Nasr, MS, Salman, AJ, Ghayyib, RJ, Shubbar, A, Al-Mamoori, S, Al-khafaji, Z, Hashim, TM, Hasan, ZA and Sadique, MM

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Review

Effect of Clay Brick Waste Powder on the Fresh and Hardened Properties of Self-Compacting Concrete: State-of-the-Art and Life Cycle Assessment

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Abstract: Sustainability and reducing environmental damage caused by CO_2 emissions have become issues of interest to researchers in the construction sector around the world. Reducing the cement content in concrete by partially substituting it with by-products or waste falls within this field as the cement industry is responsible for 7% of global CO_2 emissions. On the other hand, self-compacting concrete (SCC) is one of the special types of concrete that contains a large amount of powder (most of which is cement) to ensure its flow under the influence of its weight without separating its components. Therefore, to produce eco-friendly SCC, many researchers have replaced part of the cement with clay brick waste powder (CBWP) since brick units are among the most widely used building materials after concrete. Accordingly, this study aims to review previous research that included using CBWP in SCC. The effect of these wastes on the fresh, mechanical, durability and microstructural properties of cement was reviewed. Additionally, a comparison between the environmental impacts of SCCs with different CBWP contents has been conducted using the life cycle assessment (LCA) approach. It was found that the highest value of CBWP that can be used without negatively affecting the different properties of concrete is 10% by weight of cement. Moreover, regarding environmental impact, using CBWP as a substitute for cement reduces environmental damage, and the lowest environmental impact that can be achieved per strength unit (MPa) is 37.5%.

Keywords: SCC; clay brick waste powder; fresh properties; hardened properties; life cycle assessment

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Citation: Nasr, M.S.; Salman, A.J.; Ghayyib, R.J.; Shubbar, A.; Al-Mamoori, S.; Al-khafaji, Z.; Hashim, T.M.; Hasan, Z.A.; Sadique, M. Effect of Clay Brick Waste Powder on the Fresh and Hardened Properties of Self-Compacting Concrete: State-of-the-Art and Life Cycle Assessment. *Energies* **2023**, *16*, 4587. https://doi.org/10.3390/en16124587

Academic Editor: Izabela Hager

Received: 9 May 2023
Revised: 31 May 2023
Accepted: 5 June 2023
Published: 8 June 2023

1. Introduction

The continuation of population growth with time is matched by a steady demand increase in the construction sector [1]. Concrete is among the most widely used building substances [2,3], and therefore, this increase in building requirements will be reflected in greater depletion of natural resources such as aggregates [4], as well as a further increase in the production of cement [5,6], which is the main binding material in concrete.

Cement production is accompanied by high carbon dioxide emissions [7–9], estimated at about 7% of the total production around the world [10–13]. The fabrication of 1 ton of cement is associated with the emission of about 1 ton of CO_2 [14]. Therefore, the increase in cement production means an increase in global warming and more damage to the environment. To achieve sustainability in the construction sector and reduce the damage to the environment, researchers' thinking has been directed to ways or solutions to reduce the depletion of these resources and to reduce the emissions resulting from the cement industry [15,16]. Among these solutions, one possibility is to reduce the cement content in concrete by partially replacing it with by-products or waste [17,18]. Based on this idea, clay brick waste powder was used as a possible alternative to cement. Brick waste (BW) is the second-most generated construction and destruction waste after concrete waste [19]. It has been reported to be a potential alternative to cement due to its pozzolanic reaction [19–21]. Recently, the most popular way to reuse CBWP has been grinding it into a powder to partially replace the cement. Since bricks comprise some non-crystalline (amorphous) compounds due to exposure to a temperature during the brickmaking process, CBWP shows pozzolanic activity when exposed to alkalis from clinker hydration or chemical supplement [22–24].

Self-compacted concrete (SCC) is one of the special types of concrete that is characterized by the possibility of placing and compacting it under the influence of its weight [25], that is, without using any vibration effort, and it can also be transported without segregation or bleeding due to its sufficient cohesion [26]. Lowering the noise on the site, and reducing the labor required for placing concrete in addition to the ease of pouring it into complex forms or congested reinforcement places are among the most important benefits of SCC [27]. However, the quantities of cement and chemical admixtures are increased in SCC to ensure that the desired workability is obtained [28]. This prompted researchers around the world to investigate environmentally friendly (low-carbon) and sustainable options to produce green SCC [29]. The use of waste resulting from demolition is one of the main options that fall within this context [30,31]. The use of such waste as building materials has several benefits, including reducing the burden on the landfill, in addition to contributing to reducing environmental and economic damage [32,33].

While investigating the suitability of new materials to replace conventional materials for sustainable development, it is essential to evaluate the environmental performance of these materials along with their mechanical and durability properties [34]. Life cycle assessment (LCA) is one of the powerful tools that can be used to evaluate the environmental impacts of new materials [35,36]. LCA is used to identify effective methods for conducting direct comparisons between traditional and new materials, especially in the construction industry [37,38].

Among the wastes used in self-compacting concrete is clay brick waste [39]. Therefore, this research aims to review previous studies that dealt with the use of clay brick waste powder (CBWP) as a cementitious material in SCC, where its effect on various fresh and hardened properties was surveyed in order to reach conclusions that serve future research within this concept. Additionally, the environmental impacts of the CBWP and cement were evaluated using the approach of Life Cycle Assessment (LCA). Moreover, the importance of this material locally (in Iraq) is due to the fact that most residential homes for citizens are built using clay brick units. Consequently, the demolition of these houses for the purpose of rebuilding, renovating or converting them into multi-story structural buildings causes the production of large quantities of brick waste that is buried in landfills without benefit. Therefore, understanding the impact of these wastes from an environmental point of view and on the various properties of SCC through this study opens the door to its recycling, which contributes to reducing its environmental impact as well as producing green and low-carbon SCC.

The importance of this review is represented by its aim to promote the reuse of waste (CBWP) that is available locally in large quantities in a special type of concrete, SCC. It is believed that knowing the effect of these residues on the various properties of concrete (considering the different fresh and hardened tests) contributes to providing a reliable conclusion for future research on the replacement ratio that gives the best performance. Moreover, studying the environmental impact of concrete containing this material (as a cement replacement material) considering the unit of strength provides interesting information for other researchers about the actual value by which environmental damage is reduced.

2. Characterization of CBWP

The chemical composition of the CBWP mentioned in the literature can be found in Table 1. According to Abib et al. 2013 [40], the chemical analysis of CBWP showed that it comprises significant proportions of silica and alumina. Hence, it is classified as aluminosilicates. XRD analysis affirms that the amorphous phase is predominant, with the existence of some crystalline elements such as dolomite, calcite and quartz. Furthermore, Mansor et al. 2016 [41] stated that CBWP is classified as an aluminosilicate as a result of the high percentage of alumina and silica. Aliabdo et al. [42] reported that the main oxides in CBWP are silica, alumina and ferric oxide with a content of about 77%, which complies with ASTM C618 requirements. The same findings were found by He et al. [43] and Lam et al. [44]. Moreover, Kolawole et al. 2021 [45] indicated that the sum of the pozzolanic oxides (SiO_2, Al_2O_3 and Fe_2O_3) is more than 70% and CBWP is classified under the class N (natural pozzolana) of the ASTM C618. Furthermore, their results suggested that the mineralogy compounds of CBWP were mainly crystalline SiO_2 (quartz), Fe_2O_3 (hematite) and Al_2O_3 + SiO_2 (mullite). On the other hand, Shao et al. 2021 [46] indicated that the amorphous phase in CBWP is 20.1% and that quartz is the main crystalline phase.

Moreover, Ouyang et al., 2021 [47] demonstrated that CBWP mainly consisted of quartz and its particle morphology is like quartz powder. Lam et al. [44] found that the angular shape and the rough surface of CBWP particles are more so than that of cement. Furthermore, they found that the main crystalline phase of CBWP is quartz. Zhao et al., 2020 [48] have shown that increasing the grinding of the powder leads to grinding off the irregular edges and making them tend to be spherical. Additionally, Kolawole et al., 2021 [45] indicated that the CBWP had wide, little amorphous bands. Furthermore, the CBWP grains had a flat nature. In addition, the grains were well rounded and the reason for this was the grinding.

Table 1. The chemical composition of CBWP.

Ref.	Year	Oxide, %								Fineness/Average Particle Size	
		SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Alkalis (K_2O + Na_2O_3)	L.O.I	WBCP	Cement
[49]	2006	63.11	4.65	13.34	8.51	4.10	1.70	3.12	2.33	2005 cm^2/g	3030 cm^2/g
[50]	2010	41.61	14.34	14.76	11.47	6.04	---	---	2.33	≤45 μm	3490 cm^2/g
[51]	2013	75.06	1.30	14.25	5.61	1.35	0.70	0.27	0.00	---	---
[40]	2013	53.78	12.88	16.61	6.22	2.20	0.65	3.00	3.13	≤80 μm	4300 cm^2/g
[41]	2016	76.90	1.96	10.00	5.60	0.28	0.28	3.26	0.69	≤75 μm	---
[52]	2018	66.55	6.15	14.80	5.48	2.39	---	2.13	1.48	3900, 4300 and 5200 cm^2/g	3850 cm^2/g
[53]	2019	56.86	7.88	15.53	7.63	2.95	0.55	3.85	---	24.08 μm	20.67 μm
[54]	2020	58.41	15.81	9.72	5.47	2.13	0.27	1.87	3.45	4600	4640
[55]	2021	69.85	15.67	5.83	4.43	1.04	0.23	1.85	4.3	2.76 μm	6.85 μm
[56]	2021	62.80	1.70	10.40	16.30	2.20	0.60	2.70	0.50	24.80 μm	11.14 μm

3. Pozzolanic Activity of CBWP

Abib et al., 2013 [40] recorded a reduction in pozzolanic activity index of mortar containing 10% CBWP compared to the reference specimens, which indicated the low pozzolanic activity of the waste powder. Furthermore, Shah et al. 2021 [55] stated that CBWP has a relative strength index of more than 0.9, which indicates a high potential for pozzolanic activity, encouraging its use as a sustainable building substance. On the other hand, Lam et al. [44] explained that the strength activity index of CBWP, for contents of 10% to 40%, ranged from 95% to 65% at 7 days and from 97% to 71% at 28 days compared to the control mix. Moreover, they stated that the pozzolanic activity of CBWP depends on the grain size.

4. Impact of CBWP on Properties of SCC

The effect of using CBWP on various properties of SCC (or self-compacting mortar; SCM) such as freshness, durability, mechanical and microstructural properties was reviewed and presented in the following sections. Table 2 summarizes some of the relevant literature.

Table 2. Utilization of CBWP as a cementitious material in SCC or SCM.

Ref.	Year	Replacement, %	Tests	Testing Age (Days)	Main Findings
[49]	2006	0, 15 and 30%	Workability, setting time, density, ultrasonic pulse velocity (UPV) and compressive strength	28 and 56	• CBWP had an adverse impact on workability and setting time • The compressive strength was reduced • The UPV correlated strongly with the compressive strength
[50]	2010	0, 5, 10, 15, 20, 25 and 30%	Workability, compressive strength and bending tensile strength	3, 7, 28 and 91	• The workability was not affected by adding CBWP • The 5% and 10% caused an increase in compressive and tensile strength of SCM at early ages • Using ≥20% of CBWP had an adverse effect on SCM properties
[51]	2013	0, 12.5, 25, and 37.5%	Rheological properties, compressive strength and microstructure	7, 28, 366 and 1095	• The shear stress increased with the increase in CBWP content, while it was decreased after using superplasticizer (SP) • In the presence of SP, the compressive strength of the paste was enhanced at 28–1095 days for CBWP contents of 12.5% and 37.5% • Denser microstructure was obtained
[57]	2014	0, 1, 2.5 and 5%	Workability, compressive strength, autogenous shrinkage and microstructure	7, 28 and 56	• Workability was reduced when using brick powder, but the reduction was compensated by the use of SP • The CBWP contained mixtures increased the compressive strength at 28 and 56 days and the maximum gain was obtained at 1% CBWP • The higher the CBWP content, the lower the autogenous shrinkage was • The microstructure of mixtures with CBWP was improved and pore-refined

Table 2. *Cont.*

Ref.	Year	Replacement, %	Tests	Testing Age (Days)	Main Findings
[41]	2016	0, 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50%	Workability, compressive strength and splitting tensile strength	28	• The use of CBWP improved the workability of SCC • The compressive and splitting tensile strengths were decreased
[58]	2016	0, 5, 10, and 15%	Workability, compressive strength, water absorption and microstructure	7, 14, 28 and 90	• The workability was decreased • The compressive strength decreased at the early ages while it increased at the later ages • The water absorption rose • The presence of CBWP had a minor effect on microstructure and pore size
[59]	2018	0, 5, 10, and 15%	Workability, splitting tensile strength, compressive strength and modulus of elasticity	7 and 28	• The workability and mechanical tests were improved for 5% replacement, while they were adversely affected at 10% and 15%
[52]	2018	0, 5, 10, 15 and 20%	Workability, compressive strength and splitting tensile strength	7, 28 and 90	• The flowability decreased with the increase of CBWP for replacement rates $\geq$ 20% • The compressive and tensile strengths were boosted with the increase in CBWP content up to 10% • The higher the fineness of CBWP, the higher the compressive strength
[54]	2020	0, 5, 10, 15 20 and 25%	Workability, compressive strength and capillary water absorption	7 and 28	• The workability losses were observed at CBWP contents of more than 20% • The CBWP decreased the compressive strength at early ages while it increased more in the control sample at later ages • The water absorption was slightly increased after adding CBWP
[60]	2021	0, 25 and 50% by volume	Workability and sulfate resistance	28, 90, 180 and 360 days	• The workability was not affected by incorporating CBWP • The sulfate resistance was improved
[55]	2021	0, 5, 10, and 20%	Water and SP demands, setting time, mechanical strength and early age shrinkage	3, 7, 28, 60, and 90	• The water demand was increased while the SP demand was decreased • The setting time was delayed • The 10% CBWP enhanced the mechanical performance at all stages, while the 20% CBWP was 98% of the control mix at 90 days

Table 2. *Cont.*

Ref.	Year	Replacement, %	Tests	Testing Age (Days)	Main Findings
[61]	2021	0, 25 and 50% by volume	Workability, compressive strength, permeability, carbonation depth, chloride penetration and microstructure	7, 28, 90, 180, 360 and 720	• CBWP had no significant effect on the fresh properties of SCC • The compressive strength and permeability results confirmed the pozzolanic activity of CBWP at later ages (≥180 days) • The performance of mixtures containing CBWP was poor in the carbonation environment • Although the resistance to chlorides was lower than in the reference mixture at the age of 28, it was greater than the reference mixture at the ages of 360 and 720 days.
[56]	2021	0, 50 and 100% of limestone filler	Compressive and flexural strengths, water absorption, drying shrinkage, carbonation, chloride ion diffusion and sulfate resistance	7, 14, 28 and 90	• The plastic viscosity and yield stress of CBWP-based mixtures were higher than the control specimen • The compressive strength values of CBWP-based mixtures were lower, equivalent and higher than that for the reference mix at 7, 28 and 90 days, respectively • The drying shrinkage was reduced

4.1. Workability

The effect of CBWP on different properties of SCC has been investigated by several researchers. For example, Sahmaran et al., 2006 [49] found that the brick powder reduced the workability of the self-compacting mortar due to its surface roughness and angular shape, and thus its high ability to absorb free water. Karatas, 2010 [50] indicated that the workability of SCM (based on V-funnel and slump flow) is not affected by the presence of 5 to 30% of CBWP. However, it caused an increase in the viscosity of fresh SCM. Sun et al., 2014 [57] reported that using CBWP up to 5% of cement weight did not affect the slump flow where all values were more than 670 mm. Amjadi et al., 2016 [58] revealed that the slump flow of SCM was reduced in the presence of CBWP, while for the V-funnel flow time test, the time was not affected by adding the waste material. Moreover, the viscosity remained stable with the assistance of more superplasticizer. Mansor et al., 2016 [41] found that the stability and workability of the fresh SCC were improved after replacing cement with CBWP. Moreover, it was found that the water/powder ratio increased as the CBWP content increased in the mix. They attributed this behavior to the high water absorption of CBWP itself.

Irki et al. 2017 [52] pointed out that the workability decreased as the CBWP increased in the mixture. The 20% CBWP reduced the flow by 3%, while the flowability declined by 30% for substitution rates greater than 20% of CBWP. Silva et al., 2019 [53] reported that CBWP can replace the cement (by volume) in the range 12.5% to 50% to produce SCC with good self-compaction and workability. The flow, V-fennel and L-box results conformed to EFNARC specifications. Si-Ahmed1 and Kenai 2020 [54] demonstrated that replacing the cement with 0 to 15% CBWP did not influence the rheological properties of SCM. However, the workability losses were noticed clearly at the replacement ratio of 20%. Higher plastic viscosity and yield stress were recorded by Zhao et al., 2021 [56] for SCM containing CBWP (as a substitute for limestone powder) compared to the reference mix. More water should be added to produce equivalent workability.

4.2. Hardened Properties

4.2.1. Compressive Strength

Compressive strength is one of the most significant characteristics of concrete [62]. The influence of CBWP on SCC has been addressed in most SCC studies. Karatas, 2010 [50] replaced cement with 0% to 30% CBWP in self-compacting mortar. The results showed that the higher the percentage of CBWP in the mixture, the lower the compressive strength. It was also found that the compressive strength at the early ages (3 and 7) for the contents of 5% and 10% is higher than the reference mixture. However, for 5% CBWP at 91 days of age, the resistance was equal to that of the reference samples. Abib et al., 2013 [40] showed that the use of 5% CBWP gave a similar compressive strength to that for free-CBWP specimens. Heikal et al., 2013 [51] stated that the compressive strength of self-compacting paste increased for the ages of 28–1095 days after replacing the cement with 12.5% and 37.5% CBWP. Furthermore, it was reported that the SCC compressive strength declined in the absence of superplasticizer, while it increased when superplasticizer was added. Sun et al., 2014 [57] substituted the cement simultaneously with CBWP (1%, 2.5% and 5% by weight) and fly ash. The results showed that the compressive strength of CBWP mixtures at 28 and 56 days was higher than that for the control mix. However, the 1% CBWP recorded the highest strength compared to all other mixtures. Amjadi et al., 2016 [58] utilized CBWP as cement replacement materials in proportions of 5%, 10% and 15% in SCM. Silica fume was used in all mixtures by 10% of cement weight. The compressive strength was reduced by the rate of 3 to 17% in the presence of waste materials. Mansor et al., 2016 [41] investigated the effect of replacing the cement with 5 to 50% CBWP in 5% steps in SCC. They found that CBWP decreased the compressive strength of SCC.

Irki et al., 2018 [52] studied the effect of change fineness of CBWP on the properties of SCM. The result indicated that using 5% CBWP as a cement replacement improved the compressive strength by 13%. Moreover, the higher the fineness of CBWP, the higher the compressive strength. Silva et al., 2019 [53] used red clay brick residue to replace the cement (in proportions of 0, 12.5, 25, 37.5 and 50% by volume) in SCC. The results showed that up to 90 days, the compressive strength of CBWP-containing mixtures reduced the compressive strength. However, beyond that (at 180 and 360 days), the 12.5%, 25% and 37.5% substitution rates of CBWP resulted in equal or even higher strength than the control mix. Si-Ahmed1 and Kenai 2020 [54] proved that, at early ages, the compressive strength of SCM decreased with the increasing rate of CBWP up to 15%. However, in the long term, the compressive strength of mixtures containing CBWP exceeded that of the reference mixture. Silva et al. 2021 [63] studied the impact of CBWP as a cementitious material with waste concrete (as a recycled coarse aggregate; RCA) in SCC. It was found that, at early ages (up to 90 days), the CBWP with RCA led to a decrease in the compressive strength. However, at 360 days of curing, the SCC showed no significant reduction in compressive strength when the RCA contents were at a medium level (25 to 50%), which indicated that the development of pozzolanic activity of CBWP at later ages has compensated for the loss in compressive strength that occurred at the early ages. Zhao et al., 2021 [56] focused on replacing the limestone powder with CBWP in SCM. The replacement rates were 0%, 50% and 100%. The results showed that the compressive strength at the age of 7 days had decreased slightly, but at the age of 28 days the reduction was compensated for by the pozzolanic reaction of the CBWP.

4.2.2. Splitting Tensile Strength

The splitting tensile strength is valuable because it is one of the characteristics used in the structural design of concrete [64]. Abib et al., 2013 [40] found that replacing the cement with 5% CBWP imparted the same value for the control SCC. Mansor et al., 2016 [41] recorded that the tensile strength values of SCC containing CBWP were lower than in the

CBWP-free sample. Irki et al., 2017 [52] detected that the splitting tensile strength at the ages of 7 to 90 days increased with the increase in CBWP content in the mix up to 10% substitution, which showed 107% improvement at 90 days compared to the control sample. The work of Silva et al., 2019 [53] indicated that the splitting tensile strength was reduced at 28 days by 1.50–15.29% in relation to the control mix. On the other hand, the strength increased with time and the sample with 25% CBWP content recorded the highest strength at 360 days of curing. Silva et al. 2021 [63] indicated that CBWP has the ability to fill nano-sized voids in recycled aggregate concrete and improve tensile strength.

4.2.3. Flexural Strength

The characteristics of deflection, shear strength and brittleness of concrete are affected by its flexural strength [65]. Thus, the flexural strength of concrete is a necessary characteristic in the design. Karatas, 2010 [50] noted that at early ages, the tensile strength values of SCC in bending for 5 and 10% proportions were higher than those of the reference mixture. However, the values were equal at the ages of 28 and 91. Silva et al., 2019 [53] found that the flexural strength at 28 days declined by 2.66% and 26.79% for 25% and 50% replacement of cement by CBWP, respectively. However, at 360 days, the 25% CBWP sample showed increased flexural strength by 1.94%, while the 50% substitution lowered it by 12.26%. Shah et al., 2021 [55] researched the impact of replacing cement with 5%, 10% and 15% CBWP on properties of self-compacting paste (SCP). The results indicated that the 10% CBWP gave flexural and compressive strength more than the control mix at the ages 3 to 90 days. Moreover, the 20% replacement of cement with CBWP imparted approximately equal values to that for the reference specimen.

4.2.4. Water Absorption

Among the basic mechanisms by which the transmission of aggressive factors into concrete is influenced is water absorption [66]. Therefore, its determination is an important issue for SCC. The work of Amjadi et al., 2016 [58] indicated that the water absorption of SCM was increased after replacing the cement with 5 to 15% CBWP. The rate of increase increased with the substitution percentage. According to Silva et al., 2019 [53], the absorption of water of brick powder mixtures increased up to 28 days compared to the reference sample. However, at later ages, with the progress of curing, the water absorption decreased as a result of the hydration process. Si-Ahmed1 and Kenai, 2020 [54] showed that the CBWP increased the capillary water absorption of SCM slightly compared to the CBWP-free mixtures. Shah et al., 2021 [55] revealed that using CBWP reduced the water absorption of self-compacting paste, which indicated that CBWP mixes are less porous and more durable than CBWP-free mixtures. Silva et al., 2021 [63] indicated that CBWP can reduce the water absorption of self-compacted concrete at later ages due to the increased CSH content as a result of its pozzolanic activity as well as the hydration progression of ordinary Portland cement.

4.2.5. Shrinkage

Sun et al., 2014 [57] reported that the autogenous shrinkage of SCC decreased with the increase of CBWP in the mix (CBWP content was in the range of 1 to 5%). Another study conducted by Zhao et al., 2021 [56] showed that the substitution of limestone by CBWP decreased the drying shrinkage of SCM due to its pozzolanic activity, which refined the pore structure. Shah et al., 2021 [55] found that 20% CBWP could reduce the early-age shrinkage from −500 to −300 µm/m of SCP; thus, the volumetric stability is improved.

4.2.6. Sulfate Attack

Silva et al., 2021 [60] addressed the resistance of SCC incorporating 0%, 25% and 50% CBWP as cement replacement material (by volume). The specimens were immersed in 5% $MgSO_4$ and Na_2SO_4 for 360 days. The compressive strength, mass loss and length change results indicated that CBWP exhibited an adequate performance compared to the reference SCC. Zhao et al., 2021 [56] stated that the replacing of limestone filler with CBWP did not appear to worsen the behavior of SCM.

4.2.7. Chloride Resistance

Silva and Delvasto, 2021 [61] indicated that, at later ages, the CBWP had increased the SCC's resistance to the permeation of chlorides as a result of the pozzolanic activity, which led to pore refinement in addition to the formation of Friedel's salt as a result of chemical fixation. However, at early ages, the resistance to chlorides was reduced compared to the reference specimen. Zhao et al., 2021 [56] reported that replacing the limestone filling with CBWP did not result in a significant weakening of the mortar's resistance to the diffusion of chloride ions.

4.2.8. Carbonation Resistance

Silva and Delvasto, 2021 [61] found that the presence of CBWP increased the carbonation rate of SCC. The authors attributed this to the consumption of Portlandite as a result of the pozzolanic reaction between it and the CBWP, which reduced the alkalinity of the mixture. This behavior was observed despite the refinement of the pores at the later ages (180 days). Moreover, Zhao et al., 2021 [56] revealed that substitution of limestone filler in SCC with CBWP increased the carbonation depth as a result of increasing the porosity of the matrix.

4.2.9. Microstructure

Heikal et al., 2013 [51] indicated that the CBWP worked to densify the microstructure in the presence of the SCC superplasticizer. This densification resulted from the reaction of the CBWP granules with $Ca(OH)_2$ resulting from the hydration of the cement, which led to an increase in the hydrated calcium silicate (C-S-H) gel, thus refining the pores and improving the compressive strength. On the other hand, Amjadi et al., 2016 [58] reported that the CBWP did not significantly influence the distribution of the size of the pores, while it led to an increase in the percentage of large pores and a decrease in the percentage of small pores with increasing proportions of CBWP.

5. Discussion

Table 1 includes the chemical composition and fineness of brick waste that was previously used in SCC. It is clear from the table that the brick residues consist mainly of aluminates and silicates, where the silicate values range approximately from 41.61 [50] to 76.90 [41], and the alumina values are within the range 5.83 [55] to 16.61 [40], while the ferric oxide values ranged between 4.43 [55] and 16.30 [56]. It is also noted that the calcium oxide values were relatively low. This difference in the content of oxides in the remnants of the used brick waste may be due to the variation in its content in the raw materials used in the manufacture of the brick units.

The total oxides (silica + alumina + ferric oxide) evident in the above table exceed the 70% proportion specified by ASTM C618 for the pozzolanic material, and therefore, in terms of chemical composition, brick waste could be a pozzolanic material. However, the chemical composition alone is not sufficient to determine the effectiveness of the material, as the type of phase (crystalline or amorphous) and its proportion to silicon oxide (the main component of brick waste) must be known. Some research [46] indicated that the percentage of this phase was around 20%, while this was not indicated in most of the previous studies. It is believed that determining the glass phase is important when using brick waste as a substitute for cement, as it reflects the pozzolanic activity of this material. The formation of the glass phase depends mainly on the temperature at which the brick units were burned during the manufacturing process (heat treatment). In fact, it is difficult to determine the temperature history of the burning of the bricks whose waste (after demolition) was used in previous studies because it may have been manufactured many years before the demolition.

For fresh properties, it was noted throughout the literature that the effect of the presence of CBWP on the workability of SCC fluctuated between no effect on the workability [57], a negative effect [56,58], improving the workability [41], and improving it up to a certain level of replacement [50,52,54]. It is believed that the cause of this oscillation is related to the surface roughness and the shape of the grains (angular or a tend towards being spherical), which in turn are greatly affected by grinding. The more grinding, the smaller the grain edges (and thus internal friction), the more spherical the shape, and the better the workability.

Regarding the hardening properties, specifically the compressive strength, it is observed that it can be concluded that the percentage of addition and the age of the test have a clear influence on the compressive strength of SCC-containing CBWP. However, the use of CBWP at 5% of the weight of cement improved (or equivalent to the control mix) the strength at the early and later ages [50,57]. As for increasing the substitution, most studies found a decline in the compressive strength at early ages and then compensated for the reduction (or even improvement) at later ages [53,54,63]. The term early ages have varied in previous research between 28 and more than 360 days. However, in general, the strength losses have been compensated by a large percentage at the age of 90 days. This discrepancy in the results may be due to the effectiveness of the waste used, which is affected by several factors, including the chemical composition of the raw materials, the temperature of burning the brick units (during the manufacturing process) and the degree of grinding, which affects the speed of the reaction of the material.

As for the tensile strength, the literature indicated that there is an equivalent strength or a little improvement when using CBWP at rates of 5 to 10% [40,52], and its effect appeared after the ages of 28 and 90 days. Compared to the compressive strength, it is noted that the results of the tensile [50] and flexural [55] strengths were positive up to 10% replacement ratio, while this percentage reached 15% for compression. The reason for this is that the tensile strength is more affected than the compressive strength by packing and the presence of voids, which is related to the improvement of the interfacial transition zone and pore refinement of the microstructure.

As for durability tests, previous studies have shown that CBWP has a range of effects between reducing [53,63] and increasing [58] the water absorption of concrete, but in general, it tended to reduce water absorption at later ages. Regarding shrinkage, the CBWP caused a reduction in SCC shrinkage, while it did not affect the performance of concrete in sulfate resistance. On the other hand, the CBWP negatively affects the depth of carbonation in SCC. As for the chlorides, their effect is not completely clear, despite the decrease in the penetration of chlorides at later ages.

6. Life Cycle Assessment (LCA)

A vital factor that must be taken into consideration during the use of CBWP as replacement to cement is how sustainable this powder would be and how it would contribute to reducing the environmental impacts of cement. One of the best options to accomplish this is to conduct Life Cycle Assessment (LCA) for SCC with different CBWP contents and compare it with that of SCC without CBWP (control). In this research, the mix design of SCC with five different CBWP contents (0%, 12.5%, 25%, 37.5% and 50%) as a volumetric replacement for cement from [53] was used to quantify the environmental impacts of these mixtures using the LCA method. The LCA values of all the mixtures were evaluated using the open-access software 'Open LCA'. This software provides details about different environmental problems such as energy usage, global warming potential, depletion of resources and toxic effects. The life cycle impact assessment method used in this study was the CML-IA. Details of the mix design used in this research are presented in Table 3 (all quantities presented in (kg/m^3)).

Table 3. Mix design of the SCCs (kg/m^3) [53].

Mix Id	Cement	CBWP	Fine Aggregate	Coarse Aggregate	Water	Superplasticizer
M1	500	0	895.1	686.2	202.5	5.3
M2	437.5	53.2	895.1	686.2	202.5	5.3
M3	375	106.4	895.1	686.2	202.5	5.3
M4	312.5	159.6	895.1	686.2	202.5	5.3
M5	250	212.8	895.1	686.2	202.5	5.3

According to [67], CBWP is considered waste material and the information needed in the LCA impact inventory only included the energy required during the grinding process (medium-voltage electricity consumption).

The system boundaries used for this research are from 'cradle to gate' to avoid any complications associated with post-use, transportation, and because recycling of the final product will be the same as CBWP encapsulated within the concrete. The scope used in this research comprises the following stages:

- The final target is the production of 1 m^3 of concrete (this includes extraction of raw materials, material production, preparation processes (e.g., grinding of the CBWP) and mixing of materials).
- As the CBWP could be collected from different places and the supply of the other raw materials varies, emissions from transportation were not considered in this research.
- A normalization approach was adapted in this research as not all the products developed the same compressive strength. The normalization was performed based on the impact per MPa of compressive strength of the concrete at 28 days and 360 days. Table 4 presents the results of compressive strength tests of the concrete as estimated from [51].

Table 4. The compressive strength of SCCs in MPa estimated from [51].

	28 Days	360 Days
M1	45	52
M2	42	53
M3	38	56
M4	35	55.5
M5	27	45.5

According to [68], the highest environmental impacts are acidification, eutrophication, global warming and ozone layer depletion. Therefore, in this research, those four environmental impacts were calculated along with the depletion of fossil fuels.

6.1. Acidification

Acidification refers to the high acidity levels from the existence of heavy metals in soil and water, and is usually measured with reference to SO_2 [69]. Figure 1 presents the results of the acidification potential associated with the production of 1 m^3 of SCCs with different CBWP contents. As can be seen from Figure 1, the acidification potential of SCCs decreased with increasing CBWP contents. This decrement was about 8.8%, 17.6%, 26.5% and 35.3% for the mixtures with CBWP contents of 12.5%, 25%, 37.5% and 50% relative to the control mixture (0% CBWP), respectively.

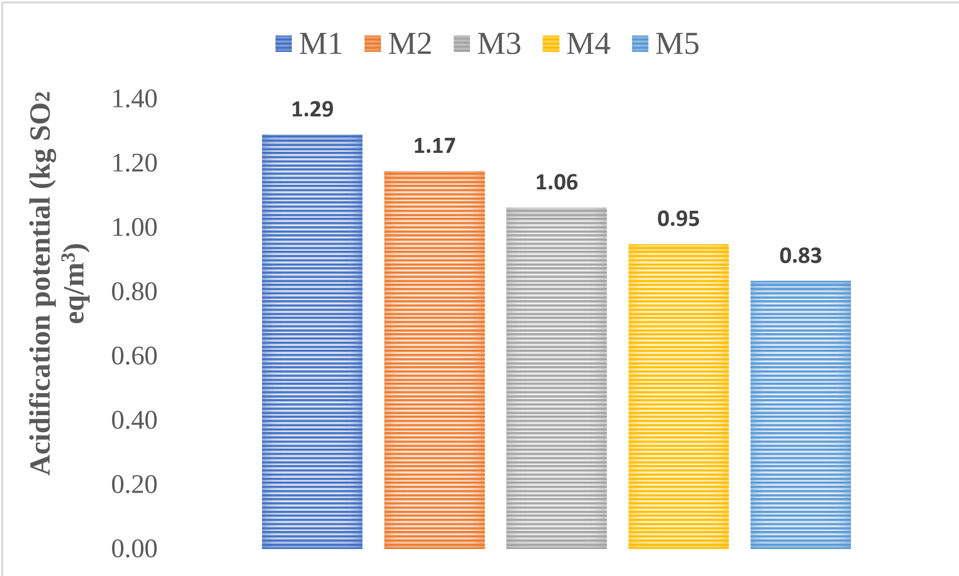

Figure 1. Acidification potential (kg SO_2 eq./m^3 of concrete).

Figure 2 presents the acidification potential of the SCC ingredients. As can be seen from Figure 2, cement has the largest acidification potential among other ingredients, with the maximum contribution for the mixture with 0% CBWP (M1) (which contributes to about 73% of the total). With an increase in the content of CBWP, the acidification potential from cement decreased to about 56% for M5. The acidification potential of CBWP ranged between 0–1.57%.

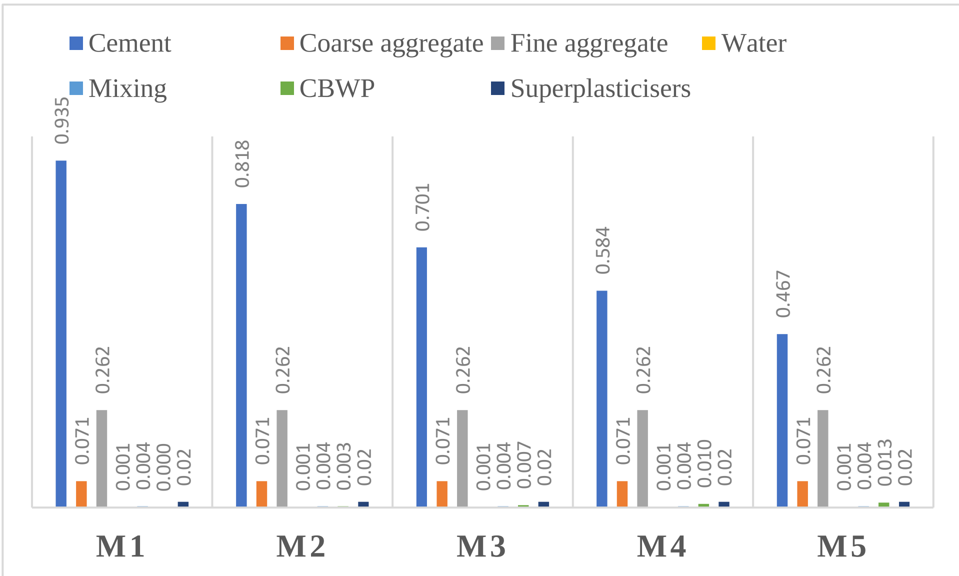

Figure 2. Acidification potential contribution of the SCC components (kg SO_2 eq./m^3 of concrete).

The results of the acidification potential impact per MPa of compressive strength of the SCCs at 28 days and 360 days are presented in Figure 3. Figure 3 shows that the SO_2 eq. m^{-3}/MPa of all mixtures is about the same at the age of 28 days. Figure 3 also shows that, although M5 has showed about 18 MPa reduction in the compressive strength relative to M1, their kg SO_2 eq. m^{-3}/MPa was relatively similar. After extending the age of curing to 360 days, the development in the compressive strength for mixtures with CBWP was higher than that of M1; therefore, their kg SO_2 eq. m^3/MPa ratios were lower than that of M1.

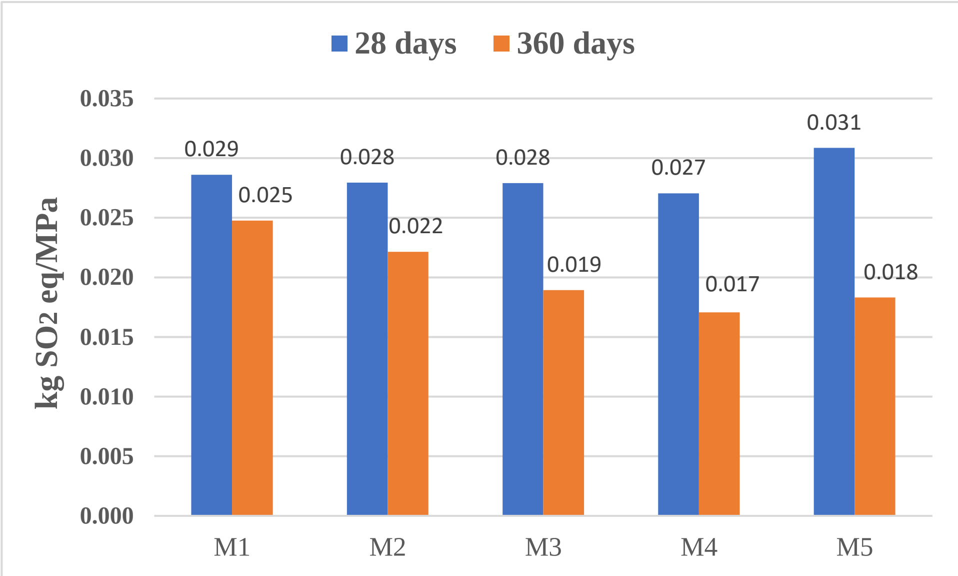

Figure 3. kg SO_2 eq./MPa of SCCs.

6.2. Eutrophication

Eutrophication refers to high mineral and nutrient contents in water that negatively affect aquatic lifeforms [70]. Eutrophication potential is usually assessed by levels of equivalent phosphate (PO_4 eq.). Figure 4 presents the results of the eutrophication potential associated with the production of 1 m^3 of SCCs with different CBWP contents. As can be seen from Figure 4 that the eutrophication potential of SCCs decreased with as the content of CBWP increased. This decrement ranged between 0.03 kg PO_4 eq. for M2 and 0.12 kg PO_4 eq. for M5.

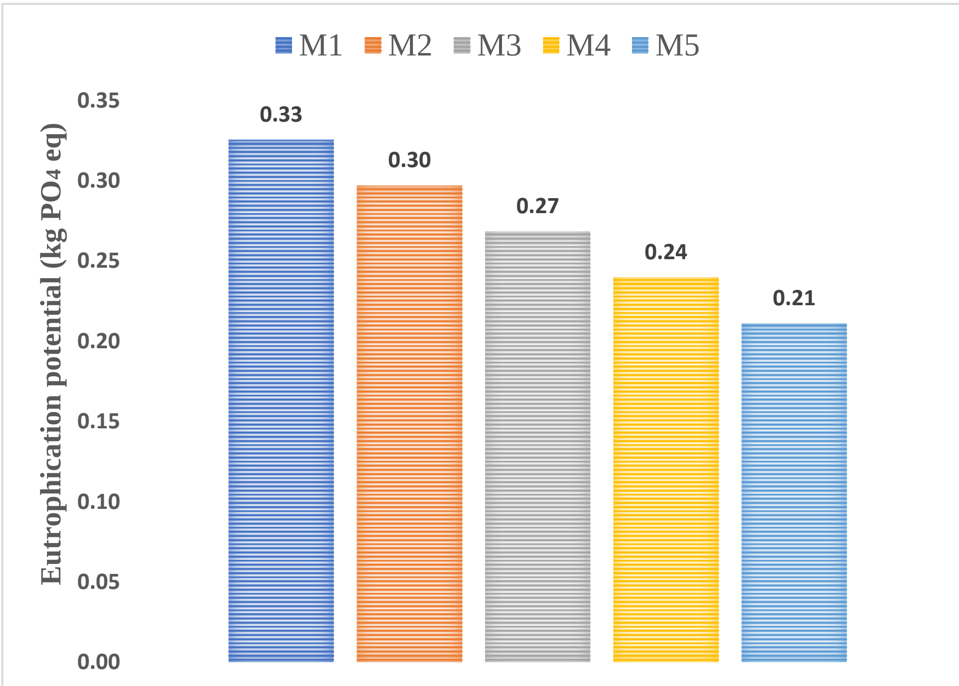

Figure 4. Eutrophication potential (kg PO_4 eq./m^3 of concrete).

Figure 5 shows the contribution of different SCC ingredients on eutrophication potential. As can be seen from Figure 5, cement has the largest eutrophication potential among other ingredients, followed by fine aggregate. The acidification potential of CBWP was ranged between 0–2.92%. The highest contribution of cement was recorded for mixture M1 (which contributes to about 74% of the total). After increasing the content of CBWP, the eutrophication potential of cement decreased gradually to about 57% for M5.

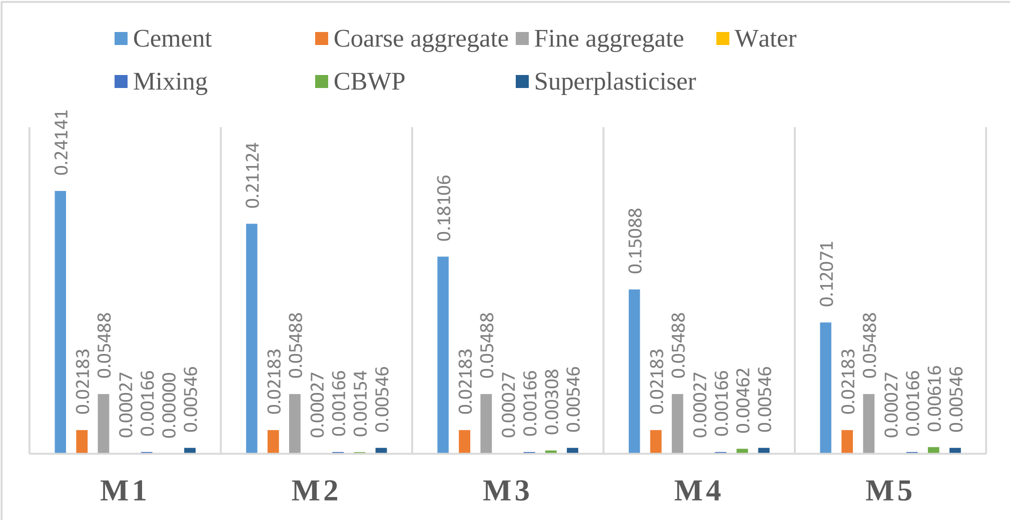

Figure 5. Eutrophication potential contribution of the SCC components (kg PO_4 eq./m^3 of concrete).

The result of the eutrophication potential impact per MPa of compressive strength of the SCCs at 28 days and 360 days are presented in Figure 6. Figure 6 shows that kg PO_4 eq./MPa decreased after increasing the CBWP content from 0 to 37.5%, then it also increased for mixture M5. After extending the age of curing to 360 days, their kg PO_4 eq./MPa ratios were lower than that of M1, with the lowest value of 4.32×10^{-3} kg PO_4 eq./MPa recoded for mixture M4.

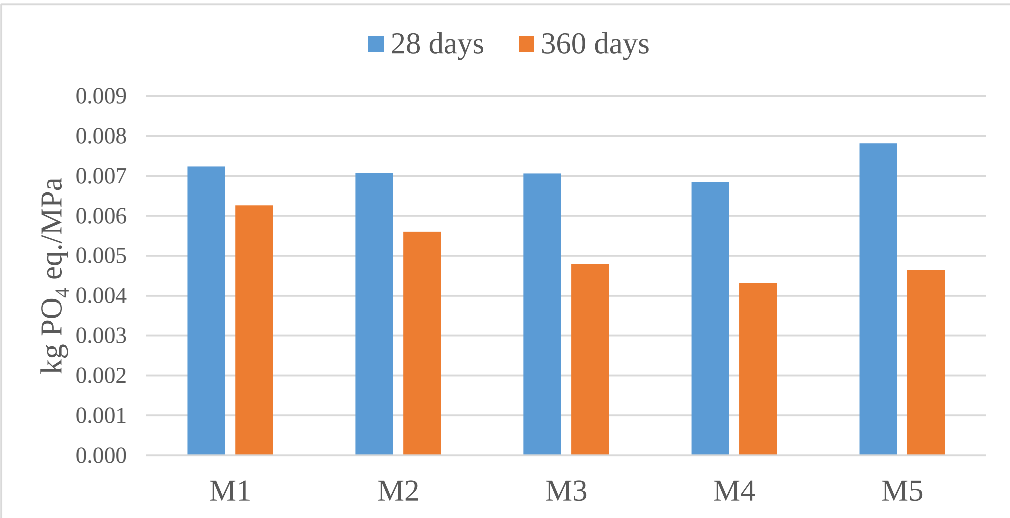

Figure 6. kg PO_4 eq./MPa.

6.3. Global Warming Potential (GWP100a)

GWP is a measurement that has been developed to assess the ability of greenhouse gas to trap heat in the atmosphere and it is measured in reference to (CO_2) [71]. In this research, the 100-year GWP of the investigated materials was calculated. Figure 7 presents the results of the 100-year GWP associated with the production of 1 m^3 of SCCs with different CBWP content. According to Figure 7, the 100-year GWP of SCCs decreased after increasing the content of CBWP. This decrement was about 10.8%, 21.6%, 32.4% and 43.2%

for the mixtures with CBWP contents of 12.5%, 25%, 37.5% and 50% relative to the control mixture (0% CBWP), respectively.

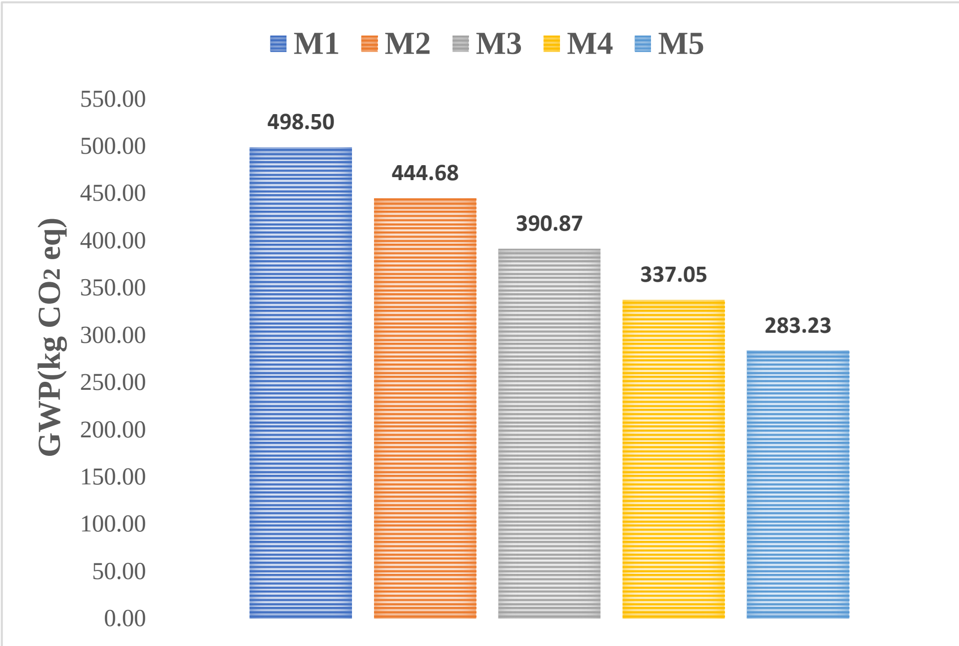

Figure 7. Global warming potential (kg CO_2 eq.).

Figure 8 presents the contributions of different SCCs ingredients to GWP. As can be seen from Figure 8, cement has the highest GWP among other ingredients. The GWP of CBWP ranged between 0 kg CO_2 eq. for M1 to 2.96 kg CO_2 eq. for M5. The highest contribution of cement was recorded for mixture M1 (which contributes to about 436.44 kg CO_2 eq). After increasing the content of CBWP to 50% (M5), the GWP of cement decreased to 218.22 kg CO_2 eq.

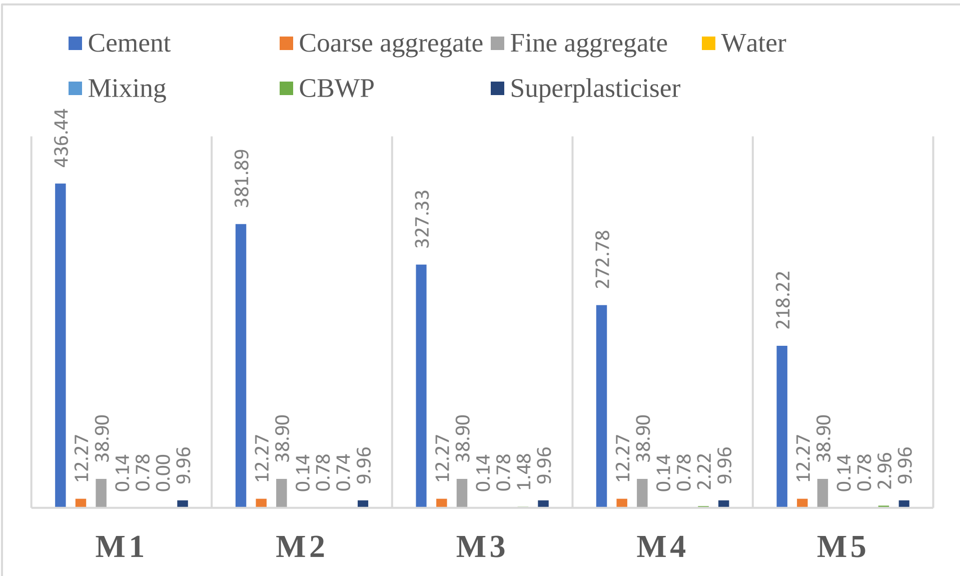

Figure 8. GWP contribution of the SCC components (kg CO_2 eq./m^3 of concrete).

The results of the 100-year GWP impact per MPa of compressive strength of the SCCs at 28 days and 360 days are presented in Figure 9. Figure 6 indicated that at the age of 28 days, the kg CO_2 eq./MPa decreased with an increase in the CBWP content from 0 to

37.5%, then it also increased slightly for mixture M5. After extending the age of curing to 360 days, their kg CO_2 eq./MPa ratios were lower than that of M1, with the lowest value being 9.63 kg CO_2 eq./MPa recoded for mixture M4 (37.5% CBWP).

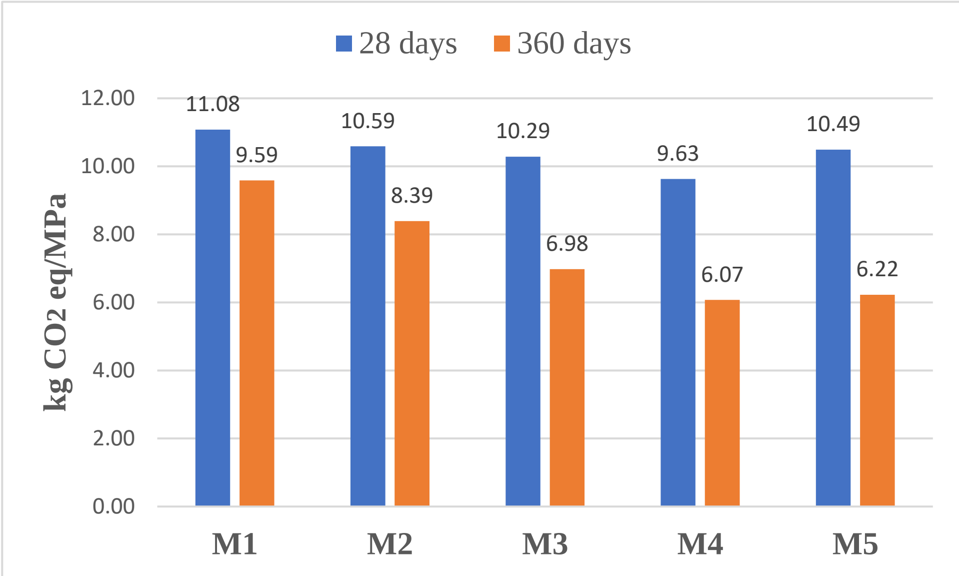

Figure 9. kg CO_2 eq./MPa.

6.4. Ozone Layer Depletion

Depletion of the ozone layer is caused by the release of greenhouse gases into the atmosphere (mainly chlorofluorocarbons (CFCs)) [72]. As shown in Figure 10, both cement and CBWP have a low impact on the depletion of the ozone layer. Figure 10 presents the results of the depletion of the ozone layer associated with the production of 1 m^3 of SCCs with different CBWP contents. As can be seen from Figure 10, the depletion of the ozone layer caused by SCCs decreased with increasing contents of CBWP.

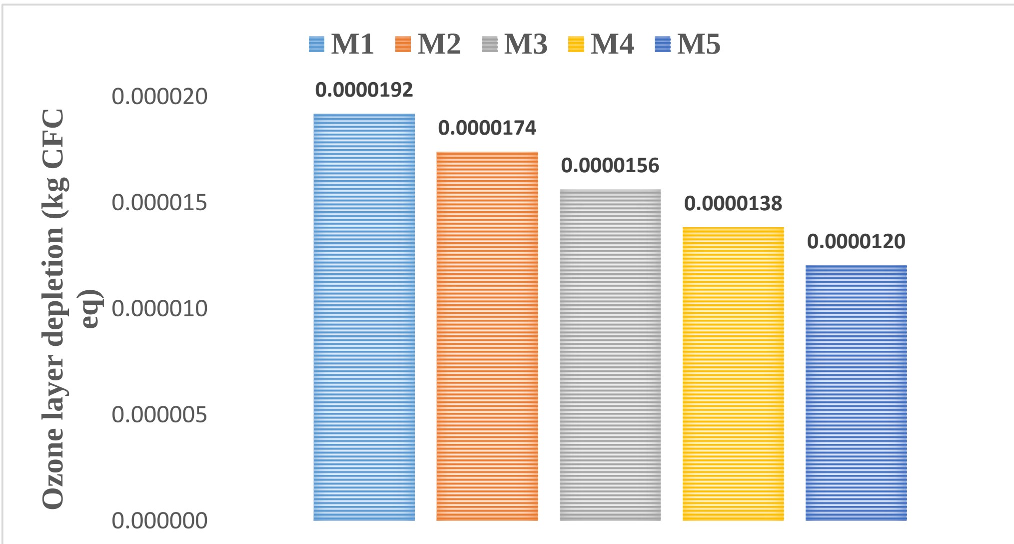

Figure 10. Ozone layer depletion (kg CFC eq.).

Figure 11 shows the contribution of different SCCs ingredients on ozone layer depletion. Figure 11 indicates that cement has the largest ozone layer depletion potential among other ingredients, followed by fine aggregate. The ozone layer depletion potential of CBWP ranged between 0% and 1.11% of the total. The highest contribution of cement was recorded for mixture M1 (which contributes to about 76% of the total). After increasing the content of CBWP, the ozone layer depletion potential of cement decreased gradually to about 60.5% for M5.

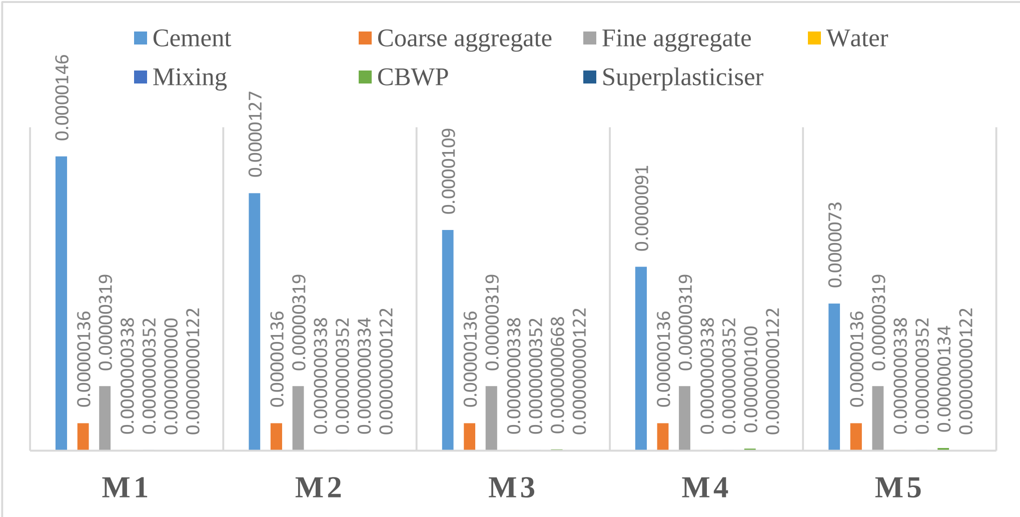

Figure 11. Ozone layer depletion contribution of the SCCs components (kg CFC eq./m^3 of concrete).

The results of the ozone layer depletion impact per MPa of compressive strength of the SCCs at 28 days and 360 days are presented in Figure 12. Figure 12 indicates that at the age of 28 days, the kg CFC eq. m^{-3}/MPa of mixtures decreased with increasing contents of CBWP up to 37.5% (M4), while it also increased for M5. At the age of 360 days, the development in the compressive strength for mixtures with CBWP was higher than that of M1; therefore, all mixtures with different CBWP contents have showed lower CFC eq. m^{-3}/MPa ratios relative to the control mix (M1).

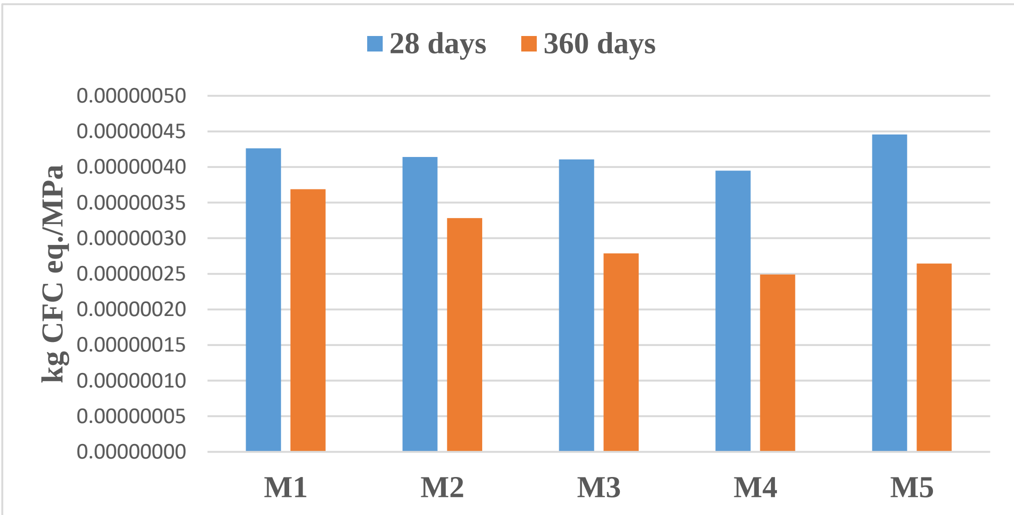

Figure 12. kg CFC eq./MPa.

6.5. Depletion of Fossil Fuels (Energy Consumption)

Figure 13 presents the results of the energy consumption associated with the production of 1 m^3 of SCCs with different CBWP contents. As can be seen from Figure 13, the energy consumption of SCCs decreased with increasing contents of CBWP. This decrement ranged between 147 MJ for M2 and about 588 MJ for M5.

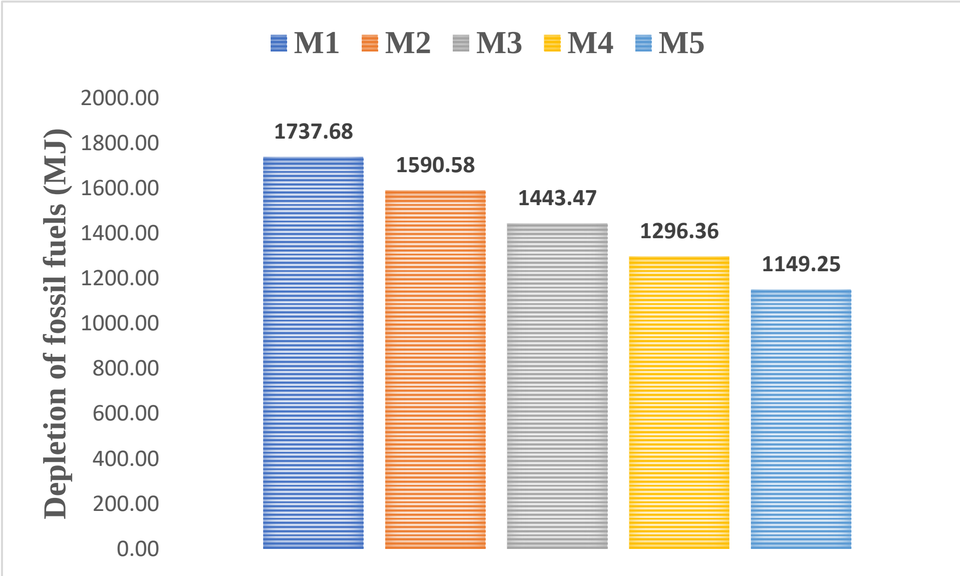

Figure 13. Depletion of fossil fuels (MJ).

Figure 14 shows the contributions of different SCC ingredients to energy consumption. Figure 14 shows that the highest energy consumption ingredient is cement among other ingredients, followed by fine aggregate and superplasticizer, while the energy consumption ranged between 0 MJ for M1 and 15.06 MJ for M5. The highest contribution of cement was recorded for mixture M1 (which contributes to about 70% of the total). After increasing the content of CBWP, the energy consumption from cement decreased gradually to about 53% for M5.

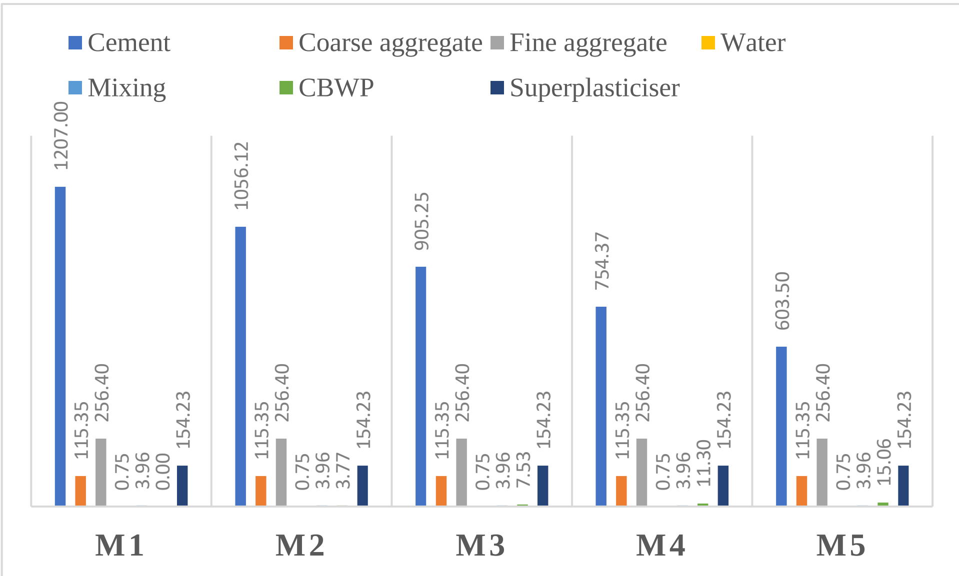

Figure 14. Energy consumption contribution of the SCC components (MJ/m^3 of concrete).

The result of the energy consumption impact per MPa of compressive strength of the SCCs at 28 days and 360 days are presented in Figure 15. Figure 15 shows that at the age of 28 days, the MJ/MPa decreased with increasing CBWP contents from 0 to 37.5%, while it also increased for mixture M5. At the age of 360 days, the results indicated that the mixtures have different CBWP MJ/MPa values relative to the control mixture (M1).

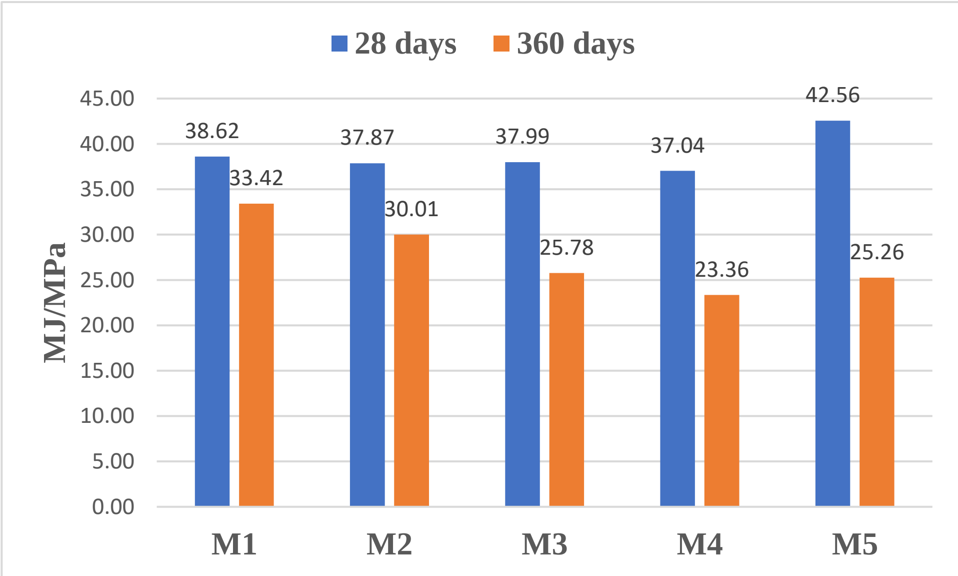

Figure 15. MJ/MPa.

According to the obtained results from the LCA (Figures 1–15), it can be clearly stated that from an environmental point of view, CBWP is a viable alternative to cement and can significantly contribute to reducing the overall negative environmental impacts associated with SSC production.

7. Conclusions

Based on a review of previous studies on the effect of using brick waste as a cementitious material, the following can be concluded:

1. Brick waste consists mainly of aluminates and silicates, and the sum of the basic oxides is in accordance with the specifications of ASTM C618. Therefore, brick waste can be considered a pozzolanic material.
2. Although very few studies have examined it, the proportion of the glass phase in the CBWP is relatively low, which explains the weak pozzolanic activity at early ages.
3. CBWP can be used in proportions of 5 to 15% without significantly affecting the workability of SCC.
4. Increased use of the superplasticizer improves the workability of CBWP-based SCC and reduces shear stresses. However, this is not recommended, as from an environmental point of view, increasing the superplasticizer could significantly increase the CO_2 footprint along with the cost of SCC.
5. Increased grinding reduces the sharp angles of the granules and makes them tend to be spherical, thus improving the workability.
6. The upper limit for the use of brick waste is 10% to ensure that the mechanical performance (compressive, tensile and flexural strengths) is equivalent or slightly higher than that of SCC-free CBWP, and this effect appears at later ages (greater or equal to 90 days).
7. The use of CBWP improved the durability properties (water absorption and shrinkage) of SCC at later ages, and it did not negatively affect the sulfate resistance. However, it causes an increase in the carbonation depth as a result of its pozzolanic activity.
8. LCA was conducted to quantify the environmental impacts of different components of SCC. The results of the LCA indicated that cement has the largest impact among other ingredients of the SCC.
9. Replacing the cement partially with CBWP resulted in a reduction in the environmental impacts of SCC.

10. If the mechanical properties (compressive strength (MPa)) of SCC are taking into consideration in the calculation of the optimum CBWP content, the results indicated that replacing the cement with 37.5% CBWP provided the lowest environmental impacts per strength unit (MPa).

8. Future Works

The followings are some suggestions for future works:

1. Critically reviewing the effect of using CBWP in SCC on non-destructive tests such as ultra-sonic pulse velocity test and rebound hammer test.
2. Considering the post-use, transportation, and end of use of SCC in the calculations of LCA.

Author Contributions: Conceptualization, M.S.N., A.S. and R.J.G.; validation, A.J.S., Z.A.-k., Z.A.H. and S.A.-M.; formal analysis, A.J.S.; investigation, M.S., T.M.H., R.J.G. and A.J.S.; resources, A.J.S. and Z.A.-k.; writing—original draft preparation, M.S.N., Z.A.-k. and A.J.S.; writing—review and editing, M.S.N., A.S. and R.J.G.; visualization, A.J.S., Z.A.H., Z.A.-k. and S.A.-M.; supervision, M.S.N.; project administration, M.S.N and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within this article.

Acknowledgments: The authors would like to thank Al-Mustaqbal University College and Al-Furat Al-Awsat Technical University for providing technical support for this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Environment, U.N.; Scrivener, K.L.; John, V.M.; Gartner, E.M. Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cem. Concr. Res.* **2018**, *114*, 2–26.
2. Nasr, M.S.; Ali, I.M.; Hussein, A.M.; Shubbar, A.A.; Kareem, Q.T.; AbdulAmeer, A.T. Utilization of locally produced waste in the production of sustainable mortar. *Case Stud. Constr. Mater.* **2020**, *13*, e00464. [CrossRef]
3. Habert, G.; Miller, S.A.; John, V.M.; Provis, J.L.; Favier, A.; Horvath, A.; Scrivener, K.L. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat. Rev. Earth Environ.* **2020**, *1*, 559–573. [CrossRef]
4. Tam, V.W.Y.; Soomro, M.; Evangelista, A.C.J. A review of recycled aggregate in concrete applications (2000–2017). *Constr. Build. Mater.* **2018**, *172*, 272–292. [CrossRef]
5. Kisku, N.; Joshi, H.; Ansari, M.; Panda, S.K.; Nayak, S.; Dutta, S.C. A critical review and assessment for usage of recycled aggregate as sustainable construction material. *Constr. Build. Mater.* **2017**, *131*, 721–740. [CrossRef]
6. Díaz, Y.C.; Berriel, S.S.; Heierli, U.; Favier, A.R.; Machado, I.R.S.; Scrivener, K.L.; Hernández, J.F.M.; Habert, G. Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies. *Dev. Eng.* **2017**, *2*, 82–91. [CrossRef]
7. Tayeh, B.A.; Hadzima-Nyarko, M.; Zeyad, A.M.; Al-Harazin, S.Z. Properties and durability of concrete with olive waste ash as a partial cement replacement. *Adv. Concr. Constr.* **2021**, *11*, 59–71.
8. Letelier, V.; Henríquez-Jara, B.I.; Manosalva, M.; Parodi, C.; Ortega, J.M. Use of waste glass as a replacement for raw materials in mortars with a lower environmental impact. *Energies* **2019**, *12*, 1974. [CrossRef]
9. Adesina, A. Recent advances in the concrete industry to reduce its carbon dioxide emissions. *Environ. Chall.* **2020**, *1*, 100004. [CrossRef]
10. Shubbar, A.A.F.; Jafer, H.M.; Dulaimi, A.F.D.; Atherton, W.; Al-Rifaie, A. The Development of a Low Carbon Cementitious Material Produced from Cement, Ground Granulated Blast Furnace Slag and High Calcium Fly Ash. *Int. J. Civ. Environ. Struct. Constr. Archit. Eng.* **2017**, *11*, 905–908.
11. Nasr, M.S.; Hasan, Z.A.; Abed, M.K.; Dhahir, M.K.; Najim, W.N.; Shubbar, A.A.; Dhahir, H.Z. Utilization of High Volume Fraction of Binary Combinations of Supplementary Cementitious Materials in the Production of Reactive Powder Concrete. *Period. Polytech. Civ. Eng.* **2021**, *65*, 335–343. [CrossRef]
12. Atef, M.; Bassioni, G.; Azab, N.; Abdellatif, M.H. Assessment of cement replacement with fine recycled rubber particles in sustainable cementitious composites. *J. Mech. Behav. Mater.* **2021**, *30*, 59–65. [CrossRef]
13. Hamad, M.A.; Nasr, M.; Shubbar, A.; Al-Khafaji, Z.; Al Masoodi, Z.; Al-Hashimi, O.; Kot, P.; Alkhaddar, R.; Hashim, K. Production of Ultra-High-Performance Concrete with Low Energy Consumption and Carbon Footprint Using Supplementary Cementitious Materials Instead of Silica Fume: A Review. *Energies* **2021**, *14*, 8291. [CrossRef]

14. Hawileh, R.A.; Abdalla, J.A.; Fardmanesh, F.; Shahsana, P.; Khalili, A. Performance of reinforced concrete beams cast with different percentages of GGBS replacement to cement. *Arch. Civ. Mech. Eng.* **2017**, *17*, 511–519. [CrossRef]
15. Tayeh, B.A.; Hasaniyah, M.W.; Zeyad, A.M.; Awad, M.M.; Alaskar, A.; Mohamed, A.M.; Alyousef, R. Durability and mechanical properties of seashell partially-replaced cement. *J. Build. Eng.* **2020**, 101328. [CrossRef]
16. Aziz, M.A.; Zubair, M.; Saleem, M.; Alharthi, Y.M.; Ashraf, N.; Alotaibi, K.S.; Aga, O.; Al Eid, A.A.A. Mechanical, non-destructive, and thermal characterization of biochar-based mortar composite. *Biomass Convers. Biorefinery* **2023**, 1–14. [CrossRef]
17. Sakir, S.; Raman, S.N.; Kaish, A.B.M.A. Utilization of By-Products and Wastes as Supplementary Cementitious Materials in Structural Mortar for Sustainable Construction. *Sustainability* **2020**, *12*, 3888. [CrossRef]
18. Kubba, H.Z.; Nasr, M.S.; Al-Abdaly, N.M.; Dhahir, M.K.; Najim, W.N. Influence of Incinerated and Non-Incinerated waste paper on Properties of Cement Mortar. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *671*, 012113. [CrossRef]
19. Adesina, A.; Awoyera, P. Overview of trends in the application of waste materials in self-compacting concrete production. *SN Appl. Sci.* **2019**, *1*, 962. [CrossRef]
20. Bektas, F.; Turanli, L.; Wang, K.; Ceylan, H. Comparative performance of ground clay brick in mitigation of alkali–silica reaction. *J. Mater. Civ. Eng.* **2007**, *19*, 1070–1078. [CrossRef]
21. Zheng, L.; Ge, Z.; Yao, Z.Y.; Sun, R.J.; Dong, J.G. The properties of concrete with recycled clay-brick-powder. *Appl. Mech. Mater.* **2011**, *99*, 826–831. [CrossRef]
22. Zhao, Y.; Gao, J.; Xu, Z.; Li, S.; Luo, X.; Chen, G. Long-term hydration and microstructure evolution of blended cement containing ground granulated blast furnace slag and waste clay brick. *Cem. Concr. Compos.* **2021**, *118*, 103982. [CrossRef]
23. Schackow, A.; Stringari, D.; Senff, L.; Correia, S.L.; Segadães, A.M. Influence of fired clay brick waste additions on the durability of mortars. *Cem. Concr. Compos.* **2015**, *62*, 82–89. [CrossRef]
24. Li, H.; Dong, L.; Jiang, Z.; Yang, X.; Yang, Z. Study on utilization of red brick waste powder in the production of cement-based red decorative plaster for walls. *J. Clean. Prod.* **2016**, *133*, 1017–1026. [CrossRef]
25. Al-Hadithi, A.I.; Hilal, N.N. The possibility of enhancing some properties of self-compacting concrete by adding waste plastic fibers. *J. Build. Eng.* **2016**, *8*, 20–28. [CrossRef]
26. Shi, C.; Wu, Z.; Lv, K.; Wu, L. A review on mixture design methods for self-compacting concrete. *Constr. Build. Mater. J.* **2015**, *84*, 387–398. [CrossRef]
27. Zhang, H.; Yuan, H.; Ge, Z.; Wu, J.; Fang, C.; Schlangen, E.; Šavija, B. Fresh and hardened properties of self-compacting concrete containing recycled fine clay brick aggregates. *Mater. Struct.* **2021**, *54*, 159. [CrossRef]
28. Sun, C.; Chen, Q.; Xiao, J.; Liu, W. Utilization of waste concrete recycling materials in self-compacting concrete. *Resour. Conserv. Recycl.* **2020**, *161*, 104930. [CrossRef]
29. Gupta, N.; Siddique, R.; Belarbi, R. Sustainable and greener self-compacting concrete incorporating industrial by-products: A review. *J. Clean. Prod.* **2021**, *284*, 124803. [CrossRef]
30. Kumar, K.R.; Shyamala, G.; Awoyera, P.O.; Vedhasakthi, K.; Olalusi, O.B. Cleaner production of self-compacting concrete with selected industrial rejects-an overview. *Silicon* **2021**, *13*, 2809–2820. [CrossRef]
31. Duan, Z.; Singh, A.; Xiao, J.; Hou, S. Combined use of recycled powder and recycled coarse aggregate derived from construction and demolition waste in self-compacting concrete. *Constr. Build. Mater.* **2020**, *254*, 119323. [CrossRef]
32. Gautam, L.; Jain, J.K.; Jain, A.; Kalla, P. Valorization of bone-china ceramic powder waste along with granite waste in self-compacting concrete. *Constr. Build. Mater.* **2022**, *315*, 125730. [CrossRef]
33. Li, L.G.; Lin, Z.H.; Chen, G.M.; Kwan, A.K.H. Reutilizing clay brick dust as paste substitution to produce environment-friendly durable mortar. *J. Clean. Prod.* **2020**, *274*, 122787. [CrossRef]
34. Huarachi, D.A.R.; Goncalves, G.; de Francisco, A.C.; Canteri, M.H.G.; Piekarski, C.M. Life cycle assessment of traditional and alternative bricks: A review. *Environ. Impact Assess. Rev.* **2020**, *80*, 106335. [CrossRef]
35. Standardization, I.O. *Environmental Management: Life Cycle Assessment; Requirements and Guidelines*; ISO: Geneva, Switzerland, 2006; Volume 14044.
36. Seco, A.; Omer, J.; Marcelino, S.; Espuelas, S.; Prieto, E. Sustainable unfired bricks manufacturing from construction and demolition wastes. *Constr. Build. Mater.* **2018**, *167*, 154–165. [CrossRef]
37. De Miranda Santos, S.D.F.O.; Piekarski, C.M.; Ugaya, C.M.L.; Donato, D.B.; Braghini Júnior, A.; De Francisco, A.C.; Carvalho, A.M.M.L. Life cycle analysis of charcoal production in masonry kilns with and without carbonization process generated gas combustion. *Sustainability* **2017**, *9*, 1558. [CrossRef]
38. Buyle, M.; Braet, J.; Audenaert, A. Life cycle assessment in the construction sector: A review. *Renew. Sustain. Energy Rev.* **2013**, *26*, 379–388. [CrossRef]
39. Boucherit, D.; Debiebt, F.; Kenai, S.; Khalfaoui, M.A.; Chellali, S. Experimental Study on Marble and Brick Powders as Partial Replacement of Cement in Self-compacting Mortar. *Curr. Mater. Sci. Former. Recent Pat. Mater. Sci.* **2020**, *13*, 45–57. [CrossRef]
40. Abib, Z.E.; Gaher-Abib, H.; Kharchi, F. Effect of clay fines on the behavior of self-compacting concrete. *Engineering* **2013**, *5*, 213–218. [CrossRef]
41. Mansor, A.M.; Hamed, A.M.M.; Borg, R.P. Effect of fine clay brick waste on the properties of self compacting concrete. *Alex. Eng. J.* **2016**, 1–7.
42. Aliabdo, A.A.; Abd-Elmoaty, A.-E.M.; Hassan, H.H. Utilization of crushed clay brick in concrete industry. *Alex. Eng. J.* **2014**, *53*, 151–168. [CrossRef]

43. He, Z.; Shen, A.; Wu, H.; Wang, W.; Wang, L.; Yao, C.; Wu, J. Research progress on recycled clay brick waste as an alternative to cement for sustainable construction materials. *Constr. Build. Mater.* **2021**, *274*, 122113. [CrossRef]
44. Lam, M.N.-T.; Nguyen, D.-T.; Nguyen, D.-L. Potential use of clay brick waste powder and ceramic waste aggregate in mortar. *Constr. Build. Mater.* **2021**, *313*, 125516. [CrossRef]
45. Kolawole, J.T.; Olusola, K.O.; Babafemi, A.J.; Olalusi, O.B.; Fanijo, E. Blended cement binders containing bamboo leaf ash and ground clay brick waste for sustainable concrete. *Materialia* **2021**, *15*, 101045. [CrossRef]
46. Shao, J.; Gao, J.; Zhao, Y.; Chen, X. Study on the pozzolanic reaction of clay brick powder in blended cement pastes. *Constr. Build. Mater.* **2019**, *213*, 209–215. [CrossRef]
47. Ouyang, X.; Wang, L.; Fu, J.; Xu, S.; Ma, Y. Surface properties of clay brick powder and its influence on hydration and strength development of cement paste. *Constr. Build. Mater.* **2021**, *300*, 123958. [CrossRef]
48. Zhao, Y.; Gao, J.; Liu, C.; Chen, X.; Xu, Z. The particle-size effect of waste clay brick powder on its pozzolanic activity and properties of blended cement. *J. Clean. Prod.* **2020**, *242*, 118521. [CrossRef]
49. Şahmaran, M.; Christianto, H.A.; Yaman, İ.Ö. The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars. *Cem. Concr. Compos.* **2006**, *28*, 432–440. [CrossRef]
50. Karatas, M.; Turk, K.; Acikgenc, M.; Ulucan, Z.C. Effect of elazig region waste brick powder on strength and viscosity properties of self compacting mortar. In Proceedings of the 9th International Congress on Advances in Civil Engineering, Trabzon, Turkey, 27–30 September 2010.
51. Heikal, M.; Zohdy, K.M.; Abdelkreem, M. Mechanical, microstructure and rheological characteristics of high performance self-compacting cement pastes and concrete containing ground clay bricks. *Constr. Build. Mater.* **2013**, *38*, 101–109. [CrossRef]
52. Irki, I.; Debieb, F.; Ouzadid, S.; Dilmi, H.L.; Settari, C.; Boukhelkhel, D. Effect of Blaine fineness of recycling brick powder replacing cementitious materials in self compacting mortar. *J. Adhes. Sci. Technol.* **2018**, *32*, 963–975. [CrossRef]
53. Silva, Y.F.; Lange, D.A.; Delvasto, S. Effect of incorporation of masonry residue on the properties of self-compacting concretes. *Constr. Build. Mater.* **2019**, *196*, 277–283. [CrossRef]
54. Si-Ahmed, M.; Kenai, S. Behavior of self-compacting mortars based on waste brick powder. *Curr. Mater. Sci. Former. Recent Pat. Mater. Sci.* **2020**, *13*, 39–44. [CrossRef]
55. Shah, M.U.; Usman, M.; Hanif, M.U.; Naseem, I.; Farooq, S. Utilization of Solid Waste from Brick Industry and Hydrated Lime in Self-Compacting Cement Pastes. *Materials* **2021**, *14*, 1109. [CrossRef]
56. Zhao, Z.; Grellier, A.; Bouarroudj, M.E.K.; Michel, F.; Bulteel, D.; Courard, L. Substitution of limestone filler by waste brick powder in self-compacting mortars: Properties and durability. *J. Build. Eng.* **2021**, *43*, 102898. [CrossRef]
57. Sun, R.; Huang, D.; Ge, Z.; Hu, Y.; Guan, Y. Properties of self-consolidating concrete with recycled clay-brick-powder replacing cementitious material. *J. Sustain. Cem. Mater.* **2014**, *3*, 211–219. [CrossRef]
58. Amjadi, R.; Monazami, M.; Mohseni, E.; Azar Balgouri, H.; Ranjbar, M.M. Effectiveness of different recycled materials in self-compacting mortar. *Eur. J. Environ. Civ. Eng.* **2017**, *21*, 1485–1501. [CrossRef]
59. Abdulrazzaq, O.A. Effect of Clay Bricks Powder on the Fresh and Hardened Properties of Self-Compacting Concrete. *Iraqi J. Civ. Eng.* **2018**, *12*, 78–89.
60. Silva, Y.F.; Delvasto, S. Sulfate attack resistance of self-compacting concrete with residue of masonry. *Constr. Build. Mater.* **2021**, *268*, 121095. [CrossRef]
61. Silva, Y.F.; Delvasto, S. Durability of self-compacting concrete with addition of residue of masonry when exposed to carbonation and chlorides mediums. *Constr. Build. Mater.* **2021**, *297*, 123817. [CrossRef]
62. Dehestani, M.; Nikbin, I.M.; Asadollahi, S. Effects of specimen shape and size on the compressive strength of self-consolidating concrete (SCC). *Constr. Build. Mater.* **2014**, *66*, 685–691. [CrossRef]
63. Silva, Y.F.; Delvasto, S.; Izquierdo, S.; Araya-Letelier, G. Short and long-term physical and mechanical characterization of self-compacting concrete made with masonry and concrete residue. *Constr. Build. Mater.* **2021**, *312*, 125382. [CrossRef]
64. Zain, M.F.M.; Mahmud, H.B.; Ilham, A.; Faizal, M. Prediction of splitting tensile strength of high-performance concrete. *Cem. Concr. Res.* **2002**, *32*, 1251–1258. [CrossRef]
65. Meisuh, B.K.; Kankam, C.K.; Buabin, T.K. Effect of quarry rock dust on the flexural strength of concrete. *Case Stud. Constr. Mater.* **2018**, *8*, 16–22. [CrossRef]
66. Nasr, M.S.; Hussain, T.H.; Kubba, H.Z.; Shubbar, A.A. Influence of using high volume fraction of silica fume on mechanical and durability properties of cement mortar. *J. Eng. Sci. Technol.* **2020**, *15*, 2492–2506.
67. Robayo-Salazar, R.A.; Mejía-Arcila, J.M.; de Gutiérrez, R.M. Eco-efficient alkali-activated cement based on red clay brick wastes suitable for the manufacturing of building materials. *J. Clean. Prod.* **2017**, *166*, 242–252. [CrossRef]
68. Marcelino-Sadaba, S.; Kinuthia, J.; Oti, J.; Meneses, A.S. Challenges in Life Cycle Assessment (LCA) of stabilised clay-based construction materials. *Appl. Clay Sci.* **2017**, *144*, 121–130. [CrossRef]
69. Cape, J.N.; Fowler, D.; Davison, A. Ecological effects of sulfur dioxide, fluorides, and minor air pollutants: Recent trends and research needs. *Environ. Int.* **2003**, *29*, 201–211. [CrossRef]
70. Freitas, F.F.; Furtado, A.C.; Piñas, J.A.V.; Venturini, O.J.; Barros, R.M.; Lora, E.E.S. Holistic Life Cycle Assessment of a biogas-based electricity generation plant in a pig farm considering co-digestion and an additive. *Energy* **2022**, *261*, 125340. [CrossRef]

71. Movilla-Quesada, D.; Lagos-Varas, M.; Raposeiras, A.C.; Muñoz-Cáceres, O.; Andrés-Valeri, V.C.; Aguilar-Vidal, C. Analysis of greenhouse gas emissions and the environmental impact of the production of asphalt mixes modified with recycled materials. *Sustainability* **2021**, *13*, 8081. [CrossRef]
72. Di Filippo, R.; Bursi, O.S.; Di Maggio, R. Global warming and ozone depletion potentials caused by emissions from HFC and CFC banks due to structural damage. *Energy Build.* **2022**, *273*, 112385. [CrossRef]