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Effect of Solar-Generated Electric Curing System on the Flexural Strength of Conventional and Metakaolin-Based Concrete

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Abstract: The primary objective of concrete curing is to enhance the strength and durability of concrete components used in construction. This study investigated the efficiency of a solar-generated electric curing system compared with conventional water ponding for conventional and metakaolin-based concrete. Concrete beams (100 × 100 × 400 mm, 40 MPa) were cast, with half cured by ponding for 28 days and the rest subjected to solar-electric curing for three days. Flexural strength tests and statistical analyses (ANOVA) revealed significant differences among curing methods and mix types ($F(3,8) = 32.56$, $p = 7.83 \times 10^{-5}$). Water-cured specimens generally exhibited higher flexural strengths, but electrically cured metakaolin concrete achieved 88.8% of the 28-day water-cured strength within just three days, with mean values of 3.90 ± 0.18 MPa compared to 4.38 ± 0.07 MPa for water curing.

The inclusion of 20% metakaolin enhanced hydration kinetics, microstructural densification, and water resistance, leading to improved mechanical and durability performance. These findings demonstrate the efficiency of solar-electric curing in accelerating strength development while conserving time, water, and energy. Overall, the results confirm that solar-electric curing is a sustainable, energy-efficient, and technically viable alternative to conventional ponding, particularly in regions with limited water availability and abundant solar resources.

Keywords: *Flexural strength, curing technologies, cementitious materials, sustainability*

1. INTRODUCTION

Concrete is a manufactured material widely used for construction purposes. Although it is artificial, concrete possesses several desirable properties [1, 2]. However, CO_2 emissions from cement production have become a major environmental concern. The quest for cost-effective and eco-friendly green concrete has led to the use of supplementary cementitious materials (SCMs) and innovative technologies that improve sustainability and enhance the performance of structural concrete. Mukhtar [3] reported that incorporating metakaolin as an SCM reduces cement consumption, thereby lowering carbon emissions. Recent studies have shown that metakaolin enhances the self-healing capacity of concrete [4] by promoting the formation of additional C–S–H gel, which improves the microstructural integrity of the material. Studies on sustainable concrete production have also shown that inadequate curing leads to incomplete hydration, resulting in weaker, less durable concrete prone to cracking and other defects [5, 6].

According to ACI Committee 308 [7], curing maintains optimal temperature and moisture conditions to allow concrete to hydrate and develop the required strength. Neville [8] also emphasized that proper curing is essential for achieving concrete's desired strength, durability, and long-term performance. Traditional curing methods typically involve water ponding or spraying, though other conventional techniques are also used to facilitate timely project delivery. Mokhtar et al. [9] compared air-cured and water-cured specimens and found that water curing increased flexural strength by approximately 15% compared to air curing.

Amusan et al. [10] investigated the effects of different curing techniques on concrete density and compressive strength. They found that both parameters increased with longer curing durations, with ponding producing the highest compressive strength, followed by wet covering. The authors concluded that adequate curing enhances both density and strength and emphasized that choosing an appropriate curing method is crucial to achieving structural stability [10]. Gabriel-Wettey et al. [11] investigated the compressive and flexural strengths of concrete specimens under four distinct curing methods: immersion, wet-jute-sack covering, plastic-sheet covering, and water spraying. The immersion-curing method yielded the highest compressive and flexural strengths at 7, 14, 21, 28, and 56 days of curing [11].

However, when water ponding is impractical, alternative curing methods such as electric, membrane, steam, microwave, and infrared curing are used. Although numerous curing methods, such as steam curing, microwave curing, and membrane curing, have been investigated to accelerate strength gain and improve concrete performance, each approach presents distinct limitations. Steam curing, while effective for precast operations, demands high energy input and may cause thermal cracking due to rapid temperature gradients. Microwave curing offers rapid strength development but requires specialized equipment and consumes significant energy. Membrane curing reduces surface moisture loss but often fails to ensure uniform internal hydration, particularly in high-performance concretes.

Amusan et al. [12] evaluated propylene glycol (PG) as an internal curing agent and reported that PG addition eliminated the need for external water, saving both water and labour associated with conventional curing. Concrete self-cured with propylene glycol exhibited higher strength and improved workability compared with conventionally cured concrete. Zhang et al. [13] investigated electric curing methods, including resistive heating, electromagnetic fields, and electric blankets, and reported that these methods accelerated early-age strength development in concrete.

Uygunoğlu and Hocaoğlu [14] examined the effects of different mix compositions and voltage levels on concrete maturity and compressive strength. The authors applied electrical current for 24 hours to freshly cast concrete specimens measuring 100 × 100 × 350 mm and observed that alternating-current (AC) intensity accelerated concrete maturity by enabling it to reach its optimum internal temperature without compromising compressive strength. In a related study, the authors found that applying electric current reduced the final setting time of concrete across all tested voltage levels, concluding that electrical curing reduces hydration time [15]. Shahriar et al. [16] further demonstrated that electric curing mitigates frost damage, while Yanhai et al. [17] reported that for ordinary Portland cement (OPC) systems, electric curing enhanced early-age strength but slightly reduced later-age strength, whereas fly-ash concrete benefited at both ages.

Although several studies have explored electric curing of ordinary Portland cement systems; however, there is limited understanding of how supplementary cementitious materials such as metakaolin respond to this accelerated curing regime. Metakaolin, with its high aluminosilicate reactivity, may interact differently with the thermal and ionic effects associated with electric curing. Furthermore, many developing regions experience erratic power supply and scarcity of potable water, often resulting from oil spills and environmental contamination, conditions that pose significant challenges to effective concrete curing.

By contrast, solar-generated electric curing offers a sustainable, low-carbon alternative that harnesses renewable solar energy to deliver controlled electrical heating and stimulation. This method accelerates hydration without excessive thermal stress or water consumption. Unlike previous studies focusing solely on temperature or moisture regulation, the present study integrates solar power conversion with electric current application as a hybrid green curing technology. Hence, this research not only contributes to sustainable curing innovations but also demonstrates the potential of solar-electric curing as a practical solution in regions with unreliable grid power and limited water resources.

Therefore, this study focuses on the combined influence of electric curing and metakaolin incorporation on strength development and microstructural performance, particularly under a solar-powered electric curing system. The objective is to evaluate the effect of solar-generated electric curing on the flexural strength of both metakaolin-based and conventional concrete.

2. MATERIALS AND METHOD

A. Materials

The experimental program for this study employed the following materials and apparatus: fine aggregate, coarse aggregate, ordinary Portland cement, water, solar power source, electrodes, and steel reinforcement. The fine aggregate used was natural river sand obtained from Ibogun in the Ifo Local Government Area of Ogun State, Nigeria. The fine aggregate was clean and free of impurities such as clay or organic matter, and possessed a coarse texture suitable for concrete production. The coarse aggregate was crushed granite of 19 mm nominal size, angular in shape to ensure proper bonding and non-flaky in texture. Sieve analysis of both fine and coarse aggregates was carried out in accordance with standard specifications [18]. Potable water free from organic compounds, oils, acids, and alkalis was used for mixing. The cement used was ordinary Portland cement (42.5 MPa grade), packaged in 50 kg bags, and a high-range water-reducing admixture (superplasticizer) was added to improve workability. All materials complied with relevant standards and specifications [18-20].

Metakaolin is a pozzolanic material produced by calcining kaolin clay at temperatures between 650 °C and 850 °C. The resulting metakaolin possesses a high surface area, fine particle size, high pozzolanic reactivity, and a characteristic white colour. The metakaolin complied with all relevant specifications [21]. The electrical energy for this project was supplied by a solar power system, chosen for its renewable nature and environmental sustainability, as well as to mitigate the unreliable grid power supply in the study area. The system comprised a 1.8 kW photovoltaic

(PV) array made up of six monocrystalline solar panels rated at 300 W each, connected in series. The DC power generated was fed into a 3.2 kVA pure sine wave inverter (rated output: 230 V AC, 50 Hz) to produce alternating current for the curing setup. A 24 V–220 Ah deep-cycle battery bank was installed to stabilize the supply and store excess energy for nighttime or cloudy periods.

B. ***Methods***

- **Mixing of specimen**

Concrete mix design involves selecting appropriate constituent materials and determining their proportions to produce concrete with the desired strength, durability, and workability in a cost-effective manner. For specimen preparation, fine and coarse aggregates, cement, metakaolin, water, and superplasticizer were batched by weight according to the designed mix ratio. The fine aggregate was first spread on a clean surface, after which cement and metakaolin were added, followed by water and superplasticizer. All materials were thoroughly mixed to achieve a uniform and homogeneous blend. The mix proportions used in this study are presented in Table 1. In the conventional mix, cement served as the sole binder (100%), whereas in metakaolin concrete, 20% of the cement was replaced with metakaolin (80% cement + 20% metakaolin).

TABLE 1: CONSTITUENTS OF THE CONCRETE SPECIMEN

Concrete Specimen	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Metakaolin (kg)	Water (kg)	Superplasticizer (kg)
Metakaolin concrete	4.903	9.06	13.6	1.226	2.452	0.221
Conventional Concrete	6.129	9.06	13.6	0.0	2.452	0.221

- **Casting of concrete**

Concrete was prepared by mixing fine aggregate, coarse aggregate, cement, metakaolin, water, and superplasticizer. The dry materials were mixed for three minutes, after which two-thirds of the water was added, followed by the remaining one-third. Mixing continued for an additional five minutes to ensure uniform consistency. Workability was assessed using a slump test conducted in accordance with BS 1881 [22]. After testing, the fresh concrete was placed in prismatic moulds measuring 100 × 100 × 400 mm, which were cleaned and oiled to facilitate easy demoulding. Each mould was filled in three equal layers, and 25 blows were applied per layer to remove entrapped air. Excess concrete was leveled and the surface finished smoothly with a trowel.

- **Curing of concrete**

Curing involves maintaining optimal moisture levels and temperature conditions for sufficient time to ensure proper hydration and strength development. In this study, water-based curing served as the control method; specimens were immersed in water for 28 days to achieve full hydration and strength. Additionally, solar-powered electric curing was applied to the remaining specimens. The specimens were cured under alternating current (AC) voltages ranging from 60 to 80 V for 72 hours. Two copper plates were embedded in the concrete as electrodes to allow current flow and measure changes in electrical resistivity and mechanical performance. The contact surfaces of the copper plates were coated with silver paint to enhance electrical conductivity. A thermocouple was embedded between the electrodes (Figure 1) to monitor internal temperature during the curing process.

The solar-generated electric curing system was designed to ensure a stable and environmentally sustainable power supply during the experimental process. The inverter output was regulated by a charge controller to ensure consistent current delivery to the specimens throughout the 72-hour curing period. The configuration maintained a steady AC voltage between 60 and 80 V, providing reliable curing conditions while minimizing dependence on the unstable grid power supply.

Fig. 1: Electric curing set-up

C. Tests on Hardened Concrete

- **Flexural strength test**

The flexural strength test is a standard method used to evaluate the resistance of concrete to bending loads, commonly referred to as the modulus of rupture test. In this study, rectangular beam specimens were tested in accordance with the specified standard [23]. The specimens were subjected to a gradually increasing load applied at the midpoint until failure occurred by cracking or complete rupture, as illustrated in Figure 2.

During testing, the midspan deflection was recorded using a dial gauge to determine the extent of bending under the applied load. This test is essential for assessing the ability of concrete to withstand tensile stresses induced by bending. The results provide critical input for the design and evaluation of structural members and ensure that the concrete satisfies the required strength specifications. All tests were conducted in accordance with the standard procedures [24].

Fig. 2: Loading of beam specimen

- **Water absorption test**

The water absorption test measures the percentage increase in mass of a specimen after immersion in water, calculated as the ratio of weight gain to the dry weight of the sample. A higher water absorption value indicates greater porosity and lower durability, whereas a lower value signifies a denser and more durable concrete. This test was conducted on the water-cured concrete specimens in accordance with the standard [25].

3. RESULTS AND DISCUSSION

A. Sieve Analysis Results

The results of the sieve analyses for both fine and coarse aggregates are presented in Figures 3 and 4. The particle-size distribution curves indicate that the aggregates used met the standard grading requirements [23]. The values of the uniformity coefficient (C_u) and the coefficient of curvature (C_c) for the aggregates are shown in Table 2. Both coefficients were greater than 1, indicating that the aggregates were well-graded and suitable for producing high-quality concrete [24].

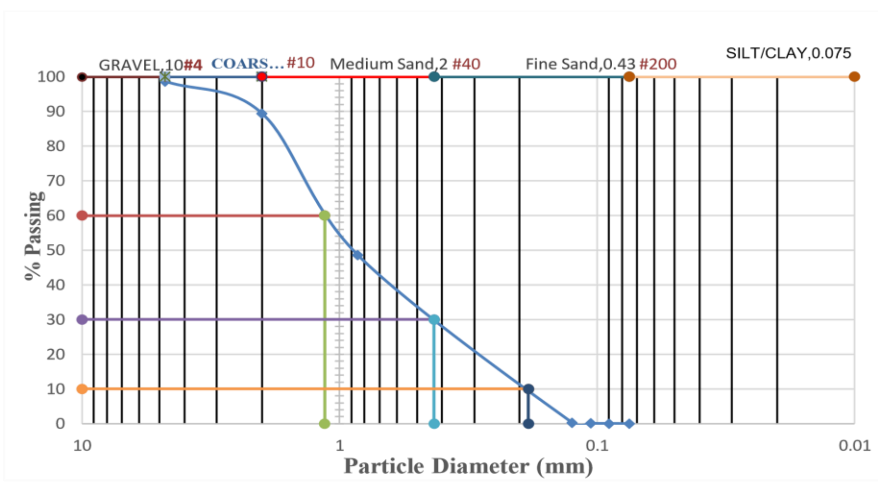

Fig. 3: Cumulative frequency distribution of fine aggregate

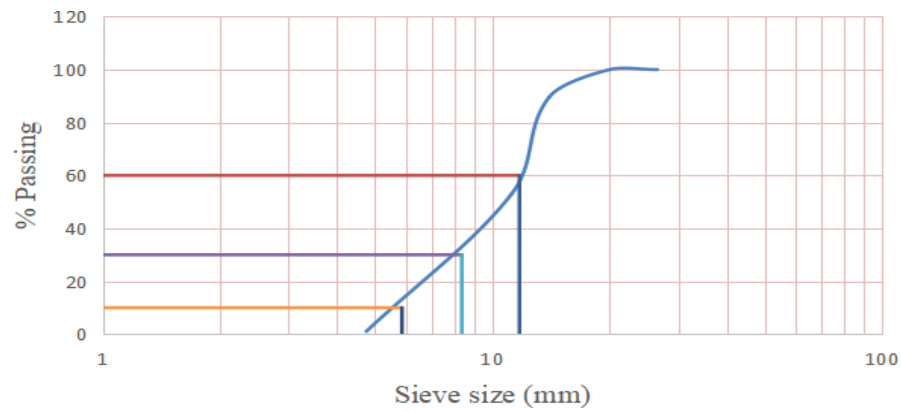

Fig. 4: Particle distribution curve for coarse aggregate

TABLE 2: RESULTS OF C_U AND C_C FOR FINE AND COARSE AGGREGATES

Aggregate type	D_{10}	D_{30}	D_{60}	C_u	C_c
Fine aggregate	0.175	0.450	1.141	1.01	2.54
Coarse aggregate	5.862	8.348	11.739	1.01	1.41

B. Slump Test Results

The slump-test results for conventional and metakaolin concretes are summarized in Table 3. The results show moderate slump values of 40 mm and 45 mm for metakaolin and conventional concretes, respectively, indicating moderate workability.

TABLE 3: SLUMP TEST RESULTS

Concrete specimen	Slump value (mm)
Metakaolin concrete	40
Conventional concrete	45

C. Water Absorption Test Results

The water-absorption results for both concrete types are presented in Figure 5. For conventional concrete, Sample 1 exhibited a water-absorption rate of 0.43%, which was higher than those of Samples 2 (0.33%) and 3 (0.32%). This indicates greater porosity and lower resistance to water penetration in Sample 1. Conversely, Samples 2 and 3 recorded lower absorption values of 0.33% and 0.32%, respectively, suggesting a denser microstructure and improved impermeability.

For metakaolin concrete, Sample 1 recorded a slightly higher absorption rate of 0.32%, while Samples 2 and 3 exhibited the lowest values of 0.22%. This reduction reflects the positive influence of metakaolin incorporation, which promotes the formation of additional calcium silicate hydrate (C–S–H) through its pozzolanic reaction with calcium hydroxide. The resulting microstructural refinement reduces pore connectivity and enhances the concrete's overall compactness.

From a durability standpoint, the lower water absorption observed in metakaolin concrete directly translates to improved resistance against common deterioration mechanisms such as chloride ingress, sulfate attack, alkali–silica reaction, and freeze–thaw damage. Since water serves as the transport medium for aggressive ions, a denser matrix with reduced absorption helps mitigate reinforcement corrosion and extends service life. The water absorption values of all mixes were well below the 10% limit specified by BS 1881 for durable concrete, confirming their suitability for structural use in humid or moderately aggressive environments.

These results therefore demonstrate that replacing 20% of cement with metakaolin not only improves impermeability but also enhances long-term durability, particularly under solar-electric curing where consistent moisture maintenance can be challenging. This finding aligns with the mechanical performance trends observed in flexural testing, where metakaolin concretes exhibited higher bending resistance. The combined mechanical and durability benefits underscore the potential of metakaolin-modified concrete as a sustainable material solution in water-scarce regions when integrated with solar-generated electric curing systems.

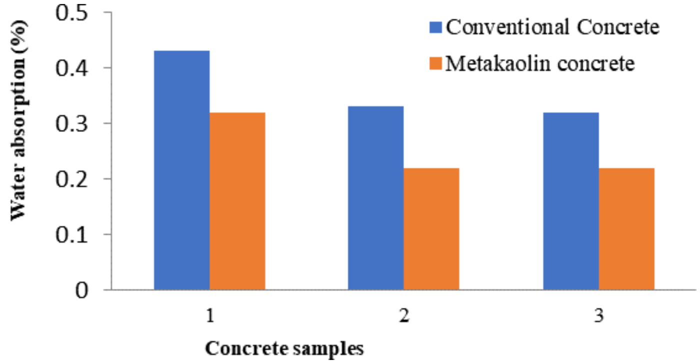

Fig.5: Water absorption percentage

D. Electric Curing Test

Table 4 presents the temperature-time relationship during electric curing. The table shows the variations in voltage, current, power, and temperature over the 72-hour solar-powered electric curing period. The maximum internal temperature (60 °C) was recorded after 24 hours of curing. The applied voltage ranged from 60 V to 85 V, with maximum power consumption (125.7 W) occurring during the initial curing stage. The results indicate that moisture content and hydration rate directly influenced the current flow during the curing process, consistent with previous findings by Uygunoğlu and Hocaoğlu [14, 15].

E. Flexural Test Results

The study evaluated the flexural strength of both conventional and metakaolin concretes under two curing regimes: water ponding and solar-powered electric curing. Flexural strength tests were conducted for each method, and the results are summarized in Tables 5 and 6. Water-ponded specimens exhibited higher flexural strength than electrically cured specimens for both concrete types. Specifically, the electrically cured conventional and metakaolin concretes achieved average flexural strengths of 3.40 MPa and 3.89 MPa, respectively, whereas the water-cured counterparts reached 4.33 MPa and 4.38 MPa. This confirms that water-cured specimens were generally more resistant to bending stresses, consistent with the findings of Mokhtar et al. [9] and Amusan et al. [10].

TABLE 4: TEMPERATURE AND TIME RELATIONSHIP OF ELECTRICALLY CURED SAMPLES

Duration (hr)	Voltage (volt)	Current (amp)	Power (watts)	Temperature (°C)
0:00	60	2.096	125.71	35
12:00	70	2.124	147.14	42
24:00	70	1.305	91.23	60
36:00	70	0.948	66.32	55
48:00	85	0.615	51.85	50
60:00	85	0.408	34.67	38
72:00	85	0.279	23.60	36

However, the electrically cured metakaolin concrete exhibited significantly higher flexural strength than its conventional counterpart, which can be attributed to the enhanced pozzolanic reactivity of metakaolin under thermal and ionic stimulation. Notably, the electrically cured specimens attained 88.8% of the 28-day flexural strength of water-cured concrete within only three days, corroborating the observations of Zhang et al. [13]. The improved performance of metakaolin-blended concrete under solar-electric curing confirms its favourable response to accelerated hydration. The combined thermal and electrochemical effects appear to intensify metakaolin's pozzolanic reaction, leading to denser microstructural development.

Moreover, the solar-electric curing system demonstrated remarkable early-age performance, achieving mechanical properties comparable to those of water-ponded specimens cured for 28 days. This highlights the system's ability to accelerate hydration and strength development using renewable energy. Unlike conventional electric curing, which depends on continuous grid power, the solar-electric setup operated entirely on renewable solar energy, thereby reducing energy costs and carbon footprint while maintaining high curing efficiency. These findings collectively establish the solar-electric curing method as a sustainable and technically viable alternative for high-performance, metakaolin-based concrete.

TABLE 5: RESULTS OF FLEXURAL STRENGTH TEST FOR CONVENTIONAL CONCRETE

Curing method	Curing age (days)	Samples	Flexural strength (N/mm^2)	Average flexural strength (N/mm^2)	Ultimate load (kN)	Ultimate deflection (mm)
Water Ponding	28	WP 1	4.41	4.33	11.25	1.68
		WP 2	4.30		10.75	2.33
		WP 3	4.27		10.68	2.00
Electric Curing	3	EC 1	3.21	3.40	8.03	1.51
		EC 2	3.57		8.93	1.25
		EC 3	3.43		8.56	2.21

TABLE 6: RESULTS OF FLEXURAL STRENGTH TEST FOR METAKAOLIN CONCRETE

Curing method	Curing age (days)	Concrete samples	Flexural strength (N/mm^2)	Average flexural strength (N/mm^2)	Ultimate load (kN)	Ultimate deflection (mm)
Water ponding	28	WP 1	4.44	4.38	11.10	2.41
		WP 2	4.31		10.78	2.27
		WP 3	4.40		11.00	2.35
Electric curing	3	EC 1	3.74	3.89	9.35	1.91
		EC 2	4.10		10.25	2.11
		EC 3	3.87		9.68	1.97

TABLE 7**: STATISTICAL SUMMARY OF FLEXURAL STRENGTH VALUES**

Groups	Count	Sum	Average	Standard deviation	Variance
Conventional (Electric)	3	10.21	3.403333	0.181474	0.032933
Conventional (Water)	3	12.98	4.326667	0.073006	0.005433
Metakaolin (Electric)	3	11.71	3.903333	0.182299	0.033233
Metakaolin (Water)	3	13.15	4.383333	0.066581	0.004433

TABLE 8: ANOVA OF FLEXURAL STRENGTHS OF THE CONCRETE SPECIMENS

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.856825	3	0.618942	32.5616	7.83E-05	4.066181
Within Groups	0.152067	8	0.019008			
Total	2.008892	11				

F. ***Statistical Anaysis of Flexural Strength***

A one-way analysis of variance (ANOVA) was conducted to compare the flexural strengths of concrete under four conditions: Conventional (Electric), Conventional (Water), Metakaolin (Electric), and Metakaolin (Water) curing. Tables 7 and 8 summarize the statistical analysis of the flexural strengths obtained for all specimen groups. The results revealed a statistically significant difference among the groups ($F(3,8) = 32.56$, $p = 7.83 \times 10^{-5}$), indicating that the curing method and concrete composition both significantly influenced flexural strength.

The mean flexural strengths were 3.40 ± 0.18 MPa for Conventional (Electric), 4.33 ± 0.07 MPa for Conventional (Water), 3.90 ± 0.18 MPa for Metakaolin (Electric), and 4.38 ± 0.07 MPa for Metakaolin (Water). Post-hoc analysis using Tukey's HSD test showed significant differences between Conventional (Electric) and all other groups ($p < 0.05$), as well as between Metakaolin (Electric) and Metakaolin (Water). No significant difference was found between the two water-cured concretes, or between Conventional (Water) and Metakaolin (Electric) ($p > 0.05$).

The findings indicate that water curing consistently produced higher flexural strengths than electric curing. However, the inclusion of 20% metakaolin in the mix significantly improved performance under electric curing, narrowing the strength gap between the two curing methods. This supports the findings that metakaolin enhances hydration and microstructural development, making solar-powered electric curing a promising sustainable alternative where water availability is limited.

4. CONCLUSION

This study evaluated the performance of metakaolin-blended concrete subjected to solar-electric curing compared with conventional ponding. Based on the findings, the following conclusions are drawn:

- Solar-electric curing significantly accelerated early-age strength development, with 3-day compressive strengths comparable to or exceeding 28-day ponded specimens.
- The combination of electrical stimulation and metakaolin incorporation enhanced hydration kinetics and microstructural densification, contributing to improved mechanical performance.
- The solar-electric curing system demonstrated high energy efficiency by utilizing renewable solar power, thereby reducing curing time, water consumption, and dependence on grid electricity.
- Despite the shorter curing duration, solar-electric cured specimens achieved comparable microstructural integrity and strength retention to conventionally cured samples.
- The study confirms the feasibility of solar-electric curing as a sustainable, time-efficient, and scalable alternative for metakaolin-based concrete, especially in regions with abundant solar resources.
- Solar-electric cured specimens exhibited greater resistance to water penetration than conventionally cured samples.
- It is acknowledged that the laboratory-scale nature, small sample size, and limited curing duration may constrain direct field application; hence, further large-scale and long-term studies are recommended to validate performance trends.

Overall, the solar-generated electric curing system demonstrated strong potential as a sustainable, time-efficient, and energy-saving alternative to conventional water curing for metakaolin-based concrete, particularly in regions with abundant solar resources.

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