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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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4 **1 A state of the art review to enhance the industrial scale waste utilization in sustainable**  
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6 **2 unfired bricks**  
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10 **3 Vivek Gupta<sup>a</sup>, Hwa Kian Chai<sup>b</sup>, Yong Lu<sup>b</sup>, Sandeep Chaudhary<sup>a\*</sup>**  
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25 **11 Abstract**

26  
27 Manufacturing of unfired bricks, in which fines are stabilized using cementitious or chemical  
28 binders, has huge potential to incorporate various wastes as a building construction material.  
29 Although researchers have successfully attempted various wastes in unfired bricks at the  
30 laboratory scale, their industrial-scale incorporation is still limited and unexplored. From an  
31 industrial point of view, mix proportions, mixing strategies, molding methods, and curing  
32 conditions are of equal importance. However, the unavailability of comprehensive knowledge  
33 related to manufacturing aspects hampers the industrial-scale implementation of research  
34 outcomes regarding waste incorporation in unfired bricks. This study summarizes the research  
35 outcomes related to waste incorporated unfired bricks, highlighting the manufacturing aspects  
36 from the industrial point of view. In this paper, mix proportions attempted, approaches for  
37 selecting the liquid content, adopted mixing strategies, compaction parameters, and curing  
38 conditions in previous studies are discussed for various waste incorporated bricks. Studies are  
39 classified based on the binder used for stabilization, and the effects of influencing parameters on  
40 the mechanical performance of bricks are discussed in detail. Furthermore, some industrial  
41 challenges related to unfired brick production in Indian scenario are discussed. Studies related to  
42 mixture proportioning, mixing optimization and hybrid curing development for a multi-waste  
43 incorporated system are expected to be future research trend for waste stabilization in unfired  
44 bricks. The comprehensive knowledge presented here is expected to support in the selection of  
45 suitable manufacturing aspects, which in turn enhances the waste utilization in unfired bricks at  
46 an industrial scale.  
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54 **32 Keywords:** Unfired brick, Wastes, Mix optimization, Compaction, Curing, Industrial-scale  
55 **33 production**  
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75	Acknowledgment

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4 **78 1. Introduction**

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7 79 Sundried mud blocks have been used for construction for centuries, especially in rural regions  
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9 80 and in the desert [1,2]. Ancient bricks were composed of soil, molded by hand, and cured  
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11 81 directly in sunlight without compaction. A lot of modifications in raw materials and  
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14 82 manufacturing processes have been made from time to time to improve the performance of the  
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16 83 bricks on various parameters. In the modern world, unfired bricks are made by stabilizing soil or  
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18 84 sand using a variety of binders. The stabilized bricks show enhanced properties due to the  
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21 85 improved bonding between the fine particles as compared to unstabilized bricks. The unfired  
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24 86 bricks are nowadays machine manufactured instead of hand-molded as in earlier days. Bricks are  
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26 87 compacted by vibrating or compressing the fresh mix. Sometimes, fresh mixes are prepared with  
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29 88 self-compacting properties and are just poured in the molds directly.

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32 89 Curing of unfired bricks in sunlight takes a longer time to achieve strength. Different curing  
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34 90 techniques were attempted by researchers [3–5] to accommodate the changes in raw materials  
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37 91 and to achieve the required properties in a shorter time. However, the selection of suitable curing  
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39 92 techniques depends on the raw materials and mainly on the binder used for the stabilization. In  
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41 93 general, cementitious binders (cement or lime) are used to stabilize the unfired bricks. However,  
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44 94 the high carbon footprints [6,7] associated with the use of these binders are considered as the  
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47 95 major shortcoming.

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50 96 The growing need for sustainable and eco-friendly construction practice has motivated  
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52 97 researchers to investigate for viable alternatives to conventional cement and lime-based  
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54 98 materials. Brick stabilization by chemical binders developed through alkali activation or  
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57 99 geopolymerization mechanisms confirms the recent emphasis on sustainable production [8]. In a  
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59 100 recent study [9], an eco-friendly biopolymer has been used as an alternative binder. On the other

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101 hand, the use of additives to optimize the binder quantity can be an alternative approach to  
102 decrease the overall carbon footprint of the unfired bricks. In some studies [5,10], gypsum was  
103 used to optimize the amount of cementitious binders for enhanced stabilizing effect. However,  
104 the use of costly resources as an additive to optimize the binder is not an ideal solution.

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

115 The use of waste materials in place of soil seems to be a viable option in conserving natural  
116 resources. Researchers have incorporated various waste materials in unfired bricks as a substitute  
117 to clay, such as fly ash [13], phosphogypsum [17], diatomaceous earth [10], ceramic mud [18],  
118 quarry dust [19], billet scale [19], stone mud [15], brick dust [15], recycled paper mill residue  
119 [20], crushed sand [21], and bottom ash [22]. In some studies, the sand was blended with fly ash  
120 [5], bio briquette ash [23], and phosphogypsum [24] and used as a fine aggregate. Although the  
121 studies mentioned above have proven the feasibility for the incorporation of various wastes in  
122 unfired bricks at a laboratory scale, the incorporation of wastes in unfired bricks at the industrial  
123 scale is still limited. For the manufacturing of waste incorporated bricks, comprehensive

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124 knowledge about manufacturing and other industrial aspects, as shown in Fig. 1, is necessary.

125 Manufacturing feasibility can only be accessed with the collective knowledge about  
126 proportioning of raw materials, mixing strategy, and way of compaction and curing conditions  
127 suitable to incorporate the wastes. After assessing the manufacturing feasibility, the developed  
128 product is to be evaluated on technical and sales aspects. For industrial implementation, all the  
129 aspects are equally important and need to be evaluated before accepting for full-scale production.

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

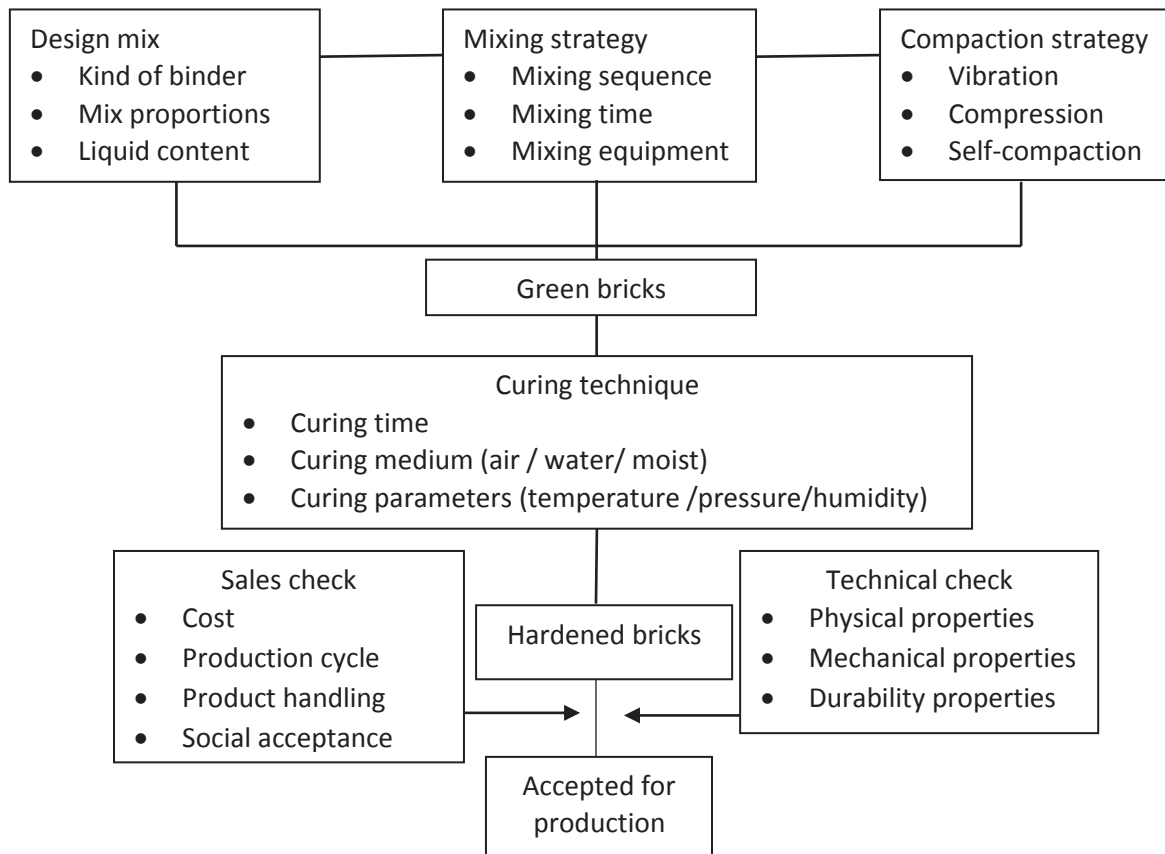


Fig. 1 Manufacturing and other industrial aspects required for waste incorporation in unfired

## 145 2. Previous reviews and gap

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

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154 **Table-1** Reviews published in last decade on unfired bricks and its alternatives<sup>#</sup>

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]

<sup>#</sup>Please refer to the section titled “Abbreviation” for details.



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4 155 In the year 2011, Raut et al. [26] reviewed the physico-mechanical and thermal properties of  
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6 156 bricks incorporating various types of industrial and agricultural wastes in masonry bricks. The  
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9 157 added advantages of unfired bricks, including the low embodied-energy, were highlighted. In the  
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12 158 year 2013, Zhang [29] presented an extensive review of waste incorporation in masonry bricks,  
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14 159 categorizing them based on their production methodology. However, their main focus was waste  
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16 160 incorporation in the bricks rather than the parameters of the manufacturing process. In the year  
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19 161 2014, Muñoz-Velasco et al. [31] presented a review focusing on the manufacturing parameters  
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21 162 such as pre-conditioning, mixing water, shaping method, sample size, drying, and firing  
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23 163 conditions used in the production of waste incorporated clay bricks. These manufacturing  
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25 164 parameters are to be optimized for the required product characteristics by analyzing the influence  
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28 165 of waste incorporation on them. From the manufacturing point of view, the influence of these  
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30 166 parameters on product characteristics is of prime importance. However, in the above review,  
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33 167 only studies related to fired bricks were covered. A most recent review was given by Gavali et al.  
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35 168 [38] on the development of alkali-activated bricks. A brief review of raw material characteristics,  
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37 169 manufacturing processes (experimental conditions opted), and properties only of alkali-activated  
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39 170 bricks (part of unfired brick) were summarized from the experimental design point of view.  
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44 171 It is clear from the above that the previous review studies mentioned in Table-1, majorly focused  
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46 172 on the optimized amount of wastes for incorporation in unfired bricks, whereas, the other  
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48 173 manufacturing parameters were not emphasized. The unfired bricks have advantages over the  
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50 174 alternatives in terms of lower embodied energy, mainly due to their environment-friendly  
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52 175 manufacturing process. A comprehensive review of studies related to suitable mix proportions,  
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54 176 mixing strategies, molding methods, and curing conditions are highly required to scale up waste  
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56 177 incorporation in unfired bricks at an industrial scale. Such a focused review is expected to  
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178 support in the selection of suitable manufacturing aspects, which in turn can enhance the waste  
179 utilization in unfired bricks at an industrial scale. Therefore, considering the need for the focused  
180 review, the studies related to unfired bricks have been summarized in the present review to  
181 enhance the industrial scale waste utilization in sustainable unfired bricks.

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

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

198 Table-2 Cementitious binders used to stabilize waste in unfired bricks/blocks<sup>#</sup>

S. No.	Cementitious binder used	Waste and other raw materials stabilized	Focus of the optimization	A <sub>MWC</sub>	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 Chindapasirt	[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	Izemouren 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 <sub>2</sub> (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 <sup>3</sup> )	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.

199 Table-3 Chemical binders used to stabilize the wastes in unfired bricks<sup>#</sup>

S. No.	Chemical binders used	Wastes and other raw materials stabilized	Focus of the optimization	Author/(s)	Ref.
1	NaOH (10M), and Na <sub>2</sub> SiO <sub>3</sub>	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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> 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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> , 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 <sub>2</sub> SiO <sub>3</sub>	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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> (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 <sub>2</sub> SiO <sub>3</sub> (S/N-3.47)	GGBS (0%-30%), and clay (70%-100%)	G2, G3, G4, G5	Ferone et al.	[85]
21	NaOH, and Na <sub>2</sub> SiO <sub>3</sub> (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

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4 215 partially in addition to other materials such as clay, sand, crushed sand, crushed lime stone  
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7 216 aggregates, expanded polystyrene (EPS) beads, sand powder, calcium chloride and gypsum in  
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9 217 unfired bricks as shown in Table-2.

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12 218 In some studies, fibers were used in the stabilized unfired bricks such as waste plastic fibers [39],  
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15 219 wood fiber waste [40], straw fibers [87], polystyrene fabric [2], and oil palm fibers [41]. In a  
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17 220 study [2], different fibers were added in varying geometrical arrangements in two sandwich  
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19 221 layers to make the bricks earthquake resistant. In the studies mentioned in Table-2, the focus of  
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21 222 researchers was to optimize the type of binder (F1), amount of the binder (F2), internal  
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23 223 proportioning in case of blended binders (F3) and blended fines (F4), and the liquid content (F5)  
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25 224 to get an optimized brick mix.

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30 225 To determine the optimum molding water content, researchers used different approaches as  
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32 226 shown in Table-2, i.e. standard proctor test (SPT), standard consistency test (SCT), uniform flow  
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35 227 consistency (UC) and standard compaction method (SC). In some studies [15,42], SPT was used  
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37 228 to determine the optimum moisture content (OMC) of the mix and equivalent to OMC was taken  
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39 229 as molding water content. In some other studies [13,14,43], SCT was used to determine the water  
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42 230 content to achieve the required consistency, and 90% of that was selected as molding water  
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44 231 content. Based on the uniform consistency required, water content was adjusted in some studies  
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47 232 [17,19,20,44–46] to achieve the required consistency parameter. The static compaction method  
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49 233 proposed by the Center for Development of Enterprises (C.D.E.) [88] was used by Izemmouren  
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51 234 et al. [21] to determine the optimum molding water content, acknowledging the non-suitability of  
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54 235 proctor test as quoted by Reddy and Jagdish [89]. Similarly, at constant static pressure, the  
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57 236 optimum molding water content was determined in a previous study [12,21] and used to cast the  
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59 237 bricks.



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4 238 As can be seen in Table-2, many studies did not specify their approach to select the water  
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6 239 content. Some of such studies kept the water to binder ratio or the water content in the mix  
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9 240 constant, whereas some others considered it as a variable parameter. In a few studies [41,47–49],  
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11 241 details related to molding water content are not specified as such. However, the research  
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14 242 outcomes of these studies regarding waste incorporation in unfired bricks are significant and are  
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16 243 therefore incorporated in Table 2.  
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19 244 It is noted that ample studies are available related to wastes stabilization in unfired bricks using  
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22 245 cementitious binders. Dry mix proportions summarized in the above sections can give a  
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24 246 reference to the probable binders to be utilized to stabilize a particular waste in unfired bricks.  
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27 247 However, the influence of varying proportions on mechanical performance is separately  
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29 248 discussed in section 7 on the effect of influencing parameters. It is also noted that many studies  
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32 249 did not specify the approach to select water content. Few studies which mentioned the approach  
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34 250 are found to have a wide diversity between their approaches. However, no study is found to be  
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37 251 commenting on the appropriate approach to select the water content. In view of this, it has been  
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39 252 challenging to determine the trial range to incorporate the wastes at an industrial scale, since the  
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41 253 same type of wastes could significantly differ in their characteristics because of their different  
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44 254 origins [90].  
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### 47 **3.2 Bricks stabilized by chemical based binders**

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49 256 Different types of chemical binders, namely sodium hydroxide, sodium silicate and their blended  
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52 257 forms, were used by researchers to stabilize the various wastes in unfired bricks as shown in  
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54 258 Table-3. The wastes investigated in these studies included fly ash, bottom ash, copper mine  
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57 259 tailings, cement kiln dust, CFBC bottom ash, alumino-silicate rich tuff (Bafoundou Tuff), water-  
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59 260 cooled slag, clay brick waste, weathered coal fly ash, rice husk ash (RHA) crumb rubber, GGBS,  
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4 261 boiler ash, water-cooled slag, and metakaolin. These wastes were used alone or in combination  
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6 262 with sand, manufactured sand (M-sand) and clay, as shown in Table-3.  
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10 263 In the application of chemical binders, the amount of binder in the mix can be varied in two  
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12 264 ways, i.e. by varying the molar concentration or by varying total liquid content. As observed  
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14 265 from previous studies summarized in Table 3, the focus has been to optimize the type of binder  
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16 266 (denoted as G1), the concentration of binder (G2), internal proportioning in cases of blended  
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18 267 binders (G3) and blended fines (G4), and the liquid content (G5) to get an optimized brick mix.  
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20 268 In some studies [91,92], chemical binders were also used to produce waste incorporated unfired  
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22 269 bricks, but because these studies did not focus on the mix optimization, so they are not included  
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24 270 in Table 3.  
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### 27 271 **3.3 Bricks stabilized by other binders**

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30 272 Other than cementitious and chemical binders, some mixed/alternative binders were used to  
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32 273 produce the unfired bricks, as shown in Table-4. In a study [9], a bio-based binder made from  
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34 274 alginate was attempted to stabilize the soil. Some researchers [93–96] stabilized the clay bricks  
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36 275 using waste materials without using conventional cementitious or chemical binders. In a recent  
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38 276 study [97], a different approach was attempted, where a mixture of chemical and cementitious  
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40 277 binders was used to produce solid bricks by stabilizing three different types of boiler ashes. In  
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42 278 another study [98], CNF binder system (A mixture of hydrated lime, sodium carbonate, and fly  
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44 279 ash with an internal ratio of 4.3:1:14.7) along with NaOH was used to stabilize red mud in  
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46 280 unfired bricks. Mixed binders seem to be appropriate to overcome the cost considerations  
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48 281 regarding the chemical binders. The potential of such mixed binders may be further explored to  
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50 282 stabilize the other wastes.  
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283 Table-4 Mixed/alternative binders used to stabilize the wastes in unfired bricks<sup>#</sup>

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) <sub>2</sub> , Na <sub>2</sub> CO <sub>3</sub> , 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

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4 295 bricks. Researchers used different approaches to select the liquid content in case of unfired  
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6 296 bricks stabilized by cementitious binders. In some studies (Table-2), wastes as fines were  
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9 297 incorporated in blended forms considering their own advantages and limitations, whereas, in  
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12 298 some other studies (Table-2), binders were used in blended forms to stabilize the waste.  
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15 299 Secondly, chemical binders are generally used in liquid form and do not significantly contribute  
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17 300 in terms of physical volume as compared to the cementitious binder. Cementitious binders have a  
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19 301 low cost as compared to chemical binders. However, by using a chemical binder, a high volume  
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22 302 of wastes can be incorporated in unfired bricks. Locally available waste having low  
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25 303 transportation cost may give the cost advantage to use costly chemical binders in unfired bricks.  
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27 304 The use of mixed binders (cementitious and chemical) attempted by Poinot et al. [97] may  
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29 305 provide a cost-effective solution. Alkali activated bricks produced in the study could achieve  
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32 306 approximately 7.5 MPa compressive strength within one day using a low molarity NaOH  
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35 307 solution (0-5 M) along with lime as binder.  
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#### 38 308 **4. Mixing strategy used for unfired bricks**

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41 309 Currently, there is no agreed or standardized mixing strategy to prepare the fresh brick mix at an  
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43 310 industrial scale in India. The adopted mixing strategies at the laboratory scale vary considerably  
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46 311 within the literature, and they are generally based upon the characteristics of raw materials used  
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49 312 to prepare the mix. Researchers often adopted an improvised mixing strategy or previously cited  
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51 313 strategy for the selected raw materials. However, limited discussions were made in the  
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53 314 publications regarding the suitability of the adopted mixing strategy. In this section mixing  
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56 315 strategy used by various researchers to prepare the brick mix is summarized. No specific studies  
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58 316 related to variation in mixing sequence, mixing time and speed, and mixing equipment have been  
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4 317 found. Therefore, a brief review on the effect of mixing strategy for other construction materials  
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7 318 has been added to provide useful insights to the importance of mixing strategy.  
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#### 10 319 **4.1 Mixing sequence**

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12 320 The mixing sequences used by various researchers to prepare the fresh brick mixes for unfired  
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14 321 bricks are summarized in Table-5. Researchers adopted different mixing sequences, such as  
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17 322 single-stage, two-stage, and three-stage mixing sequences to handle the heterogeneity in the  
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19 323 physical state of the different raw materials. The selection of a suitable mixing sequence seems  
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22 324 to be essential to manage the ingredients with varying physical states in the blended mix. Ahmari  
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24 325 and Zhang [68] adopted a single-stage mixing sequence as only one ingredient is stabilized  
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27 326 using the alkaline solution in the study. In another study, Zhao et al. [60] mixed all the dry  
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29 327 ingredients along with water in a single-stage mixing sequence. However, the two-stage mixing  
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32 328 sequence is the most common to handle dry binders and liquids.  
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35 329 As shown in Table-5, majority of researchers adopted the two-stage mixing sequence in the case  
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37 330 of blended mix. In these studies, dry ingredients were commonly mixed in the first stage, and  
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40 331 liquid content was added separately in the second stage. However, in some studies [24,63,81,96],  
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42 332 dry ingredients were incorporated in two stages, and liquid content was added with them in any  
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45 333 of the stages.  
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334 Table-5 Mixing strategy used to prepare the fresh mix in various studies related to unfired bricks<sup>#</sup>

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.		[22]
		2. Adding the water, and further mixing	Water	10 min.	Pan mixer	
		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]

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		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 °C 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	--		[54]
		2. Liquid content was added, and mixed.	Water and superplasticizer	5 min.	Pan mixer	
		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.		[56]
		2. Surface saturated coarse aggregates were added, and mixed again	Oil palm kernel shell (pre-soaked for 1 h)		Mechanical mixer	
		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	--		[41]
		2. Water was added, and remixed	Water	2-3 min.	Concrete mixer	
15	Sodupe-Ortega et al.	1. Dry raw materials were mixed.	Cement, crumb rubber, and crushed limestone	3 min.		[62]
		2. Stop the mixing, and keep the mix at rest	--	2 min.	Concrete mixer, and industrial mixer	
		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.		[40]
		2. Chemical admixtures in solution form, and water were added, and mixed again.	An aqueous solution of CaCl <sub>2</sub> , and water	2 min.	Concrete mixer	
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.		[98]
		2. NaOH with water was added.	NaOH (with ref. to mix), and water	--	Mechanical mixer	
		3. Binder was added, and mixed again.	Ca(OH) <sub>2</sub> , Na <sub>2</sub> CO <sub>3</sub> , and fly ash	3 min.		

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



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4 335 As can be seen in Table-5, some researchers adopted the three-stage mixing sequence. In the  
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6 336 studies [19,45,56], the first two stages were dedicated to dry mixing of solids, and in the third  
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8  
9 337 stage, liquid content was added. However, in another study [22] with a three-stage mixing  
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11 338 sequence, all the dry ingredients were mixed in the first stage of mixing. After that, water was  
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14 339 added in the second stage and foam was injected into the mixed slurry in the third stage of  
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16 340 mixing. In a few studies [54,98], to handle the solid ingredients with different characteristics,  
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19 341 some of the ingredients were added in the first stage. After that, liquid content was added and  
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21 342 mixed in the second stage of mixing. In the third stage of mixing, the remaining dry ingredients  
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23  
24 343 were added and mixed to get the homogeneous mix.

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26  
27 344 Pre-screening of ingredients is another important aspect of ensuring the homogeneity of the mix.  
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29 345 Algin and Turgut [50] reported the issues related to lump formation and accumulation at the one  
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31  
32 346 side of the mixer during mixing of unprocessed cotton waste and lime powder waste. To enable  
33  
34 347 the mixing, pre-processing of cotton waste was done before incorporating in cement stabilized  
35  
36 348 bricks. In a study [81], fine ingredients were pre-screened from 90-micron sieve, and coarse  
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39 349 ingredient was pre-screened from 1 mm sieve before the mixing. In another study [24], a  
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41 350 different approach was adopted to handle waste phosphogypsum. Hydrated lime was added into  
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44 351 the phosphogypsum to neutralize residual acid impurities in the first stage of mixing. After that,  
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46 352 in the second stage of mixing, other ingredients were added and mixed to get a homogeneous  
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49 353 mixture. In another study [63], the EPS beads were pre-wetted before mixing in dry ingredients.

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52 354 Different approaches[13,20] were used to handle the wet raw materials in the mix. Raut et al.[20]  
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54 355 adopted the two-stage mixing sequence to incorporate highly wet recycled paper mill residue in  
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57 356 the bricks. In the first stage, cement and highly fibrous, wet and lumpy paper mill residue were  
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59 357 mixed using a specially designed mixer. In the second stage, additional water required was added  
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4 358 and mixed again to get a homogenous mix. In the other study[13], the dry ingredients were pre-  
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7 359 screened from 4.75 mm sieve and mixed in the dry state at the first stage of mixing. In the  
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9 360 second stage of mixing, slaked lime slurry, pre-screened from 1.18 mm sieve was added to the  
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11 361 dry mix and kneaded to get uniform consistency mix. Water content was calculated based on the  
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14 362 standard consistency requirement, and 90% of that was maintained in the semi-dry mix based on  
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16 363 measurements. However, in industrial set up, bulk slaking of quick lime is done in big slaking  
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19 364 tanks. As per the author`s manufacturing experience, it is difficult to provide controlled quantity  
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21 365 of water just sufficient for slaking of quick lime in the practicing industrial setup for such bricks  
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23  
24 366 in India.

#### 25 26 27 367 **4.2 Mixing time**

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29 368 Mixing time used by various researchers has been stage-wise summarized in Table-5. It was  
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31  
32 369 observed that the total mixing time used for mixing was varied in the range of 4 min. – 15 min.  
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34 370 In some studies, as shown in Table-5, mixing time was either partially specified or not specified.  
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37 371 To understand the mixing strategies, mixing data related to these studies have been incorporated  
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39 372 in Table-5, whereas for further analysis, these studies have been excluded. Further discussion has  
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42 373 been made only for the studies which have mentioned the stage-wise mixing time details, as  
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44 374 shown in Table-5. In a study [60] with one stage mixing sequence, mixing was done for 5 min. in  
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46 375 a single stage. Studies [15,40,47,50,65,95] incorporating the raw ingredients in two stages  
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49 376 typically had the total mixing time vary between 4-5 min. The mixing time used for mixing of  
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51 377 dry ingredients was varied between 1-3 min. Whereas the mixing time used for mixing of liquid  
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53  
54 378 in the second stage varied in the range 2-3 min.

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57 379 In the studies [15,50,65], the mixing time used for dry blending of solids in the first stage was  
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59 380 either equal or less than that used to mix the liquid in the second stage whereas the opposite trend

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4 381 was observed in the studies [40,47,95]. In the studies [19,45], a three-stage mixing sequence was  
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7 382 used, and the same duration (2 min.) was given for each stage of mixing. As noted above for the  
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9 383 two-stage mixing studies, the mixing duration typically varied between 4-5 min., whereas, in  
10  
11 384 some studies [78,81], mixing was done for a long duration up to 15 min.  
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### 14 385 **4.3 Mixing equipment**

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17 386 Mixing equipment used by various researchers are summarized in Table-5. It can be seen that the  
18  
19 387 researchers used different mixing equipment, namely industrial mixer, pan mixer, concrete  
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21 388 mixer, mechanical mixer or laboratory mixer to mix the raw materials. Raut et al. [20] adopted a  
22  
23 389 unique mixing methodology to incorporate highly wet recycled paper mill residue in forced  
24  
25 390 compacted bricks. A special mixer with multiple blades was designed and fabricated to shear the  
26  
27 391 mix of cement and highly fibrous and lumpy paper mill residue with every rotation. The primary  
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29 392 purpose was to scatter the mix to get a homogenous mix with cement. After mixing in the first  
30  
31 393 stage, to maintain the homogeneity further, water was sprayed using air pumps over the mixture  
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33 394 in the second stage and mixing was done again. A similar arrangement of air pump was used for  
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35 395 spraying the homogeneous water in the mix in some other studies [5,50,65]. In a study [5], a ball  
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37 396 mill was used for mixing dry ingredients, and water was added using a sprayer.  
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44 397 In the majority of literature, only the name of equipment was reported except [47], which  
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46 398 mentioned the speed of the mixer in the studies related to unfired bricks. Focused studies on the  
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48 399 effect of mixing speed are not available related to unfired brick mixes. Therefore a brief review  
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50 400 related to the effect of mixing strategy, especially concerning the mixing speed, on other  
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52 401 construction materials is added in the next subsection.  
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#### 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

425 binder (slaked lime) [13], a higher potential may be expected by adopting the pre-screening  
 426 approach.

### 427 5. Molding and compaction methods used for unfired bricks.

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

432 **Table-6** Molding and compaction method used in various studies related to unfired bricks<sup>#</sup>

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 al.	Forced compacted	--	230×105×80	[20]
10	Izemouren 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 <sup>-1</sup> ,	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.

## 434 **5.1 Vibro-compacted**

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

## 445 **5.2 Forced-compacted**

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

454 In a study [20], a unique two-stage casting process was adopted to handle the high moisture-  
455 holding capacity of fibrous recycled paper mill residue to get smooth-surfaced bricks after  
456 drying. The two-stage casting procedure was found helpful to avoid uneven irregular shaped

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4 457 bricks produced with single-stage casting process. In another study [68], Ahmari and Zhang  
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7 458 compacted the specimen in two stages and carried out investigations for optimum compaction  
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9 459 parameters. In the first stage, minor compaction was used, whereas, in the second stage, the  
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11 460 compacted specimen was further compressed for a longer forming duration of about 10 min.  
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13  
14 461 Specimens were compared at different loading rates and varying water content. The elastic  
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16 462 deformation was observed to be less at high forming pressure and low water content (25 MPa  
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18 and 12%), which was attributed to the effective volume decrease of voids within granular matrix  
19 463  
20  
21 464 [68] at the applied condition.

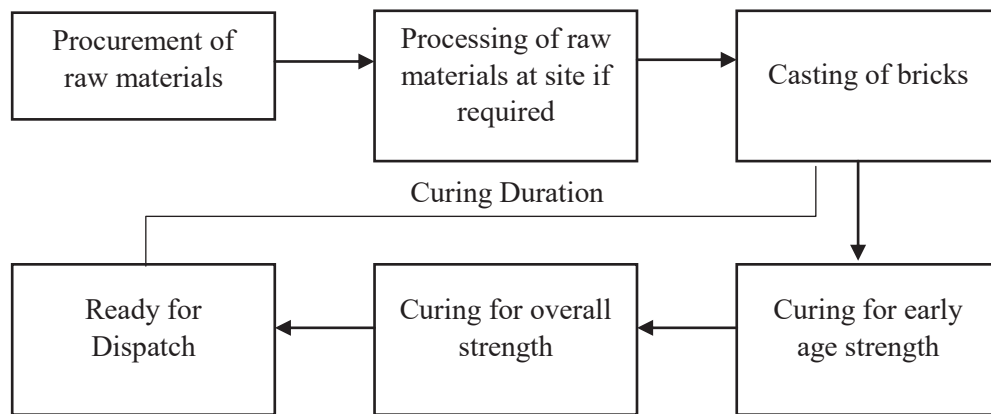
### 24 465 **5.3 Self compacted and manually compacted**

26 466 As shown in Table-6, in many studies brick mixes were prepared with self-compacting properties  
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29 467 or just manually tamped without a hydraulic press. Specimens were cast in cubical and cuboidal  
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32 468 shape in the above-cited studies. Brick mixes with self-compacting properties may save the  
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34 469 considerable cost of compression and vibration equipment.

## 38 470 **6. Curing conditions used for unfired bricks**

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41 471 Selection of suitable curing conditions, i.e. the surrounding environment conditions (temperature,  
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43 472 pressure, and humidity) and the curing medium (air, water, airtight or combination of them) for  
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45 473 the specified period (curing duration) is crucial for a brick mix to achieve the targeted  
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48 474 performance parameters cost-effectively. Curing duration of bricks is the period required to  
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50 475 develop the targeted strength from the casting of fresh bricks to the dispatch of hardened bricks,  
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53 476 which has a direct impact on the production cycle, as shown in Fig. 2. The optimum curing  
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55 477 conditions majorly depend on raw material characteristics that indirectly govern the rate of  
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57 478 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 bag (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°C whereas in studies [65,66,68,78], oven-dried curing was done at 35°C-115°C. In airtight curing [12,15,42], surrounding conditions

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4 495 may be similar to air curing/moist curing except for the interaction of the material with the  
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7 496 surrounding air/moisture. In studies [19,21], airtight curing was done for the whole curing  
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9 497 duration whereas, in a study [47], samples were subjected to water curing for 1 day after 27 days  
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12 498 of airtight curing. In some studies [2,5,39], samples were put under wet gunny bags at ambient  
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14 499 temperature, to minimize the evaporation loss.

## 17 500 **6.2 Moist curing at ambient and elevated temperature**

20 501 Moist curing means curing of bricks at a high relative humidity (RH) (95%-100%) and ambient  
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23 502 temperature. At elevated temperature, it can be termed as steam curing. In studies [45,48,63],  
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25 503 moist curing of bricks was done for 28 days or until the testing at 95% or greater RH and a  
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28 504 temperature between 20-27°C. In some studies [21,81,98], steam curing was done for a particular  
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30 505 duration ranging between 6 h to 90 days or until the testing at 95% or greater RH and a  
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33 506 temperature between 40-75°C. In some studies, bricks were kept in air for 1-2 days to achieve  
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35 507 sufficient green strength [5,21,45,63,81] whereas, in other studies [17,47,48,98], bricks were  
36  
37  
38 508 directly subjected to moist/steam curing.

## 41 509 **6.3 Water curing at ambient or elevated temperature**

44 510 In water curing [50,55,62,65], initial curing was done for 24 h either in the air or in the moist  
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47 511 condition to achieve sufficient green strength, and after that, samples were put either in the water  
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49 512 or in limewater for curing at 20-24°C. In a separate study [43], long initial curing for a week was  
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51  
52 513 done under moist wet burlap bags before subjecting to water curing, whereas, in another study  
53  
54 514 [54], water immersion duration was taken as variable between 0-28 days.

#### 515 **6.4 Autoclaved Curing**

516 Many studies [10,49,51,53,59,60,64,96] used autoclaved curing for unfired bricks, as shown in  
517 Table-7. In autoclaved curing, initially, bricks are kept for a pre-autoclaving duration to achieve  
518 sufficient green strength. After achieving green strength, bricks are put for autoclaving for a  
519 particular duration. Autoclaving duration includes the total time required for ramping up, holding  
520 and ramping down. In some studies [39,51], pre-autoclaving duration was kept constant as 24 h,  
521 whereas some studies [10,64] varied this duration in the range of 6 – 48 h and 1 – 11 days  
522 respectively. The majority of studies specified only the holding duration except [53], which  
523 specified the ramping up and ramping down durations as 2 h and 3 h, respectively. In some  
524 studies [10,49] holding duration was kept constant as 4 h whereas, in other studies  
525 [51,53,59,60,64,96], the holding duration was taken as a variable in a particular range between 2  
526 – 14 h. In a study [10], the steam temperature was kept constant at 130°C, whereas in another  
527 study [53], the steam temperature was varied between 170°C and 190°C. Constant steam pressure  
528 was considered in [10,49] as 0.14 MPa and 0.80 MPa respectively whereas, in other studies  
529 [51,59,60,64,96] the steam pressure was taken as a variable in a particular range between 0.5- 2.0  
530 MPa.

531 **Table-7** Curing strategies adopted by researchers in previous studies related to unfired bricks<sup>#</sup>

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 Chindapasirt	1.1 Initial curing	1 – 11 days	Moist	23°C, and 90% RH	[10]
		1.2 Autoclaved curing	4 h	Steam	130°C, 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 °C	
		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°C, 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°C	
		1.4 Air drying	For 1 day just before testing	Air	23 ± 2°C	
6	Oti et al.	Airtight moist curing	Till the end of the curing	Airtight	At RT (20 °C).	[15]
7	Singh and Garg	Ambient to elevated temp. in moist conditions	Up to 90 days	Moist	27°C – 50°C, 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 °C, and RH>95%	[19]
10	Izemouren 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 °C	
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°C	
		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 °C, 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 °C	
		1.3 Elevated temp. air curing	24 h	Air	115 °C	
30	Malhotra and Tehri	Ambient moist curing	28 days	Moist	27±1°C, 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 °C, and 50 % RH	[66]
33	Ahmari and Zhang	Elevated temp. air curing	7 days	Air	90°C	[68]
34	Abdullah et al.	Elevated temp. air curing	1 h – 24 h	Air	40°C - 95°C	[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°C, 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°C, 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.

## 532 **7. Mechanical performance of unfired bricks**

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

### 539 **7.1 Influence of mix proportions on the properties of unfired bricks stabilized by** 540 **cementitious binders**

#### 541 *7.1.1 Type of binder*

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

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4 554 Liu et al. [55] compared the different types of cement (alumina cement, slag cement, Portland  
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7 555 cement and, grounded cement clinker) to stabilize the wastewater sludge in unfired bricks. The  
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9 556 highest compressive strength of 40.3 MPa could be achieved with alumina cement. Whereas, for  
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11 557 a similar mixing ratio, only 7.7 MPa compressive strength could be achieved with Portland  
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13 558 cement of 32.5 R grade. Shon et al. [58] compared different binders (cement and lime), with or  
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15 559 without class F fly ash, to stabilize the stockpiled CFBC ash and observed that a mixture of lime  
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17 560 and class F fly ash resulted in the highest strength of unfired bricks in adopted curing conditions.  
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19 561 Further,  $\text{CaCl}_2$  incorporation in the mix resulted in a high early age (3 days) strength and a little  
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21 562 increase in 28 days compressive strength.  
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26  
27 563 Zhang et al. [64] compared two different binders, namely lime and cement, in addition to CFBC  
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29 564 slag and CFBC fly ash in autoclaved bricks. Cement was found better as compared to lime, as no  
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31 565 effective increase in strength was observed in the case of lime after autoclaving the bricks. Yang  
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33 566 et al. [49] treated the phosphogypsum at two different autoclaving conditions and compared their  
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35 567 compressive strength, along with the raw phosphogypsum. The highest strength was observed in  
36  
37 568 case of low autoclaved phosphogypsum (120 °C, 0.12 MPa and 16 h), whereas the lowest  
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39 569 strength was observed with the raw phosphogypsum.  
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#### 44 45 570 *7.1.2 Amount of binder*

46  
47 571 The influence of the varying amount of binder was observed by various researchers [13,18–  
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49 572 20,49,51–53,55,59] while incorporating the wastes in unfired bricks. Wattanasiriwech et al. [18]  
50  
51 573 observed the effect of varying cement content to stabilize the waste mud collected from the tile  
52  
53 574 industry. With 15% cement content, stabilized paver blocks could achieve 35 MPa compressive  
54  
55 575 strength after 28 days of curing. However, at 30% cement, since rapid hydration occurred, paver  
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57 576 block could achieve 35 MPa within 7 days and a maximum of 54 MPa compressive strength after  
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4 577 14 days of curing. A similar increase in compressive strength was observed with the increase in  
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7 578 cement content in many waste incorporated bricks [19,55]. Whereas in another study [20], almost  
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9 579 constant compressive strength ( $9\pm 1$  MPa) was observed at varying cement content (5% – 20%)  
10  
11 580 in recycled paper mill residue (80% - 95%) bricks.

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14  
15 581 Contreras et al. [52] observed the increase in the compressive strength with the increase in binder  
16  
17 582 content (cement/lime) regardless of the type of C&D waste aggregate. However, in the case of  
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19 583 lime, at a higher lime percentage (35%), a slight decrease was observed in the compressive  
20  
21 584 strength. The increase in compressive strength was more prominent in case of cement than lime  
22  
23 585 at similar percentage incorporation in the mix. In another study, Kumar [13] investigated the  
24  
25 586 optimum amount of lime in brick mixes containing lime, fly ash, and phosphogypsum and found  
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27 587 maximum compressive strength at 30% lime content.

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32 588 Çiçek and Çinçin [59] varied the lime content (8%-12%) in lime fly ash bricks and obtained the  
33  
34 589 maximum compressive strength of approximately 12 MPa at 12% lime content by autoclaved  
35  
36 590 curing. Yang et al. [49] varied percentage of lime (5%-15%) to stabilize phosphogypsum in a fly  
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38 591 ash sand autoclaved bricks. With the increase in lime content, compressive strength and flexural  
39  
40 592 strength of the bricks increased. Fang et al. [53] varied the ratio of lime to sand powder. They  
41  
42 593 observed an increase in the compressive strength in stabilized copper tailing bricks with the  
43  
44 594 increase in the ratio of lime to sand powder in constant autoclaving parameters. Çiçek and  
45  
46 595 Tanriverdi [51] observed the increase in compressive strength with the increase in percentage  
47  
48 596 lime, and 12% was considered as optimum content. At a higher lime content, no significant  
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50 597 effect on mechanical strength was observed. Variation in the optimum amount of lime among the  
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52 598 different studies may be due to the variation in adopted curing conditions and the characteristics  
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54 599 of the stabilized waste.

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4 600 Some researchers [5,10,21,22,40,42,43,54] partially replaced the cementitious binder and  
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6  
7 601 optimized the amount of the binder in unfired bricks. Pahraraji et al. [22] incorporated GGBS  
8  
9 602 (10%-20%) as partial replacement of hydrated lime and Portland cement in coal ash bricks. The  
10  
11  
12 603 amount of hydrated lime and Portland cement in cement ash bricks was saved by 20% on using  
13  
14 604 GGBS and an increase in 28 days compressive strength was achieved by 13% and 42%,  
15  
16 605 respectively for hydrated lime and Portland cement. Kumar [43] observed the increase in  
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18  
19 606 compressive strength with the increase in partial replacement of lime with phosphogypsum  
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21  
22 607 irrespective of fly ash content. Ling and Teo [54] partially replaced the cement with rice husk ash  
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24 608 and observed maximum compressive strength at 10% replacement of cement by rice husk ash in  
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26 609 the sand- EPS unfired bricks. Muntohar [42] used lime and RHA at varying internal ratios and  
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28  
29 610 observed optimum compressive strength at lime to RHA ratio (1:1) in unfired clay bricks.  
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31  
32 611 Torkaman [40] replaced the 50% cement content with rice husk ash, and with waste lime powder  
33  
34 612 and could achieve similar compressive strength of unfired blocks.  
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36  
37 613 Pimraksa and Chindaprasirt [10] observed a decrease in compressive strength by 7% in lime  
38  
39 614 stabilized diatomaceous earth bricks by incorporating 5% gypsum as partial replacement of lime.  
40  
41  
42 615 Reddy and Gourav [5] used gypsum as an additive in lime stabilized fly ash-sand bricks. With a  
43  
44 616 2% gypsum additive, 28 days compressive strength increased significantly (~7 times) at 10.5%  
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46 617 lime content in lime stabilized fly ash bricks. The contradictory results may be due to different  
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48  
49 618 reaction mechanisms by different wastes or at different doses of gypsum. Izemmouren et al. [21]  
50  
51  
52 619 investigated the effect of partial replacement of lime with fly ash in soil crushed sand bricks in  
53  
54 620 steam curing conditions for 24 h. Higher dry (16 MPa) and wet (14.72 MPa) compressive  
55  
56 621 strengths were achieved at 30% substitution of lime with fly ash as compared to the control mix  
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58  
59 622 (at 10% lime content without fly ash) having dry (10 MPa) and wet compressive strength (7

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4 623 MPa) respectively. The wet and dry compressive strengths increased on up to 30% replacement  
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7 624 of lime with fly ash irrespective of lime content (6%-10%).  
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### 10 625 *7.1.3 Internal proportioning of blended binders*

11  
12 626 In some studies [17,24], blended cementitious binders were used. In a study [17], the influence of  
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14  
15 627 partial replacement of hydrated lime with Portland cement was observed in the phosphogypsum-  
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17 628 fly ash-lime mix. At 10% replacement of hydrated lime with Portland cement, an increase in the  
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19  
20 629 7 days compressive strength (13.72 MPa) was observed as compared to the compressive strength  
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22 630 (7.71 MPa) for the mix without cement. However, the difference between the compressive  
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24  
25 631 strengths of mix with cement (22.41 MPa) and without cement (20.07 MPa) was found less after  
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27 632 28 days of curing. In another study [24], hydrated lime and cement were used together to  
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30 633 stabilize the phosphogypsum in sand bricks along with a different hydration recrystallization  
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32 634 curing technique to produce early age strength bricks. Using 4% Portland cement and 1.5%  
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35 635 hydrated lime, 21.8 MPa compressive strength was achieved within 7 days in stabilized  
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37 636 phosphogypsum sand bricks.  
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### 40 637 *7.1.4 Internal proportioning of blended fines*

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43 638 Different wastes were incorporated as fines, and the influence of varying internal proportion of  
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46 639 blended fines was analyzed on the compressive strength of unfired bricks. Partial replacement of  
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48 640 clay with alumina waste [12] decreased the strength of unfired bricks, whereas the incorporation  
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50 641 of brick dust waste (BDW) as replacement of mud stone clay [15] increased the strength of  
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53 642 unfired bricks. The probable reason given for the decreased compressive strength of the bricks  
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55 643 was the decrease in cohesion between the particles due to the addition of alumina filler waste  
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57  
58 644 [12]. Whereas, the increased performance in the case of BDW was attributed to its pozzolanic  
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60 645 property, better mechanical size distribution and the mineral composition obtained with the  
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4 646 addition of BDW in the mix[15]. Sometimes, researchers relate the increase in the compressive  
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7 647 strength with the increased density of bricks, which is attributed to improved particle packing.  
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9 648 Replacement of one ingredient having lower specific gravity with the other having higher  
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11 649 specific gravity resulted in the increased fresh density of the mix [19]. Hence, the increased fresh  
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14 650 density may not truly replicate the improved particle packing in cases with blended mixes.

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17 651 The optimum proportion of one ingredient in a blended mix may shift due to change in the  
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19 652 respective proportioning of other ingredients. The optimum amount of fly ash incorporation in  
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22 653 Fal-G mix (a combination of fly ash, lime and gypsum) shifted due to a change in the internal  
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24 654 proportion of other ingredients [13]. Raut et al. [44] observed the increase in the compressive  
25  
26 655 strength of bricks with the incorporation of RHA as a replacement (0%-20%) of recycled paper  
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28 656 mill residue in cement stabilized unfired bricks. Increased compressive strength was attributed to  
29  
30  
31 657 the pozzolanic property of RHA. Whereas, the lesser increase in compressive strength at higher  
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34 658 (15%-20%) replacement was attributed to an effective reduction of fibrous content and decrease  
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37 659 in the homogeneity of the mix. Zhou et al. [24] varied the internal proportion of phosphogypsum  
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39 660 (neutralized with hydrated lime) and sand in unfired bricks. They observed the optimum  
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41 661 compressive strength at 75% phosphogypsum and 19.5% sand.

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43  
44 662 In some cases, the effect of varying proportions was evaluated for more than one ingredient in  
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46  
47 663 the mix. Raut and Gomez [41] compared the partial replacement of glass powder and palm oil  
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49 664 fuel ash in place of crusher dust and observed that the partial replacement of glass powder was  
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51  
52 665 more effective in terms of strength gain as compared to palm oil fuel ash for the studied mix.  
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54 666 Similarly, Shon et al. [58] observed the effect of varying proportions of different fines (clay and  
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57 667 sand) by incorporating stockpiled fly ash to produce unfired bricks and found better results when  
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59 668 replaced the sand as compared to clay. In some cases, the use of blended fines resulted in higher  
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4 669 strength as compared to their individual incorporation in the mix. Use of cotton waste and paper  
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7 670 waste independently could produce the bricks of 7-10 MPa compressive strength. In contrast, in  
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9 671 combination, bricks of 22 MPa compressive strength could be achieved [46], which establishes  
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11 672 the significance of using blended fines in unfired bricks.

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15 673 Muntohar and Rahman [56] incorporated OPKS in different sizes as aggregates in cement sand  
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17 674 bricks. A decrease in the compressive strength with the increase in the volumetric percentage of  
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19 675 OPKS was observed for larger size aggregates (4.75-9.5 mm and >9.5 mm) whereas for the  
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21 676 smaller size of aggregates (2.36-4.75 mm) optimum compressive strength was observed at 50%  
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23  
24 677 volume of OPKS aggregate in the mix. Zhang et al. [64] incorporated the CFBC fly ash (77%-  
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26 678 97%) and CFBC slag (0%-20%) with or without cement (3%) in autoclaved bricks. With the  
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28  
29 679 increase in slag content, the compressive strength increased by more than 50%, and by 8% for  
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31 680 the autoclaved bricks with and without cement respectively. It indicated that the increase in  
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33 681 strength was due to possible reactions between slag and cement. L16 orthogonal array [60] can  
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35 682 be used with maximum three variable factors and each with four varying levels to design the  
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37 683 reduced number of mixes seeking for the optimum mix formulations. Zhao et al. [60] optimized  
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39 684 lime, gypsum, sand and hematite tailing mix using L16 orthogonal array. With the increase in  
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41 685 lime and sand content, the compressive strength increased, whereas, with the increase in gypsum  
42  
43 686 content, compressive strength decreased. Sodupe-Ortega et al. [62] observed the compressive  
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45 687 strength with the incorporation of crumb rubber in unfired bricks at both laboratory and factory  
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47 688 conditions. At factory conditions, higher percentage rubber incorporation (20%-30%) resulted in  
48  
49 689 high quantity (30%-45%) of defective and rejected products. It signifies the efforts required to  
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51 690 scale up the research outcomes of a laboratory study to the actual industrial scale. The effects of  
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53 691 waste incorporation were also studied by some other researchers, as tabulated in Table-8.  
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692 **Table-8** Effect of variation in fines on compressive strength of unfired bricks<sup>#</sup>

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.

693 *7.1.5 Liquid content*

694 A few studies [5,10,18] observed the effect of varying liquid content in bricks stabilized by  
695 cementitious binders. Pimraksa and Chindaprasirt [10] observed the effect of varying liquid  
696 content in lime stabilized unfired bricks. The liquid content was varied in the range of 45%-60%,

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4 697 and maximum strength was observed at 50% mixing water. An increase in compressive strength  
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7 698 was explained by the flocculation of clay particles due to a reduction in repulsive forces with the  
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9 699 increase in water content. After the optimum point, the decrease in compressive strength was  
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11 700 attributed to a reverse compaction effect caused by the dispersed solid particles. The water/solid  
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13 701 ratio was reported as an important parameter for compaction and hydration of cementitious  
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15 702 materials [10]. Zhang et al. [64] varied the molding water content in the range of 20 - 29%. An  
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17 703 increase in compressive strength was observed with the increase in molding water content up to  
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19 704 26%, whereas a slight decrease was observed at higher water content.  
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24 705 In some studies [18,96], an increase in compressive strength was observed in the entire selected  
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26 706 range. Wattanasiriwech et al. [18] observed the effect of molding water content on cement  
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28 707 stabilized mud bricks. An increase in the molding water content up to 20% increased the  
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30 708 compressive strength of the mix. Beyond 20%, the mix was reported too runny in compaction  
31  
32 709 and compression was reported not feasible. The increase in compressive strength was attributed  
33  
34 710 to the diminishing of pore size in the mix with the increase in molding water content. Zhao et al.  
35  
36 711 [96] reported the forming water content as influencing parameters for the mechanical strength of  
37  
38 712 the bricks. Lower water content affects the uniformity in the mixing process, whereas higher  
39  
40 713 water content would lead to a high bleeding rate. Therefore, water content was varied in an  
41  
42 714 optimum range of 6% - 8.5% for observing the effect on compressive strength of bricks. In the  
43  
44 715 optimum range, strength increased with the increased molding water content. It may be noted  
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46 716 that the selected range in both the studies [18,96] differ significantly, which indicates the  
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48 717 dependence of molding liquid content on the raw materials and other production parameters.  
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56 718 Contrary to [18,96], in the studies [63,98], a continuous decrease in the compressive strength was  
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58 719 observed with the increase in water to binder ratio in the mix. The reduction in the strength was  
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4 720 attributed to the increase in the pores due to the evaporation of excess water. It may also be noted  
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7 721 that in the studies [63,98], the mix was either self compacted or manually temped rather than  
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9 722 forced compacted. There is a possibility for excess water without bleeding in the mix due to low-  
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11 723 level compaction.  
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## 14 724 **7.2 Influence of mix proportions on the properties of unfired bricks stabilized by chemical** 15 16 17 725 **binders** 18 19

### 20 726 *7.2.1 Type of binder* 21 22

23 727 The influence of variation in the type of the binder was observed in a few studies [70,76]. Chen et  
24  
25 728 al. [70] used different kinds of binders, such as sodium silicate, sodium hydroxide, potassium  
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27 729 oxide, lithium oxide solutions to stabilize the CFBC bottom ash. The compressive strength of  
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29 730 geopolymers made with sodium silicate solution (1.5 silicate modulus, the ratio of  $\text{SiO}_2/\text{Na}_2\text{O}$  in  
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31 731 the solution was termed as silicate modulus of solution) and various 5M hydroxide solutions was  
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33 732 found in order of  $\text{Na}_2\text{SiO}_3 > \text{LiOH} > \text{KOH} > \text{NaOH}$  respectively. Mohsen and Mostafa [76]  
34  
35 733 compared the compressive strength of NaOH stabilized clay with the alkaline  $\text{Na}_2\text{SiO}_3$  stabilized  
36  
37 734 clay. The compressive strength of the clay stabilized with alkaline silicate was found higher as  
38  
39 735 compared to the clay stabilized with NaOH, irrespective of the type of the clay and curing  
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41 736 temperature.  
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### 48 737 *7.2.2 Amount of binder* 49 50

51 738 Many researchers studied the influence of variation in the amount of the binder. With the  
52  
53 739 increase in the concentration of NaOH or KOH between 5M-18M, an increase in the  
54  
55 740 compressive strength was observed in many studies [67–71] while stabilizing the different  
56  
57 741 wastes, such as copper mine tailings, cement kiln dust, CFBC bottom ash, alumino-silicate rich  
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4 742 tuff, and crumb rubber in unfired bricks. Radhakrishna et al. [74] observed no significant  
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6 743 difference in compressive strength at 3-7 days with varying concentrations of NaOH (8M – 12  
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9 744 M). However, at 28 days, with a higher concentration of NaOH, higher compressive strength was  
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11 745 observed. Other than hydroxides, Chen et al. [70] used the sodium silicate with varying silicate  
12  
13 746 modulus (1.2-2.0). The optimum compressive strength was obtained at 1.5 silicate modulus in  
14  
15 747 CFBC bottom ash bricks, and a sudden decrease was observed after 1.5 silicate modulus.  
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### 20 748 *7.2.3 Internal proportioning of blended binders*

21  
22 749 The influence of the internal proportioning of blended chemical binders was studied [73,75].  
23  
24 750 Ferone et al. [73] used the blended binders (NaOH and Na<sub>2</sub>SiO<sub>3</sub>) at two different SiO<sub>2</sub>/Na<sub>2</sub>O  
25  
26 751 ratios (0.61 and 0.76). The compressive strength was found to be higher for the higher  
27  
28 752 SiO<sub>2</sub>/Na<sub>2</sub>O (0.76) ratio in the low range of water/total solids ratio (0.28-0.31). However, for a  
29  
30 753 high range of water/total solids ratio (0.45 -0.49), no significant change was observed. Sukmak et  
31  
32 754 al. [75] varied the ratio of Na<sub>2</sub>SiO<sub>3</sub>/ NaOH (0.7-2.3) and found maximum compressive strength  
33  
34 755 at 1.5 Na<sub>2</sub>SiO<sub>3</sub>/ NaOH ratio irrespective of the liquid to fly ash ratio (0.3 -0.8) in fly ash bricks.  
35  
36 756 However, the optimum ratio of liquid to fly ash was observed as 0.7 in a varying range of  
37  
38 757 Na<sub>2</sub>SiO<sub>3</sub>/ NaOH ratio (0.4 – 1.5) for fly ash clay bricks. It may be noted that the optimum liquid  
39  
40 758 to fines ratio varies with the change in internal proportioning of binders.  
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### 48 759 *7.2.4 Internal proportioning of blended fines*

49  
50 760 The influence of proportioning of blended fines in chemical stabilized bricks was reported in  
51  
52 761 previous studies [66,69,77,78,80]. Hwang and Huynh [66] partially replaced the sand with  
53  
54 762 unground rice husk ash in unfired bricks. The compressive strength decreased with the increased  
55  
56 763 replacement of sand with unground rice husk ash in bricks. The reduction in the strength was  
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58 764 attributed to a loss in structural compactness due to the rising volume of capillary pores caused  
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4 765 by highly porous particles of unground rice husk ash. Huynh et al. [77] replaced the fly ash with  
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6 766 rice husk ash in NaOH stabilized sand bricks. A decrease in compressive strength was observed  
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9 767 for all replacements (0%-50%), up to 14 days of curing. However, at 28 days, 10% RHA  
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11 768 replacement resulted in higher strength as compared to RHA-free bricks. Abdullah et al. [78]  
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13  
14 769 increased the fly ash to sand ratio (1:2 – 1:5) and observed the decrease in compressive strength.  
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16 770 However, due to poor workability found at 1:2 ratio, 1:3 ratio was selected as the most suitable  
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19 771 proportion to study the influence of other parameters.  
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22 772 Ahmari and Zhang [69] added the cement kiln dust (0%-10%) by the weight of total solids with  
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24 773 copper mine tailings (90%-100%) to prepare NaOH stabilized bricks. An increase in  
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26  
27 774 compressive strength was observed with the increasing percentage of cement kiln dust at both 10  
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29 775 M and 15 M NaOH concentrations. The probable reasons for the increase in compressive  
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31 776 strength were given as follows [69]; (i) Additional support in the dissolution of -Si and -Al  
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34 777 species from mine tailings was expected due to increased alkalinity by dissolved Ca; (ii)  
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37 778 Additional silica and alumina species present in cement kiln dust might result in more  
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39 779 geopolymeric gel; and (iii) Fine particles of cement kiln dust, the hydration reaction of Ca, and  
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41 780 pozzolanic reaction helped in the denser microstructure. Freidin [80] replaced the fly ash with  
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44 781 bottom ash in water glass stabilized bricks. A higher strength was observed with the fly ash, and  
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46 782 bottom ash mixes as compared to fly ash mixes. Secondly, to achieve a particular compressive  
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49 783 strength, the amount of water glass required was less in the case of mixes with fly ash and  
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51 784 bottom ash. The optimum ratio of fly ash and bottom ash was selected based on the maximum  
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54 785 bulk specific gravity of the mixture.  
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4 786 *7.2.5 Liquid content*

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7 787 The influence of varying liquid content was observed in previous studies [67–69,73,75,80]. In  
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9 788 the case of chemical binders, the influence was more prominent as it directly increases the  
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11 789 amount of binder. An increase in compressive strength was observed with the increase in the  
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13  
14 790 molding liquid content while incorporating different wastes in unfired bricks [68,69]. The  
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16 791 increase in compressive strength was attributed to a higher amount of NaOH introduced with a  
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18  
19 792 higher amount of liquid content. Ferone et al. [73] varied the H<sub>2</sub>O / total solids ratio maintaining  
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21 793 the constant SiO<sub>2</sub>/Na<sub>2</sub>O ratio in the mix by incorporating dry and wet fly ash to prepare unfired  
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23  
24 794 bricks. The decrease in compressive strength was observed with the increase in H<sub>2</sub>O / total solids  
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26 795 ratio. In a study [67], a higher alkaline solution to fly ash ratio (0.4-0.8) resulted in higher  
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29 796 compressive strength of rubberized interlocking blocks. Whereas, in another study [75], the  
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31 797 optimum liquid to fly ash (LF) ratios were observed as 0.5 and 0.6 for fly ash bricks and fly ash  
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33  
34 798 clay bricks, respectively in a varying range of LF ratio (0.3-0.8) for both types of bricks. Other  
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36 799 than hydroxides, an increase in compressive strength was observed with the increase in water  
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38 800 glass content in both the fly ash mixes and the fly ash-bottom ash mixes in chemical stabilized  
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41 801 ash bricks [80].

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44 802 **7.3 Influence of compaction parameters**

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46 803 Unfired bricks are compacted via several methods, such as vibration and compression, and  
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49 804 sometimes mixes are prepared with self-compacting properties. The studies in which the bricks  
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51 805 were compacted by the vibration method, the compaction parameters (vibration frequency and  
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54 806 amplitude) were rarely communicated. Studies dedicated to the optimization of compaction  
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56 807 parameters are not available for vibro-compacted unfired bricks. However, for compressed  
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4 808 bricks, researchers usually reported on the compaction pressure, and in some studies [51,60,64]  
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7 809 the compaction pressure was taken as a variable.  
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10 810 Çiçek and Tanriverdi [51] varied the forming pressure in the range of 0 – 30 MPa and observed  
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12 811 an increase in the compressive strength with the increase in the forming pressure up to 20 MPa.  
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14 812 Zhang et al. [64] varied the compaction pressure in the range of 10 - 29 MPa. An increase in  
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16 813 strength was observed up to 25 MPa, whereas at higher forming pressure, compressive strength  
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18 814 decreased. Zhao et al. [60] varied the forming pressure in the range of 12 - 24 MPa and observed  
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20 815 an increase in the compressive strength with the increase in forming pressure. However, beyond  
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22 816 20 MPa, change in compressive strength was little. Hence 20 MPa was suggested as an optimum  
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24 817 forming pressure. Too high compaction pressure would result in high dense bricks, which was  
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26 818 not recommended as to avoid the increase in unnecessary dead load without much contribution to  
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28 819 the compressive strength [60].  
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#### 34 35 820 **7.4 Influence of curing parameters** 36

37 821 In some studies [5,18,21], different curing regimes were compared. Wet burlap curing (without  
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39 822 additive) at ambient temperatures gives considerably low compressive strength values as  
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41 823 compared to steam curing and wet burlap curing with additive [5]. Steam-curing for 24 h  
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43 824 significantly increased the dry and wet compressive strength of blocks when compared with  
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45 825 moist curing at 28 days ambient temperature [21]. In a number of studies  
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47 826 [10,17,21,43,51,53,59,60,64,78,96], the influence of varying curing parameters were investigated  
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49 827 on unfired bricks. Out of these, some studies [10,51,53,59,60,64,96] optimized the curing  
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51 828 parameters of autoclaved curing such as pre-curing period, temperature holding time, steam  
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53 829 temperature, and steam pressure. Zhang et al. [56] observed an increase in the compressive  
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55 830 strength of bricks with an increase in the pre-curing period (6 - 48 h). However, after a certain  
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4 831 optimum value (24 h), the rate of increase in compressive strength was not so significant. In  
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7 832 another study [10], pre-curing was varied in the range of 1-11 days, and the maximum  
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9 833 compressive strength was observed corresponding to 6 days. It was reported that less than 3 days  
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11 834 pre-curing could promote the cracking within bricks due to insufficient green strength.

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15 835 Fang et al. [53] observed an increase in compressive strength with an increase in holding time up  
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17 836 to 8 h. Beyond 8 h, a slight lowering of compressive strength was observed at 9 h of holding  
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19 837 duration. In some other studies [51,59,60,64,96], the optimum holding time was found in the  
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21 838 range of 6 – 8 h. Fang et al. [53] varied the autoclaving temperature in the range of 170 - 190 °C  
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23 839 and observed a significant increase in compressive strength up to 180 °C. At further increase in  
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25 840 the temperature (180-190 °C), the increase in compressive strength was reported as insignificant.  
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29 841 Zhao et al. [96] varied the steam pressure in the range of 0.75 - 1.75 MPa and observed a rapid  
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31 842 increase in compressive strength until 1.2 MPa and above 1.2 MPa the rate of increase in  
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33 843 compressive strength slowed down. In studies [51,59,60,64], the optimum steam pressure was  
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35 844 observed in the range of 1.2-1.5 MPa.

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40 845 Some researchers [17,21,43,78] studied the optimized temperature and duration of elevated air  
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42 846 curing and steam curing for unfired bricks. Singh and Garg [17] observed an increase in  
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44 847 compressive strength with the increase in curing temperature (27°C– 50°C) for different types of  
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46 848 the cementitious binder. Izemmouren et al. [21] varied the duration of steam curing between 6 –  
47  
48 849 30 h and observed maximum strength for 24 h. Kumar [43] observed the effect of water curing at  
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50 850 elevated temperature as compared to ambient temperature on the increase in strength and  
51  
52 851 hardening of the bricks. A significant increase in early age strength was observed at elevated  
53  
54 852 water curing at 50 °C. Abdullah et al. [48] studied the influence of varied curing temperature  
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56 853 (40°C - 95 °C) and varied curing duration (1 h – 24 h) on geopolymeric brick under elevated air  
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4 854 curing conditions and observed highest compressive strength at 70 °C and after 24 h of curing  
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7 855 duration.

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10 856 In some studies [18,24,54], hybrid curing techniques were used for the curing of bricks.  
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12 857 Wattanasiriwech [18] studied the influence of two different curing methods on the strength of  
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14 858 paver blocks. In the first type of curing, they covered the blocks with a damp cloth and sprayed  
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17 859 water every 24 h in a closed plastic box. In another type of curing, the blocks were immersed for  
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20 860 5 min. in water every 24 h. The 5-minute immersion with wet cloth curing in an enclosed plastic  
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22 861 box was found more effective than without immersion curing in terms of strength gain for paver  
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24 862 blocks. Zhou et al. [24] adopted a novel hydration–recrystallization process for curing, with a  
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27 863 combination of sprinkling water, elevated temperature and submerged water conditions. A  
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29 864 higher compressive strength of 21.8 MPa was achieved by adopting this novel curing technique  
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32 865 as compared to 9.5 MPa compressive strength achieved by control samples. Ling and Teo [54]  
33  
34 866 designed four different curing regimes to analyze the effect of partial water curing on EPS beads  
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37 867 incorporated cement-RHA-sand bricks. Partially or fully water cured bricks had higher strength  
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39 868 as compared to completely air-cured bricks. With the increase in the partial duration of water  
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42 869 curing, the compressive strength of bricks increased for all the curing ages under investigation. It  
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44 870 may be noted that in general, the hybrid curing is promising for optimizing the properties of  
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47 871 unfired bricks, and more studies are required to consolidate a systematic curing scheme on this  
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49 872 basis.

## 50 51 52 873 **8. Some industrial challenges related to unfired brick production in India**

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54 874 Economic viability is a deciding factor to incorporate any waste as an ingredient in the industry.  
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57 875 The majority of research studies so far have considered waste as a cost-free material, but it is not  
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59 876 true from the manufacturer’s point of view. Procurement of waste incurs logistic costs to brick  
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4 877 manufacturers. In a country like India, the majority of vehicles use diesel as fuel. Since per liter  
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7 878 diesel costs Rs. 70 – 80 (1 USD ≈70 Rs.) in India, the average procurement cost is not less than  
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9 879 Rs. 3-4 per ton per km. Importing a raw material from a 200 – 300 km. distant source, the  
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11 880 procurement of even unprocessed waste costs not less than Rs. 0.6- 1.2 per kg. In the Indian  
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14 881 scenario, the weight and selling price of a typical brick (90 mm×90 mm×190 mm) range  
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16 882 between 2.5 – 3.2 kg and Rs. 4 – Rs. 6 (~Rs. 1.5- 1.8 per kg) respectively. The average  
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19 883 procurement cost for waste (Rs. 0.6 – 1.2 per kg) is very significant compared to the selling price  
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21 884 of brick (Rs. 1.5 -1.8 per kg).

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24 885 As the procurement cost of waste mainly depends on the distance between the source of waste  
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27 886 and the industry, locally sourced wastes may have better economic feasibility. For local  
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29 887 utilization of wastes in unfired brick industries, waste maps are to be prepared similar to the  
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32 888 other geographical maps. As shown in Section 3, unfired bricks have high potential to  
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34 889 incorporate different types of wastes. Thus mapping of the wastes is considered helpful not only  
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37 890 for effective waste management but also to resolve for a cost-effective way of sourcing suitable  
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39 891 raw materials to be used for producing unfired bricks.

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42 892 In India, the use of slaked lime for industrial scale manufacturing of fly ash based unfired bricks  
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44 893 is a common practice. Slaked lime is prepared on-site by slaking of quick lime in large  
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47 894 uncovered slaking tanks. Providing well-controlled water quantity for slaking of lime is essential  
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50 895 because a deficient supply of water in the tank may lead to partial carbonation of quick lime or  
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52 896 may lead to incomplete slaking of quick lime. Unslaked lime particles may lead to cracking in  
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54 897 bricks due to expansive slaking of quick lime particles during the curing phase. Also in the rainy  
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57 898 season, the water content of lime slaked in uncovered slaking tanks may exceed the required  
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59 899 quantity for the brick mix. Excess water may lead to shrinkage crack development in the bricks.  
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900 Also, in the wet condition of slaked lime, it is difficult to ensure the required proportion of  
901 hydrated lime in the brick mix due to an unknown quantity of water in the slaked lime.  
902 Therefore, to control the amount of water in the brick mix, it is proposed to use dry hydrated  
903 lime powder instead of slaked lime to avoid the above mentioned industrial challenge.

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

913 **9. Conclusion**

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

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



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4 921 overcome the limitations of individual raw materials in wastes incorporated unfired  
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6 922 bricks.

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9 923 2. Approaches to select the molding water content have been found quite diverged among  
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11 924 the various studies. Limited focused studies are available related to optimizing the  
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14 925 molding water content in the case of cementitious binders, whereas, in the case of  
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16 926 chemical binders, researchers focused primarily on the optimization of liquid content in  
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19 927 the brick mix.

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21 928 3. Two-stage mixing sequence has been found to be the most common to handle dry raw  
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23 929 materials with similar physical states, whereas, suitable modifications are required to  
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26 930 incorporate the raw materials with varying physical state. However, no focused study has  
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29 931 been found to analyze the effect of different mixing sequences or mixing equipment  
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31 932 related to unfired bricks.

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33 933 4. Compaction of the mix has been found to depend on the liquid content in the brick mix  
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36 934 whereas in other cementitious mixes the compaction is dependent on rheology. Focused  
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38 935 studies are therefore required to understand the correlation of liquid content and rheology  
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41 936 of the low moist mix regarding unfired bricks.

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43 937 5. Forced compaction method has been found as the most popular molding method  
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46 938 regarding waste-incorporated stabilized unfired bricks.

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48 939 6. Ample studies are available related to optimizing the curing parameters of autoclaved  
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50 940 curing. However, in limited studies, hybrid curing techniques have also been attempted.  
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53 941 The use of low-cost hybrid curing conditions at ambient or low elevated temperature is  
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55 942 expected to be future research trend to overcome the limitation of autoclaved curing  
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4 943 regarding the high initial infrastructure cost to stabilize the waste incorporated unfired  
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6 944 bricks.

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9 945 7. The waste maps similar to other geographical maps are required to enhance the industrial  
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11 946 scale incorporation of wastes in unfired bricks, particularly in India. This will help to  
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13 947 overcome the existing challenges of the Indian manufacturing industry. Further,  
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15 948 powdered form of hydrated lime is suggested in place of slaked lime. However,  
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17 949 incorporating the change in raw material requires significant research on other  
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19 950 manufacturing parameters.

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24 951 The comprehensive review from the industrial perspective presented here will support the  
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26 952 selection of appropriate manufacturing parameters, which in turn will enhance the waste  
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28 953 utilization in unfired bricks and support to produce low cost eco-efficient unfired bricks at  
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30 954 industrial scale. For researchers, it provides research gaps and future research trends related to  
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32 955 unfired bricks.

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37 956 In the present article, the influence of varying manufacturing parameters on mechanical  
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39 957 properties is covered. In the future, a separate review on other performance parameters related to  
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41 958 unfired bricks can be carried out to understand the influence on durability properties and change  
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43 959 in microstructure, mineralogy, and the reaction mechanism of different binders used to stabilize  
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45 960 the unfired bricks.

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50 961 **Abbreviation**

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

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3		
4	CA	Coarse aggregates;
5	CKD	Cement kiln dust;
6		
7	CS	Compressive strength;
8	D	Diameter;
9	EPS	Expanded polystyrene;
10	F	Frequency;
11	F/S	Ratio of fly ash to sand;
12		
13	F1	Type of binder;
14	F2	Amount of binder;
15	F3	Internal proportioning of blended binders;
16	F4	Internal proportioning of blended fines;
17	F5	Liquid content;
18	FA	Fine aggregates;
19		
20	G1	Type of binder;
21	G2	Concentration of binder;
22	G3	Internal proportioning in case of blended binders;
23	G4	Internal proportioning in case of blended fines;
24	G5	Liquid content;
25	H	Height;
26	h	Hour;
27		
28	H/S	Ratio of NaOH to Na <sub>2</sub> SiO <sub>3</sub> ,
29		
30	H1	Type of binder;
31	H2	Amount of binder;
32	H3	Internal proportioning in case of blended binders;
33	H4	Internal proportioning in case of blended fines;
34	H5	Liquid content;
35	HL	Hydrated lime;
36		
37	M	Molar;
38		
39	M-Sand	Manufactured sand;
40	MSWI-FA	Municipal solid waste incineration ash;
41	MT	Mine tailings;
42	NDC	Not disclosed, and constant water content;
43	NDV	Not disclosed and variable water content;
44		
45	NHL	Natural hydraulic lime;
46	Op.	Optimum point;
47	Ref.	Reference;
48	RH	Relative Humidity;
49		
50	RHA	Rice husk ash;
51	RT	Room temperature;
52	S/N	Ratio of SiO <sub>2</sub> to Na <sub>2</sub> O;
53		
54	S1	Special size (details are mentioned in section 5.1);
55	SC	Standard compaction method;
56	SCT	Standard consistency test;
57	SP	Steam pressure;
58	SPT	Standard proctor test;
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60	Temp.	Temperature;
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4 UC Uniform consistency/ flow criteria;  
5 WCS Water-cooled slag;  
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