 7 mm)	undefined	by molding	3	160 × 40 × 50	undefined
[54]	dried and sieved (undefined)	40.5%	by molding	150	100 × 100 × 100	at laboratory conditions for 28 days (undefined)
[55]	sieved (max. size 7.5 mm)	16%–25%	by extrusion	3	undefined	at room temperature at 20°C for 56 days
[56]	sieved (max. size 0.96 mm)	26%	by molding	2	φ30 × 15	at room temperature for 48 h (undefined)
[57]	undefined	20%	by molding	5	150 × 150 × 150	covered with wet bags for a week (undefined)
[58]	sieved (max. size 8.8 mm)	34%	by molding	6	115 × 105 × 215	covered with a wet cloth (undefined)
[59]	undefined	18.65%	by molding	72	120 × 60 × 60	at laboratory conditions at 26°C for 28 days
[60]	sieved (max. size 0.32 mm)	30%	by molding	6	40 × 40 × 160	at room temperature for 30 days (undefined)
[61]	sieved (max. size 2 mm)	19%	by molding	5	290 × 140 × 100	sun dried at 27°C for 21 days
[62]	undefined	20%	by molding	undefined	40 × 40 × 160	at laboratory conditions at 20°C–22°C (undefined)
[63]	sieved (max. size 20 mm)	38.7%	by molding	11	150 × 150 × 150	covered with wet bags and allowed to cure for a week
[64]	sieved (max. size 4.8 mm)	13.33%	by pressure undefined	3	340 × 340 × 110	at laboratory conditions for 28 days (undefined)
[65]	undefined	17%	by molding	11	215 × 102.5 × 65	at room temperature at 20°C for 90 days
[66]	undefined	11.48%	by molding	360	φ38 × 76	undefined

found in the Indian subcontinent) [36], rice husk ash [40], date palm fiber [48], brick dust [55], wood cutting waste [56], polypropylene fiber [30], *Hibiscus cannabinus* fiber [39], and corn plant [62].

In general, BD is directly related to CS and inversely related to water absorption (WS). In addition, a decrease in density also lead to an improvement in the thermal and sound insulation performance of adobe bricks.

The water absorption test is commonly used to quantify the durability of adobe brick in wet environments and used as an indicator for the adobe bricks resistance to immersion. The creation of porosity due to the incorporation of additives in the adobe bricks lead to an increase in water absorption. The voids in the samples while immersed, are filled with water which can penetrate the material easily, with a preferential pathway depending on the structure of pores and the way they are interconnected.

High value of water absorption for adobe bricks is not desirable as it affects durability and resistance to natural conditions.

Most building standards specify the allowable water absorption of adobe bricks to be no more than 15% [108] to 20% [114] by weight. Many specimens that were stabilized using waste satisfy the water absorption requirements for adobe bricks, apart from plastic fiber [57], lime [60], waste tea [22], and blastfurnace slag [34] as shown in Fig. 5. Water absorption plays a significant role in bonding between fiber and soil particles. High water absorption may damage the fiber-soil bonding, which results in increase shrinkage during drying due to evaporation. On the contrary, too low water absorption lead to brittle adobe brick, eventually leading to strength loss of the structure over time.

The minimum water absorption recorded was for date

Table 3 Tests conducted and referenced standards from literature

ref. no.	XRD	PS	LS	SEM	WA	BD	AP	WS	CS	TC	FS	relevant standards
[22]	-	X	X	X	-	X	-	-	X	-	-	BIA [76], ASTM C67 [77], TS 704 [78], TS 705 [79]
[23]	-	-	-	-	-	X	-	-	X	-	X	UNE-EN 196-1 [80], UNE-EN 1015-2 [81], UNE-EN 12190 [82], EN 83-821-925 [83]
[24]	-	-	-	X	-	X	-	-	-	-	X	ASTM 106 [84]
[25]	-	X	X	X	-	X	-	-	X	-	-	BS 1924-2 [85], BS EN 771-1 [86]
[26]	-	-	X	-	-	X	-	-	X	X	X	ASTM E2392 [87], SAZ 724 [88], ASTM D2487-11 [89], BS 1377-2 [90], BS 3921 [91]
[27]	-	-	-	-	-	X	-	-	X	-	-	BS 1924-2 [85]
[28]	-	X	-	-	-	X	-	-	-	-	X	undefined
[29]	X	-	X	X	X	X	X	X	X	X	X	ASTM C20-00 [92], ASTM C67 [77], IS 4860 [93], BS 3921 [91], ASTM C618-15 [94]
[30]	-	X	-	-	-	-	-	-	-	X	X	NMAC14.7.4 [95]
[31]	X	-	-	-	-	X	-	-	-	-	X	ASTM D422-63 [96], ASTM D2487-11 [89], NMAC14.7.4 [95], NZS 4297 [97], NZS 4298 [98], ASTM E2392 [87], ASTM C1018 [99]
[32]	-	X	-	-	X	X	-	-	X	-	-	BS 1377-2 [90], BS 3921 [91], MS 76 [100]
[33]	-	X	-	X	-	-	-	-	X	-	X	BS EN 771-1 [86], BS 1377-2 [90]
[34]	-	-	-	-	X	X	-	-	X	-	-	BS 1924-2 [85], BS EN 771-1 [86], BS EN 197-1 [101], BS EN 771-3 [102], US EPA 2003 [103]
[35]	-	-	-	-	-	X	-	-	X	-	X	IS 2720-4 [104], IS 2720-5 [105], IS 2720-7 [106]
[36]	-	X	-	-	X	X	-	-	-	-	X	IS 1498 [107], IS 2720-4 [104], IS 1725 [108], IS 2720-10 [109], IS 2720-5 [105], IS 2720-7 [106], IS 4332-1 [110], IS 4332-3 [111]
[37]	-	X	-	-	-	-	-	-	X	-	-	undefined
[38]	-	X	-	-	-	X	-	-	X	-	X	ASTM C67 [77], ASTM D422-63 [96]
[39]	X	-	-	X	-	-	-	-	X	X	X	ASTM D 3822-07 [112]
[40]	-	X	-	-	X	-	-	-	X	-	X	SNI 15-2094 [113], SNI 03-6458 [114]
[41]	-	X	-	-	-	X	-	-	X	-	X	ASTM D2487-11 [89], IBC 14.01 [115], NMAC14.7.4 [95]
[42]	-	X	-	-	-	-	-	-	X	-	X	BIS 1725 [116]
[43]	X	-	-	-	X	X	-	-	X	-	-	ESS 1234 [117], ESS 584-1 [118]
[44]	-	-	-	-	-	X	-	-	X	-	X	undefined
[45]	-	-	-	-	-	X	-	-	X	-	X	EN 12372 [119], UNE 103101 [120]
[46]	X	-	-	X	-	X	-	-	X	-	X	ASTM D 790 [121]
[47]	X	-	-	X	X	X	-	-	X	X	-	TIS 77 [122]
[48]	-	-	-	-	X	-	-	-	X	-	X	undefined
[49]	X	X	-	-	X	-	-	-	X	-	-	undefined
[50]	X	X	-	-	X	X	-	-	-	X	X	ASTM C 1113-99 [123]
[51]	-	X	-	-	X	-	-	-	X	X	X	XP P13-901 [124]
[52]	-	X	-	-	X	-	-	-	X	-	-	ASTM D2487-11 [89]
[53]	X	X	-	-	-	X	-	-	X	-	X	EN 1015-11 [125]
[54]	-	X	-	-	X	X	-	-	X	-	X	DIN 18952 [126]

(Continued)

ref. no.	XRD	PS	LS	SEM	WA	BD	AP	WS	CS	TC	FS	relevant standards
[55]	-	-	-	-	X	X	-	-	X	-	-	BS 1924-2 [85], BS 5628-3 [127], BS EN 771-1 [86]
[56]	-	X	-	-	X	-	-	-	X	-	-	NMAC14.7.4 [95]
[57]	X	-	-	-	-	X	X	-	X	-	-	ASTM C 384 [128]
[58]	-	X	-	-	-	-	-	-	X	-	-	undefined
[59]	-	-	-	-	X	-	-	-	X	-	-	undefined
[60]	X	-	-	X	X	-	-	-	-	X	X	NF P14-306 [129]
[61]	-	X	-	X	X	X	-	-	X	-	X	BS EN 771-1 [86], NZS 4298 [98], BS EN 772-1 [130], ASTM D559-03 [131]
[62]	-	-	-	-	-	-	-	-	X	-	X	UNE-EN 196-1 [80]
[63]	X	X	-	-	-	-	-	-	X	X	-	TS 2514 [132]
[64]	X	X	-	X	X	-	-	-	X	-	X	NBR 8492 [133]
[65]	-	-	-	-	-	-	-	-	X	-	-	BS EN 771-1 [86], BS EN 772-1 [130]
[66]	-	-	-	-	X	X	-	-	X	-	-	IS 2720-4 [104], IS 2720-5 [105], IS 2720-7 [106], IS 2720-10 [109], IS 2720-2 [134]

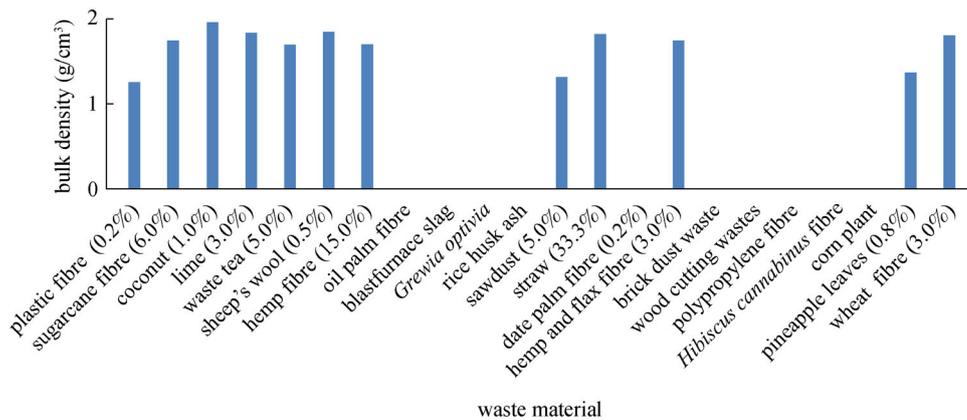


Fig. 4 BD of adobe bricks made using different waste additive.

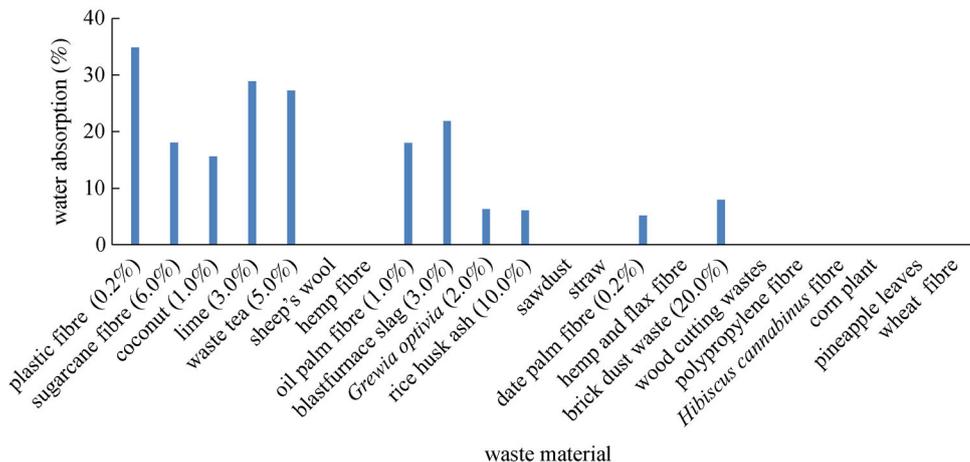


Fig. 5 WA of adobe bricks made from various waste additive.

palm fiber [51], rice husk ash [40], and *Grewia optivia* [36] having values of 5.30%, 6.20%, and 6.51%, respectively. This indicates improvement in durability with addition of these additives.

In general, water absorption of the adobe blocks increases with increase waste additives content. This increase may be attributed to the absorbent nature of additives which creates pathway through adobe blocks, thereby allowing more water to be absorbed by the bricks. However, decrease in water absorption with increase in additive content were reported in some studies [36,40,60].

The values recommended for minimum allowable CS for adobe bricks are very wide ranging and vary across national boundaries. The lowest allowable strength limits set in most current adobe brick standards range from 1.20 to 2.10 MPa [51]. The results of compression tests reported in the literature vary from 1.53 to 7.60 MPa [22,46], with the most common values being between 4.37 and 6.20 MPa [23,65]. This strength is suitable for many building purposes such as load-bearing construction. It is worth mentioning that the failure mode of the control sample was always sudden and very quick, while that of the composite material was more ductile and gradual. This means that the fibers affect the brittle behavior of the soil mix.

It is notable from Fig. 6 that the highest compressive strength for adobe brick is obtained with a waste tea additive, but with a correspondingly higher than average water absorption value of 27.30%, see Fig. 5. The compressive strength of adobe bricks incorporating waste tea is about 6 times greater than the minimum value recommended by most standards. It is also interesting that, despite possessing the lowest BD, plastic fiber reinforced adobe has almost 2.5 times the compressive strength of coconut fiber reinforced adobe, which has the highest BD, see Fig. 4.

The reason for increase in compressive strength with

increase in content of additives attributed to well soil fiber interaction and resultant bond between clay mix and added additive. The development of strength properties of reinforced adobe bricks mainly depends on the formation of fiber-soil, soil-soil, and fiber-fiber bonds. The strength of these bonds mainly depends on the dimension, surface conditions, and quantity of additives added to the soil. First, fiber-soil bond, new bond introduced in reinforced samples, is responsible for stress transmission within soil composite. This is known as fiber bridging mechanism in composite, which binds soil grains together more firmly unlike in the case of unreinforced soil samples. This phenomenon is responsible for increase in strength with the increase in additive content up to an optimum point. Secondly, soil-soil bond is the one and only bond in unreinforced samples which is responsible for unreinforced samples strength. Finally, fiber-fiber bond is the weakest bond among the three bonds and do not contribute to the composite strength.

As additive content increased above the optimal value, a loss of fiber bond was observed as fiber-fiber bond increased thus decreasing the formation of fiber-soil and soil-soil interactions leading to a lower compressive strength [30]. The effect of fiber on the properties of adobe bricks was therefore depended more on the quantity of fiber interact with the soil matrix and the fiber pull-out characteristics than on total fiber content [24]. It is important to note that higher strengths are achievable using binder such as cement or lime. The compressive strength of the cement-stabilized bricks is 70% higher than the bricks reinforced with waste additives such as lime [23,44].

Clearly, more fundamental research is needed if we are to fully understand the complex intersections of additive type on the different material properties that are of interest. One might, for example, empirically investigate the

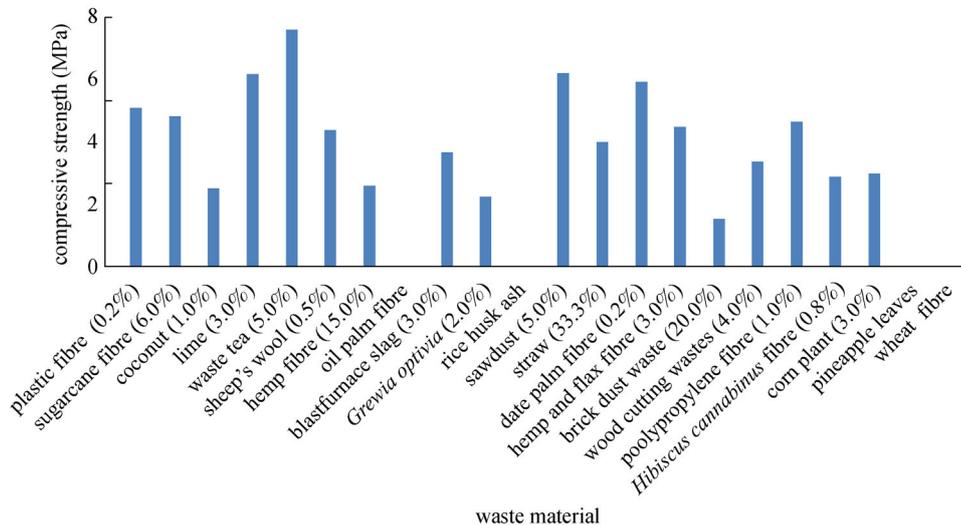


Fig. 6 CS of adobe bricks made from various waste additive.

combination of different percentages of waste tea with other waste materials such as date palm fiber, which has the lowest water absorption of 5.30%, to reduce water absorption while improving physical and mechanical properties. Moreover, new adobe bricks made from waste tea and date palm fiber could be tested for the physical, mechanical and thermal properties summarized in Table 3. Lastly, in order to underpin the sustainability credentials of adobe bricks, carbon lifecycle analysis for commercial production of innovative adobe bricks should be performed.

For future significant commercial production and application of these studies of waste-created adobe brick, several aspects need to be carefully considered. First, potential contaminants within waste additives should be managed in an effective and safe manner. Leaching tests can be carried out in line with ASTM and/or other building standard methods. Secondly, current low public acceptance of adobe bricks made from waste materials needs to be tackled through public awareness campaigns on the economic and environmental benefits of using waste-based adobe bricks. Physical properties such as color, efflorescence, and toughness are essential for public acceptance. These properties should be studied in all research papers on adobe bricks for industrial use. Finally, to encourage more adobe brick makers to incorporate waste materials in their process, adobe standards should be relevant and respond to regulatory and market needs.

5 Conclusions

The present study reviews the utilization of waste materials as reinforcement in adobe brick production. The following conclusions can be drawn from this review.

1) The use of wastes as additives in adobe production is not only environmentally friendly, affordable and energy efficient, but can also lead to the production of sustainable and durable adobe bricks by enhancing some of its physical, mechanical and thermal properties.

2) Almost all the waste additives studied in the literature are within the acceptable limit of design standards for stabilized adobe bricks in term of BD, WA, and CS.

3) Several types of test were reported in the literature. However, TC and WS tests were only carried out in limited studies.

4) Although a wide variety of waste additives have been studied for inclusion in adobe bricks, commercial-scale production remains untested. We attribute this primarily to potential contamination from waste additives, lack of appropriate adobe standards and low public acceptance.

5) Researches must define their implemented production methodology (soil characterization, sample preparation, drying and testing) in detail. Shaping pressure, for

example, plays an important role in the density of adobe which influences all other brick properties. However, this information is missing in most studies on adobe brick in the literature.

6) Although the benefits of including a single waste additive in adobe bricks is evident in the literature, further research on combinations of waste material, such as waste tea and date palm fiber, is suggested.

7) To extend the production of new, improved types of environmentally friendly adobe brick made using waste additives, further research that integrates scientific, technical, environmental, regulatory and economic impacts of such adobe bricks is needed.

8) The use of waste materials in adobe brick production provides an economic contribution and also helps protects the environment. The proposed use of waste stabilizers will help promote sustainable development in the construction industry.

Various methodologies to design and develop adobe bricks from waste additives are reviewed. Important characteristic of the bricks, incorporating different waste additives, are studied in accordance with the relevant standards. Enhanced performance of the waste/fiber reinforced adobe bricks in terms of lightweight and compressive strength is useful for researchers and designer interested in developing sustainable construction material. Despite these efforts toward improving the mechanical and thermal properties of adobe bricks, it is evident that full understanding of its behavior is still far from being conclusive. The main limitation in the literature is obtaining the optimum fiber content without considering the full response of adobe bricks. Further, appropriate design procedure for fiber-reinforced adobe brick structure has not been proposed. Therefore, the authors aim to carry out a detailed study on adobe bricks reinforced with chicken feather and sugarcane bagasse through experimental work and finite element modeling to address these issues.

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