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MATURITY-BASED PREDICTION OF BATCHING PLANT CONCRETE STRENGTH AND SLUMP LOSS EVALUATION UNDER ENVIRONMENTAL EFFECTS

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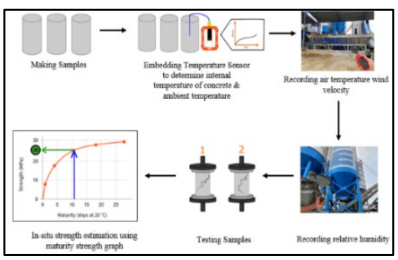
Graphical abstract



Abstract

As large-scale construction projects continue to expand in Bangladesh, the use of batching plants for large-scale concrete production is on the rise. Ensuring the quality and workability of concrete has become increasingly vital, particularly as mass concrete is used for casting. Multiple destructive and non-destructive techniques are utilized to evaluate or estimate the in-situ strength of concrete. Common destructive testing methods include the following tests which are commonly employed to assess concrete strength: splitting tensile strength test, compressive strength, concrete core, bending strength, impact test, semi destructive testing method includes pullout test and Non-destructive techniques, on the other hand, include shock pulse measurement, ultrasonic wave propagation, and maturity testing. The maturity method, which estimates concrete strength during the early curing stages, is a widely accepted indirect approach. This method relies on the concrete's internal temperature, which corresponds to the heat produced by the chemical curing process. While most studies to date have focused on maturity models under controlled laboratory conditions, where temperature and curing are regulated, a significant gap remains in research regarding the application of these models in batching plant trial mixes. In such conditions, environmental variables such as air/wind speed, humidity and ambient atmospheric temperature and can fluctuate significantly, influencing the maturity of the concrete. In most existing calculations, external variables like humidity and ambient atmospheric temperature are often disregarded. This study aims to address these environmental parameters and offers a more precise prediction of concrete strength development in real-world conditions by using a complex maturity model, developed in accordance with ASTM C1074. This model considers ambient temperature, relative humidity, wind speed, and introduces coefficients that reflect the impact of each factor. The incorporation of wind velocity into the maturity equation is an innovative aspect of this study to the best of the author's knowledge. After including wind velocity, the complex maturity approach achieved a coefficient of determination $R^2 = 0.9326$, nearer to R^2 values for standard (ASTM C1074-2019) maturity method which is 0.9694, demonstrating its enhanced reliability aligned with traditional maturity methods. The findings show an inverse relationship between evaporation rate and slump, a key discovery for optimizing the workability of concrete under fluctuating environmental conditions. The evaporation rate was determined using a nomograph found in ACI publications. In conclusion, the study highlights the practical application of the advanced maturity method in large-scale construction projects in Bangladesh.As most previous research has focused on controlled laboratory environments, this method not only allows for an accurate assessment of concrete strength but also optimizes curing time, ultimately improving economic efficiency throughout the construction process.

Keywords: Maturity method, Concrete strength, Environmental factors, Batching plant, Workability, Evaporation rate.

1.0 INTRODUCTION

The construction industry is experiencing rapid growth, with continuous advancements aimed at improving quality, operational efficiency, and reducing overall costs. Innovations in materials, machinery, and production technologies have led to the development of construction products with enhanced strength, durability, and wear resistance. These advancements enhance both the reliability and safety of construction projects, while also substantially increasing cost efficiency, thereby making construction investments more economically viable. One of the key strategies for cost reduction is optimizing construction processes. For example, improving the efficiency of formwork removal can result in considerable time savings, reduced overhead costs, and lower labor expenses [1-2].

Concrete, a key material in the construction sector, ranks as the second most commonly used substance worldwide. Both cement and concrete are essential to the continuous growth and development of civil infrastructure [3].They are widely applied in the construction of significant structures, including skyscrapers, bridges, buildings, stadiums, underground facilities, and power plants [4]. Globally, each year, approximately 30 billion tonnes of concrete are consumed, while cement production surpasses 4 billion tonnes annually [5]. Over time, concrete has evolved with the development of various specialized types, including superior performance concrete, fiber-reinforced concrete, self-compacting mixes, geopolymer-based concrete, and ultra-strength concrete. Recently, there has been growing interest in environmentally sustainable concrete production, with research focused on incorporating alternative cementitious materials and recycled aggregates derived from waste products. A large portion of studies centers around optimization of mix designs, enhancing concrete strength, durability, and the microstructural characteristics of these advanced concrete formulations [6]. By 2024, 56,289 studies on concrete technology have been published, mainly focusing on examining the strength characteristics of concrete [7]. As a result, ensuring adequate strength development during the curing process is vital to preserving the quality of construction [8].

A range of both destructive test and non-destructive methods are employed to assess or estimate the in-situ concrete strength. Destructive testing includes methods such as the compressive strength, splitting tensile strength bending strength, concrete core extraction, pullout and impact test. while non-destructive techniques comprise shock pulse testing, ultrasonic wave propagation, and maturity testing. Concrete samples cured on-site are generally formed and cured according to the standards of the American Society for Testing and Materials (ASTM) C31 (2019). These samples are then analyzed in a lab to determine their compressive strength, following ASTM C39 (2021), typically at intervals shortly after pouring. Timely strength evaluations are crucial for tasks like removal of formwork, curing, and road surface opening. Structural engineers typically authorize the removal of formwork once the concrete attains approximately 75% of its target strength, with typically only three to four specimens tested to gauge the overall strength of concrete.

Developing an innovative method for directly assessing concrete's compressive strength at construction sites is crucial, as it allows for the immediate analysis and interpretation of test results to assess the strength of concrete in real time [15]. This can be accomplished through structural health monitoring systems, which use sensors, microcontrollers, and mathematical algorithms to estimate the compressive strength of concrete [16]. Several studies have incorporated sensors into concrete to track parameters like maturity index, temperature, and electrical resistivity, which are then used to gauge the concrete's strength [17]. Recent studies have placed greater emphasis on digital or automated temperature sensors [18]. The concrete maturity method, a non-destructive testing (NDT) technique, utilizes digital temperature sensors to monitor concrete strength development, which is influenced by the curing temperature of the surrounding environment [19]. Widely used for estimating early concrete strength, especially within the first 14 days, the maturity method depends on monitoring temperature fluctuations throughout the hydration process.. Strength predictions are based on models such as ASTM C1074 (2019) and CEB-FIB (FIB 2012) [17]. These predictions are subsequently verified by contrasting them with experimental data collected.at various intervals (1, 3, 7, 14, and 28 days). By integrating sensor data with the maturity method, it becomes possible to monitor concrete strength in real time [20].This approach, as outlined in ASTM C1074 (2019), is employed on construction sites to evaluate concrete strength, improving construction efficiency and potentially reducing energy and labor costs [21]. Similar to other non-destructive testing techniques, the maturity method does not require the removal or destruction of concrete samples, enabling continuous strength monitoring without compromising the structural integrity of the concrete [22]. This can be accomplished through structural health monitoring systems, which use sensors, microcontrollers, and mathematical algorithms to estimate the compressive strength of concrete [16]. Several studies have incorporated sensors into concrete to track parameters like maturity index, temperature, and electrical resistivity, which are then used to gauge the concrete's strength [17]. Recent studies have placed greater emphasis on digital or automated temperature sensors [18]. The concrete maturity method, a non-destructive testing (NDT) technique, utilizes digital temperature sensors to monitor concrete strength development, which is influenced by the curing temperature of the surrounding environment [19]. Widely used for estimating early concrete strength, especially within the first 14 days, the maturity method depends on monitoring temperature fluctuations throughout the hydration process.. Strength predictions are based on models such as ASTM C1074 (2019) and CEB-FIB (FIB 2012) [17]. These predictions are subsequently verified by contrasting them with experimental data collected.at various intervals (1, 3, 7, 14, and 28 days). By integrating sensor data with the maturity method, it becomes possible to monitor concrete strength in real time [20].This approach, as outlined in ASTM C1074 (2019), is employed on construction sites to evaluate concrete strength, improving construction efficiency and potentially reducing energy and labor costs [21]. Similar to other non-destructive testing techniques, the maturity method does not require the removal or destruction of concrete samples, enabling continuous strength monitoring without compromising the structural integrity of the concrete [22].

The principle of concrete maturity is founded on the notion that the strength and other characteristics of concrete are strongly influenced by both its age and the temperature conditions it experiences. It posits that concrete samples sharing the same maturity index will demonstrate comparable strength, regardless of the exact time and temperature factors that contributed to their maturation.. The maturity index of in-situ concrete, determined by its age and temperature history, is utilized to predict its strength development. This prediction is based on a predefined calibration of the time-temperature-strength correlation, which is determined through laboratory tests conducted on the particular concrete mix [23-26].

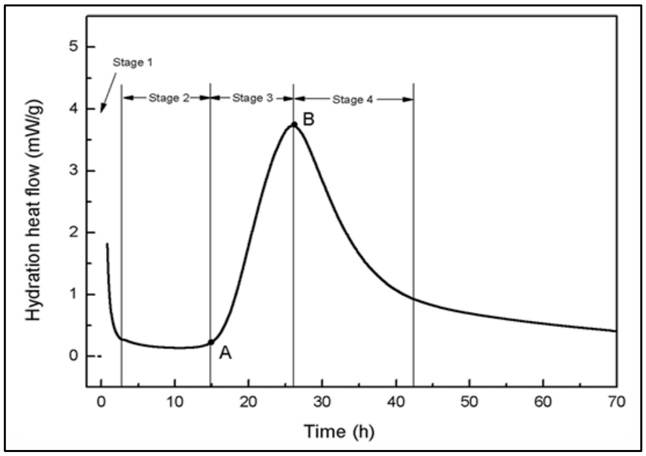


Figure 1 The relationship between heat rate and time during cement hydration [35]

Calculating the maturity index at a specific time requires monitoring the temperature of the concrete during the curing process, which is influenced by the heat released through hydration. Figure 1 illustrates the relationship between hydration heat flow and time during cement hydration, showing different stages of the process. An increased heat of hydration signifies a quicker early strength gain in the concrete [29]. The exothermic hydration reactions are crucial to the strength development of concrete, leading to a significant temperature increase during the early stages of hydration [30]. This heat release is essential for the hydration process, as cementitious materials react with water to produce hydration products within the concrete [31]. Monitoring and quantifying the heat evolution is crucial for understanding the progression of hydration reactions and predicting the concrete's strength [32]. By evaluating the heat generation in freshly mixed concrete, it becomes possible to optimize the mix design, reduce early-age cracking and shrinkage, and ensure structural stability. Furthermore, assessing heat production assists in predicting important concrete properties such as workability, setting time, and strength [33], which are vital for the concrete's overall performance and durability. Forensic analysis of concrete failures can also be conducted by examining heat generation (in Joules), which helps identify early-age problems and determine their underlying causes [34].Despite progress in the field, there is still limited understanding and data regarding the early-age strength development of concrete. Only a small number of studies have successfully predicted early-age strength using temperature-based models [6]. Nzimbi et al. [36] developed a strength-maturity relationship for coral sand concrete incorporating bamboo leaf ash. Calibration curves for estimating strength were derived using various models, including logarithmic, modified exponential, modified hyperbolic, and dose-response Hill models, along with the Nurse-Saul and Arrhenius maturity indices. Reddy et al. [37] investigated different mixtures, including those with polypropylene and fly ash, both with and without coarse aggregate, to assess the real-time strength of concrete using the maturity method. Their study focused on the internal temperature of the concrete, which is influenced by curing chemical reactions, while excluding external factors such as ambient temperature and relative humidity. Utepov et al. [8] enhanced the maturity method based on ASTM C1074 by incorporating the effects of ambient temperature and relative humidity, with coefficients that quantify their impact on the maturity analysis. Lukpanov et al. [38] explored modern technologies, such as wireless sensors and IPS instrumentation, for determining concrete strength in cubic specimens. Tekle et al. [14] examined the application of the maturity method to predict the strength of in-situ concrete slabs subjected to cold weather during early-age curing, utilizing temperature sensors embedded within the slabs to monitor internal temperature for strength estimation. Nandhini and Karthikeyan [6] provided a comprehensive review of research on early-age concrete strength prediction using maturity models and in-situ strength-maturity methods.Kishore S and Arun Kumar A [39] designed a portable, economical automated system utilizing the Internet of Things (IoT) for real-time evaluation of mortar and concrete compressive strength, employing the maturity method in accordance with ASTM C1074. The accuracy of the sensor's strength predictions was confirmed by comparing the estimated compressive strength with experimental results obtained from both accelerated and standard water curing techniques.

Alongside predicting concrete compressive strength through maturity analysis, a separate study was conducted to evaluate concrete workability. Environmental factors, including air temperature, relative humidity, concrete temperature, wind speed, and water evaporation rate, significantly influence the workability of concrete. The slump test was used to evaluate workability, specifically observing changes in slump values due to fluctuations in the water evaporation rate from the concrete. The evaporation rate was calculated using a nomograph (Fig. 2), which incorporates variables such as air temperature, relative humidity, concrete temperature, and wind speed.

The drying process of freshly poured concrete is heavily affected by the evaporative conditions in the job-site microclimate. To estimate the cumulative impact of air and concrete temperature, relative humidity, and wind speed, equations are frequently applied, which are visually depicted in the evaporation rate nomograph (Fig. 2) available in several ACI publications and other references [43]. Both the fresh and hardened properties of concrete are shaped by factors such as air temperature, relative humidity, and wind speed [40-41]. Almusallam found that high temperatures, low humidity, and strong winds—whether individually or in combination—accelerate the evaporation of bleeding water, leading to concrete shrinkage and the development of tensile stresses.

If these shrinkage-induced stresses, which occur due to rapid evaporation of bleeding water, surpass the concrete's tensile strength, cracking may occur. The study also emphasized the influence of environmental conditions during casting on both fresh and hardened concrete properties. It explored how factors like air temperature, wind speed, and relative humidity affect plastic shrinkage, compressive strength, pulse velocity, and the pore structure of concrete. The results highlight that the

exposure conditions during casting significantly affect the overall properties of the concrete.

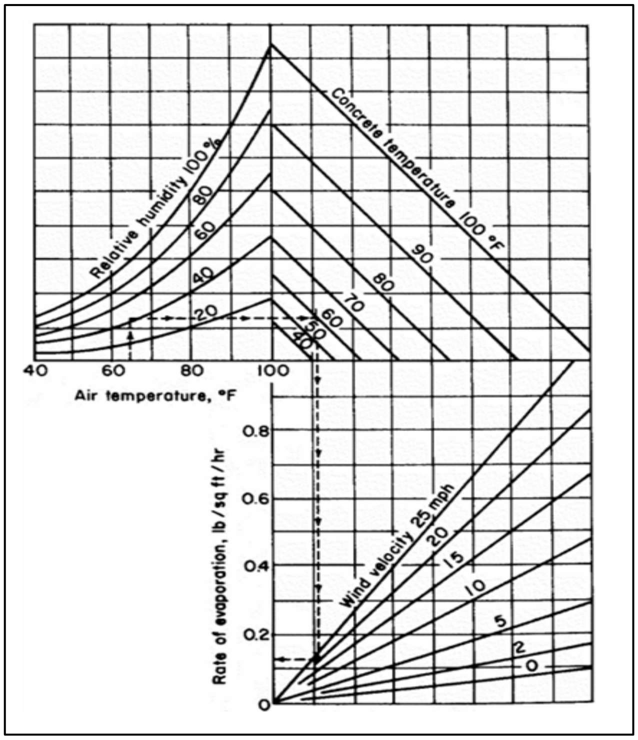


Figure 2 ACI nomograph for estimating the rate of evaporation [43]

As large-scale construction projects continue to grow in Bangladesh, the use of batching plants for producing concrete in substantial quantities is increasing. Ensuring the quality and workability of concrete has become increasingly important in recent times, as mass concrete is being produced for casting. Maintaining the quality of mass concrete presents challenges due to the large volumes involved, making it more difficult to control and monitor consistently. While many existing studies have primarily concentrated on maturity models applied under controlled laboratory conditions, where temperature and curing are regulated, there is a noticeable gap in research regarding the application of these models in batching plant trial mixes, where the environmental conditions, for instance, the surrounding temperature, humidity, and wind velocity, vary significantly and effect of these environmental parameter on maturity of concrete will be investigated in our study to uplift the accuracy of strength prediction through maturity analysis. Furthermore, we aim to integrate all relevant environmental factors, including relative humidity, air temperature along with internal temperature of concrete, and specifically velocity of wind, to develop a more comprehensive equation for calculating maturity. This method aims to offer a more precise prediction of concrete strength under actual field conditions. A key innovation of this study is the incorporation of wind velocity as a parameter in the complex maturity equation, as previous research has not investigated its inclusion in such a model. Furthermore, there is a lack of detailed data on the water evaporation from freshly placed concrete surfaces exposed to the dynamic environmental conditions typically encountered in field settings. The specific effects of environmental variables including relative humidity, air temperature, wind or air speed, and concrete temperature on variations in slump have not been thoroughly examined, yet these factors are critical in influencing the workability of concrete. Therefore, variation of slump value and evaporation rate with time will be observed in this study.

2.0 EVOLUTION OF THE MATURITY METHOD

The maturity method, introduced in England in the 1950s, is a non-destructive technique used to estimate the early strength of concrete. It emerged from research on accelerated curing methods, where scientists investigated the impact of temperature and time on the strength development of concrete. Since its introduction, the method has gained extensive application in North America, especially in pavement engineering, where it is commonly employed in the construction of rigid concrete pavements [44]. The maturity technique was first introduced primarily in the context of steam curing [27]. In its early applications, the method was employed to monitor the progression of concrete strength and to identify the optimal time for formwork removal [28]. Research on the combined influence of time and temperature on concrete strength dates back to the early 20th century. [45]. By the 1950s, several researchers had suggested combining these two factors into a single index [46, 47], with Saul being the first to formally name this index as maturity [47]. In its early applications, the method served both to monitor the strength gain of concrete and to identify the appropriate timing for formwork removal [28]. In 1951, Saul introduced the "maturity rule," It was proposed that, for a specific concrete mix, specimens achieving the same maturity value—defined by the temperature-time relationship—would develop similar strength, irrespective of the particular time and temperature conditions that contributed to that maturity [44]. When Saul initially introduced this concept, a datum temperature of −10.5 °C was used. The maturity principle suggests that concrete exposed to different time-temperature combinations will exhibit comparable strength once the same maturity value is attained, regardless of the exact thermal conditions. This implies that for any given time-temperature combination, a clear correlation exists between strength and maturity function. Carino (1991) further emphasized that "the strength of a concrete mix, when properly placed, consolidated, and cured, is influenced by its age and temperature history" [44]. Figure 3 illustrates the application of the maturity technique for concrete cured under both cold and high temperature conditions. At lower curing temperatures, achieving the target maturity takes longer compared to higher temperatures; however, once the same maturity is attained in both cases, the resulting strength is expected to be equivalent, as shown in Figure 3 [48–49].

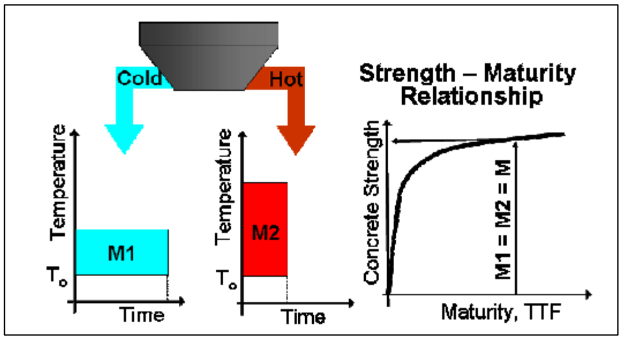


Figure 3: Impact of temperature history on the calculation of maturity [44]

The American Society has formalized the "Standard Practice for Estimating Concrete Strength by the Maturity Method" (ASTM C-1074, 2019) [52], outlining two methods for calculating maturity functions—the equivalent age method and the method named temperature-time factor. These methods are extensively used in research to evaluate the maturity index based on recorded temperature histories [48–56].

Establishing the strength-maturity relationship requires several coordinated steps with the concrete mix. Initially, both strength development and temperature history must be tracked. This involves casting multiple specimens and performing strength tests at different ages, while temperature data is collected through a monitoring device embedded in the fresh concrete. Common methods for evaluating strength include compression testing of molded cylinders and bending testing of beams. During these tests, the maturity of the concrete should also be recorded [44]. Maturity is calculated by analyzing the temperature data to determine the maturity index at the particular time of each strength evaluation. After gathering all strength data along with their respective maturity indices, the strength-maturity relationship can be established using the data and computational analysis tools [48–49].

3.0 MODELS ON CONCRETE MATURITY

3.1 Existing Models To Determine Maturity Index

Maturity models are essential tools used to estimate the strength development of concrete during its curing process. These models provide a means to predict concrete maturity by considering factors such as temperature, curing time, and sometimes environmental conditions. The maturity index offers a practical method for assessing concrete strength in the early stages of curing, which is crucial for ensuring that concrete reaches its required strength for structural integrity. Various models have been developed over time to improve the accuracy of maturity calculations, each considering different variables and environmental influences. This section explores the existing models used to determine the maturity index. ASTM C 1074 specifies two distinct forms of maturity functions:

3.1.1 Maturity Model of Nurse & Saul

McIntosh (1949) was the first to recognize that the progression of concrete strength could be attributed to the combined influence of time and temperature. He introduced the concept of a "datum temperature," which he described as the "no-hardening temperature," below which no strength development would occur. McIntosh found that concrete strength development could be effectively modeled by multiplying time and temperature. However, this simplified method proved to be inaccurate under varying curing temperatures. Nurse (1949), a researcher investigating accelerated curing techniques, studied steam curing and examined specimens exposed to different curing temperatures and durations. By plotting concrete strength against the time-temperature product, Nurse observed a curved relationship. Building on Nurse's work, Saul (1951) introduced the concept of "maturity" and defined it as the time-temperature factor. He also integrated McIntosh's concept of the reference temperature, leading to the development of a mathematical expression for the maturity concept, known as the Nurse-Saul maturity function, which is detailed in ASTM C 1074 (2011) [57]:

$$M(t) = \sum_{t=0}^{t*} (Ta - To).\Delta t$$

Where:

M(t) = maturity, represented as the time-temperature product at age t* (°C·hrs)

Δt = time interval (hrs)

t* = concrete age at the time of strength estimation (hrs)

Ta = average concrete temperature during Δt (°C)

T_0 = datum temperature (°C)

Figure 4 displays a diagram depicting the use of the Nurse-Saul maturity function and its related parameters. The temperature history is shown by the blue curve, while the grey shaded region represents the maturity or time-temperature factor, calculated using the Nurse-Saul approach. The figure also highlights the datum temperature (T_0), noting that any time-temperature values below this threshold are excluded from the maturity calculation [57].

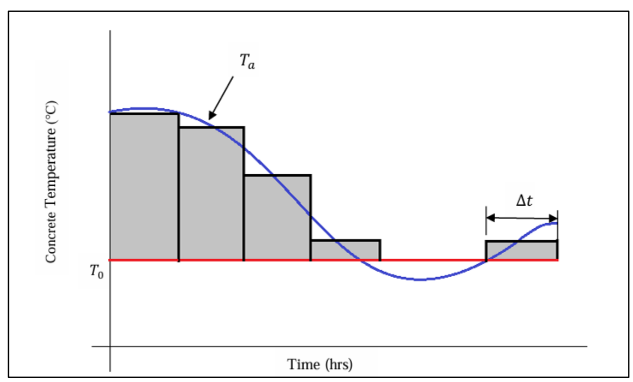


Figure 4 Utilization of the Nurse-Saul maturity function [44]

In 1951, Saul [58] established a datum temperature of −10.5°C for application in the maturity function.Later, in 1992, Carino and Tank [60] conducted experimental studies on various cement types and water-binder ratios ratios as mentioned in Table 1, revealing that Saul's proposed datum temperature was often inaccurate, as it tended to be above 0°C. They also found that the inclusion of cement replacement materials influenced the reference temperature. Furthermore, Wade [59] evaluated the maturity method for predicting concrete strength and concluded that the Nurse-Saul maturity function provided more accurate strength forecasts when a reference temperature of 0°C was used within a curing temperature range of 4°C to 40°C.

Table 1 Datum Temperatures Determined through Experimentation [53]

Cement Type	w/c = 0.45	w/c = 0.60
Type I	11°c	9°c
Type II	9°c	6°c
Type III	7°c	7°c
Type I + 20% Fly Ash	-5°c	0°c
Type I + 50% Slag	8°c	10°c
Type I + Retarder	5°c	5°c
Type I + Accelerator	8°c	9°c

3.1.2 Arrhenius Maturity Model

The Arrhenius equation was first used to model concrete strength development after it was discovered that the effect of temperature on the rate of cement hydration could be effectively described using the Arrhenius equation within a temperature range of 4.4°C to 110°C. This concept was later extended when a function derived from the Arrhenius equation was introduced to calculate maturity in terms of Equivalent Age, using the apparent activation energy of concrete.The Nurse-Saul maturity function is defined as follows [57]:

$$Te = \sum_{t=0}^{t*} e^{-Q[\frac{1}{Ta} - \frac{1}{Ts}]} . \Delta t \qquad (2)$$

Where:
Te = Maturity expressed as Equivalent Age (hrs)
Δt = Time interval (hrs)
t* = Concrete age at the time of strength estimation (hrs)
Ta = Average concrete temperature during Δt (K)
Ts = Specified temperature (K)
Q = Activation energy (E) divided by the universal gas constant (R)

ASTM C 1074 (2011) recommends an activation energy range of 40,000 J/mol to 45,000 J/mol for Type I cement without admixtures, though it does not provide specific guidelines for other cementitious materials. Similar to the approach for determining datum temperature in the Nurse-Saul maturity function, ASTM C 1074 (2011) details an experimental method for measuring activation energies, which was initially developed by Carino and Tank [55]. In the same study where datum temperatures were established, activation energies were also calculated and are summarized in Table 2 presented in J/mol [57]:

Table 2 Activation Energies Determined Experimentally [55]

Cement Type	w/c = 0.45	w/c = 0.60
Type I	63,000 J/mol	48,000 J/mol
Type II	51,100 J/mol	42,700 J/mol
Type III	43,000 J/mol	44,000 J/mol
Type I + 20% Fly Ash	30,000 J/mol	31,200 J/mol
Type I + 50% Slag	44,700 J/mol	56,000 J/mol
Type I + Retarder	44,600 J/mol	50,200 J/mol
Type I + Accelerator	38,700 J/mol	38,700 J/mol

3.2 Correlation Between Concrete Strength And Maturity

To investigate the correlation between concrete cube strength and maturity, a best-fit curve is created by plotting the compressive strength test results against their respective maturity values. This curve, referred to as the calibration graph for the strength-maturity relationship, is used to predict the in-situ strength of the concrete [57,6].

Carino (1991) identified three types of curves to describe the strength-maturity relationship: Hyperbolic (Carino, 1991), logarithmic (Plowman, 1956), and exponential (Freiesleben Hansen & Pederson, 1977) models. According to Carino’s findings, ASTM C1074 recommends using either the exponential or hyperbolic models. He pointed out that the logarithmic model has certain drawbacks, as it assumes strength increases continuously with maturity and does not accurately reflect the nearly linear trend observed at low maturity levels [57].

3.2.1 Logarithmic Function

The logarithmic function, proposed by Plowman in 1956 [61] and presented in equation (3), is used to represent the maturity index. When represented on a logarithmic scale, it produces a straight-line curve, which fails to accurately depict the true strength-maturity relationship. This model implies that strength keeps increasing as the maturity index rises, without considering a maximum strength limit. Studies have shown that the logarithmic model tends to overpredict in-situ concrete strengths [62,63].

$$S = a + b \log M \qquad (3)$$

Where a is the constant representing strength in MPa and b is the constant for the maturity rate in MPa/hrs or MPa/°C·hrs.

3.2.2 Exponential Function

Hansen & Pedersen (1991) explored the development of concrete strength under isothermal curing conditions and introduced an exponential model to describe this process. The model is given by the following equation:

$$S = S_u * e^{-(\frac{\tau}{m})^{\beta}} \qquad (4)$$

Here, τ represents the time constant (hrs.), and β is the shape parameter. This function describes the gradual development of strength during the curing process. The time constant (τ) indicates the age at which concrete reaches 37% of its ultimate strength (Su) [62]. Buys (2019) [64] noted that the hyperbolic model is particularly sensitive to strength changes at early ages compared to later stages. Based on this observation, the exponential model is proposed for accurately predicting both early and later strength developments.

3.2.3 Adjusted Hyperbolic Model

The modified hyperbolic function, introduced by Carino (1991) [65], is described by the equation below:

$$S = Su * \frac{k(M - Mo)}{1 + k(M - Mo)} \qquad (5)$$

In this context, S denotes the compressive strength in MPa, Su represents the ultimate compressive strength in MPa, M refers to maturity, which can be expressed as either equivalent age (hours) or temperature-time factor (°C·hours), k is the rate constant for strength development (1/°C·hours), and Mo indicates the maturity threshold at which concrete starts to gain strength. The parameters Su, k and $M0$ are determined through regression analysis based on curing temperatures for each concrete mix. According to ASTM C 1074 [66], the modified hyperbolic function is recommended for modeling concrete strength. Carino (1991) introduced a maturity offset (MO) to reflect that strength development only initiates once the maturity surpasses a specific threshold. A higher rate constant (k) indicates rapid strength development, while a lower rate constant suggests slower strength development. Carino and Lew (1992) [62] recommended the modified hyperbolic model for analyzing concrete strength-maturity data for up to 28 days.

4.0 METHODOLOGY

This study focuses on predicting the strength of concrete produced in a batching plant through maturity-based methods, incorporating environmental variables such as ambient temperature, wind speed, air humidity, and concrete temperature. To accurately assess maturity, the internal temperature of the concrete and the surrounding ambient temperature were recorded using thermometers. Relative humidity was measured with a hygrometer, while wind velocity was monitored using an anemometer. Beside that some more equipment's has been shown in figure 7(a,b) for maturity testing by Helal et al. (2015) [19] and also for concrete temperature monitoring with wireless sensors by Barroca et al. (2013) [70].

Three concrete trial mixes with varying proportions of fine aggregate, coarse aggregate, cement, and water were prepared for both laboratory testing and batching plant production. And we have chosen trial mix 1 with ratio 1: 1.59: 2.32 for maturity based prediction of concrete strength and monitored the value of concrete strength starting from day 1 upto day 28 which is furnished in Table 9 and consequently complex maturity equation was developed considering the environmental variables and plotted against the concrete strength of batching plant (Figure 13) and brief illustration of methodology has been depicted in Figure 6.

Slump values were recorded for the batching plant mixes, with the concrete temperature monitored during slump testing using a digital thermometer. Environmental factors such as wind velocity, air temperature, relative humidity & concrete temperature influence moisture evaporation from the concrete, which in turn affects slump and overall workability. Consequently, the evaporation rate is a critical factor in determining concrete workability. For given conditions of mix temperature, wind velocity, air temperature, relative humidity and the evaporation rate was estimated using the nomograph presented in Figure 2. This nomograph, referenced in several ACI publications [43], illustrates the relationship between temperature, humidity, wind speed, and water evaporation rate from concrete. Furthermore, evaporation rate was plotted against the slump value obtained for particular environment variables and relation between slump value and concrete evaporation rate are assessed for both the batching plant and laboratory trial mixes to assess the variations across the two environments illustrated in Figure 11 (a,b,c) and Figure 12 (a,b,c).

Concrete mixes were designed according to ACI mix design procedures in both cases. Cylindrical specimens measuring 200 millimeter in height and 100 millimeter in diameter were cast, cured, and tested for compressive strength at intervals ranging from 1 to 28 days.

4.1 Development of Complex Maturity Equation Considering Environmental Parameters

Utepov et al. refined the traditional Nurse-Saul method for assessing concrete maturity by integrating additional environmental factors, such as the internal temperature of the concrete, ambient temperature, and relative humidity, into the original maturity equation. This improved approach, referred to as complex maturity (Mc), incorporates three main parameters: internal temperature (IT), ambient temperature (AT), and ambient relative humidity (ARH). The modified model is expressed in Equation (6) [8].

$$M_c = \sum M_i . \gamma_i = M_{IT} . \gamma_{IT} + M_{AT} . \gamma_{AT} + M_{ARH} . \gamma_{ARH} \tag{6}$$

$$M_{IT} = M(t);\ M_{AT} = \sum(AT.\Delta t);\ \ M_{AT} = \sum(ARH.\Delta t) \tag{7}$$

In this context, i represents the different factors affecting the concrete's strength development, including internal temperature (IT), ambient temperature (AT), and ambient relative humidity (ARH), each of which contributes to the overall maturity of the concrete. The maturity of each parameter (IT, AT, and ARH) is calculated using Equation (7). The average weight of each parameter over the 28-day curing period is determined by Equation (8), which captures the collective influence of these factors on the strength of the concrete during the curing process [8].

$$\Upsilon_i = \frac{1}{28}\sum_{t=1}^{t=28} \gamma_{i,t} \tag{8}$$

Expanding on the aforementioned factors of internal temperature (IT), ambient temperature (AT), and ambient relative humidity (ARH), Equation (8) can be further expanded to incorporate these factors in Equation (9) [8].

$$\Upsilon_{IT} = \frac{1}{28}\sum_{t=1}^{t=28} \gamma_{IT,t}\ ; \Upsilon_{AT} = \frac{1}{28}\sum_{t=1}^{t=28} \gamma_{AT,t}\ ; \Upsilon_{ARH} = \frac{1}{28}\sum_{t=1}^{t=28} \gamma_{ARH,t} \tag{9}$$

Wind velocity (WV) is another important factor that might affect the evaporation rate, which subsequently influences the maturity of concrete. Wind velocity contributes to cooling the concrete's surface and can impact the hydration process.

To incorporate the effect of wind velocity (WV) in km/hr., an additional parameter will be introduced into the maturity equation:

$$Mwv = \sum WV.\Delta t \tag{10}$$

Incorporating wind velocity into the model improves its accuracy in predicting concrete strength development under diverse real-world environmental conditions using the maturity function. The maturity value associated with wind velocity is incorporated into the overall complex maturity equation as an additional factor.

Therefore, Equation (6) can be expanded as

$$M_c = \sum M_i.\gamma_i = M_{IT}.\gamma_{IT} + M_{AT}.\gamma_{AT} + M_{ARH}.\gamma_{ARH} + M_{WV}.\gamma_{WV} \quad (11)$$

$$\Upsilon WV = \frac{1}{28}\sum_{t=1}^{28} \Upsilon wv\,.\,t \quad (12)$$

In this study, the contribution of each environmental parameter—internal temperature (IT), ambient temperature (AT), ambient relative humidity (ARH), and wind velocity (WV) at a specific time t is calculated using Equation (13) [8]:

$$\Upsilon i, t = |r_{i,t}| / \sum |r_{i,t}| \quad (13)$$

Where ϒi,t denotes the correlation between each environmental variable (AT, IT and ARH) and the concrete's compressive strength at curing age t, which ranges from 1 to 28 days. It is essential to highlight that the sum of all the weights consistently equals 1, as expressed in Equation (14) [8]:

$$\sum \gamma_{i,t} = \sum \gamma_i = 1 \quad (14)$$

4.2 Evaluating Methods for Maturity Function Analysis

The maturity function concept allows for the development of a mixture-specific calibration curve that correlates maturity with the compressive strength of concrete, as shown in Figure 6. This relationship, together with the predicted in-situ maturity of the concrete, is subsequently used to estimate its in-situ strength [67].

Figure 5 (a) Measuring wind velocity and air temperature using anemometer (b) Measuring relative humidity using hygrometer

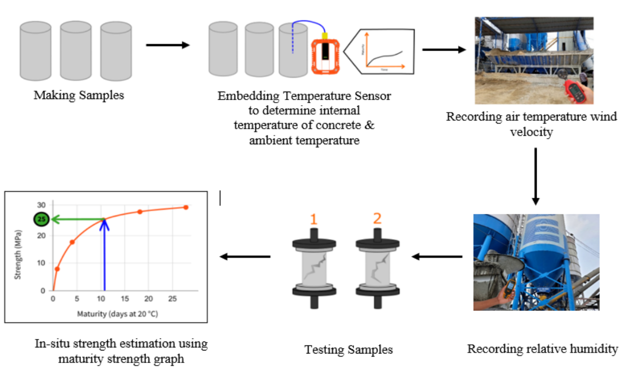


Figure 6 Research Methodology for Experimental Analysis

The maturity testing system, including the thermocouple configuration, is depicted in Figure 7 [69]. Thermocouples embedded within the fresh concrete continuously track internal temperature variations over time. This temperature data is then used to calculate a maturity index, providing a reliable estimate of the concrete's early-age properties. The experimental procedure followed ASTM C-1074 standards. The maturity function was determined by placing a sensor inside the concrete cube, as shown in Figure . 6(b). A wireless sensor, encased in cement mortar, was embedded within the cube. A custom data acquisition system was developed to capture the analog signals from the sensor and convert them into digital data, enabling real-time monitoring of early-age temperature fluctuations in the concrete samples [6]. This study mainly focuses on monitoring the internal temperature of concrete using wireless sensors embedded within concrete cylinders. The complex maturity (Mc) will then be calculated based on the internal temperature, absolute humidity, air temperature, and wind velocity. In this study, wind velocity was measured using an anemometer as shown in Figure 5.

Figure 7(a) Maturity testing equipment [69] (b) Concrete Temperature monitoring with wireless sensors [70]

Table 3 Laboratory Testing Record Template for Investigating the Complex Interaction between Concrete Maturity and Concrete Strength

t	Parameters				*CS*
	IT	*AT*	*ARH*	Wind Velocity (Km/hr)	
0.5	21.40	23.7	29.5	10.98	0
1	21.52	23.2	30.3	13.68	0
1.5	21.91	23.1	33.6	17.1	0.3
2	22.2	22.8	33.9	14.44	0.68
2.5	22.6	22.4	34.4	13.07	0.87
3	22.9	22.1	35.2	13.03	1.2
3.5	23.5	22.5	37.1	13.82	1.76
....	....	....	....	....	....
672	11.88	13.8	40.9	16.88	53.88

This table 3 presents a laboratory testing record template used to examine the relationship between concrete maturity and compressive strength (CS). It includes various parameters such as the internal temperature (IT), air temperature (AT), relative air humidity (ARH), and wind velocity, recorded at different time intervals (t), ranging from 0.5 hours to 672 hours. The data highlights the changes in compressive strength as a function of these variables, reflecting the influence of environmental conditions on concrete's curing process.

4.3 Materials

The materials used for the experimental study include high-quality constituents such as OPC cement, Sylhet sand, Gabbro crushed stone, and Sikaplast 204 TH BD admixture, ensuring optimal concrete mix performance.

- Cement- OPC (Type 1/ CEM 1), Grade 52.5N
- Sand- Sylhet Sand (FM > 2.50)
- Crushed stone- Gabbro, UAE
- Admixture- Sikaplast 204 TH BD

Figure 8 Materials, batching plant, and CTM machine used for concrete production

Figure 8 illustrates the cement, fine and coarse aggregates, the batching plant used for proportioning and mixing the concrete, and the compression testing machine (CTM) employed for strength testing, in order to document the actual production and testing conditions of the study.

4.3.1 Mix Proportion

- Grade of Concrete: G 30

The table 4 presents the material quantities and mix ratios used in three concrete trial mixes, detailing the amounts of water, cement, fine aggregate, coarse aggregate, and admixture based on weight.

Table 4 Material quantities and mix ratios used in three concrete trial mixes

Trial No.	Material	Water (Liter)	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Admixture (kg)
Trial 1	Quantity (Weight basis)	176	450	716	1043	4.275
	Ratio	0.39	1	1.59	2.32	0.0095
Trial 2	Quantity (Weight basis)	160	400	800	1043	3.6
	Ratio	0.40	1	2	2.61	0.009
Trial 3	Quantity (Weight basis)	166	425	764	1043	4.038
	Ratio	0.39	1	1.8	2.61	0.009

4.3.2 Physical Properties Of Material

Some physical tests were conducted for the materials used in this study and the results are presented below in Table 5 and Table 6:

Table 5: Physical Properties of cement

Property	Cement
Compression Test	
03 days (MPa)	23.5
07 days (MPa)	32.9
Normal Consistency (%)	24.5
Initial Setting Time (Minutes)	154
Final Setting Time (Minutes)	249
Fineness of cement (m^2/kg)	385
Specific Gravity	3.11

Table 6: Physical Properties of Fine and Coarse Aggregate

Property	FA	CA
FM	2.84	-
Bulk Unit Weight (Kg/m^3)	1610	1670 (Dry Rodded)
Loose Unit Weight (Kg/m^3)	1440	1520
Specific Gravity (OD)	2.6	2.71
Specific Gravity (SSD)	2.62	2.73

4.3.3 Chemical Composition Of Material

A detailed analysis of the chemical composition of the cement and admixtures is presented below in Table 7 and Table 8:

Table 7: Chemical Composition of cement (%)

Element	Cement
SiO_2	20.75
Al_2O_3	5.08
Fe_2O_3	3.48
CaO	61.93
MgO	1.03
SO_3	2.08
C3A	7.57
Na_2O	0.435
Cl	0.036
P_2O_5	-
TiO_2	-
$CaCO_3$	-
Cr_2O_3	-
Insoluble Residue (IR) %	0.4
LOI (Loss of Ignition)	3.18

Table 8: Chemical Composition of admixture

Property	Results
Appearance	Turbid, Amber
Specific Gravity	1.092
Dry Material Content (%)	28.3
pH	7.0
Chloride Content (%)	0.0002

4.4 Experimental Work

The concrete mix was employed to cast cylindrical specimens with a diameter of 100 mm and a height of 200 mm [71]. All samples were cured under controlled temperature and humidity conditions. Compressive strength tests were conducted daily from day 1 to day 28, with a total of 84 cylinders prepared in sets of three specimens. Temperature sensors were placed at the center of two cylinders to continuously record internal temperature data at one-hour intervals throughout the 28-day curing period. In addition to monitoring internal temperature, wind velocity, ambient temperature, and relative humidity were simultaneously recorded using an anemometer and hygrometer, following the procedure outlined in [72].To incorporate the influence of wind velocity in the maturity calculation, the cylindrical samples were submerged in a water pool created on the construction site, and curing was performed in an open-air environment.

4.4.1 Compressive Strength

A laboratory test was conducted to assess the compressive strength of the cylindrical specimens, as illustrated in Figures 8 and 9. The procedure follows the specifications provided in ASTM standards C39/C39M and C192/C192M for cylindrical testing. All specimens were tested in a saturated surface-dry state, ensuring that any excess moisture was removed prior to testing. For each mix variation, including the control mix, three identical specimens were subjected to a consistent loading rate.Compressive strength measurements were taken at day 1 to day 28.

Figure 9 The load was applied to the cylindrical specimen to determine its compressive strength. strength.

Figure 10 a) A Crushed cylinder from batching plant b) A Crushed cylinder from lab trial

Figure 9 shows Cylindrical concrete specimen under axial loading in the compression testing machine, used to determine the compressive strength of the mix.

Figure 10 shows typical failure pattern of concrete cylinders after compressive strength testing: (a) crushed cylinder from the batching plant and (b) crushed cylinder from the laboratory trial, showing comparable cracking and spalling, which indicates similar compressive behavior of both concretes.

4.4.2 Slump test

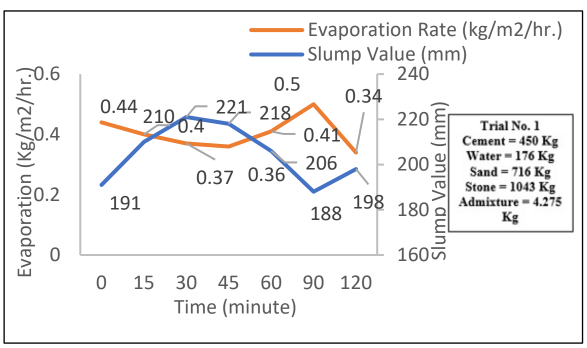
The slump test evaluates the workability of concrete by examining its flowability under its own weight and its resistance to deformation. The procedure adheres to the guidelines outlined in ASTM standard C143/C143M. Prior to conducting the slump measurement, the temperature of the concrete mix is recorded. The mix was designed to obtain a slump of 150–200 mm on fresh concrete at the time of casting. All slump tests and placements were completed within 2 hours of batching to limit the influence of initial setting on workability. This slump range is most common in mega projects of Bangladesh because it ensures workable fresh concrete suitable for pumping, placement, and proper compaction without excessive segregation or bleeding, especially in heavily reinforced areas. This range allows the concrete to flow more easily, making it simpler to place and compact without compromising structural integrity. This slump range is more fluid facilitating smoother movement through pump pipelines. This mix design reduces the reliance on intensive vibration during placement and lowers the likelihood of honeycombing, which in turn limits subsequent repair requirements and construction costs.

Figure 11 Measurement of slump and recording of the temperature of the mix

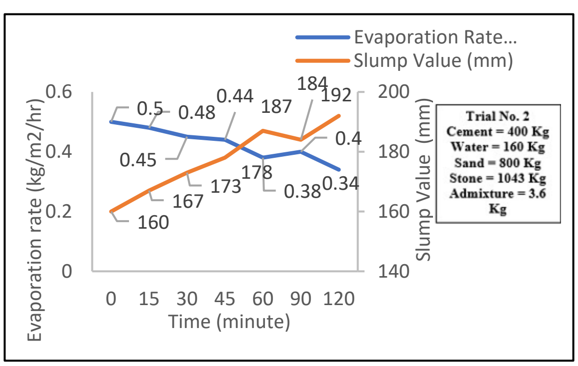
5.0 RESULT AND DISCUSSION

5.1 Impact Of Water Evaporation On Slump Variations Over Time For Laboratory Test

The following graphs illustrate how water evaporation influences the slump behavior of concrete mixtures across different trials. They present a time-based comparison between evaporation rate and slump values under varying mix proportions. The graphs illustrate the relationship between evaporation rate and slump value over time for three different trials. In all trials, as evaporation increases, the slump value initially rises, reaching a peak, before gradually decreasing as evaporation continues. This trend suggests that higher evaporation rates initially lead to a wetter, more fluid mixture, which increases the slump, but prolonged evaporation reduces the slump as the mixture loses moisture. The findings highlight the inverse relationship between evaporation and slump, indicating that controlling evaporation could be crucial for managing material consistency in practical applications.



(a)



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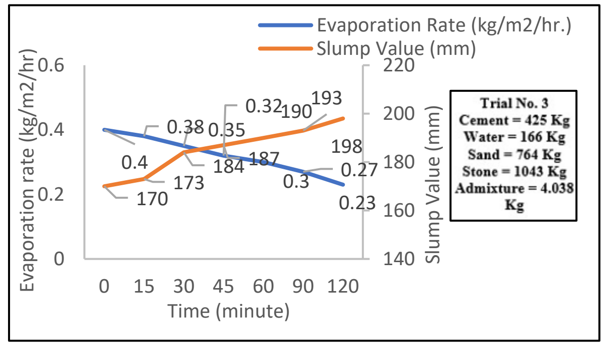


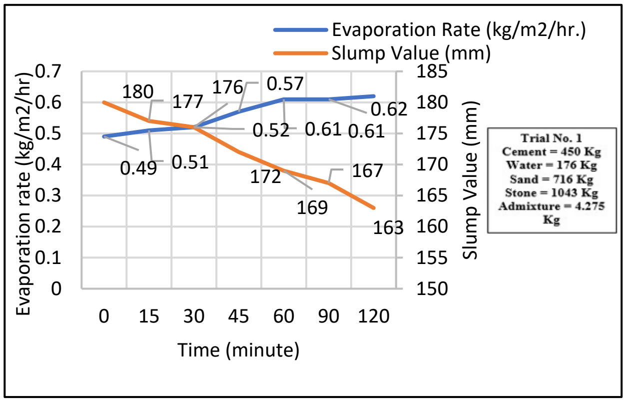
(c)

Figure 12 a) Effect of water evaporation on slump variations over time for trial no.1 b) Effect of water evaporation on slump variations over time for trial no.2 c) Effect of water evaporation on slump variations over time for trial no.3

In Trial 1, a polycarboxylate superplasticizer (4.275 kg) was used with a water-cement ratio of approximately 0.39. This admixture, known for improving dispersion and water retention, is sensitive to variations in water content. Even small changes in water addition can lead to significant fluctuations in slump and potential bleeding. Initially, the admixture likely released fluidizing agents, causing a temporary increase in slump despite a slight reduction in evaporation. However, after about 30 minutes, the continued evaporation of free water outpaced the admixture's effect, resulting in a decline in slump. In Trials 2 and 3, which also had similar or slightly lower water-cement ratios (≈0.40 and ≈0.39), but varied in terms of sand and admixture content, evaporation quickly reduced the available free water, leading to an increase in stiffness. While slump initially rose due to ongoing hydration and the action of the superplasticizer, this was soon overtaken by slump loss as evaporation continued.

5.2 Impact Of Water Evaporation On Slump Variations Over Time For Batching Plant

The following graphs display the relationship between water evaporation rates and slump values across three different trials. Each trial presents a time-based analysis of the effects of various mix proportions on these parameters. The graphs illustrate the impact of water evaporation on the slump value of concrete over time across three distinct trials, with the evaporation rate (kg/m²/hr) plotted against the slump value (mm). In all three trials, as the evaporation rate increases, the slump value decreases, indicating that higher evaporation leads to reduced workability of the concrete. This trend suggests that as water evaporates, the mixture becomes less flowable. The impact of evaporation on slump is more pronounced in some trials, possibly due to variations in mix proportions, highlighting the need for controlling evaporation rates to maintain optimal concrete consistency



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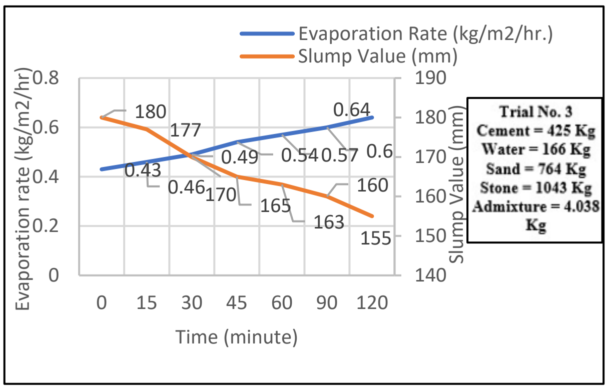

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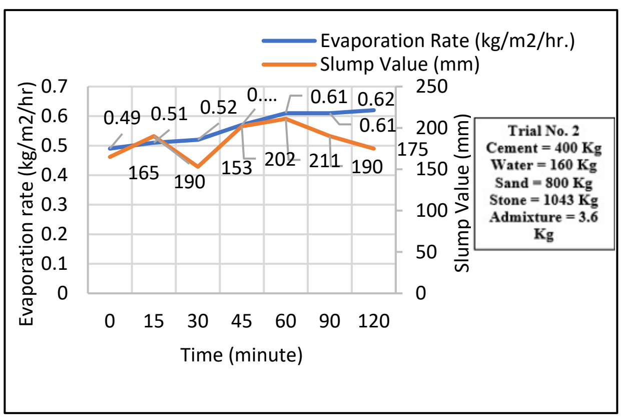

(c)

Figure 13a) Effect of water evaporation on slump variations over time for trial no.1 b) Effect of water evaporation on slump variations over time for trial no.3 c) Effect of water evaporation on slump variations over time for trial no.2

In the batching plant, concrete is exposed to wind and low humidity, which accelerates evaporation and typically leads to reduced slump, consistent with industry observations under hot-weather conditions (Hot Weather Concrete, Madison Sloan, June 24, 2024). Trials 1 and 3 conform to this general trend, showing decreased slump as evaporation increases. In contrast, Trial 2, with a slightly lower water–cement ratio (0.40) and reduced admixture dosage (3.6 kg), exhibited a temporary slump increase. This behavior is likely due to re-tempering during batching—adding water or admixture to maintain workability—and the delayed release of fluidizing agents from the polycarboxylate admixture, rather than a direct effect of evaporation. Field practice often adds water during transport to restore slump, but such re-tempering can temporarily increase slump even as evaporation continues.

In Figure 12, the observed slump loss over the 2-hour period was initially attributed primarily to evaporation. However, it is essential to recognize that slump reflects the workability and consistency of fresh concrete, which can be affected by several factors beyond moisture loss. Notably, the setting time of concrete significantly influences slump reduction; as hydration progresses, the mix stiffens, resulting in decreased slump. Slump values represent means ± SD (n=3) over 2 hours, computation as per ASTM C143 for both Figures 12 and 13.

Table 9 Relationship between Complex Maturity and Compressive strength for batching plant cylinders

Age, Days	Maturity of i Parameter				Correlation Coefficients between i Parameters and Compressive Strength				Weights of Maturity of i Parameters				Complex Maturity, M_c ^{0}C. Days	Compressive strength in cylinders, MPa
t	M_{IT}	M_{AT}	M_{ARH}	M_{WV}	$\|r_{IT}\|$	$\|r_{AT}\|$	$\|r_{ARH}\|$	$\|r_{WV}\|$	γ_{IT}	γ_{AT}	γ_{ARH}	γ_{WV}	M_c	CS
1	30.81	39.65	20.40	0.92	0.68	0.28	0.55	0.56	0.33	0.14	0.27	0.27	18.07	10.18
2	55.31	106.36	36.65	12.15	0.92	0.86	0.88	0.78	0.27	0.25	0.26	0.23	41.72	14.40
3	78.10	173.60	51.08	11.18	0.06	0.54	0.54	0.89	0.03	0.27	0.27	0.44	59.97	17.64
4	99.36	245.23	64.13	9.55	0.38	0.16	0.20	0.76	0.25	0.11	0.13	0.51	77.95	20.36
5	123.44	301.32	79.22	19.89	0.30	0.16	0.51	0.94	0.16	0.08	0.27	0.49	99.28	22.77
6	151.48	343.36	98.36	19.51	0.53	0.17	0.52	0.72	0.27	0.09	0.27	0.37	116.30	24.94
7	173.32	393.16	110.62	16.10	0.73	0.74	0.71	0.61	0.26	0.27	0.25	0.22	130.25	26.94
8	196.70	441.31	131.29	29.13	0.57	0.54	0.42	0.82	0.24	0.23	0.18	0.35	152.71	28.80
9	222.2	484.48	144.22	22.90	0.64	0.79	0.41	0.65	0.26	0.32	0.16	0.26	165.53	30.55
10	243.46	528.43	156.85	29.23	0.75	0.63	0.78	0.75	0.26	0.22	0.27	0.26	182.28	32.20
11	263.19	575.37	168.95	31.91	0.79	0.68	0.60	0.68	0.29	0.25	0.22	0.25	197.63	33.77
12	284.53	629.17	178.73	34.49	0.74	0.64	0.58	0.8	0.27	0.23	0.21	0.29	213.70	35.27
13	302.88	676.13	192.89	37.75	0.42	0.42	0.43	0.77	0.21	0.21	0.21	0.38	229.52	36.71
14	320.96	723.04	200.88	38.85	0.62	0.50	0.45	0.84	0.26	0.21	0.19	0.35	242.85	38.10
15	343.18	766.1	208.79	39.12	0.56	0.62	0.60	0.62	0.23	0.26	0.25	0.26	256.13	39.44
16	360.29	820.36	223.78	34.45	0.66	0.56	0.62	0.79	0.25	0.21	0.24	0.30	269.99	40.73
17	380.19	865.54	236.88	36.94	0.40	0.02	0.21	0.7	0.30	0.02	0.16	0.53	285.30	41.98
18	403.45	926.9	248.40	46.27	0.39	0.02	0.21	0.78	0.28	0.01	0.15	0.56	305.93	43.20
19	425.37	969.23	260.87	43.65	0.39	0.06	0.37	0.67	0.26	0.04	0.25	0.45	319.13	44.38
20	445.18	1020.75	277.93	48.21	0.01	0.02	0.99	0.58	0.01	0.01	0.62	0.36	337.18	45.54
21	467.36	1098.89	286.64	44.05	0.22	0.08	0.42	0.71	0.15	0.06	0.29	0.50	354.24	46.66
22	476.11	1155.03	289.32	50.91	0.17	0.03	0.41	0.83	0.12	0.02	0.28	0.58	367.81	47.76
23	490.67	1201.65	296.92	48.11	0.25	0.04	0.43	0.69	0.18	0.03	0.30	0.49	378.77	48.83
24	510.89	1269.38	302.73	50.17	0.11	0.03	0.41	0.72	0.09	0.02	0.32	0.57	395.47	49.88
25	525.89	1328.20	312.44	55.46	0.13	0.01	0.44	0.76	0.10	0.01	0.33	0.57	411.98	50.91
26	540.8	1381.87	322.48	54.82	0.13	0.06	0.41	0.65	0.33	0.14	0.27	0.27	425.52	51.92
27	556.45	1432.73	331.96	59.00	0.08	0.06	0.43	0.59	0.27	0.25	0.26	0.23	440.49	52.91
28	581.95	1487.66	341.96	59.34	0.30	0.04	0.42	0.64	0.03	0.27	0.27	0.44	456.82	53.88
Mean Value									0.21	0.15	0.26	0.38		

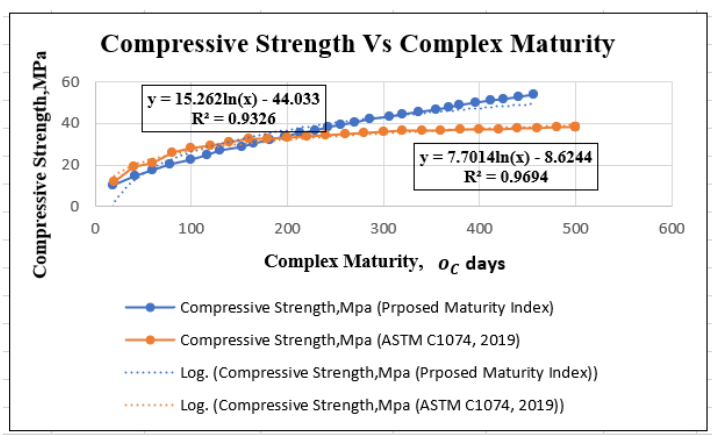

Figure 14 Relationship between compressive strength and complex maturity for the proposed maturity index and the conventional ASTM C1074 (2019) method

The correlation coefficients and corresponding weights for each parameter were computed daily and presented in Table 7, with the average weight over the 28-day period applied in Equation (6). To establish the relationship between complex maturity and compressive strength, a trend line was fitted using the most suitable equation, connecting the compressive strength of cylindrical specimens to the complex maturity calculated from Equation (6). The resulting relationship follows a logarithmic function, represented as $S = a \cdot \ln(M) + b$ in Figure 13, where S denotes strength and M represents concrete maturity. This complex maturity-strength relationship is then utilized to estimate the current strength of the concrete by monitoring internal and external temperatures, relative humidity, and wind speed.

The higher slope of the proposed index indicates a greater sensitivity of predicted strength to changes in maturity compared with the conventional method, especially at higher maturity levels. Although both models exhibit strong correlation with the test data (high R^2 value) the differences in regression parameters highlight how incorporating additional influencing factors into the complex maturity index can modify the predicted rate of strength gain relative to the standard ASTM C1074 formulation.

6.0 CONCLUSION

Based on the experimental investigation aimed at developing a method to assess concrete strength using complex maturity—including wind velocity—and analyzing the effect of water evaporation on slump changes over time, the following conclusions were reached:

1. The weights assigned to various maturity parameters indicate that wind velocity may have a unique effect on complex maturity, distinguishing it from other environmental factors like temperature and humidity. This addition is a novel refinement to the traditional complex maturity equation, incorporating the influence of wind on the concrete curing process.
2. The correlation coefficients presented in Table 7 suggest that wind velocity may have a moderate but notable effect on the compressive strength of concrete. Higher wind velocity could expedite the curing process, resulting in earlier strength development, as reflected in the data. The graph shows a positive correlation between compressive strength and increased complex maturity, with wind velocity potentially contributing to this trend alongside other factors like temperature and relative humidity.
3. The study reveals a strong correlation ($R^2 = 0.9326$) between complex maturity (after inclusion of wind velocity parameter) and the compressive strength of concrete. This high coefficient of determination highlights the robustness of the model for real-time monitoring and strength prediction, which is crucial for ensuring quality control throughout the construction process.
4. Incorporating wind velocity likely enhances the accuracy of compressive strength predictions at various complex maturities. The table provides a detailed analysis, and the graph further supports this by showing a more precise correlation between compressive strength and complex maturity. This suggests that the influence of wind velocity on hydration rates may improve the reliability of the predictive model.
5. The batching plant setup exhibits a more consistent and linear relationship between the evaporation rate and slump, whereas the laboratory test setup reveals greater fluctuations, potentially due to more rigid environmental controls or the limited sample size.
6. The observed relationship between slump value and evaporation rate was derived from a real-world construction project where ready-mix concrete was transported to the site. To ensure the concrete mixture remained workable during the travel time, admixtures were utilized to preserve its fluidity and workability. These admixtures function by slowing down the hydration reaction, thereby preventing a significant reduction in slump over time. As a result, the slump value is adjusted to compensate for moisture loss, allowing the workability of the concrete mix to be maintained.
7. The study offers important insights into how water evaporation affects concrete slump. It establishes an inverse correlation between evaporation rate and slump, a finding that is critical for optimizing the workability of concrete under varying environmental conditions.
8. The study highlights the significance of managing water evaporation to preserve workability and mitigate adverse effects on concrete quality, particularly in hot and windy conditions. This focus plays a key role in promoting cost-efficient and sustainable construction practices.
9. The paper emphasizes the practical application of the improved and enhanced maturity method in real-world scenarios, particularly within large-scale construction projects in Bangladesh. This is significant as most existing research predominantly concentrates on controlled laboratory environments.

Evaluating the complex maturity of concrete facilitates an accurate estimation of its current strength, thereby reducing the required curing time and improving cost efficiency in construction projects. The proposed method considers the effects of wind velocity in addition to internal and ambient temperatures, ambient relative humidity, on strength development, providing highly reliable data throughout the early curing period.

7.0 FUTURE SCOPE OF STUDY

1. Study can be extended beyond the initial trial mix to include additional mix designs. Testing various proportions and constituents will clarify how the model performs across different batching configurations.
2. Maturity model can be applied to concrete of varying grades and strengths. Such validation across a wider spectrum of grade classes will confirm whether the model maintains accuracy with different strength targets and mixes compositions.
3. The model can be assessed under extreme temperature conditions. Conducting experiments in both very hot and very cold climates will reveal how temperature extremes may influence maturity indices and strength predictions.
4. A quantitative cost–benefit analysis can be performed to evaluate the economic advantages of implementing the

model in practice. Estimating potential savings from optimized curing times and reduced material wastage will strengthen the case for its adoption.

5. Model can be applied in different geographic regions and climatic zones. International field trials will provide insight into performance across diverse environments and construction practices, broadening the study's relevance.
6. Model’s performance can be investigated with other binder types and supplementary cementitious materials. Incorporating various cement formulations and additives will help determine its suitability for a wider range of concrete technologies.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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