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A state of the art review to enhance the industrial scale waste utilization in sustainable unfired bricks

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Abstract

Manufacturing of unfired bricks, in which fines are stabilized using cementitious or chemical binders, has huge potential to incorporate various wastes as a building construction material. Although researchers have successfully attempted various wastes in unfired bricks at the laboratory scale, their industrial-scale incorporation is still limited and unexplored. From an industrial point of view, mix proportions, mixing strategies, molding methods, and curing conditions are of equal importance. However, the unavailability of comprehensive knowledge related to manufacturing aspects hampers the industrial-scale implementation of research outcomes regarding waste incorporation in unfired bricks. This study summarizes the research outcomes related to waste incorporated unfired bricks, highlighting the manufacturing aspects from the industrial point of view. In this paper, mix proportions attempted, approaches for selecting the liquid content, adopted mixing strategies, compaction parameters, and curing conditions in previous studies are discussed for various waste incorporated bricks. Studies are classified based on the binder used for stabilization, and the effects of influencing parameters on the mechanical performance of bricks are discussed in detail. Furthermore, some industrial challenges related to unfired brick production in Indian scenario are discussed. Studies related to mixture proportioning, mixing optimization and hybrid curing development for a multi-waste incorporated system are expected to be future research trend for waste stabilization in unfired bricks. The comprehensive knowledge presented here is expected to support in the selection of suitable manufacturing aspects, which in turn enhances the waste utilization in unfired bricks at an industrial scale.

Keywords: Unfired brick, Wastes, Mix optimization, Compaction, Curing, Industrial-scale production

Contents

1. Introduction

Sundried mud blocks have been used for construction for centuries, especially in rural regions and in the desert [1,2]. Ancient bricks were composed of soil, molded by hand, and cured directly in sunlight without compaction. A lot of modifications in raw materials and manufacturing processes have been made from time to time to improve the performance of the bricks on various parameters. In the modern world, unfired bricks are made by stabilizing soil or sand using a variety of binders. The stabilized bricks show enhanced properties due to the improved bonding between the fine particles as compared to unstabilized bricks. The unfired bricks are nowadays machine manufactured instead of hand-molded as in earlier days. Bricks are compacted by vibrating or compressing the fresh mix. Sometimes, fresh mixes are prepared with self-compacting properties and are just poured in the molds directly.

Curing of unfired bricks in sunlight takes a longer time to achieve strength. Different curing techniques were attempted by researchers [3–5] to accommodate the changes in raw materials and to achieve the required properties in a shorter time. However, the selection of suitable curing techniques depends on the raw materials and mainly on the binder used for the stabilization. In general, cementitious binders (cement or lime) are used to stabilize the unfired bricks. However, the high carbon footprints [6,7] associated with the use of these binders are considered as the major shortcoming.

The growing need for sustainable and eco-friendly construction practice has motivated researchers to investigate for viable alternatives to conventional cement and lime-based materials. Brick stabilization by chemical binders developed through alkali activation or geopolymerization mechanisms confirms the recent emphasis on sustainable production [8]. In a recent study [9], an eco-friendly biopolymer has been used as an alternative binder. On the other hand, the use of additives to optimize the binder quantity can be an alternative approach to decrease the overall carbon footprint of the unfired bricks. In some studies [5,10], gypsum was used to optimize the amount of cementitious binders for enhanced stabilizing effect. However, the use of costly resources as an additive to optimize the binder is not an ideal solution.

Disposal of waste materials is an ecological issue that can be partially resolved by incorporating them as an ingredient for unfired bricks [11]. While incorporating wastes as partial replacement of binder gives an added advantage to decrease the overall carbon footprint of the product. Researchers [12–15] have used various wastes (phosphogypsum, fly ash, and granulated blast furnace slag) to partially replace the cementitious binders (cement and lime) in unfired bricks. As only a small quantity of binder is used for stabilization in the bricks, the utilization of wastes as a replacement of clay seems to be more significant from a recycling point of view [16]. Being abundantly available in nature, soil has been an obvious choice of manufacturers to use in unfired bricks by adopting a suitable binder. However, the use of topsoil for brick manufacturing is detrimental to the environment.

The use of waste materials in place of soil seems to be a viable option in conserving natural resources. Researchers have incorporated various waste materials in unfired bricks as a substitute to clay, such as fly ash [13], phosphogypsum [17], diatomaceous earth [10], ceramic mud [18], quarry dust [19], billet scale [19], stone mud [15], brick dust [15], recycled paper mill residue [20], crushed sand [21], and bottom ash [22]. In some studies, the sand was blended with fly ash [5], bio briquette ash [23], and phosphogypsum [24] and used as a fine aggregate. Although the studies mentioned above have proven the feasibility for the incorporation of various wastes in unfired bricks at a laboratory scale, the incorporation of wastes in unfired bricks at the industrial scale is still limited. For the manufacturing of waste incorporated bricks, comprehensive knowledge about manufacturing and other industrial aspects, as shown in Fig. 1, is necessary. Manufacturing feasibility can only be accessed with the collective knowledge about proportioning of raw materials, mixing strategy, and way of compaction and curing conditions suitable to incorporate the wastes. After assessing the manufacturing feasibility, the developed product is to be evaluated on technical and sales aspects. For industrial implementation, all the aspects are equally important and need to be evaluated before accepting for full-scale production.

Many review papers are available on unfired bricks. A brief recap about previous reviews is presented next in Section 2. The majority of review studies focused on the limited aspects of design mix and curing conditions only from waste incorporation perspective, whereas mixing and compaction strategies used were not discussed in detail. However, as shown in Fig. 1, these aspects are also equally important, which are well covered here. In the present review, studies are classified by the binders used for stabilization: cementitious and chemical based binders. The approach to select the liquid content and the variations attempted in mix proportions are highlighted. Secondly, the mixing and compaction strategies adopted by various researchers are presented in separate sections. Along with these production-related aspects, the influence of mix proportioning, compaction parameters, and curing parameters on the mechanical performance of unfired bricks are also presented. In the end, industrial challenges related to unfired bricks production in Indian scenario are discussed. The comprehensive knowledge presented in this industry-oriented review unfolds many research gaps of industrial importance to the researchers. It will enable the manufacturers to select the appropriate manufacturing parameters to enhance the waste utilization at industrial scale in unfired bricks.

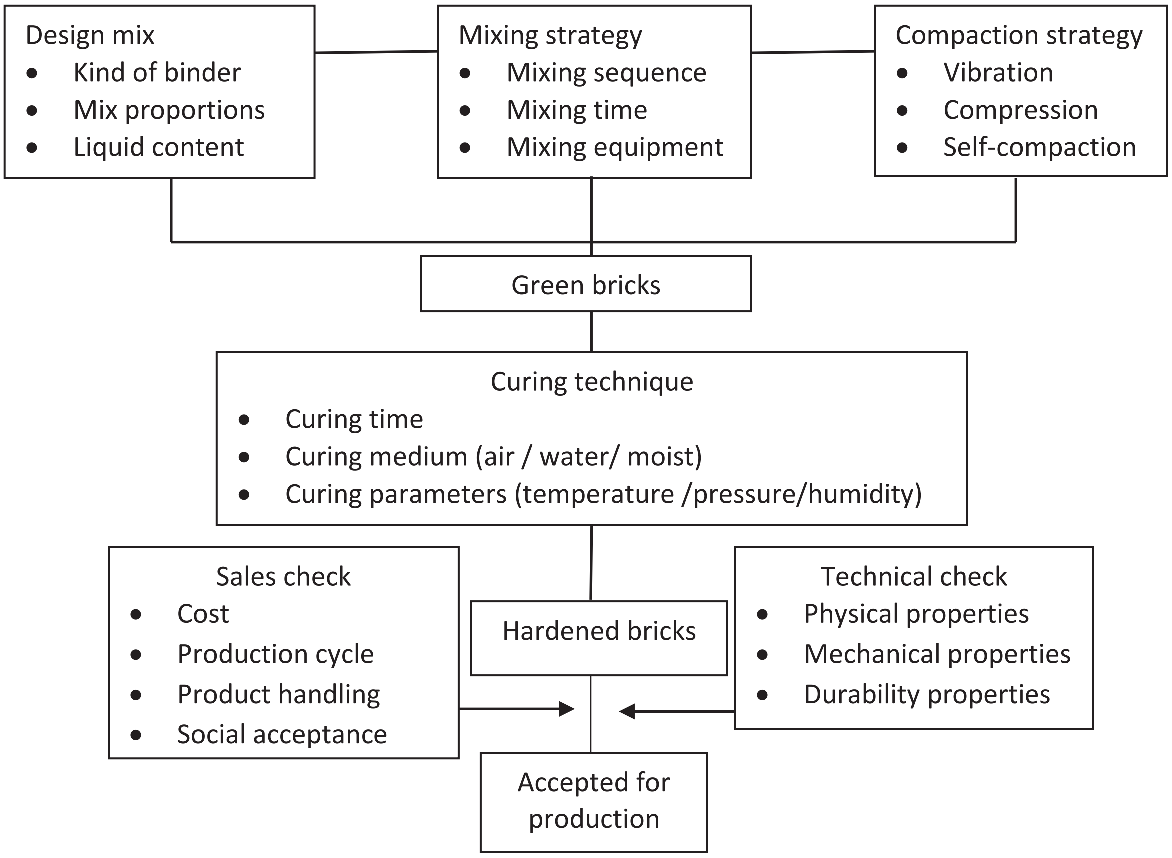

Fig. 1 Manufacturing and other industrial aspects required for waste incorporation in unfired

2. Previous reviews and gap

The development of unfired bricks and its alternatives (fired clay bricks) has been reviewed extensively in the last decade by various researchers, as shown in Table-1. Some researchers have covered unfired bricks as a sub-scope of their study, whereas some others have covered them partly. Review papers on alternative bricks have also been summarized in Table-1 to understand better the focus of the review in the last decade. In most of the review papers mentioned in Table-1, the main focus was the feasibility of waste incorporation in the bricks. Waste incorporation perspective was adopted to review the research progress related to the development of the bricks since a long lime [25].

Table-1 Reviews published in last decade on unfired bricks and its alternatives$^{\#}$

S. No.	Author(/s)	Year	Major focus area	Coverage of unfired bricks	Products focused	Ref.
1	Raut et al.	2011	Industrial and agriculture solid waste	As a sub-scope	Unfired and fired bricks	[26]
2	Kadir and Mohajerani	2011	Recycling of waste materials	No	Fired clay bricks	[27]
3	Madurwar et al.	2013	Agro waste incorporation	As a sub-scope	Particle boards, Thermal insulator, Bricks, Cementitious material, Aggregate, and Fiber reinforcement	[28]
4	Zhang	2013	Waste materials	As a sub-scope	Bricks produced through firing, cementing and geopolymerization	[29]
5	Bories et al.	2014	Pore-forming renewable and mineral resources	No	Fired clay bricks	[30]
6	Muñoz-Velasco et al.	2014	Waste incorporation	No	Fired clay bricks	[31]
7	Monteiro and Vieira	2014	Waste materials incorporation	No	Fired bricks	[32]
8	Ibrahim et al.	2015	Fly ash with the foaming agent	Partly	Geopolymer bricks	[33]
9	Muñoz V. et al.	2016	Wastes incorporation	No	Fired clay bricks	[34]
10	Boltakova et al.	2017	Inorganic industrial wastes	No	Construction ceramics	[35]
11	Murmur and Patel	2018	Composition and properties of bricks and manufacturing parameters	As a sub-scope	Stabilized earth blocks and waste incorporated fired and unfired bricks	[7]
12	Zhang et al.	2018	Alternative materials and strength developing process	As a sub-scope	Bricks	[36]
13	Al-fakih et al.	2019	Waste material incorporation	As a sub-scope	Masonry bricks	[37]
14	Gavali et al.	2019	Industrial waste incorporation	Partly	Alkali activated bricks	[38]

#Please refer to the section titled "Abbreviation" for details.

In the year 2011, Raut et al. [26] reviewed the physico-mechanical and thermal properties of bricks incorporating various types of industrial and agricultural wastes in masonry bricks. The added advantages of unfired bricks, including the low embodied-energy, were highlighted. In the year 2013, Zhang [29] presented an extensive review of waste incorporation in masonry bricks, categorizing them based on their production methodology. However, their main focus was waste incorporation in the bricks rather than the parameters of the manufacturing process. In the year 2014, Muñoz-Velasco et al. [31] presented a review focusing on the manufacturing parameters such as pre-conditioning, mixing water, shaping method, sample size, drying, and firing conditions used in the production of waste incorporated clay bricks. These manufacturing parameters are to be optimized for the required product characteristics by analyzing the influence of waste incorporation on them. From the manufacturing point of view, the influence of these parameters on product characteristics is of prime importance. However, in the above review, only studies related to fired bricks were covered. A most recent review was given by Gavali et al. [38] on the development of alkali-activated bricks. A brief review of raw material characteristics, manufacturing processes (experimental conditions opted), and properties only of alkali-activated bricks (part of unfired brick) were summarized from the experimental design point of view.

It is clear from the above that the previous review studies mentioned in Table-1, majorly focused on the optimized amount of wastes for incorporation in unfired bricks, whereas, the other manufacturing parameters were not emphasized. The unfired bricks have advantages over the alternatives in terms of lower embodied energy, mainly due to their environment-friendly manufacturing process. A comprehensive review of studies related to suitable mix proportions, mixing strategies, molding methods, and curing conditions are highly required to scale up waste incorporation in unfired bricks at an industrial scale. Such a focused review is expected to support in the selection of suitable manufacturing aspects, which in turn can enhance the waste utilization in unfired bricks at an industrial scale. Therefore, considering the need for the focused review, the studies related to unfired bricks have been summarized in the present review to enhance the industrial scale waste utilization in sustainable unfired bricks.

3. Binders and liquid content used to stabilize waste in unfired bricks

Wastes are incorporated in both forms as partial replacement of binders and also as fines in unfired bricks. The selection of a suitable binder, its optimum quantity, and the amount of liquid content for required plasticity are of considerable significance to stabilize the wastes in unfired bricks. Different types of binders, such as cementitious, chemical based, and others, were used to stabilize the unfired bricks. The majority of cementitious binders, as shown in Table-2, were used in dry form except for slaked lime, and suitable amount of water was added in the dry mix. The resultant water content at the time of molding of bricks, including the free moisture present with raw materials and the added water before the molding of the bricks, can be termed as “molding water content”. Researchers used different approaches to select the appropriate molding water content in case of dry cementitious binders. However, chemical binders, as shown in Table-3, were used in solution form. Liquid content may significantly affect the rheology of the fresh mix, which leads to the varying green density at fresh state as well as the density at hardened state on compaction. In this section, type and amount of binders, internal proportioning of binders and fines, the approach adopted and the selected appropriate liquid content to stabilize the waste in previous studies are presented.

Table-2 Cementitious binders used to stabilize waste in unfired bricks/blocks[#]

S. No.	Cementitious binder used	Waste and other raw materials stabilized	Focus of the optimization	A_{MWC}	Author/(s)	Ref.
1	Cement (15%), and lime (2%)	Clay (50%), pumice (15%), gypsum (3%), and plastic fiber (0.1%)/straw (2%)/polystyrene fabric (0.5%)	F1	NDC	Binici et al.	[2]
2	Lime (3.5%- 26.25%)	Fly ash (0.35:0.65 F/S), gypsum (0.5% - 10%), and sand (0.35: 0.65 F/S)	F2,F4,F5	NDV	Reddy and Gourav	[5]
3	HL (10%-50%)	Diatomaceous earth, and gypsum (0%-15%)	F2, F5	NDV	Pimraksa and Chindaprasirt	[10]
4	Cement (3%), NHL (3%), and calcareous lime (3%)	Fly ash (7%), alumina filler waste (20%, 40%, 60%), and clay (70%, 50%, 30%)	F1, F4,	SC	Miqueleiz et al.	[12]
5	Lime (10% - 60%)	Phosphogypsum (10%-40%), and fly ash (20%-80%)	F2, F4	SCT	Kumar	[13]
6	Lime (3%)	GGBS (11%), mud stone clay (52%-65%), and brick dust waste (0%-13%)	F4	SPT	Oti et al.	[15]
7	HL (18%-20%), and Portland cement (0%-2%).	Calcined phosphogypsum (40%), and fly ash (40%)	F3	UC	Singh and Garg	[17]
8	OPC (15-30%)	Waste mud from ceramic tile industry	F2, F5	NDV	Wattanasiriwech et al.	[18]
9	Cement (10%-15%)	Quarry dust (50%-60%), fly ash (0%-40%), and billet scale (0%-40%)	F2, F4	UC	Shakir et al.	[19]
10	43 grade OPC (5- 20%)	Recycled paper mill residue (80% - 95%)	F2	UC	Raut et al.	[20]
11	Lime (6%-10%)	Fly ash (0% - 40% of lime percentage), soil , and crushed sand (0.7 :0.3)	F2, F4	SC	Izemmouren et al.	[21]
12	HL (10% - 30%) / cement (10% - 30%)	GGBS (30:70, 50:50, 70:30, B/G), fly ash (10%), and bottom ash (60%)	F1, F2, F4	NDC	Pahroraji et al.	[22]
13	53 grade OPC (10%)	Bio briquette ash (5%-55%), and sand (35%-85%)	F4	NDC	Sakhare and Ralegaonkar	[23]
14	Cement (4%), HL (1.3% - 1.7%)	Phosphogypsum (65% -85%), and sand (9.3%-29.7%)	F2, F3, F4	NDC	Zhou et al.	[24]
15	Cement (5%-15%)	Plastic fibers (carry bag fibers (0.1%-0.2%), PET bottle fibers (0.1%-0.2%) and soil	F1, F2	NDC	Subramaniaprasad et al.	[39]

16	Cement (25%-50%)	Wood fiber waste (0%-25%), rice husk ash (0%-25%), limestone powder (0%-25%), and river sand (25%-50%)	F2, F4	NDC	Torkaman et al.	[40]
17	Lime (15%)	Glass powder (20%-35%) palm oil fuel ash (20%-35%), crusher dust (15%-45%), and oil palm fiber (0.25% - 1% by weight of binder)	F4, F2	--	Raut and Gomez	[41]
18	Hydrated lime (0%-15%)	Rice husk ash (0%-15%), sand (0%-30%), and clay (56%-100%)	F2, F4	SPT	Muntohar	[42]
19	Lime (5%-30%)	Calcined phosphogypsum (5%-30%), and fly ash (60%-90%)	F2, F4	SCT	Kumar	[43]
20	43 grade OPC (10%)	Recycled paper mill residue (70%-80%), and rice husk ash (10% - 20%)	F4	UC	Raut et al.	[44]
21	Cement (10%-23%)	Fly ash (26%-50%), and bottom ash (37%-57%)	F2,F4	UC	Naganathan et al.	[45]
22	Cement (10%)	Recycled paper mill residue (85%-89%), cotton waste (1%-5%)	f4	UC	Rajput et al.	[46]
23	Lime (8%,12%), cement (5%,8%), lime (3%,4%) + cement (5%,8%) and cement (5%,8%) + resin (50% of the compacting water weight)	Sand, and clay (30%:70%)	F2	--	Guettala et al.	[47]
24	GGBS, lime, and gypsum (81:15:4) (20%-50%)	Sand (50%-80%)	F2	--	Malhotra and Tehri	[48]
25	Lime (5%-15%)	Phosphogypsum (30%-50%), fly ash and sand (in internal ratio (1:2))	F1, F2	--	Yang et al.	[49]
26	Cement (11.36%-16.27%)	Cotton waste (0%-5.6%), and lime powder waste (88.64%-78.09%)	F4	NDC	Algin and Turgut	[50]
27	Lime (8%-14%)	Quartz sand (0%-40%), and fly ash (50%-90%)	F2,F4	NDC	Cicek and tanriverdi	[51]
28	Cement (10%-30%), and lime (10%-35%)	Construction and demolition waste aggregate (65%-90%)	F2	NDC	Contreras et al.	[52]
29	Lime (6.7%-13.3%)	River sand (0%-83%), sand powder (0%-13.3%), and copper tailings (0%-88%)	F2,F4	NDV	Fang et al.	[53]
30	Cement (20%-25% by volume)	By volume: rice husk ash (0%-5%), sand (37.5%), and EPS beads (37.5%)	F2	NDC	Ling and Teo	[54]
31	Alumina cement/ slag	Wastewater sludge	F1,F2, F5	NDV	Liu et al.	[55]

	cement/ Portland cement (32.5R and 42.5R)/ grounded cement clinker (B/F-1:0.5-1)					
32	Cement (1part by volume	Oil palm kernel shell (1-3 part by volume), and sand (1 part by volume)	F4	NDC	Muntohar and Rahman	[56]
33	Cement (5.71%)	Natural river sand and crushed granite aggregates (0%-91.42%), and recycled aggregate (0%-91.42%)	F4	NDV	Poon et al.	[57]
34	Cement (3%) / lime (3%)	Class C fly ash (7%), stockpiled CFBC ash (ground (58.3% -100%) and unground (62.3%-85.3%)), sand (13% - 30%), clay (10-30%), and $CaCl_2$ (1.7%)	F1,F4	NDC	Shon et al.	[58]
35	Slaked lime (8% - 12%)	Fly ash (88% - 92%)	F2	NDC	Çiçek and Çinçin	[59]
36	Lime (6%-15%)	Hematite tailings (62%-89%), sand (5%-20%), and gypsum (0%-3%)	F2, F4	NDC	Zhao et al.	[60]
37	Cement (6.97%)	FA (73.64%), and CA (19.37%); by volume of cement: wood ash (0%-15%), and lime mud (0%-15%); by volume of FA: saw dust (0%-20%), and superplasticizer (1%)	F2,F4	NDC	Madrid et al.	[61]
38	Cement (11%-14.25%)	Crumb rubber (0%-40% by volume of crushed lime stone), and crushed lime stone (89%-85.75%)	F4	NDV	Sodupe-Ortega et al.	[62]
39	Cement (400 - 500 kg/m^3)	EPS beads (15-25% of total volume of concrete), sand (35%-41%), and crushed stone (59%-65%)	F2, F4, F5	NDV	Xu et al.	[63]
40	Cement (3%) / Lime (3%)	CFBC fly ash (77%-100%), and CFBC slag (0%-20%)	F1,F4,F5	NDV	Zhang et al.	[64]
41	Cement (10.73%)	Waste lime stone (77.87%-85.92%), and waste glass powder (0%- 8.05%)	F4, F5	NDV	Turgut	[65]

#Please refer to the section titled “Abbreviation” for details.

Table-3 Chemical binders used to stabilize the wastes in unfired bricks$^{\#}$

S. No.	Chemical binders used	Wastes and other raw materials stabilized	Focus of the optimization	Author/(s)	Ref.
1	NaOH (10M), and Na_2SiO_3	RHA (ground-11.55%, unground 0-28.45%), fly ash (17.32%), and sand (42.68%-71.13%)	G4	Hwang and Huynh	[66]
2	NaOH(8M–14M), and Na_2SiO_3 (H/S-1:3)	Crumb rubber with fly ash (ratio-1:1)	G2, G5	Mohammed et al.	[67]
3	NaOH solution (10 M,15 M)	Copper MT	G2, G5	Ahmari and Zhang	[68]
4	NaOH solution (10-15M)	Copper MT (90-100%), and cement kiln dust (0- 10%)	G2, G4, G5	Ahmari and Zhang	[69]
5	Na_2SiO_3 (S/N: 1.2 – 2.0), NaOH (5 M, 10 M), KOH (5 M, 10 M), and LiOH (5M)	CFBC bottom ash	G1, G2	Chen et al.	[70]
6	NaOH solution (4 M- 12 M)	Alumino-silicate rich tuff, (Bafoundou Tuff)	G2	Diop and Grutzeck	[71]
7	NaOH	WCS (0% - 100%), and clay brick waste (0% - 100%)	G4	Ezzat et al.	[72]
8	Na_2SiO_3 solution, NaOH in solid, and NaOH in solution form (10 M,14 M)	Weathered coal fly ash	G2, G3	Ferone et al.	[73]
9	NaOH (8M - 12M), and Na_2SiO_3 (H/S-1:2.5)	Fly ash (40%), GGBS (10%), recycled water in solution, and M-sand (50%)	G2	Radhakrishna et al.	[74]
10	Na_2SiO_3, NaOH (10M) (H/S-0.4-2.3)	Fly ash (23%), and clay (77%)	G3, G5	Sukmak et al.	[75]
11	NaOH, and mix of NaOH and Na_2SiO_3	Calcined clay	G1, G2	Mohsen and Mostafa	[76]
12	NaOH (10 M)	Fly ash (25.27% - 11.15%), rice husk ash (0% - 11.5%), and sand (74.72%)	G4	Huynh et al.	[77]
13	NaOH (10 M), and Na_2SiO_3 (H/S-1:2.5)	Fly ash (16.66%-33%), and sand (66%- 83.33%)	G4	Abdullah et al.	[78]
14	NaOH (12 M), and Na_2SiO_3 (H/S-1:2.5)	Bottom ash (20%-80%), and fly ash (20% - 80%)	G4	Deraman et al.	[79]
15	Sodium silicate	Fly ash and bottom ash	G4, G5	Freidin	[80]
16	NaOH, and sodium silicate solution (H/S- 2:1)	WCS (25%-100%), metakaoline (0%, 60%), CKD (25%-75%), and sand (15% - 50%)	G4	Khater et al.	[81]

17	NaOH (8M), and Na_2SiO_3 (H/S-1:1-1:9)	Recycled glass (77%), and fly ash (23%)	G3,G5	Arulrajah et al.	[82]
18	NaOH (0.31%-5.71%), and Na_2SiO_3 (50.50%-53.29%)	Red mud (10%-18%), metakaolin (22%-30%), and aluminium powder (0.025%-0.1%)	G3,,G4,G5	Ascensão et al.	[83]
19	NaOH (10M-17M), and Na_2SiO_3 (S/N-1.15)	MSWI-FA (48%-60%), and coal fly ash (16%-20%),	G2, G4, G5	Ferone et al.	[84]
20	NaOH (5M-10M), and Na_2SiO_3 (S/N-3.47)	GGBS (0%-30%), and clay (70%-100%)	G2, G3, G4, G5	Ferone et al.	[85]
21	NaOH, and Na_2SiO_3(S/N-1.6)	Fly ash (0%-100%), and brick powder (0%-100%)	G4,G5	Rovnanik et al.	[86]

#Please refer to the section titled “Abbreviation” for details.

3.1 Bricks stabilized by cementitious binder

Different cementitious binders were used by researchers (Table-2) to stabilize the wastes in unfired bricks such as Portland cement, alumina cement, slag cement, natural hydraulic lime, calcareous lime, quick lime, slaked lime, and hydrated lime. The stabilized wastes include various ash wastes, industrial wastes, mining wastes and other discarded materials. The different ash wastes stabilized using the cementitious binders were as follows: fly ash, bio briquette ash, rice husk ash, wood ash, palm oil fuel ash, stockpiled fly ash, bottom ash, and circulating fluidized bed combustion (CFBC) fly ash (Table-2). Other than ash wastes, some industrial wastes were incorporated in unfired bricks such as ground granulated blast furnace slag (GGBS), alumina filler waste, ceramic tile mud waste, billet scale, brick dust waste, CFBC slag, quarry dust, construction and demolition (C&D) waste, cotton waste, phosphogypsum, and recycled paper mill residue (Table-2). Besides these, some other discarded materials were also used in unfired bricks such as lime powder waste, glass powder waste, lime mud waste, sawdust, crushed granite aggregates, copper tailings, hematite tailings, diatomaceous earth, oil palm kernel shell (OPKS), wastewater sludge and crumb rubber (Table-2). These wastes were incorporated fully or partially in addition to other materials such as clay, sand, crushed sand, crushed lime stone aggregates, expanded polystyrene (EPS) beads, sand powder, calcium chloride and gypsum in unfired bricks as shown in Table-2.

In some studies, fibers were used in the stabilized unfired bricks such as waste plastic fibers [39], wood fiber waste [40], straw fibers [87], polystyrene fabric [2], and oil palm fibers [41]. In a study [2], different fibers were added in varying geometrical arrangements in two sandwich layers to make the bricks earthquake resistant. In the studies mentioned in Table-2, the focus of researchers was to optimize the type of binder (F1), amount of the binder (F2), internal proportioning in case of blended binders (F3) and blended fines (F4), and the liquid content (F5) to get an optimized brick mix.

To determine the optimum molding water content, researchers used different approaches as shown in Table-2, i.e. standard proctor test (SPT), standard consistency test (SCT), uniform flow consistency (UC) and standard compaction method (SC). In some studies [15,42], SPT was used to determine the optimum moisture content (OMC) of the mix and equivalent to OMC was taken as molding water content. In some other studies [13,14,43], SCT was used to determine the water content to achieve the required consistency, and 90% of that was selected as molding water content. Based on the uniform consistency required, water content was adjusted in some studies [17,19,20,44–46] to achieve the required consistency parameter. The static compaction method proposed by the Center for Development of Enterprises (C.D.E.) [88] was used by Izemmouren et al. [21] to determine the optimum molding water content, acknowledging the non-suitability of proctor test as quoted by Reddy and Jagdish [89]. Similarly, at constant static pressure, the optimum molding water content was determined in a previous study [12,21] and used to cast the bricks.

As can be seen in Table-2, many studies did not specify their approach to select the water content. Some of such studies kept the water to binder ratio or the water content in the mix constant, whereas some others considered it as a variable parameter. In a few studies [41,47–49], details related to molding water content are not specified as such. However, the research outcomes of these studies regarding waste incorporation in unfired bricks are significant and are therefore incorporated in Table 2.

It is noted that ample studies are available related to wastes stabilization in unfired bricks using cementitious binders. Dry mix proportions summarized in the above sections can give a reference to the probable binders to be utilized to stabilize a particular waste in unfired bricks. However, the influence of varying proportions on mechanical performance is separately discussed in section 7 on the effect of influencing parameters. It is also noted that many studies did not specify the approach to select water content. Few studies which mentioned the approach are found to have a wide diversity between their approaches. However, no study is found to be commenting on the appropriate approach to select the water content. In view of this, it has been challenging to determine the trial range to incorporate the wastes at an industrial scale, since the same type of wastes could significantly differ in their characteristics because of their different origins [90].

3.2 Bricks stabilized by chemical based binders

Different types of chemical binders, namely sodium hydroxide, sodium silicate and their blended forms, were used by researchers to stabilize the various wastes in unfired bricks as shown in Table-3. The wastes investigated in these studies included fly ash, bottom ash, copper mine tailings, cement kiln dust, CFBC bottom ash, alumino-silicate rich tuff (Bafoundou Tuff), water-cooled slag, clay brick waste, weathered coal fly ash, rice husk ash (RHA) crumb rubber, GGBS, boiler ash, water-cooled slag, and metakaolin. These wastes were used alone or in combination with sand, manufactured sand (M-sand) and clay, as shown in Table-3.

In the application of chemical binders, the amount of binder in the mix can be varied in two ways, i.e. by varying the molar concentration or by varying total liquid content. As observed from previous studies summarized in Table 3, the focus has been to optimize the type of binder (denoted as G1), the concentration of binder (G2), internal proportioning in cases of blended binders (G3) and blended fines (G4), and the liquid content (G5) to get an optimized brick mix. In some studies [91,92], chemical binders were also used to produce waste incorporated unfired bricks, but because these studies did not focus on the mix optimization, so they are not included in Table 3.

3.3 Bricks stabilized by other binders

Other than cementitious and chemical binders, some mixed/alternative binders were used to produce the unfired bricks, as shown in Table-4. In a study [9], a bio-based binder made from alginate was attempted to stabilize the soil. Some researchers [93–96] stabilized the clay bricks using waste materials without using conventional cementitious or chemical binders. In a recent study [97], a different approach was attempted, where a mixture of chemical and cementitious binders was used to produce solid bricks by stabilizing three different types of boiler ashes. In another study [98], CNF binder system (A mixture of hydrated lime, sodium carbonate, and fly ash with an internal ratio of 4.3:1:14.7) along with NaOH was used to stabilize red mud in unfired bricks. Mixed binders seem to be appropriate to overcome the cost considerations regarding the chemical binders. The potential of such mixed binders may be further explored to stabilize the other wastes.

283 Table-4 Mixed/alternative binders used to stabilize the wastes in unfired bricks#

S. No.	Binders used	Waste and other raw materials stabilized	Focus of the optimization	Author/(s)	Ref.
1	Bio-based binder: Alginate (1-5:1000 by weight of soil)	Soil	H1	Dove et al.	[9]
2	Processed tea waste (0%-5%)	Soil	H2	Demir	[93]
3	MgO rich kiln dust (0%-18%)	Soil	H2	Espuelas et al.	[94]
4	Phosphogypsum (0%-25%), and natural gypsum (0%-25%)	Soil (75%-100%)	H2	Degirmenci	[95]
5	Fly ash, slag, clinker dust and some activator (15%)	Low silicon tailings (85%)	H5	Zhao et al.	[96]
6	NaOH (0 M – 5M), and lime (10%)	Clay (0%- 30%), and boiler ash (60%- 90%)	H2	Poinot et al.	[97]
7	$Ca(OH)_2$, Na_2CO_3, and fly ash (internal ratio: 4.3:1:14.7) (70%-100%)	Red mud (0%-30%), and NaOH (0%-5%)	H2,H4,H5	Kim et al.	[98]

#Please refer to the section titled “Abbreviation” for details.

284 Conventionally, several trial mixes are designed to optimize the mix through varying one variant 285 at a time. A large number of trial mixes are required to optimize these multiple variables in the 286 blended mix with the conventional approach. A suitable mix design methodology can be adopted 287 to avoid large numbers of trial mixes. In previous studies [66,67,99], trial mixes were designed 288 using different mix design methodologies, such as response surface methodology, densified 289 mixture design algorithm (DMDA) method, and Taguchi mix design methodology. The 290 methodologies were found to be helpful to reduce the number of trial mixes significantly and to 291 optimize multivariate mixes effectively.

292 Overall in this section, it is first noted that different binders may be used to stabilize various 293 wastes in unfired bricks. In recent studies, a shift towards the use of waste fly ash as the base 294 material in place of the traditional use of soil or sand has been observed to produce the unfired

bricks. Researchers used different approaches to select the liquid content in case of unfired bricks stabilized by cementitious binders. In some studies (Table-2), wastes as fines were incorporated in blended forms considering their own advantages and limitations, whereas, in some other studies (Table-2), binders were used in blended forms to stabilize the waste.

Secondly, chemical binders are generally used in liquid form and do not significantly contribute in terms of physical volume as compared to the cementitious binder. Cementitious binders have a low cost as compared to chemical binders. However, by using a chemical binder, a high volume of wastes can be incorporated in unfired bricks. Locally available waste having low transportation cost may give the cost advantage to use costly chemical binders in unfired bricks. The use of mixed binders (cementitious and chemical) attempted by Poinot et al. [97] may provide a cost-effective solution. Alkali activated bricks produced in the study could achieve approximately 7.5 MPa compressive strength within one day using a low molarity NaOH solution (0-5 M) along with lime as binder.

4. Mixing strategy used for unfired bricks

Currently, there is no agreed or standardized mixing strategy to prepare the fresh brick mix at an industrial scale in India. The adopted mixing strategies at the laboratory scale vary considerably within the literature, and they are generally based upon the characteristics of raw materials used to prepare the mix. Researchers often adopted an improvised mixing strategy or previously cited strategy for the selected raw materials. However, limited discussions were made in the publications regarding the suitability of the adopted mixing strategy. In this section mixing strategy used by various researchers to prepare the brick mix is summarized. No specific studies related to variation in mixing sequence, mixing time and speed, and mixing equipment have been found. Therefore, a brief review on the effect of mixing strategy for other construction materials has been added to provide useful insights to the importance of mixing strategy.

4.1 Mixing sequence

The mixing sequences used by various researchers to prepare the fresh brick mixes for unfired bricks are summarized in Table-5. Researchers adopted different mixing sequences, such as single-stage, two-stage, and three-stage mixing sequences to handle the heterogeneity in the physical state of the different raw materials. The selection of a suitable mixing sequence seems to be essential to manage the ingredients with varying physical states in the blended mix. Ahmari and Zhang [68] adopted a single-stage mixing sequence as only one ingredient is stabilized using the alkaline solution in the study. In another study, Zhao et al. [60] mixed all the dry ingredients along with water in a single-stage mixing sequence. However, the two-stage mixing sequence is the most common to handle dry binders and liquids.

As shown in Table-5, majority of researchers adopted the two-stage mixing sequence in the case of blended mix. In these studies, dry ingredients were commonly mixed in the first stage, and liquid content was added separately in the second stage. However, in some studies [24,63,81,96], dry ingredients were incorporated in two stages, and liquid content was added with them in any of the stages.

Table-5 Mixing strategy used to prepare the fresh mix in various studies related to unfired bricks$^{\#}$

S. No.	Author/(s)	Mixing sequence	Raw materials	Mixing time	Mixing equipment	Ref.
1	Reddy and Gourav	1. Dry mixing of the ingredients	Fly ash, lime, and gypsum	10 min.	Ball mill	[5]
		2. Addition of water	Water	--	Air sprayer for water, and mixing manually	
2	Miqueleiz et al.	1. Mixing of all dry ingredients thoroughly	Clay, alumina filler, and binder	--	--	[12]
		2. Addition of water in dry mix, and mixing	Water	5 min.	Industrial mixer	
3	Kumar	1. Mixing of dry ingredients	Calcined gypsum, and fly ash (screened from 4.75 mm sieve)	--	--	[13]
		2. Adding the wet slurry of ingredients, and mixing	Slaked lime slurry (sieved from 1.18 mm sieve)		Kneaded for uniform consistency	
4	Oti et al.	1. Mixing of all dry ingredients	Lime, GGBS, mud stone clay, and brick dust waste	2 min.	Laboratory mixer	[15]
		2. Adding of water, and further mixed	Water	2 min.	hand-mixed	
5	Shakir et al.	1. Mixing of dry ingredients-I	Cement, and quarry dust	2 min.	--	[19]
		2. Adding dry ingredients-II, and mixed	Billet scale, and fly ash	2 min.		
		3. Adding the water, and mixed again	Water	2 min.		
6	Raut et al.	1. Mix the highly fibrous and lumpy wet waste with the dry binder.	OPC, and recycled paper mill residue	2 min.	Special mixer, and air pumps to spray the water	[20]
		2. Spray the water, and mixed again		5 min.		
7	Pahroraji et al.	1. Mixing of all the dry ingredients	Hydrated lime/cement, GGBS, fly ash, and bottom ash	1 min.	Pan mixer	[22]
		2. Adding the water, and further mixing	Water	10 min.		
		3. Injecting foam into the mixed slurry, and mixing till the proper blending	Foam	--		
8	Zhou et al.	1. Mixing of dry ingredients-I	Hydrated lime, and phosphogypsum	--	--	[24]
		2. Adding dry ingredients-II and water, and mixing to get a homogeneous mixture	River sand, cement, and water			
9	Algin and Turgut	1. Mixing of dry ingredients	Cement, lime powder waste, and cotton waste	1 min.	Concrete mixer, and air pump to	[50]

		2. Added water during mixing	Water	3 min.	spray water	
10	Guettala et al.	1. Dry ingredients are mixed together	Soil (pre-dried at 63 ℃ for 24 h), sand, and stabilizer (lime/ cement)	3 min.	51 malaxer (at 139 rev./min.)	[47]
		2. Added water, and mixed again	Water	2 min.		
11	Ling and Teo	1. Dry ingredients-I were mixed.	Sand, cement and RHA	--	Pan mixer	[54]
		2. Liquid content was added, and mixed.	Water and superplasticizer	5 min.		
		3. Dry ingredients were added, and mixed again.	EPS beads	3 min.		
12	Muntohar and Rahman	1. Dry ingredients-I were mixed	Cement, and sand	10-15 min.	Mechanical mixer	[56]
		2. Surface saturated coarse aggregates were added, and mixed again	Oil palm kernel shell (pre-soaked for 1 h)			
		3. Water is added, and remixed	Water			
13	Naganathan et al.	1. Dry ingredients-I were mixed	Bottom ash and Cement	2 min.	--	[45]
		2. Dry ingredients-II was added, and again mixed.	Fly ash	2 min.		
		3. Water was added, and mixed again.	Water	2 min.		
14	Raut and Gomez	1. Dry ingredients including fibers were mixed together in the first step	Lime, glass powder, palm oil fuel ash, crusher dust, and oil palm fiber	--	Concrete mixer	[41]
		2. Water was added, and remixed	Water	2-3 min.		
15	Sodupe-Ortega et al.	1. Dry raw materials were mixed.	Cement, crumb rubber, and crushed limestone	3 min.	Concrete mixer, and industrial mixer	[62]
		2. Stop the mixing, and keep the mix at rest	--	2 min.		
		3. Added liquid solution progressively during the mixing	Water, and superplasticizer	--		
16	Xu et al.	1. EPS beads were wetted in partial water		--	--	[63]
		2. Dry ingredients-I, and remaining water were added, and mixed at low speed	Cement, and sand	3 min.		
		3. Dry ingredient-II was added, and mixed again.	Crushed stone	3 - 5 min.		
17	Zhao et al.	All the ingredients were mixed with water in a single step.	Hematite tailings, sand, lime, and gypsum	5 min.	--	[60]
18	Subramaniaprasad et al.	1. Mixing of dry ingredients was done	Cement, and soil	--	--	[39]
		2. Water was added in the second step (Fibers were added during the mixing by hand)	Water, and fibers (plastic fibers)			

19	Torkaman et al.	1. Mixing of dry ingredients in the first step	Cement, wood fiber waste, rice husk ash, limestone, and river sand	3 min.	Concrete mixer	[40]
		2. Chemical admixtures in solution form, and water were added, and mixed again.	An aqueous solution of $CaCl_2$, and water	2 min.		
20	Turgut	1. Dry ingredients were mixed in the first step	Waste limestone, cement , and waste glass powder	1 min.	Concrete mixer for mixing, and air sprayer for water addition	[65]
		2. Water was added during the mixing in the second step	Water	3 min.		
21	Binici et al.	1. Dry ingredients are mixed together	Cement, lime, clay, pumice, gypsum, and fibers	--	--	[2]
		2. Addition of water, and mixing till a uniform consistency	Water			
22	Ahmari and Zhang	Mix the dry ingredients with the alkaline solution	Alkaline solution, and dry mine tailings	10 min.		[68]
23	Abdullah et al.	1. Mixing of dry ingredients	Fly ash, and sand	5 min.	--	[78]
		2. Adding alkaline solution, and mixing	Alkaline solution	10 min.		
24	Khater et al.	1. Addition of dry ingredients with the alkaline activator, and mixing	Slag, metakaolin/ cement kiln dust (screened from 90-micron sieve), and alkaline activator	10 min.	Mixing by hand	[81]
		2. Addition of sand in the wet mix, and mixing	Sand (screened from 1 mm sieve)	5 min.	Electronic mixer	
25	Degirmenci	1. Dry ingredients are mixed together	Phosphogypsum /natural gypsum, and soil	3 min.	Mechanical mixer	[95]
		2. Added water, and mixed again	Water	2 min.		
26	Zhao et al.	1. Cementing materials were mixed, and ground.	Cementing material (fly ash, slag, clinker dust, and some activator)	--	--	[96]
		2. Fines, and water were added, and mixed	Low silicon tailings			
27	Kim et al.	1. Red mud slurry, and water was added	Red mud, and water	2 min.	Mechanical mixer	[98]
		2. NaOH with water was added.	NaOH (with ref. to mix), and water	--		
		3. Binder was added, and mixed again.	$Ca(OH)_2$, Na_2CO_3, and fly ash	3 min.		

#Please refer to the section titled “Abbreviation” for details.

As can be seen in Table-5, some researchers adopted the three-stage mixing sequence. In the studies [19,45,56], the first two stages were dedicated to dry mixing of solids, and in the third stage, liquid content was added. However, in another study [22] with a three-stage mixing sequence, all the dry ingredients were mixed in the first stage of mixing. After that, water was added in the second stage and foam was injected into the mixed slurry in the third stage of mixing. In a few studies [54,98], to handle the solid ingredients with different characteristics, some of the ingredients were added in the first stage. After that, liquid content was added and mixed in the second stage of mixing. In the third stage of mixing, the remaining dry ingredients were added and mixed to get the homogeneous mix.

Pre-screening of ingredients is another important aspect of ensuring the homogeneity of the mix. Algin and Turgut [50] reported the issues related to lump formation and accumulation at the one side of the mixer during mixing of unprocessed cotton waste and lime powder waste. To enable the mixing, pre-processing of cotton waste was done before incorporating in cement stabilized bricks. In a study [81], fine ingredients were pre-screened from 90-micron sieve, and coarse ingredient was pre-screened from 1 mm sieve before the mixing. In another study [24], a different approach was adopted to handle waste phosphogypsum. Hydrated lime was added into the phosphogypsum to neutralize residual acid impurities in the first stage of mixing. After that, in the second stage of mixing, other ingredients were added and mixed to get a homogeneous mixture. In another study [63], the EPS beads were pre-wetted before mixing in dry ingredients.

Different approaches[13,20] were used to handle the wet raw materials in the mix. Raut et al.[20] adopted the two-stage mixing sequence to incorporate highly wet recycled paper mill residue in the bricks. In the first stage, cement and highly fibrous, wet and lumpy paper mill residue were mixed using a specially designed mixer. In the second stage, additional water required was added and mixed again to get a homogenous mix. In the other study[13], the dry ingredients were pre-screened from 4.75 mm sieve and mixed in the dry state at the first stage of mixing. In the second stage of mixing, slaked lime slurry, pre-screened from 1.18 mm sieve was added to the dry mix and kneaded to get uniform consistency mix. Water content was calculated based on the standard consistency requirement, and 90% of that was maintained in the semi-dry mix based on measurements. However, in industrial set up, bulk slaking of quick lime is done in big slaking tanks. As per the author`s manufacturing experience, it is difficult to provide controlled quantity of water just sufficient for slaking of quick lime in the practicing industrial setup for such bricks in India.

4.2 Mixing time

Mixing time used by various researchers has been stage-wise summarized in Table-5. It was observed that the total mixing time used for mixing was varied in the range of 4 min. – 15 min. In some studies, as shown in Table-5, mixing time was either partially specified or not specified. To understand the mixing strategies, mixing data related to these studies have been incorporated in Table-5, whereas for further analysis, these studies have been excluded. Further discussion has been made only for the studies which have mentioned the stage-wise mixing time details, as shown in Table-5. In a study [60] with one stage mixing sequence, mixing was done for 5 min. in a single stage. Studies [15,40,47,50,65,95] incorporating the raw ingredients in two stages typically had the total mixing time vary between 4-5 min. The mixing time used for mixing of dry ingredients was varied between 1-3 min. Whereas the mixing time used for mixing of liquid in the second stage varied in the range 2-3 min.

In the studies [15,50,65], the mixing time used for dry blending of solids in the first stage was either equal or less than that used to mix the liquid in the second stage whereas the opposite trend was observed in the studies [40,47,95]. In the studies [19,45], a three-stage mixing sequence was used, and the same duration (2 min.) was given for each stage of mixing. As noted above for the two-stage mixing studies, the mixing duration typically varied between 4-5 min., whereas, in some studies [78,81], mixing was done for a long duration up to 15 min.

4.3 Mixing equipment

Mixing equipment used by various researchers are summarized in Table-5. It can be seen that the researchers used different mixing equipment, namely industrial mixer, pan mixer, concrete mixer, mechanical mixer or laboratory mixer to mix the raw materials. Raut et al. [20] adopted a unique mixing methodology to incorporate highly wet recycled paper mill residue in forced compacted bricks. A special mixer with multiple blades was designed and fabricated to shear the mix of cement and highly fibrous and lumpy paper mill residue with every rotation. The primary purpose was to scatter the mix to get a homogenous mix with cement. After mixing in the first stage, to maintain the homogeneity further, water was sprayed using air pumps over the mixture in the second stage and mixing was done again. A similar arrangement of air pump was used for spraying the homogeneous water in the mix in some other studies [5,50,65]. In a study [5], a ball mill was used for mixing dry ingredients, and water was added using a sprayer.

In the majority of literature, only the name of equipment was reported except [47], which mentioned the speed of the mixer in the studies related to unfired bricks. Focused studies on the effect of mixing speed are not available related to unfired brick mixes. Therefore a brief review related to the effect of mixing strategy, especially concerning the mixing speed, on other construction materials is added in the next subsection.

4.4 Effect of mixing strategy variation in other construction material

Variation in mixing strategy, such as mixing sequence, mixing time and mixing speed, and mixing equipment affects the performance of the prepared mixes. A detailed review [100] on the influence of mixing procedure and mixer type is available on fresh and hardened properties of concrete. In another study [101], it was observed that mixing time and mixing speed had a significant influence on the pore structure of the binder paste. With the increase in mixing time, the compressive strength of cement mortar decreased. Further, at high-speed mixing (1000 rpm) with 1 minute mixing time resulted in a ~20% increase in compressive strength as compared to normal speed mixing (140 rpm) with 10 minute mixing time. The rheological response of cement pastes was found to be significantly influenced by mixing sequence and superplasticiser dosage at different temperatures [102]. Similarly, Williams et al. [103] analyzed the rheological parameters regarding the effect of different mixing equipment and varying mixing speed on cement paste. In another study, Hiremath and Yaragal [104] analyzed the influence of the mixing method, speed, and duration on fresh and hardened properties of reactive powder concrete. In engineered cementitious composites [105], improved fiber distribution and mechanical properties were observed by adjusting the mixing sequence. Similarly, in high-performance concrete [106], properties were found to be significantly influenced by mixing techniques.

Overall in this section (Section 4), it is noted that mixing strategies significantly influence the performance of fresh mixes. However, more focused studies are required for brick mixes. In some studies [13,81], pre-screened raw materials were mixed. Unprocessed waste materials may contain foreign elements in it. Prescreening would be a better approach to ensure a better quality product. In the case of lumpy raw material, pre-screening with a fine size sieve would break the lumps and ensure better distribution within the brick matrix. Especially in case of wet lumpy binder (slaked lime) [13], a higher potential may be expected by adopting the pre-screening approach.

5. Molding and compaction methods used for unfired bricks.

Different molding and compaction methods, such as vibro-compaction, forced compaction, and self-compaction and manual tamping, were used to cast the unfired bricks, as shown in Table-6. Only in a few studies [40,62], more than one compaction method was used; however, a comparison between the adopted methods was not made.

Table-6 Molding and compaction method used in various studies related to unfired bricks#

S. No.	Author/(s)	Mode of compaction	Compaction parameter/(s)	Sample shape/ size (mm)	Ref.
1	Binci et al.	Vibro-compacted	--	150×150×150	[2]
2	Reddy and Gourav	Forced compacted	Screw jack arrangement	38(D)×76(H)(C)	[5]
3	Pimraksa and Chindaprasirt	Forced compacted	3.5 MPa	150×75×35	[10]
4	Miqueleiz et al.	Forced compacted	13 MPa	125×60×40	[12]
5	Kumar	Vibro-compacted	--	S1	[13]
6	Kumar	Vibro-compacted	2 layer compaction	220×110× 75	[14]
7	Wattanasiriwech	Forced compacted	25 MPa – 75 MPa	--	[18]
8	Shakir et al.	Self compacted	--	200×90×60	[19]
9	Raut et el.	Forced compacted	--	230×105×80	[20]
10	Izemmouren et al.	Forced compacted	5 MPa	100×100×200	[21]
11	Zhou et al.	Forced compacted	30 MPa	240×115×53	[24]
12	Algin and Turgut	Forced compacted	1 min. and 2 -40 ton	105×90×75, 105×225×75	[50]
13	Cicek and tanriverdi	Forced compacted	--	45 mm (D) with fix weight (100 gm)	[51]
14	Fang et al.	Forced compacted	20 MPa	100×100×50	[53]
15	Guettala et al.	Forced compacted	15 MPa	100×100×200	[47]
16	Kumar	Vibro-compacted	--	220×100×75	[43]
17	Ling and Teo	Self compacted/ manual tamping	--	215×102.5×65	[54]
18	Liu et al.	Vibro-compacted	F-2800-3000 cm^{-1},	40×40×160	[55]

			A- 0.75 mm		
19	Muntohar	Forced compacted	15 MPa	230×110×55, 150×150×600	[42]
20	Muntohar and Rahman	Forced compacted	5 MPa	200×100×80	[56]
21	Naganathan et al.	Self compacted	--	200×90×60	[45]
22	Raut and Gomez	Vibro-compacted	--	200×100×100	[41]
23	Shon et al.	Forced compacted	55.2 MPa	90×65×90	[58]
24	Sodupe-Ortega et al.	Manual tamping	In 3 layers	100×100×100	[62]
		Forced compacted	69 kPa, 5 sec.	100×115×250	
25	Xu et al.	Self compacted	--	100×100×100	[63]
26	Yang et al.	Forced compacted	20 MPa	240×115×53	[49]
27	Zhang et al.	Forced compacted	10-30 MPa	50 (D) × 50 (H) (C), 240×115×53	[64]
28	Zhao et al.	Forced compacted	20 MPa	50 (D) ×23 (H) (C)	[60]
29	Subramaniaprasad et al.	Forced compacted	1.25-7.50 MPa	101.5 (D) × 117 (H) (C)	[39]
30	Torkaman et al.	Vibro compacted	1 min.	150×150×150	[40]
		Forced compacted	--		
31	Turgut	Forced compacted	160 MPa for 1 min.	225×105×150	[65]
32	Malhotra and Tehri	Forced compacted	~ 5 MPa	190×90×90	[48]
33	Çiçek and Çinçin	Forced compacted	4.6 MPa-12.26 MPa	45(D)×100(H)(C)	[59]
34	Hwang and Huynh	Forced compacted	35 MPa	220×105×60	[66]
35	Ahmari and Zhang	Forced compacted	10 min.	33.4(D)×72.5(H) (C)	[68]
36	Abdullah et al.	Forced compacted	10 MPa	--	[78]
37	Khater et al.	Vibro-compacted	--	25×25×25	[81]
38	Degirmenci	Self compacted	--	50×50×50, 40×40×160	[95]
39	Zhao et al.	Forced compacted	~12.5 - 22.5 MPa	240× 115×53	[96]
40	Kim et al.	Self compacted/ manual tamping	--	50×50×50	[98]

#Please refer to the section titled “Abbreviation” for details.

5.1 Vibro-compacted

Many studies [2,13,14,40,41,43,55,81] used vibro-compaction method to compact the bricks. However, the majority of studies did not mention the compaction parameters such as duration of vibration, frequency, and amplitude of vibrator except the studies [40,55]. Liu et al. [55] mentioned the frequency- 2800-3000 cm^{-1} and amplitude- 0.75 mm of vibrator used during the casting, whereas Torkaman et al. [40] mentioned the vibration duration as 1 minute. Majority of studies cast cubical or cuboidal shapes specimen whereas specimen size varied considerably among different studies. In a study [13], special-shaped hollow blocks were cast using vibration. Hollow blocks of 150 mm cubic size with four hollow space of 45 mm × 45 mm square size were cast using battens with a uniform 20 mm web and shell thickness using a vibrating table. Battens used to create hollow space were removed after 2 h of casting.

5.2 Forced-compacted

As shown in Table-6, majority of studies used compression method to cast the bricks, applying hydraulic press. Whereas, in a study [5], a screw jack arrangement was used to compact and extrude the cylindrical specimens of lime fly ash compacts. In general, compaction pressure was mentioned by researchers, whereas some of them [40,50,68] mentioned the compression duration. Few studies [18,39,50,59,64,96] varied the compaction pressure and analyzed the influence on performance parameters of the bricks. Majority of studies cast cubical and cuboidal shaped specimens except for the studies [5,39,51,59,60,64,68], which cast the cylindrical specimen of the brick mix.

In a study [20], a unique two-stage casting process was adopted to handle the high moisture-holding capacity of fibrous recycled paper mill residue to get smooth-surfaced bricks after drying. The two-stage casting procedure was found helpful to avoid uneven irregular shaped bricks produced with single-stage casting process. In another study [68], Ahmari and Zhang compacted the specimen in two stages and carried out investigations for optimum compaction parameters. In the first stage, minor compaction was used, whereas, in the second stage, the compacted specimen was further compressed for a longer forming duration of about 10 min. Specimens were compared at different loading rates and varying water content. The elastic deformation was observed to be less at high forming pressure and low water content (25 MPa and 12%), which was attributed to the effective volume decrease of voids within granular matrix [68] at the applied condition.

5.3 Self compacted and manually compacted

As shown in Table-6, in many studies brick mixes were prepared with self-compacting properties or just manually tamped without a hydraulic press. Specimens were cast in cubical and cuboidal shape in the above-cited studies. Brick mixes with self-compacting properties may save the considerable cost of compression and vibration equipment.

6. Curing conditions used for unfired bricks

Selection of suitable curing conditions, i.e. the surrounding environment conditions (temperature, pressure, and humidity) and the curing medium (air, water, airtight or combination of them) for the specified period (curing duration) is crucial for a brick mix to achieve the targeted performance parameters cost-effectively. Curing duration of bricks is the period required to develop the targeted strength from the casting of fresh bricks to the dispatch of hardened bricks, which has a direct impact on the production cycle, as shown in Fig. 2. The optimum curing conditions majorly depend on raw material characteristics that indirectly govern the rate of chemical reactions involved to achieve the required performance.

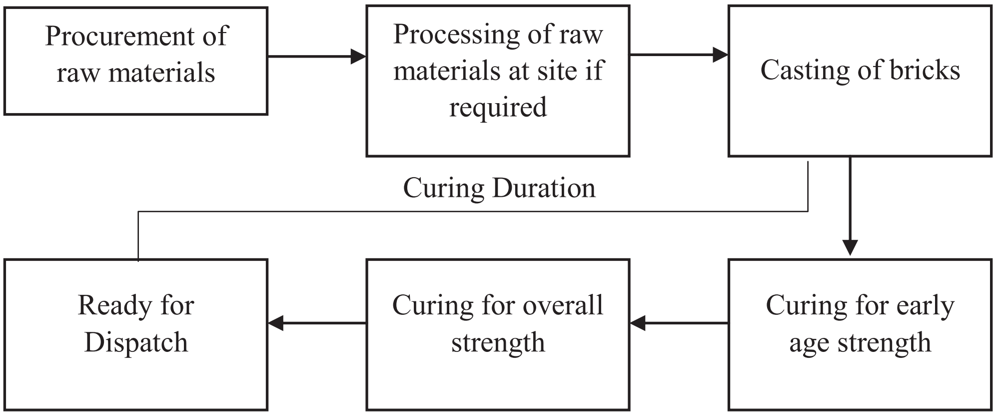

Fig. 2 Typical production cycle of unfired bricks

Unfired bricks can be cured via several methods, such as air curing, water curing, and moist curing at atmospheric pressure and via autoclaved curing at elevated pressure. Air curing can be done at ambient temperature (ambient air curing) or elevated temperature (oven curing). At ambient temperature, bricks can be wrapped with plastic sheets (airtight curing) or put under wet gunny beg (wet burlap curing) to conserve the molding moisture in the bricks. In some studies, airtight samples were further put in moist conditions to ensure minimum moisture loss. Few researchers, however, varied the medium or the other curing parameters during the curing and adopted special multi-staged curing strategies for the production of unfired bricks. In this article, such curing techniques were referred to as hybrid curing techniques.

6.1 Air curing / air-tight/wet burlap curing at ambient or elevated temperature

Curing at ambient temperature in the air, with the relative humidity (RH) similar to natural environmental conditions can be termed as ambient air curing, whereas at elevated temperature, the air is relatively dry and the curing techniques are termed as oven-dried curing. In some studies [40,58,95], ambient air curing was done at 23-25℃ whereas in studies [65,66,68,78], oven-dried curing was done at 35℃-115℃. In airtight curing [12,15,42], surrounding conditions may be similar to air curing/moist curing except for the interaction of the material with the surrounding air/moisture. In studies [19,21], airtight curing was done for the whole curing duration whereas, in a study [47], samples were subjected to water curing for 1 day after 27 days of airtight curing. In some studies [2,5,39], samples were put under wet gunny bags at ambient temperature, to minimize the evaporation loss.

6.2 Moist curing at ambient and elevated temperature

Moist curing means curing of bricks at a high relative humidity (RH) (95%-100%) and ambient temperature. At elevated temperature, it can be termed as steam curing. In studies [45,48,63], moist curing of bricks was done for 28 days or until the testing at 95% or greater RH and a temperature between 20-27℃. In some studies [21,81,98], steam curing was done for a particular duration ranging between 6 h to 90 days or until the testing at 95% or greater RH and a temperature between 40-75℃. In some studies, bricks were kept in air for 1-2 days to achieve sufficient green strength [5,21,45,63,81] whereas, in other studies [17,47,48,98], bricks were directly subjected to moist/steam curing.

6.3 Water curing at ambient or elevated temperature

In water curing [50,55,62,65], initial curing was done for 24 h either in the air or in the moist condition to achieve sufficient green strength, and after that, samples were put either in the water or in limewater for curing at 20-24℃. In a separate study [43], long initial curing for a week was done under moist wet burlap bags before subjecting to water curing, whereas, in another study [54], water immersion duration was taken as variable between 0-28 days.

6.4 Autoclaved Curing

Many studies [10,49,51,53,59,60,64,96] used autoclaved curing for unfired bricks, as shown in Table-7. In autoclaved curing, initially, bricks are kept for a pre-autoclaving duration to achieve sufficient green strength. After achieving green strength, bricks are put for autoclaving for a particular duration. Autoclaving duration includes the total time required for ramping up, holding and ramping down. In some studies [39,51], pre-autoclaving duration was kept constant as 24 h, whereas some studies [10,64] varied this duration in the range of 6 – 48 h and 1 – 11 days respectively. The majority of studies specified only the holding duration except [53], which specified the ramping up and ramping down durations as 2 h and 3 h, respectively. In some studies [10,49] holding duration was kept constant as 4 h whereas, in other studies [51,53,59,60,64,96], the holding duration was taken as a variable in a particular range between 2 – 14 h. In a study [10], the steam temperature was kept constant at 130℃, whereas in another study [53], the steam temperature was varied between 170℃ and 190℃. Constant steam pressure was considered in [10,49] as 0.14 MPa and 0.80 MPa respectively whereas, in other studies [51,59,60,64,96] the steam pressure was taken as a variable in a particular range between 0.5- 2.0 MPa.

Table-7 Curing strategies adopted by researchers in previous studies related to unfired bricks#

S. No.	Author/(s)	Curing strategy	Curing duration	Curing medium	Curing parameter (temp./pressure/RH)	Ref.
1	Binici et al.	Wet burlap air curing	7 days	Air	--	[2]
2	Pimraksa and Chindaprasirt	1.1 Initial curing	1 – 11 days	Moist	23℃, and 90% RH	[10]
		1.2 Autoclaved curing	4 h	Steam	130℃, and SP- 0.14 MPa	
3	Reddy and Gourav	1.1/2.1 Initial curing	24 h	Air		[5]
		1.2 Steam curing	Till testing age	Moist	80 ℃	
		2.2 Wet burlap curing	Till testing age	---	---	
4	Miqueleiz et al.	Airtight curing in a moisture chamber	Till the end of the curing	Airtight	---	[12]
5	Kumar	1.1 Ambient air curing	1-2 days	Air	27±3℃, and RH > 80%.	[14]
		1.2 Wet burlap curing	Till the sufficient green strength	Air	---	
		1.3 Water curing	Till one day before testing	Water	23 ± 2℃	
		1.4 Air drying	For 1 day just before testing	Air	23 ± 2℃	
6	Oti et al.	Airtight moist curing	Till the end of the curing	Airtight	At RT (20 ℃).	[15]
7	Singh and Garg	Ambient to elevated temp. in moist conditions	Up to 90 days	Moist	27℃ – 50℃, and 90% RH	[17]
8	Wattanasiriwech	1. Wet burlap curing without water immersion	Closed in a plastic box covered with damp cloth, and water sprayed every 24 h till testing	---	---	[18]
		2. Wet burlap curing with water immersion	Immersed for 5 min. in water every 24 h till testing			
9	Shakir et al.	Airtight wet burlap curing	Overnight cured in a plastic box	Airtight	22 ℃, and RH>95%	[19]
10	Izemmouren et al.	1.1/2.1 Initial curing	First 24 h	Airtight		[21]
		1.2 Airtight curing	28 days – 18 months	Airtight		
		2.2 Steam curing	6 – 30 h.	Steam	75 ℃	
11	Zhou et al.	1.1 Wet curing and sprinkled water thrice a day	1 day	Air		[24]
		1.2 Ambient air curing	2 days	Air		
		1.3 Elevated temp. air curing	2 h	Air	180℃	
		1.4 Ambient air cooling	--	Air	RT	
		1.5 Water curing	1 h	Water		
		1.6 Ambient air drying	--	Air		

12	Algin and Turgut	1.1 Initial curing	24 h	Air		[50]
		1.2 Lime saturated water curing	28 days	Water		
		1.3 Elevated temp. air curing	24 h	Air	105 °C	
13	Cicek and tanriverdi	1.1 Initial curing	24 h	Air		[51]
		1.2 Autoclaved curing	3 h - 12 h	Steam	SP- 0.5 - 2 MPa	
14	Fang et al.	Autoclaved curing	Holding time (5h - 9h), ramping up (2 h), and ramping down (3 h)	Steam	170 °C - 190 °C	[53]
15	Guettala et al.	1. Humid curing	28 days	Airtight	70% RH	[47]
		2.1 Humid curing	27 days	Airtight		
		2.2 Water curing	1 day	Water	20 °C	
16	Kumar	1.1 Initial curing under wet gunny bag	7 days	Air		[43]
		1.2 Water curing	Until testing	Water	23±2°C, and 50°C	
17	Ling and Teo	1. Water curing	28 days	Water and air	24±2°C, and 100% RH	[54]
		2. Partial water curing-2 days			24±2°C, and 100% RH in water; 26±3°C, and 73±5% RH in air	
		3. Partial water curing-6 days				
		4. Air dry curing		Air	26±3°C, and 73±5% RH	
18	Liu et al.	1.1 Initial curing	24 h	Moist	20°C, and 100% (RH)	[55]
		1.2 Water curing	Up to 28 days	Water	20°C	
19	Muntohar	Airtight curing under moist condition	28 days	Airtight	30°C	[42]
20	Naganathan et al.	1.1 Initial curing under wet cloth	2 days	Air		[45]
		1.2 Moist curing	Until testing	Moist	22 °C, and 95% (RH)	
21	Shon et al.	1.1 Initial curing	24 h	Moist	23 °C, and 100% (RH)	[58]
		1.2 Ambient air curing	Till the testing age	Air		
22	Sodupe-Ortega et al.	1.1 Initial curing	24 h	Air		[62]
		1.2 Water curing	Until testing	Water	20 ± 1 °C	
		2. As per EN 12390-2	--	--	23 ± 4 °C	
23	Xu et al.	1.1 Initial curing	24 h	Air	24 °C	[63]
		1.2 Moist curing	Until testing age	Moist	20 ±1 °C, and 95% (RH)	
24	Yang et al.	Autoclaved curing	4 h	Steam	SP- 0.80 MPa	[49]
25	Zhang et al.	1.1 Initial curing	6-48 h	Air	25–30°C, and 80%-90%	[64]

					(RH)	
		1.2 Autoclaved curing	Holding (3-8 h)	Steam	SP- 0.5 - 2.0 MPa,	
26	Zhao et al.	1.1 Initial curing-I	2.5 h	Airtight	--	[60]
		1.2 Initial curing-II	Up to 24 h	Air	--	
		1.3 Autoclaved curing	4-9 h	Steam	SP: 0.8-1.8 MPa	
27	Subramaniaprasad et al.	Wet burlap air curing	28 days	Air	--	[39]
28	Torkaman et al.	1.1 Initial curing	24 h	Airtight	--	[40]
		1.2 Ambient air curing	Up to 28 days	Air	25±1 ℃, and 60±5 % (RH)	
29	Turgut	1.1 Initial curing	24 h	Air	RT	[65]
		1.2 Lime water curing	Up to 28 days	Lime water	22 ℃	
		1.3 Elevated temp. air curing	24 h	Air	115 ℃	
30	Malhotra and Tehri	Ambient moist curing	28 days	Moist	27±1℃, and 95% RH	[48]
31	Çiçek and Çinçin	Autoclaved curing	2h – 8h	Steam	6 – 12 bar	[59]
32	Hwang and Huynh	Ambient air curing	Until testing age	Air	35 ℃, and 50 % RH	[66]
33	Ahmari and Zhang	Elevated temp. air curing	7 days	Air	90℃	[68]
34	Abdullah et al.	Elevated temp. air curing	1 h – 24 h	Air	40℃ - 95℃	[78]
35	Khater et al.	1.1 Initial curing	For first 24 h	Air	RT	[81]
		1.2 Elevated temp. moist curing	Until the testing	Air	40℃, and 100% RH	
36	Degirmenci	Ambient air curing	Until testing age	Air	--	[95]
37	Zhao et al.	1.1 Initial curing	6 h	Airtight	--	[96]
		1.2 Autoclaved curing	4 - 14 h	Steam	SP: 0.75 - 1.75 MPa	
38	Kim et al.	Elevated temp. moist curing	3 days, 7 days and 28 days	Air	60℃, and 99% RH	[98]

Note:-1,2,3…denotes a variety of curing methods adopted, whereas 1.1,1.2,1.3….denotes the different stages of the curing method 1.
#Please refer to the section titled "Abbreviation" for details.

7. Mechanical performance of unfired bricks

Researchers have stabilized various wastes in unfired bricks using different stabilizers. Various parameters, such as mix proportions, compaction parameters, curing parameters, were optimized based on the mechanical performance of bricks. In this section, the effects of variation in the above-stated manufacturing parameters on the mechanical properties of unfired bricks have been summarized, which would be helpful in providing useful insights for incorporating different wastes in unfired bricks.

7.1 Influence of mix proportions on the properties of unfired bricks stabilized by cementitious binders

7.1.1 Type of binder

The influence of variation in the binder was observed by various researchers while incorporating different wastes. Miqueleiz et al. [12] compared different binders, such as cement, calcareous lime, and natural hydraulic lime in ash-clay bricks. Use of cement gave the highest short term strength at 28 days (22 MPa). Whereas, in the long term, at 90 days, mixes with cement and calcareous lime achieved a similar strength (~27 MPa). The reasons given for the improved long term performance in the case of the calcareous lime [12] were the presence of free lime content, better interaction between lime and soil particles and pozzolanic reaction between lime and coal ash. Pahroraji et al. [22] compared the hydrated lime and Portland cement in coal ash bricks. Approximate 4 times higher compressive strength was observed with Portland cement as compared to hydrated lime based coal ash bricks at 7 days of curing, whereas, at 56 days of curing, the compressive strength of the bricks with Portland cement was only 1.5 times higher. However, compressive strengths for higher curing age (>56 days) were not mentioned.

Liu et al. [55] compared the different types of cement (alumina cement, slag cement, Portland cement and, grounded cement clinker) to stabilize the wastewater sludge in unfired bricks. The highest compressive strength of 40.3 MPa could be achieved with alumina cement. Whereas, for a similar mixing ratio, only 7.7 MPa compressive strength could be achieved with Portland cement of 32.5 R grade. Shon et al. [58] compared different binders (cement and lime), with or without class F fly ash, to stabilize the stockpiled CFBC ash and observed that a mixture of lime and class F fly ash resulted in the highest strength of unfired bricks in adopted curing conditions. Further, $CaCl_2$ incorporation in the mix resulted in a high early age (3 days) strength and a little increase in 28 days compressive strength.

Zhang et al. [64] compared two different binders, namely lime and cement, in addition to CFBC slag and CFBC fly ash in autoclaved bricks. Cement was found better as compared to lime, as no effective increase in strength was observed in the case of lime after autoclaving the bricks. Yang et al. [49] treated the phosphogypsum at two different autoclaving conditions and compared their compressive strength, along with the raw phosphogypsum. The highest strength was observed in case of low autoclaved phosphogypsum (120 ℃, 0.12 MPa and 16 h), whereas the lowest strength was observed with the raw phosphogypsum.

7.1.2 Amount of binder

The influence of the varying amount of binder was observed by various researchers [13,18–20,49,51–53,55,59] while incorporating the wastes in unfired bricks. Wattanasiriwech et al. [18] observed the effect of varying cement content to stabilize the waste mud collected from the tile industry. With 15% cement content, stabilized paver blocks could achieve 35 MPa compressive strength after 28 days of curing. However, at 30% cement, since rapid hydration occurred, paver block could achieve 35 MPa within 7 days and a maximum of 54 MPa compressive strength after

14 days of curing. A similar increase in compressive strength was observed with the increase in cement content in many waste incorporated bricks [19,55]. Whereas in another study [20], almost constant compressive strength (9±1 MPa) was observed at varying cement content (5% – 20%) in recycled paper mill residue (80% - 95%) bricks.

Contreras et al. [52] observed the increase in the compressive strength with the increase in binder content (cement/lime) regardless of the type of C&D waste aggregate. However, in the case of lime, at a higher lime percentage (35%), a slight decrease was observed in the compressive strength. The increase in compressive strength was more prominent in case of cement than lime at similar percentage incorporation in the mix. In another study, Kumar [13] investigated the optimum amount of lime in brick mixes containing lime, fly ash, and phosphogypsum and found maximum compressive strength at 30% lime content.

Çiçek and Çinçin [59] varied the lime content (8%-12%) in lime fly ash bricks and obtained the maximum compressive strength of approximately 12 MPa at 12% lime content by autoclaved curing. Yang et al. [49] varied percentage of lime (5%-15%) to stabilize phosphogypsum in a fly ash sand autoclaved bricks. With the increase in lime content, compressive strength and flexural strength of the bricks increased. Fang et al. [53] varied the ratio of lime to sand powder. They observed an increase in the compressive strength in stabilized copper tailing bricks with the increase in the ratio of lime to sand powder in constant autoclaving parameters. Çiçek and Tanriverdi [51] observed the increase in compressive strength with the increase in percentage lime, and 12% was considered as optimum content. At a higher lime content, no significant effect on mechanical strength was observed. Variation in the optimum amount of lime among the different studies may be due to the variation in adopted curing conditions and the characteristics of the stabilized waste.

Some researchers [5,10,21,22,40,42,43,54] partially replaced the cementitious binder and optimized the amount of the binder in unfired bricks. Pahroraji et al. [22] incorporated GGBS (10%-20%) as partial replacement of hydrated lime and Portland cement in coal ash bricks. The amount of hydrated lime and Portland cement in cement ash bricks was saved by 20% on using GGBS and an increase in 28 days compressive strength was achieved by 13% and 42%, respectively for hydrated lime and Portland cement. Kumar [43] observed the increase in compressive strength with the increase in partial replacement of lime with phosphogypsum irrespective of fly ash content. Ling and Teo [54] partially replaced the cement with rice husk ash and observed maximum compressive strength at 10% replacement of cement by rice husk ash in the sand- EPS unfired bricks. Muntohar [42] used lime and RHA at varying internal ratios and observed optimum compressive strength at lime to RHA ratio (1:1) in unfired clay bricks. Torkaman [40] replaced the 50% cement content with rice husk ash, and with waste lime powder and could achieve similar compressive strength of unfired blocks.

Pimraksa and Chindaprasirt [10] observed a decrease in compressive strength by 7% in lime stabilized diatomaceous earth bricks by incorporating 5% gypsum as partial replacement of lime. Reddy and Gourav [5] used gypsum as an additive in lime stabilized fly ash-sand bricks. With a 2% gypsum additive, 28 days compressive strength increased significantly (~7 times) at 10.5% lime content in lime stabilized fly ash bricks. The contradictory results may be due to different reaction mechanisms by different wastes or at different doses of gypsum. Izemmouren et al. [21] investigated the effect of partial replacement of lime with fly ash in soil crushed sand bricks in steam curing conditions for 24 h. Higher dry (16 MPa) and wet (14.72 MPa) compressive strengths were achieved at 30% substitution of lime with fly ash as compared to the control mix (at 10% lime content without fly ash) having dry (10 MPa) and wet compressive strength (7

MPa) respectively. The wet and dry compressive strengths increased on up to 30% replacement of lime with fly ash irrespective of lime content (6%-10%).

7.1.3 Internal proportioning of blended binders

In some studies [17,24], blended cementitious binders were used. In a study [17], the influence of partial replacement of hydrated lime with Portland cement was observed in the phosphogypsum-fly ash-lime mix. At 10% replacement of hydrated lime with Portland cement, an increase in the 7 days compressive strength (13.72 MPa) was observed as compared to the compressive strength (7.71 MPa) for the mix without cement. However, the difference between the compressive strengths of mix with cement (22.41 MPa) and without cement (20.07 MPa) was found less after 28 days of curing. In another study [24], hydrated lime and cement were used together to stabilize the phosphogypsum in sand bricks along with a different hydration recrystallization curing technique to produce early age strength bricks. Using 4% Portland cement and 1.5% hydrated lime, 21.8 MPa compressive strength was achieved within 7 days in stabilized phosphogypsum sand bricks.

7.1.4 Internal proportioning of blended fines

Different wastes were incorporated as fines, and the influence of varying internal proportion of blended fines was analyzed on the compressive strength of unfired bricks. Partial replacement of clay with alumina waste [12] decreased the strength of unfired bricks, whereas the incorporation of brick dust waste (BDW) as replacement of mud stone clay [15] increased the strength of unfired bricks. The probable reason given for the decreased compressive strength of the bricks was the decrease in cohesion between the particles due to the addition of alumina filler waste [12]. Whereas, the increased performance in the case of BDW was attributed to its pozzolanic property, better mechanical size distribution and the mineral composition obtained with the addition of BDW in the mix[15]. Sometimes, researchers relate the increase in the compressive strength with the increased density of bricks, which is attributed to improved particle packing. Replacement of one ingredient having lower specific gravity with the other having higher specific gravity resulted in the increased fresh density of the mix [19]. Hence, the increased fresh density may not truly replicate the improved particle packing in cases with blended mixes.

The optimum proportion of one ingredient in a blended mix may shift due to change in the respective proportioning of other ingredients. The optimum amount of fly ash incorporation in Fal-G mix (a combination of fly ash, lime and gypsum) shifted due to a change in the internal proportion of other ingredients [13]. Raut et al. [44] observed the increase in the compressive strength of bricks with the incorporation of RHA as a replacement (0%-20%) of recycled paper mill residue in cement stabilized unfired bricks. Increased compressive strength was attributed to the pozzolanic property of RHA. Whereas, the lesser increase in compressive strength at higher (15%-20%) replacement was attributed to an effective reduction of fibrous content and decrease in the homogeneity of the mix. Zhou et al. [24] varied the internal proportion of phosphogypsum (neutralized with hydrated lime) and sand in unfired bricks. They observed the optimum compressive strength at 75% phosphogypsum and 19.5% sand.

In some cases, the effect of varying proportions was evaluated for more than one ingredient in the mix. Raut and Gomez [41] compared the partial replacement of glass powder and palm oil fuel ash in place of crusher dust and observed that the partial replacement of glass powder was more effective in terms of strength gain as compared to palm oil fuel ash for the studied mix. Similarly, Shon et al. [58] observed the effect of varying proportions of different fines (clay and sand) by incorporating stockpiled fly ash to produce unfired bricks and found better results when replaced the sand as compared to clay. In some cases, the use of blended fines resulted in higher strength as compared to their individual incorporation in the mix. Use of cotton waste and paper waste independently could produce the bricks of 7-10 MPa compressive strength. In contrast, in combination, bricks of 22 MPa compressive strength could be achieved [46], which establishes the significance of using blended fines in unfired bricks.

Muntohar and Rahman [56] incorporated OPKS in different sizes as aggregates in cement sand bricks. A decrease in the compressive strength with the increase in the volumetric percentage of OPKS was observed for larger size aggregates (4.75-9.5 mm and >9.5 mm) whereas for the smaller size of aggregates (2.36-4.75 mm) optimum compressive strength was observed at 50% volume of OPKS aggregate in the mix. Zhang et al. [64] incorporated the CFBC fly ash (77%-97%) and CFBC slag (0%-20%) with or without cement (3%) in autoclaved bricks. With the increase in slag content, the compressive strength increased by more than 50%, and by 8% for the autoclaved bricks with and without cement respectively. It indicated that the increase in strength was due to possible reactions between slag and cement. L16 orthogonal array [60] can be used with maximum three variable factors and each with four varying levels to design the reduced number of mixes seeking for the optimum mix formulations. Zhao et al. [60] optimized lime, gypsum, sand and hematite tailing mix using L16 orthogonal array. With the increase in lime and sand content, the compressive strength increased, whereas, with the increase in gypsum content, compressive strength decreased. Sodupe-Ortega et al. [62] observed the compressive strength with the incorporation of crumb rubber in unfired bricks at both laboratory and factory conditions. At factory conditions, higher percentage rubber incorporation (20%-30%) resulted in high quantity (30%-45%) of defective and rejected products. It signifies the efforts required to scale up the research outcomes of a laboratory study to the actual industrial scale. The effects of waste incorporation were also studied by some other researchers, as tabulated in Table-8.

Table-8 Effect of variation in fines on compressive strength of unfired bricks[#]

S. No.	Variation in fines	Effect on CS	Author/(s)	Ref.
1	↑Crumb rubber content	↓	Sodupe-Ortega et al.	[62]
2	↑EPS beads content (15%-25%)	↓	Xu et al.	[63]
3	↑Waste wood fibers in place of natural river sand	↓	Torkaman et al.	[40]
4	↑Waste limestone in place of waste glass powder up to 9.37% by weight	↑	Turgut	[65]
5	↑Glass powder in place of crusher dust.	↑	Raut and Gomez	[41]
	↑Palm oil fuel ash in place of crusher dust.	↑		
6	↑Sand in place of stockpiled ash	↑	Shon et al.	[58]
	↑Clay in place of stockpiled ash	↑		
7	↑Fibrous material (cotton waste and paper waste)	≈	Rajput et al.	[46]
8	↑Phosphogypsum (30%-50%)	↓	Yang et al.	[49]
9	↑Red mud	↓	Kim et al.	[98]
10	Phosphogypsum in place of fly ash	↑	Kumar	[43]
11	↑Fly ash to bottom ash ratio (Op. at 1:1.25)	Op.	Naganathan et al.	[45]
12	↑Quartz powder (Op.20%)	Op.	Cicek and tanriverdi	[102]
13	↑Bio briquette ash in place of sand (Op. at 35%)	Op.	Sakhare and Ralegaonkar	[23]
14	↑Fly ash to billet scale ratio (Op. at 1:1)	Op.	Shakir et al.	[19]
15	↑Alumina filler in place of clay	↓	Miqueleiz et al.	[12]
16	Varying proportion of phosphogypsum, and sand (Op.-75%:19.5%)	Op.	Zhou et al.	[24]
17	CFBC slag in place of CFBC fly ash	↑	Zhang et al.	[64]
18	↑River sand to sand powder ratio	↑	Fang et al.	[53]
	↑Copper tailing content	↓		

#Please refer to the section titled "Abbreviation" for details.

7.1.5 Liquid content

A few studies [5,10,18] observed the effect of varying liquid content in bricks stabilized by cementitious binders. Pimraksa and Chindaprasirt [10] observed the effect of varying liquid content in lime stabilized unfired bricks. The liquid content was varied in the range of 45%-60%, and maximum strength was observed at 50% mixing water. An increase in compressive strength was explained by the flocculation of clay particles due to a reduction in repulsive forces with the increase in water content. After the optimum point, the decrease in compressive strength was attributed to a reverse compaction effect caused by the dispersed solid particles. The water/solid ratio was reported as an important parameter for compaction and hydration of cementitious materials [10]. Zhang et al. [64] varied the molding water content in the range of 20 - 29%. An increase in compressive strength was observed with the increase in molding water content up to 26%, whereas a slight decrease was observed at higher water content.

In some studies [18,96], an increase in compressive strength was observed in the entire selected range. Wattanasiriwech et al. [18] observed the effect of molding water content on cement stabilized mud bricks. An increase in the molding water content up to 20% increased the compressive strength of the mix. Beyond 20%, the mix was reported too runny in compaction and compression was reported not feasible. The increase in compressive strength was attributed to the diminishing of pore size in the mix with the increase in molding water content. Zhao et al. [96] reported the forming water content as influencing parameters for the mechanical strength of the bricks. Lower water content affects the uniformity in the mixing process, whereas higher water content would lead to a high bleeding rate. Therefore, water content was varied in an optimum range of 6% - 8.5% for observing the effect on compressive strength of bricks. In the optimum range, strength increased with the increased molding water content. It may be noted that the selected range in both the studies [18,96] differ significantly, which indicates the dependence of molding liquid content on the raw materials and other production parameters.

Contrary to [18,96], in the studies [63,98], a continuous decrease in the compressive strength was observed with the increase in water to binder ratio in the mix. The reduction in the strength was attributed to the increase in the pores due to the evaporation of excess water. It may also be noted that in the studies [63,98], the mix was either self compacted or manually temped rather than forced compacted. There is a possibility for excess water without bleeding in the mix due to low-level compaction.

7.2 Influence of mix proportions on the properties of unfired bricks stabilized by chemical binders

7.2.1 Type of binder

The influence of variation in the type of the binder was observed in a few studies [70,76]. Chen et al. [70] used different kinds of binders, such as sodium silicate, sodium hydroxide, potassium oxide, lithium oxide solutions to stabilize the CFBC bottom ash. The compressive strength of geopolymers made with sodium silicate solution (1.5 silicate modulus, the ratio of SiO_2/Na_2O in the solution was termed as silicate modulus of solution) and various 5M hydroxide solutions was found in order of $Na_2SiO_3 > LiOH > KOH > NaOH$ respectively. Mohsen and Mostafa [76] compared the compressive strength of NaOH stabilized clay with the alkaline Na_2SiO_3 stabilized clay. The compressive strength of the clay stabilized with alkaline silicate was found higher as compared to the clay stabilized with NaOH, irrespective of the type of the clay and curing temperature.

7.2.2 Amount of binder

Many researchers studied the influence of variation in the amount of the binder. With the increase in the concentration of NaOH or KOH between 5M-18M, an increase in the compressive strength was observed in many studies [67–71] while stabilizing the different wastes, such as copper mine tailings, cement kiln dust, CFBC bottom ash, alumino-silicate rich tuff, and crumb rubber in unfired bricks. Radhakrishna et al. [74] observed no significant difference in compressive strength at 3-7 days with varying concentrations of NaOH (8M – 12 M). However, at 28 days, with a higher concentration of NaOH, higher compressive strength was observed. Other than hydroxides, Chen et al. [70] used the sodium silicate with varying silicate modulus (1.2-2.0). The optimum compressive strength was obtained at 1.5 silicate modulus in CFBC bottom ash bricks, and a sudden decrease was observed after 1.5 silicate modulus.

7.2.3 Internal proportioning of blended binders

The influence of the internal proportioning of blended chemical binders was studied [73,75]. Ferone et al. [73] used the blended binders (NaOH and Na_2SiO_3) at two different SiO_2/Na_2O ratios (0.61 and 0.76). The compressive strength was found to be higher for the higher SiO_2/Na_2O (0.76) ratio in the low range of water/total solids ratio (0.28-0.31). However, for a high range of water/total solids ratio (0.45 -0.49), no significant change was observed. Sukmak et al. [75] varied the ratio of Na_2SiO_3/ NaOH (0.7-2.3) and found maximum compressive strength at 1.5 Na_2SiO_3/ NaOH ratio irrespective of the liquid to fly ash ratio (0.3 -0.8) in fly ash bricks. However, the optimum ratio of liquid to fly ash was observed as 0.7 in a varying range of Na_2SiO_3/ NaOH ratio (0.4 – 1.5) for fly ash clay bricks. It may be noted that the optimum liquid to fines ratio varies with the change in internal proportioning of binders.

7.2.4 Internal proportioning of blended fines

The influence of proportioning of blended fines in chemical stabilized bricks was reported in previous studies [66,69,77,78,80]. Hwang and Huynh [66] partially replaced the sand with unground rice husk ash in unfired bricks. The compressive strength decreased with the increased replacement of sand with unground rice husk ash in bricks. The reduction in the strength was attributed to a loss in structural compactness due to the rising volume of capillary pores caused by highly porous particles of unground rice husk ash. Huynh et al. [77] replaced the fly ash with rice husk ash in NaOH stabilized sand bricks. A decrease in compressive strength was observed for all replacements (0%-50%), up to 14 days of curing. However, at 28 days, 10% RHA replacement resulted in higher strength as compared to RHA-free bricks. Abdullah et al. [78] increased the fly ash to sand ratio (1:2 – 1:5) and observed the decrease in compressive strength. However, due to poor workability found at 1:2 ratio, 1:3 ratio was selected as the most suitable proportion to study the influence of other parameters.

Ahmari and Zhang [69] added the cement kiln dust (0%-10%) by the weight of total solids with copper mine tailings (90%-100%) to prepare NaOH stabilized bricks. An increase in compressive strength was observed with the increasing percentage of cement kiln dust at both 10 M and 15 M NaOH concentrations. The probable reasons for the increase in compressive strength were given as follows [69]; (i) Additional support in the dissolution of -Si and -Al species from mine tailings was expected due to increased alkalinity by dissolved Ca; (ii) Additional silica and alumina species present in cement kiln dust might result in more geopolymeric gel; and (iii) Fine particles of cement kiln dust, the hydration reaction of Ca, and pozzolanic reaction helped in the denser microstructure. Freidin [80] replaced the fly ash with bottom ash in water glass stabilized bricks. A higher strength was observed with the fly ash, and bottom ash mixes as compared to fly ash mixes. Secondly, to achieve a particular compressive strength, the amount of water glass required was less in the case of mixes with fly ash and bottom ash. The optimum ratio of fly ash and bottom ash was selected based on the maximum bulk specific gravity of the mixture.

7.2.5 Liquid content

The influence of varying liquid content was observed in previous studies [67–69,73,75,80]. In the case of chemical binders, the influence was more prominent as it directly increases the amount of binder. An increase in compressive strength was observed with the increase in the molding liquid content while incorporating different wastes in unfired bricks [68,69]. The increase in compressive strength was attributed to a higher amount of NaOH introduced with a higher amount of liquid content. Ferone et al. [73] varied the H_2O / total solids ratio maintaining the constant SiO_2/Na_2O ratio in the mix by incorporating dry and wet fly ash to prepare unfired bricks. The decrease in compressive strength was observed with the increase in H_2O / total solids ratio. In a study [67], a higher alkaline solution to fly ash ratio (0.4-0.8) resulted in higher compressive strength of rubberized interlocking blocks. Whereas, in another study [75], the optimum liquid to fly ash (LF) ratios were observed as 0.5 and 0.6 for fly ash bricks and fly ash clay bricks, respectively in a varying range of LF ratio (0.3-0.8) for both types of bricks. Other than hydroxides, an increase in compressive strength was observed with the increase in water glass content in both the fly ash mixes and the fly ash-bottom ash mixes in chemical stabilized ash bricks [80].

7.3 Influence of compaction parameters

Unfired bricks are compacted via several methods, such as vibration and compression, and sometimes mixes are prepared with self-compacting properties. The studies in which the bricks were compacted by the vibration method, the compaction parameters (vibration frequency and amplitude) were rarely communicated. Studies dedicated to the optimization of compaction parameters are not available for vibro-compacted unfired bricks. However, for compressed bricks, researchers usually reported on the compaction pressure, and in some studies [51,60,64] the compaction pressure was taken as a variable.

Çiçek and Tanriverdi [51] varied the forming pressure in the range of 0 – 30 MPa and observed an increase in the compressive strength with the increase in the forming pressure up to 20 MPa. Zhang et al. [64] varied the compaction pressure in the range of 10 - 29 MPa. An increase in strength was observed up to 25 MPa, whereas at higher forming pressure, compressive strength decreased. Zhao et al. [60] varied the forming pressure in the range of 12 - 24 MPa and observed an increase in the compressive strength with the increase in forming pressure. However, beyond 20 MPa, change in compressive strength was little. Hence 20 MPa was suggested as an optimum forming pressure. Too high compaction pressure would result in high dense bricks, which was not recommended as to avoid the increase in unnecessary dead load without much contribution to the compressive strength [60].

7.4 Influence of curing parameters

In some studies [5,18,21], different curing regimes were compared. Wet burlap curing (without additive) at ambient temperatures gives considerably low compressive strength values as compared to steam curing and wet burlap curing with additive [5]. Steam-curing for 24 h significantly increased the dry and wet compressive strength of blocks when compared with moist curing at 28 days ambient temperature [21]. In a number of studies [10,17,21,43,51,53,59,60,64,78,96], the influence of varying curing parameters were investigated on unfired bricks. Out of these, some studies [10,51,53,59,60,64,96] optimized the curing parameters of autoclaved curing such as pre-curing period, temperature holding time, steam temperature, and steam pressure. Zhang et al. [56] observed an increase in the compressive strength of bricks with an increase in the pre-curing period (6 - 48 h). However, after a certain optimum value (24 h), the rate of increase in compressive strength was not so significant. In another study [10], pre-curing was varied in the range of 1-11 days, and the maximum compressive strength was observed corresponding to 6 days. It was reported that less than 3 days pre-curing could promote the cracking within bricks due to insufficient green strength.

Fang et al. [53] observed an increase in compressive strength with an increase in holding time up to 8 h. Beyond 8 h, a slight lowering of compressive strength was observed at 9 h of holding duration. In some other studies [51,59,60,64,96], the optimum holding time was found in the range of 6 – 8 h. Fang et al. [53] varied the autoclaving temperature in the range of 170 - 190 ℃ and observed a significant increase in compressive strength up to 180 ℃. At further increase in the temperature (180-190 ℃), the increase in compressive strength was reported as insignificant. Zhao et al. [96] varied the steam pressure in the range of 0.75 - 1.75 MPa and observed a rapid increase in compressive strength until 1.2 MPa and above 1.2 MPa the rate of increase in compressive strength slowed down. In studies [51,59,60,64], the optimum steam pressure was observed in the range of 1.2-1.5 MPa.

Some researchers [17,21,43,78] studied the optimized temperature and duration of elevated air curing and steam curing for unfired bricks. Singh and Garg [17] observed an increase in compressive strength with the increase in curing temperature (27℃ – 50℃) for different types of the cementitious binder. Izemmouren et al. [21] varied the duration of steam curing between 6 – 30 h and observed maximum strength for 24 h. Kumar [43] observed the effect of water curing at elevated temperature as compared to ambient temperature on the increase in strength and hardening of the bricks. A significant increase in early age strength was observed at elevated water curing at 50 ℃. Abdullah et al. [48] studied the influence of varied curing temperature (40℃ - 95 ℃) and varied curing duration (1 h – 24 h) on geopolymeric brick under elevated air curing conditions and observed highest compressive strength at 70 ℃ and after 24 h of curing duration.

In some studies [18,24,54], hybrid curing techniques were used for the curing of bricks. Wattanasiriwech [18] studied the influence of two different curing methods on the strength of paver blocks. In the first type of curing, they covered the blocks with a damp cloth and sprayed water every 24 h in a closed plastic box. In another type of curing, the blocks were immersed for 5 min. in water every 24 h. The 5-minute immersion with wet cloth curing in an enclosed plastic box was found more effective than without immersion curing in terms of strength gain for paver blocks. Zhou et al. [24] adopted a novel hydration–recrystallization process for curing, with a combination of sprinkling water, elevated temperature and submerged water conditions. A higher compressive strength of 21.8 MPa was achieved by adopting this novel curing technique as compared to 9.5 MPa compressive strength achieved by control samples. Ling and Teo [54] designed four different curing regimes to analyze the effect of partial water curing on EPS beads incorporated cement-RHA-sand bricks. Partially or fully water cured bricks had higher strength as compared to completely air-cured bricks. With the increase in the partial duration of water curing, the compressive strength of bricks increased for all the curing ages under investigation. It may be noted that in general, the hybrid curing is promising for optimizing the properties of unfired bricks, and more studies are required to consolidate a systematic curing scheme on this basis.

8. Some industrial challenges related to unfired brick production in India

Economic viability is a deciding factor to incorporate any waste as an ingredient in the industry. The majority of research studies so far have considered waste as a cost-free material, but it is not true from the manufacturer's point of view. Procurement of waste incurs logistic costs to brick manufacturers. In a country like India, the majority of vehicles use diesel as fuel. Since per liter diesel costs Rs. 70 – 80 (1 USD ≈70 Rs.) in India, the average procurement cost is not less than Rs. 3-4 per ton per km. Importing a raw material from a 200 – 300 km. distant source, the procurement of even unprocessed waste costs not less than Rs. 0.6- 1.2 per kg. In the Indian scenario, the weight and selling price of a typical brick (90 mm×90 mm×190 mm) range between 2.5 – 3.2 kg and Rs. 4 – Rs. 6 (~Rs. 1.5- 1.8 per kg) respectively. The average procurement cost for waste (Rs. 0.6 – 1.2 per kg) is very significant compared to the selling price of brick (Rs. 1.5 -1.8 per kg).

As the procurement cost of waste mainly depends on the distance between the source of waste and the industry, locally sourced wastes may have better economic feasibility. For local utilization of wastes in unfired brick industries, waste maps are to be prepared similar to the other geographical maps. As shown in Section 3, unfired bricks have high potential to incorporate different types of wastes. Thus mapping of the wastes is considered helpful not only for effective waste management but also to resolve for a cost-effective way of sourcing suitable raw materials to be used for producing unfired bricks.

In India, the use of slaked lime for industrial scale manufacturing of fly ash based unfired bricks is a common practice. Slaked lime is prepared on-site by slaking of quick lime in large uncovered slaking tanks. Providing well-controlled water quantity for slaking of lime is essential because a deficient supply of water in the tank may lead to partial carbonation of quick lime or may lead to incomplete slaking of quick lime. Unslaked lime particles may lead to cracking in bricks due to expansive slaking of quick lime particles during the curing phase. Also in the rainy season, the water content of lime slaked in uncovered slaking tanks may exceed the required quantity for the brick mix. Excess water may lead to shrinkage crack development in the bricks.

Also, in the wet condition of slaked lime, it is difficult to ensure the required proportion of hydrated lime in the brick mix due to an unknown quantity of water in the slaked lime. Therefore, to control the amount of water in the brick mix, it is proposed to use dry hydrated lime powder instead of slaked lime to avoid the above mentioned industrial challenge.

Another aspect is related to the cost comparison of different wastes for incorporation in unfired bricks. In India, standard size bricks are sold or purchased in bulk, measured by a certain brick number or volume. So, volumetric cost should normally be considered. However, wastes are procured and incorporated by weight in the bricks. Since the wastes differ in their specific volume, the wastes procured from a similar distance may have different volumetric cost. Therefore, in a country like India, the wastes should be compared based on their volumetric cost to determine the economic feasibility. Bulk density or specific gravity of different ingredients summarized in Table-S1 (attached as supplementary data) can be used to determine the volumetric costs of different wastes incorporated unfired bricks.

9. Conclusion

In the present article, a comprehensive review of studies related to unfired bricks, from an industrial perspective, has been presented to enhance the waste utilization in sustainable unfired bricks, and based on the review, the following conclusions have been drawn.

1. To stabilize the blended fines in unfired bricks, the cementitious binders are still the most used. However, a high amount of wastes can be incorporated using chemical binders in unfired bricks. The mixed binders (combinations of cementitious and chemical binders) along with the blended fines are expected to be the focus of future researches to

overcome the limitations of individual raw materials in wastes incorporated unfired bricks.

2. Approaches to select the molding water content have been found quite diverged among the various studies. Limited focused studies are available related to optimizing the molding water content in the case of cementitious binders, whereas, in the case of chemical binders, researchers focused primarily on the optimization of liquid content in the brick mix.
3. Two-stage mixing sequence has been found to be the most common to handle dry raw materials with similar physical states, whereas, suitable modifications are required to incorporate the raw materials with varying physical state. However, no focused study has been found to analyze the effect of different mixing sequences or mixing equipment related to unfired bricks.
4. Compaction of the mix has been found to depend on the liquid content in the brick mix whereas in other cementitious mixes the compaction is dependent on rheology. Focused studies are therefore required to understand the correlation of liquid content and rheology of the low moist mix regarding unfired bricks.
5. Forced compaction method has been found as the most popular molding method regarding waste-incorporated stabilized unfired bricks.
6. Ample studies are available related to optimizing the curing parameters of autoclaved curing. However, in limited studies, hybrid curing techniques have also been attempted. The use of low-cost hybrid curing conditions at ambient or low elevated temperature is expected to be future research trend to overcome the limitation of autoclaved curing

regarding the high initial infrastructure cost to stabilize the waste incorporated unfired bricks.

7. The waste maps similar to other geographical maps are required to enhance the industrial scale incorporation of wastes in unfired bricks, particularly in India. This will help to overcome the existing challenges of the Indian manufacturing industry. Further, powdered form of hydrated lime is suggested in place of slaked lime. However, incorporating the change in raw material requires significant research on other manufacturing parameters.

The comprehensive review from the industrial perspective presented here will support the selection of appropriate manufacturing parameters, which in turn will enhance the waste utilization in unfired bricks and support to produce low cost eco-efficient unfired bricks at industrial scale. For researchers, it provides research gaps and future research trends related to unfired bricks.

In the present article, the influence of varying manufacturing parameters on mechanical properties is covered. In the future, a separate review on other performance parameters related to unfired bricks can be carried out to understand the influence on durability properties and change in microstructure, mineralogy, and the reaction mechanism of different binders used to stabilize the unfired bricks.

Abbreviation

≈	No significant change;
↑	Increase;
↓	Decrease;
A	Amplitude;
A_{MWC}	Approach to select molding water content;
B/G	Ratio of binder: GGBS;
C	Cylindrical shaped;

CA	Coarse aggregates;
CKD	Cement kiln dust;
CS	Compressive strength;
D	Diameter;
EPS	Expanded polystyrene;
F	Frequency;
F/S	Ratio of fly ash to sand;
F1	Type of binder;
F2	Amount of binder;
F3	Internal proportioning of blended binders;
F4	Internal proportioning of blended fines;
F5	Liquid content;
FA	Fine aggregates;
G1	Type of binder;
G2	Concentration of binder;
G3	Internal proportioning in case of blended binders;
G4	Internal proportioning in case of blended fines;
G5	Liquid content;
H	Height;
h	Hour;
H/S	Ratio of NaOH to Na_2SiO_3,
H1	Type of binder;
H2	Amount of binder;
H3	Internal proportioning in case of blended binders;
H4	Internal proportioning in case of blended fines;
H5	Liquid content;
HL	Hydrated lime;
M	Molar;
M-Sand	Manufactured sand;
MSWI-FA	Municipal solid waste incineration ash;
MT	Mine tailings;
NDC	Not disclosed, and constant water content;
NDV	Not disclosed and variable water content;
NHL	Natural hydraulic lime;
Op.	Optimum point;
Ref.	Reference;
RH	Relative Humidity;
RHA	Rice husk ash;
RT	Room temperature;
S/N	Ratio of SiO_2 to Na_2O;
S1	Special size (details are mentioned in section 5.1);
SC	Standard compaction method;
SCT	Standard consistency test;
SP	Steam pressure;
SPT	Standard proctor test;
Temp.	Temperature;

UC	Uniform consistency/ flow criteria;
WCS	Water-cooled slag;

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