

## Influence of Design Compressive Strength, Curing Methods, and Casting Conditions on the Plastic Shrinkage of Concrete

Tamim A. Samman\*

Civil and Environmental Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia

\*Corresponding author: [tamimsamman@yahoo.com](mailto:tamimsamman@yahoo.com)

Received 23 December 2025, Received in revised form 7 May 2026

Accepted 7 June 2026, Available online 30 September 2026

### ABSTRACT

*Plastic shrinkage cracking remains a major durability concern in concrete structures constructed under hot, arid climatic conditions, where high temperatures, low relative humidity, and wind accelerate early-age moisture loss. This study experimentally investigates the effects of concrete compressive strength, curing method, and casting time on cumulative water loss (CWL) and plastic shrinkage cracking. Concrete panels (600 × 900 × 30 mm) were prepared using four strength grades (23, 40, 60, and 84 MPa) and exposed to simulated field conditions representative of summer climates. Four curing techniques were examined, namely air-dry (AR), water spray (WS), wet burlap (BLC), and a resin-based (RB) curing compound. The results demonstrate a strong dependency of plastic shrinkage behavior on concrete strength and curing regime. Normal-strength concrete (23 MPa) exhibited no visible plastic shrinkage cracking under all exposure conditions, despite reaching evaporation rates up to 2.22 kg/m<sup>2</sup>·h. In contrast, high-strength concrete showed significantly higher cracking susceptibility due to reduced bleeding capacity. The 84 MPa concrete panels developed a maximum cracking area of 1118 mm<sup>2</sup> when air-dried and exposed to noon sunlight. Cumulative water loss in air-dried specimens reached up to 55%, whereas RB-cured specimens exhibited substantially lower CWL values, limited to approximately 7–13% across all strength levels. Application of the resin-based curing compound eliminated visible plastic shrinkage cracking, while wet burlap and water spray curing significantly reduced crack formation compared to air-dry conditions. The findings emphasize the critical role of early-age curing strategies and casting time in controlling moisture loss and mitigating plastic shrinkage cracking, thereby enhancing the durability and service performance of concrete structures in hot-climate environments.*

**Keywords:** Plastic shrinkage crack; concrete curing; normal-strength concrete; high-strength concrete; and water loss

### INTRODUCTION

Plastic shrinkage is an early-age phenomenon that occurs within the first few hours after concrete placement, while the material is still in a plastic state and has not yet developed sufficient tensile strength. It is mainly associated with rapid evaporation of surface moisture, inadequate bleeding, and the development of capillary pressure within the fresh cement paste (Boshoff et al. 2020; Sadiqul & Gupta 2016). When moisture loss from the surface exceeds the rate at which bleed water can replace it, tensile stresses begin to develop near the surface, leading to the formation of plastic shrinkage cracks. These cracks are commonly observed in concrete elements with large, exposed surface

areas, such as slabs, pavements, and bridge decks (Alshammari et al. 2023; Sadiqul & Gupta, 2016). Although plastic shrinkage cracks form at very early ages, their consequences extend well beyond construction. They increase surface permeability and provide pathways for the ingress of aggressive substances, which may accelerate reinforcement corrosion, promote physical and chemical deterioration, and reduce long-term durability and serviceability (Alshammari et al. 2023; Folorunsho et al. 2024; Sadiqul & Gupta 2016). The risk of plastic shrinkage cracking becomes particularly severe in hot, arid climates. High ambient temperature, low relative humidity, solar radiation, and drying winds significantly increase evaporation rates during the first few hours after casting.

The tendency of concrete to undergo plastic shrinkage is strongly influenced by mixture design parameters that govern moisture movement and early-age behavior. These include the water-to-binder ratio, cement paste volume, type and dosage of chemical and mineral admixtures, and the targeted compressive strength (Lai et al. 2022; Nasir et al. 2023). Concrete with higher water-to-cement ratios generally exhibits greater bleeding, which may help delay surface drying under moderate conditions. However, under severe drying environments, higher water contents can also lead to rapid evaporation and increased shrinkage. In contrast, modern high-strength concrete mixtures are typically designed with low water-to-binder ratios, silica fume, and high-range water-reducing admixtures. While these mixtures offer improved mechanical performance and dense microstructure, they often exhibit reduced bleeding capacity and are therefore more vulnerable to early-age moisture loss (Andreu & Etxeberria, 2016; Lai et al. 2022; Nasir et al. 2023). Several studies show that increases in water-to-binder ratio and paste volume generally raise plastic and drying shrinkage and reduce compressive strength, whereas mixtures optimized for packing density and reduced capillary porosity exhibit lower shrinkage (Andreu & Etxeberria, 2016; Lai et al. 2022, 2021; Nasir et al. 2023). However, the combined influence of design compressive strength level, associated mix proportions, and early-age plastic shrinkage response remains insufficiently quantified, particularly under realistic field environments.

In addition to the mixture composition, construction practices, and environmental conditions at the time of casting, plastic shrinkage development is also influenced by the casting process next (Safiuddin et al. 2018; Tutkun et al. 2023). Factors such as concrete temperature, ambient air temperature, relative humidity, wind speed, and time of placement directly influence evaporation rates and the formation of capillary stresses (Alshammari et al. 2023; Ghoddousi et al. 2019; Moelich et al. 2022; Nasir et al. 2017). Hot-weather concrete is particularly sensitive to casting time. Concrete placed during midday or early afternoon is exposed to higher temperatures and lower humidity, leading to rapid moisture loss shortly after finishing. Numerous studies have shown that early initiation of curing is essential to limit plastic shrinkage cracking, especially during the first one to three hours after placement (Nasir et al. 2023, 2017). Various surface curing techniques have been proposed to reduce evaporation, including water spraying, wet burlap, plastic sheets, and membrane-forming curing compounds. While these methods are generally effective, their performance depends strongly on environmental severity, application timing, and compatibility with the concrete mixture (Alshammari et al. 2023; Boshoff et al. 2020; Markin et al. 2024; Nasir et

al. 2023). Resin-based curing compounds, in particular, have shown promising results in forming continuous surface membranes that significantly reduce early-age water loss. However, comparative data evaluating different curing methods under identical environmental and mixture conditions remain limited.

From a mechanical perspective, the main reason for plastic shrinkage and subsequent cracking is the rapid evaporation of water from the concrete surface (Eren & Marar 2010; Ghourchian et al. 2019). Cracking may occur under certain conditions even when the same materials and construction procedures are used. This variation is largely attributed to changes in environmental factors, such as temperature, relative humidity, and wind speed, which directly influence the rate of surface evaporation (Bertelsen et al. 2020; Pelisser et al. 2010). If this rate surpasses the speed at which excess water bleeds to the surface, plastic shrinkage and cracking can occur (Hisham et al. 2018; Androuët & Charron 2021; Kayondo et al. 2019; Moelich et al. 2021). Upon placement, the aggregate and cement settle while the water rises or bleeds out. The rate at which this water appears, and its total volume, depends on the depth of the concrete, the materials, the mix proportions, and the concrete's temperature. Additionally, the rate and duration of bleeding are affected when evaporation from the surface exceeds the rising rate of bleeding water surface (Ghourchian et al. 2018; Leemann et al. 2014; Safiuddin et al. 2018; Sirajuddin & Gettu 2018).

The loss of surface sheen on fresh concrete indicates the point at which the rate of evaporation exceeds the rate of bleeding (Boshoff et al. 2020; Wyrzykowski et al. 2015). At this stage, free water is no longer available on the surface to compensate for moisture loss. The time required for the concrete to reach this condition depends on several factors, including ambient temperature, relative humidity, wind speed, and the properties of the concrete mixture (Combrinck et al. 2018; Sivakumar & Santhanam, 2007). Once surface drying begins, the concrete has gained only limited stiffness and has not yet developed sufficient tensile strength to resist shrinkage-induced stresses. As a result, capillary tension develops within the pore water, increasing the likelihood of plastic shrinkage cracking if moisture loss continues (Saliba et al. 2011; Uno 1998).

Despite extensive work on individual parameters, such as environmental conditions, admixtures, and fibers, there remains a limited integrated understanding of how design compressive strength, specific curing methods, and realistic casting conditions interact to govern plastic shrinkage and associated cracking risk in conventional concrete. Many studies investigate the impact of various curing methods to prevent plastic shrinkage cracking. Alshammari et al. (2023) found that prolonged curing techniques, particularly moist curing of concrete, minimizing shrinkage cracks.

This is because moisture curing maintains a proper moisture content on the concrete surface, reducing its porosity and leading to a denser microstructure that is less susceptible to water loss. Studies by Nasir et al. (2023) demonstrated that concrete prepared and cured under harsh field conditions shows that water–cement ratio, casting temperature (25–45 °C), and curing regime jointly control plastic and drying shrinkage as well as strength development: higher w/c increases plastic/drying shrinkage and lowers strength, while an intermediate casting temperature (~32 °C) minimizes shrinkage and maximizes strength. In related studies, Nasir et al. (2022) found that greener concrete mixtures containing multiple supplementary cementitious materials showed that binder composition, casting temperature, and curing method (wet burlap or curing compound) strongly influence early-age strength and drying shrinkage. The results indicated that casting temperatures below approximately 38 °C are necessary to reduce potential durability problems in blended concrete systems.

Studies by ACI Committee 308 (ACI-308, 2016) highlight the important aspects of curing duration and methods. Various methods exist to mitigate plastic shrinkage cracking, including curing techniques, power floating, cold water, shrinkage-reducing admixtures, and fibers. The most common curing method involves covering concrete with plastic sheets or wet burlap. Nasir et al. (2017) found that plastic sheets reduced plastic shrinkage cracks by up to 25%, while Al-Amoudi et al. (2007) reported no significant improvement in drying shrinkage with wet burlap. However, research on the effects of damp burlap on plastic shrinkage remains limited. Power floating, applied after the bleed water has evaporated, helps seal micro- and plastic-shrinkage cracks, although deeper cracks may resurface depending on timing (Golewski 2023). Combrinck & Boshoff (2013) confirmed its effectiveness in closing surface cracks. Cold water can slow evaporation and temperature rise in hot conditions, potentially reducing shrinkage. However, Jacobsen et al. (2015) found that ice water may worsen microcracking. In contrast, Xie et al. (2018) observed that replacing 50% of mixing water with crushed ice reduced drying shrinkage in ultra-high-performance concrete. Superplasticizers, commonly used to enhance workability, may increase bleed water and contribute to plastic shrinkage cracking. Combrinck et al. (2018) experimentally confirmed that higher superplasticizer dosages led to wider plastic shrinkage cracks.

Although plastic shrinkage cracking has been widely investigated, most studies focus on individual factors such as environmental severity, fiber/admixture use, or a single

curing approach, often under controlled laboratory conditions. There remains limited experimental evidence that simultaneously evaluates how design compressive strength level (as a proxy for mixture composition and bleeding capacity) interacts with practical curing methods and realistic casting periods (morning/noon/afternoon/evening) under hot-weather exposure. In particular, comparative datasets linking evaporation demand, cumulative water loss, crack initiation time, and cracking severity across a wide range of strengths remain scarce. This gap limits the ability to provide field-oriented recommendations for selecting curing strategies and placement timing, especially for high-strength concrete in hot and arid climates.

In addition, determining the most effective methods for managing plastic shrinkage remains challenging due to the lack of systematic experimental comparisons among commonly used mitigation approaches. To address this gap, the present study aims to investigate the combined influence of design compressive strength level, curing method, and casting condition on the plastic shrinkage behavior of concrete. Early-age moisture loss, crack initiation, cracking severity, and strength development were monitored under controlled yet representative environmental conditions. To address this gap, the present study examines the combined effects of concrete strength level, curing method, and casting condition on plastic shrinkage cracking.

## MATERIALS AND TESTING METHODS

### MATERIALS

Ordinary Portland cement with a specific gravity of 3.15, a fineness of 256 m<sup>2</sup>/kg (Blaine surface area), and a soundness of 0.35% was used in the research. The chemical properties of the cement are shown in Table 1. For the concrete mix, crushed coarse aggregate was employed, featuring a maximum size of 9.5 mm, a fineness modulus of 5.65, a bulk unit weight of 1659 kg/m<sup>3</sup>, and a specific gravity of 2.78. Natural sand was also utilized with a fineness modulus of 2.95, a bulk unit weight of 1881 kg/m<sup>3</sup>, and a specific gravity of 2.65. Sieve analysis of the coarse and fine aggregates is illustrated in Figure 1. A densified silica fume with a specified gravity of 2.2 and a bulk density of approximately 600 kg/m<sup>3</sup>, along with the superplasticizer Complast-430, was used in some mixtures, as shown in Table 2.

TABLE 1. Chemical analysis of ordinary Portland Cement used in the experiment.

| No | Oxide                                    | Percent |
|----|------------------------------------------|---------|
| 1  | Silica ( $\text{SiO}_2$ )                | 20.20   |
| 2  | Alumina ( $\text{Al}_2\text{O}_3$ )      | 6.29    |
| 3  | Ferric Oxide ( $\text{Fe}_2\text{O}_3$ ) | 3.40    |
| 4  | Lime ( $\text{CaO}$ )                    | 63.20   |
| 5  | Magnesia ( $\text{MgO}$ )                | 2.50    |
| 6  | Potassa ( $\text{K}_2\text{O}$ )         | 0.26    |
| 7  | Soda ( $\text{Na}_2\text{O}$ )           | 0.72    |
| 8  | Sulfur Trioxide ( $\text{SO}_3$ )        | 2.51    |

TABLE 2. Key properties of superplasticizer.

| No | Property                | Description                         |
|----|-------------------------|-------------------------------------|
| 1  | Appearance              | Light Brown liquid                  |
| 2  | Density                 | $1.06 \pm 0.01$ at room temperature |
| 3  | pH                      | 5-7                                 |
| 4  | Chloride content        | <0.1%                               |
| 5  | Water reduction ability | 25-35%                              |

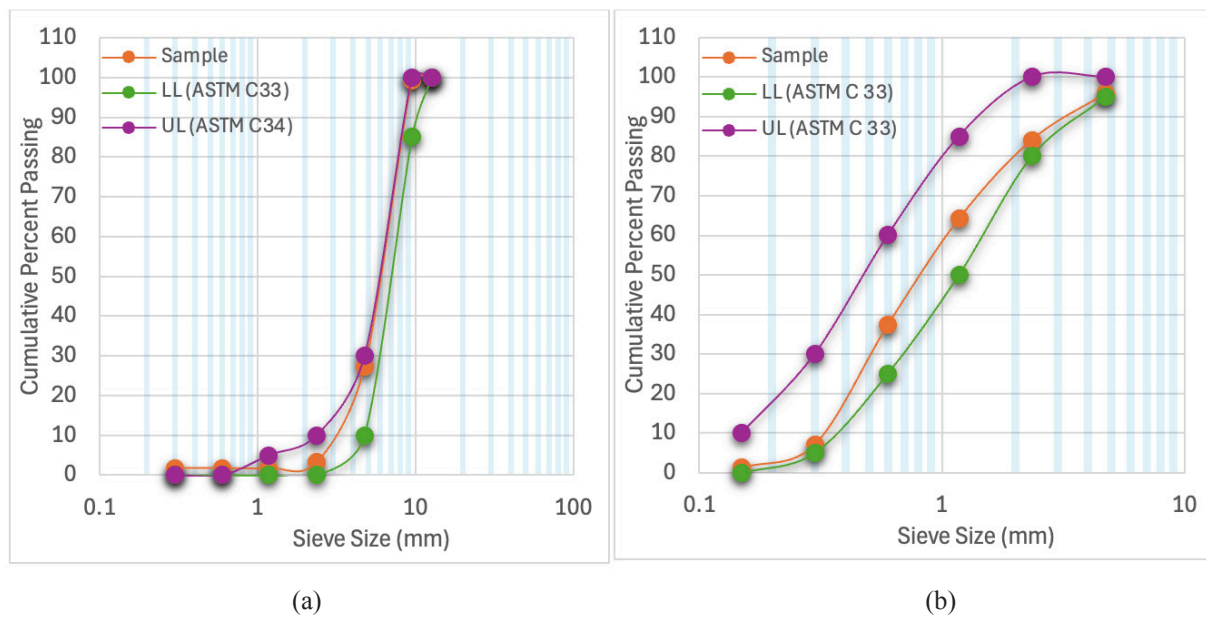


FIGURE 1. Sieve Analysis: (a) Coarse Aggregate and (b) Wash Sand.

## CONCRETE MIX PROPORTIONING AND MIXING

The concrete mixtures were designed to cover a broad range of strength levels commonly encountered in practice, from normal-strength to high-strength concrete. Target compressive strengths of 23, 40, 60, and 84 MPa were selected to examine how strength level and associated mix characteristics influence plastic shrinkage behavior. Using this wide strength range allowed comparison between mixtures with distinctly different water–cement ratios, bleeding capacities, and early-age moisture movement, all of which are known to play an important role in plastic shrinkage cracking.

The normal-strength concrete mixture (23 MPa) was proportioned at 1:1.5:3 (cement: fine aggregate: coarse aggregate) with a water–cement ratio of 0.70, in accordance with conventional construction practice. For the higher-strength mixtures (40 and 60 MPa), the water–cement ratio was reduced to 0.40 and 0.33, respectively. A high-range water-reducing admixture (Complast 430) was used in these mixtures to maintain adequate workability despite the lower water content. For the highest-strength mixture

(84 MPa), silica fume was incorporated at 10% by weight of cement together with a low water–cement ratio of 0.25. The addition of silica fume was necessary to achieve the targeted strength level, as it improves particle packing, refines the pore structure, and enhances the interfacial transition zone. Its use also reflects common practice in the production of high-strength concrete and allowed investigation of plastic shrinkage behavior under conditions where bleeding is significantly reduced and sensitivity to early-age moisture loss is increased.

All materials were accurately weighed prior to mixing to ensure consistency. Mixing was carried out in a laboratory drum mixer, where cement and aggregates were first dry-mixed, followed by the addition of water and chemical admixtures. The total mixing time was approximately 2–3 minutes, after which a uniform and cohesive mixture was obtained. Slump tests were performed to verify workability, and minor adjustments, such as adding superplasticizer, were made when necessary to maintain consistent fresh concrete properties. The schematic representation of the concrete mixing process is shown in Figure 2.



FIGURE 2. Schematic representation of the concrete mixing procedure

TABLE 3. Mixture proportions for plastic shrinkage tests.

| Mixture No. | Mixture Proportion by wt. (C: F.A: C. A) | W/C Ratio | Admixture (% wt. of cement) | Silica Fume (% wt. of Cement) | 28-day Com. Strength (MPa) |
|-------------|------------------------------------------|-----------|-----------------------------|-------------------------------|----------------------------|
| 1.          | 1:1.5:3                                  | 0.7       | 0.0                         | 0.0                           | 23                         |
| 2.          | 1:2.2:1.6                                | 0.4       | 1.0                         | 0.0                           | 40                         |
| 3.          | 1:2.2:1.6                                | 0.33      | 5.0                         | 0.0                           | 60                         |
| 4.          | 1:1.0:2.0                                | 0.25      | 5.0                         | 10.0                          | 84                         |

C=Cement, F.A = Fine Aggregate, C. A= Coarse Aggregate

## EXPERIMENTAL PROCEDURES

The experimental program was conducted to investigate the plastic shrinkage behavior of concrete under varying strength levels, casting conditions, and curing regimes. Following modern concrete shrinkage testing methods, the study employed rectangular concrete panels measuring 600x900x30 mm, made with 18 mm plywood and featuring an inner aluminum lining to minimize water absorption by the mold sides, similar to those described Boshoff et al. (2020) and Nasir et al. (2017) in which concrete slabs are exposed to controlled drying conditions and monitored for mass loss and cracking. Forty-three (43) concrete panels were cast indoors following ASTM C1579, with concrete compacted using the tamping technique (Alshammari et al. 2023; Sayahi et al. 2022). The surface was smoothed by sliding a wooden bar in a single direction along the panel's length. Soon after casting, each panel was positioned outdoors on a digital weighing balance to measure mass loss over time. Each panel weighed just over 6 kg and was rigid enough to avoid bending or deflection during handling. An electric fan was set at the 600 mm edge, maintaining a constant wind speed of 15 km/h to simulate natural conditions, while air temperature and relative humidity were continuously monitored. Forty-three concrete panels were prepared and examined in this study. Four curing methods were applied: air-dry curing (AR), water-spray curing (WS), wet burlap curing (BLC), and a resin-based (polyamides) curing compound (RB). Additionally, concrete was cast at four different times: morning (M) from 7 AM to 12 PM, noon (N) from 12 PM to 3 PM, afternoon (AN) from 4 PM to 6 PM, and evening (E) from 7 PM to 12 AM. Table 4 illustrates the average temperature and humidity for morning, noon, afternoon, and evening throughout the summer in the Jeddah region of Saudi Arabia. The water loss from the concrete was recorded as cumulative water loss (CWL), calculated as the percentage of mixing water loss due to evaporation every 10 to 15 minutes for up to 5 hours. The maximum rate of evaporation ( $\text{kg/m}^2\cdot\text{h}$ ) was calculated using the following formula:

TABLE 4. Average temperature and Humidity at different periods of the day.

| Time of Day        | Temperature (°C) | Humidity (%) |
|--------------------|------------------|--------------|
| Morning (7-11 AM)  | 30-42            | 50-60        |
| Noon (12-3 PM)     | 39-43            | 45-55        |
| Afternoon (4-9 PM) | 35-37            | 45-55        |
| Evening (7-12 AM)  | 31-34            | 55-65        |

Plastic shrinkage cracks were visually observed, and the total area of plastic shrinkage cracking ( $\text{mm}^2$ ) was recorded. The crack initiation time (in minutes) was recorded as the duration from surface finishing to the appearance of the first visible crack. Observations were conducted at 10 to 15-minute intervals for up to 5 hours, documenting the quantity of cracks, their lengths, and widths. The experiments took place in the summer. The plastic shrinkage testing program included multiple variables, so each test specimen was clearly labeled to indicate its specific test conditions. For instance, panel P-23-M denotes a plain concrete panel made with a 23 MPa mixture, placed outdoors during the morning exposure period (7-12 AM). The schematic of the experimental program is shown in Figure 3.

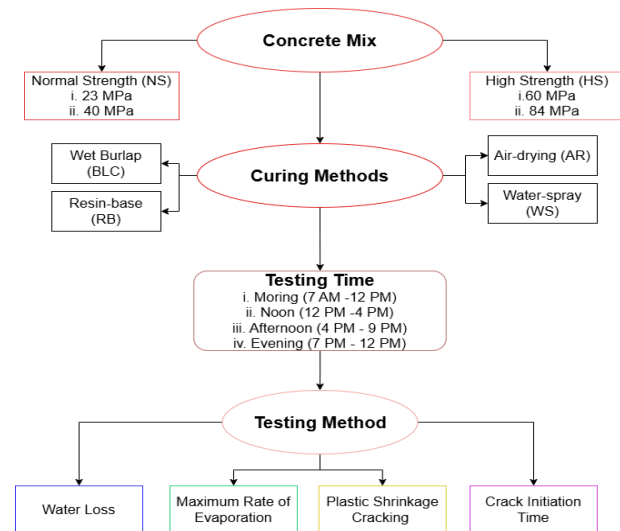


FIGURE 3: Schematic representation of Experimental Procedure.

## RESULTS AND DISCUSSION

Table 5 presents a summary of the test conditions and measured responses for all concrete panel specimens. The table includes mixture proportions, environmental exposure parameters, curing methods, and resulting plastic shrinkage characteristics. Four concrete strength levels (23, 40, 60, and 84 MPa) were examined under different casting times and curing regimes, including air-dry (AR), water spray (WS), wet burlap (BLC), and resin-based curing (RB).

Environmental parameters recorded during testing include air temperature, relative humidity, and wind speed. Although the wind speed was kept constant at 15 km/h for all panels, temperature and humidity varied significantly with casting time. Noon exposure generally corresponded

to higher temperatures (up to about 44 °C) and lower humidity, while evening conditions were associated with lower temperatures and higher humidity. The maximum evaporation rate ranged from approximately 0.22 to 2.22 kg/m<sup>2</sup>·h. The highest evaporation rates were consistently observed for air-dried panels cast at noon, particularly for lower-strength concrete with higher water–cement ratios. In contrast, panels cured with resin-based curing showed substantially lower evaporation rates, typically around 0.22 kg/m<sup>2</sup>·h, regardless of concrete strength or casting time.

Cumulative water loss followed similar trends. Air-dried specimens experienced the highest total water loss, reaching values above 55% in some high-strength concretes. Water-spray curing reduced water loss but remained sensitive to environmental severity. Wet burlap curing significantly limited water loss, while resin-based curing provided the most consistent moisture retention, with total water loss generally below 10–15%. Plastic shrinkage cracking was strongly influenced by both concrete strength and curing methods. No visible cracks were observed in the 23 MPa concrete panels under any exposure condition, indicating sufficient bleeding capacity at this strength level. In contrast, cracking became pronounced in 40, 60, and especially 84 MPa concrete. The largest cracking area, reaching 1118 mm<sup>2</sup>, occurred in the 84 MPa concrete under air-dry curing at noon. Water spray and wet burlap reduced cracking considerably, while resin-

based curing effectively prevented visible cracking across all mixtures and exposure periods.

Crack initiation time further reflected these trends. High-strength concrete subjected to air-dry curing exhibited early cracking, in some cases within 20–30 minutes of finishing. In contrast, panels protected by resin-based or wet burlap curing did not exhibit crack initiation during the monitoring period.

The results obtained in this study are consistent with previous findings on plastic shrinkage behavior. Increased cracking in higher-strength concrete observed under air-dry conditions agrees with studies reporting that low water–cement ratios reduce bleeding and increase susceptibility to early-age cracking (Ghourchian et al. 2018; Snoeck et al. 2020; Soleimanbeigi et al. 2025). In contrast, the absence of cracking in the 23 MPa concrete supports earlier observations that higher bleeding capacity can delay surface drying despite high evaporation rates (Beushausen & Arito, 2018). The early crack initiation recorded in high-strength mixtures is also consistent with studies linking cracking to the imbalance between shrinkage-induced stresses and tensile strength development (Bakhshi & Mobasher 2011). Furthermore, the effectiveness of resin-based curing in preventing cracking aligns with previous research highlighting the superior moisture-retention capability of membrane-forming curing compounds (Al-Gahtani 2010; Maslehuddin et al. 2013).

TABLE 5. Summary of Concrete Panel Test Condition and Results

| Panel No. | Panel Designation | f <sub>c</sub> (MPa) | A/C | W/C | Adm. (%) | SF (%) | Air Temp. (°C) | Rel. Humi. % | Max. rate of Evp. (kg/m <sup>2</sup> ·h) | Total H <sub>2</sub> O Loss % | Total Cracking Area (mm <sup>2</sup> ) | Crack Init. Time (min) |
|-----------|-------------------|----------------------|-----|-----|----------|--------|----------------|--------------|------------------------------------------|-------------------------------|----------------------------------------|------------------------|
| 1.        | AR-23-M           | 23                   | 4.5 | 0.7 | 0        | 0      | 26-34          | 87-95        | 1.22                                     | 38.90                         | 0                                      | 0                      |
| 2.        | AR-23-N           | 23                   | 4.5 | 0.7 | 0        | 0      | 37-40          | 69-78        | 2.22                                     | 56.53                         | 0                                      | 0                      |
| 3.        | AR-23-AN          | 23                   | 4.5 | 0.7 | 0        | 0      | 29-37          | 81-90        | 1.89                                     | 24.76                         | 0                                      | 0                      |
| 4.        | AR-23-E           | 23                   | 4.5 | 0.7 | 0        | 0      | 28-30          | 85-89        | 0.892                                    | 18.52                         | 0                                      | 0                      |
| 5.        | AR-40-M           | 40                   | 3.8 | 0.4 | 1        | 0      | 26-34          | 86-95        | 1.11                                     | 49.17                         | 156                                    | 100                    |
| 6.        | BLC-40-M          | 40                   | 3.8 | 0.4 | 1        | 0      | 27-36          | 82-93        | 0.223                                    | 1.21                          | 0                                      | 0                      |
| 7.        | WS-40-M           | 40                   | 3.8 | 0.4 | 1        | 0      | 28-37          | 88-99        | 0.740                                    | 41.06                         | 80                                     | 130                    |
| 8.        | RB-40-M           | 40                   | 3.8 | 0.4 | 1        | 0      | 28-38          | 80-93        | 0.222                                    | 8.90                          | 0                                      | 0                      |
| 9.        | AR-40-N           | 40                   | 3.8 | 0.4 | 1        | 0      | 35-39          | 70-89        | 2.11                                     | 50                            | 252                                    | 40                     |
| 10.       | BLC-40-N          | 40                   | 3.8 | 0.4 | 1        | 0      | 37-41          | 66-75        | 1.11                                     | 8.76                          | 0                                      | 0                      |
| 11.       | WS-40-N           | 40                   | 3.8 | 0.4 | 1        | 0      | 37-40          | 77-84        | 1.45                                     | 43.26                         | 100                                    | 80                     |
| 12.       | RB-40-N           | 40                   | 3.8 | 0.4 | 1        | 0      | 37-40          | 65-80        | 0.223                                    | 9.18                          | 0                                      | 0                      |
| 13.       | AR-40-AN          | 40                   | 3.8 | 0.4 | 1        | 0      | 29-36          | 81-91        | 1.67                                     | 47.17                         | 172                                    | 60                     |
| 14.       | BLC-40-AN         | 40                   | 3.8 | 0.4 | 1        | 0      | 28-38          | 73-79        | 0.892                                    | 5.42                          | 0                                      | 0                      |
| 15.       | WS-40-AN          | 40                   | 3.8 | 0.4 | 1        | 0      | 34-39          | 82-92        | 0.892                                    | 27.50                         | 90                                     | 90                     |
| 16.       | RB-40-AN          | 40                   | 3.8 | 0.4 | 1        | 0      | 28-38          | 73-79        | 0.222                                    | 7.16                          | 0                                      | 0                      |
| 17.       | AR-40-E           | 40                   | 3.8 | 0.4 | 1        | 0      | 29-30          | 98-99        | 0.444                                    | 26.26                         | 0                                      | 0                      |

*continue...*

...cont.

|     |           |    |     |      |   |    |       |       |       |       |      |     |
|-----|-----------|----|-----|------|---|----|-------|-------|-------|-------|------|-----|
| 18. | AR-60-M   | 60 | 3.8 | 0.33 | 5 | 0  | 29-40 | 67-93 | 0.963 | 47.74 | 217  | 80  |
| 19. | BLC-60-M  | 60 | 3.8 | 0.33 | 5 | 0  | 27-37 | 79-91 | 1.00  | 4.29  | 0    | 0   |
| 20. | WS-60-M   | 60 | 3.8 | 0.33 | 5 | 0  | 30-37 | 85-98 | 1.89  | 58.93 | 0    | 0   |
| 21. | RB-60-M   | 60 | 3.8 | 0.33 | 5 | 0  | 27-38 | 79-91 | 0.223 | 13.45 | 0    | 0   |
| 22. | AR-60-N   | 60 | 3.8 | 0.33 | 5 | 0  | 36-41 | 70-85 | 1.67  | 54.09 | 375  | 30  |
| 23. | BLC-60-N  | 60 | 3.8 | 0.33 | 5 | 0  | 35-38 | 78-84 | 1.22  | 9.83  | 0    | 0   |
| 24. | WS-60-N   | 60 | 3.8 | 0.33 | 5 | 0  | 36-38 | 77-84 | 1.33  | 39.94 | 26   | 100 |
| 25. | RB-60-N   | 60 | 3.8 | 0.33 | 5 | 0  | 35-38 | 77-84 | 1.00  | 11.17 | 0    | 0   |
| 26. | AR-60-AN  | 60 | 3.8 | 0.33 | 5 | 0  | 30-38 | 80-93 | 1.55  | 28.66 | 223  | 50  |
| 27. | BLC-60-AN | 60 | 3.8 | 0.33 | 5 | 0  | 31-39 | 67-75 | 1.22  | 11.06 | 0    | 0   |
| 28. | WS-60-AN  | 60 | 3.8 | 0.33 | 5 | 0  | 30-38 | 67-75 | 1.45  | 47.14 | 0    | 0   |
| 29. | RB-60-AN  | 60 | 3.8 | 0.33 | 5 | 0  | 30-38 | 67-75 | 0.223 | 4.61  | 0    | 0   |
| 30. | AR-60-E   | 60 | 3.8 | 0.33 | 5 | 0  | 27-29 | 98-99 | 0.333 | 23.24 | 0    | 0   |
| 31. | AR-84-M   | 84 | 3.0 | 0.25 | 5 | 10 | 27-36 | 84-93 | 0.889 | 30.18 | 258  | 60  |
| 32. | BLC-84-M  | 84 | 3.0 | 0.25 | 5 | 10 | 27-38 | 83-99 | 0.223 | 2.03  | 0    | 0   |
| 33. | WS-84-M   | 84 | 3.0 | 0.25 | 5 | 10 | 27-44 | 68-90 | 0.780 | 47.01 | 120  | 110 |
| 34. | RB-84-M   | 84 | 3.0 | 0.25 | 5 | 10 | 31-39 | 82-98 | 0.334 | 4.80  | 0    | 0   |
| 35. | AR-84-N   | 84 | 3.0 | 0.25 | 5 | 10 | 37-40 | 78-85 | 1.33  | 55.35 | 1118 | 20  |
| 36. | BLC-84-N  | 84 | 3.0 | 0.25 | 5 | 10 | 37-40 | 78-85 | 1.11  | 32.69 | 0    | 0   |
| 37. | WS-84-N   | 84 | 3.0 | 0.25 | 5 | 10 | 38-44 | 64-82 | 1.45  | 40.94 | 748  | 30  |
| 38. | RB-84-N   | 84 | 3.0 | 0.25 | 5 | 10 | 35-39 | 81-90 | 0.892 | 7.73  | 0    | 0   |
| 39. | AR-84-AN  | 84 | 3.0 | 0.25 | 5 | 10 | 30-38 | 82-94 | 1.11  | 26.23 | 293  | 20  |
| 40. | BLC-84-AN | 84 | 3.0 | 0.25 | 5 | 10 | 31-40 | 68-98 | 1.00  | 2.40  | 0    | 0   |
| 41. | WS-84-AN  | 84 | 3.0 | 0.25 | 5 | 10 | 31-41 | 69-90 | 1.00  | 30.55 | 141  | 30  |
| 42. | RB-84-AN  | 84 | 3.0 | 0.25 | 5 | 10 | 34-38 | 82-93 | 0.223 | 7.53  | 0    | 0   |
| 43. | AR-84-E   | 84 | 3.0 | 0.25 | 5 | 10 | 29-30 | 98-99 | 0.222 | 13.00 | 0    | 0   |

A/C: Aggregate/cement ratio, w/c: water/cement ratio, Adm.: Admixture (% by wt. of cement), SF: Silica Fume, Humi: Humidity, Evp: Evaporation.

### WATER LOSS

The evaluation of cumulative water loss (CWL) for specimens cured with burlap cover (BLO) and water spray (WS) proved challenging due to variations in total water content caused by the addition of curing water. As a result, only the specimens treated with the resin-based curing compound were directly compared with those cured by the air-dry method. Figure 3 illustrates the cumulative percentage of mixing water lost by evaporation for concrete panels cured by air-dry and resin-based methods at different casting times (M, N, AN, E). A general pattern of a sharp increase in CWL for composite panels exposed to N, AN, and E was observed across all mixes. The increase in average CWL for NS concrete exposed to N, AN, and E during the initial 3 hours was 44.78%, 30.16%, and 12.16%, compared to increases of 22.44%, 24.8%, and 56.33% for exposure during the subsequent 2 hours. A similar trend was observed for HS concrete, where exposure to N, AN, and E for the initial 3 hours resulted in increases of 48.35%,

33.57%, and 11.82% in CWL, compared to increases of 16.3%, 27.06%, and 51.57% for exposure during the subsequent 2 hours. The initial higher rate of water loss is predominantly due to the dual impacts of water consumption during the initial bout of cement hydration and evaporation driven by ambient climatic conditions. Contrary to the above, both the NS and HS concrete panels exposed to the M condition showed a consistent, but moderate, rise in CWL across all exposure durations of 5 hours, mainly due to a lower water evaporation rate. As expected, the concrete panels cast at noon exhibited the highest CWL, while the samples cast in the evening showed the lowest CWL.

For the 40 MPa concrete specimens, the CWL for plain concrete ranged from 0% to 50%, whereas the CWL for RB-treated concrete was significantly lower, ranging from 0% to 9%. This indicates that the RB curing compound effectively reduced water loss, which can be attributed to its efficient surface reducing ability (Figure 4). The CWL rate in the RB-curing specimens remained relatively consistent throughout the morning, noon, and afternoon.

In contrast, the plain concrete exhibited the highest CWL rate in the morning, gradually decreasing at noon, afternoon, and evening periods. Similarly, for the 60 MPa specimens, the CWL rate in plain concrete was between 0-55%, while in RB-curing concrete, it reduced to 0-13%, as illustrated in Figure 5. The CWL rate in the RB-treated concrete remained constant during the morning and noon but slightly reduced in the afternoon due to lower relative humidity. The CWL rate for plain concrete peaked at noon due to higher temperatures. Furthermore, in RB-curing concrete, the peak CWL rate was observed within the first 2 hours, after which it stabilized.

In the case of 84 MPa concrete, plain concrete exhibited a CWL rate of 0-55%, while RB-curing specimens had a significantly lower rate of 0-7%, as shown in Figure 6. This confirms the effectiveness of the RB curing compound in reducing water loss. The CWL rate for RB-curing specimens remained nearly constant during noon and afternoon, but was lower in the morning due to relatively lower temperatures. In plain concrete, the highest CWL rate was observed at noon, likely due to peak ambient temperatures at that time. Furthermore, the CWL rate in RB-treated concrete was highest during the first hour and

decreased over the next 4 hours, indicating that the curing compound retained moisture more effectively as exposure time increased.

The trends in water loss observed in this study are consistent with existing findings in the literature. (Wang et al. 2024) demonstrated that water loss decreases as curing efficiency improves, with untreated specimens showing the highest losses. Similar behavior was observed in the current study, where air-dried specimens exhibited the maximum cumulative water loss, while moisture evaporation was significantly limited during resin-based curing. Recent studies on self-curing systems further support these results. (Huseien et al. 2024) reported reduced water loss under air curing when effective moisture-retaining agents were used, emphasizing the importance of early-age moisture control. In addition, external water curing has been shown to reduce cumulative water loss and promote microstructural densification, as reported by (Abdul Razak et al. 2004; El-Hallak et al. 2024). These mechanisms are consistent with the reduced water loss and improved cracking resistance observed in the present study under effective curing conditions.

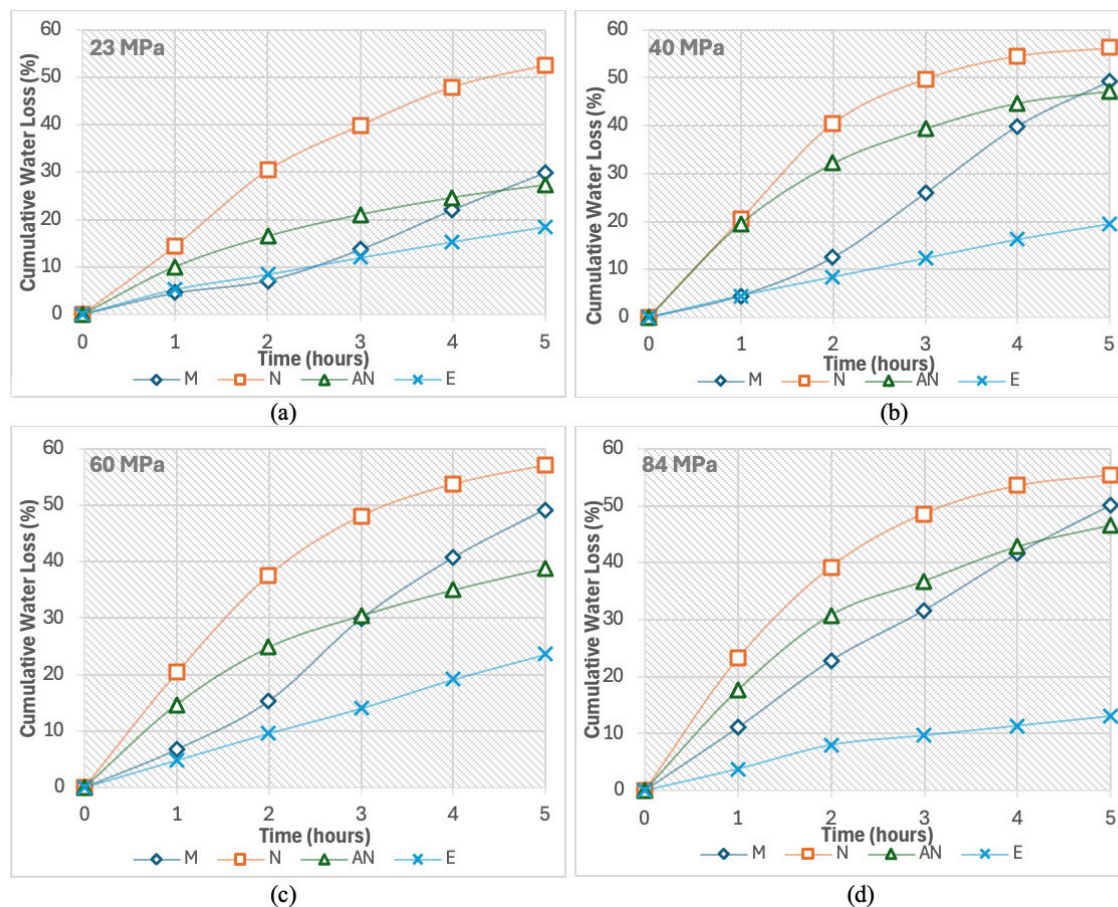


FIGURE 4. Cumulative water loss from different strengths of concrete panels after 5 hours of exposure: (a) 23 MPa concrete, (b) 40 MPa concrete, (c) 60 MPa concrete, and (d) 84 MPa

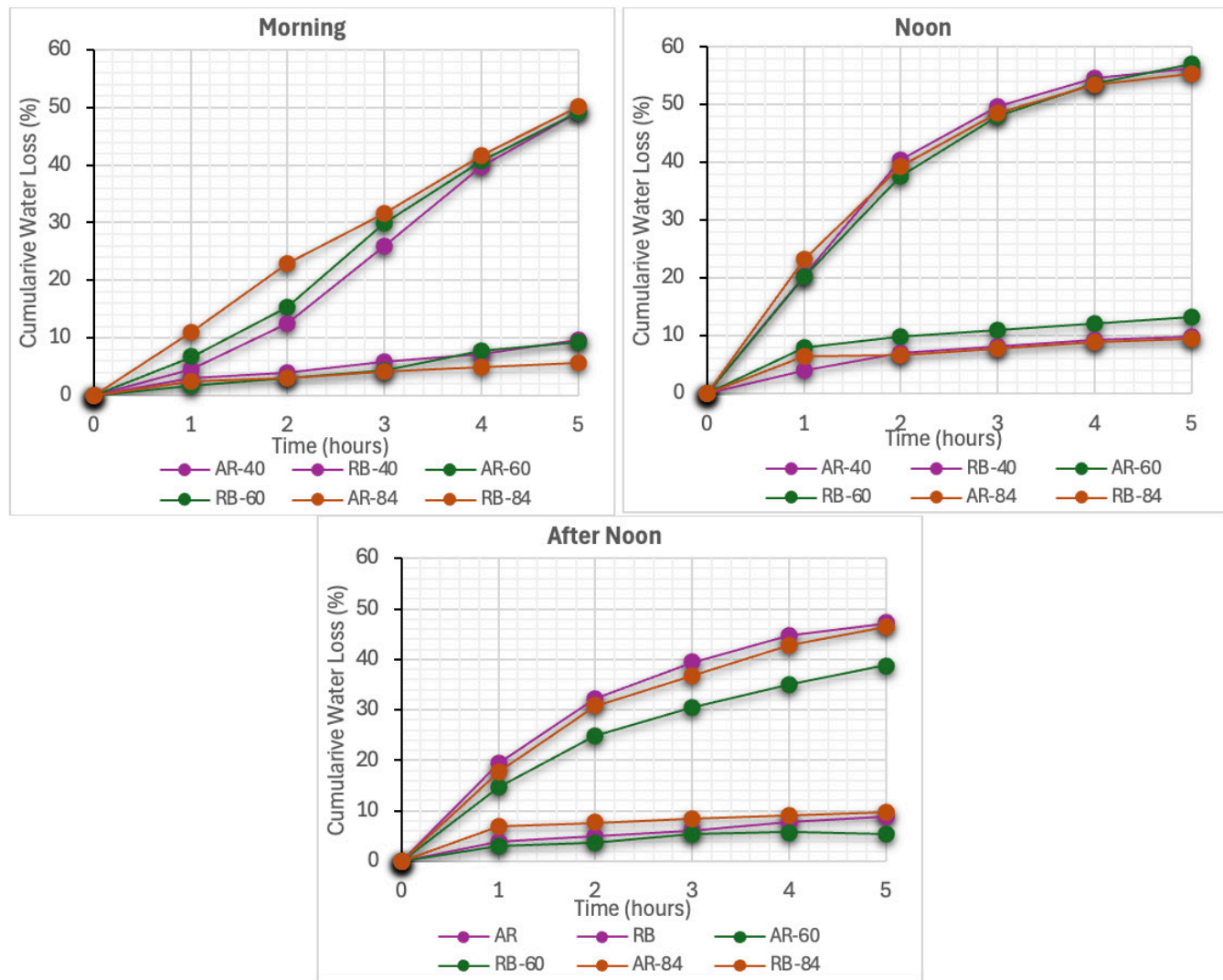


FIGURE 5. Cumulative water loss from air-dried and raised base concrete panels over a 5-hour exposure period for 40 MPa, 60 MPa, and 84 MPa compressive strengths at different casting times.

#### MAXIMUM RATE OF EVAPORATION

The maximum evaporation rates for air-dry concrete across four mixes during the first five hours of air-dry (AR) curing are shown in Figure 5. All concrete mixes had evaporation rates between 0.333 and 2.22 kg/m<sup>2</sup>-h. Notably, the rate peaked at 2.22 kg/m<sup>2</sup>-h at noon for the 23 MPa concrete strength, likely due to high temperatures, while it dropped to 0.334 kg/m<sup>2</sup>-h in the evening for the 60 MPa concrete. The 23 MPa strength mix (WIC ratio = 0.70) exhibited the highest evaporation rate of 2.22 kg/m<sup>2</sup>-h, whereas the other mixes reached a maximum of only 1.3 kg/m<sup>2</sup>-h, indicating that higher strength concrete mixes tend to have lower maximum evaporation rates. Furthermore, Figure 6 shows

the maximum evaporation rates for AR- and RB-curing compounds across the four mixes during the same five-hour window. The minimum evaporation rate observed for 84 MPa plane concrete with the RB curing compound was 0.222 kg/m<sup>2</sup>-h in the afternoon, while the maximum was 1.0 kg/m<sup>2</sup>-h for 60 MPa plane concrete at noon. In pure air-dry conditions, 84 MPa concrete had a minimum evaporation rate of 0.222 kg/m<sup>2</sup>-h in the evening, and a maximum rate of 1.23 kg/m<sup>2</sup>-h was noted in the plane concrete of 40, 60, and 84 MPa at noon. This suggests that concrete treated with the RB curing compound exhibits lower evaporation rates compared to regular plane concrete without RB.

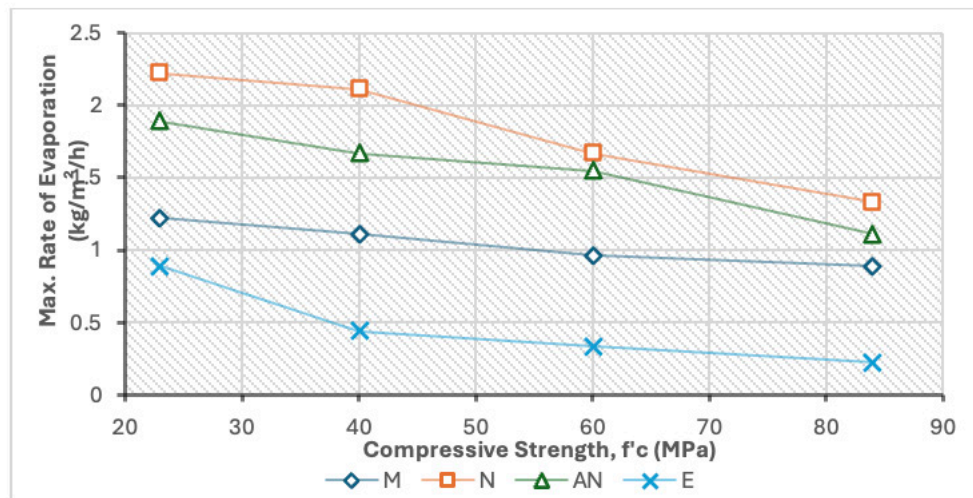


FIGURE 6. Maximum rate of evaporation of Air-Dry concrete panels of different concrete mixes.

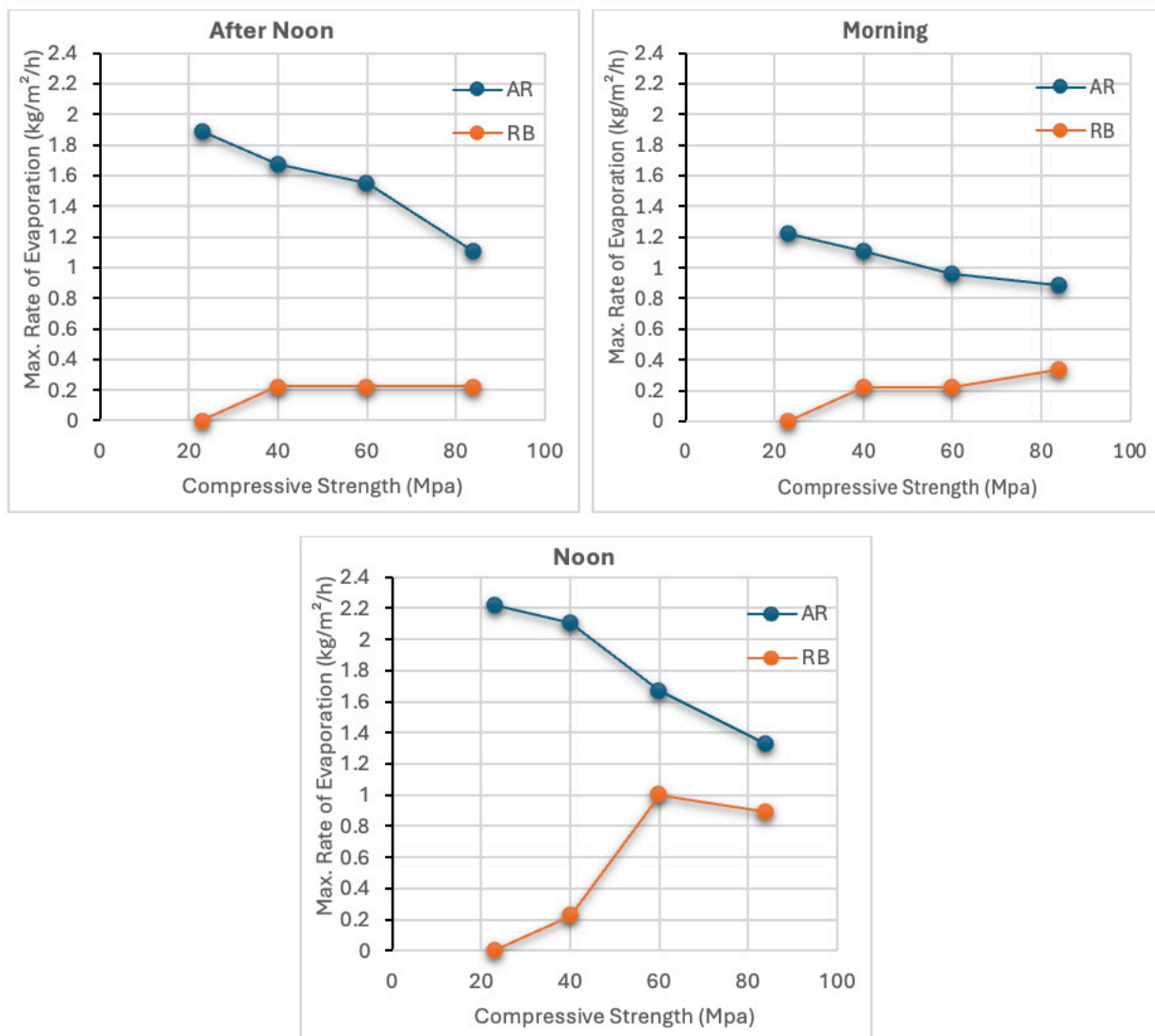


FIGURE 7. Maximum evaporation rate from air-dry and raised base concrete panels of different concrete mixes.

### PLASTIC SHRINKAGE CRACKING

The total area of plastic shrinkage cracking for the different concrete mixes is illustrated in Figure 7. The 23 MPa concrete strength mix showed no cracks under high temperatures, variable relative humidity, and a 15 km/h wind speed. In contrast, when exposed to direct sunlight, the other three concrete strengths (40, 60, and 84 MPa) exhibited cracking. Notably, the extent of cracking increased when the same wind speed was applied. Among these, the 84 MPa concrete panels were the most prone to plastic shrinkage cracking, with a maximum cracking area of 1118 mm. The 23 MPa concrete mix reached a maximum

evaporation rate of 1.67 kg/m<sup>2</sup>·h without developing any cracks. This lack of cracking is likely due to its higher water-cement (W/C) ratio, which allowed sufficient water to bleed to the surface, keeping it mobile and semi-plastic and thus preventing cracks. On the other hand, plastic shrinkage cracking was apparent in concrete mixes with compressive strengths of 40, 60, and 84 MPa. These three mixes varied in the amount of superplasticizer, while the 84 MPa concrete mix also contained silica fume. Furthermore, the cracking area observed with AR curing was greater than that of the BLC, WS, and RB curing compounds for the 40, 60, and 84 MPa mixes.

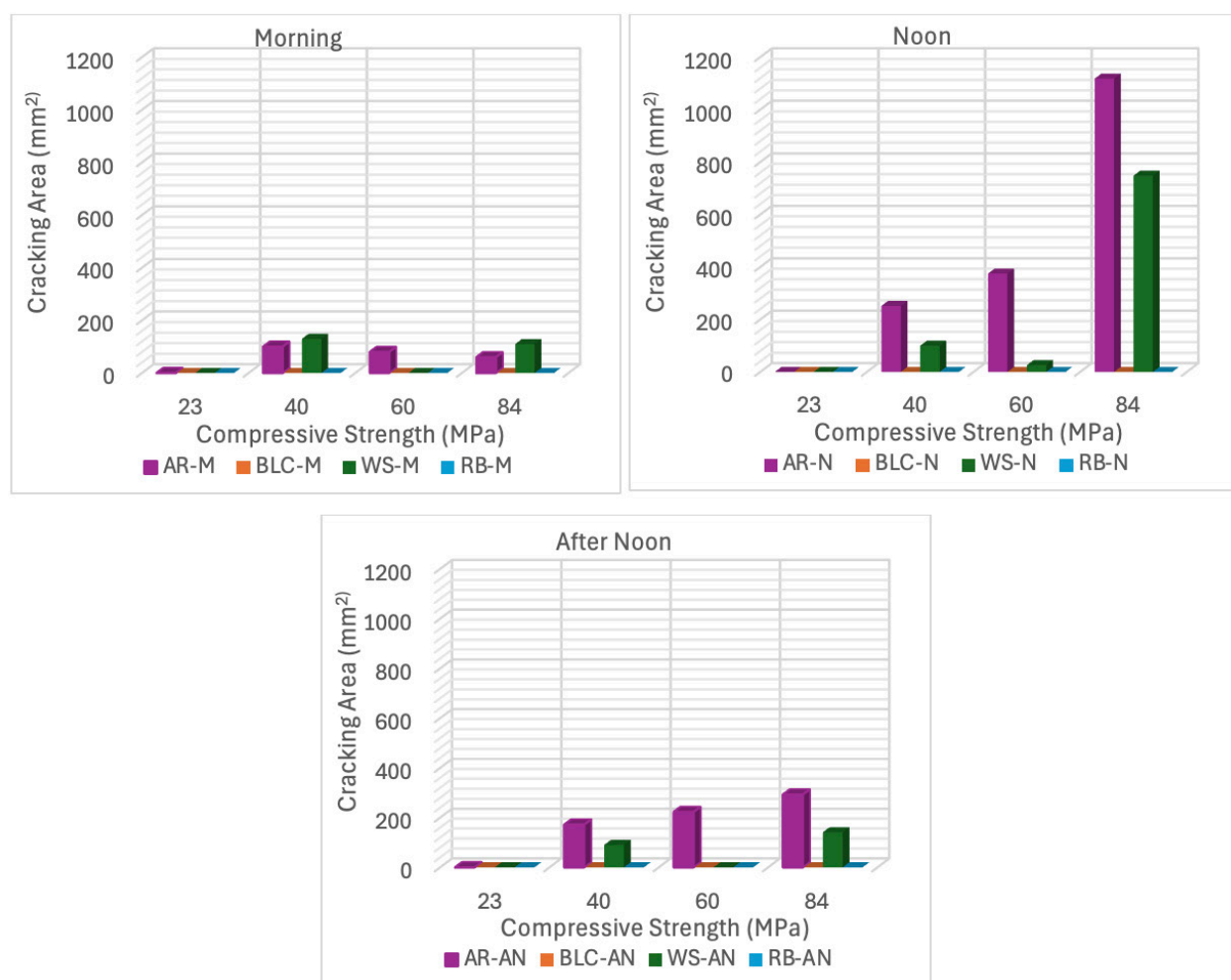


FIGURE 8. Plastic shrinkage area as a function of concrete strength under varying exposure periods.

### CRACK INITIATION TIME

Figure 8 shows the time to first crack of the concrete surface after finishing the panel surface for each mix. The 23 MPa, 40 MPa, and 60 MPa mixes that utilized BLC and RB curing compounds did not exhibit any cracks. Cracking in the 40 MPa mix with AR curing occurred after 30 minutes.

Meanwhile, the high-strength concrete mixes of 60 MPa and 84 MPa started to crack after 30 and 20 minutes, respectively. This indicates that higher concrete strength results in earlier crack formation. Across morning, noon, and afternoon, cracks appeared sooner in the air-dry environment compared to the water spray (WS) method.

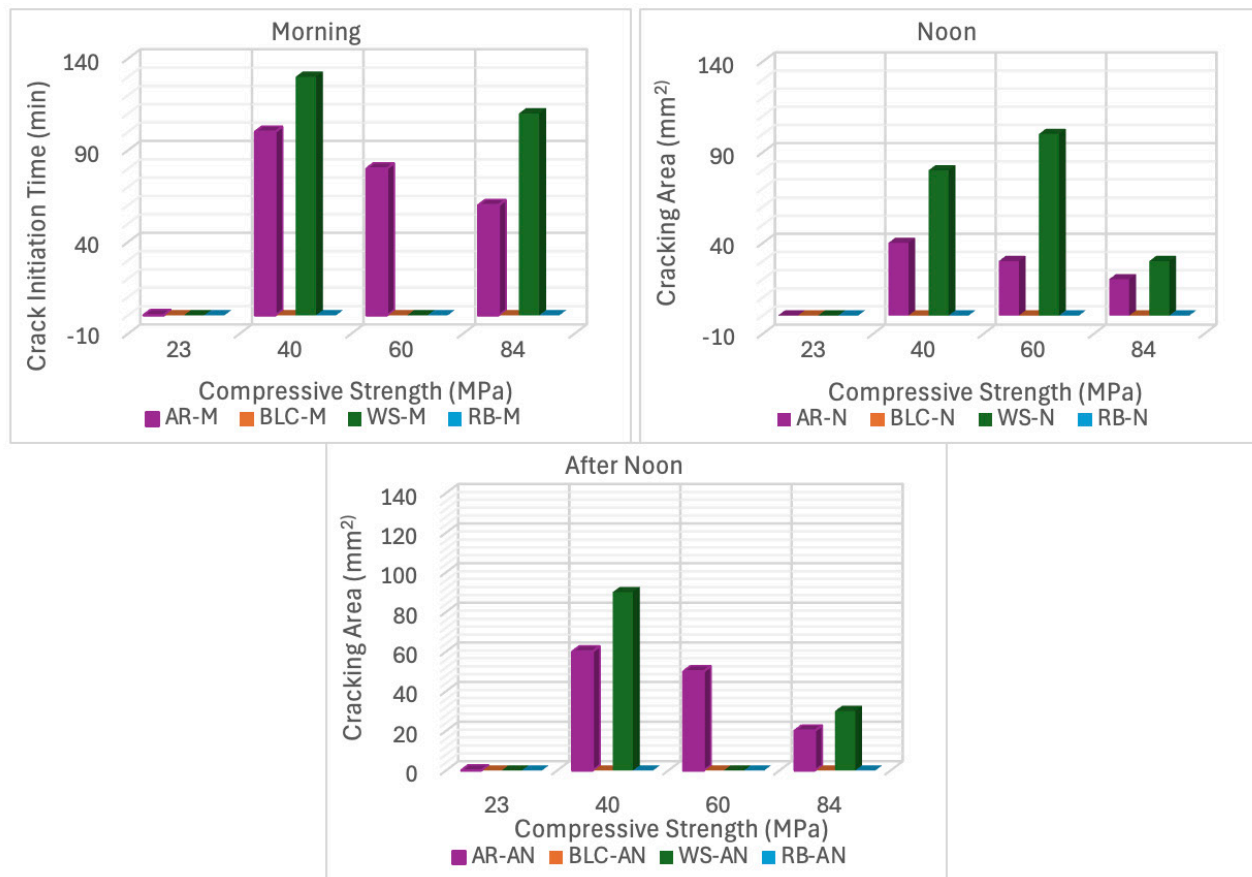


FIGURE 9. Influence of concrete strength on crack initiation time.

## CONCLUSION

The experimental findings highlight how compressive strength, environmental conditions, and curing methods significantly influence cumulative water loss (CWL) and the cracking behavior of concrete. From these results, the following conclusions can be drawn:

1. It was observed that higher-strength concrete was prone to plastic shrinkage cracking. The 84 MPa concrete mix exhibited the largest area of plastic shrinkage cracking, measured at 1118 mm<sup>2</sup> under AR curing conditions at noon, while the 23 MPa concrete mix showed no visible cracks.
2. Temperature variation and relative humidity in outdoor conditions are crucial factors in forming concrete cracks. Casting concrete at noon is the most critical period when ambient temperatures are high and humidity is low. During this time, 23 MPa concrete shows the highest evaporation rate of 2.22 kg/m<sup>2</sup>-h, while 84 MPa concrete experiences evaporation of about 1.3 kg/m<sup>2</sup>-h, which is 41.4% lower than 23 MPa concrete. In contrast, a significantly lower evaporation rate was observed in the evening, regardless of concrete strength.
3. The highest cumulative water loss (CWL) and the most severe plastic shrinkage cracks were observed under air-dry (AR) curing at noon, reaching 1118 mm<sup>2</sup> for 84 MPa concrete. In contrast, wet burlap (BLC) and water-spray (WS) curing significantly reduced crack formation to 32.69 mm<sup>2</sup> and 40.94 mm<sup>2</sup>, respectively, demonstrating better crack resistance than the AR method. Resin-based (RB) curing proved to be the most effective, minimizing cracks to 7.73 mm<sup>2</sup>, significantly reducing evaporation rates, and enhancing concrete durability across all strength levels.
4. Crack development in high-strength concrete occurred before that in normal-strength concrete. Under air-drying curing, the 84 MPa concrete mix began to crack after 20 minutes, while the 40 MPa concrete cracked after 30 minutes. However, no shrinkage cracks were observed when RB curing was applied to the concrete surface.

The study emphasizes the importance of strategic curing methods and proper timing for concrete casting to enhance durability and serviceability. The effectiveness of the RB curing compound in reducing CWL highlights its potential to improve concrete performance under various environmental conditions. Furthermore, understanding how ambient factors affect concrete behavior enables better planning and execution of preventive strategies, ultimately contributing to the longevity of concrete structures.

## ACKNOWLEDGMENT

This project received funding from the Department of Civil and Environmental Engineering at King Abdulaziz University in Jeddah. The author expresses gratitude to the department for its technical and financial support.

## DECLARATION OF COMPETING INTEREST

None.

## REFERENCES

- Abdul Razak, H., Chai, H.K. & Wong, H.S. 2004. Near surface characteristics of concrete containing supplementary cementing materials. *Cement and Concrete Composites* 26(7): 883–889.
- ACI Committee 224. 2002. *Control of cracking in concrete structures*. ACI 224R-01. Farmington Hills, MI: American Concrete Institute.
- ACI Committee 308. 2016. *Guide to external curing of concrete*. ACI 308R-16. Farmington Hills, MI: American Concrete Institute.
- Ahmed, H., Khalil, W. & Jumaa, N.H. 2018. Shrinkage of high performance lightweight concrete exposed to hot-dry weather conditions. *MATEC Web of Conferences* 162: 02004.
- Al-Amoudi, O.S.B., Maslehuddin, M., Shameem, M. & Ibrahim, M. 2007. Shrinkage of plain and silica fume cement concrete under hot weather. *Cement and Concrete Composites* 29(9): 690–699.
- Al-Gahtani, A.S. 2010. Effect of curing methods on the properties of plain and blended cement concretes. *Construction and Building Materials* 24(3): 308–314.
- Alshammari, T.O., Pilakoutas, K. & Guadagnini, M. 2023. Effect of curing methods on plastic shrinkage cracking. *Construction Materials* 3(2): 244–258.
- Androuët, C. & Charron, J.P. 2021. Shrinkage mitigation of an ultra-high performance concrete submitted to various mixing and curing conditions. *Materials* 14(14): 3982.
- Bakhshi, M. & Mobasher, B. 2011. Simulated shrinkage cracking in the presence of alkali resistant glass fibers. In *Advances in FRC Durability and Field Applications*, edited by Aldea, C.M. & Ekenel, M. ACI Special Publication SP-280-03. Farmington Hills, MI: American Concrete Institute.
- Bertelsen, I.M.G., Ottosen, L.M. & Fischer, G. 2020. Influence of fibre characteristics on plastic shrinkage cracking in cement-based materials: A review. *Construction and Building Materials* 230: 116769.
- Beushausen, H. & Arito, P. 2018. The influence of mix composition, w/b ratio and curing on restrained shrinkage cracking of cementitious mortars. *Construction and Building Materials* 174: 38–46.
- Boshoff, W., Mechtcherine, V., Snoeck, D., Schröfl, C., De Belie, N., Ribeiro, A.B., Cusson, D., Wyrzykowski, M., Toropovs, N. & Lura, P. 2020. The effect of superabsorbent polymers on the mitigation of plastic shrinkage cracking of conventional concrete, results of an inter-laboratory test by RILEM TC 260-RSC. *Materials and Structures* 53(4): 79.
- Collins, T.M. 1989. Proportioning high-strength concrete to control creep and shrinkage. *ACI Materials Journal* 86(6): 576–580.
- Combrinck, R. & Boshoff, W.P. 2013. Typical plastic shrinkage cracking behaviour of concrete. *Magazine of Concrete Research* 65(8): 486–493.
- Combrinck, R., Steyl, L. & Boshoff, W.P. 2018. Interaction between settlement and shrinkage cracking in plastic concrete. *Construction and Building Materials* 185: 1–11.
- El-Hallak, M., El-Hassan, H., El-Dieb, A. & Alzamly, A. 2024. Synergic effect of metal-organic frameworks and process parameters on the properties of concrete subjected to accelerated carbonation. *Construction and Building Materials* 414: 135016.
- Eren, Ö. & Marar, K. 2010. Effect of steel fibers on plastic shrinkage cracking of normal and high strength concretes. *Materials Research* 13(2): 135–141.
- Folorunsho, A.B., Kim, S. & Park, C. 2024. A review on the performance of fibers on restrained plastic shrinkage cracks. *Buildings* 14(8): 2477.
- Ghoddousi, P., Abbasi, A.M., Shahrokhinasab, E. & Abedin, M. 2019. Prediction of plastic shrinkage cracking of self-compacting concrete. *Advances in Civil Engineering* 2019: 1296248.
- Ghouchian, S., Wyrzykowski, M., Baquerizo, L. & Lura, P. 2018. Performance of passive methods in plastic shrinkage cracking mitigation. *Cement and Concrete Composites* 91: 148–155.
- Ghouchian, S., Wyrzykowski, M., Plamondon, M. & Lura, P. 2019. On the mechanism of plastic shrinkage cracking in fresh cementitious materials. *Cement and Concrete Research* 115: 251–263.

- Golewski, G.L. 2023. The phenomenon of cracking in cement concretes and reinforced concrete structures: The mechanism of cracks formation, causes of their initiation, types and places of occurrence, and methods of detection—A review. *Buildings* 13(3): 765.
- Gonzalez-Corominas, A. & Etxeberria, M. 2016. Effects of using recycled concrete aggregates on the shrinkage of high performance concrete. *Construction and Building Materials* 115: 32–41.
- Huseien, G.F., Memon, R.P., Baghban, M.H., Faridmehr, I. & Wong, L.S. 2024. Effective microorganism solution-imbued sustainable self-curing concrete: Evaluation of sorptivity, drying shrinkage and expansion. *Case Studies in Construction Materials* 20: e03255.
- Islam, G.M.S. & Gupta, S.D. 2016. Evaluating plastic shrinkage and permeability of polypropylene fiber reinforced concrete. *International Journal of Sustainable Built Environment* 5(2): 345–354.
- Jacobsen, S., Scherer, G.W. & Schulson, E.M. 2015. Concrete–ice abrasion mechanics. *Cement and Concrete Research* 73: 79–95.
- Kayondo, M., Combrinck, R. & Boshoff, W.P. 2019. State-of-the-art review on plastic cracking of concrete. *Construction and Building Materials* 225: 886–899.
- Lai, M.H., Binhowimal, S.A.M., Griffith, A.M., Hanzic, L., Chen, Z., Wang, Q. & Ho, J.C.M. 2022. Shrinkage, cementitious paste volume, and wet packing density of concrete. *Structural Concrete* 23(1): 488–504.
- Lai, M.H., Binhowimal, S.A.M., Griffith, A.M., Hanzic, L., Wang, Q., Chen, Z. & Ho, J.C.M. 2021. Shrinkage design model of concrete incorporating wet packing density. *Construction and Building Materials* 280: 122448.
- Leemann, A., Nygaard, P. & Lura, P. 2014. Impact of admixtures on the plastic shrinkage cracking of self-compacting concrete. *Cement and Concrete Composites* 46: 1–7.
- Markin, S., Combrinck, R. & Mechtcherine, V. 2024. Specifics of plastic shrinkage in 3D-printed concrete elements. *Cement and Concrete Research* 184: 107512.
- Maslehuddin, M., Ibrahim, M., Shameem, M., Ali, M.R. & Al-Mehthel, M.H. 2013. Effect of curing methods on shrinkage and corrosion resistance of concrete. *Construction and Building Materials* 41: 634–641.
- Moelich, G.M., Kruger, P.J. & Combrinck, R. 2022. A plastic shrinkage cracking risk model for 3D printed concrete exposed to different environments. *Cement and Concrete Composites* 130: 104516.
- Moelich, G.M., van Zyl, J.E., Rabie, N. & Combrinck, R. 2021. The influence of solar radiation on plastic shrinkage cracking in concrete. *Cement and Concrete Composites* 123: 104182.
- Nasir, M., Adesina, A., Ibrahim, M., Khan, M.U., Baghabra Al-Amoudi, O.S., Imran Ali, S., Maslehuddin, M. & Saqer Alotaibi, K. 2022. Role of casting and curing conditions on the strength and drying shrinkage of greener concrete. *Environmental Science and Pollution Research* 29(48): 72598–72610.
- Nasir, M., Alimi, W.O., Adeoluwa Oladapo, E., Imran, M. & Kazmi, Z.A. 2023. Behavior of drying and plastic shrinkage of Portland cement concrete prepared and cured under harsh field. *Developments in the Built Environment* 16: 100252.
- Nasir, M., Baghabra Al-Amoudi, O.S. & Maslehuddin, M. 2017. Effect of placement temperature and curing method on plastic shrinkage of plain and pozzolanic cement concretes under hot weather. *Construction and Building Materials* 152: 943–953.
- Pelisser, F., Santos Neto, A.B.S., La Rovere, H.L. & de Andrade Pinto, R.C. 2010. Effect of the addition of synthetic fibers to concrete thin slabs on plastic shrinkage cracking. *Construction and Building Materials* 24(11): 2171–2176.
- Safiuddin, M., Kaish, A.B.M.A., Woon, C.O. & Raman, S.N. 2018. Early-age cracking in concrete: Causes, consequences, remedial measures, and recommendations. *Applied Sciences* 8(10): 1730.
- Saliba, J., Rozière, E., Grondin, F. & Loukili, A. 2011. Influence of shrinkage-reducing admixtures on plastic and long-term shrinkage. *Cement and Concrete Composites* 33(2): 209–217.
- Samman, T.A., Mirza, W.H. & Wafa, F.F. 1996. Plastic shrinkage cracking of normal and high-strength concrete: A comparative study. *ACI Materials Journal* 93(1): 36–40.
- Sayahi, F., Emborg, M., Hedlund, H. & Ghasemi, Y. 2022. Experimental validation of a novel method for estimating the severity of plastic shrinkage cracking in concrete. *Construction and Building Materials* 339: 127794.
- Sirajuddin, M. & Gettu, R. 2018. Plastic shrinkage cracking of concrete incorporating mineral admixtures and its mitigation. *Materials and Structures* 51(2): 48.
- Sivakumar, A. & Santhanam, M. 2007. A quantitative study on the plastic shrinkage cracking in high strength hybrid fibre reinforced concrete. *Cement and Concrete Composites* 29(7): 575–581.
- Snoeck, D., Moerkerke, B., Mignon, A. & De Belie, N. 2020. In-situ crosslinking of superabsorbent polymers as external curing layer compared to internal curing to mitigate plastic shrinkage. *Construction and Building Materials* 262: 120819.
- Soleimanbeigi, A., Hayati, P., Sobhani, J. & Saffarian, P. 2025. Synergistic effects of *Sporosarcina ureae* and silica fume on self-healing and plastic shrinkage cracks in bio-green concrete pavement. *Results in Engineering* 26: 105526.
- Tutkun, B., Barlay, E.S., Yalçinkaya, Ç. & Yazıcı, H. 2023. Effect of internal curing on shrinkage and cracking potential under autogenous and drying conditions. *Construction and Building Materials* 409: 134078.

- Uno, P.J. 1998. Plastic shrinkage cracking and evaporation formulas. *ACI Materials Journal* 95(4): 365–375.
- Wang, W., Shen, A., Zhou, J., Cang, Y., Zhang, X. & Tong, Y. 2024. Shrinkage evolution and mechanism of self-curing concrete cooperatively cured with superabsorbent polymers and waterborne epoxy coatings. *Journal of Building Engineering* 96: 110606.
- Wyrzykowski, M., Trtik, P., Münch, B., Weiss, J., Vontobel, P. & Lura, P. 2015. Plastic shrinkage of mortars with shrinkage reducing admixture and lightweight aggregates studied by neutron tomography. *Cement and Concrete Research* 73: 238–245.
- Xie, T., Fang, C., Mohamad Ali, M.S. & Visintin, P. 2018. Characterizations of autogenous and drying shrinkage of ultra-high performance concrete (UHPC): An experimental study. *Cement and Concrete Composites* 91: 156–173.
- Yamamoto, Y. & Kobayashi, S. 1986. Effect of temperature on the properties of superplasticized concrete. *ACI Journal Proceedings* 83(1): 80–87.