A Review on Use of Crushed Brick Powder as a Supplementary Cementitious Material

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Abstract. In India, it is estimated that 250 billion bricks are produced annually in about 100,000 kilns present all over the country. Mainly due to inefficient production processes, most of the blocks manufactured are of inferior quality, which ultimately becomes a significant source of waste production. The characteristics of Construction and Demolition wastes (C&D) are difficult to predict, but a considerable component of this type of solid waste comprises of bricks in masonry work. As more and more civil structures are nearing the end of their expected lifespan, proper management and disposal of C&D wastes are necessary to obtain a sustainable environment. Ground waste clay brick is a prospective pozzolanic material due to dehydroxylation of clay minerals during its manufacturing process at temperatures between 450˚C and 700˚C, leading to the disintegration of crystalline phases and formation of reactive anhydrous amorphous phases. A review of the existing literature regarding the use of crushed brick powder (CBP) from waste bricks as well as demolition debris as a supplementary cementitious material has been conducted. It has been observed that the pozzolanic character of clay used for making brick comes from calcining it at an optimum temperature, which is different for different clays. Cement replacement by CBP in concrete mostly causes increased compressive, flexural, and split – tensile strength at 28 and 90 days, indicating good pozzolanic behaviour. 10 – 25% replacement by CBP gives acceptable values of Strength Activity Index (SAI) at 7 and 28 days. Pore refinement causing the formation of additional hydration products due to pozzolanic reaction as well as filler effect of CBP are the primary factors causing improved durability of concrete. Limited research has been done on the effect of the chemical composition of raw clay on the pozzolanic potential of CBP. Future scope in this area can be on enhancement of pozzolanicity in CBP, the study of high volume replacement of CBP in concrete, and the effect of CBP replacement on corrosion of rebar.

1. Introduction
The most widely used construction binding material cement can be categorised as non-hydraulic and hydraulic. In today’s fast-paced construction, non-hydraulic cement is preferred less because of desired conditions requirement with delay in strength gain, whereas hydraulic cement set and harden even in the presence of water. Hydraulic cement remains a primary construction material for the buildout of infrastructure all over the world, and there is less possibility that any other materials would replace it in the coming future. Global production of cement in the year 2015 was about 3.5 billion metric tons, and it is expected to touch 4.83 billion metric tons by 2030. China stands tall with 2.35 billion metric ton cement production in the year 2015, followed by India and the United States with the production of 270 and 83.4 million metric tons respectively in the same year [1]. Manufacture of cement is an energy-intensive process with the emission of carbon dioxide and other greenhouse gases. Industrial waste and
agricultural wastes such as fly ash, blast furnace slag, silica fume, rice husk ash, and bagasse have been used as partial replacement of ordinary Portland cement (OPC) as an environment-friendly solution without having to sacrifice the quality and strength. It has already been reported that these materials improve concrete durability and reduce the risk of thermal cracking in mass concrete. However, the availability of industrial waste locally and season dependency of agricultural wastes brings out limitations of its use. Among all waste products applicable to replace cement partially, waste fired clay bricks are one which is readily available locally. Bricks are generally treated as waste when some damaged bricks are manufactured in the production line or due to poor handling at the construction site or when demolishing any existing structure with fire clay bricks as one of its building blocks.

Globally, 1.5 trillion bricks are produced annually with Southeast Asia, South Asia, and China being the large brick manufacturing region in the world, producing about 87 percent of the total bricks produced globally. Around 67 percent of the global bricks production is produced by China alone, followed by India, producing about 13 percent of the total bricks [2-4]. These bricks are typically fired in small-scale traditional kilns. The quality of fired brick depends both on the quality of green bricks as well as on the firing process. The tunnel kiln is ranked best in terms of fired brick quality. The Fixed chimney bull trench kiln (FCBTK) lacks uniform distribution of temperature in the firing zone, thereby 60-70% bricks are properly fired, whereas high draught zig-zag kiln has more uniform temperature distribution, and hence 80-90% of the bricks are appropriately fired. 95%, 80%, and 60% are the quality bricks produced by tunnel kiln, high draught zig-zag kiln, and FCBTK, respectively. The remaining production is either inferior (under-fired and over-burnt), and there are losses due to breakages too. In India, the estimated annual production of bricks by FCBTK alone is 185 billion bricks out of an estimated 250 billion bricks in a year [4], i.e., 74 billion bricks generated are of not good quality.

Construction and Demolition Waste (C&D) characteristics are difficult to predict; however, the primary components of this waste comprise of bricks from masonry work. Annually India produces 10-12 million tons of Construction, Demolition, and Excavation waste material. Figure 1 shows the typical composition of C&D waste in India[5]. As more and more civil structures are nearing the end of their awaited lifespan, management and disposal of C&D wastes is the need of the hour to attain a sustainable built environment. In a report by Cheng et al. [6], it is stated that at least 20 billion m$^3$ of clay bricks produced in China will turn into solid waste in the next five decades, accounting for about 50% CDW. This scenario is highly applicable in the Indian backdrop too.

![Figure 1. Typical composition of C&D waste in India](image)

Grounded waste clay bricks are a prospective pozzolanic material due to the dehydroxylation of clay minerals during its manufacturing process at temperatures between 450°C and 700°C [7]. Hence, the reuse of waste brick in powdered form in cement-based composite materials can significantly bring social and economic benefits. In the present framework, there is an urgent requirement for sustainable use of waste bricks in the building and construction industry. Unless a systematic effort is made to correctly incorporate these types of waste materials into sustainable construction practices, dire wastage of finite natural resources will continue to occur. Keeping these views in context, a review of the existing literature regarding the use of crushed brick powder from waste bricks as well as demolition debris at
this moment referred to as crushed brick powder (CBP) unless specified otherwise as a supplementary cementitious material has been conducted.

2. Pozzolanic nature of brick dust
Pozzolans’ characteristics are supposed to be determined by their ability to react with lime and the ability to form insoluble products with binding materials. According to ASTM C125 [8], a pozzolan is defined as “a siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in the finely divided form in the presence of moisture, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties.” Clay minerals like kaolinite, illite, montmorillonite, palygorskite, and others are present in clay deposits together with impurities of non-clay materials like calcite, quartz, feldspar, mica, sulfides, and anatase [9]. The primary raw material for preparing ordinary bricks are the clay deposits with less proportion of clay minerals. The obtained content is processed to get a workable mass to mould into a brick shape. These shaped bricks are then usually fired to a temperature above 800˚C. Loss of structural water of clay minerals at temperatures between 450˚C and 700˚C leads to crystal lattice deterioration resulting in anhydrous compound with amorphous structure [7]. This transformation of the crystalline network to a disordered, unstable amorphous state as a result of thermal treatment is responsible for bringing pozzolanic characteristics to it. Baronio et al. [10] put forward the following three hypothetical chemical reactions between calcium hydrate, amorphous silica, and alumina in case of kaolinitic clays:

\[
\begin{align*}
AS_2 + 6CH + 9H & \rightarrow C_4AH_{13} + 2CSH \\
AS_2 + 5CH + 3H & \rightarrow C_3AH_6 + 2CSH \\
AS_2 + 3CH + 6H & \rightarrow C_2ASH_8 + CSH
\end{align*}
\]

AS$_2$- metakaolinite, CH-lime, H-water, C$_4$AH$_{13}$- tetra calcium aluminate hydrate, CSH-tobermorite, C$_3$AH$_6$- tricalcium aluminate hydrate, C$_2$ASH$_8$-hydrate gehlenite.

They studied both kaolinitic clay and common clay, which are used in the manufacture of bricks. When pozzolanic tests were carried out on both the types of clays, common clay did not show many positive results, which was attributed to its composition, whereas kaolinitic earth was shown to possess excellent pozzolanic characteristics. The authors concluded that modern bricks seldom possess pozzolanic characters as they are fired at higher temperatures and may not contain the proper content of clays. Firing temperature above 900°C was not recommended for producing pozzolanic materials. But this claim was disputed by Wild et al. [11]. In his study, eight different types of bricks were analysed. Based on the chemical tests for pozzolanic and strength development of mortars, it was concluded that all the ground brick types exhibit pozzolanic activity. The type of clay used in brick manufacture also influences the pozzolanic properties of CBP. Ambroise et al. [12] put the order of reactivity of thermally activated (TA) clays with lime and water-based on experimental observations as TA-kaolinite > TA-montmorillonite > TA- poorly-crystallized mica (illite) > TA-well crystallized micas. It can be concluded that depending on many factors like phase composition and range of firing temperature, fired clay building bricks may show a variety of pozzolanic activity; however, evaluation for the pozzolanic activity of CBP as supplementary cementitious material is necessary.

3. Chemical and physical characteristics of brick dust
As described by Akinshipe et al. (2017) [13], the clay brick firing process consists of 6 steps, with calcium sulphate (CaSO$_4$) being the most likely compound formed during the firing process. The first stage, evaporation, occurs at 20 – 150°C, during which the mechanical water is evaporated. At 149 – 650°C, i.e., dehydration stage, combustion of the combined water and carbonaceous matter takes place. At 300 – 982°C, oxidation of iron residues and remaining carbonaceous things takes place. The full strength of fired bricks is formed during the vitrification process (900 – 1316°C) through the sintering of clay particles and the melting of clay mass. The final stages are flashing (1150 – 1316°C), required to bring a proper colour to the brick and cooling (1316 - 20°C), after which the final product is obtained.
Crushed clay brick powder used by various researchers come from two primary sources: discarded bricks from brick kilns which do not meet the required standards due to improper heating regimes producing over burnt or under burnt bricks, presence of cracks, warping, asymmetrical dimensions and other imperfections [14-19] or demolished masonry from construction sites (construction and demolition waste) [20-23]. Both these materials fall under the category of solid wastes. Table 3 gives a comparison of the chemical constituents of bricks obtained from different sources. It can be observed that the variation of various chemical components is not very high. Manoharan et al. [24] studied the brick production process with the help of alluvial clay. The composition of alluvial clay before firing is included in Table 3 and can be referred for comparison with CBP.

| Component                        | SiO₂  | Al₂O₃ | Fe₂O₃ | K₂O  | MgO  | Na₂O | CaO  | P₂O₅ | TiO₂ | SO₃ | LOI |
|----------------------------------|-------|-------|-------|------|------|------|------|------|------|-----|-----|
| Heat treated clay [16]           | 54.8  | 19.1  | 6     | 3.2  | 1.8  | 0.5  | 9.4  | —    | 2.9  | 0.6 |
| Ground crushed waste calcined clay brick [19] | 63.89 | 25.49 | 7.73  | 0.95 | 0.04 | traces | 0.29 | —    | —    | —   |
| Red clay brick waste [25]        | 49.9  | 16.6  | 6.5   | 4.4  | 5.5  | 0.5  | 9.7  | 0.2  | 0.8  | 3.3 | 2.4 |
| Clay brick demolished waste [20] | 54.2  | 15.4  | 7.6   | —    | 2.5  | —    | 6.8  | —    | 1.1  | 6.2 |
| Alluvial Clay (TRY)             | 62.75 | 16.41 | 6.37  | 1.87 | 3.90 | 1.68 | 3.53 | —    | 0.5  | 3.39|
| Alluvial Clay (KOM) [24]        | 64.23 | 15.7  | 5.52  | 3.62 | 2.35 | 0.8  | 3.42 | —    | 0.92 | 4.74|

Carbon content in cement must be carefully controlled as it is known to have detrimental effects on concrete properties. LOI can characterise carbon content, and it was experimentally proved [21] that LOI decreases as the amount of CBP in hybrid recycled concrete powder increases. The physical characteristics of CBP are summarised in Table 4.

| Table 2. Physical characteristics of CBP. |
|------------------------------------------|
| Blaine specific surface area [22]       | 6485 m²/kg |
| Density [22]                             | 2660 kg/m³ |
| Specific gravity [14]                    | 2.65       |
| Mean particle size [25]                  | 20.9 µm    |

Naceri et al. (2009) [26] found that specific weight decreased with the increasing quantity of CBP substituted in cement. Also, the incorporation of CBP in cement was found to reduce the grinding time (reduction in consumption of energy).

4. **Effect of CBP on the hydration of cement-based on microstructural development**

The study of microstructural properties of cement paste with the progress of hydration is essential because it is well established that the strength and durability properties of concrete originate from its internal microstructure and can be significantly enhanced by making suitable changes to the microstructure. Well-developed relations between microstructure and properties of concrete are not present, mainly because it is not an intrinsic characteristic of the material and subject to changes in morphology and formation of hydration products with the progress of time, humidity, and other ambient factors.
4.1. Normal consistency and setting time
Cement replacement by more percentage of brick dust, increased the water demand of cement paste, as reported by Naceri et al. (2009) [26]. A double effect was observed by the authors: the quantity of water required to have a paste of standard consistency increased along with a decrease in the set times. The reduction in the setting time was attributed to the increased gypsum/clinker ratio.

However, Lin et al. (2010) [27] reported that there was increase in setting time with the increase in amount of waste brick added to pastes. Both initial and final setting times were longer than that of corresponding OPC paste and varied as 5h 9m – 6h 30m (IST), 6h 49m – 8h 42m (FST). Kim et al. (2012) [28] also reported an increased initial and final setting times for cement pastes replaced with increased amount of waste concrete powder. Decrease of C₃A and C₃S responsible for accelerating the hydration process caused the delay in setting time values.

Increased setting times, although insignificant, was further reported by Bektas et al. [29]. The w/c ratio and IST were found to be increased as CBP was increased from 15 to 25%. FST remains the same as the control paste for a 15% sample, whereas a significant increase was not seen for a 25% sample.

| % Waste brick replacement cement | 0% | 5% | 10% | 15% | 20% |
|---------------------------------|----|----|-----|-----|-----|
| w/c %                           | 27.4 | 28.2 | 28.4 | 28.8 | 29.2 |
| Increasing (+)%                 | 0 | +2.92 | +3.65 | +5.11 | +6.57 |
| IST (min)                       | 162 | 156 | 135 | 129 | 124 |
| Decreasing (-)%                 | 0 | -3.71 | -16.67 | -20.37 | -23.46 |
| FST (min)                       | 274 | 254 | 250 | 248 | 243 |
| Decreasing (-)%                 | 0 | -7.3 | -8.76 | -9.49 | -11.32 |

4.2. Scanning electron microscopy (SEM)
Electron microscopy is one of the most powerful techniques for studying the microstructure of cementitious materials. Morphological studies of early age hydration showing fracture surfaces during the evolution of microstructure can be satisfactorily done with the help of SE images. However, it provides qualitative information only and is not of much use when the degree of reaction becomes significant. By using polished sections for BSE image analysis, quantitative information about the different phases formed at different hydration periods can be determined [30].

On conducting a microstructural analysis of paste specimens, Aliabdo et al. (2013) [20] concluded that CBP could be satisfactorily used as a filler material as the sample having the highest amount of CBP displayed the best pore structure. Densification of the matrix occurs as a result of the production of additional hydrates due to pozzolanic activity. SEM micrographs of cement paste prepared with varying percentages of red CBP was shown by Li et al. (2016) [31]. The presence of quartz sand and cement hydration products like CH and CSH were observed. The structure of blended paste was found to be denser than that of reference paste.

Quantitative evaluation of microstructure roughness of cement mortar replaced with 30% CBP using atomic force microscopy was carried out by Liu et al. (2014) [21]. The intrinsic roughness of cement paste is expressed by the root mean square (RMS) roughness and lies within the range (115 – 492 nm). The RMS roughness of one of the regions containing sand and CBP reached a relatively high value of 595 nm, whereas the cement paste region had a value of 470 nm. Based on these results, it was concluded that the roughness of the cement paste is increased due to the presence of CBP but lies within an acceptable range. It was further determined that CSH gels formed a weaker bond with CBP than that with sand. Nanoindentation test results also revealed the presence of a weaker ITZ around hybrid CBP particles.

Heikal et al. (2012) [15] studied the SEM micrographs of cement paste substituted with 37.5% CBP hydrated for different periods with and without SCC admixture. The expected hydration products of CSH, CH, ettringite, etc. were observed. A denser microstructure was found in the presence of SCC superplasticiser with the formation of microcrystals of CSH as the main hydration product.
4.3. Thermal Analysis

Thermal analysis refers to any technique adopted to carry out measurements involving desired parameters by varying the temperature. Standard methods often used in conjunction with each other include thermogravimetric analysis and differential thermal analysis. In the thermogravimetric study, the change of weight of a substance is monitored while subjecting it to varying temperatures. In cases where the mass changes are tiny and cannot be determined by TGA, differential thermal analysis (DTA) is used. In this method, the temperature difference between the sample and an inert reference is determined such that the reaction can be classified as endothermic or exothermic.

Navrátilová et al. (2016) [7] studied the pozzolanic properties of brick dust on lime mortars. Three mortars MREF (reference), MFL (highest pozzolanic activity), and MOH (lowest pozzolanic activity) were studied for TG and DTG. MFL and MOH mortars were found to lose water in the temperature range of 100 - 400°C. These mortars were also found to have lower calcium hydroxide content than that of MREF mortar. TG curve of MFL containing brick dust with higher pozzolanic activity was found to decrease more than the TG curve of MOH mortar.

Aliabdo et al. (2013) [20] reported TGA results of CBP replaced cement paste. The highest amount of weight loss was seen for reference paste, indicating the highest amount of CSH and ettringite content. Reference paste was also determined to have the highest amount of calcium hydroxide, reaffirming the pozzolanic nature of CBP. Liu et al. (2014) [21] reported an exothermic peak at 340°C, corresponding to the burning of cellulose particles on using hybrid recycled powder obtained from demolition waste with cement. The rate of increase of CH from 7 to 28 days was found to be more significant for the control specimen than for the other samples. Further observations include the decrease of CH content from 28 to 91 days in all different samples except the control specimen, indicating ongoing pozzolanic reaction by Bektas et al. [29].

The degree of hydration is another parameter that can be calculated from the thermogravimetric analysis. Lin et al. (2009) [27] determined both the degree of hydration and gel/space ratio with the help of parameters obtained from TGA. Gel/space ratio is known to be significantly governing the concrete compressive strength, increasing with the progress of hydration. As the gel/space ratio increases, partial filling of pores takes place, causing an increase of concrete compressive strength. The authors reported a comparable gel/space ratio of 10% replacement with that of OPC at 60 days. But 50% replacement caused a significant decrease in the same. Increased degree of hydration with the increase of curing time indicating active pozzolanic reaction was also seen. A reduction of hydration for 50% replacement at 60 days was attributed to a low concentration of Ca\(^{2+}\) ions in the pore solution. Similar findings were reported by Bediako et al. (2018) [32] regarding the degree of hydration and pozzolanic reactivity of CBP. Filler effect of CBP particles was attributed to the promotion of early age hydration of cement.

Kishar et al. (2012) [33] studied the effect of calcium chloride on the outcome of CBP pastes and determined the amount of chemically combined water content in all the pastes studied with the help of ignition method. Combined water was found to increase for all the pastes up to 180 days as a result of the addition of CaCl\(_2\). The formation of the inner product, CSH, is believed to have accelerated due to the acquisition of CaCl\(_2\). Ge et al. (2015) [34] evaluated the amount of non-evaporable water (NEW) as the mass loss of ground powder specimen between 105 – 950°C. With an increase of CBP, the NEW values were found to decrease insignificantly but not in an equal manner. The phenomenon was attributed to enhanced cement hydration due to internal curing and pozzolanic activity of CBP.

The heat of hydration: Heat of hydration of binder pastes with the progress of time can be measured quantitatively with the help of a calorimeter. Bediako et al. (2018) [32] demarcated the heat evolution curve into four parts: initial stage, dormant part, accelerated peak point, and deceleration part with maximum heat flow occurring in the third portion. The peak point corresponding to maximum heat flow was found to be higher for control paste than CBP blended paste, proving that reduced heat liberation occurs in the early periods, which can be useful in the construction of mass concrete structures. Bektas et al. [29] reported similar findings on replacing 15 and 25% CBP in cement. They further noted a delay in time at which the peak temperature was recorded indicating the presence of CBP has a retarding effect on the hydration process. The presence of CaCl\(_2\) in the blended paste containing CBP and cement had an accelerating effect on the hydration reaction as observed from the increased intensity of the endothermic peak of the DTA curve [33].
4.4. X-ray diffraction (XRD)
Qualitative information about the presence of different hydration products formed in cement paste, unhydrated cement minerals (allite, bellite, ferrite), and mineral phases (mullite, quartz) can be determined by XRD analysis. Refinement techniques provide quantitative information about the intensity of these phases. Afshinnia et al. (2015) [35] carried out an XRD analysis of mortar specimens with varying CBP percentages after one year. Portlandite peaks were found to have decreased or even disappeared in the samples replaced with CBP owing to its pozzolanic nature. Only at 10% replacement level, the peak was comparable with that of the reference sample. Further comparisons were carried out using brick as fine aggregate, and it was determined that CBP as SCM shows better pozzolanic activity as compared to CBP as fine aggregate owing to its higher specific surface area.

The presence of portlandite, ettringite, calcite, quartz, and CSH were detected by Aliabdo et al. (2013) [20] on CBP replaced cement pastes. The authors reported that the presence of CBP in cement paste does not have any significant effect on the mineral compositions of the matrix. XRD peaks of C₃S, CSH, CAH, CASH were reported by Lin et al. (2009) [27] with the conclusion that a dense and homogenous system is formed, which provides excellent long term strength. In a study on the utilization of red CBP for use as plaster [29], a reduced intensity of CH peak was reported for the samples replaced with CBP, indicating that the presence of red CBP has a strong influence on CH content. In the presence of CaCl₂, the intensity of CH peaks was found to be higher, indicating increased CH content, owing to the nature of CaCl₂ as an accelerating admixture [33].

5. Effect of CBP on properties of cement mortar

5.1. Workability of mortars
Schackow et al. (2015) [18] performed a flow test in which specimens with constant w/c ratio were cured for 28 and 90 days in Ca(OH)₂ saturated water at 23°C and 65 – 80% relative humidity. The flow index of the mixtures with an increasing percentage of replacement was found to decrease as finer CBP particles increased the water consumption. Hence, the negative impact on workability was observed, and the requirement of extra water or superplasticisers was seen. A replacement of 10% is recommended for satisfactory workability having a constant w/c ratio.

5.2. Strength activity index
Afshinnia et al. (2015) [35] determined the SAI of mortar cubes containing 0%, 10%, 25%, and 50% CBP at 7, 28 and 90 days according to ASTM C109. The 28 days SAI was reported as 92%, 86%, and 59%, respectively. The SAI values were found to increase gradually for mortar mixes with 25% CBP (79%, 86%, and 91% at 7, 28, and 90 days). However, this was not observed in mortar mixes with 10% CBP. 50% replacement by CBP did not show an acceptable level of pozzolanic activity. All kinds of CBP cannot be considered as pozzolanic material, especially if they contain large amounts of crystalline minerals like quartz and feldspar [20]. In this paper, the authors conducted the SAI test according to ASTM C618 requirements. SAI values were found to be 76.5% and 81.8% at 7 and 28 days, respectively, affirming the pozzolanic properties of CBP used. Two types of bricks: slab bricks (SB) and wall bricks (WB) were used in the experimentation process by [36]. The 75% limit proposed by ASTM C618 was met by both the materials used with SB showing better pozzolanic activity than WB. When tested with a 0.5 w/b ratio and 30% CBP replacement, the SAI was found to be 75% [21]. As concrete substituted with CBP requires a higher amount of water to maintain suitable workability, the compressive strength of mortar cubes was tested with a higher w/b ratio. The SAI value was found to be within limits (70%).

5.3. Compressive strength of mortar
Standard mortar mixes according to European standards containing cement replaced with CBP or heat-treated clay were prepared by [12]. The authors studied ten different mixtures. Strength at early ages was considerably low, but long term strength (90 days) was unaffected. Relative intensity (strength at particular age/strength of reference mortar at the same age) at different ages was found to decrease with the increase in the level of replacement. Heat-treated clay was found to give better early age strength, but ground brick gave better long term strength due to the presence of a higher quantity of glass.
Demir et al. (2011) [37] prepared CBP replaced cement mortars to calculate its compressive strength. Seven different types of mixtures were made and stored at 20°C for 24 hours after which they were cured under three different types of conditions: continuous curing under lime saturated tap water (TW), constant exposure to 5% sodium sulphate solution (SS) and a continual exposure to 5% ammonium nitrate solution (AN). On the simultaneous evaluation of all the different experimental conditions to which the cubes were exposed, it was determined that there was an improvement in 28 days strength values when replacement exceeded 5%. On observing long term strength of 90 and 180 days, 10 – 15% replacement gave promising results. O’Farell et al. (2001) [38] reported that increasing the amount of CBP in cement mortar caused decreasing compressive strength values relative to reference up to 28 days. However, after 90 days, the strength of some mortars with low levels of replacement was found to exceed the reference mortars. This effect was attributed to the formation of additional CSH gel due to the pozzolanic reaction, which causes the pores to fill up and hence refines the matrix. The connectivity of the capillary pores is significantly reduced as a result if this infilling effect. Reduced compressive strength on increasing percentages of CBP in cement mortar was also reported by [20]. 25% replacement caused a decrease of 25.5% in the 28-day compressive strength. The mortar was prepared in a mix proportion of 1:3:0.5 (binder: sand: water).

Replacement of waste glass, brick, and tile waste was done in percentages of 10%, 20%, 25%, 30%, and 40%, respectively [39]. 25% cement replacement independent of the waste type caused a reduction in compressive strength of 20%, whereas 40% replacement caused a decrease of 30%. The evolution of strength from 28 to 90 days was found to be higher for tile powder (25 – 30%) than for brick powder (15 – 20%). 25% addition of glass powder caused a reduction in mortar strength of 20 – 30%. At a maximum level of replacement, reduction in strength was found to be 37 – 45%. The compressive strength was also found to be improved with the increase in fineness of particle. The authors reported that out of all the various ceramic wastes studied, only tile waste powder provided sufficient pozzolanicity. The other materials being fired at a lower temperature did not possess pozzolanic properties. Cubic cement paste specimens of size 1 inch containing CBP and calcium chloride were prepared with a fixed water/solid ratio of 0.25 [33]. The compressive strength of pastes incorporated with CaCl₂ was found to be higher than that of ordinary pastes. Mixtures with 10 – 30% CBP showed a steep increase in compressive strengths from 90 – 180 days due to the accelerating effect by CaCl₂ and decreased porosity of the paste. The use of 10% CBP was determined to be the optimum percentage for the improvement of compressive strength. Lin et al. [27] assessed the compressive strength of CBP blended cement pastes by an unconfined compressive strength test. Reference pastes had the highest compressive strength, whereas 50% CBP addition had the lowest strength due to an insufficient quantity of CH present to activate the CBP. 10 – 20% replacement gave strength values similar to OPC at 60 days.

5.4. Flexural strength of mortar
In the experiments conducted by Naceri et al. (2009) [26], flexural strength was found to decrease with an increasing amount of CBP up to 28 days. But at 90 days, 10% CBP replaced mortars attained strength comparable to that of reference mortars. Zheng et al. (2011) [40] showed that for varying levels of cement replacement and different average particle sizes, the flexural strength was not significantly affected. CBP obtained from bricks, and roofing tiles were used as cement replacement by Ioannou et al. (2009) [41]. From experimental data collected, it was concluded that long term strength (90 days) increased on using CBP, but on increasing w/b ratio, it decreased drastically. Due to the addition of surplus water, the porosity of the mortars increases, which adversely affects the compressive strength.

6. Effect of CBP on mechanical properties of concrete
Increasing values of the slump with the corresponding decrease in compacting factor with increased CBP replacement was stated by Wild (1996) [11]. Olofinnade et al. (2016) [17] put forward that for 10 – 20% cement replacement by CBP, the workability of concrete was possible to be kept constant. However, at constant w/c ratio, a decrease in a slump was observed for cement replacement up to 40%, resulting in reduced workability. Similar observations were reported by Ge et al. (2015) [34] regarding slump loss. Three different types of CBP having different particle sizes, water absorption values, and strength activity indices were used by the authors in this study (A – high, B – medium, C – low). The
higher slump was observed when the replacement level was small, and the particles were coarser. Slump loss was acceptable up to 10% replacement for type A and B, whereas type C CBP showed acceptable slump loss up to 20% replacement. As established earlier, CBP has higher water demand, more angularity, and rough texture, all of which contribute towards loss of slump. High water demand is also responsible for decreasing the flow of the mix [23]. Typical properties of hardened concrete put forward by different authors are discussed in table 4.

**Table 4. Comparison of mechanical properties of hardened concrete containing CBP.**

| Year | Author               | Materials used                                                                 | Conclusions                                                                 | Remarks                                                                 |
|------|----------------------|-------------------------------------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------|
| 2016 | Olofinnade et. al.   | OPC (ASTM Type I), waste clay brick.                                          | • A decrease in bulk density of hardened concrete.                          | • CBP can be used as an SCM up to 15% replacement.                      |
|      | [17]                 |                                                                               | • Increase in 28 days compressive and tensile strength up to 10% replacement.|                                                                        |
| 2013 | Heikal et al.        | OPC, ground clay bricks, polycarboxylate SCC admixture, superplasticiser.    | • In the absence of SCC, increasing GCB decreased compressive strength.     | • GCB acts as a pozzolanic filler material reducing compressive strength. But it also causes the formation of denser matrix. |
|      | [15]                 |                                                                               | • Increase of 28 days compressive strength in the presence of SCC admixture. |                                                                        |
| 2015 | Ge et al.            | OPC, waste clay brick, HRWR.                                                  | • A decrease in early age compressive strength but comparable compressive, flexural and split tensile strength at 90 days. | • Replacement level influenced strength reduction more than the particle size. |
|      | [34]                 |                                                                               | • A decrease in static modulus of elasticity with an increase in replacement level. | • The initial reduction in compressive strength is due to the dilution effect and low reactivity of CBP, but the final increase is due to internal curing and pore structure improvement. |
| 2016 | Zhu et al.           | 42.5 OPC, powder obtained from clay bricks and cement solids, superplasticiser. | • A decrease in compressive and flexural strength on replacing silica fume in reactive powder concrete with recycled powder. | • Silica fume and cement have higher pozzolanic activity than recycled powder. |
|      | [23]                 |                                                                               | • A reduction in flexural strength, a slight change in compressive strength on replacing cement in RPC with recycled powder. | • GGBFS can replace RPC with silica fume and recycled powder up to 10%. |
|      |                      |                                                                               | • RPC with recycled powder and GGBFS caused increased compressive and flexural strengths up to 10% replacement at 28 days. |                                                                        |
| Year | Authors         | Cement, CBP from                        | CBP replacement effects                                                                 | Optimum combination                  |
|------|-----------------|-----------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------|
| 2017 | Letelier et al. | ASTM type P cement, CBP from demolition debris, natural and recycled aggregates. | • CBP replacement caused filler effect compensating the strength loss due to the use of recycled aggregates. • The combined impact of CBP and RA is more pronounced in flexural strength and static elasticity modulus. | • Optimum combination is determined as 30% RA and 5% CBP. |
| 2012 | Ge et al. [43]  | 42.5 OPC, CBP from recycled construction waste, HRWR. | • w/c ratio is the primary factor affecting the mechanical properties of concrete containing CBP. • Though the addition of CBP tends to reduce the compressive strength, it can be avoided by adopting proper mix design. • Flexural strength of CBP concrete is similar to that of reference. | • According to orthogonal experimental analysis, the optimal concrete mix consists of w/c ratio 0.26, 33% sand, 0.06 mm CBP size and 25% replacement. |
| 1996 | Wild [11]      | OPC type I, waste Fletton brick, crushed flint. | • Increased compressive strength after 90 days with 10% replacement. • Comparable 90 days compressive strength with 20% replacement. | • CBP has potential pozzolanic properties making it a suitable SCM. |
| 2007 | Bektas et al. [29] | Type I Portland cement, ground clay brick, oolitic limestone, natural siliceous aggregate. | • The use of GCB reduces early age strength. • Ultimate compressive strength is comparable or higher than the control specimen. • Equal or higher split tensile, flexural strength and modulus of elasticity at 90 and 180 days. | • CBP from demolished masonry can be used as an SCM. |

7. Effect of CBP on the durability of concrete

7.1. Shrinkage

The amount of water that can be held by cement paste is determined by its pore structure and amount of environmental humidity. Reduced relative humidity in the ambient atmosphere will cause concrete to become dimensionally unstable due to the loss of adsorbed water from CSH, resulting in the formation of shrinkage strain. Two types of shrinkage may occur; thermal shrinkage due to cooling effect and drying shrinkage due to loss of moisture [44]. It is observed that shrinkage increased with increasing time and percentage replacement from the variation of shrinkage strain with the increasing replacement of cement by CBP [26]. A significant reduction in autogenous shrinkage was reported by [34]. 10% replacement of cement by CBP was seen to decrease autogenous shrinkage by 35.9%. Reduction in the formation of hydration products at the early stages is a possible reason for this. Another probable mechanism is that the internal curing effect by CBP kept the capillary pores of the paste saturated, reducing internal stresses and associated strains.
Zhu et al. (2016) [23] also reported a reduced level of shrinkage with the increased replacement of cement by CBP in concrete due to smaller recycled powder particles filled up the pores in concrete, hindering water evaporation and hence reducing shrinkage. The durability of cement mortar and concrete replaced with different levels of CBP studied by various authors is summarised in table 5.

**Table 5. Summary of durability properties**

| Parameters    | Authors                        | Conclusions                                                                 | Remarks                                                                                       |
|---------------|--------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Sulphate Resistance | O’Farell et al. (2006) [16]     | • Increasing replacement level gives increased resistance to expansion.      | • QC mortars offer better performance than SC mortars due to better pozzolanic activity.   |
|               |                                 | • Performance of ground brick > heat treated clay > OPC.                     |                                                                                               |
|               |                                 | • Quenched clay provides better resistance than slowly cooled clay.         |                                                                                               |
|               | Filho et al. (2007) [19]        | • Reduction in tensile strength loss of control mortars exposed to 5% magnesium sulphate solution at 200 days. | • Reduction of CH, C₃A, and formation of additional hydrates refines the pore structure impeding the advancement of aggressive agents. |
|               | Schackow et al. (2015) [18]     | • Low sulphate resistance.                                                  | • The porous structure of control mortar is more efficient in accommodating the expansive reaction products formed during exposure. |
|               | Wild et al. (1997) [45]         | • CBP calcined at 1000 – 1100°C provides excellent sulphate resistance in a mortar. | • The poor performance of CBP calcined at low temperatures is due to the presence of crystalline activated clay and high initial levels of sulphate. |
|               | O’Farell et al. (1999) [46]     | • High CaO/glass ratio increases sulphate expansion and vice versa.         | • Chemical and mineralogical composition (especially CaO), type of CBP, glass content, oxides present, initial sulphate content are responsible for sulphate resistance. |
|               | Binici et al. (2012) [47]       | • Addition of red brick dust and basaltic pumice at 15% for each additive gives high sulphate resistance. | • Less ettringite formation in mortars exposed to sodium sulphate solution seen from SEM images. |
| Chloride Resistance | Filho et al. (2007) [19]        | • Reduction in chloride ion penetration.                                    | • Pore refinement due to pozzolanic activity retarded ionic transport in the matrix.         |
|               | Schackow et al. (2015) [18]     | • Low chloride absorption.                                                  | • Improvement in microstructure allows crystallisation/dissolution of NaCl without causing stress to surround material. |
|               | Gonçalves et al. (2009) [14]    | • Reduction in chloride ion penetration more for metakaolin than for CBP.   | • Pore structure refinement is responsible for chloride ion resistance.                        |
### Resistance to synthetic seawater

| Authors          | Details                                                                                           |
|------------------|--------------------------------------------------------------------------------------------------|
| O’Farell et al. (2000) [48] | - Reduced resistance is seen when ground brick contains high CaO, low glass, and low sulphate content.  
- Replacement by CBP minimises the formation of brucite and gypsum layer on the surface of the mortar.  
- 30% replacement reduces strength loss on exposure to seawater. |
| O’Farell et al. (2006) [16]   | - Heat-treated clay is more effective in reducing expansion than CBP when exposed to synthetic seawater.  
- Increased solubility of CH in seawater, the formation of brucite skin around mortar prism inhibits advancement of seawater solution. |

### Carbonation

| Authors          | Details                                                                                           |
|------------------|--------------------------------------------------------------------------------------------------|
| Schackow et al. (2015) [18] | - A significant effect was not observed at 28 days on replacement by CBP.  
- At 90 days, 10 and 25% provided the lowest rate of carbonation. |
|                   | - Refinement of pore structure due to the formation of additional CSH reduces carbonation rate.    |

#### 7.2. Porosity and sorptivity

Water in its pure form is a cause of physical degradation in concrete, and as a transporter of aggressive ions acts as an agent of chemical degradation. The structural transformation of water trapped in the concrete matrix (like freezing) causes internal stress build-up. It is well known that during the process of hydration, the products of hydration formed occupy more space than that held initially by cement and water. On complete hydration of 1 cm³ of cement, the space required for its total accommodation is approximately 2 cm³. However, there remain some voids that remain unoccupied by either cement or any hydration product. These are called capillary voids. The porosity of concrete gives a picture of the volume of capillary voids present. Sorptivity, on the other hand, is described as the ability of a porous material to absorb or desorb any liquid by the action of capillarity.

Ortega et al. (2018) [22] reported that CBP caused increased pozzolanic reaction leading to pore refinement of the modified mortars. Filler effect of CBP (determined by impedance spectrometry) is also responsible for the improvement of pore structure. Pore size distribution and threshold radius are affected by the addition of CBP in mortar. At shorter times, increased intruded pore volume, reduction in microscopic pores, and the increase in threshold radius were observed. Positive effects were mostly found at longer curing ages. Pore refinement occurred on the addition of gypsum [38]. Compressive strength is seen to increase the reduction of the threshold radius.

Singh et al. (2006) [49] reported lower pore diameter and porosity at all curing periods, which contrasts with the behaviour of CBP, where lower porosity was observed at longer curing times only. Gonçalves et al. (2009) [14] reported a higher reduction in sorptivity for metakaolin than ground brick modified mortars. In the case of the use of CBP, total porosity was found to increase with a corresponding gradual decrease of sorptivity. Refinement of porous structure leading to smaller pore size in spite of higher total porosity is the reason for this observation. More replacement up to 40% caused an increase in both porosity and sorptivity. Sabir et al. (1998) [50] developed an automated testing system for the measurement of sorptivity in mortar and concrete. It was found that at short curing periods and higher replacement levels, the sorptivity of modified mortars increased as compared to that...
of control because of the presence of residual porosity, which had not yet been filled by hydration products of an ongoing slow pozzolanic reaction. However, sorptivity decreased as the curing time increased, with some mortars giving lower values than that of control mortar.

7.3. Alkali silicate reaction
Reactive siliceous minerals present in aggregate on coming in contact with free lime of concrete forms a gel. This gel on coming in contact with water absorbs a large amount of moisture by osmosis. As a result, concrete expands and generates internal tensile stresses in its matrix, which causes it to crack. Mineral additives like silica fume react with a sufficient amount of alkalis to reduce the volume of ASR products formed [44, 51].

Afshinnia et al. (2015) [35] carried out a study in which ground crushed brick was used as a cementitious material, and clay brick was used as an aggregate material. High replacement levels (25%) of CBP caused a significant reduction of ASR. On using crushed brick as a replacement for fine aggregate, no beneficial effect on ASR mitigation was seen. Thus, it was concluded that the fineness of CBP played an essential role in mitigating ASR. By conducting EDS analysis, it was further determined that the alkali content of ASR gel obtained from a control specimen was much higher than that obtained from CBP modified samples. ASR gel from CBP containing mortars also contained more elevated calcium, had higher viscosity, and caused considerable swelling.

A positive effect of CBP on ASR mitigation was also reported by Turanli et al. (2003) [52]. The use of CBP from both slabs and walls caused a reduction in expansion with an increase in replacement. 30% replacement provided optimum results with slab brick dust performing marginally better than wall brick dust. Incorporation of CBP caused a delay in the start of expansion due to filling up of pore space. But, the effectiveness of the material reduced at later ages. Observation of increased expansion rate at later stages led to this conclusion.

8. Conclusion
1. The principal chemical component of CBP is silica and alumina, along with other minor compounds in smaller amounts. SEM images show that CBP has angular morphology and is amorphous.
2. The pozzolanic character of clay used for making brick comes from calcining it at a particular optimum temperature, which is different for different clays. Hence, not all types of CBP show pozzolanic character. Future scope in this area remains in the investigation of parameters for the enhancement of pozzolanicity in CBP.
3. TG analysis of mortars and pastes containing CBP revealed that CH content at more extended curing periods is less as compared to standard OPC samples. CBP addition also results in an increased degree of hydration and decreased heat of hydration. A decrease of CH peaks was observed from XRD analysis.
4. 10 – 25% replacement by CBP gives acceptable values of Strength Activity Index at 7 and 28 days. The compressive strength of mortars containing CBP is lower than control at the beginning but increases at more extended curing periods (90 – 180 days). Similar results were observed for flexural strength tests.
5. Cement replacement by CBP in concrete mostly causes increased compressive, flexural, and split – tensile strength at 28 and 90 days, indicating good pozzolanic behaviour.
6. Pore refinement causing the formation of additional hydration products due to pozzolanic reaction as well as filler effect of CBP are the primary factors causing improved durability of concrete.
7. The future scope can be extended to the study of high volume replacement of CBP in concrete and the effect of CBP replacement on corrosion of rebar.

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