Prediction of 28-day Compressive Strength of Concrete from Early Strength and Accelerated Curing Parameters

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***Abstract*-Predicting 28-day compressive strength of concrete is an important research task for many years. In this study, concrete specimens were cured in two phases, initially at room temperature for a maximum of 30 h and later at a higher temperature for accelerated curing for a maximum of 3 h. Using the early strength obtained after the two-phase curing and the curing parameters, regression equations were developed to predict the 28-day compressive strength. For the accelerated curing (higher temperature curing) both conduction and radiation heating methods were attempted. The results show that multiple linear regression model, which uses the conduction heating process, performs best.**

Keywords-cement concrete, accelerated curing, microwave curing, prediction, compressive strength.

I. INTRODUCTION

The compressive strength of cement concrete obtained after 28 days of moist curing is used in the quality control of constructions. However, for economical quality control, for reworking before the concrete gets hardened and for reducing the waiting time, finding the 28-day compressive strength at an earlier time with a reasonable accuracy is necessary. The 28-day compressive strength of a concrete can be estimated in lesser time by either one of the following: (a) finding the chemical and physical characteristics of the ingredients of concrete and then finding 28-day strength using the previously established regression relationship between some of these characteristics and 28-day strength; (b) finding the early (3 or 7 day) strength and then finding 28-day strength using the previously established regression relationship between the early strength and 28-day strength; (c) finding the strength at an early age with accelerated curing then finding 28-day strength using the previously established regression relationship between the early strength with accelerated curing and 28-day strength.

The first method requires very less time while the accuracy is poor. The second method is time consuming while the accuracy is best. Hence, there exist a trade-off between time and accuracy. The third method is preferred as the time required is less and better accuracy is expected as the concrete is hardened considerably by accelerated curing. There are many ways of accelerating the curing process of a concrete test specimen. By accelerating the gain of strength, strength-testing schedule is shortened and thus it is contemplated that the 28-day strength can be predicted as early as one day with reasonable accuracy. In this study, conduction and radiation heating methods were used and the prediction of 28-day strength was attempted.

II. PREVIOUS WORKS

Based on the chemical and physical composition and properties of the materials, a linear regression model was developed to predict the compressive strength of cement mortar cube at less than or equal to 28 days [1]. Acceleration of curing or strength gain was being studied since 1930s. Patch [2] is one of the pioneers who studied the acceleration of the curing process of concrete cylinder with 8 hours of boiling. Later in 1950's King continued the research on the acceleration through heating process, established curves through experiments, relating strength obtained after 7 hours of specified heating procedure and 7-day or 28-day strength [3]. Alshamsi [4] experimented cement mortar mix using a test setup to record continuous temperature using electronic gadgets. He identified that microsilica reduced the time to reach peak temperature whereas ground granulated blast furnace slag considerably extended the time to reach peak temperature. Kim *et al.* [5] investigated the strength development for various curing histories involving both at 5°C and 40°C curing temperature at selected times while being cured at a temperature of 20°C for the remaining days. They used two water cement ratios. A new model for the strength prediction was developed. They also identified the crossover effect that curing with a high temperature results in higher early-age strength and attains lower strength at a later-age. However, curing with a low temperature results in lower early-age strength and attains almost the same strength at a later-age. Using ordinary Portland cement and trass cement, Ozkul [6] investigated the strength development of concrete by thermal curing process with warm water and boiling water. From the linear regressions, it was found that ordinary Portland cement is better suitable for thermal curing. Kim *et al.* [7][8] reported the results of curing temperature and aging on the strength and elastic modulus of concrete using fly ash. A prediction model was developed using the experimental data. They found that the crossover effect exist on split-tensile strength also.

In the conduction process, between surface and central core of the concrete block, a temperature gradient develops causing stress. Microwave heating which is radiation based does not have this problem and hence it is hypothesised that the temperature distribution is more uniform and heating is faster. Hence it is expected that the microwave based thermal curing to perform better than the conduction based thermal curing. In the last two decades, very few have studied the usage of microwave energy for curing cement mortar or concrete [9]-[16] and there is good scope for extensive research in this field.

III. MATERIALS AND METHOD

In this study, both conduction curing and radiation curing were adopted. The objective of the present work is to predict the 28-day strength using the strength at an early age with accelerated curing and curing parameters. This involves (a) developing regression relationships between the set of parameters of accelerated curing along with the early strength and the 28-day strength and (b) comparing accuracies of prediction due to conduction curing and radiation curing.

Portland-Pozzolana Cement confirming to IS:1489 (Part-1):1991 [17] was used in this study. The specific gravities of cement, fine aggregate and course aggregate are 3.18, 2.69 and 2.94 respectively. The fineness moduli of fine and course aggregates were 2.4 and 7.2 respectively. River sand was used as fine aggregate which was well graded, clean and uncrushed while the coarse aggregate was angular crushed stone with 20-mm nominal maximum size. The specific surface area of the cement was 36.14 m^2/N. The cement had a normal consistency of 32%. The initial and final setting times of the cement were 38 and 360 min respectively. Potable water was used for mixing and curing of concrete.

Concrete cubes were cast in 100 mm cube moulds and were properly vibrated for consolidation. Different Concrete mixes such as 1:2:4, 1:1.5:3, 1:1:2, 1:2.16:2.52, 1:1.65:2.92 were used with a constant water cement ratio of 0.46. A two phase curing schedule was used in this study. In the first phase, the cubes were cured at room temperature at a moist condition. In the second phase, the cubes were subjected to adiabatic curing at higher temperature for a specific duration. After both phases of curing, the cube was allowed to cool down to room temperature and was subjected to the compression testing to find the compressive strength. The parameters noted in the above process were used for predicting the 28-day strength.

Delay period (D) is time duration from the casting of a cube to the time subjecting it to the thermal curing. During the delay period, the cube was kept in moist condition at room temperature which varies diurnally between the range of 25°C and 35°C. Different delay periods of 6h, 12h, 18h, 24h and 30h were considered.

Thermal curing duration (T) is the time duration during which the cube is subjected to higher temperature above the ambient temperature either by conduction process or by radiation process. In the case of conduction curing, the temperature was maintained in the curing tank through a thermostat attached immersion heater element which had an accuracy of ± 2°C in the range of the temperatures used in the study. The different discrete temperatures (t) considered were 55°C, 65°C and 75°C. The thermal curing durations adopted were 1h, 2h and 3h. In the case of radiation curing, a commercially available domestic microwave oven (IFBK024) was used. The temperature control of the domestic microwaves is generally achieved by controlling the Watts supplied to the magnetron. Hence, in the radiation curing, in place of temperature, the Wattage (W) was used as a parameter. The different discrete Wattages considered were 900, 720, 540, and 360 Watt. The thermal curing durations adopted in the case of radiation curing were 20 min, 30 min, 40 min, 50 min and 60 min.

After the two phase curing process, the cube was allowed to cool for about 20 to 30 min before subjecting it to the compression test. The compression strength of the cubes were found in the laboratory using a digital compression testing machine of 3000 kN capacity as per IS:516:1959 [18]. The strength thus obtained after undergoing the two phase curing was called early strength (S_e) as this was the strength at much earlier than 28 days. The compressive strength obtained from control specimens that undergo the regular 28 days of moist curing at the room temperature S_{28} were also found for various mix proportions already specified.

IV. RESULTS AND DISCUSSIONS

In the case of conduction curing, the database generated fits to the linear multiple regression equation (1) with a coefficient of determination, r^2, of 0.905 and RMSE is 1.1067.

$$S_{28} = -0.3974D - 0.1023T - 1.0655t + 1.4697S_e + 27.0110 \qquad (1)$$

When attempted to fit a exponential multiple regression equation, equation (2) was obtained which has a r^2 of 0.879 and RMSE equal to 1.2485.

$$S_{28} = 26.8731 \times 0.9864^D \times 0.9965^T \times 0.9641^t \times 1.0517^{S_e} \qquad (2)$$

In equations 1 and 2, *D* is the delay time in hours, *T* is the curing temperature in C and *t* is the conduction curing duration in hours.

For the microwave based thermal curing, the database generated fits to the linear multiple regression equation (3) with a r^2 of 0.779 and RMSE equal to 4.994.

$$S_{28} = -1.6118D - 0.2406T - 0.0194W + 3.3051S_e + 47.000 \qquad (3)$$

When attempted to fit a exponential multiple regression equation, equation (4) was obtained which has a r^2 of 0.774 and RMSE equal to 2.821.

$$S_{28} = 47.3057 \times 0.9539^D \times 0.9931^T \times 0.9995^W \times 1.1024^{S_e} \qquad (4)$$

In equations 3 and 4, *D* is the delay time in hours, *M* is the radiation curing duration in minutes and *W* is the Watts used for radiation curing. In the all the regression analysis, the F statistic was used to ascertain that, these relationships did not occur by chance. The percentage errors obtained by the above four equations are estimated and error histogram was plotted and presented in figures 1 through 4. The error histogram clearly indicates that the equation, which uses the conduction based curing parameters, outperform.

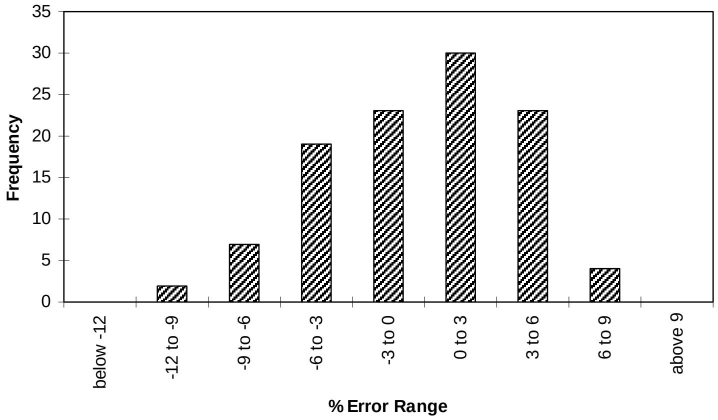

Fig. 1. Error histogram from the predictions using the linear relation for conduction curing

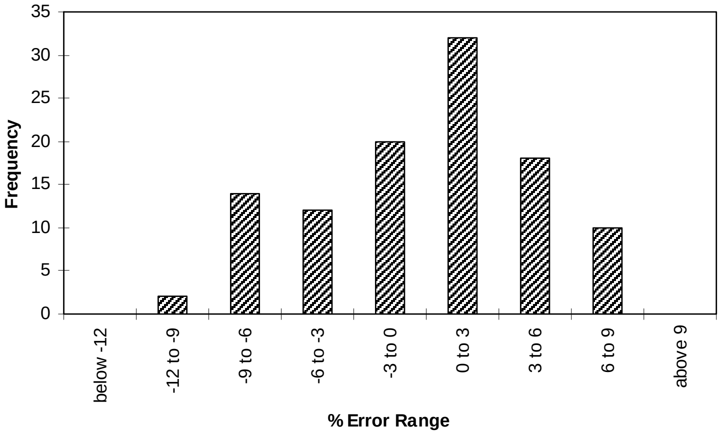

Fig. 2. Error histogram from the predictions using the exponential relation for conduction curing

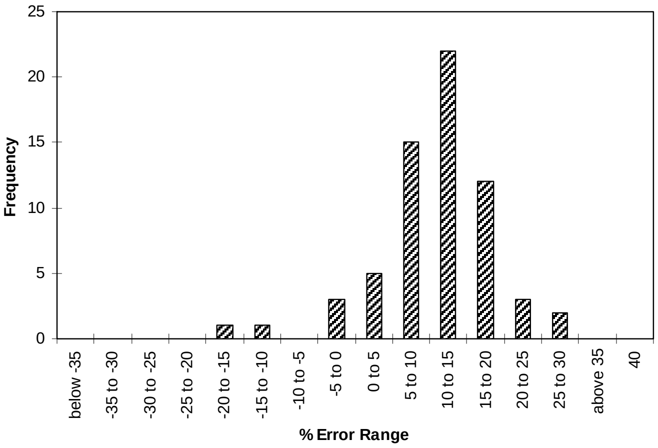

Fig. 3. Error histogram from the predictions using the linear relation for radiation curing

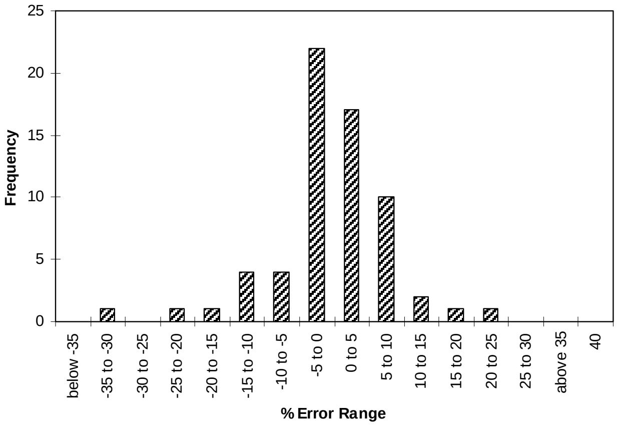

Fig. 4. Error histogram from the predictions using the exponential relation for radiation curing

V. SENSITIVITY ANALYSIS

In equation (1), changing the constant 27.0110 by ± 10% does not change the r^2 and the root mean square error (RMSE) changes to 2.9190. Changing the coefficient of D (-0.3974) by ± 10% changes the r^2 to 0.8973 and the RMSE changes to 1.3532. Changing the coefficient of T (-0.1023) by ± 10% changes the r^2 to 0.9042 and the RMSE changes to 1.2940. Changing the coefficient of t (-1.0655) by ± 10% changes the r^2 to 0.9041 and the RMSE changes to 1.1304. Changing the coefficient of S_e (1.4697) by ± 10% changes the r^2 to (0.8977, 0.8943) and RMSE changes to 2.1326. Both increasing by 10% and decreasing by 10% have the same effect on the r^2 and the RMSE except for the coefficient of S_e. In the case of the coefficient of S_e, increasing the coefficient by 10% changes the r^2 to 0.8977 while decreasing the coefficient by 10% changes the r^2 to 0.8943. The RMSE values indicate that S_e is most sensitive while the r^2 values indicate that S_e and D are the most sensitive variables.

In equation (2), changing the constant 26.8731 by ± 10% does not change the r^2 and the RMSE changes to (3.1468, 3.1433). Changing the coefficient of D (0.9864) by ± 10% changes the r^2 to (0.0147, 0.0127) and the RMSE changes to (229.25, 23.46). Changing the coefficient of T (0.9965) by ± 10% changes the r^2 to (0.0239, 0.0241) and the RMSE changes to (22837.03, 28.85). Changing the coefficient of t (0.9641) by ± 10% changes the r^2 to (0.6335, 0.5870) and the RMSE changes to (6.8348, 5.9035). Changing the coefficient of S_e (1.0517) by ± 10% changes the r^2 to (0.6755, 0.1814) and RMSE changes to (78.1053, 20.9261). Except for the constant, changing the coefficients affects both the r^2 and the RMSE seriously. Based on the comparison, the sensitivity results of equations (1) and (2), it can be concluded that the multiple linear equation (1) is the robust equation.

In equation (3), changing the constant 47.000 by ± 10% does not change the r^2 and the RMSE changes to 5.4346. Changing the coefficient of D (-1.6118) by ± 10% changes the r^2 to (0.7653, 7650) and the RMSE changes to 4.3586. Changing the coefficient of M (-0.2406) by ± 10% changes the r^2 to 0.7769 and the RMSE changes to 2.8654. Changing the coefficient of W (-0.0194) by ± 10% changes the r^2 to (0.7742, 0.7744) and the RMSE changes to 2.9798. Changing the coefficient of S_e (3.3051) by ± 10% changes the r^2 to (0.7656, 0.7589) and RMSE changes to 4.9938. The r^2 values indicate that D and S_e are the most sensitive variables while the RMSE values indicate that S_e is most sensitive.

In equation (4), changing the constant 47.3057 by ± 10% does not change the r^2 and the RMSE changes to (4.4483, 4.5585). Changing the coefficient of D (0.9539) by ± 10% changes the r^2 to (0.1365, 0.0414) and the RMSE changes to (250.47, 30.93). Changing the coefficient of M (0.9931) by ± 10% changes the r^2 to (0.0163, 0.0188) and the RMSE changes to (2327.66, 33.79). Changing the coefficient of W (0.9995) by ± 10% changes the r^2 to (0.0060, 0.0063) and the RMSE changes to (2.8×10^{38}, 35.29). Changing the coefficient of S_e (1.1024) by ± 10% changes the r^2 to (0.5011, 0.0028) and RMSE changes to (93.57, 26.00). Except for the constant, changing the coefficients affects both the r^2 and the RMSE seriously. Based on the comparison of the sensitivity results of equations (3) and (4), it can be concluded that the multiple linear equation (3) is the robust equation.

In this study, a domestic microwave oven was used for radiation curing. Domestic microwave ovens use time slicing which is a simplistic intermittent control. For example, a domestic microwave oven when set to operate at 50% of the maximum power (900 Watts), it does not work at 450 Watts, instead it applies microwave at 900 Watts for 50% of the total time. However, commercial microwave ovens apply the microwave continuously at 450 Watts and thus they are called variable-power microwave systems. The time slicing in the domestic microwave machine causes unsteady heating. This may be a reason for poor predictability of 28-day strength from microwave cured concrete. Further, from experience it was found that the domestic microwave ovens fail frequently when operated at full power for longer duration like an hour.

VI. CONCLUSIONS

It is found that the multiple linear regression model developed for conduction curing is better suitable for predicting the 28-day strength with a r^2 of 0.9 and RMSE of 1.1 MPa. Though the microwave curing is expected to strengthen the concrete better, the results of the study do not agree with this. Compared to the microwave based curing, the conduction based curing is better in the prediction of 28-day strength using multiple linear or exponential regression models with higher accuracy. However, other different forms of relationships may need to be explored. Extending the research with variable-power microwave oven may provide further clarity. The results in general encourage for further research in this field.

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