PEF-ACCELERATED CURING ON COMPRESSIVE STRENGTH OF CEMENT COMPOSITES

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Abstract

This study investigates the accelerated curing of cement composite materials using Pulsed Electric Field (PEF) technology. The mechanical and physical properties of cement blended with Biomass Ash (BA) and Recycled Concrete Aggregate (RCA) were evaluated to enhance the sustainability of construction materials. The accelerated curing was performed by applying a PEF at an electric field intensity of 1 kV/cm with BA and RCA contents ranging from 0 to 20% by weight (wt.%). Curing durations varied from 0 to 50 minutes at room temperature (25 ± 2°C), followed by standard 28-day water curing. During PEF treatment, the internal temperature increased from 35°C to 64°C due to electro-thermal conversion. The compressive strength of specimens incorporated with 5 wt.% BA showed a reduction (20–24 MPa), with a more significant decrease observed at higher BA contents (10–20 wt.%, 13–14 MPa). In contrast, cement blended with RCA maintained higher structural integrity; the compressive strength decreased slightly during the first 20 minutes and remained constant at approximately 32 MPa up to 50 minutes. Comparative results reveal that cement blended with BA exhibited a lower density and greater strength degradation compared to RCA-blended composites. The reduction in strength at extended durations is attributed to microstructural defects and increased porosity. Overall, the findings indicate that while PEF effectively accelerates the hydration process, optimizing curing duration is critical to avoid the 'shell effect' and maintain mechanical performance. PEF curing shows promise for developing high-performance, sustainable cement materials by utilizing industrial waste efficiently.

Keywords: Accelerated curing, Biomass ash, Pulsed Electric Field (PEF), Recycled concrete aggregate, Sustainable construction materials

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Introduction

The application of PEF represents a promising alternative for accelerated cement curing in the future. This method has the potential to replace conventional acceleration techniques, which predominantly rely on thermal energy or microwave radiation to increase temperature and enhance the mechanical strength of cement materials (Che et al., 2025; Nepomnyashchev, & Titov., 2023; Ma et al., 2023; Wang et al., 2023). Thermal curing methods, such as steam curing, typically require high energy consumption and may present certain disadvantages. Elevated temperatures accelerate the hydration process between cement and water, potentially leading to microcracking due to rapid heat transfer. These microcracks can adversely affect the mechanical and physical properties of cement materials, compromising their long-term durability. In line with global trends toward sustainable construction, the integration of industrial and agricultural waste into cement systems has gained significant attention. In this study, Biomass Ash (BA) and Recycled Concrete Aggregate (RCA) were selected as supplementary materials to promote a circular economy and reduce the environmental impact associated with waste disposal. BA, sourced from rubberwood combustion, and RCA, derived from crushed concrete, are promising for sustainable applications; however, their incorporation often leads to slower initial strength development compared to traditional Portland cement. Accelerated curing using PEF enables control over the intensity of the electric field and curing duration, thereby promoting the hydration process between cement and water. This approach allows for a significant reduction in construction time without inducing thermal stress commonly associated with conventional steam curing methods. According to studies employing Direct Electric Curing (DEC), strength development within just one day can be comparable to that achieved through standard curing processes over 28 days (Che et al., 2025; Nepomnyashchev, & Titov., 2023). Therefore, the application of PEF is expected to enhance the hydration kinetics and overcome the limitations of waste-blended cements. Consequently, the research team initiated a preliminary investigation into the use of PEF technology for accelerated curing of cement composites containing BA and RCA to evaluate their preliminary mechanical properties and potential for high-performance sustainable materials.

Objectives

To investigate the accelerated curing of cement composites containing Biomass Ash (BA) and Recycled Concrete Aggregate (RCA) using Pulsed Electric Field (PEF) technology, and to evaluate their mechanical and physical properties before and after PEF curing.

Materials and methods

The PEF: PEF technology has been applied across a wide range of fields, including medical applications, tissue separation techniques, and microbial inactivation processes in fruit juices such as orange juice and apple juice. (Mosqueda-Melgar., 2008) PEF has also been utilized for extracting compounds from plant materials or other substrates, such as calcium from bone, among others. (Yongguang and Guidan, 2008) The core components of a PEF system consist of three primary elements. The first is the pulse shape, which includes square waveforms, exponential waveforms, and half sine waveforms. (Kempkes, 2010), the second component is the modulator, which functions to convert low-voltage electrical input into high-voltage pulsed output. This can be achieved using devices such as spark gap switches, including thyratrons, or solid-state electronic components such as silicon-controlled rectifiers, the third component is the treatment chamber, where high-voltage pulses are transmitted to the positive and negative electrode terminals. The operating principle of the PEF system involves converting low-voltage alternating current into high-voltage direct current, which is then stored in capacitors. The stored energy is subsequently discharged via a switching device known as a spark gap, and delivered to the curing chamber (Figure 1). (Kantala et al. 2022), the distance between electrodes can be used to calculate the electric field intensity generated within the curing chamber, based on Equation (1). (Jose et al. 2010).

$$E = \frac{V}{d} \tag{1}$$

Where E represents the electric field intensity (V/cm) V is the voltage applied across the electrodes (V) and d is the distance between the electrodes cm).

Hydration reactions in cement under the influence of an electric field: The hydration reaction is an exothermic process, meaning that heat is released during the reaction. In cement, hydration occurs when cement particles interact with water, initiating a chemical process that leads to hardening and the development of strength in concrete. During hydration, various compounds in the cement chemically react with water to form new substances possessing binding properties and structural integrity. This reaction results in the formation of crystalline products such as calcium silicate hydrate (CSH), which is the primary strengthcontributing compound in cement and concrete, as well as calcium hydroxide (CH) and other related compounds. The hydration process is illustrated by Equation (2).

$$C_3S + (x+y)H_2O \rightarrow C_x - S_y - H_z + CH + \Delta H \tag{2}$$

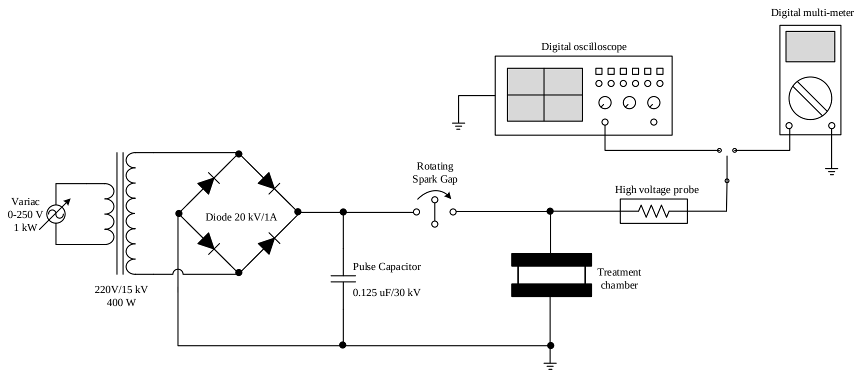


Figure 1. Diagram of the PEF System

In other words, the introduction of water into cement initiates the formation of CSH. (3CaO・SiO_2), $C_xS_yH_z$ and calcium hydroxide (CH). When PEF are applied, Ca^{2+} and OH^- ions exhibit enhanced mobility, accelerating the dissolution of cement particles and promoting the rapid formation of CSH, which leads to improved mechanical strength. Moreover, the intermittent application of electric field intensity facilitates hydration reactions at the surface of cement particles, thereby reducing the reaction time required. The mechanism of ionic migration during electric field-assisted cement curing can be described by Equation (3). (Nernst-Planck) (Susanto et al., 2015; Yang et al., 2017; Gawel et al., 2022)

$$J_i = -D_i \nabla c_i + z_i F \mu_i c_i E \tag{3}$$

Portland cement particles: Portland cement type I was used as the primary binder in the mixture, in accordance with THAI INDUSTRIAL STANDARD 2594-2556 (Hydraulic cement)

Preparation of BA and RCA Powders: The RCA powder was obtained from compressive strength testing specimens, and subsequently pulverized using a fine grinding machine, according to the method described by Sua-iam and Makul (2024). BA was sourced from Thai Solar Energy Public Company Limited as a by-product of shredded rubberwood combustion. Both RCA and BA powders were sieved to obtain the desired particle sizes using coarse and fine mesh sieves with openings of 140 mesh (105 microns). The resulting RCA and BA particles are illustrated in Figures 2a-b (1×), and Figures 2c-d (50×), respectively.

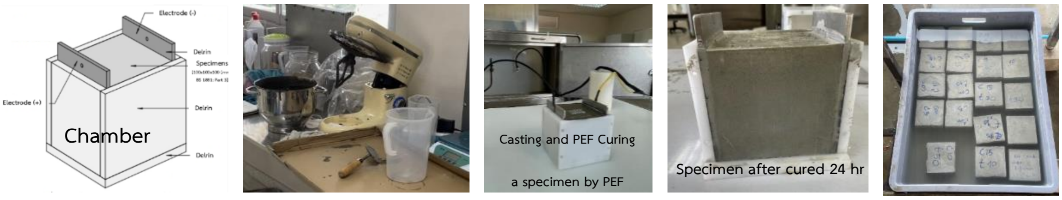
Specimen preparation and accelerated curing procedure: The cement mixture was prepared by combining Portland cement with either BA or RCA, with a total mixing duration of 10 minutes. Initially, portland cement was mixed with BA or RCA for 5 minutes, adjusting the content of each additive as specified. Subsequently, water was added and mixed for an additional 5 minutes, following the mix design presented in Table 1. The resulting mixture was then poured into a forming and curing chamber comprising Delrin polymer insulation and both positive and negative electrode plates. Specimens were cast in cubic molds of 100×100×100 mm in accordance with BS 1881: Part 3 (as shown in Figure 3a–b).

a. RCA, 105 μ (x1) b. BA, 105 μ (x1) c. RCA, 105 μ (x50) d. BA, 105 μ (x50)

Figure 2. preparation steps of RCA powder and BA derived from rubberwood chip.

Table 1: Mix proportions used in this study

Materials	Ingredient (wt.%)	Additive Type
Portland cement	100	Binder
Vary RCA	0, 5, 10, 15, and 20	Supplementary Cementitious Materials (SCMs)
Vary BA	0, 5, 10, 15, and 20	
Water	50	Mixing water for hydration reaction



a. b. c. d. e.

Figure 3. (a) Mold setup for specimen forming chamber, (b) Mixing equipment for cement material with BA and RCA powders, (c) Casting and accelerated curing of specimens using PEF, (d) Specimens after PEF treatment and 24-hour setting period, (e) Continued curing in water for 28 days at room temperature.

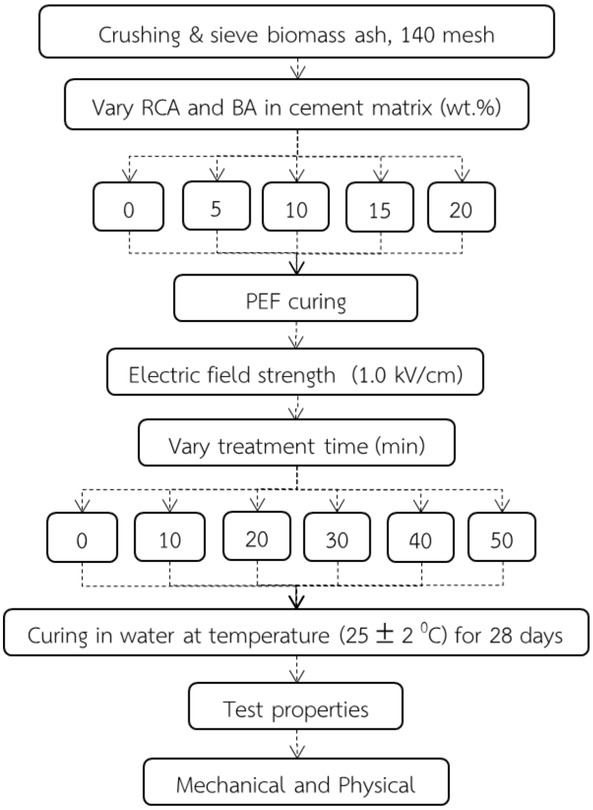


Figure 4. Diagram of research procedure

Accelerated curing using PEF: Portland cement blended with RCA or BFA powders was subjected to accelerated curing using a PEF at an electric field intensity of 1 kV/cm and a frequency of 1 Hz. The curing duration was varied at intervals of 0, 10, 20, 30, 40, and 50 minutes, as illustrated in Figure 3d. Following the PEF treatment, the specimens were held in the forming chamber for 24 hours to maintain shape integrity (Figure 3e). Afterward, the specimens were demolded and immersed in water for continued curing over a period of 28 days at room temperature (25 ± 2 °C), as shown in Figure 3f. The overall experimental procedure is depicted in Figure 4.

Experimental equipment used in this study

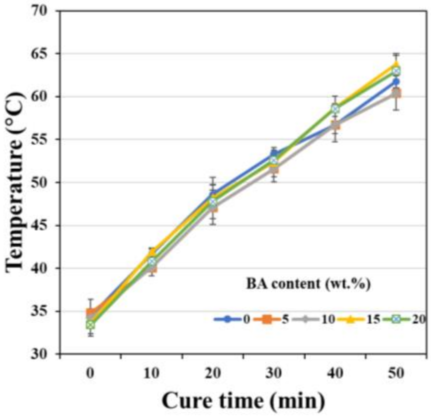
PEF Machine: The electric field and wave laboratory for food, agriculture and materials Research Unit of Applied Electric Field in Engineering (RUEE), College of Integrated Science and Technology, Rajamangala University of Technology Lanna (RMUTL), Chiang Mai 50220, Thailand.

Compressive strength testing was conducted using a compression machine: manufactured by ELE International (UK), with a force capacity of 3,000 kN and a loading rate of 3 kN/s, in accordance with BS 1881: Part 4.

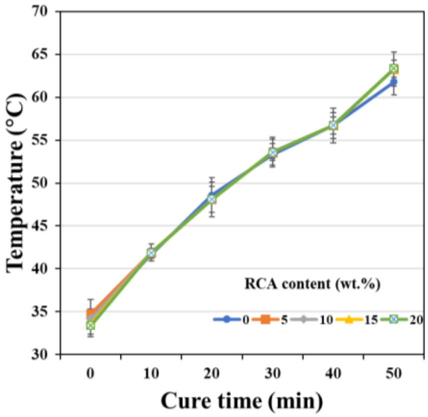
a. b. c.

Figure 5. (a) PEF equipment, (b) Compressive strength testing machine during specimen loading, (c) Compressive strength testing of the specimen

Results and discussion



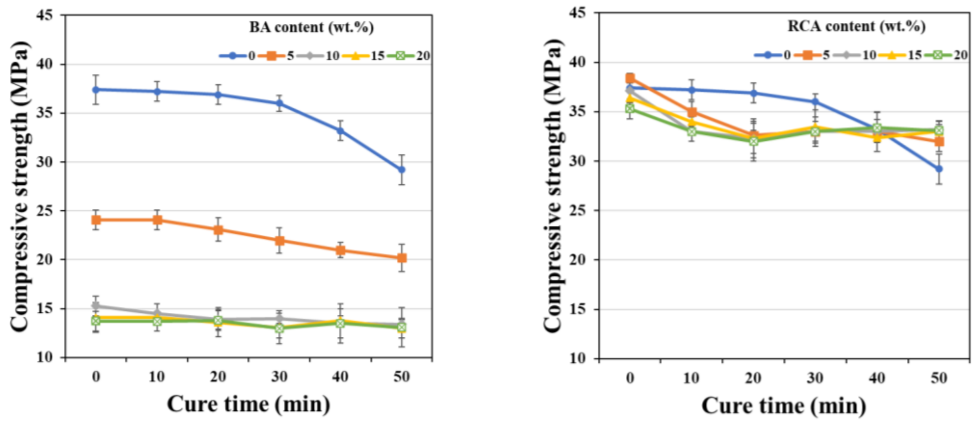
a.



b.

Figure 6. Relationship between temperature and curing time under PEF treatment

Figure 6 illustrates the relationship between temperature and curing duration under PEF treatment, using an electric field intensity of 1 kV/cm and varying curing times from 0 to 50 minutes. Experimental results indicate that as the curing time increases, temperature also rises. Hydration reactions begin upon the addition of water to cement in combination with additives at a concentration of 0–20 wt.%, releasing heat and causing the temperature to exceed ambient conditions (25 ± 2 °C). At time zero, the measured temperature was approximately 35 °C. To monitor these changes, a thermocouple sensor was installed at the bottom of the specimen in the treatment chamber to record the temperature throughout the PEF treatment. Extended PEF curing from 10 to 50 minutes led to temperature increases ranging from 41 to 64 °C, respectively. This rise is attributed to the conversion of electrical energy into thermal energy. Furthermore, increasing the dosage of both additives had no significant effect on the temperature response.

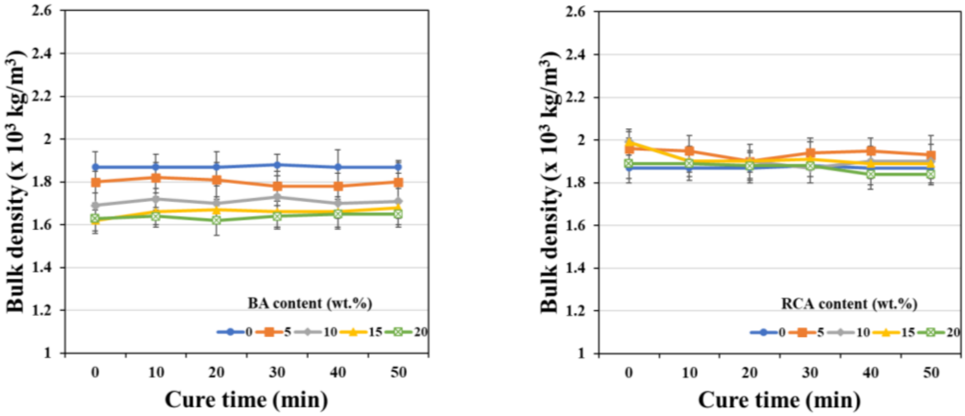


a. b.

Figure 7. Relationship between compressive strength and curing time under PEF Treatment

Figure 7 depicts the relationship between compressive strength and curing time under PEF treatment, with an electric field intensity of 1 kV/cm and curing durations ranging from 0 to 50 minutes. The discussion of these results is separated into two parts: Figure 7a for mixtures incorporating Biomass Ash (BA) and Figure 7b for those containing Recycled Concrete Aggregate (RCA). Regarding the BA-blended mixtures (Figure 7a), the experimental results show that for mixtures containing 0 wt.% BA, compressive strength remained relatively unchanged during the initial curing period of 0–30 minutes (36–37 MPa). However, strength decreased significantly at 40–50 minutes (21–24 MPa), which may be attributed to an over-curing effect known as the 'shell effect' (Gurski et al., 2023; Zhou et al., 2023). When BA was added at 5 wt.%, compressive strength declined further, with values ranging from 20–24 MPa, likely due to reduced CSH formation. Mixtures with BA content between 10–25 wt.% exhibited a pronounced drop in strength, stabilizing between 13–14 MPa, which may be attributed to diminished CSH phases and the emergence of fine pores.

In contrast, for the RCA-blended mixtures (Figure 7b), the specimens showed a slight decrease in compressive strength during the 10–20 minute interval (33–38 MPa) and stabilized at later curing durations from 30 to 50 minutes. RCA-enhanced mixtures demonstrated higher overall strength than those with BA, possibly due to increased CSH formation after PEF treatment and subsequent 28-day water curing. These findings correlate with the higher density of RCA mixtures, which generally translates to greater mechanical strength and compressive resistance. Nevertheless, overall mechanical performance tended to decline after PEF treatment followed by extended water curing. This effect may be caused by excessive electric field intensity (1 kV/cm) for the mix proportions used in this study. Future research should investigate optimized electric field intensities to better understand their impact on mechanical properties.



a. b.

Figure 8. Relationship between bulk density and curing time under PEF treatment

Figure 8 presents the relationship between specimen density and curing time under PEF treatment. The experimental results reveal that increasing the PEF curing time had no significant effect on the density of mixtures containing BA and RCA. Mixtures incorporating BA exhibited densities in the range of 1.6×10^3 kg/m^3, while RCA mixtures showed higher densities of approximately 1.9×10^3 kg/m^3. This difference is attributed to the inherently greater density of RCA compared to BA.

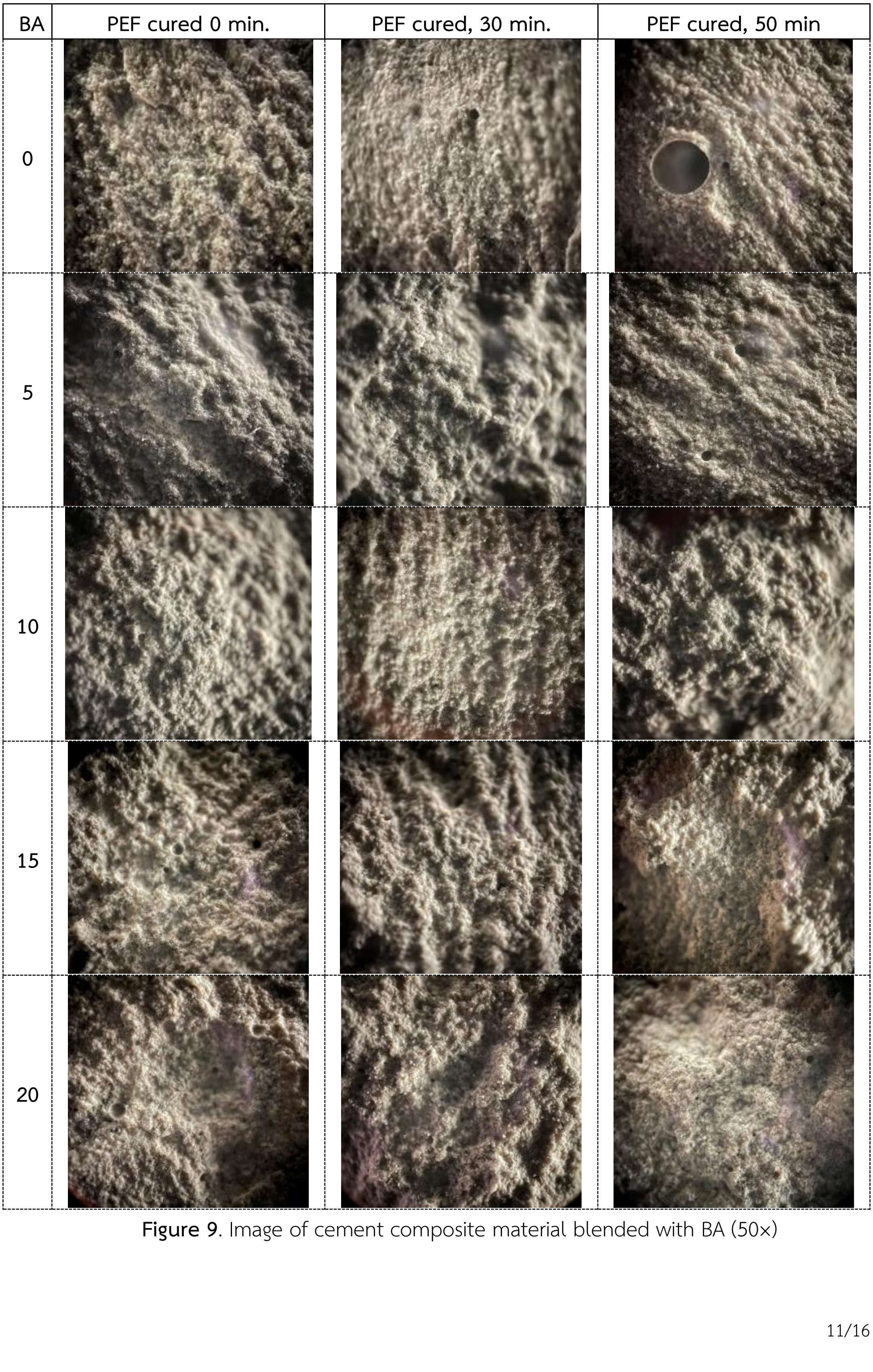


Figure 9. Image of cement composite material blended with BA (50×)

Figure 9 displays the microstructure of cement composites blended with Biomass Ash (BA) at various curing durations (0, 30, and 50 minutes) and replacement levels (0–20 wt.%). At the initial stage (0 min) and shorter curing durations (30 min), the matrix appears relatively continuous. However, for samples subjected to extended PEF treatment for 50 minutes, the emergence of microvoids and surface irregularities becomes clearly visible. These defects are particularly prominent in samples with higher BA content (15–20 wt.%), indicating that prolonged electric field exposure may disrupt the matrix uniformity in these specific mix proportions.

RCA	PEF cured 0 min.	PEF cured, 30 min.	PEF cured, 50 min
0			
5			
10			
15			

20

Figure 10. Image of cement composite material blended with RCA (50×)

Figure 10 illustrates the physical surface and microstructure of samples incorporating Recycled Concrete Aggregate (RCA). Compared to the BA mixtures, the RCA-blended composites exhibit a more compact and denser matrix across all curing intervals. Although some fine pores are observable at 50 minutes of PEF treatment, the overall structure remains more intact than that of the BA counterparts. This observation is consistent with the higher bulk density and superior compressive strength previously recorded for RCA-based specimens.

Conclusions

This study demonstrates that Pulsed Electric Field (PEF) technology effectively accelerates the hydration of cement composites through electro-thermal conversion, with internal temperatures rising progressively from 35 °C to 64 °C as curing duration increases to 50 minutes. The incorporation of Recycled Concrete Aggregate (RCA) yielded superior mechanical performance and higher density compared to Biomass Ash (BA) blends, owing to the inherently higher density of RCA and enhanced CSH formation. While PEF successfully promotes rapid curing, extended treatment beyond 30 minutes leads to significant strength reduction, particularly in BA-blended samples, due to over-acceleration and micro-void formation. These findings indicate that RCA is a promising sustainable additive for PEF-accelerated systems, with optimal performance observed in mixtures containing 5–20 wt.% RCA. Consequently, optimizing PEF curing duration is essential to maintain structural integrity while achieving efficient, high-performance cement material production.

Recommendation

Recommendations Based on Research Findings

1. The accelerated curing period under PEF between 0–50 minutes serves as an initial stage to stimulate the hydration reaction. At this phase, the temperature effect has not yet extended or reached the complete progress of hydration."

2. Utilizing RCA as an additive enables both material bulk enhancement and the valorization of industrial waste. Notably, compressive strength reached up to 32 MPa after 30 minutes of accelerated curing via PEF.

Recommendations for Future Research

Future studies should employ statistical experimental designs to analyze the interactions between PEF curing parameters and additive contents on the mechanical and physical properties of cement composites.

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