

Research Article

Real-Time Monitoring of Concrete Strength Evolution Using Embedded Wireless Sensors

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Article Info	Abstract
Article History	The maturity technique offers a practical approach for forecasting early-age strength development. This study aimed to evaluate the accuracy of Giatec's SmartRock sensors by comparing their measurements with conventional specimen test results derived from the maturity index. Twelve concrete combinations were evaluated, with compressive strengths ranging from 20 to 45 MPa. The nine concrete mixes were designed with varying proportions of cement, sand, coarse aggregate, water, and admixture, as summarised in Table 1. The cement content ranged from 290 to 430 kg/m ³ , water-to-cement ratios varied from 0.27 to 0.51, and admixture dosages ranged from 0.5% to 1.2% by weight of cement, depending on the desired strength level (20-63 MPa). Cylinder tests performed at 1, 3, 7, 14, and 28 days provided the data necessary to calibrate the maturity–strength relationships. The resulting correlations between compressive strength and maturity index showed excellent accuracy, with coefficients of determination (R^2) ranging from 0.986 to 0.999 across all twelve mixes (20-45 MPa). These results confirm that the SmartRock maturity method reliably predicts early-age strength and offers real-time assessment of in-situ concrete performance. The best-fit Vipulanandan models yielded coefficients of determination (R^2) ranging from 0.986 to 0.999, demonstrating excellent agreement between sensor-predicted and laboratory-measured strengths. Predicted early-age strengths (3–7 days) differed from test values by less than 5%, confirming the reliability of the SmartRock system for field applications. The study concludes that the maturity method, when properly calibrated, provides a robust and non-destructive means to predict in-place concrete strength in real time, enabling faster formwork removal and improved construction quality control.
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1. Introduction

Accurate estimation of in-situ concrete strength during early curing is critical for ensuring structural safety, optimising construction schedules, and improving quality control. Conventional strength evaluation methods, such as cylinder or cube compression tests, are destructive and provide results only at discrete

ages (typically 1, 3, 7, 14, and 28 days). As a result, these methods offer limited insight into continuous strength development and may lead to conservative decision-making or premature formwork removal.

Concrete is one of the most widely used construction materials due to its low cost, durability, and versatility in forming safe and reliable structures. However, early-age strength estimation remains challenging due to the complexity of concrete mixtures comprising cement, aggregates, water, and admixtures, as well as uncertainties in field-curing conditions. Inaccurate early-age strength assessment can increase the risk of structural damage or failure during construction.

To address these limitations, non-destructive testing (NDT) techniques have been increasingly adopted. Among them, the maturity method provides a practical and reliable solution for estimating in-place concrete strength. Defined in ASTM C1074, this method relates the temperature history of hydrating concrete to its strength development through a maturity index. By continuously monitoring concrete temperature and calculating the accumulated temperature–time factor, engineers can estimate real-time concrete strength without destructive testing.

Recent advances in wireless sensing technology have further enhanced the applicability of the maturity method. Giatec's SmartRock sensor is an embedded, wireless temperature sensor that records data at short intervals and automatically computes the maturity index using ASTM C1074 equations. This technology enables continuous, real-time monitoring of early-age concrete strength without interrupting the curing process or requiring repeated cylinder breaks. Despite these advantages, the accuracy and reliability of SmartRock sensors across different mix designs and curing conditions require systematic experimental validation. Therefore, the main objective of this study is to evaluate the precision of SmartRock sensors in estimating in-situ concrete strength by comparing their predictions with standard compressive strength tests. Twelve different concrete mixes were investigated, calibration curves between maturity index and compressive strength were developed using the Vipulanandan model, and prediction accuracy was assessed using the coefficient of determination (R^2). The findings aim to validate the use of SmartRock sensors for real-time, non-destructive strength assessment and to support improved on-site decision-making in modern construction projects.

2. Literature Review

Determining the compressive strength of concrete is one of the most critical challenges in the construction industry. Traditionally, compressive strength is verified through cylinder tests conducted at

specific ages, commonly at 1, 3, 7, 14, 21, and 28 days. While effective for quality assurance, these tests provide limited information between testing intervals and do not reflect the continuous strength development of concrete in the field.

To overcome these limitations, numerous standards and studies [1-11] recommend evaluating early-age concrete strength (typically within the first 14 days) using the maturity method. The fundamental principle of concrete maturity states that "concrete of the same mix at the same maturity has approximately the same strength regardless of the combination of temperature and age that produced the maturity" [12]. Since concrete temperature can be recorded at short time intervals, the maturity method provides a detailed representation of early-age temperature history and strength development.

The maturity concept is based on the Arrhenius theory of temperature-dependent chemical reaction kinetics and is widely used to predict cement hydration and strength development [13]. Concrete gains strength when its temperature exceeds a datum temperature, commonly taken as 32 °F (0 °C). The Nurse–Saul equation is widely used to compute the maturity index:

$$M(t) = \sum (T_a - T_0) \Delta t \quad (1)$$

where $M(t)$ is the maturity index at age t , T_a is the average concrete temperature, Δt is the time interval, and T_0 is the datum temperature [12]. This relationship demonstrates that concrete mixtures with identical maturity indices exhibit comparable strength development regardless of curing temperature or duration. ASTM C1074, *Standard Practice for Estimating Concrete Strength by the Maturity Method*, provides comprehensive guidelines for applying this technique. The maturity method is non-destructive, objective, and efficient, offering a reliable alternative to traditional in-situ strength evaluation techniques. Once a maturity–strength calibration curve is established and validated for a specific mix design, compressive strength can be estimated on-site in real time, eliminating delays associated with specimen transportation and laboratory testing [14].

Recent studies have highlighted the benefits of computerised batching and improved mixture consistency, which reduce variability and enhance the reliability of maturity-based strength predictions. However, each concrete mixture requires pre-calibration, as maturity–strength relationships are mix-specific. Wireless maturity sensors such as Giatec's SmartRock have been introduced to automate temperature monitoring and maturity calculations, transmitting data at regular intervals (e.g., every 15 minutes) and reducing reliance on destructive testing [15, 16]. Although prior research has demonstrated

the potential of maturity-based systems for early-age strength prediction, most studies have focused on limited mix designs or controlled laboratory conditions. Further investigation is needed to evaluate the performance of wireless maturity sensors across a wider range of practical concrete compositions and curing scenarios.

The main objective of this study is to verify SmartRock sensor readings with standard specimen test results, which depend on the maturity index. For this purpose, 9 different mixes were studied, and cylinder samples were tested for compressive strength. The compressive strengths at various ages were combined with the predicted maturity from the SmartRock sensor, and maturity and compressive strength curves were subsequently generated.

3. Methodology

Figure 1. Conceptual illustration of the concrete maturity concept, showing the relationship between curing temperature, time, and strength development. Figure 2. Relationship between the maturity index and compressive strength of concrete, demonstrating the increase in strength with increasing maturity over time.

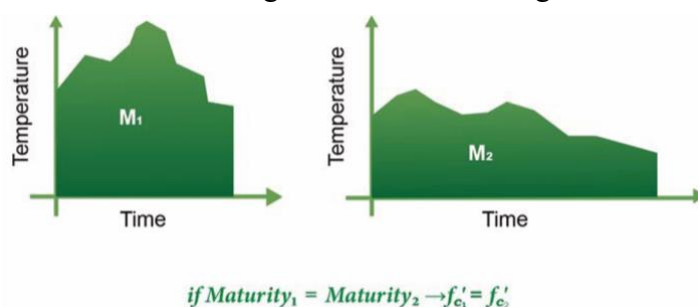


Figure 1. A conceptual diagram illustrating the principles of concrete maturity, showing the relationship between temperature, time, and strength development

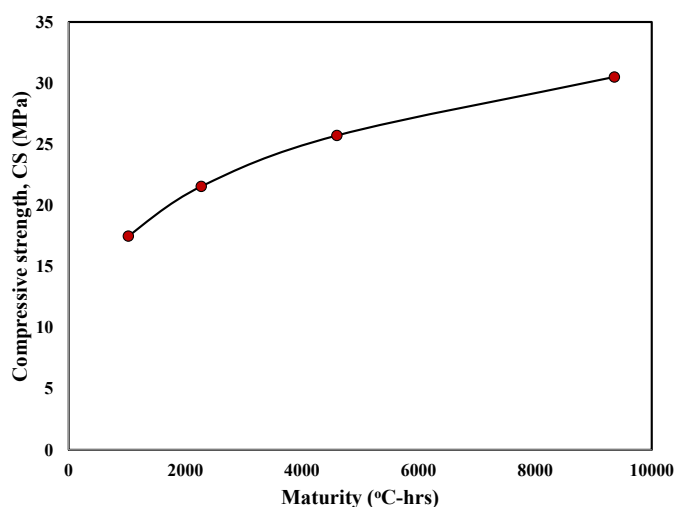


Figure 2. A graph displaying the correlation between the maturity index and compressive strength of concrete, highlighting how strength increases over time

According to ASTM C1074, a structured procedure is outlined for developing the maturity curve and estimating compressive strength (Figures 3 and 4). The maturity-strength curve shows the relationship between the maturity index and compressive strength for a specific concrete mix design developed in the laboratory.

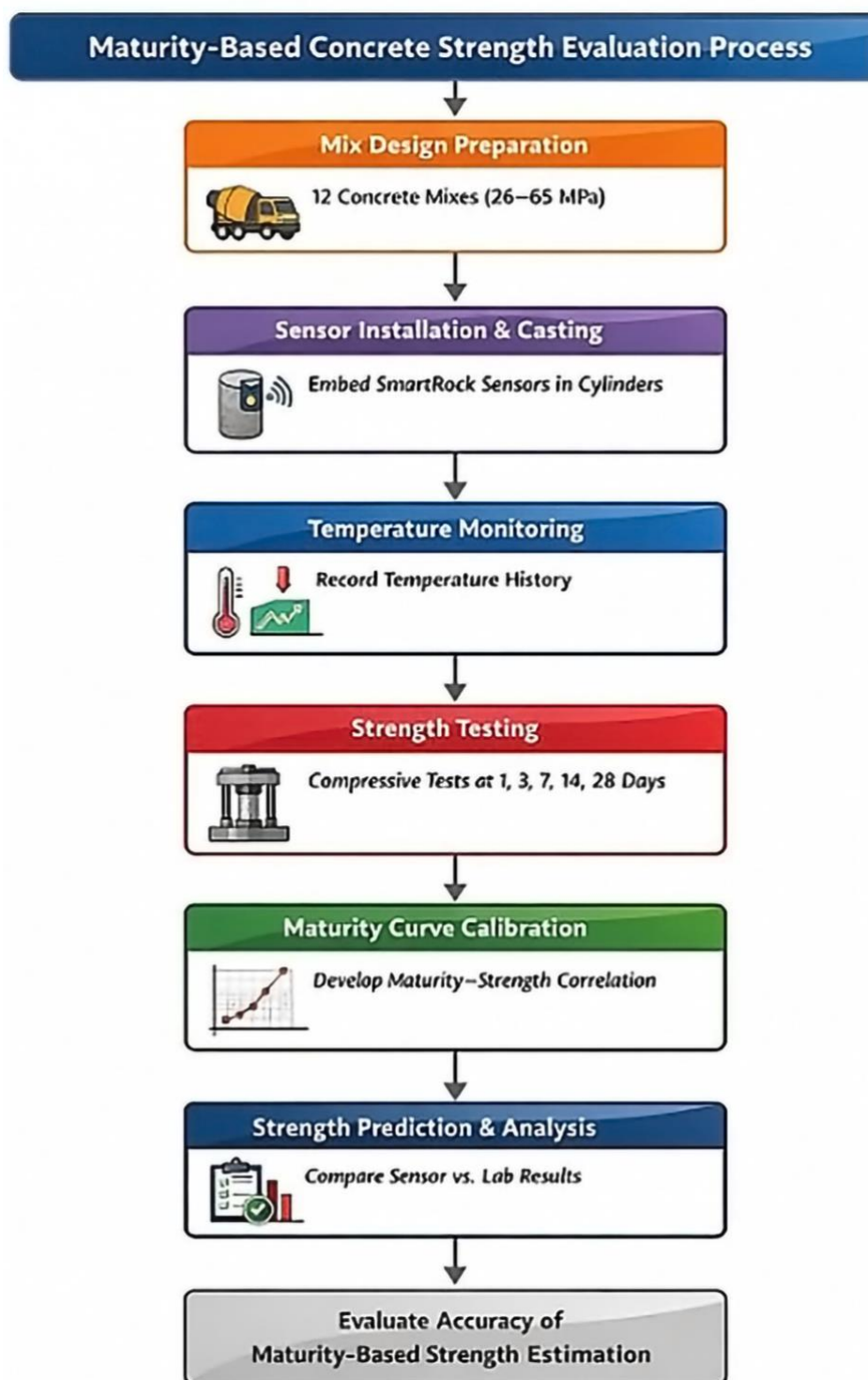


Figure 3. Step-by-step flowchart outlining the methodology of the research, including concrete mix design, sensor placement, data collection, and analysis

This process involves casting cylindrical concrete specimens (as shown in Figure 5), curing them under semi-adiabatic conditions, and embedding temperature sensors in at least two specimens to monitor the hydration temperature history. Compressive strength is measured at 1, 3, 7, 14, and 28 days. The maturity index is calculated at these times using Equation 1, and the data are used to plot a curve correlating strength with the maturity index (Figure 6). Ensuring consistency between the mix design and the project application is essential for reliable results.

$$\text{Compressive strength } f'_c = a + b \log M \quad (2)$$

Once the maturity-strength curve is established, the in-situ concrete strength may be approximated by utilising the hydration temperature history. To do this, the thermal history of the concrete components must be documented post-pouring using embedded sensors placed in areas that are typically crucial for exposure conditions, curing, and structural specifications. Regular quality control assessments must be conducted to verify the precision of the maturity-strength curve. These restrictions reduce errors in estimating in-place strength caused by the inherent limitations of the concrete maturity-measuring technique.



Figure 4. Cylinder and cube specimens used for compressive strength testing, showing their size and shape

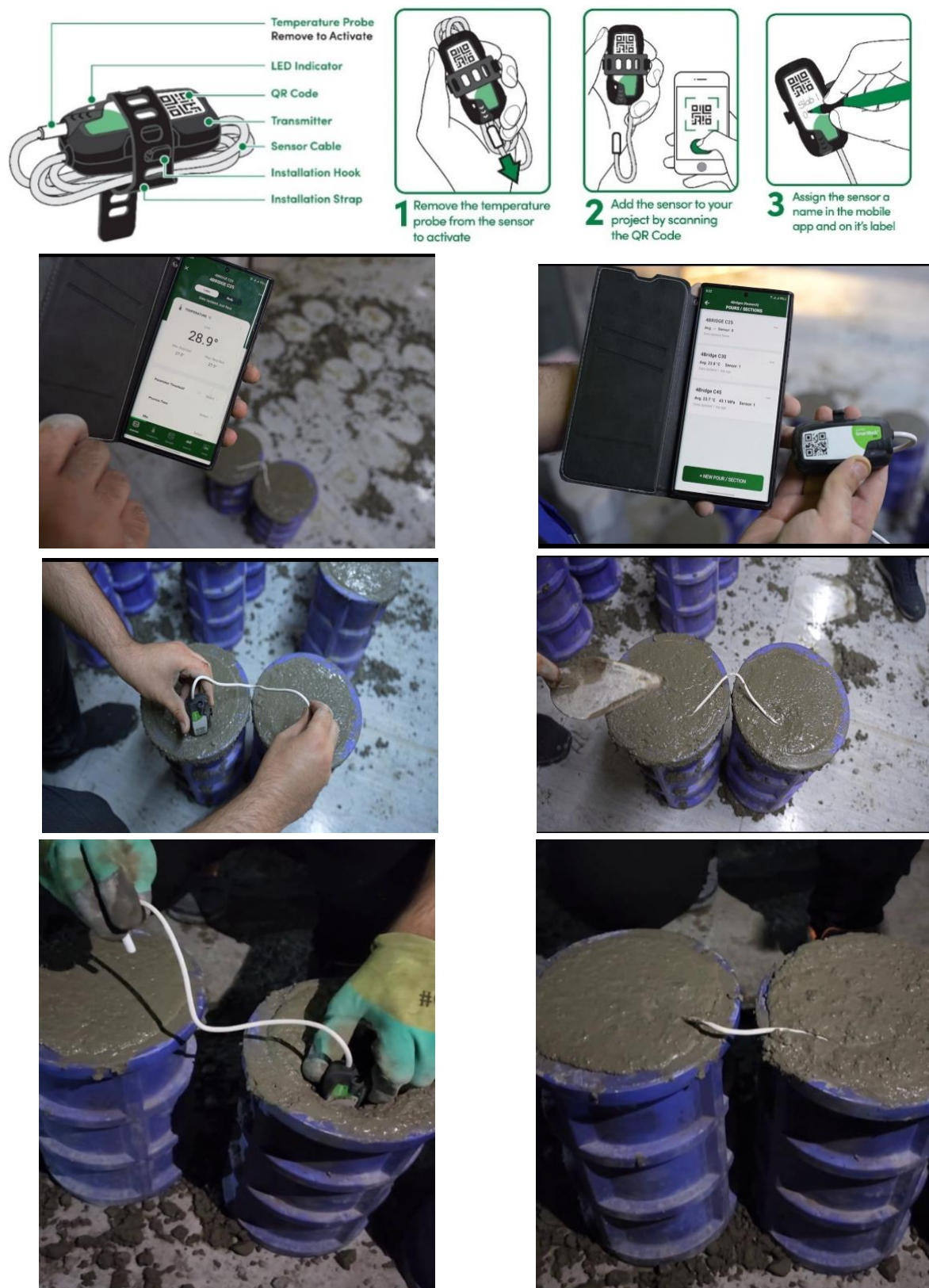


Figure 5. Process of Embedding SmartRock Sensor in Fresh Concrete for Real-Time Temperature Monitoring (a) Placement of SmartRock sensor within the fresh concrete, (b) Final positioning of the sensor in the cured concrete specimen, and (c) Close-up view showing the sensor embedded in the concrete matrix

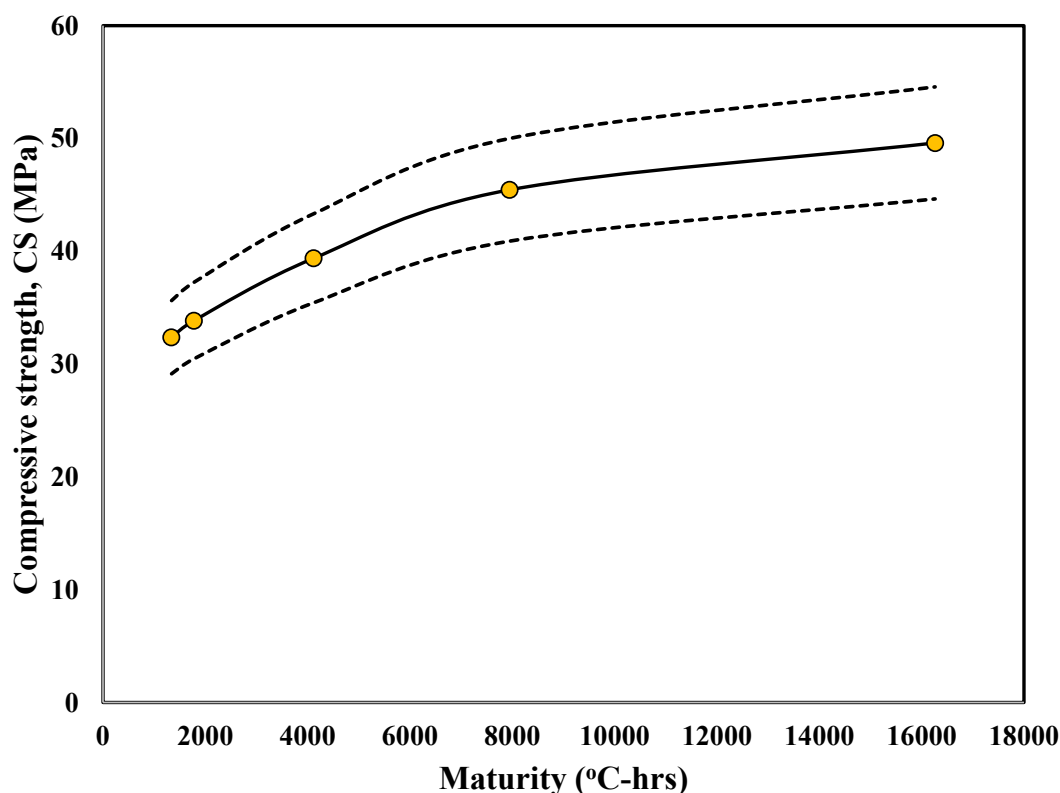


Figure 6. The relationship between the calculated maturity index and measured compressive strength for different concrete mixes

4. Experimental Works

The laboratory test results at various ages were graphed against the temperature-age curve, as shown in Table 1. The mix proportions (cement, sand, aggregate, water, and admixtures) were adjusted to achieve concrete compressive strengths ranging from 24 to 40 MPa, as indicated. Well-graded sand and aggregates of varying maximum sizes were utilised, and factory mixers supplied all mixtures. A series of validation cubes and cylinders was produced for each combination type. The sets comprised 15 cylinders for compressive strength testing at various ages and 2 additional cylinders with an embedded logger. Cylinders were cured in the field for 24 hours before being transported to the testing laboratory (ASTM-C31). They underwent curing for the initial 24 hours and were thereafter transported to the testing laboratory for final curing. The implanted logger was observed in the laboratory during the curing process. All data was stored in the software linked to the SmartRock sensor. The cylinders underwent laboratory testing at 1, 3, 7, 14, and 28 days to ascertain their compressive strength. The laboratory test results at various ages were plotted against the SmartRock temperature-age curve to generate the maturity-strength curve for each mixture. The final SmartRock maturity strength curve will be the calibrated curve projected for the designated mix.

Table 1. Mix proportions from different ready-mix concrete factories

Different Mix for SmartRock application						
Mix.	Concrete Factory	Mix Grade	Mix proportions			
			Water (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)
M1	Gokce	C20	100	290	1220	790
M2	4Bridge	C20	135	300	1150	815
M3	Emsal	C24	170	330	944	956
M4	4Bridge	C24	135	300	1150	815
M5	Gokce	C24	100	290	1220	790
M6	4Bridge	C36	125	385	1060	830
M7	Cement Power	C36	123.5	385	1030.3	904.4
M8	Darin	C40	116	430	1081	812
M9	Iberia	C40	116	430	1081	812

5. Results and analysis

5.1. Compressive Strength from Laboratory

For each mix, 15 cylinders were tested for compressive strength at 1, 3, 7, 14, and 28 days. The results are presented in Table 2. For each age, the values in Table 2 are the averages of three cylinders and represent the cylindrical compressive strength of concrete.

Table 2. Laboratory concrete compressive strength results

Mix.	Concrete grade	Concrete compressive strength (MPa) at age				
		1 day	3 day	7 day	14 day	28 day
M1	C20	9.6±1.5	18.4±0	23.7±2.0	26.8±2.5	28.7±2.0
M2	C20	7.2±2.0	16.5±2.0	22.7±2.0	25.8±2.0	28.2±2.0
M3	C24	9±2	17.4±2.0	22.1±2.0	24.5±3.0	26.5±2.0
M4	C24	17.2±3	23.0±2.0	27.7±2.0	29.9±3.0	32.3±2.0
M5	C24	15.1± 2.0	20.8±3.0	25±3.0	27.9±2.0	31.6±2.0
M6	C36	25.3± 2.5	38.2±3.0	42.9±3.0	48±3.0	51.5±3.0
M7	C36	14.6± 1.5	30.1±3.0	38.9±3.0	45.3±3.0	46.2±3.0
M8	C40	42.7± 3.0	56.2±3.0	58.3±3.0	63.2±3.0	64.4±3.0
M9	C40	30.7± 2	40.4±4	47.8±3	52.2±3	56.2±3

5.2. SmartRock Sensor Temperature-Age Curves

The SmartRock sensor records the concrete temperature every 15 minutes and plots the relationship between temperature and time. The temperature-age curves for each mix are shown in Figure 7.

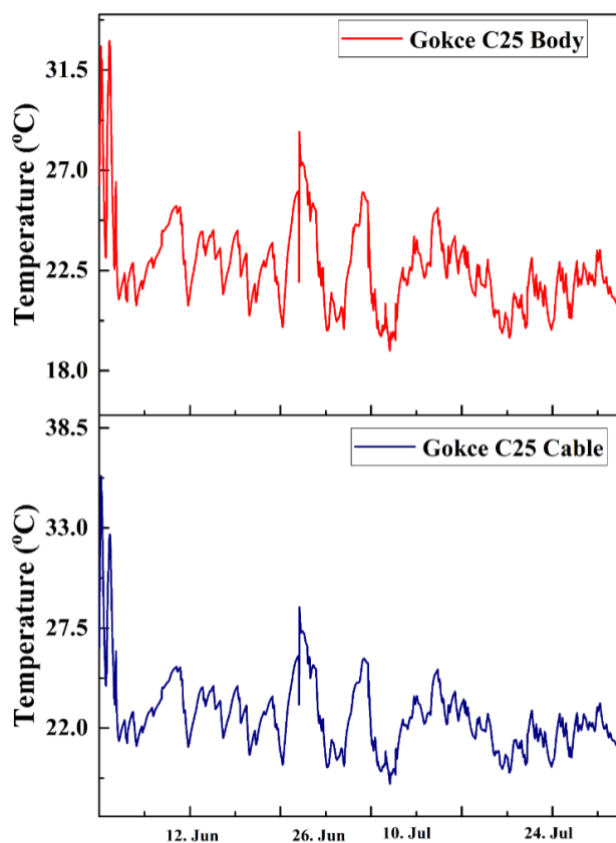


Figure 7a. A collection of line graphs showing the temperature variations over time for nine different concrete mixtures, recorded using SmartRock sensors

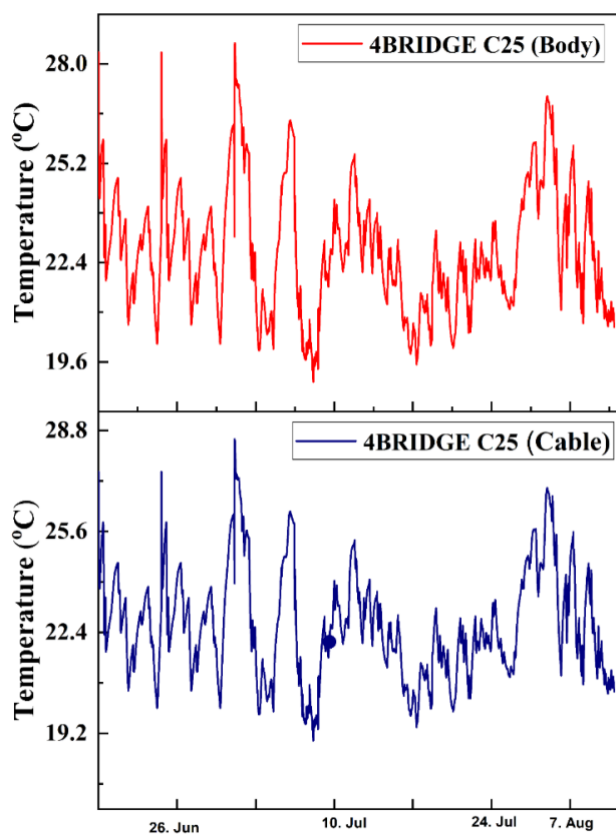


Figure 7b. Temperature-age curve for M2

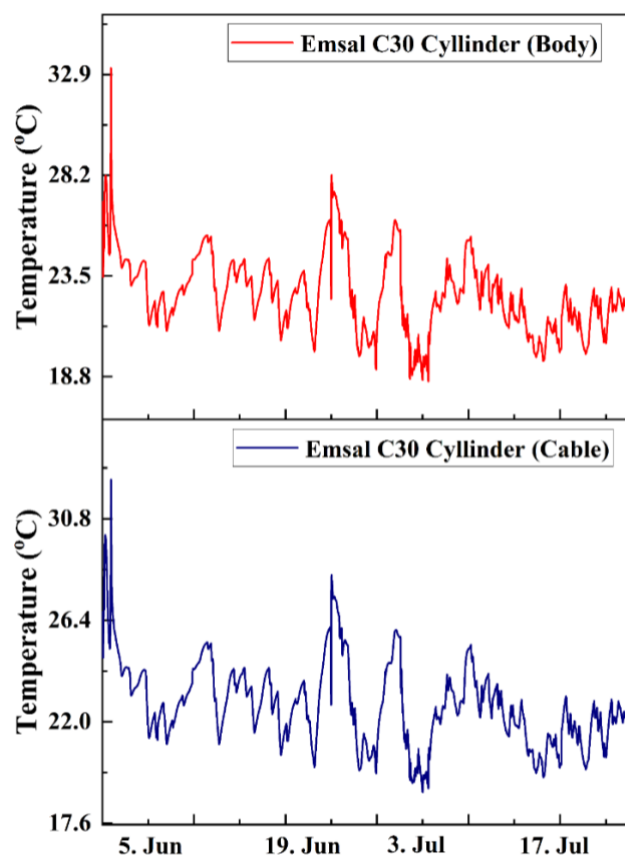


Figure 7c. Temperature- age curve for M3

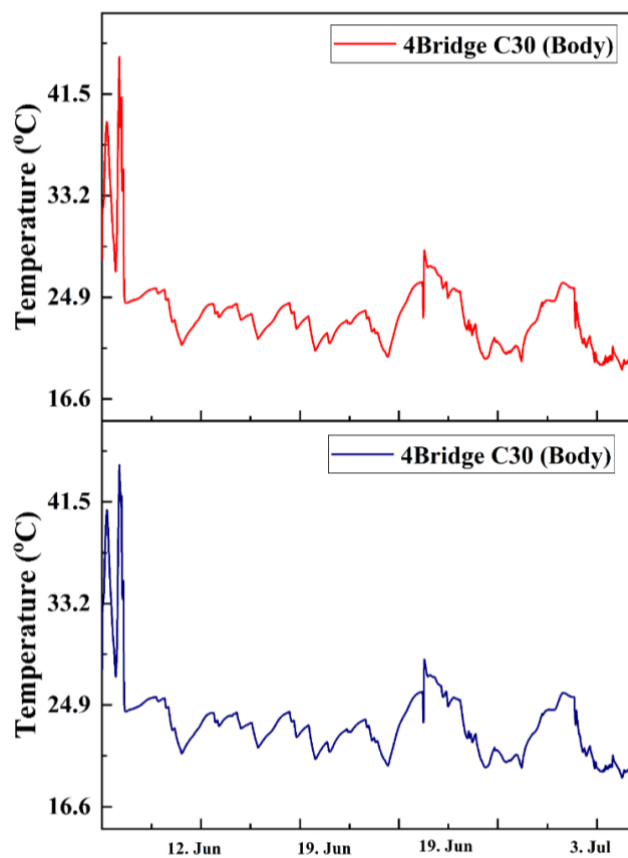


Figure 7d. Temperature-age curve for M4

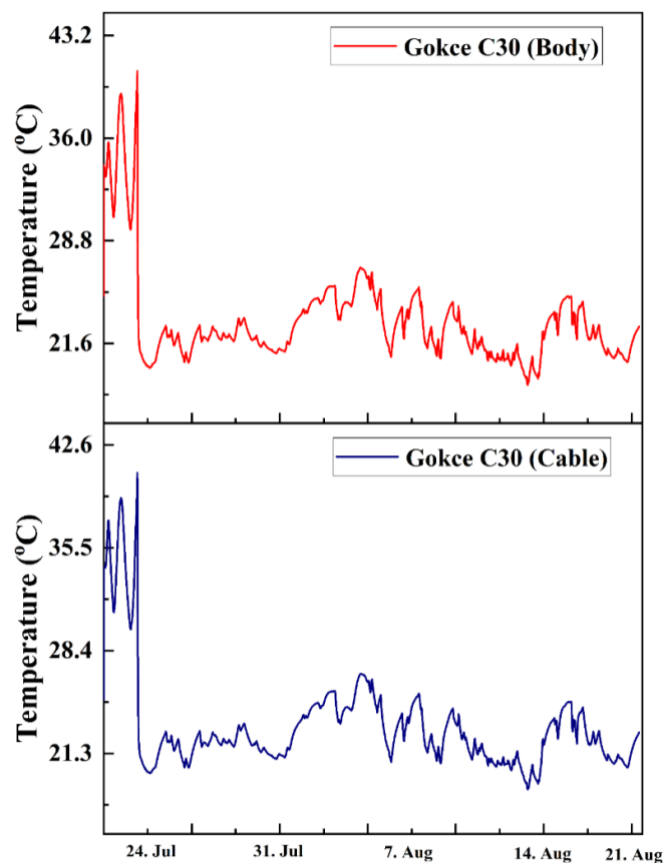


Figure 7e. Temperature- age curve for M5

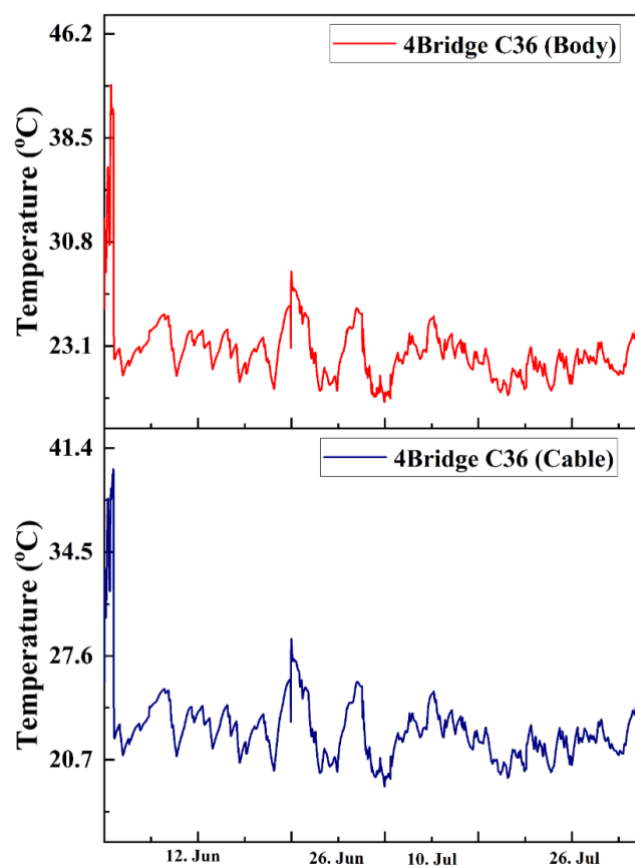


Figure 7f. Temperature-age curve for M6

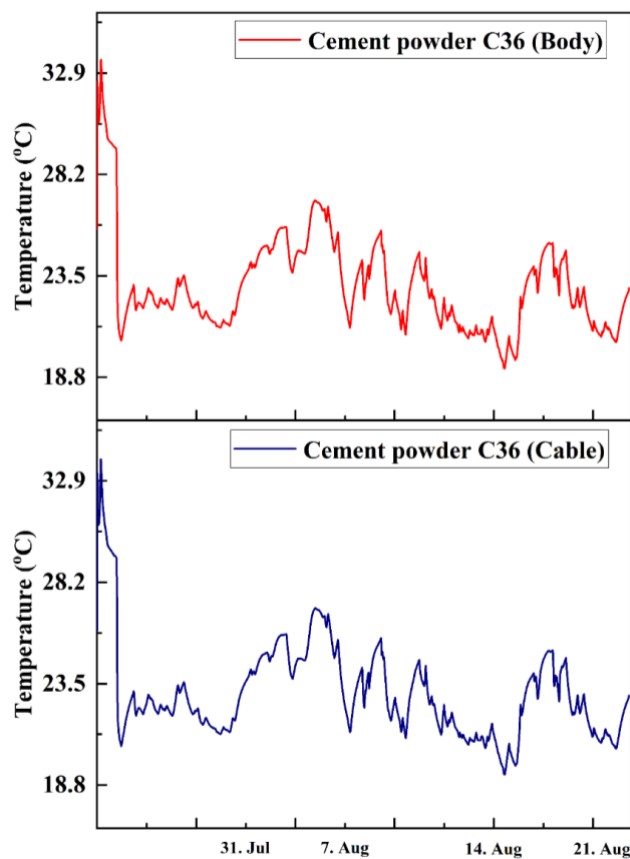


Figure 7g. Temperature-age curve for M7

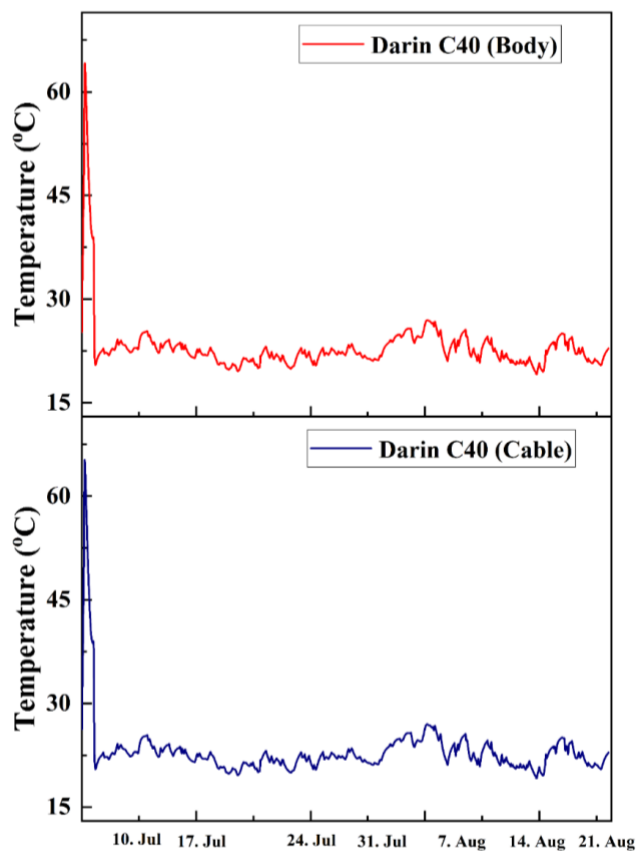


Figure 7h. Temperature-age curve for M8

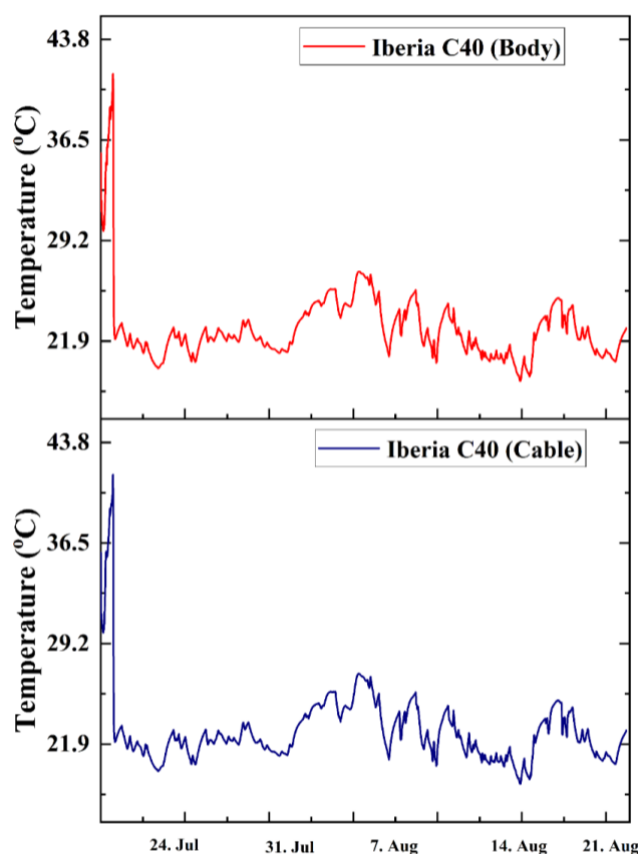


Figure 7i. Temperature-age curve for M9

5.3. The Correlation Between Maturity and Compressive Strength

To predict the precise relationship between maturity and compressive strength for each mix, the laboratory compressive strength results were used with the temperature-age curves to calibrate the maturity-strength curve and then obtain the strength-age curve.

The maturity and compressive strength curves for each mix are shown in Figure 8, using the Vipulanandan Equation with high accuracy and low root-mean-square error (Eq. 3) [17].

$$\text{Compressive strength} = a + \frac{x}{c + d * X} \quad (3)$$

where a, b, c, and d are model parameters, and X is the variable, here is maturity.

The coefficient of determination for all mixes M1-M9 using the following equations (Eq. 3.1 to Eq. 3.9) was between 0.986 and 0.999, which indicates that the equation almost predicts 100% of the compressive strength of concrete based on maturity values for all mixes.

$$\begin{aligned} M1 \quad \text{Compressive strength} &= 31.15 - \frac{-21.75}{0.716 + 0.0005 * \text{Maturity}} \\ R^2 &= 0.999 \end{aligned} \quad (3.1)$$

$$M2 \text{ Compressive strength} = 30.18 + \frac{-20.82}{0.716 + 0.0006 * \text{Maturity}} \quad (3.2)$$

$$R^2 = 0.999$$

$$M3 \text{ Compressive strength} = 28.51 + \frac{-19.77}{0.617 + 0.00059 * \text{Maturity}} \quad (3.3)$$

$$R^2 = 0.998$$

$$M4 \text{ Compressive strength} = 34.41 + \frac{-19.98}{0.7 + 0.0005 * \text{Maturity}} \quad (3.4)$$

$$R^2 = 0.998$$

$$M5 \text{ Compressive strength} = 35.87 + \frac{-25.1}{1.07 + 0.00029 * \text{Maturity}} \quad (3.5)$$

$$R^2 = 0.994$$

$$M6 \text{ Compressive strength} = 58.05 + \frac{-30.76}{1.15 + 0.00022 * \text{Maturity}} \quad (3.6)$$

$$R^2 = 0.998$$

$$M7 \text{ Compressive strength} = 49.37 + \frac{-21.66}{0.256 + 0.00049 * \text{Maturity}} \quad (3.7)$$

$$R^2 = 0.99$$

$$M8 \text{ Compressive strength} = 72.37 - \frac{108.92}{4.62 + 0.00083 * \text{Maturity}} \quad (3.8)$$

$$R^2 = 0.987$$

$$M9 \text{ Compressive strength} = 59.23 - \frac{83.55}{2.05 + 0.00147 * \text{Maturity}} \quad (3.9)$$

$$R^2 = 0.998$$

The SmartRock sensor measures concrete strength development over time by monitoring temperature, using the maturity method. Per the American Society for Testing and Materials (ASTM C1074) [5], the correlation between concrete temperature and maturity index, known as the temperature-time factor, can be determined using the Nurse-Saul maturity function. The recorded time history allows the computation of a maturity index that reliably estimates early-age concrete strength as a function of time. If the concrete maturity data indicates that the strength meets or exceeds the required threshold, this information will inform the potential time and cost savings achievable through early form removal. Conversely, suppose the maturity data reveal that the concrete strength remains below the requisite level for form removal. In that case, the quality control engineer will defer the removal until the concrete attains the necessary stability.

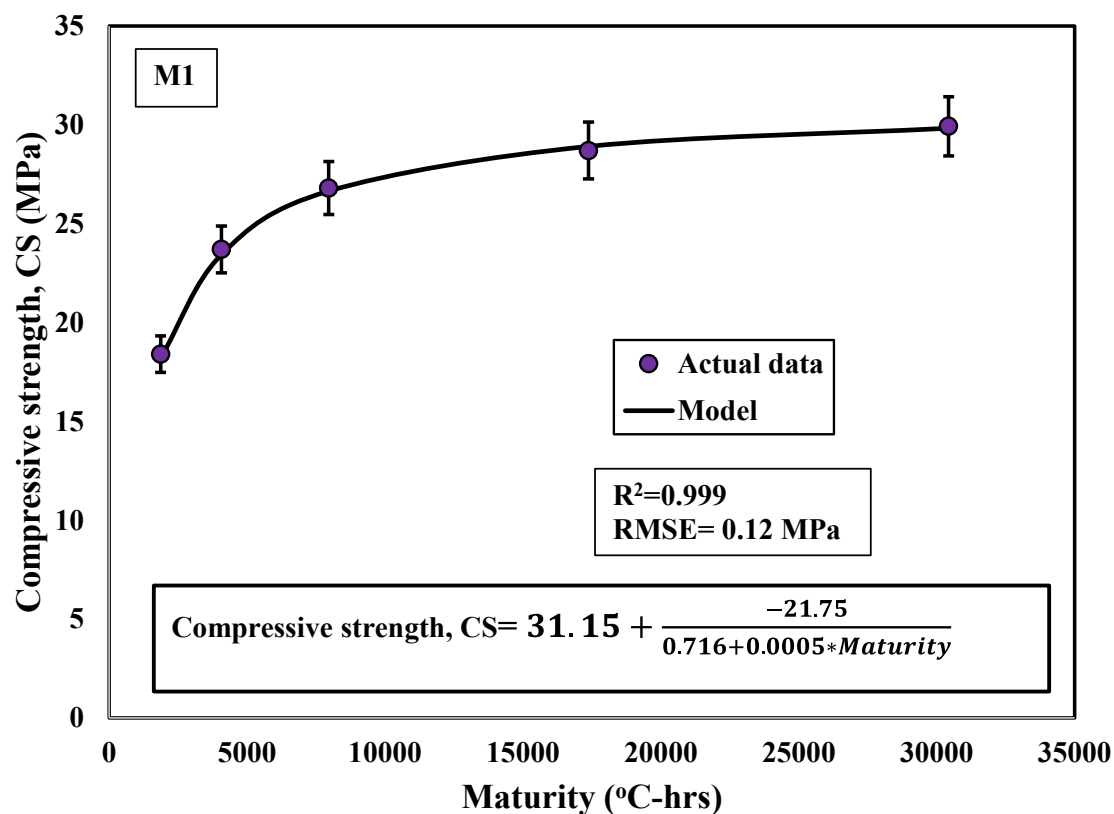


Figure 8a. Individual graphs representing the predicted compressive strength of each concrete mix based on the maturity method and laboratory test results

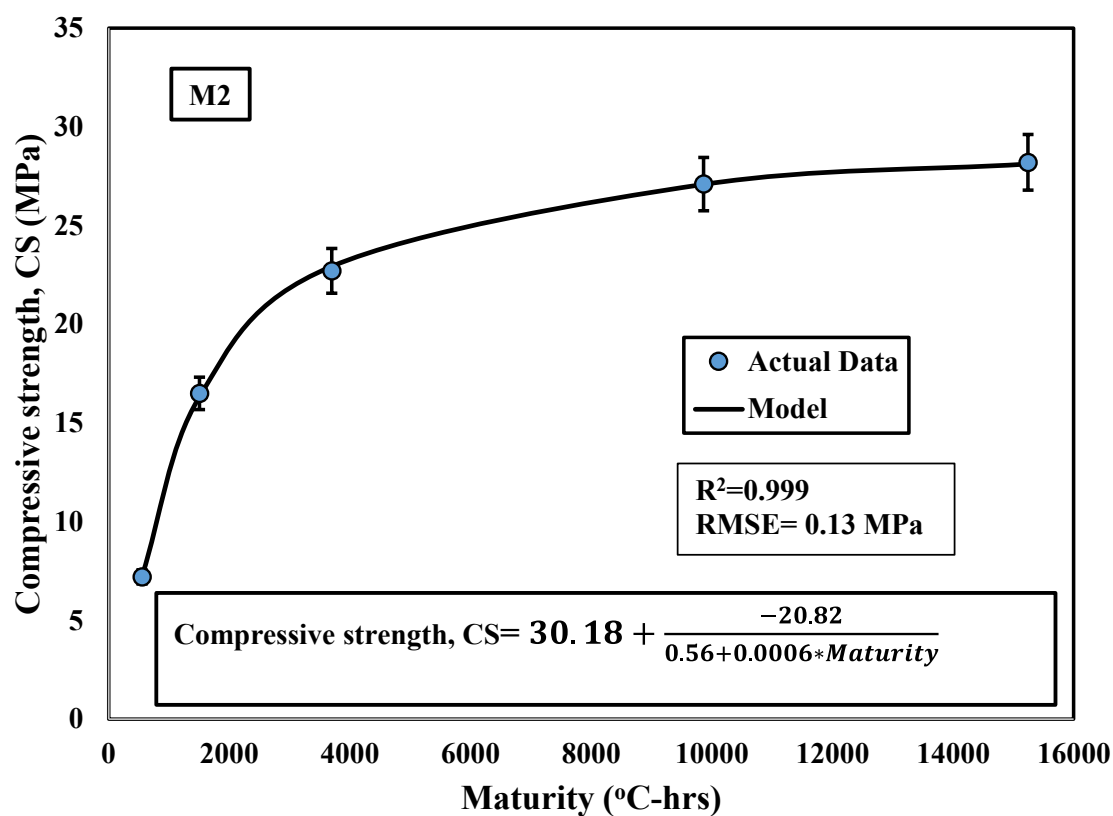


Figure 8b. Maturity-Strength curve for mix M2

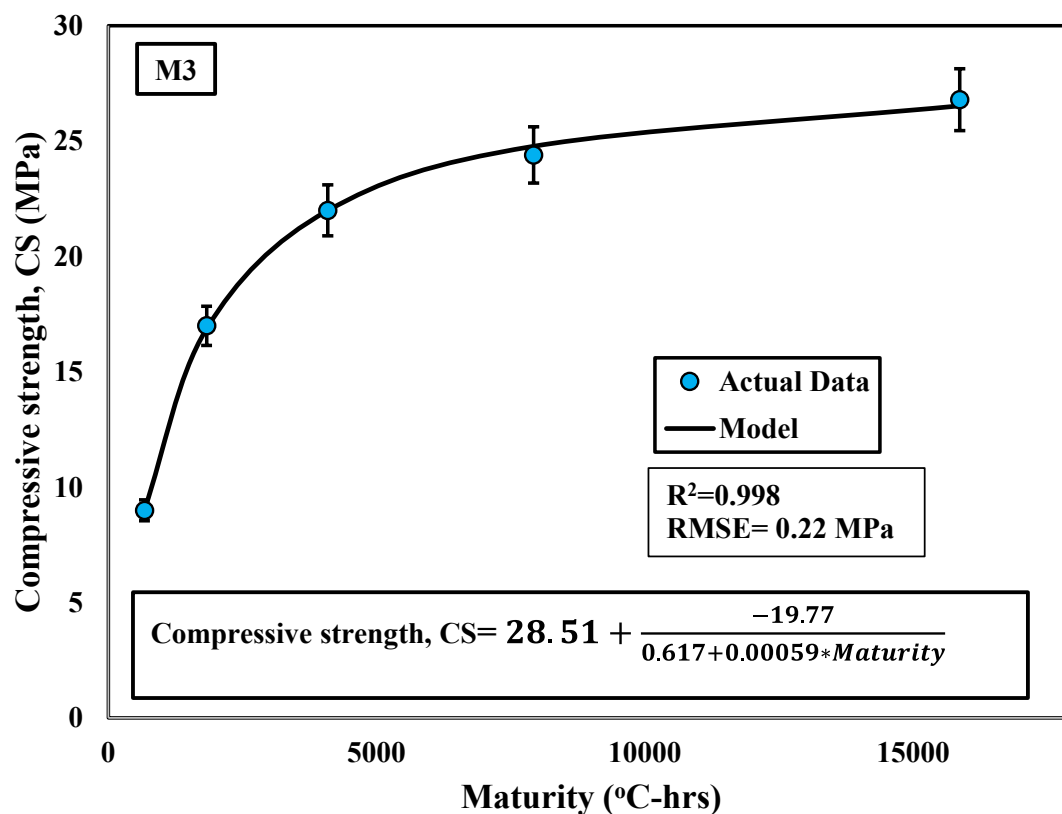


Figure 8c. Maturity-Strength curve for mix M3

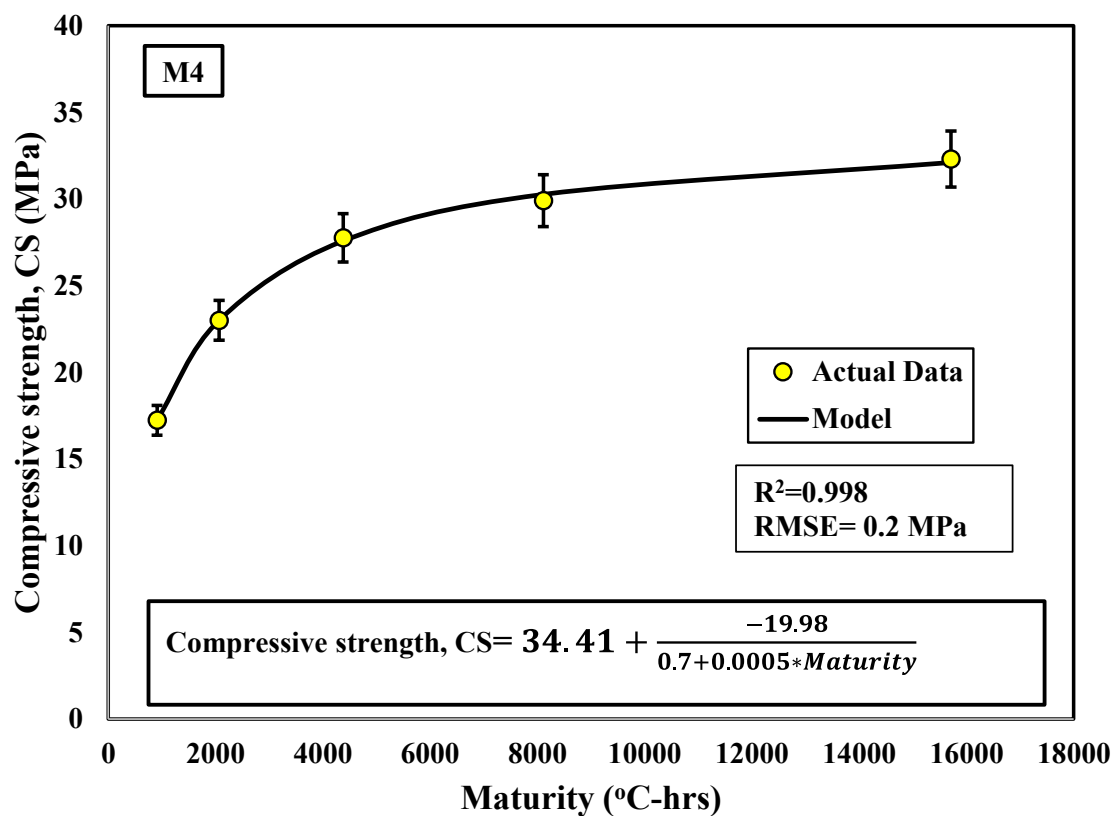


Figure 8d. Maturity-Strength curve for mix M4

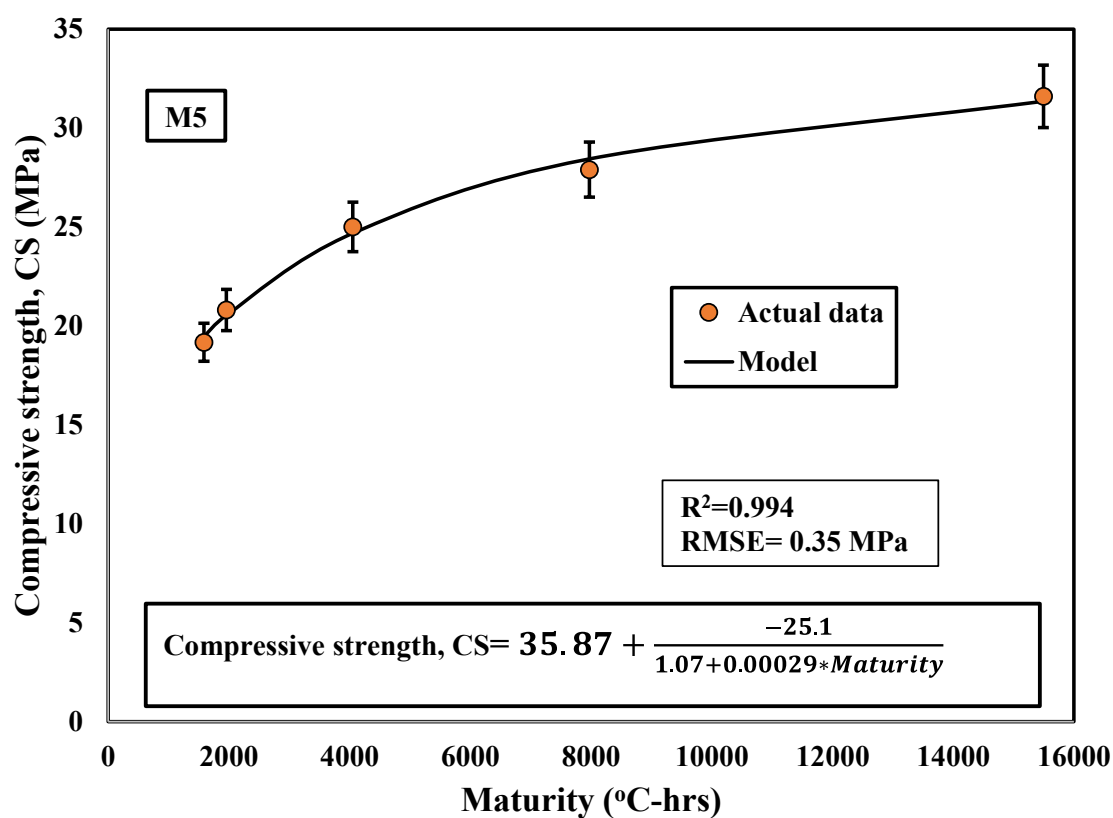


Figure 8e. Maturity-Strength curve for mix M5

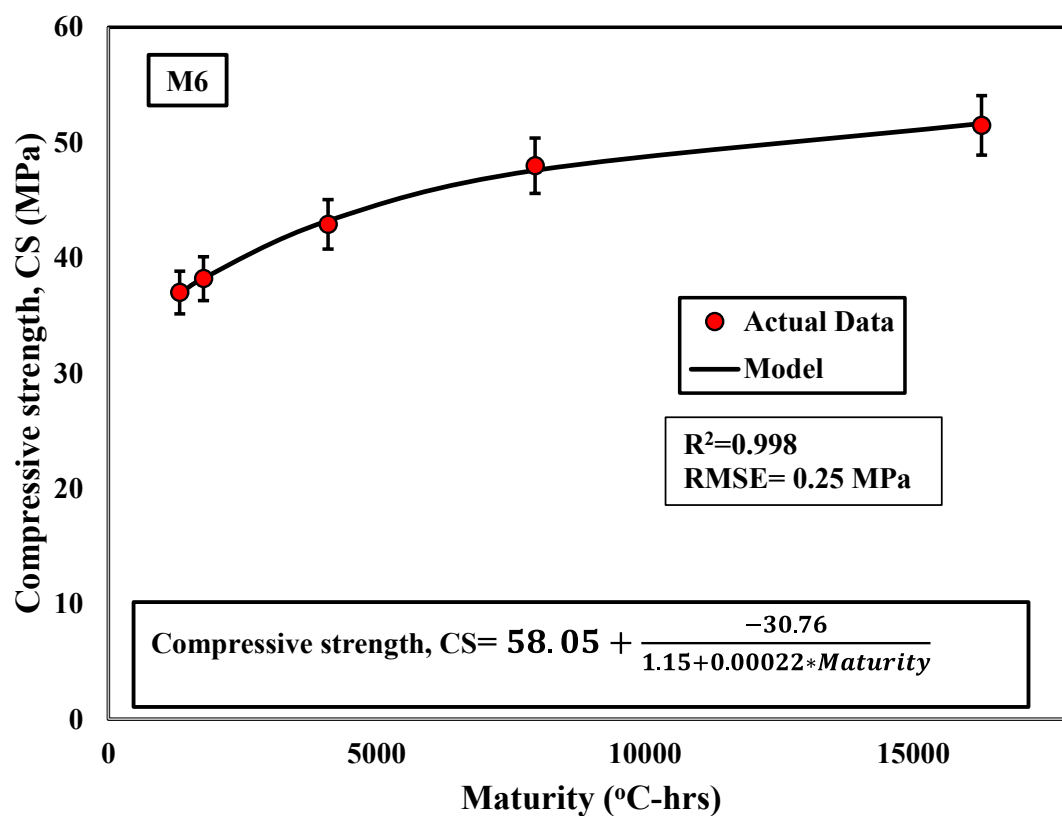


Figure 8f. Maturity-Strength curve for mix M6

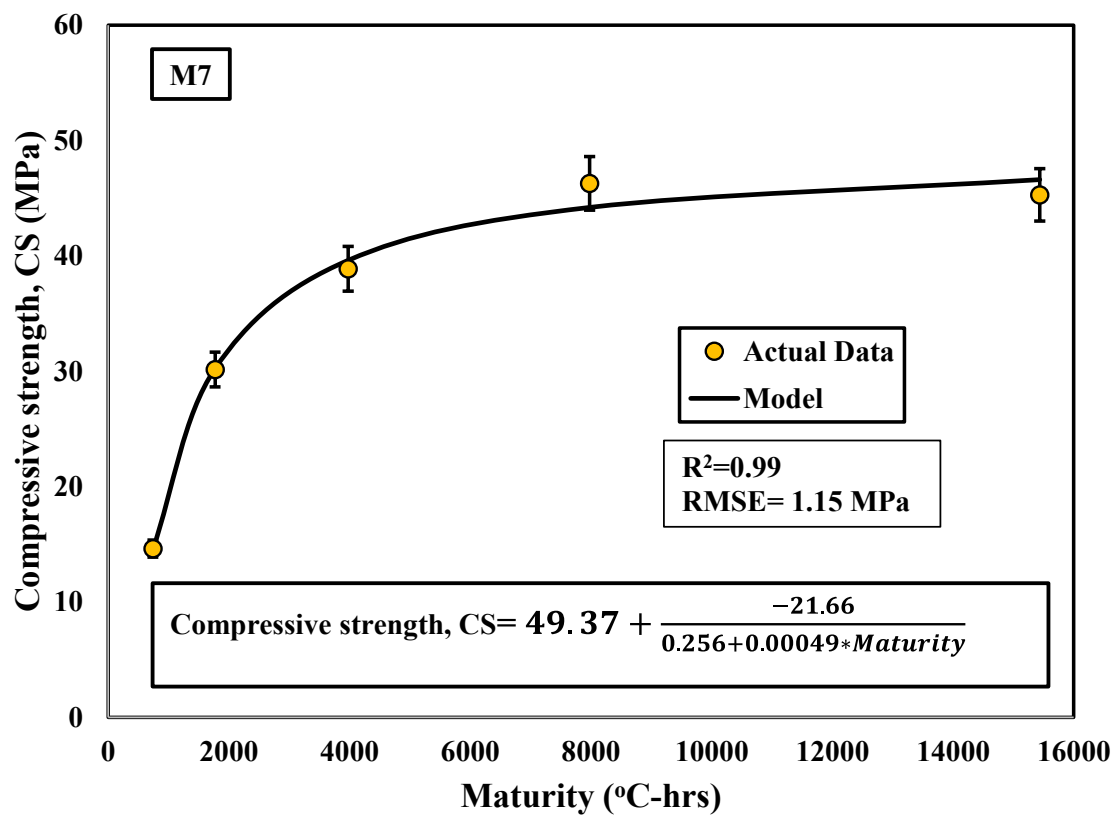


Figure 8g. Maturity-Strength curve for mix M7

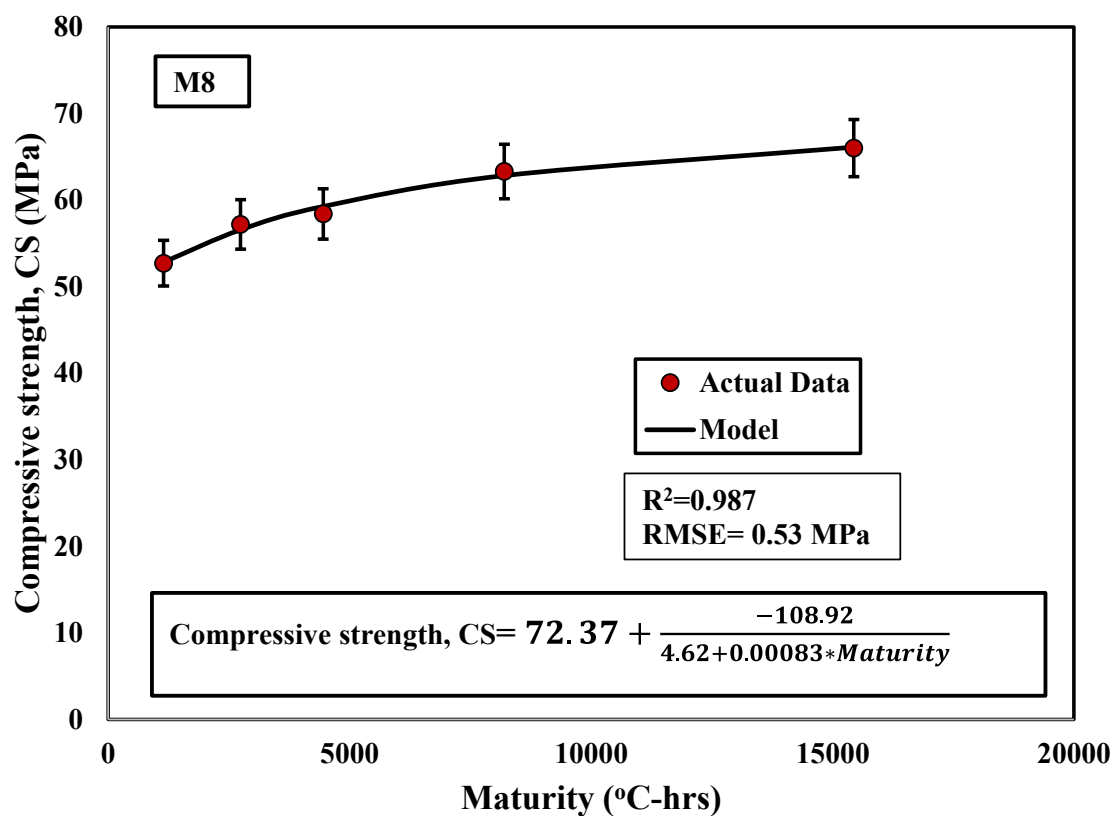


Figure 8h. Maturity-Strength curve for mix M8

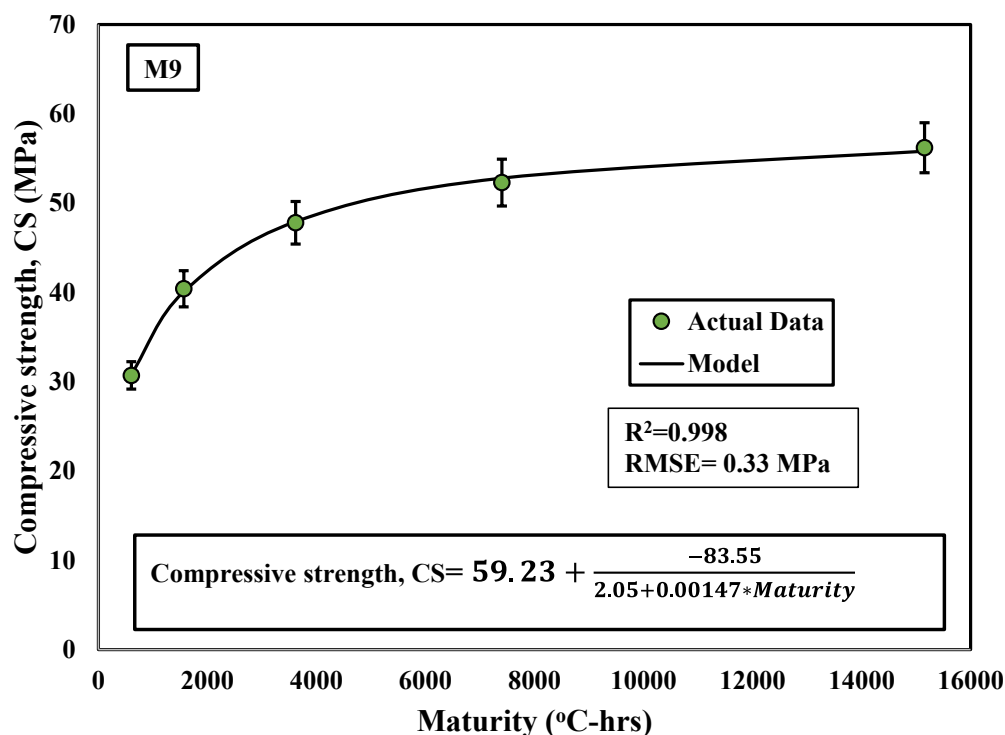


Figure 8i. Maturity-Strength curve for mix M9

5. Conclusions

The maturity-strength curve can be calibrated using laboratory results and SmartRock-estimated temperature-age relations to determine the optimal relationship between maturity and strength. It can be used to estimate concrete strength in any structural element where the same mix and grade of concrete are used. The main conclusions are;

- 1) The study verified that monitoring temperature fluctuations over time with SmartRock sensors accurately captures the temperature-time relationship, a crucial factor for forecasting concrete strength. The temperature data collected by the sensors played a vital role in accurately calculating the maturity index, which directly correlates with the growth in concrete strength.
- 2) SmartRock sensors reliably capture concrete temperature histories, enabling the precise calculation of the maturity index.
- 3) The maturity index strongly correlates with compressive strength, confirming the maturity method's applicability in real construction environments.
- 4) The non-destructive and continuous monitoring approach offers significant advantages over traditional destructive testing methods.
- 5) Real-time strength estimation supports improved on-site decision-making, potentially reducing

construction time and costs while enhancing quality control.

- 6) The maturity-strength relationship remained consistent across various concrete mixes, demonstrating the adaptability of this technique.
- 7) The results confirmed the practical usefulness of the ASTM C1074 maturity technique in real-life situations. The maturity index, derived from temperature data, provided a reliable assessment of concrete strength in its early stages, confirming the method's applicability to contemporary building techniques.
- 8) An evident association was found between the maturity index obtained from the SmartRock sensors and the compressive strength outcomes from conventional cylinder testing. This correlation highlights the maturity technique's dependability and the SmartRock sensors' precision in forecasting concrete strength.
- 9) The study experimented on twelve distinct concrete mixtures, each with varied levels of compressive strength ranging from 20 to 45 MPa. The results revealed that the maturity-compressive strength curves were similar across all mixtures. This demonstrates the adaptability of the SmartRock sensors and the maturity technique in effectively managing various concrete compositions.
- 10) A key benefit emphasised in this study is the SmartRock sensors' non-invasive nature. Unlike conventional techniques that damage the sample, these sensors provide a continuous, non-destructive approach to monitor concrete strength, resulting in more efficient, less wasteful testing procedures.
- 11) The use of SmartRock sensors has significant practical consequences. Real-time monitoring and prediction of concrete strength enhances on-site decision-making, potentially leading to shorter construction timeframes and enhanced quality control. This method can result in substantial cost reductions and improved structural integrity.
- 12) The study has presented strong evidence supporting the use of SmartRock sensors and has suggested opportunities for further research. Potential future research areas include long-term strength forecasting, the influence of environmental conditions on sensor precision, and the integration of other intelligent building technologies.
- 13) The study suggests that construction practitioners should consider using SmartRock sensors for projects that require accurate strength monitoring and quality management. Training on using these sensors and understanding the maturity method will be essential for maximising their benefits.

Data Availability Statement: The data supporting the findings of this study are included within the article. Additional experimental and sensor monitoring data are available from the corresponding author upon reasonable request.

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Declaration of Competing Interest: The authors declare that they have no known competing interests.

Research Involving Human/Animal Participants: This article does not involve any studies conducted by the authors on animals or human participants.

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