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*Review paper*

# RECYCLED BRICK POWDER AS SUSTAINABLE SUPPLEMENTARY CEMENTITIOUS MATERIAL: A REVIEW

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**Abstract**

*This paper investigates the potential of recycled brick powder as a sustainable alternative for partial replacement of Portland cement in cement composites. Given the significant impact of the cement industry on global CO2 emissions, finding environmentally friendly solutions has become a key goal in the construction industry. Recycled brick powder, as a secondary material, demonstrates considerable pozzolanic activity and the potential to reduce the environmental footprint of cement production. A systematic literature review indicates that replacing cement with recycled brick powder in the range of 10–20% improves the mechanical properties, reduces shrinkage and water absorption, and also improves chloride and carbonation resistance of cement-based composites, due to the pozzolanic activity and filler effect of recycled brick powder. This paper provides insights into the various aspects of using recycled brick powder in cement-based composites, contributing to waste reduction and enhancing the sustainability of construction materials.*

**Key words:** *Recycled brick powder, Cement-based composites, Fresh properties, Mechanical properties, Chloride resistance, Carbonation resistance.*

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# 1. INTRODUCTION

The cement industry is one of the most significant sources of carbon dioxide ($CO_2$) emissions, a greenhouse gas with the most pronounced impact on global warming. In fact, 8% of total global $CO_2$ emissions come from the cement industry, which is responsible for 27% of total direct $CO_2$ emissions from industrial sectors, making it the second-largest $CO_2$-source among industries [1]. According to the International Energy Agency (IEA) [2], annual cement production is expected to reach 4.4 billion tons by 2050.

There are several effective approaches to reducing $CO_2$ emissions caused by the cement industry. Some of the main strategies include: (i) increasing reliance on renewable energy sources to reduce emissions associated with energy consumption, (ii) improving clinker production processes to lower emissions generated by chemical reactions, and (iii) implementing carbon capture, utilization, and storage (CCUS) technologies [3, 4].

In addition, partial cement replacement with alternative binding materials, such as industrial by-products, and adequately treated some of the construction and demolition (C&D) wastes, can further reduce greenhouse gas emissions, as these materials have a lower carbon footprint [5].

Bricks are considered the second most common construction material after concrete and are treated as waste in cases of damage during manufacturing, building, or demolition processes (Fig. 1). During the firing process in brick production, the crystalline structure of clay-based raw materials undergoes dehydroxylation, forming a reactive amorphous structure that results in pozzolanic activity [6]. After the waste brick is ground into a powder with an appropriate particle size distribution this powder can be used as a supplementary cementitious material (SCM) in mortars or concrete [7-11].

*Figure 1. Brick waste generated during construction and demolition activities [12].*

Kolawole et al. [13] determined that the total content of main oxides ($SiO_2$, $Al_2O_3$, and $Fe_2O_3$) in RBP exceeds 70%, leading to the classification of RBP as a Class N pozzolan according to ASTM C618 [14]. Its mineralogical composition mainly consists of crystalline $SiO_2$ (quartz), $Fe_2O_3$ (hematite), and $Al_2O_3$ + $SiO_2$ (mullite). Similar results were reported by He et al. [15] as well as Aliabdo et al. [16]. Shao et al. [6] showed that the amorphous phase in RBP is 20.1%, while quartz represents the main crystalline phase. Lam et al. [17] and Abib et al. [18] also found that RBP contains a high percentage of silica and alumina, and stated that the main crystalline phase is quartz.

Ouyang et al. [19] investigated the particle morphology of RBP and found that the particles resemble quartz dust, while Lam et al. [17] determined that RBP particles have angular shapes and rougher surfaces compared to cement particles. Increased grinding of the powder leads to the removal of irregular edges, making RBP particles more spherical, as demonstrated by Zhao et al. [20]. Finally, Kolawole et al. [13] reported that RBP particles are wide, with a slightly amorphous band, and flattened as a result of the milling process.

This review aims to collect and analyze the latest research related to the use of RBP, as an environmentally friendly alternative to cement in cement-based composites, with regard to the selected fresh and hardened properties.

## 2. PROPERTIES OF CEMENT-BASED COMPOSITES WITH RBP

### 2.1. Fresh Properties

#### 2.1.1. Water Demand

Although the use of RBP leads to a decrease in the workability of cement-based materials, compared to other types of waste particles, such as granite, marble and ceramic powder, RBP has the least impact on increasing water demand [21]. Nas et al. [22] demonstrated that mortar with a 5% RBP replacement had the same water absorption rate as the reference sample, suggesting that lower replacement ratios may not significantly affect mixture properties. However, the general trend shows that higher RBP content in the mix leads to increased water demand, with particle size and cement replacement level playing key roles. This is mainly attributed to the irregular shape and porous surfaces of RBP [23]. Chen et al. [24] emphasized that RBP particles smaller than 10 μm exhibit a higher specific surface area, which results in stronger water absorption and increased inter-particle friction, thereby raising the water demand in cement-based mortars. Zhao et al. [20] investigated the effect of varying RBP particle sizes on the water demand required to achieve standard consistency with 30% cement replacement. Their results showed that while the inclusion of 30% RBP increased water demand, this effect diminished with smaller particle sizes. The explanation lies in the smoother surface and more regular shape of finer RBP particles, which enhances the lubrication effect and mitigates the influence of increased surface area [25].

#### 2.1.2. Rheological Properties

The presence of RBP as SCM in cement-based materials can significantly affect their rheological behavior, particularly by increasing the yield stress [26]. This effect is attributed to the irregular and porous structure of RBP particles, which, compared to cement particles, absorb more water and increase inter-particle friction. Their porosity allows water to be retained within the pores, reducing the thickness of the water film in the mix, while the rough particle surfaces further contribute to inter-particle friction [21]. Additionally, the particle size of RBP plays a role in determining the yield stress. When RBP particles with larger diameters are used to replace cement, yield stress tends to increase; conversely, smaller RBP particles lead to a reduction in yield stress. Finer RBP provides better volume distribution, more efficient void filling, and thicker water films around particles, all of which reduce friction and improve workability [21].

Nevertheless, cement pastes with RBP contents between 10% and 40% exhibit shear-thinning behavior-viscosity decreases with increased shear rate. This phenomenon is attributed to the breakdown of particle flocs at higher shear rates, which releases additional free water into the mix and lowers the viscosity [27-29]. Despite the shear-thinning effect, the overall impact of RBP on increasing yield stress remains evident, especially when coarser and rougher particles with higher water absorption capacity are used.

### 2.1.3. Flowability

The flowability of cement composites containing RBP is influenced by several factors. Primarily, RBP has a higher water absorption capacity compared to cement, which reduces the amount of free water in the mixture and increases overall water demand [30]. The rough and irregular surface of RBP particles can also increase friction and hinder the flow of the mix [31-33]. However, prolonged grinding of RBP helps break down larger pores, reducing its water absorption ability. Simultaneously, the particles become finer and more rounded, which may reduce friction and improve flowability. RBP may also contribute to better dispersion of cement particles during the early stages of hydration, and accelerate the transformation of free water into gel water. The relative slump of concrete is determined by comparing the slump value of the mix with RBP to that of the control mix. Most studies have reported a decrease in the flowability of fresh mixtures with increased RBP content [34,35]. For example, Kırgız [36] observed slump reductions by 4.60%, 19.07%, and 46.77% for 5%, 7%, and 10% RBP replacement, respectively, compared to the reference concrete. Similar conclusions were drawn in the study by Senol et al. [37], where the addition of 20% RBP negatively affected the filling capacity of the self-compacting concrete in both V-funnel and L-box tests. These results were also confirmed by Liu et al. [38] and Ge et al. [39].

Nevertheless, some studies indicate the opposite trend. Arif et al. [40] recorded an increase in slump values by 10.6% and 29.8% for 5% and 10% cement replacement with RBP, respectively, compared to control samples. Additionally, research by Ma et al. [41] showed that for the same cement replacement level, with a decrease in RBP particle size, there was an increase in the cement paste slump, although in no case did the slump exceed that of the control mixture.

## 2.2. Hardened properties

### 2.2.1. Compressive Strength

The inclusion of RBP as SCM in cement-based composites can, under specific conditions, lead to improved compressive strength. For instance, Olofinnade et al. [42] found that concrete with 10% RBP as SCM exhibited higher 28-day compressive strength compared to reference. However, they also noted that increasing the RBP content beyond this point led to a reduction in strength, recommending a maximum replacement level of 15%. Similar recommendations were made by Letelier et al. [43] and Liu et al. [44], while Toledo Filho et al. [45] and Kirgiz et al. [36] suggested an optimal replacement of cement with 10–20% RBP. Ge et al. [46] demonstrated that concrete with 25% RBP could reach up to 50 MPa in compressive strength, provided that an optimized mix design is used: a water-to-binder ratio of 0.26, 33% sand content, and RBP particle size of 0.06 mm. According to Zheng [47], mortars with 20% and 30% RBP as SCM showed 7.6% and 21.6% lower strength, respectively, compared to those with 10% RBP after 14 days of curing, while Ortega et al. [11] observed that mortars containing 10% RBP exhibited higher compressive strength after 400 days compared to the control sample.

In addition to the level of cement replacement, the fineness of the RBP also plays a crucial role. Irki et al. [48] evaluated different Blaine fineness levels (390, 430, and 520 kg/m²) and demonstrated that increased fineness positively affects compressive strength of self-compacting mortar up to a certain threshold beyond which the strength decreases. Finer particles yielded higher strength at the same replacement level. Similarly, Ma et al. [23] found that the 28-day compressive strength of mortar was improved when using RBP with D50 = 6 μm and 12 μm, but only for replacement levels below 15%.

### 2.2.2. Flexural and Tensile Strength

The mechanical properties of cement-based composites incorporating RBP are strongly influenced by RBP fineness and the level of cement subtitution with it. Studies have shown that when these parameters are properly optimized, RBP can enhance both flexural and tensile strength due to RBP's pozzolanic activity and filler effect. For example, Usha Rani et al. [49] found that concrete with 10% and 20% RBP exhibited higher flexural strength after 28 days compared to the control sample, while at 30% RBP, a slight decrease was observed but still within a range of the reference value. Similarly, Duan et al. [25] reported a slight reduction in flexural strength with increasing RBP content, though even at 30% replacement the values remained similar to those of the control mortar. Zheng [47] confirmed that flexural strength values for concretes with 10%, 20%, and 30% RBP did not significantly differ from that of mix without RBP, while similar conclusions were made about the tensile strength of concrete with RBP. Consistently, Ge et al. and Ortega et al. [46,11] concluded that RBP does not have a major adverse effect on the tensile and flexural strength of cement-based composites. Furthermore, Naceri et al. [50] observed improvements in flexural strength for mortars with 5% and 10% RBP after 90 days of curing, while higher RBP contents led to a gradual decline.

However, not all studies present consistent findings. Olofinnade et al. [42] noted that even with less than 10% RBP, a slight drop in tensile strength was detected, with more pronounced reductions at higher contents. Similar trends were observed by Ma et al. [41], who reported a continuous decrease in flexural strength with increased level of RBP as SCM.

Apart from the dosage, RBP fineness also plays a key role. Ma et al. [41] showed that finer particles sizes enhance flexural strength compared to larger ones at the same replacement level. Irki et al. [48] also highlighted the positive influence of Blaine fineness, i.e. their tests showed that mortars containing RBP with Blaine values of 390, 430, and 520 kg/m², at replacement levels between 5% and 20%, exhibited improved tensile strength compared to the control samples, both after 28 and 90 days of curing. Based on the overall analysis, it can be concluded that the addition of RBP as SCM may positively impact the tensile and flexural strength of cement-based composites-but only if the cement replacement level and RBP's particle fineness are carefully optimized.

### 2.2.3. Shrinkage Properties

Cracking due to shrinkage in cement composites represents an increasingly relevant issue due to their widespread use. This highlights the importance of a deeper understanding of the shrinkage behavior of cementitious materials containing RBP. According to various studies, RBP as SCM can significantly reduce shrinkage, though many factors influence this effect. Ge et al. [39] observed a substantial reduction (about 35.9%) in autogenous shrinkage with the use of 10% RBP. This shrinkage-reducing effect can be attributed to several mechanisms. First, the usage of RBP as SCM leads to a reduction in the early hydration products formation, which results in a reduced formation of small pores and thereby limiting autogenous shrinkage of cementitious material. Second, due to its high water absorption capacity, RBP acts as an internal water reservoir, while gradually releases moisture, which helps saturate capillary pores and mitigates shrinkage [51]. Furthermore, Ma et al. [41] reported that cement-based composites, containing 7.5%, 15%, and 30% RBP as SCM, exhibited lower 42-day drying shrinkage by 3.6%, 6.3%, and 11.6%, respectively, compared to a control value.

Additionally, RBP particle size plays a significant role in the shrinkage behavior of cement-based composites. Liu et al. [38] found that fine RBP particles help reduce total mortar shrinkage, whereas larger particles can lead to an increase in shrinkage by 2-3%. Finer RBP improves the pore structure by acting as both a filler and a pozzolanic material, ultimately lowering shrinkage [52]. However, some negative effects have also been reported. Naceri et al. [50] and Rovnaník et al. [53] observed that excessive water absorption by RBP can accelerate evaporation, potentially increasing shrinkage in cement-based materials. In summary, RBP as a SCM has a significant effect on the shrinkage of cementitious materials, particularly on its reduction. Nonetheless, to fully utilize its potential, further research is needed, especially in optimizing the level of cement substitution and fineness of RBP in concrete and mortar mixtures.

### 2.2.4. Water Absorption

Studies have shown that increasing the content of RBP up to a certain level can reduce water absorption in cement-based composites. Ortega et al. [11] found that the capillary absorption coefficient of concrete containing 20% RBP as SCM, with diameter about 8.5 μm, was 19.2% lower than that of control. Ma et al. [41] found that the use of fine RBP had a more pronounced effect on reducing water absorption compared to coarser particles. However, excessive use of low-fineness RBP may increase water uptake, indicating the importance of carefully balancing both fineness and level of cement substitution. Similar findings were reported by Schackow et al. [9], who tested mortars with average RBP particles smaller than 5 μm. After 28 days of curing, the mortars containing RBP as SCM (up to 40%) had lower water absorption and reduced porosity compared to the control one. A nearly linear relationship was observed between RBP content and porosity reduction - higher RBP levels led to lower porosity, up to a certain threshold. Furthermore, Schackow et al. [9] compared the water absorption coefficients of mortars with and without RBP after 90 days of curing. While there were no significant differences in water absorption within the first 10 minutes, samples containing RBP exhibited a clear reduction in the absorption coefficient after 90 minutes. This effect was attributed to a combination of the filler effect and pozzolanic activity of RBP, which reduced capillary channels and hindered fluid transport. Interestingly, at 40% RBP content, a slight increase in absorption coefficient was observed, suggesting that there is an optimal dosage of RBP, beyond which the benefits may be reversed due to changes in the microstructure.

### 2.2.5. Chloride Resistance

Chloride ions from the environment pose a continuous threat to reinforced concrete structures due to the risk of steel bar corrosion, which severely compromises concrete durability [54]. Therefore, evaluating the resistance of cement-based composites with RBP to chloride penetration is of growing importance. Gonçalves et al. [55] found that mortars containing 10% and 20% RBP as SCM showed improved resistance to chloride ingress, which they attributed to the pore refinement in cement-based matrix. Similar results were reported by Ortega et al. [11], who observed that chloride migration coefficients in mortars with 10% and 20% RBP were reduced by 31.70% and 48.15%, respectively, compared to the control. They concluded that the synergy between the pozzolanic activity and filler effect of RBP contributes to a denser, less permeable microstructure. However, not all findings are consistent. Ge et al. [46], who tested concrete with 10%, 20%, and 30% RBP, found that the sample with 30% RBP had the lowest chloride resistance.

### 2.2.6. Carbonation Resistance

Concrete's resistance to carbonation depends on the composition and density of the cement matrix, as $CO_2$ penetration reduces pH and accelerates steel corrosion [56,57]. The process involves diffusion of $CO_2$ through the pore structure, dissolution in pore water, and reaction with hydration products to form calcium carbonate [57,58]. According to Shao [59], the depth of carbonation in mortar increased with higher RBP content during accelerated testing-reaching a maximum of 13.8 mm at 40% RBP as SCM after 28 days of carbonation. Conversely, under natural carbonation conditions, Schackow et al. [9] observed the carbonation depths under natural conditions after 28 and 90 days for mortars with and without the addition of RBP. The addition of RBP did not significantly affect the degree of carbonation after 28 days, but differences in behavior were noted after 90 days. Mortars containing 10% and 25% RBP showed lower carbonation rates compared to the control value. Moderate RBP content can enhance matrix density and reduce permeability, thereby slowing down carbonation process. However, excessive RBP reduces the content of calcium hydroxide, while lowering alkalinity and increasing vulnerability to carbonation [9,59].

## 3. CONCLUSION

The incorporation of RBP into cement-based materials significantly affects both fresh and hardened properties, with outcomes depending on both the replacement level and the fineness of the used RBP as SCM.

In the fresh state, with increasing the presence of RBP as SCM in mix there is an increase in water demand due to the irregular shape and porous surfaces of coarser RBP particles. However, this effect decreases with smaller RBP particle sizes due to their smoother surface and more regular shape, which improves the lubrication effect and mitigates the impact of the increased surface area. Rheological properties such as yield stress and viscosity tend to deteriorate with higher RBP content and coarser grading, although these effects can be mitigated through the use of finer particles. Regarding flowability, most studies report a reduction in slump and flow diameter with increasing RBP content, although some findings indicate the opposite trend - highlighting the importance of controlling particle size and optimizing mix design.

When it comes to the mechanical properties of the hardened composite, results indicate that small amounts of RBP as SCM (up to 15%) can even enhance compressive strength, especially when finely ground particles are used. In contrast, higher levels of cement replacement with RBP lead to strength reduction. A similar trend is observed in terms of flexural and tensile strength, i.e. with careful adjustment of fineness and level of cement substitution, RBP can maintain or even improve these properties.

In a term of shrinkage, RBP has proven beneficial by significantly reducing both autogenous and drying shrinkage of cementitious materials. The usage of fine RBP particles as SCM helps reduce total shrinkage, while cement replacement up to 30% with RBP (with optimal fineness) results in the decreasing of drying shrinkage of the cement-based composites.

The addition of RBP as SCM in the optimum range, as well with optimal fineness, can lead to the refinement in pore structure and reduction of the permeability of the cement-based matrix. Therefore, the use of RBP up to 40% as SCM can lower water absorpiton of cement-based composites. Moderate amounts of RBC (10–20%) can improve the resistance of the cement-based materials to chloride penetration, while RBP in the range of 10-25% as SCM reduces the carbonation rate.

A systematic literature review indicates that replacing cement with RBP (with optimal fineness) in the range of 10–20% improves the mechanical properties, reduces shrinkage and water absorption, and also improves some durability properties such as chloride and carbonation resistance of cement-based composites, while contributing to the reduction of C&D waste disposal.

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