Smart Structures and Systems, *Vol. 31*, *No. 1* (*2023*) *1-11*
https://doi.org/10.12989/sss.2022.31.1.001

Application of internet of things for structural assessment of concrete structures: Approach via experimental study

D. Jegatheeswaran [a] and P. Ashokkumar*

Department of Civil Engineering, *Sona College of Technology*, *Salem - 636005*, *Tamilnadu*, *India*

(*Received September 20*, *2021*, *Revised May 6*, *2022*, *Accepted May 17*, *2022*)

Abstract. Assessment of the compressive strength of concrete plays a major role during formwork removal and in the pre-stressing process. In concrete, temperature changes occur due to hydration which is an influencing factor that decides the compressive strength of concrete. Many methods are available to find the compressive strength of concrete, but the maturity method has the advantage of prognosticating strength without destruction. The temperature-time factor is found using a LM35 temperature sensor through the IoT technique. An experimental investigation was carried out with 56 concrete cubes, where 35 cubes were for obtaining the compressive strength of concrete using a universal testing machine while 21 concrete cubes monitored concrete's temperature by embedding a temperature sensor in each grade of M25, M30, M35, and M40 concrete. The mathematical prediction model equation was developed based on the temperature-time factor during the early age compressive strength on the 1st, 2nd, 3rd and 7th days in the M25, M30, M35, and M40 grades of concrete with their temperature. The 14th, 21st and 28th day's compressive strength was predicted with the mathematical predicted equation and compared with conventional results which fall within a 2% difference. The compressive strength of concrete at any desired age (day) before reaching 28 days results in the discovery of the prediction coefficient. Comparative analysis of the results found by the predicted mathematical model show that, it was very close to the results of the conventional method.

Keywords: Aurdino; early age of concrete; internet of things; non-destructive test; prediction of concrete strength; temperature LM35 Sensor and temperature time factor

1. Introduction

Technology has been developing continuously and rapidly in all fields including Civil Engineering (Cui *et al.* 2017). In this, structural health monitoring is a recent technology in the Civil Engineering field which overcomes all traditional methods including non-destructive testing (Ye *et al.* 2019). The main advantage of non-destructive testing methods is that it obtains real-time information of structures and minimizes dumping of waste generated by conventional testing methods (Abd Elaty 2014). These techniques were used in Civil Engineering applications such as important functional buildings, dams, and bridges (Blumauer *et al.* 2020). Heat is liberated in mass concrete due to hydration which is essential for concrete to develop strength (Al-Swaidani *et al.* 2017). To predict concrete's early age compressive strength, ASTM standards were used. ASTM C 918 (ASTM, 2002) "Standard Test Method to measure Early-Age Compressive Strength and Projecting Later-Age Strength" and ASTM C 1074-98 "Standard Practice to estimate concrete Strength by the Maturity Method" (Kim *et al.* 1998). The maturity method was used in this research based on ASTM C1074 (ASTM 1998). By using this method, normal and High-Strength Concrete strength could be easily predicted from the temperature generated through hydration (Kim and Rens 2008). By using the maturity method, compressive strength at the 28th and 90th day can be predicted based on compressive strength data and the time-temperature factor from the 1st and 2nd days (Sadowski *et al.* 2018). The main research goal was to measure concrete temperature anytime and from anywhere. Some sensors work through signals upto a range of 40 ft (12 m). To overcome this issue, in this study used the LM35 sensor and IoT techniques (John *et al.* 2020). Sensors were used to calculate the temperature in the concrete during hydration (Erdal *et al.* 2018). Sensors are developed and designed to monitor the health of concrete structures economically and to meet specific demands (Ghiasi and Ghasemi 2018). LM35 temperature sensors, Aurdino, and ESP8266 are devices used to measure temperature in concrete to predict its compressive strength (Ashokkumar Palanisamy and Sampath, 2020). With the advantages of sensor technology, (LM35 temperature sensor) and IoT, were both interlinked in this research to monitor temperature data with the help of an online cloud server called "Thingspeak", which is an IoT Platform (Hannan *et al.* 2018). Arduino is an open-source platform to run any hardware electronic prototype through coding. Wireless network sensors are also used to monitor results without hindrance, with the help of Zigbee & raspberry pi to measure early age compressive strength of concrete through the use of wireless technology (Olawale *et al.* 2012). The process of collecting and monitoring temperature data is very tedious as the process is entirely

*Corresponding author, Assistant Professor,
E-mail: ashokdce@gmail.com
[a] Professor

http://www.techno-press.org/?journal=sss&subpage=7
ISSN: 1738-1584 (Print), 1738-1991 (Online)

manual (John *et al*. 2020). Moreover, it is impossible to collect data from remote places. To overcome these issues, the Internet of Things (IoT) technique is a solution. The Internet of Things (IoT) is a modern technique, which interconnects various electronics devices with embedded sensors. A communication system is setup between the object and other IoT- enabled devices which connect, collect and exchange data (Yikici and Chen 2015). In this work, temperature data was collected directly from the cloud through a microcontroller and Wi-Fi router. To collect data from the sensor, many open source IoT applications are available (Leng *et al*. 2006). Here an application called Thingspeak a top IoT open source application was used to store and retrieve data by using the http protocol through Internet. It is a website that anyone can create to receive and store data in a registered mail ID from the source. In this research, thingspeak played an important role in collecting temperature data transferred from Arduino and storing it in a registered mail. The novelty of this paper is the prediction of the compressive strength of concrete sing sensor and IoT techniques. To find the compressive strength of concrete, normally conventional methods and non-destructive methods like ultrasonic pulse velocity, rebound hammer test, etc.., are used (Utepov *et al*. 2019). The drawbacks of these methods is that they need physical contact with the specimen (Yoon *et al*. 2017). To avoid this, this paper provides a solution without physical contact called the non-contact method.

2. Materials used

The strength of concrete depends on the basic properties like the water-cement ratio, cementitious content, aggregate gradations and compaction level. The materials used are Cement of OPC 53 grade, fine aggregate and coarse aggregate with a maximum size of 20 mm. Superplasticizer Conplast SP430 was used to enhance concrete's workability. Specific gravity was conducted on cement using a density bottle, a Le-Chatelier flask. The average values of specific gravity of cement lines were from 3 to 3.25. Coarse aggregate particles were retained in a 4.75 mm (No. 4) sieve while sand particles passed through the 9.5 mm sieve, and almost entirely through the 4.75 mm (No. 4) sieve, and the 75 µm (No. 200) sieve were used in the study. Table 1 shows that the result of basic properties of materials conforms to the IS code provisions.

Table 1 Basic properties of materials

Properties	Values
Fineness of cement	6%
Specific gravity of cement	3.15
Normal consistency of cement	31%
Initial setting time of cement	28 minutes
Specific gravity of fine aggregate	2.54
Bulk density of fine aggregate	1541.33 kg/m^3
Fineness modulus of fine aggregate	2.90%
Specific gravity of coarse aggregate	2.73
Bulk density of coarse aggregate	1432.26 kg/m^3
Fineness modulus of coarse aggregate	2.90%

2.1 Hardware used

Sensor:	LM 35 temperature sensor
Microcontroller:	Arduino Mega 2560 microcontroller board
Wi-Fi:	ESP 8266 ESP-01

2.2 Arduino board

The Arduino ATMega 2560 microcontroller board which works on the ATmega 2560 datasheet shown in Fig. 1 was used. It has 54 digital inputs or output pins and also 16 analog input pins. The board contains four communication pins to transmit and receive data through WiFi or Bluetooth. ESP 8266 ESP-01 was the wireless transceiver module which can either host an application or outsource all Wi-Fi network functions from another application processor. Here coding plays a vital role in managing the sensor's work. Coding helps crack the digital-analog value to regular temperature values. IoT (Internet of Things) stores temperature readings directly to the cloud. Arduino consists of both a physical programmable circuit board (often referred to as a microcontroller) and a piece of software, or IDE (Integrated Development Environment) that runs on computer and which here is used to write and upload computer code to the physical board (Olawale *et al*. 2012).

2.3 Arduino coding and circuit connect

Arduino runs on the computer with the help of Arduino IDE, which easily controls the working of the board or microcontroller through programming. Coding for this research was done so that that the reading from the temperature sensor was sent to the online server via the ESP01 Wi-Fi module. Circuit connection was made with the Arduino ATMega2560 board and temperature sensor as shown in Fig. 1. The wires were fixed and joined with the help of a wire sleeve. The temperature sensor was joined to

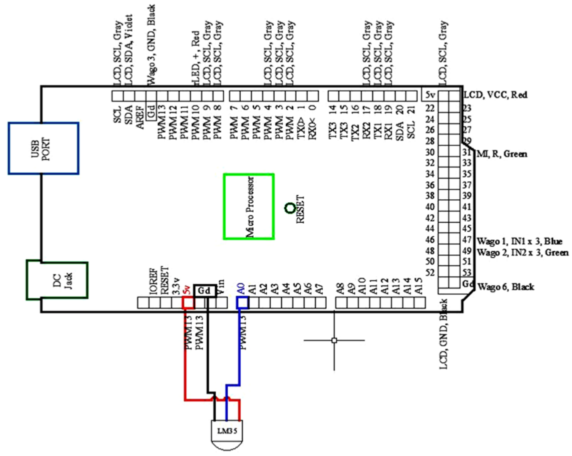

Fig. 1 Arduino ATMega 2560 Microcontroller and Temperature Sensor

the wire through soldering it with positive, analog, and ground pin of sensors.

3. Maturity method

There are two steps to predict concrete's compressive strength using the maturity method (Brooks *et al*. 2007). The first is to develop the maturity curve, which represents the relationship between the time-temperature factor and concrete's compressive strength to determine the maturity function (Yoon *et al*. 2017). The second step predicts concrete's compressive strength at specific ages using the maturity function (Jin *et al*. 2017). As per IS standard, (Standard 2000) a cube specimen was used instead of cylinder to provide the value of b (slope of the line) for the cube specimen as directed from ASTM C918-02 (ASTM 2002). No correction factor was required as it was incorporated. ASTM C 1074 provides a simpler approach for the maturity function which relates the time and temperature factors. This is arrived through thermodynamic principles. The maturity function in ASTM C 1074-98 (ASTM 1998), shown in Eq. (1) can be used to calculate the temperature-time factor as follows

$$M(t) = \sum (T_a - T_0)\Delta t \tag{1}$$

Where:

- $M(t)$ = temperature-time factor at age t, degree-days or degree-hours,
- Δt = time interval, days or hours,
- T_a = average concrete temperature during the time interval, Δt, °C and
- T_o = datum temperature, °C. (Ranging from 0°C to 10°C)

From literature studies, datum temperature was fixed as zero (Plowman 1956). ASTM C 918-02 deals with the estimation of b (slope of the line) in the predicting equation. It is recommended that this be found using regression analysis or by plotting. The plot is for cylinder strength and the logarithm of the maturity index corresponds with the cylinder. Here comes the role of strength, the line is plotted for cube strength with the logarithm of the maturity index corresponding to the cube. b was arrived at (slope of the line) using regression and plotting as directed by ASTM C 918 – 02 for cube specimen. Fig. 2 is used to predict the slope value (b) and concrete strength based on early-age concrete as provided in ASTM C 918-02. The relationship between the cumulative temperature-time factor (x-axis is in logarithmic scale) and concrete compressive strength is shown in Eq. (2).

$$S_m = S_m + b(\log M - \log m) \tag{2}$$

Where:

- S_M = Projected strength in maturity index M,
- S_m = Measured compressive strength in maturity index m,
- b = Slope of the line,
- M = Maturity index under standard curing conditions, and
- m = Maturity index of the specimen tested at an early age.

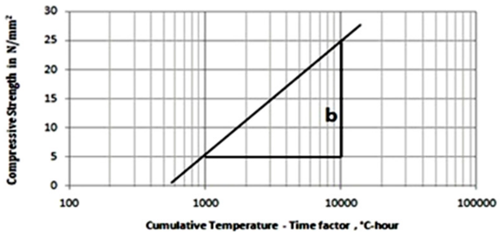

Fig. 2 Value of slope line

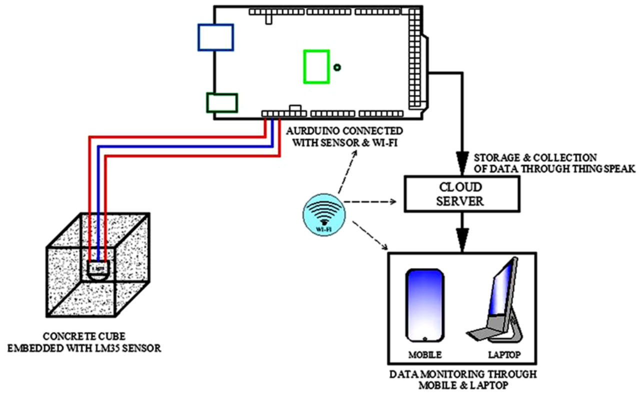

Fig. 3 Schematic diagram of the experimental setup

Fig. 4 Concrete with sensor embedded immediately after casting

3.1 Experimental programme

The schematic diagram of the experimental setup is shown in Fig. 3. The LM35 temperature sensor was embedded in the core portion of the concrete cube and the sensor's output, and ground pins were connected to the Arduino Atmega 2560 which turn was linked to a WI-FI connection is shown in Fig. 4. The code was prepared and uploaded in the microprocessor so that collected temperature data from the sensor would be sent and stored in the Thingspeak cloud server. Real-time and stored data could be easily accessed by a Laptop or Mobile phone at any time and from anywhere through the HTTP protocol.

Thermocouple sensors or LM35 temperature sensors were used to sense temperature in the concrete. Due to its advantages, the LM35 temperature sensor was used in this work as shown in Fig. 5. This type of temperature sensor can sense temperature in a range from -55°C to 150°C. But operating temperature must not exceed -10°C for improved

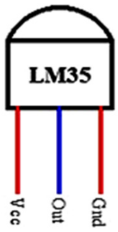

Fig. 5 Temperature sensor

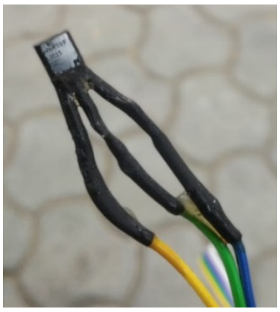

Fig. 6 Sensor tightly packed by water-resisting coating

accuracy. The sensor was placed inside the cube with an effective water-resistive coating. To make the sensor waterproof, a sleeve coating as shown in Fig. 6 was used.

3.2 Casting of concrete

Concrete was cast for grades M25, M30, M35, and M40. The mix ratio arrived after calculations as per IS 10262-2019 is given in Table 2 (Nataraja and Das 2010). To obtain the daily strength for each grade of concrete, five numbers of concrete cubes were cast for conventional testing and three specimens were cast with a Temperature Sensor which is placed at the core of concrete to obtain the temperature in the concrete. Concrete cubes size of 150 mm × 150 mm × 150 mm were cast for 1, 2, 3, 7, 14, 21, and 28 days to obtain the compressive strength of concrete.

3.3 Monitoring the temperature of concrete

When concrete is cured, temperature inside it will be simultaneously sensed by the sensor and the cloud through the Wi-Fi and Arduino setup. Here, the time interval frequency was set as five minutes, and hence every five minutes concrete's temperature was sent to the Thingspeak server. Two numbers of concrete cubes were cast to compare and check the temperature, and average temperature

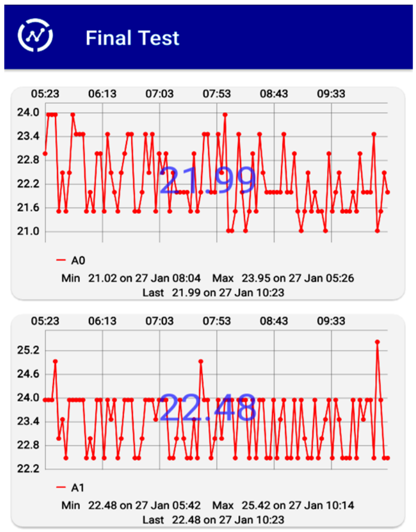

Fig. 7 Monitoring of temperature data

was noted. Fig. 7 shows how the temperature data was stored in Thingspeak cloud server. Temperature data was stored in time of temperature input format in the x-axis and temperature values in the y-axis.

4. Results and discussions

The compression strength of concrete was found with the help of a compression testing machine which had a capacity of 100 tons by applying a load at the rate of 0.6 N/mm^2 / second. The compressive strength of concrete was found for the early age of 1, 2, 3 and 7 days to create the prediction mathematical model equation, Strength for 14, 21 & 28 days was found to validate and compare results which the compressive strength of concrete for 14, 21 and 28 days has predicted from the developed model equation. Table 3 shows the average compression strength of concrete for the three specimens for grades M25, M30, M35 and M40 and the cumulative temperature-time factor (TTF) for various days which were calculated by using Eq. (1).

Fig. 8 shows the relationship between compression strength and the cumulative temperature-time factor for M25 grade concrete. Fig. 8 compares the compression strength of concrete and the TTF for the 1st, 2nd, 3^{rd,} and 7th day's compressive strength for M25 grade concrete. The function of $y = 8.2325\ln(x) - 47.716$ is the trend line for concrete's compressive strength and the cumulative Temperature time factor.

Table 2 Mix proportion for concrete

Grade	Cement kg/m^3	Fine aggregate kg/m^3	Coarse aggregate kg/m^3	Water-cement ratio	Superplasticizer Conplast SP430 (1.4% by weight of cement)
M25	336	844	1086	0.47	4.70 lit
M30	359	825	1084	0.44	5.02 lit
M35	385	798	1092	0.41	5.39 lit
M40	395	793	1085	0.41	5.53 lit

Table 3 Cumulative Temperature Time Factor (TTF) and compressive strength of concrete

Temperature Time Factor (TTF)									
Days	Hour	Cumulative TTF (°C- hour)				Compressive strength of concrete			
		M25	M30	M35	M40	M25	M30	M35	M40
1	24	609.12	684.72	775.36	872.64	5.40	6.45	7.40	7.95
2	48	1131.84	1213.90	1331.76	1632.72	9.95	11.75	12.98	13.78
3	72	1693.92	1815.60	1868.88	2176.80	13.10	15.94	17.85	19.95
7	168	4059.84	4071.12	4306.56	4371.36	20.97	25.10	28.78	31.78
14	336	9063.28	9069.52	9674.32	9792.16	28.94	34.85	39.84	43.98
21	504	12132.52	12191.52	12464.64	11105.68	29.90	36.75	41.85	45.89
28	672	14388.24	14909.92	15005.2	15348.6	31.80	38.44	43.96	48.70

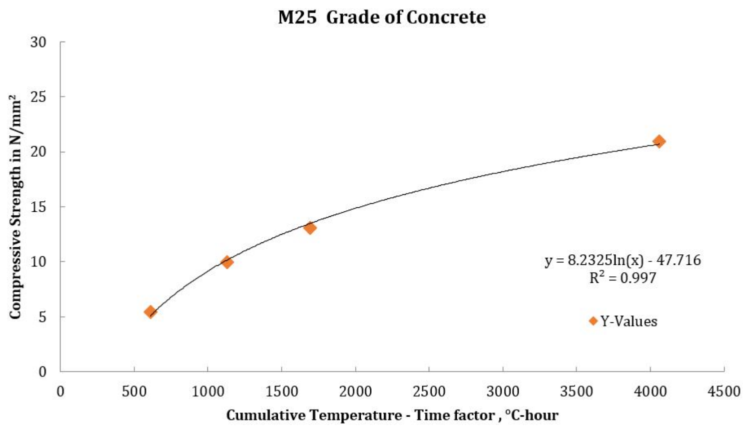

Fig. 8 Cumulative temperature time factor vs compressive strength of M25 grade of concrete

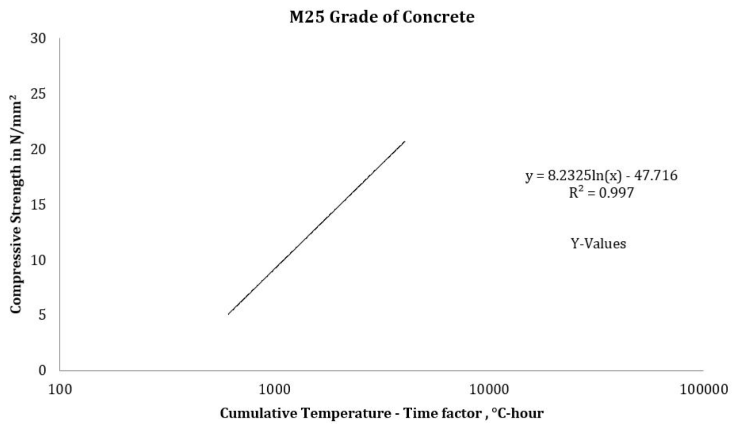

Fig. 9 Slope value of b for the M25 grade of concrete

The slope value was obtained between the cumulative temperature time of 1000°C and 10000°C as shown in Fig. 9. It was seen that the slope value of b was 19 N/mm^2 for the M25 grade of concrete was obtained from the prediction equation. Similarly, for the M30, M35 and M40 grades of concrete, the logarithmic equation (y), regression value (R^2) and Slope value (b) were calculated and are shown in Table 4.

Table 4 Prediction equations for M25, M30, M35, and M40 grade of concrete

Grade of concrete	Logarithmic equation (y)	Regression value (R^2)	Slope value (b)
M25	8.2325ln(x) - 47.716	0.9970	19.00 N/mm^2
M30	10.508ln(x) - 62.547	0.9974	24.00 N/mm^2
M35	12.62ln(x) - 77.105	0.9964	29.00 N/mm^2
M40	14.94ln(x) - 94.321	0.9858	35.00 N/mm^2

Table 5 Predicted compressive strength for 14th, 21st and 28th days

Days	Hour	Temperature Time Factor(TTF)							
		Cumulative TTF (°C- hour)				Compressive strength of concrete in N/mm^2			
		M25	M30	M35	M40	M25	M30	M35	M40
14	336	9063.28	9069.52	9674.32	9792.16	27.67	33.37	39.18	44.70
21	504	12132.52	12191.52	12464.64	13105.68	30.12	36.41	42.37	46.61
28	672	14388.24	14909.92	15005.2	15348.6	31.49	38.95	44.71	49.53

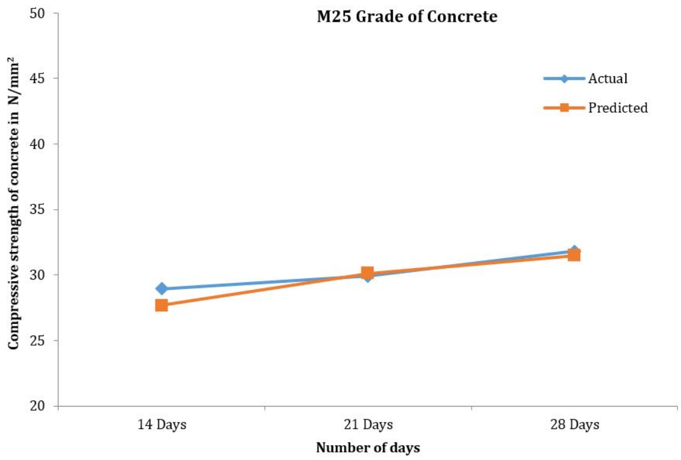

Fig. 10 Comparison of actual and predicted compressive strength of concrete for M25 grade of concrete

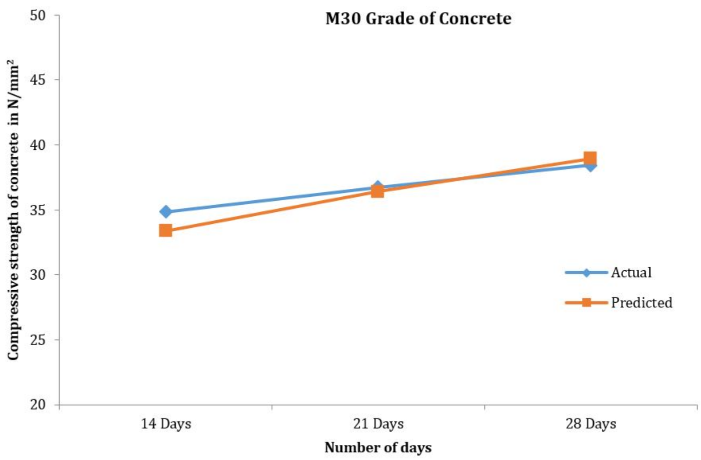

Fig. 11 Comparison of actual and predicted compressive strength of concrete for M30 grade of concrete

4.1 Predicted compressive strength from an early age

By using the Equation SM = S_m + b (log M – log m), the predicted concrete compressive strength for the 14th, 21st and 28th days was calculated using the cumulative temperature time of the 14th, 21^{st,} and 28th days. Predicted compressive strength for the M25 grade of concrete at 14th, 21st& 28th days was 27.67 N/mm^2, 30.12 N/mm^{2,} and 31.49 N/mm^2 respectively as calculated from the Cumulative temperature-time factor for early age 1st day (m) was 609.12, measured compressive strength was 5.40 N/mm^2 (S_m) and slope value was 19 N/mm^2(b). Similarly, for the M30, M35, and M40 grades of concrete, the predicted compressive strength of concrete for 14th, 21^{st,} and 28th days is shown in Table 5.

Figs. 10, 11, 12, and 13 show compare the actual and predicted compressive strength of concrete at the 14th, 21^{st,} and 28th days for the M25, M30, M35 and M40 grade of concrete respectively.

The difference between the actual and predicted compressive strength for the M20 grade of concrete at 21 and 28 days was 0.73 and 0.97 which was the prediction based on early age one-day compressive strength. Similarly, for the M30, M35, and M40 grades of concrete at ages of 21 and 28 days was 0.92 & 1.31, 1.23 & 1.68 and 1.55 & 1.69.

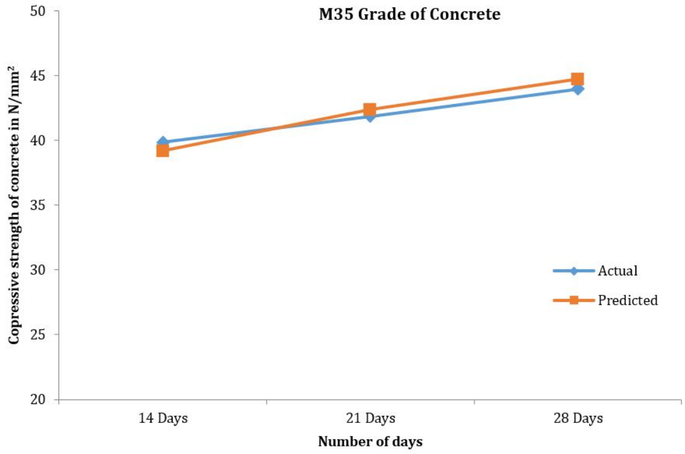

Fig. 12 Comparison of actual and predicted compressive strength of concrete for M35 grade of concrete

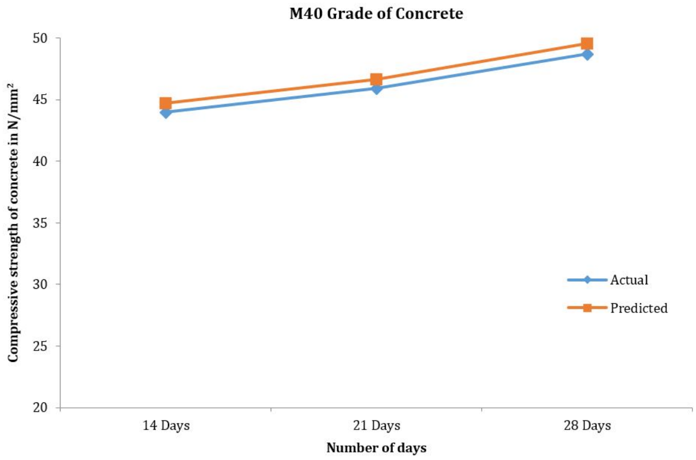

Fig. 13 Comparisons of actual and predicted compressive strength of concrete for M40 grade of concrete

Table 6 Predicted compressive strength and predicted coefficient

Grade	Description	3 Days	7 Days	14 Days	21 Days	28 Days
M25	Strength from predicated equation	13.48	21.05	27.68	30.08	31.49
	Predicted coefficient	0.43	0.66	0.87	0.95	1.00
M30	TTF	1815.6	4071.12	9069.52	12191.52	14909.92
	Strength from predicated equation	16.60	25.02	33.37	36.45	38.55
	Predicted coefficient	0.43	0.64	0.86	0.94	1.00
M35	TTF	1868.88	4306.56	9674.32	12464.64	15005.2
	Strength from predicated equation	18.47	28.99	39.18	42.37	44.71
	Predicted coefficient	0.41	0.64	0.87	0.94	1.00
M40	TTF	2176.8	4371.36	9792.16	11105.68	15348.6
	Strength from predicated equation	21.85	32.45	44.70	46.62	51.54
	Predicted coefficient	0.42	0.63	0.86	0.90	1.00

When the maturity index was measured at day 1 of the concrete's age using the equation, it was 609.12°C hour and SM value became 5.40 N/mm^2 for M25. The equation f(x) = 8.2325ln(x) – 47.716 for the M25 grade of concrete was computed from cumulative time temperature and b based on the early age day compressive strength of concrete. From the difference in value, the mathematical model prediction equation was developed as Eq. (3) for the M25 grade of concrete.

$$S_M = 19 * \log M - 47.509 \quad (3)$$

Similarly, for M30, M35, and M40, concrete grades, the predicted mathematical model equations were developed and are given in Eqs. (4), (5), and (6) respectively.

$$S_M = 24 * \log M - 61.60 \quad (4)$$

$$S_M = 29 * \log M - 76.39 \quad (5)$$

$$S_M = 35 * \log M - 94.979 \quad (6)$$

From the above developed mathematical model equations, the predicted compressive strength of concrete at the ages of 3, 7, 14, 21, and 28 days and the value of the prediction coefficients were calculated and are shown in Table 6.

From the predicted compressive strength of concrete and the predicted coefficient, the logarithmic equation and graph were generated for the M25 grade of concrete as shown in Fig. 14. For an instant, to predict the compressive strength of the M25 grade concrete for any desired day, the prediction coefficient was calculated from the logarithmic equation and the value obtained from the equation had to be multiplied by multiple factors given in Table 7.

Similarly, for grades M30, M35, and M40, the mathematical model prediction equation was found by graph and the equations are shown in Table 7.

Table 7 Mathematical prediction equation and multiplying factor

Grade of concrete	Logarithmic equation, (y)	Regression value, (R^2)	Multiplying factor (K)
M25	0.261ln(x) + 0.152	0.993	31.28
M30	0.261ln(x) + 0.143	0.995	37.61
M35	0.270ln(x) + 0.120	0.992	44.00
M40	0.259ln(x) + 0.137	0.989	52.19

Finally, to predict the compressive strength of M25 grade concrete for any desired age (days), the logarithmic equation given in Table 8 was modified as Eq. (7) by adding multiple constants (K). Similarly, Eqs. (8), (9), and (10) provided answers for the M30, M35, and M40 grades of concrete

$$fck_{25} = [0.261\text{In}(x) + 0.152] * 31.28 \quad (7)$$

$$fck_{30} = [0.261\text{In}(x) + 0.143] * 37.61 \quad (8)$$

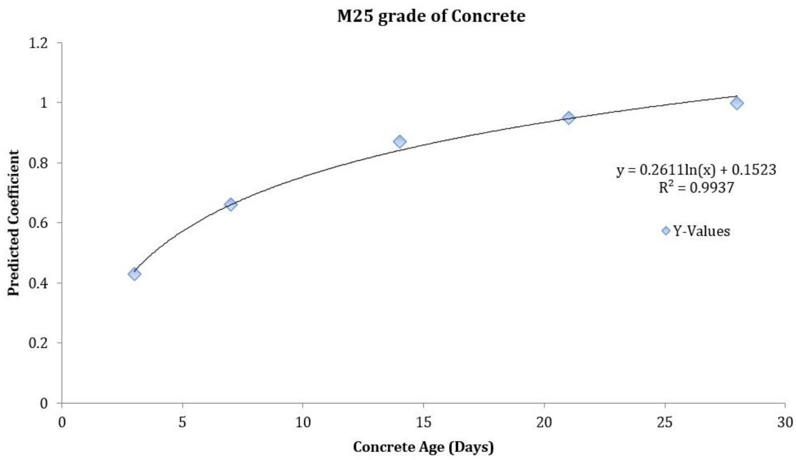

Fig. 14 Concrete age vs prediction coefficient

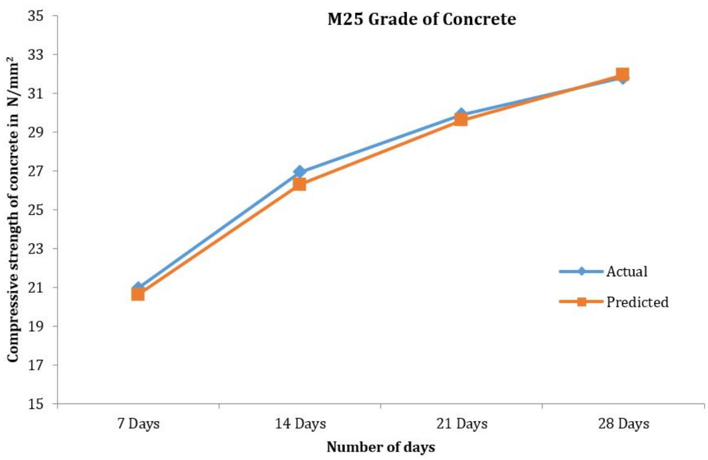

Fig. 15 Comparison of actual and predicted compressive strength of concrete for M20 grade of concrete

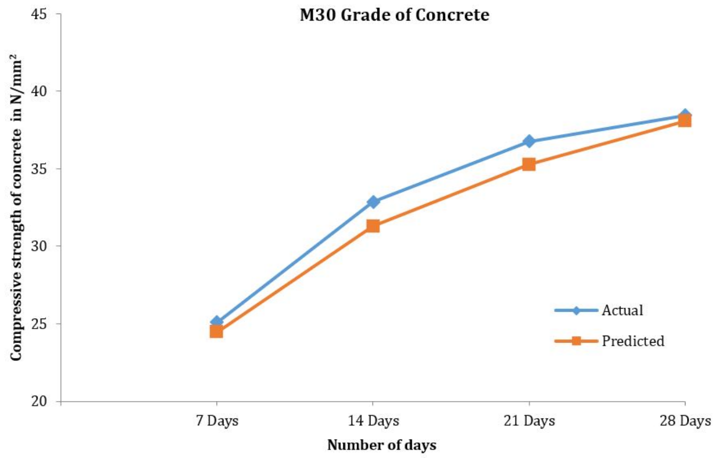

Fig. 16 Comparison of actual and predicted compressive strength of concrete for M30 grade of concrete

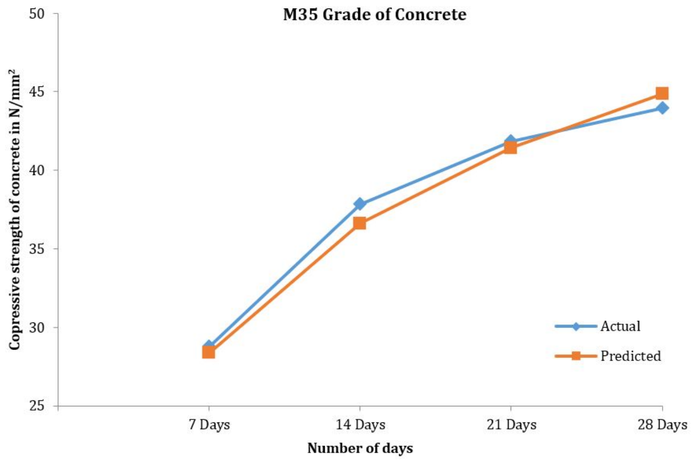

Fig. 17 Comparison of actual and predicted compressive strength of concrete for M35 grade of concrete

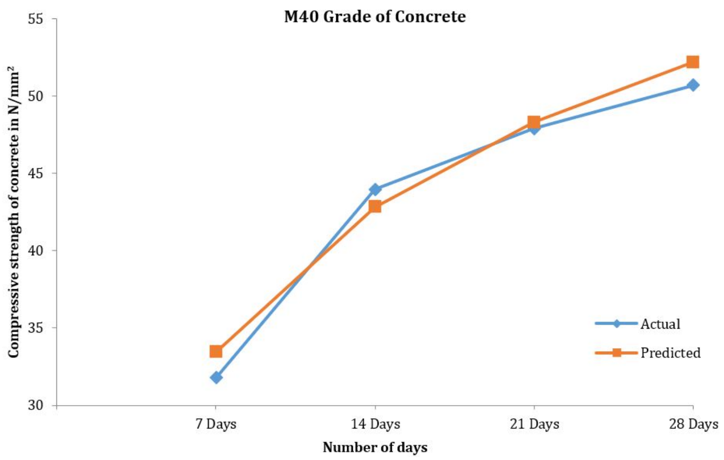

Fig. 18 Comparison of actual and predicted compressive strength of concrete for M40 grade of concrete

$$\mathrm{fck}_{35} = [0.270\mathrm{In}(x) + 0.120] * 44.00 \quad (9)$$

$$\mathrm{fck}_{40} = [0.259\mathrm{In}(x) + 0.137] * 52.19 \quad (10)$$

Where
fck = Compressive strength of concrete
x = Desired day of compressive strength
K = Multiplying the constant given in Table 7.

To validate the predicted Eqs. (7), (8), (9), and (10), the results obtained from these equations were compared with conventional results. Figs. 15, 16, 17, and 18 compare the predicted equation and the conventional results. It was found that the results obtained by the predicted equation for M25, M30, M35, and M40 grade of concrete were very close to the conventional test results.

5. Conclusions

To predict the compressive strength of concrete using the maturity method and IoT techniques has been proposed in this study.

- Most researchers used thermocouple sensors as a temperature measuring device to monitor temperature data. By using such a sensor, a data logger normally stores the data. The main drawback of this system is that it is not possible to monitor temperature data from remote places. To overcome these issues and to collect and monitor real-time temperature data from concrete, the LM35 sensor and Internet of Things techniques were adopted.
- Data collected by sensors are stored in a cloud server, which can be easily retrieved anytime and from anywhere. With the help of the above techniques, the Cumulative time-temperature factor and the early age compressive strength of concrete were calculated.
- The mathematical prediction model equation was generated, and from the generated equation compressive strength for the 14th, 21^{st,} and 28th days was calculated for M25, M30, M35, and M40 grades of concrete.
- By comparing the actual and predicted compressive strengths for M25 grade of concrete, the percentage difference was 0.73 & 0.97 for the 21st & 28th day respectively.
- Similarly, for M30, M35, and M40 grades of concrete, the difference in percentage for the 21st & 28th day was 0.92, 1.31 & 1.23, 1.68 and 1.55, 1.69 respectively.
- To predict the compressive strength of the concrete for any desired day without any temperature and destruction of concrete, the prediction coefficient was calculated from the mathematical prediction model equation which was near the actual value.
- The results from the predicted equation were very close to conventional test results. Minimum and maximum percentage differences were found to be 1.23 and 1.69 respectively which was less than 2%.
- Hence it can be stated that the maturity method using sensors and the Internet of Things (IoT) techniques is a highly reliable method to estimate the compression strength of concrete.

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