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Original Article

Early-Age Strength Development of Multi-Grade Concrete Using the Maturity Method: Calibration and Validation with Real-Time Monitoring

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Abstract - *In early ages of concrete, timely removal of formwork, post-tensioning activities, and early loading is based solely on the concrete strength achieved. It is therefore very important to predict the compressive strength of concrete. Conventional cube testing provides concrete strength at fixed ages, such as 7 days, 14 days, and 28 days, rather than real-time in-situ strength development. Here, in the present study, a concrete maturity approach was used to conduct real-time observations to predict early-age strength for M35, M40, and M45, three structural concrete grades. To measure the internal temperature history and calculate the maturity index based on the cumulative Temperature-Time Factor (TTF), an indigenous Concrete Maturity Meter system (CP-CMM) was used. Twenty cubes of concrete (150 mm) were cast and tested at 1, 3, 7, 14, 21, and 28 days to form grade-specific calibration curves for strength-maturity using regression analysis. Findings indicated that M45 exhibited the greatest early-age temperature increase, was more active in the binder, and showed the presence of Polycarboxylate Ether (PCE) superplasticizer, thereby yielding the greatest strength at all ages (12.12 MPa at 1 day and 44.16 MPa at 28 days). M40 showed high accuracy in maturity-based prediction, with minimal error (~0.5%) and a high regression correlation ($R^2 > 0.999$). M35 also showed high agreement ($R^2 > 0.998$). M45 showed a slightly greater early-age deviation (~3%) because the hydration-modifying effects of PCE, combined with the long-term predictions, were very accurate ($R^2 > 0.995$). Altogether, the paper demonstrates that maturity-based monitoring with CP-CMM is a valid and feasible method for predicting grade-specific early-age strength, supporting real-time quality control and rapid decision-making in construction.*

Keywords - *Early Stage Strength, Concrete Grade, CP-CMM, M45, Real-Time Monitoring, Temperature-Time Factor.*

1. Introduction

Concrete is the most popular building material because it is durable, flexible, and cost-effective, making it usable anywhere in the world. It is a central component of residential structures, bridges, industrial facilities, and major infrastructure. Although the attainment of compressive strength technically assesses the long-term performance of concrete at 28 days, the rate of early-age strength attainment is also crucial for construction work. Significant actions on the site, such as the removal of formwork, the movement of shuttering, post-tensioning, and early loading decisions, depend directly on early-age strength [1].

Proper forecasting of strength in early ages is thus required to ensure the safety of construction and the efficiency of the project. Poor strength development may result in structural gaps, leading to deficiencies such as cracking and excessive deflection. When concrete gains strength slowly, this can lead to premature cranking off of formwork or premature rotation under applied loads. On the other hand, the purview of conservatism in the face of uncertainty about strength development can lead to extended project duration, higher labor costs, or inefficient resource use. Therefore, improving the accuracy of on-site concrete strength is an essential issue in construction management [2].

Compressive strength is traditionally calculated from cube tests performed at defined ages of curing (usually 7 days and 28 days). Despite being approach-active and standardized, this method has severe practical drawbacks. Cube specimens are made under controlled laboratory conditions, which do not reflect the variable environmental and curing conditions that in-situ concrete experiences and to which the structure is exposed. Also, cube testing is non-continuous, staff-intensive, and fails to deliver real-time information needed to make dynamic decisions at construction sites [3].

In overcoming these drawbacks, the maturity approach has been presented as a non-destructive method for determining in-place concrete strength that accounts for the joint effects of time and temperature. The exercise here is that concrete strength development is controlled by the hydration process, which, in turn, is temperature-dependent. Elements of the same maturity, absent from varying conditions of curing, should have similar strength. In this way, one can continuously monitor temperature history (a correlation with the development of strength can be made) [4].

The use of maturity-based approaches to predict future construction strength and enhance construction efficiency is effective in several research studies. But available studies are mainly based on generalized maturity-strength associations or a mixed design, usually developed in a controlled situation. The mixing constituents of cement type, water-cement ratio, aggregate properties, and the chemical admixtures are very dependent and not universal when applying identified models in maturity relationships. As a result, the absence of mix-specific calibration poses a significant research challenge. It can hinder the practical application of maturity methods in real-world construction processes due to the variety of field conditions [5, 6].

In addition, the majority of the studied works are based on commercially developed maturity sensors and monitoring devices, and very little is done on locally developed, cost-effective solutions based on local construction practices and standards. The scarcity of comparative studies with multiple concrete grades, both with and without admixtures, within a single experimental framework is also a deficiency. This shows that the systematic calibration and verification of maturity-based strength-prediction models across various councils and for diverse concrete grades are pertinent when employing efficient, readily available monitoring systems.

In this sense, the present research will fill the aforementioned research gaps by calibrating and validating the strength-maturity of three popular structural concrete grades, namely M35, M40, and M45, and by using an indigenous Concrete Maturity Meter (CP-CMM). Practical mix designs, which are given specific attention in the study, include, but are not limited to, conventional mixes without admixtures (M35 and M40) and high-performance mixes that use a Polycarboxylate Ether (PCE)-based superplasticizer (M45).

The originality of this study is that:

- Experimental testing in the establishment of grade-specific and experimentally valid maturity-strength relations among various concrete grades,

To establish a continuous in-situ monitoring process,

- An indigenously developed CP-CMM system should be used,
- A study incorporates conventional mixes and admixture mixes as a separate incorporation mix into one study model, and
- Confirmation of the findings of research against applicable Indian standards to make the field applications.

There are no off-the-shelf or laboratory-oriented models of existing studies like the one available that offer actualized, calibrated prediction models that on-site engineers can directly apply to make immediate decisions. The results of the research will enhance construction schedules, increase construction safety, and improve resource use by enabling more accurate predictions of early-age concrete strength.

Comprehensively, this research aims to build on experience by developing smart, data-driven construction by combining real-time monitoring with scientifically calibrated maturity-based strength evaluation, thus facilitating faster, safer, and more efficient construction of concrete buildings.

2. Background and Literature Review

2.1. Early-Age Strength Development and Hydration Mechanism

It is the cement hydration process, which is very time- and temperature-sensitive, that determines the degree of concrete strength achieved at a young age. The thermochemical reaction is a complicated two-step process that entails the condensation of clinker compounds into hydration products, namely Calcium Silicate Hydrate (C-S-H) and Calcium Hydroxide (CH). Among all these, C-S-H is the most significant stage that provides strength and rigidity to hardened concrete. Several parameters, including the water-cement ratio, cement fineness, curing temperature, and admixtures, influence the rate of hydration.

Since hydration is an exothermic process, temperature evolution in concrete is a key factor in determining strength, especially at the early stages of the specimen's life. Increasing the curing temperature increases the rate of hydration, resulting in early, rapid, high-strength gain; the lower the curing temperature, the lower the rate. However, because of a rapid hydration rate, uneven microstructural development is a possibility, which can affect long-term strength and durability. Therefore, understanding the early-age strength of concrete not only provides a perspective for materials science but also serves as a construction management tool to help make better decisions during ongoing construction activities, such as the removal of the formwork, early loading, and post-tensioning for concrete players.

2.2. Maturity Method: Theory and Principle.

The concrete maturity approach offers a realistic skeleton that provides the integrated effect of time and temperature for concrete strength development. The basic assumption is that concrete samples with the same maturity index will have the same strength, disregarding their respective temperature histories. The maturity index is the cumulative effect obtained by summing up the temperature-time factor history of the concrete curing condition.

The Nurse-Saul and the Arrhenius-based equivalent age function are the most common and basic functions of maturity. The linear relationship between temperature and strength gain is necessitated by the Nurse-Saul method. At the same time, the Arrhenius model reports an exponential relationship between the rate of reaction and temperature. This method is typically adopted for research applications due to its higher accuracy. In contrast, the Nurse-Saul method is adopted in the field for its simplicity [1].

The maturity technique is mainly favorable for the reason that it allows continuous, non-destructive, real-time, in-place concrete strength evaluation. This method is particularly suitable for modern construction practices, where time and security are of prime importance.

2.3. Standard Guidelines and Implementation

ASTM C1074 is the most extensive standard used to specify a maturity method. It is a detailed report that provides specifications for operations that determine the relationship between strength and maturity with the help of lab calibration and field validation. The operations for estimating the datum temperature, the activation energy, and the calibration of curves for a specific grade of concrete define the standard of the process.

Mahendra Reddy et al. (2023) reported a datum temperature of around 10ºC for OPC (Ordinary Portland Cement) concrete under normal curing conditions, as recommended by ASTM C1074 [2]. However, Modern concrete mixes with Supplementary Cementitious Materials (SCMs) or chemical admixtures cannot be assumed to obey such standard assumptions. In such cases, due to material hydration behaviour, maturity parameter requirements must be revised. Alongside, International practices highlight the requirement for mix-specific calibrations and continuous monitoring to predict the in-situ compressive strength of concrete. Thus, compliance with standard calibration and validation is required.

2.4. Limitations of Strength Assessment Conventional

In India, the most common and acceptable method for controlling concrete quality in the construction sector is the ordinary compressive strength test conducted on cube specimens at 7, 14, and 28 days. This approach has some limitations despite its value as a benchmark.

The very first, conventional cube testing result does not provide real-time data or the strength required to make a timely decision, and it is not a very fast method. Secondly, the curing conditions in the laboratory and on-site are significantly different. Since curing in a laboratory is conducted in a controlled environment, which is not possible on-site, it tends to vary in temperature, humidity, and curing type. So, on-site strength may not be similar to the cube's strength.

The result of such limitations raises attentiveness. In maturity-based approaches, which provide a realistic, real-time assessment of strength in concrete. It has also been shown that the maturity technique helps in construction management by allowing prompt completion of activities, including de-shuttering and load applications [2].

2.5. Strength–Maturity Relationships and Calibration Studies

The concrete maturity method is entirely dependent on the relation based on the calibration result. So, it requires determining the relationship between the strength and maturity with the help of calibration. Based on several studies that have been conducted to confirm this relationship over various concrete mixes.

As shown by Buys (2019), using a representative setting, the maturity model can predict early age comprehensive strength efficiently [1]. Likewise, Nixon et.al. (2005) also evaluated a strong correlation between maturity indices and comprehensive strength at an early age by performing maturity techniques in the field test [11].

The calibration process should be carried out differently for different mix proportions, as each mix proportion accounts for changes in material properties, quantities used, and exposure conditions. Research also specifies that placement of sensors, frequency of data collection, and curing condition are important factors that decide the level of trust that can be concur to predictions.

2.6. Limitations of Traditional Maturity Models

The maturity method is helpful, but it has limitations. The cross-over effect is one of the challenges. When concrete is cured at a high temperature, it is found that the strength gain occurs swiftly. However, when considering the long run, this concrete became weaker compared to the concrete cured at a lower temperature.

Research by Oloukun et.al. (1990) found that the traditional maturity equations give incorrect results during the early stage of concrete hydration [12]. Likely, Kim and Rens (2008) figure out that changes in temperature and curing conditions are not properly addressed by the traditional maturity model [16].

Therefore, more advanced and calibration methods are required to enhance predictive performance, mainly for high-strength and modified concrete mixes.

2.7. Integration with Non-Destructive Testing (NDT)

Maturity methods can be effectively used in conjunction with other non-destructive testing methods to improve the accuracy of strength predictions. It can give continuous real-time strength from an early age. To measure concrete strength without damaging a structure, rebound hammer tests and Ultrasonic Pulse Velocity (UPV) are often used.

Amini et al. (2019) constructed predictive models combining [20] NDT results and maturity results. Similar correlations between compressive strength and UPV values were also reported by Turgut (2004) [21]. Malhotra and Carino (2003) outlined the importance of NDT in current evaluation and quality management of concrete [22].

Even though these methods are an excellent source of supplemental data, their precision will depend on the homogeneity of the Material, surface condition, and Calibration procedures. Thus, unification with the maturity technique should be conducted cautiously.

2.8. Advanced Sensing and Real-Time Monitoring Technologies

Recent sensor technology will allow the implementation of maturity-based monitoring systems to a large extent. The IoT-enabled system continuously measures temperatures and automatically calculates maturity indices.

Miller and others developed an Internet of Things (IoT) process monitor that could transmit data in real time and analyze it in the cloud [6]. The authors have shown how embedded microcontrollers can be used to monitor in situ strength [7]. Remote monitoring of large construction sites is possible through wireless communication technologies such as RFIC and LoRaWAN [27, 29].

Moreover, the developed sensing methods, such as piezoelectric, fiber-optic, and smart-aggregate sensors, among others, provide high-resolution measurements of hydration and structural behavior [10, 28, 31]. These technology solutions are more accurate and might be more expensive and technically complex.

2.9. Comparative Evaluation with Advanced Methods (AI and Predictive Models)

One of the most important developments in predicting concrete strength is the combination of maturity techniques along with AI and machine learning. An AI-based mathematics model can process a considerable amount of data and can analyze the complex relationship between different parameters that affect the development of concrete strength.

A study by Marchewka et.al. (2025) developed an AI-based system of hydration behaviour in combination with a prediction system, which gives accurate results [4]. Similarly, the traditional maturity method in combination with machine learning gives better results than the conventional method. However, AI techniques have some limitations as they require a large amount of data and computational resources, and proper validation, which can be difficult to use in practice. On the other hand, traditional maturity methods are simpler to use and more suitable for construction work.

2.10. Environmental Sensitivity and Sustainability Factors

A study by Utepov et. al. (2021) showed that environmental factors incorporated in maturity techniques predict concrete strength more accurately [13]. Environmental parameters like temperature, moisture, and type of curing have a greater effect on the hardening of concrete and the development of strength.

Sustainable materials like fly ash, GGBFS, and M-sand also influence the development of concrete strength. Research by Abdulmajid et. al. shows that geopolymer concrete shows a high maturity index and strength [23]. The research by Arulmoly et.al. (2021) and Sundaralingam et al. (2021) found that M-sand is an alternative to river sand for sustainable development. [32, 33]. Overall, both the environmental conditions and the use of sustainable materials should be considered in the maturity method to predict the strength of concrete.

2.11. Field Implementation and Case Studies

Use of maturity techniques in the field shows that it is a very effective technique for monitoring concrete strength. In a study by Mahmood et al., maturity techniques were used effectively in airport pavement construction, which helped in predicting early age strength of concrete and enabling the completion of the work on time [18]. Another system developed by Kishore and Arun Kumar (2025) with the help of IoT to monitor the concrete in real time. This system helped to forecast comprehensive strength, accuracy, and quality [3]. These studies have confirmed this, indicating that maturity can indeed be applied in the real-world construction environment, including large infrastructure projects.

Advanced and sustainable concrete systems are other systems to which the maturity method has been applied. Abdulmajid et al. (2025) also found a strong correlation between the maturity index and the compressive strength of geopolymer concrete, with a high level of prediction, yielding an R^2 of up to 0.98 [23]. Madrano et al. (2019) and Sun and Lee (2023) demonstrated that the use of maturity-based models does not harm mixes containing accelerators and additional cementitious materials, provided that appropriate calibration is conducted [24, 25]. This suggests that the maturity method is flexible yet highly susceptible to mix composition and curing conditions, depending strictly on the maturity method.

Table 1. Literature Review on Early-Age Concrete Strength Monitoring & Maturity Method

Sr. No	Authors & Year	Key Findings	Limitations / Research Gap
1	Kumarapu, Shashi & Reddy (2019) [5]	Used thermal remote sensing / infrared imaging to monitor surface temperature variations during the first 24 hours. Developed a nurse calibration curve for early strength prediction. Proposed hybrid interpretation techniques for strength gain.	A study was conducted in a controlled environment, limiting its applicability to real-world settings. The calibration curve may not be suitable for field conditions with variable ambient temperature.
2	Miller et al. (2023) [6]	Developed an IoT-enabled maturity monitoring system with cloud connectivity. Predicted early-age strength closely matched actual compressive strength. Supported construction decisions such as formwork removal and post-tensioning stages.	IoT systems may face risks of wire damage, wireless configuration issues, and dependence on cellular network connectivity.
3	Kampli, Chickerur & Chitawadagi (2023) [7]	Proposed a novel IoT-based maturity monitoring system for slabs. Lab maturity relationship accurately predicted in-situ strength. Useful for project managers for early formwork removal and cost reduction.	Limitations not clearly discussed in the abstract; field reliability under varying climate not explicitly validated.
4	Sanghee Kim et al. (2024) [8]	Studied early strength in unmanaged curing conditions using IoT-based maturity sensors. Field-cured samples showed lower maturity indices and strength than those cured under standard conditions. Demonstrated need for curing protection.	Limited to cool environment and unmanaged curing. Further studies are required for harsh climates and different mixes.
5	Miller, Ho & Talebian (2022) [9]	Provided an overview of the maturity method for in-place strength monitoring. Summarized maturity functions and modern monitoring systems. Compared the maturity method with cylinder /cube testing.	Further research is needed to improve the application of the maturity method and technology adoption; the limitations are not detailed in the abstract.
6	Gu et al. (2006) [10]	Used embedded piezoelectric (PZT) transducers to monitor strength through harmonic response amplitude. Fuzzy logic is used to correlate sensor response with strength gain.	Concrete is heterogeneous and anisotropic, making mathematical modelling difficult; sensor calibration can be complex.
7	Nixon et al. (2005) [11]	Evaluated the maturity method accuracy for field applications. Found Nurse–Saul functions most accurately across projects. Suggested different activation energies for warm- and cold-weather concreting.	Accuracy is reliable only up to an equivalent age of ~7 days. ASTM C1074 needed modifications for specific projects.
8	Oloukun et al. (1990) [12]	The reported Plowman's equation is inaccurate at early ages (the first 2 days)—proposed an improved relation that includes the heat of hydration to predict strength better.	Existing equations for 7–28 day strength can be inaccurate by up to 13%; early-age predictions require the incorporation of hydration heat.
9	Mahendra Reddy et al. (2023) [2]	Applied Nurse–Saul's maturity method for real-time strength assessment. Highlighted usefulness for non-destructive strength monitoring and unusual concrete mixes.	Experiments on unique concrete were rare; they required testing with blocks instead of real structures.
10	Utepov et al. (2021) [13]	Proposed complex maturity model including curing temperature, ambient temperature, and RH. Achieved high accuracy ($R^2 \approx 0.976$)—improved real-time monitoring reliability.	Traditional maturity models ignore ambient conditions and humidity; a complex model requires additional sensors, potentially increasing implementation costs.
11	Lim et al. (2019) [14]	Reviewed the electromechanical impedance technique for monitoring curing and strength development. Identified it as promising for	Highlighted knowledge gaps and the need for field-scale autonomous deployment.

		autonomous monitoring systems.	
12	Kasal, Lorenc & Wenighofer (2020) [15]	Presented four project case experiences using the maturity method. Showed benefits for timing critical operations like formwork stripping and post-tensioning.	Requires calibration for each concrete mix, increasing effort before field use.
13	Taewan Kim & Rens (2008) [16]	Studied the maturity method using variable temperature curing for normal and high-strength concrete. The cross-over effect disappears when adjusted for equivalent age.	The high-strength concrete results were inconclusive; traditional maturity methods do not account for the timing of peak temperature or long-term strength effects.
14	Tareen et al. (2019) [17]	Compared the maturity method with ultrasonic wave propagation and penetration resistance tests. Developed a new relationship combining maturity and sensor data for strength estimation.	Limitations include specimen size effect and the influence of compactness. Integration into practical field systems needs improvement.

In the context of the development of digital technologies, recent studies have examined the combination of maturity monitoring and Artificial Intelligence (AI) and machine learning methods. The model developed by Marchewka et al. (2025) combined hydration surveillance with AI to achieve exceptionally high kinship in predicting strength at a young age [4]. However, while using the maturity method, some problems must be considered, such as the reliability of the sensors, the quality of data collected, and the capability of the system for a large scale.

2.12. Methodological Considerations and Data Analysis

To obtain accurate results with the help of the concrete maturity method, proper planning, experimentation, and careful data analysis are very important. Calibration should be done on samples that truly represent the actual concrete to measure internal temperature accurately. Sensors must be correctly placed within the concrete. To validate the model, statistical methods like correlation (R2), Root Mean Square Error (RMSE), and comparison with the standard test results are used. However, due to the lack of complete validation, it is found that the results of many studies are less reliable for different conditions.

2.13. Research Gaps and Need for the Present Study

Despite significant improvements, several gaps remain in the research. Most research is conducted on single-grade concrete in a controlled laboratory environment and does not apply to the real-world construction environment. For high-strength concrete with admixtures, particularly M45 grade, the research is inadequate.

What is more, there are few comparative studies across different grades and no systematic examination of maturity constants. There is also no viable field application of current monitoring technologies or of integrating conventional maturity techniques.

Therefore, the present study will address these gaps by developing calibrated curves for the strength maturity of M35, M40, and M45 concrete based on a native Concrete Maturity Meter (CP-CMM). Real-world mix design is also employed in the experiment, and the predictions of maturity are tested through a compressive strength test; hence, it can also be applied to real construction settings.

This multi-grade technique will serve as a good reference model for field engineers. It will assist in embracing real-time monitoring technologies to improve the efficiency, safety, and quality of the construction.

3. Materials and Mix Proportioning

Concrete is widely used worldwide as a construction material due to its durability, high strength, and cost-effectiveness. It is made up of different ingredients by mixing cement, fine aggregate, coarse aggregate, and water. Sometimes, to improve the performance of concrete based on the requirement, admixtures are also added to the concrete. The behaviour of concrete at an early age and throughout its life span totally depends on the mix proportion of these ingredients.

The aim of this study is to predict the strength of concrete with the help of the CP-CMM instrument. To obtain accurate results and a reliable relationship between strength and maturity, it is important to use uniform mix designs and properly selected material so that the hydration process remains constant. For this medium strength to high strength commonly used concrete grades were studied (M35, M40, and M45). As cement is a binding material that controls the hydration process, which leads to the development of strength. In this experiment, for M35 and M40 grades of concrete, OPC-43 grade cement was used, while in M45 grade of concrete, OPC-53 grade cement was used. To check the quality of cement and its suitability for use, fineness and consistency tests were performed.

Aggregates are strong, durable, and occupy a large portion of concrete, and play a major role in developing the density and strength. 20 mm size of coarse aggregates was used, while river sand was used as fine aggregates, confirming zone-II grading. Important properties of aggregates, like specific gravity and water absorption, were carefully considered during concrete mix proportioning.

All concrete mixes were prepared with portable water for proper hydration and to avoid impurities that could affect strength and setting time. The water-cement ratio was carefully maintained as per the mix design to achieve the required strength.

Mix design was prepared as per IS 10262:2019 standards with moderate exposure conditions, and a 50 mm slump was considered for the desired workability.

Overall, the selection of material and testing approach helps to develop an accurate maturity relationship for different concrete grades in Indian construction conditions. Concrete mixes for M35, M40, and M45 grades were prepared. The water-cement ratios were 0.45, 0.41, and 0.34, which were selected to meet the strength and workability requirements of M35, M40, and M45.In the M45 grade mix, a Polycarboxylate Ether (PCE)- based superplasticizer (specific gravity 1.15) was used to achieve adequate workability in the concrete while keeping the water content within a sensible limit. A 20% water reduction was used, and the mix utilized an attainable consistency without unduly affecting the water-cement ratio to gain excessively high strengths.

The cement grade used in the M35 and M40 mixes in the current research was OPC 43, a normal-to-medium-strength grade suitable for structural concrete. Conversely, the M45 mix was made with OPC 53 grade to get higher strength development and high performance at lower ages. The cement content (kg/m^3) increased as the grade requirement rose, but remained within the allowable range specified in IS 10262:2019, especially in the M40 mix, where maximum cement content limits were applied. M35 and M40 water contents (L/m^3) were kept at approximately 200 L/m^3 to achieve the desired workability and correct aggregate absorption. In contrast, the water content of M45 (L/m^3) was maintained at about 164 L/m^3, despite the addition of the PCE-based superplasticizer, which helped maintain workability even with a lower water-cement ratio.

The volumes of fine and coarse aggregates (kg/m^3) were obtained according to the absolute volume method and were modified by the absorption values to obtain the correct proportions; specifically, the coarse aggregate content of the higher-grade M45 mix was somewhat higher because the values of the aggregate volume fraction were modified to attain the high-strength performance. Also, the dosage of a PCE admixture was added only to the M45 mix at 4.38 L/m3, reducing water by almost 20 percent and improving consistency at low w/c conditions. In general, the most significant governing parameter was the water-cement ratio (w/c), with 0.45 (M35), 0.41 (M40), and 0.34 (M45) as the minimum w/c ratios; the M45 minimum w/c ratio is expected to result in the fastest early strength development and maturity.

Fig. 1 C-Probe's Concrete Maturity Meter System

An indigenous C-Probe Concrete Maturity Meter (CP-CMM) supported the experimental investigation by monitoring real-time temperature and calculating maturity. The time-temperature history was captured using the CP-CMM system at the early hydration stage, allowing the prediction of strength using maturity-strength relationships established for each grade.

Figure 1 (CP-CMM System) shows the full installation and configuration of the device used in the study. The methodology has been designed to address the disadvantages of the traditional cube test, which only allows local in-situ testing and provides only a snapshot of strength, hindering continuous assessment and prompt decision-making, including the removal of formwork and the continuation of the construction process based on expected strength development.

4. Experimental Methodology

The experimental research methodology, as indicated in Figure 2 of this study, aimed to develop a strong correlation between concrete maturity and compressive strength across various grades (M35, M40, and M45) using the CP-CMM (Concrete Maturity Meter). The maturity method assumes that the joint action of time and temperature, which is considered the hydration process, is the main factor in the development of concrete strength.

Thus, by continuously monitoring the internal temperature of concrete and accumulating it over time, the maturity index can be calculated and compared with the strength. The method allows in-situ strength to be estimated in real time without waiting for cube test results.

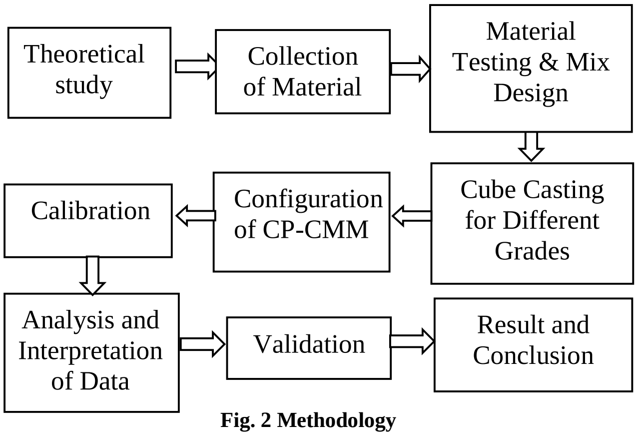


Fig. 2 Methodology

The CP-CMM uses the concept of maturity, in which the temperature sensors installed within the concrete measure changes in temperature throughout the hydration process. These have been recorded at specific time intervals and are used to calculate maturity using the time-temperature factor. The fact that maturity is the energy in the hydration process also provides a scientific explanation for the ability to predict strength gain. Once the CP-CMM system is calibrated, it can determine strength directly using a grade-specific maturity curve, which is quite handy for making early-age decisions at the construction site.

Temperature sensors were installed inside the concrete cubes during casting to obtain a valid temperature history. There were two cubes of each grade of concrete, which were representative, where two sensors were situated in the right positions. Therefore, they were in the center of the specimen and about 7cm to 8cm below the bottom of the cubes, which has the most stable and realistic hydration temperature. The sensors have been held to avoid vibration and compaction. It is one of the embedded methods to maintain a constant temperature during the first days of hydration, which are required to calculate maturity and predict strength.

The cast mix designs were prepared as 150 mm x 150 mm x 150 mm concrete cubes. The number of cubes was sufficient to test strength at different ages, as each grade was prepared to provide 20 cubes. Cubes were kept in a humid environment for 24 hours after casting to prevent moisture loss during the first setting stage. The cubes were demolded, then cured in a curing tank under standard conditions until the desired test age.

As soon as the casting and sensors were installed, as shown in Figure 3, the CP-CMM system began recording the concrete's internal temperature at predetermined intervals. The recorded temperature data was automatically saved and used to calculate maturity in the CP-CMM software. The maturity value of concrete was calculated using the relationship between time and temperature, and then it was compared with the actual compressive strength obtained from CTM. The strength of development of concrete over a period was observed by continuous monitoring for all three grades of concrete. This also showed the effect of the low water-cement ratio and the admixture used in the M45 grade of concrete.

Compressive strength tests were carried out at different ages of 1, 3, 7, 14, 21, and 28 days to study strength development. To take timely and practical decisions, such as removal of framework, load application, and further construction activities, these time intervals are selected, and the results obtained from CTM at these different ages were carefully recorded and used further to compare with the predicted strength values using the maturity method.

The compressive strength testing was conducted on a standard Compression Testing Machine (CTM) in accordance with Indian testing practice. Cubes on the CTM platform were removed from the curing tank on each testing day, dried on the surface, and placed in the center of the platform. The force was increased slowly and continuously to failure, and the maximum force at which it failed was recorded.

Fig. 3 CP-CMM with Concrete Cubes

The compressive strength was determined as the failure load divided by the cube's cross-sectional area. These experimental values were then entered into the CP-CMM calibration software to produce the best-fit maturity-strength relationship for each grade.

5. Result and Discussion

The most significant step in implementing the CP-CMM system to provide in-situ strengths that can be trusted is calibrating the strength-maturity relationship. The various concrete grades, M35, M40, and M45, were not calibrated jointly because each mix design has different cement content, water-cement ratio, and hydration behaviour. The CP-CMM system continuously measured the internal concrete temperature since casting and recorded the time history of all temperatures throughout the early stages of hydration and the curing process. The temperature profile was then used to estimate maturity, which was further compared with experimentally measured compressive strength at different ages.

Each grade of concrete cube was calibrated using the CP-CMM instrument, which had embedded temperature sensors. The sensors were used to measure the internal temperature at specified time intervals as the curing process progressed. These readings were automatically stored and accessed in the CP-CMM system and the CP-CMM software, respectively. Constant-temperature control ensured that hydration heating or ambient conditions did not cause any change that was accurately recorded. Calculation of maturity was based on this online data collection, and grade-specific strength-prediction models were developed.

5.1. M35 Concrete Calibration

Compressive strength rose to 34.29 Mpa at 17,631.21 degC-hr (28 days) and 721.64 degC-hr (1 day) in the case of M35 concrete, which was in the range of 8.16 Mpa. The result shows a smooth relationship between maturity and strength. In the first 14 days, the concrete quickly obtained strength. After that, the rate of gain of strength becomes slower. The regression equation developed for M35 grade of concrete accurately represents this behaviour and can be used as a reliable calibration curve to estimate actual strength from maturity values. Figure 4 shows the calibration of M35 concrete Grade TTF vs. compressive strength.

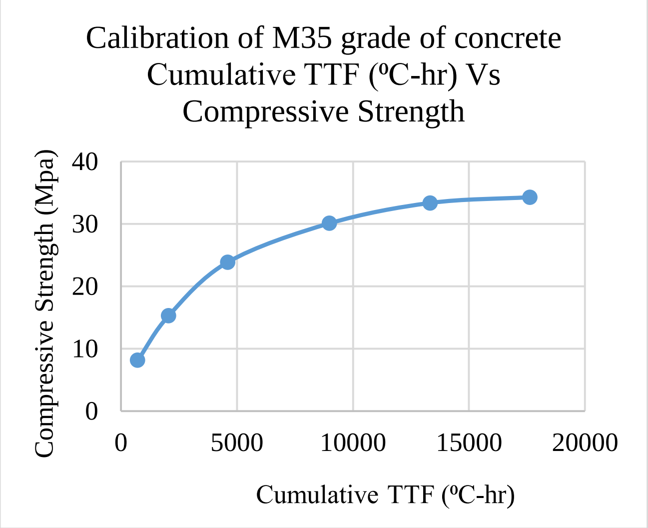


Fig. 4 Calibration of M35 Concrete Grade

5.2. M40 Concrete Calibration

Due to more cement content and a low water-cement ratio, the M40 grade of concrete showed higher strength than the M35 grade at the same maturity level. The strength rose to 39.11 MPa at 18, 233.83 degC-hr (28 days) with an initial strength of 9.89 MPa at 743.71 degC-hr (1 day). The regression analysis showed a strong correlation between cumulative TTF and compressive strength, indicating that M40 concrete has a lower maturity to achieve higher strength levels than M35 concrete. The M40 concrete calibrated model demonstrates improved early-age and long-term performance. Figure 5 shows the calibration of M40 concrete Grade TTF vs. compressive strength.

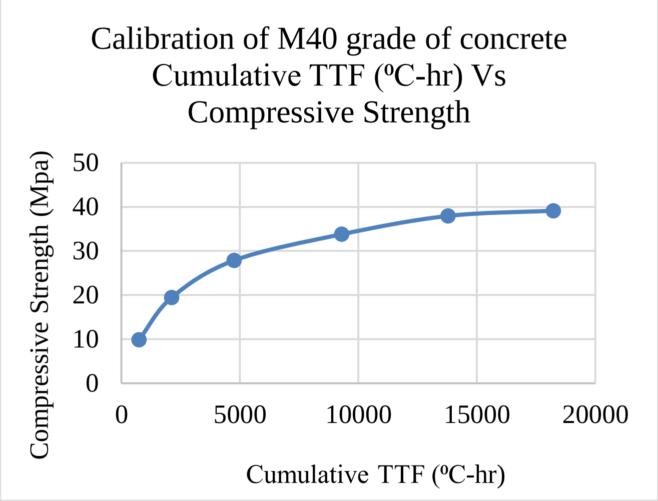


Fig. 5 Calibration of M40 Concrete Grade

5.3 M45 Concrete Calibration

The M45 concrete with a Polycarboxylate Ether (PCE)-based superplasticizer showed the greatest strength gain among all grades. The compressive strength rose to 12.12 MPa at 768.43 degC-hr (1 day) to 44.16 MPa at 18,869.43 degC-hr (28 days). The maturity-strength correlation of M45 concrete shows that the initial age-based strength increase is steeper and that the concrete continues to develop with increasing age. The effect of the PCE-based admixture is evident in improved particle dispersion and enhanced hydration efficiency, resulting in increased strength at the same maturity levels. Figure 6 shows the calibration of M45 concrete Grade TTF Vs Compressive Strength.

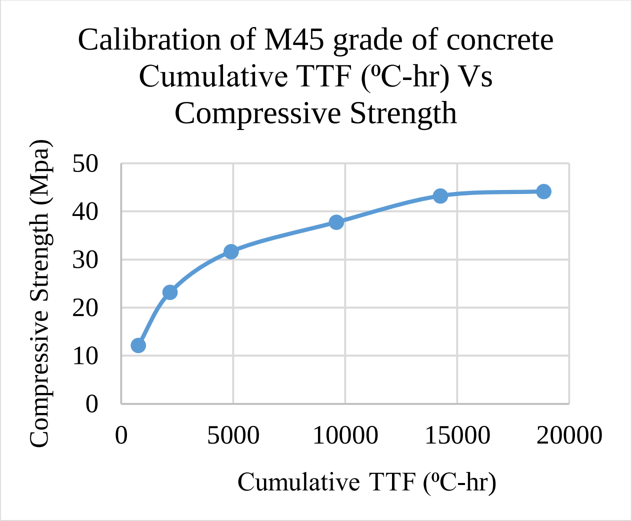


Fig. 6 Calibration of M45 Concrete Grade

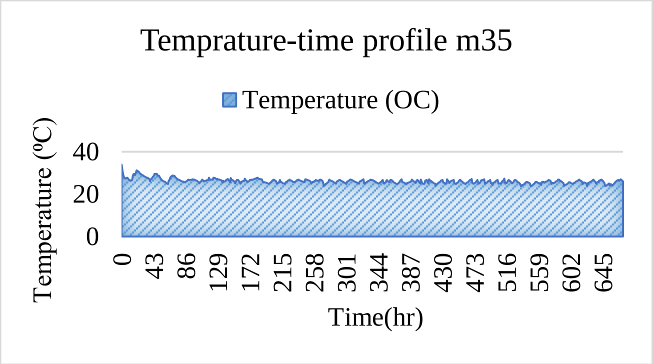
Table 2. Calibration phase – results summary

Aspect	M35 Concrete	M40 Concrete	M45 Concrete
Purpose	Establish a maturity–strength relationship	Establish a maturity–strength relationship	Establish a maturity–strength relationship
Strength at 1 Day	~8.16 MPa	~9.89 MPa	~12.12 MPa
Strength at 28 Days	~34.29 MPa	~39.11 MPa	~44.16 MPa
Strength Development Trend	Rapid gain up to 14 days, then gradual	Faster gain than M35	Steep early gain and sustained later gain
Maturity (TTF) Effect	Strength increases with TTF	Higher strength at the same TTF than M35	Highest strength at the same TTF
Influence of Mix Design	Conventional mix	Higher cement content	PCE superplasticizer improves hydration
Regression Model	Strong correlation	Very strong correlation	Strong correlation with minor early-age variation
Calibration Requirement	Grade-specific curve required	Grade-specific curve required	Grade-specific curve required
Practical Outcome	Reliable in-situ strength prediction	Accurate early-age strength estimation	Effective real-time strength monitoring
Overall Observation	Maturity method applicable	Improved performance over M35	Best performance among all grades

The chosen regression models for M35, M40, and M45 concretes were deposited as calibrated strength-maturity relationships for use during the prediction stage. These models can estimate in-situ concrete strength in real time using maturity data from the Concrete Maturity Meter (CMM), enabling informed construction decisions on formwork removal time, post-tensioning, and early loading. In general, the findings of the calibration exercise demonstrate that maturity-based prediction of strength is a sound and stable methodology that can be used to forecast the strength of various concrete grades, provided a suitable grade-specific calibration is conducted. The temperature history of the concrete specimens was recorded to determine the hydration heat development of the concrete grades M35, M40, and M45. The temperature-time profiles clearly show that the amount of heat released is highly dependent on the cement content and the binder's overall activity in each mix.

In any grade, the temperature increases rapidly at the initial stage of hydration, then slows and stabilizes. This thermal characteristic is also significant, as the temperature development at early ages directly relates to strength growth and to the prediction accuracy at maturity. Of the three grades, M45 should demonstrate the most noticeable increase in early-age, because it generally has a higher cementitious content and a faster hydration rate. This leads to a higher peak temperature and an earlier peak than in M35 and M40. M35 mix exhibits a slower, smoother temperature increase, indicating a relatively moderate rate of hydration reaction. The M40 grade is between the two and exhibits average peak temperature and thermal development. These tendencies indicate that concrete of higher grades will produce greater hydration heat at early ages, enabling it to be strengthened more quickly.

The compressive strength development of M35, M40, and M45 was tested from 1 day to 28 days, and the results show that all grades exhibit similar increases in strength with age. The strength gain curves show an anticipated pattern of high early-age strength growth, followed by a slow increase after 7 days. This process indicates the gradual hydration and densification of the microstructure with age, thereby increasing the load-carrying capacity in old age.



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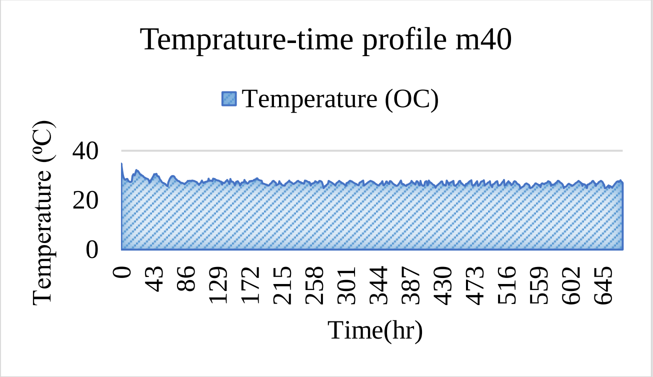

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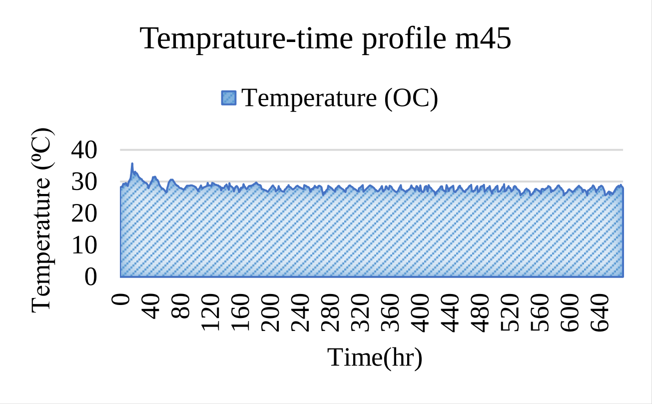
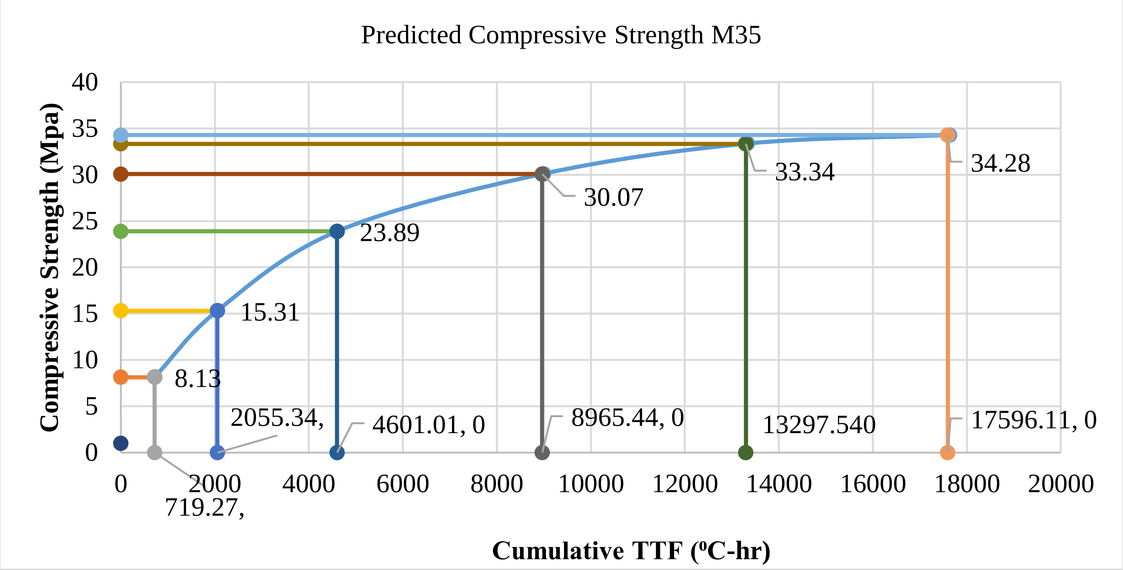


(c)

Fig. 7 Temperature-Time Profile for a) M35 b) M40 c) M45 Concrete Grade

Maturity-based strength prediction. To develop a maturity-based strength prediction, maturity index values for M35, M40, and M45 were obtained from recorded temperature histories. The maturity method is a feasible approach for predicting in-situ strength using a single parameter that integrates time and temperature effects.

The compressive strength values were plotted against the maturity index for each grade and fitted using an appropriate regression model (usually exponential or logarithmic, based on the best fit). The curves obtained show that strength increases progressively with maturity, indicating that the maturity index is a good measure of hydration progress and strength development.



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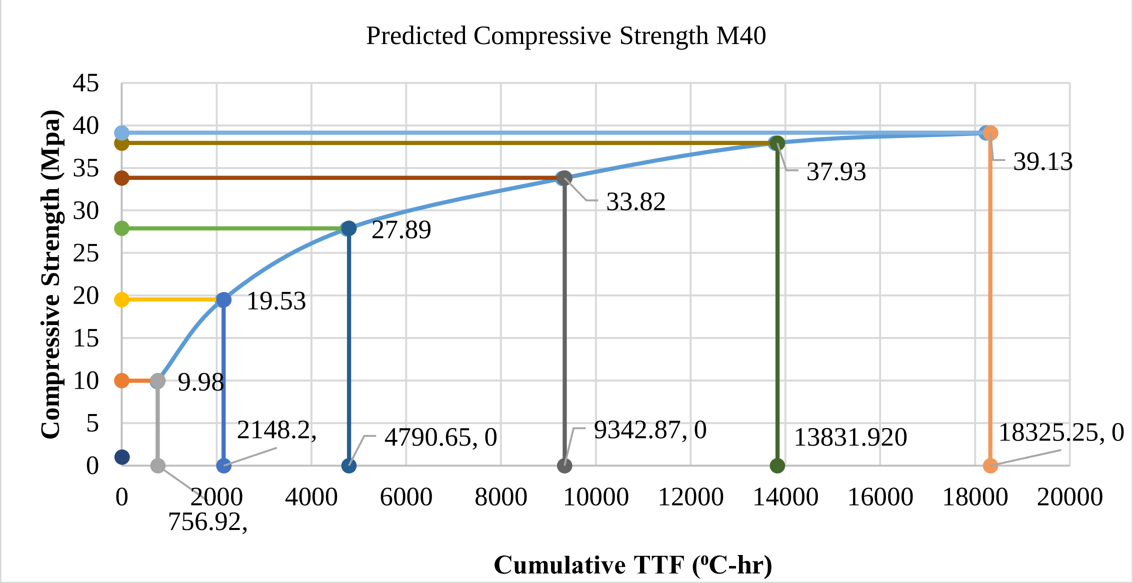

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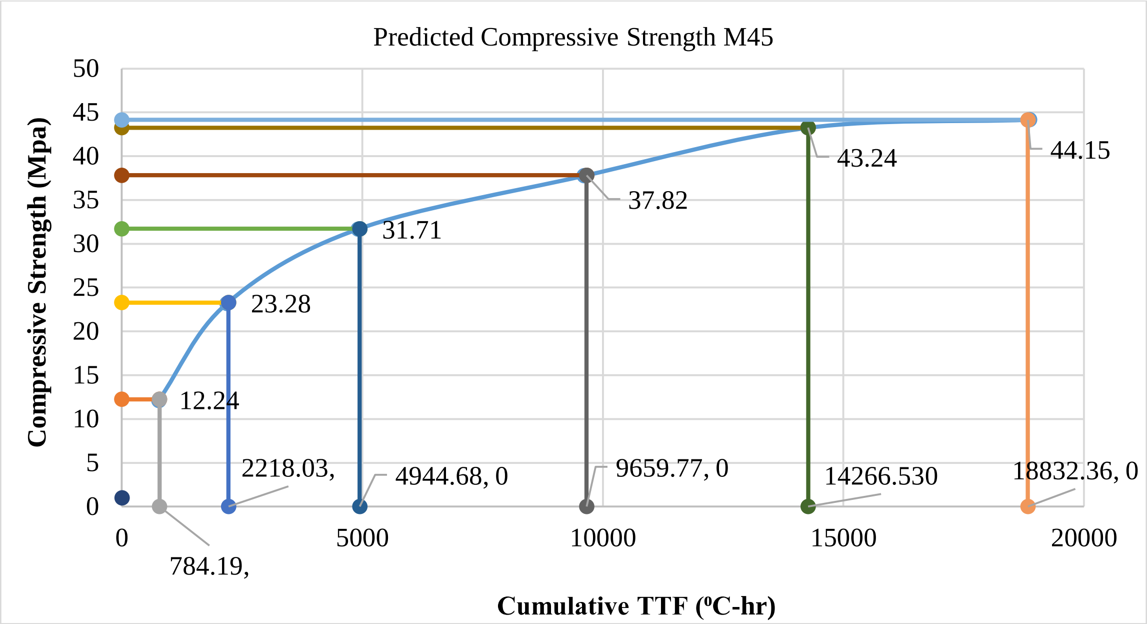

(c)

Fig. 8 Maturity-based strength prediction for a) M35 b) M40 c) M45 Concrete Grade

Table 3. Predicted Vs Measured Compressive Strength

Parameter	**M35 Concrete**	**M40 Concrete**	**M45 Concrete (with PCE)**
Strength Prediction Method	Maturity-based (TTF regression)	Maturity-based (TTF regression)	Maturity-based (TTF regression)
Age Range Evaluated	1–28 days	1–28 days	1–28 days
Agreement with Measured Strength	Very good	Excellent	Good (slight early-age deviation)
1-Day Prediction Error	~0.24 MPa	~0.12 MPa	~0.35 MPa
Maximum Error	~1.5%	~0.5%	~3.0%
Early-Age Prediction	Accurate	Highly accurate	Slight overprediction
Mid- & Late-Age Prediction	Accurate	Highly accurate	Very accurate
Regression Coefficient (R^2)	≈ 0.998	> 0.999	≈ 0.995
Effect of Mix Design	Conventional mix	Higher cement content	PCE delays early hydration
Overall Prediction Accuracy	High	Very High	High (long-term)

The compressive strength development of M35, M40, and M45 grade concretes at early ages and over the long term was assessed using a maturity-based prediction technique. The Cumulative Temperature-Time Factor (TTF), generated from observed curing temperatures, was used to estimate compressive strengths using regression models calibrated for each grade. These forecasts were later compared with experimentally determined compressive strengths of concrete cubes obtained using a Compression Testing Machine (CTM). For M35 concrete, the measured values were very similar to the predicted 28-day strength. The forecasted strength of 8.13 Mpa was close to the measured value of 7.89 Mpa, with a difference of -0.24 Mpa, which is very small.

The predictions were very accurate at three and seven days, with errors of -0.09 MPa and -0.03 MPa, respectively. It also showed good predictive power for mid- and late-age strengths at 14, 21, and 28 days, with errors ranging from 0.22 MPa to -0.51 MPa, corresponding to a maximum percentage error of about 1.5%. The regression equation showed a very good correlation with the experimental data (R2 = 0.998), indicating that TTF predictions are reliable for M35 concrete.

The prediction accuracy of the M40 grade was even greater. The estimated early-age strength at 1 day was 9.98 MPa, which was very close to the measured strength of 10.10

MPa; the difference was very slight, 0.12 MPa. It was also predicted that the error in subsequent predictions at 3, 7, 14, 21, and 28 days would always be within ±0.20 MPa, with a maximum error of about 0.5 percent. M40 concrete shows a strong relationship between cumulative TTF (maturity) and compressive strength, as the regression equation shows our R2 ≈ 0.998. M40 grade of concrete shows this high accuracy because of higher cement content and no use of admixtures, which leads to consistent hydration at early ages.

On the other hand, M45 grade of concrete, due to the presence of Polycarboxylate Ether (PCE) superplasticizer, showed a slight difference between the predicted strength and the actual measured strength, especially at an early age.

On one occasion, the predicted value of 12.24 Mpa was slightly higher than the measured value of 11.89 Mpa, resulting in an error of -0.35 Mpa. The error reached -0.49 MPa at three days and was negligible at 0.05 MPa at seven days. The largest deviation occurred at 14 days, and the predicted strength of 37.82 MPa exceeded the measured strength of 36.72 MPa by 1.10 MPa, about 3 percent.

Although there were discrepancies in the early-age predictions, the 21-day and 28-day predictions showed close agreement with the experimental value, indicating that the model captures long-term strength development. The regression model showed a high correlation of 0.995. The identified overprediction at an early age is correlated with the retarding effect of PCE superplasticizer that retards early hydration and retards the early attainment of stiffness and strength of the concrete.

Comparison of the three grades shows that all the strength predictions predicted strengths match the measured values and, therefore, the use of cumulative TTF to predict maturity-based strength is justified. M40 concrete had the best prediction accuracy, with low error across all ages, whereas M45 had a slightly higher error at low ages due to the admixture's influence on hydration kinetics. M35 had a medium level of prediction accuracy, with slight deviations at older ages. In general, the findings verify that TTF-based regression models are a powerful and sound measure of estimating the compressive strength development of conventional and high-performance concretes.

The research shows that cumulative TTF, based on penetration resistance and temperature measurements, can be successfully used to estimate concrete strength in real time without destructive testing and to better manage construction time.

The current research establishes that maturity-based strength prediction is a valid and feasible technique for early-age concrete monitoring, and the results are consistent with previous studies on maturity, IoT-based monitoring, and calibration needs. The temperature-time curve obtained with the CP-CMM showed a steep increase at the beginning of the hydration period, followed by leveling, and it directly reflects the change in hydration heat. This trend aligns well with the maturity theory and hydration kinetics from previous research, which show that early-age temperature increases control the rate of maturity gain and early-age gain in strength [1, 9].

Interestingly, the steepest increase in early-age temperature was observed in the M45 grade due to increased cementitious activity and the use of a PCE-based superplasticizer, as observed in high-performance and field-monitored concretes, where the more powerful binder activity results in more internal temperature peaks and accumulates early-age maturity [8, 16].

Moreover, the present study confirms the importance of real-time monitoring because specimens cured in the laboratory might not reflect in-place thermal histories and hydration trends, a common limitation in field evaluation research [11, 15].

The trends of compressive strengths development in all grades (1 day -28 days) were characterized by rapid early age development and slower development at later ages, as it is consistent with hydration-based strength development reported under maturity-based studies [1, 2].

The grade-to-grade comparison (M45 > M40 > M35) proves that the increase in the strength of higher-grade concretes is associated with the reduced w/c ratios and higher cement content, as higher-grade mixes gain higher strengths at the same maturity values as reported in maturity calibration studies [1, 16].

The findings also indicate the practical importance of construction operations such as formwork removal, post-tensioning, and curing optimization for construction activities through early-age strength estimation, as indicated by the preceding case studies and field monitoring reports [6, 15].

The grade-specific strength-maturity calibration curves of the current study, which were determined by cumulative Temperature-Time Factor (TTF) and regression analysis, showed a very high correlation (R^2 = ≈ 0.998 for M35, >0.999 for M40, and ≈ 0.995 for M45), which validated the reliability of the maturity index as a predictor of compressive strength when adequately calibrated. These results support maturity calibration procedures using ASTM techniques reported in the literature and indicate that calibration should be mix-specific due to differences in cement type, w/c ratio, and admixture impact [2, 11, 15].

The regression models predicted strengths that were very close to measured CTM results, with maximum errors of ≈ 1.5% at M35, ≈ 0.5% at M40, and ≈ 3% at M45 at early ages, which show trends similar to those in IoT and sensor-based maturity systems [6, 7].

The increase in the early-age deviation in M45 is slightly higher than in the high-strength concrete and PCE-admixed systems, in which altered hydration kinetics or retarded early hydration can lead to a small overprediction [1, 16]. This highlights the necessity of initial setting time calibration, especially in high-grade mixes, where maturity accumulation must be set to begin after initial setting, enhancing early-age precision in projected compressive strength [12, 16].

The CP-CMM implementation model developed in this research provides a realistic implementation path for the field. Mix calibration. Pre-deployment mix calibration uses regression-based strength-maturity curves defined for each concrete grade, and sensors are carefully placed in structural members to monitor core-zone temperatures.

Real-time TTF calculation enables immediate prediction of strength to inform construction decisions on formwork removal, post-tensioning, and curing. The model's constant improvement can be achieved through periodic comparison with cube test results, which may account for variations in materials and environmental effects [1, 6, 11, 15].

The combination of the two methodologies makes maturity-based monitoring reliable and useful for practical decision-making, as stated in today's studies of best practices in field monitoring.

6. Conclusion

This paper evaluated the compressive strength development of multi-grade concrete (M35, M40, and M45) at a young age using the maturity method and a real-time monitoring system with an indigenous CP-CMM. Based on the outcome of the experimental calibration and prediction, one can arrive at the following conclusions:

1. It is highly important to calibrate grade-specific maturity, as concrete grades exhibit unique hydration and strength development characteristics due to variations in cement content, water-cement ratios, and admixtures.
2. The historical trend of temperature indicated that hydration heat is grade-dependent, and all mixes had a high initial rate of temperature increase that then leveled off. M45 experienced the most rapid change in temperature during early age, indicating that hydration kinetics were faster and heat was more evolved than in M35 and M40.
3. It was expected that the strength increases would occur over the period of 1 to 28 days, and M45 has consistently registered the highest compressive strength across all ages, followed by M40 and M35. The strengths in 28 days were around 34.29 MPa (M35), 39.11 MPa (M40), and 44.16 MPa (M45), indicating the better performance of the higher-grade concrete.
4. The calibration curves of strength-maturity developed (TTF vs. strength) showed high correlation with the maturity index across all grades, indicating that the maturity index is a valid indicator of hydration development and strength gain.
5. Comparison of predicted and measured strength was correct CP-CMM accuracy:
   - M35 showed quite good agreement, with a maximum error of approximately 1.5% ($R^2 \approx 0.998$).
   - M40 had the highest accuracy, with a maximum error of approximately 0.5 percent ($R^2 > 0.999$).
   - M45 exhibited somewhat greater deviation at early ages (maximum error of about 3 percent) due to the effect of PCE, which retards early hydration; however, forecasting was very precise at middle-age and later ages ($R^2 \approx 0.995$).
6. Generally, the maturity-based method with cumulative TTF is a powerful, non-destructive, and real-time prediction tool, as it reduces reliance on regular destructive cube tests and enhances decision-making in construction scheduling.

6.1. Study Limitations and Future Scope

The present study primarily focused on early-age strength development of concrete using the maturity method based on the cumulative Temperature–Time Factor (TTF). While temperature evolution and strength gain were effectively captured, the initial and final setting times of concrete were not directly measured.

Consequently, the maturity accumulation was assumed to begin immediately after casting, which may introduce minor inaccuracies at very early ages, particularly in mixes containing chemical admixtures. The absence of setting time measurements limits a detailed assessment of the exact relationship between setting behaviour and maturity development.

In addition, although temperature history was continuously monitored, detailed analysis of the temperature–time profile during the first 48 hours did not explicitly correlate with the activation sequence of Bogue’s Compounds (C_3S, C_2S, C_3A, and C_4AF). Consequently, the role of specific cement phases in early-age hydration kinetics and strength development could not be clearly understood within the scope.

The work will focus on these shortcomings in the future through experimental means to determine initial and final setting time using standard penetration resistance techniques, and correlate them with maturity accumulation (TTF) to achieve a more precise initiation point for maturity-based strength prediction.

It will also be studied in further studies to determine how the temperature-time profiles in the initial 48 hours affect early-age concrete behaviour in relation to the activation of the compound mentioned by Bogue. This kind of analysis should serve to deepen the knowledge of hydration processes and lead to the improvement of the accuracy of early-age prediction of strength models, especially in high-strength and admixture-modified concretes

Conflicts of Interest

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

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References

[1] Christiaan Ernst Buys, "*Investigation of a Practical Application of the Maturity Method to Estimate the Early-Age Strength of Concrete*," Master Thesis, Stellenbosch University, pp. 1-144, 2019. [Google Scholar] [Publisher Link]

[2] N. Mahendra Reddy, Hanuma Kasagani, and U. Harshith Chowdary, "A Study on Real Time Strength Assessment of Concrete by Maturity Method," *IOP Conference Series: Earth and Environmental Science: Innovative Technology for Smart Construction Materials and Sustainable Infrastructure*, vol. 1130, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[3] S. Kishore, and A. Arun Kumar, "Real-time Monitoring and Prediction of Compressive Strength of Mortar and Concrete," *Materials Research Express*, vol. 12, no. 2, pp. 1-26, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Adam Marchewka, Patryk Ziolkowski, and Sebastián García Galán, "Real-time Prediction of Early Concrete Compressive Strength using AI and Hydration Monitoring," *Scientific Reports*, vol. 15, pp. 1-25, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[5] Kumar Kumarapu, M. Shashi, and K. Venkata Reddy, "Thermal Remote Sensing in Early Age Concrete Strength Estimation," *Conference Proceedings Applications of Geomatics in Civil Engineering*, pp. 59-70, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Dane Miller et al., "Real-time Monitoring of Early-age Compressive Strength of Concrete using an IoT-enabled Monitoring System: An Investigative Study," *Innovative Infrastructure Solutions*, vol. 8, pp. 1-15, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] Gurunath Kampli, Satyadhyan Chickerur, and M.V. Chitawadagi, "Real-time in-situ Strength Monitoring of Concrete using Maturity Method of Strength Prediction via IoT," *Materials Today: Proceedings*, vol. 88, pp. 110-118, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[8] Sanghee Kim et al., "Study on Early Age Concrete's Compressive Strengths in Unmanaged Curing Condition Using IoT-Based Maturity Monitoring," *Buildings*, vol. 14, no. 3, pp. 1-15, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[9] Dane Miller, Nhat-Minh Ho, and Nima Talebian, "Monitoring of in-place Strength in Concrete Structures using Maturity Method – An Overview," *Structures*, vol. 44, pp. 1081-1104, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[10] H. Gu et al., "Concrete Early-age Strength Monitoring using Embedded Piezoelectric Transducers," *Smart Materials and Structures*, vol. 15, no. 6, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[11] Jeffrey McMillan Nixon et al., "*Evaluation of the Maturity Method to Estimate Concrete Strength in Field Applications*," Thesis, Auburn University, pp. 1-295, 2006. [Google Scholar] [Publisher Link]

[12] Francis A. Oluokun, Edwin G. Burdette, and J. Harold Deatheridge, "Early-age Concrete Strength Prediction by Maturity—Another Look," *Materials Journal*, vol. 87, no. 6, pp. 565-572, 1990. [CrossRef] [Google Scholar] [Publisher Link]

[13] Yelbek Utepov et al., "Complex Maturity Method for Estimating the Concrete Strength Based on Curing Temperature, Ambient Temperature and Relative Humidity," *Applied Sciences*, vol. 11, no. 16, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[14] Yee Yan Lim et al., "Monitoring of Concrete Curing using the Electromechanical Impedance Technique: Review and Path Forward," *Structural Health Monitoring*, vol. 20, no. 2, pp. 604-636, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[15] Pavel Kasal, Václav Lorenc, and Werner Wenighofer, "The Use of Maturity Method for Estimating in Situ Compressive Strength of Concrete," *Solid State Phenomena*, vol. 309, pp. 103-107, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[16] Taewan Kim, and Kevin L. Rens, "Concrete Maturity Method Using Variable Temperature Curing for Normal and High-Strength Concrete. I: Experimental Study," *Journal of Materials in Civil Engineering*, vol. 20, no. 12, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[17] Najeebullah Tareen et al., "Comparative Analysis and Strength Estimation of Fresh Concrete Based on Ultrasonic Wave Propagation and Maturity Using Smart Temperature and PZT Sensors," *Micromachines*, vol. 10, no. 9, pp. 1-17, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[18] Aziz Hasan Mahmood et al., "On-site Strain and Temperature Monitoring of Belitic Calcium Sulfoaluminate Cement Concrete Airport Slabs: Feasibility of Maturity Method," *International Journal of Pavement Engineering*, vol. 26, no. 1, pp. 1-13, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[19] Setare Saremi, and Dimitrios Goulias, "Non-Destructive Testing in Concrete Maturity Modeling and Master Curve Development," *Applied Sciences*, vol. 13, no. 13, pp. 1-16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[20] Kamran Amini et al., "Development of Prediction Models for Mechanical Properties and Durability of Concrete Using Combined Nondestructive Tests," *Journal of Materials in Civil Engineering*, vol. 31, no. 2, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[21] P. Turgut, "Research into the Correlation between Concrete Strength and UPV values," *NDT Net*, vol. 12, no. 12, 2004. [Google Scholar] [Publisher Link]

[22] V.M. Malhotra, and N.J. Carino, *Handbook on Non-destructive Testing of Concrete*, 2nd ed., *CRC Press*, pp. 1-384, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[23] Rafah R. Abdulmajid et al., "Feasibility of the Maturity Concept for Strength Prediction in Geopolymer Based Materials," *Composites Science*, vol. 9, no. 7, pp. 1-16, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[24] C.T. Medrano, G. Peña-Rodríguez, and I.H. García-Páez, "Determination of Correlation of Compressive Strength with Maturity of Concrete Mixed with Accelerator," *Journal of Physics: Conference Series: 5th International Meeting for Researchers in Materials and Plasma Technology*, Cúcuta, Colombia, vol. 1386, pp. 1-6, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[25] Y. Sun, and H.S. Lee, "Determination of Coefficient "s" and Apparent Activation Energy for Fib Model Code's Maturity-based Strength Function when Applied to Fly Ash Concrete," *Construction and Building Materials*, vol. 409, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[26] Shemin T. John et al., "IoT Enabled Real-Time Monitoring System for Early-Age Compressive Strength of Concrete," *Journal of Structural Engineering*, vol. 146, no. 2, pp. 1-37, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[27] Chih-Yuan Chang, and San-Shan Hung, "Implementing RFIC and Sensor Technology to Measure Temperature and Humidity Inside Concrete Structures," *Construction and Building Materials*, vol. 26, no. 1, pp. 628-637, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[28] Min Ju et al., et al., "Piezoelectric Materials and Sensors for Structural Health Monitoring: Fundamental Aspects, Current Status, and Future Perspectives," *Sensors*, vol. 23, no. 1, pp. 1-20, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[29] T. John Shemin, Pradip Sarkar, and Robin Davis, "A Long-range Wide-area Network System for Monitoring Early-age Concrete Strength," *Journal of Construction Engineering and Management*, vol. 149, no. 1, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[30] Nikita Bhalla et al., "Monitoring Early-age Setting of Silica Fume Concrete using Wave Propagation Techniques," *Construction and Building Materials*, vol. 162, pp. 802-815, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[31] Qian Feng, Yabin Liang, and Gangbing Song, "Real-Time Monitoring of Early-Age Concrete Strength Using Piezoceramic-Based Smart Aggregates," *Journal of Aerospace Engineering*, vol. 32, no. 1, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[32] Branavan Arulmoly, Chaminda Konthesingha, and Anura Nanayakkara "Performance Evaluation of Cement Mortar Produced with Manufactured Sand and Offshore Sand as Alternatives for River Sand," *Construction and Building Materials*, vol. 297, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[33] Kosalya Sundaralingam, Arvinthan Peiris, and Navaratnarajah Sathiparan, "Manufactured Sand as River Sand Replacement for Masonry Binding Mortar," *2021 Moratuwa Engineering Research Conference (MERCon)*, Moratuwa, Sri Lanka, pp. 403-408, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[34] Yun Duan et al., "Research on the Effect of Steam Curing Temperature and Duration on the Strength of Manufactured Sand Concrete and Strength Estimation Model Considering Thermal Damage," *Construction and Building Materials*, vol. 315, 2022. [CrossRef] [Google Scholar] [Publisher Link]