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Exploring Sustainable Construction: Utilizing Printed Circuit Board Waste as a Partial Sand Replacement in Concrete Production

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Abstract

The escalating demand for concrete in construction, coupled with the environmental degradation caused by sand extraction, necessitates the exploration of alternative materials for sustainable construction practices. This study investigates the potential of utilizing Printed Circuit Board (PCB) waste as a partial replacement for sand in concrete production. This investigation is presented through experimental work to replace the sand by 10%, 20%, and 30% by volume. The applicability of the proposed mixes is demonstrated through a comparative analysis of the concrete fresh and hardened properties. This research contributes to the field of sustainable construction by offering a novel use for electronic waste, thereby mitigating the environmental impact of both the electronics and construction industries.

Keywords

Concrete; Printed Circuit Board; Sand Replacement; Sustainability

1. Introduction

Today, e-waste has become the fastest-growing waste stream in both developed and developing countries with a low degree of recycling. In the last quarter of the twentieth century, there was a technological breakthrough in electronic and electrical science. This breakthrough led to develop new electric and electronic equipment (EEE) to be sold to consumers. As technology advances rapidly, the lifecycle of electronic devices tends to shorten due to several factors including planned obsolescence, consumer demand for the latest technology, and rapid advancements in technology that make older devices obsolete (Krumay & Brandtweiner, 2016). This dynamic contributes to an increasing amount of e-waste globally (Krumay & Brandtweiner, 2016). In 2019, e-waste generated around the globe was estimated to be 53.6 million metric tons which corresponds to 7.3 Kg per capita. The global share of documented, collected, and recycled e-waste was just 17.4% of all e-waste while the remaining was dumped, traded, or burned causing serious damage to the environment (Van Yken et al., 2021). As for the recycled e-waste, recycling recovers the different valuable materials that the EEE devices are made of such as metals (tin, copper, zinc, aluminium), rare earth elements (cerium, neodymium, praseodymium), and precious metals (platinum, palladium, silver, gold), however, the process of complete extraction of the rest of the components are is still hard and expensive (Li et al., 2019; Sethurajan et al., 2019).

Among the EEE wastes, printed circuit boards (PCB) are considered the most valuable components due to their high precious and base metal content. The specific composition of PCBs varies based on their intended use and typically consists of metals (40%), plastics (30%), and ceramics (30%), making them highly diverse heterogeneous material that is hardly recycled (Van Yken et al., 2021). Recycling of PCB may include incineration (to reduce their volume for disposal), chemical treatment (to detoxify the disposed materials), thermal treatment following the incineration (thermal decomposition), or Bioremediation (detoxifying the PCB using microorganisms) (Duan et al., 2011). However, such recycling scenarios entail limitations for the complete safe disposal of the PCBs. These limitations commit to preparing properly insulated landfills for the recycled PCB to ensure the prevention of any harmful leaks to the surrounding environment (soil and groundwater). As such, some researchers proposed using PCB in the concrete industry as a replacement or addition, as a means of safe disposal for such harmful material. However, there is no solid recommendation for such an application due to the limited data availability.

Therefore, this paper explores the potential of utilizing PCB waste as a partial replacement for fine aggregates in concrete production. This investigation aims to extend the knowledge of safe disposal for the PCB instead of having special landfills. The investigation is presented through experimental work to assess the fresh and hardened properties of concrete with different PCB-sand replacement percentages. The investigated mixes were developed by replacing the sand by 10%, 20%, and 30% by volume. The presented work, not only mitigates the environmental impact by reducing landfill use, reducing toxic fumes resulting from PCB incineration, and conserving natural resources but also addresses the disposal issues of hazardous materials by transforming them into valuable construction inputs.

2. Literature Review

Sua-iam and Chatveera (2022) explored the feasibility of utilizing PCB dust as a cement replacement in self-compacting concrete. Their investigation was conducted through assessing the effect of cement replacement by 5, 10, 15, 20, 25, and 30% by volume. Sua-iam and Chatveera concluded that the PCB cement replacement is inversely proportional to the concrete workability and compressive strength. However, replacing the cement by 20% is still viable and can produce more than 50Mpa in 180 days. Also, Sua-iam and Chatveera highlighted the environmental and economic added value of using PCB as cement replacement (Sua-iam & Chatveera, 2022).

Pianchaiyaphum et al. (2021) tested the Non-metallic printed circuit board waste (NMPCB) (i.e., residue resulting from the copper recovery process of PCB) as a substitute for fine aggregates in the production of interlocking concrete blocks. The authors investigated the impact of including non-metallic fraction (NMF) residues at varying percentages (0%, 5%, 10%, 15%, and 20%) on the properties of the interlocking concrete blocks, such as density, water absorption, and compressive strength. The study found that incorporating NMF residue into concrete blocks affected their physical and mechanical properties, with a recommendation that up to 10% replacement could be environmentally beneficial without significantly compromising the structural integrity of the concrete blocks (Pianchaiyaphum et al., 2021). Similarly, Kariminia et al. (2014) proposed utilizing the NMPCB as a replacement for coarse aggregate in concrete. Their study explored replacing 5, 10, 15, and 20% by weight of coarse aggregate in control concrete with NMPCB material. However, their research finding concluded that replacing coarse aggregate with NMPCB negatively affected the concrete compressive strength and elasticity.

Ganesh et al. (2021) used crushed PCB as a fine aggregate replacement by 3, 5, 10, 15, 20, and 25% by weight in concrete. Their test included the assessment of fresh (i.e., slump) and hardened properties of concrete (i.e., compressive, flexural, and tensile splitting strength). The results showed a reduction in the concrete slump as the PCB percentage increased, whereas the concrete hardened properties showed a declining trend as the PCB percentage increased except for the 15% replacement that showed enhanced performance compared to the control mix (Ganesh et al., 2021).

Pothinathan et al. (2019) explored the potential of using PCB as a partial substitute for coarse aggregate in concrete. The investigation includes an assessment of compressive strength, durability, and self-compacting properties, with PCB replacement of 0, 5, 10, 15, and 20% by volume of coarse aggregate. They concluded that 5% replacement of PCBs as coarse aggregate can achieve comparable strength and performance to conventional concrete. Moreover, they concluded that the density of the concrete is inversely proportional to the PCB percentage (Pothinathan et al., 2019).

Premur et al. (2016) investigated the potential of incorporating Vitroplast, derived from waste-printed circuit boards, into concrete as a replacement for fine aggregates. Premur et al. (2016) substituted the sand by 5, 10, 15, and 20% by weight and assessed the concrete compressive strength and environmental safety. They observed a declining trend in compressive strength with an increase in replacement percentages. Moreover, they tested the solubility of the ground concrete to assess the hazardous impact of using the Vitroplast. However, they concluded that 10% replacement still leads to safe concrete (below the allowable limits of inert waste) (Premur et al., 2016).

3. Methodology

To assess the applicability of using PCB as sand replacement for concrete, four different concrete mixes were tested to assess their fresh and hardened properties. The four mixes included a control design concrete that was designed to reach 25Mpa according to British Standards and three similar mixes with PCB sand replacement by 10, 20, and 30% by volume. The following subsections briefly describe the conducted experimental program addressing the test matrix, material properties, mix design, and procedure.

Test Matrix

The test matrix included the testing of twenty-four standard cubes (150×150×150mm) to test the concrete compressive strength for the four mixes after seven and twenty-eight days of curing in water. Also, the test matrix included twelve beams of (100×100×500) to be tested through a three-point bending test to assess the concrete flexure tensile strength.

Material properties

Cement

Ordinary Portland cement of grade 42.5N was used in this investigation for all the developed mixes. The initial setting time was estimated to be 90 minutes, while the final setting time was four and a half hours.

Aggregate

Both fine and coarse aggregates were washed and sundried for 48 hours to ensure their cleanliness. The densities for both fine and coarse aggregate were 1513, and 1282 kg/m^3 respectively with well-graded structures as depicted in Figure 1.

PCB

The PCB used in this research is considered the bi-product of recycling e-waste. The used PCB is obtained after removing all the valuable metallic materials such as copper, aluminum, and iron. Such separation results in crushed nonmetallic materials composed of epoxy and fiber which cannot be recycled. Usually, the nonmetallic PCB materials are dumbed and burned causing significant environmental impacts. In this research, the collected PCB nonmetallic materials were crushed into fine particles through an industrial recycling production line (i.e., with smaller particle sizes than the sand used as shown in Figure 1). It is worth mentioning that the used PCB is currently dumped in a landfill which doesn't add additional cost for the proposed mixes. The used PCB had a relative density of 493 kg/m^3. Moreover, an absorption for the used PCB was 55% following the ASTM standard test (ASTM D570, 2022), which means that the used nonmetallic material can be classified as a hydrophilic material. Figure 2 depicts the conducted absorption test showing the uneven dispersion of the PCB particles and their hydrophilic property. Moreover, the chemical composition of the used PCB has been verified through an XRD test conducted at the Higher Research Institute in Egypt. The results showed that 23.58% of the used PCB was composed of copper oxide (CuO)and 14.88% of silicon dioxide ($SiO2$). Whereas the loss of ignition (LOI) was 40.95% which may cause chemical leaks after burning in the landfills highlights the significance of the proposed PCB safe disposal in the concrete. Table 1 summarizes the chemical composition of the used PCB.

Table 1: XRD results for the used PCB material

Main Constituents	(Wt%)
LOI	40.95
CuO	23.58
SiO2	14.88
Al2O3	8.06
Br	4.99
CaO	3.11
MgO	0.87
SnO2	0.656
Cl	0.57
Fe2O3	0.47
TiO2	0.43
ZnO	0.145
PbO	0.144
BaO	0.225
P2O5	0.22
SrO	0.066
MnO	0.067
Ag2O	0.024
ZrO2	0.027
NiO	0.028
SO3	0.09
Sb2O3	0.112
K2O	0.02
Na2O	0.24
CO3O4	0.007
Cr2O3	0.008

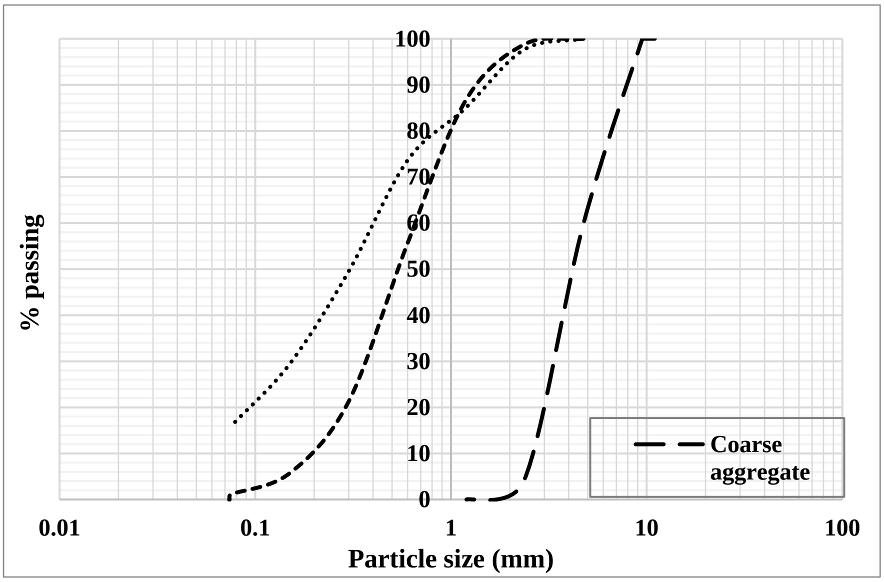

Figure 1: Sieve analysis results for the coarse, fine aggregates and the used PCB

Figure 2: Absorption test for the used PCB

Mix design and procedure

The control mix was designed to reach 25MPa at 28 days with a water-cement ratio of 0.58. As for the other three mixes, the water-cement ratios were kept constant while the fine aggregates were replaced by volume. The replacement was simply conducted by applying the ratio of the measured relative densities. Table 2 summarizes the mixing proportions for all the proposed mixes. The mixing procedure was similar for the four mixes. The mixes were named as control, or "B" followed by a number representing the PCB volume percentage. The mixing procedure started with a dry mix of cement with the coarse and fine aggregates for two minutes. Then the mixing continued for ten minutes while adding the water in portions (three times). As for the PCB, the PCB was treated as the fine aggregates where it was added in the initial dry mix. It is worth mentioning that the PCB weight was calculated based on the measured specific gravity of the PCB compared to the fine aggregate.

Table 2: Concrete mixing proportions

	Cement (Kg)	Water (liter)	Coarse Aggregate (Kg)	Fine Aggregate (Kg)	PCB (Kg)
Control	328	190	1148	756	0
B10	328	190	1148	680	24
B20	328	190	1148	605	48
B30	328	190	1148	529	73

4. Results and discussion

Fresh properties

Slump test

The standard slump test was performed for the four design mixes (i.e., for every mixing batch). All the mixes showed a true slump except for the mix with 30% replacement which showed zero slump. Generally, the PCB replacement had an inverse relationship with the concrete slump as shown in Figure 3. This observation can be attributed to the high absorption rate of the used PCB which absorbs the excess water responsible for the concrete workability.

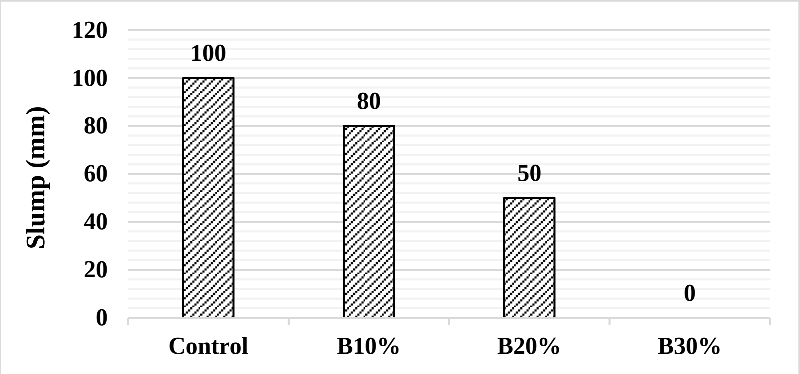

Figure 3: Slump test results

Hardened properties

Compressive strength

The concrete compressive strength was measured for the mixed concrete at 7 and 28 days to assess the impact of using PCB as fine aggregate replacement. Three cubes were tested for each of the design mixes at both testing times and their average is summarized in Figure 4. Principally, all the design mixes showed a similar trend of increasing the compressive strength from 7 to 28 days by around 35% which is within the common range of strength gain. Moreover, PCB replacement showed a reduction in the concrete compressive strength at both 7 and 28 days for the 10 and 30% compared to the control mix. However, the 20% replacement showed almost the same compressive strength compared to the control mix.

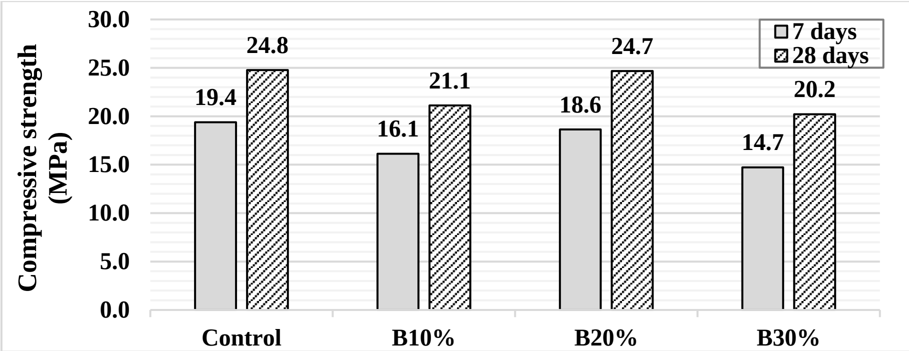

Figure 4: Compressive test results

Flexural tensile strength

The concrete flexure tensile strength was determined by averaging the results of three flexural tensile tests (i.e., three-point bending) as summarized in Figure 5. The tests were conducted at the age of 28 days. The results showed a reduction in the flexural tensile strength of the concrete with the PCB replacement, however, the results also showed an improvement in the flexural tensile strength as the PCB percentage increased. The mix with 30% replacement showed a comparable flexural tensile strength compared to the control mix with a 5% reduction (from 5.9 to 5.6 MPa). However, the 20% reduction showed a 20% reduction in the concrete flexural capacity which may still be applicable for several structural and nonstructural applications.

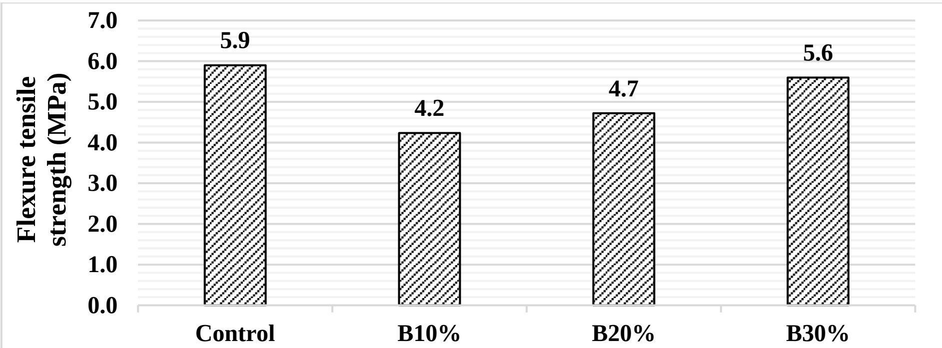

Figure 5: Flexural tensile strength test results

5. Conclusions

This paper explores the potential of utilizing PCB waste as a partial replacement for fine aggregates in concrete production. The presented investigation was conducted through experimental work assessing the fresh and hardened properties of concrete with varying PCB-sand replacement percentages (10, 20, and 30%). The presented work presents a safe disposal method for PCB which is usually dumped in landfills.

One of the key findings of this study was the inverse relationship between concrete workability and the PCB replacement percentage. Such a finding was backed by the high absorption rate of the used PCB (55%). The concrete with 20% PCB replacement is considered viable without significantly compromising structural integrity. Specifically, a 20% replacement by volume maintains comparable compressive strength to the control mix, with a reduction in the tensile flexural strength by 20%. Although challenges remain in optimizing the material properties and overcoming limitations associated with the use of PCB in concrete, the study sets a foundational framework for future investigations aimed at refining the application of e-waste materials in the construction industry.

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Ethics approval

Not applicable.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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