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Early Estimation of Hardened Concrete Strength

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Abstract: Due to the large expansion in concrete projects and due to the importance of time and its direct impact on project cost, an essential need to estimate the hardened concrete strength within the first few hours of casting the concrete. In addition to that, it is known that in most concrete projects, casting of concrete is done in a consequence stages, so if the obtained hardened concrete strength is less than the target strength, then the time could be too late to take the necessary and right action. On the other side, if the obtained hardened concrete strength is more than target one then again it is uneconomical and time is done to save the wasted money in getting such a high unnecessary strength. Based on that, in this research the available methods of predicting hardened concrete strength at early stage were reviewed. One of these methods is developed and the effect of water cement ratio and cement dose on early strength estimation is discussed. Using non linear regression analysis, a theoretical model is established to estimate consolidated concrete strength at 7 and 28 days by knowing its strength after 6 h of its casting. Accelerating tests for early determination of concrete strength are used to generate expressions for prediction of hardened concrete strength as composite function of cement content and W/C ratio. By testing more than 200 cubes, the suggested theoretical model shows a good agreement with experimental results.

Key words: Accelerated strength, concrete strength prediction, consolidated strength, water cement ratio, cement dose, king's method

INTRODUCTION

Concrete is usually placed in a structure in stages or lifts, one on top of another. Thus by the time the results of the 28 day test, or even the 7 day test, are available, a considerable amount of concrete may overlay that represented by the test specimens in question. It is then rather late for remedial measures if the concrete is too weak; if it is too strong this indicates that the mix used was uneconomical.

It is clear that it would be a tremendous advantage to be able to predict the 28 day strength within a few hours of casting. The strength of concrete at 24 h is an unreliable guide in this respect, not only because different gain strength at varying rates, but also because even small variations in temperature during the first few hours after casting have a considerable effect on the early strength, It is, therefore, necessary for the concrete to have achieved a greater proportion of its potential strength before testing and a successful test based on accelerated curing was developed by King[1]. In King's test, standard concrete cubes are made but the moulds are immediately covered by top plates, sealed with grease on the metal surfaces of a contact in order to prevent drying. Within 30 min of adding the mixing water, the cubes, in their covered mould, are placed in an airtight oven, which is then switched on. The oven temperature should reach 93°C in about an hour and the cubes are kept at this temperature for a further 5 h, i.e. the specimen will be kept in the oven for 6 h. At the end of this period the cubes are removed from the oven, stripped, allowed to cool for 30 min, then it will be tested in compression in the standard manner. Nonlinear correlation between strength of concrete at age of 28 days and accelerated strength was suggested by King[1].

An alternate scheme recommended by a committee of the Institution of Civil Engineers[2] can be used to predict the early strength. In this method, the specimen (in their moulds) are placed (at the age of 30 min) in a water path at 55°C and are kept in it for 23 h. Then the specimens are taken out, de-molded and tested in the usual manner at age 24 h.

Other methods were reported by Malhotra[3] and Carino[4] where they made a brief review of the four test procedures covered by ASTM C-684 which are:

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1. Warm-water method: This method consists of curing standard cylinders, in a water bath maintained at 35°C for 24 h immediately after molding and while still in molds. A limitation of the method is that strength gain, compared to the 28-day moist-cured concrete at normal temperature, is not high, therefore, job-site testing may be needed. In the mid-1970s, the US Corps of Engineers[10] conducted an extensive study on the evaluation of the warm-water method. It was concluded that accelerated strength testing with this method is indeed a reliable method of routine quality control for concrete.
2. Boiling-water method: This method consists of normal curing of the concrete cylinders for 24 h, followed by curing in a boiling-water bath at 100°C for 3-1/2 h and then testing 1 h later.
3. Autogenous method: In this method, immediately after casting the test cylinders are placed in insulated containers made of polyurethane foam and are tested 48 h later. No external heat source is provided, the acceleration of strength gain being achieved by the heat of hydration of cement alone. Again, the strength gain at the end of the curing period is not high and this method is judged to be the least accurate of the three.

SUGGESTED MODEL

As was shown in the above literature survey on the accelerated tests of concrete non of the above researchers consider the effect of the cement dose and the water cement ratio on the correlation between accelerated and 7 and 28 days concrete strength. Also none of them discuss the correlation between the concrete modulus of elasticity using accelerated test and normal 28 days test. In the suggested model in this research the above points were covered. The method of acceleration used in this model is similar to that suggested by King[1]. The tests were performed using several water cement ratios, w/c = 0.45, 0.5, 0.55 and 0.6. Also the effect of cement dose was observed where two series of tests were performed one with cement dose = 300 kg of cement per cubic meter and the other one was with cement dose = 350 kg m^{-3}. The constituents of the concrete mix in both series were designed according to ACI procedure, Nawy [5]. Over 200 tests were done. In each test the stress strain relationship was recorded.

RESULTS AND DISCUSSION

The results presented in Fig. 1-4 show the test results of more than 200 cube specimens grouped and analyzed

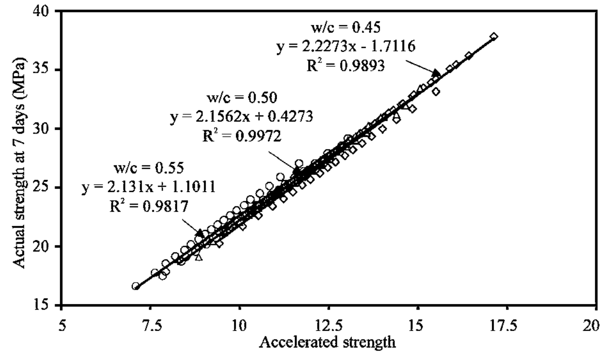

Fig. 1: Accelerated vs. 7 days strength for cement dose of 300 kg m^{-3}

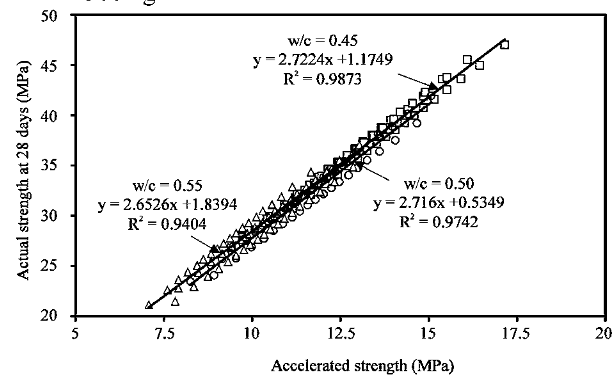

Fig. 2: Accelerated vs. 28 days strength for cement dose of 300 kg m^{-3}

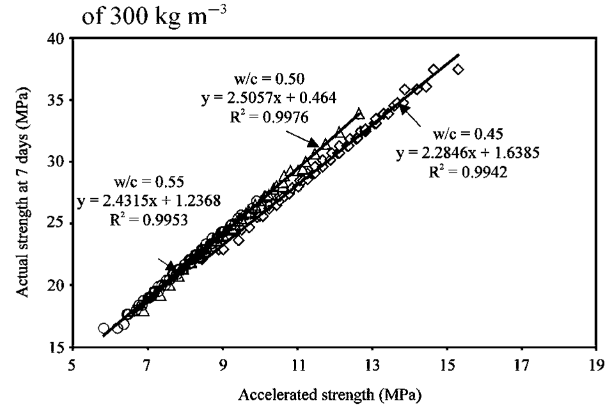

Fig. 3: Accelerated vs. 7 days strength for cement dose of 350 kg m^{-3}

to obtain a practical and easy trend curves that can be used to predict the strength of concrete at different ages for different cement content. Figure 1 and 3 show the effect of different water to cement ratios on the correlation between the accelerated strength and the strength of hardened concrete at age of 7 days for cement dose of 300 and 350 kg m^{-3}, respectively. Figure 2 and 4 show the effect of different water to cement ratios on the correlation between the accelerated strength and the strength of

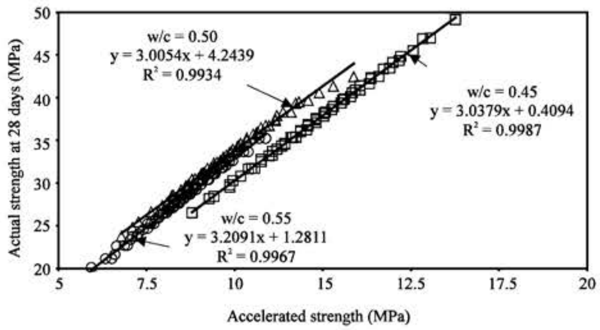

Fig. 4: Accelerated vs. 28 days strength for cement dose of 350 kg m^{-3}

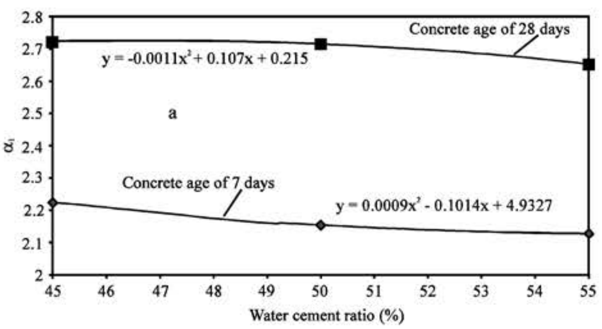

Fig. 5: Variation of the coefficient α_1 with respect to water cement ratio, cement dose = 300 kg m^{-3}

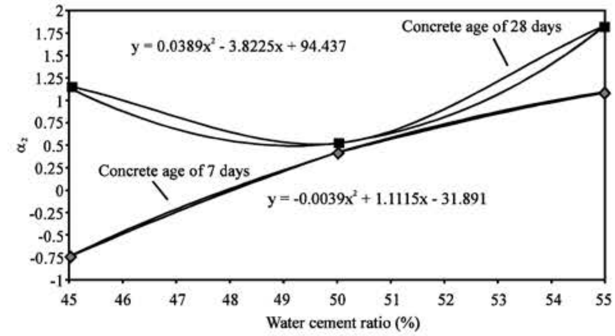

Fig. 6: Variation of the coefficient α_2 with respect to water cement ratio, cement dose = 300 kg m^{-3}

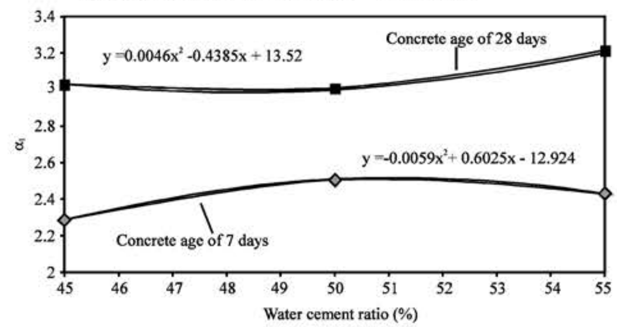

Fig. 7: Variation of the coefficient α_1 with respect to water cement ratio, cement dose = 350 kg m^{-3}

hardened concrete at age of 28 days for cement dose of 300 and 350 kg m^{-3}, respectively.

Figure 1-4, show that a linear trend curve can be obtained for the relation between the accelerated strength and the actual strength at ages of 7 and 28 days for different water to cement ratios. The relation can be written in the form:

$$F_{actual} = \alpha_1 (F_{accelerated}) + \alpha_2 \quad (1)$$

where:

F_{actual} = actual strength of hardened concrete at a certain age

$F_{accelerated}$ = Strength obtained by accelerated testing

α_1 and α_2 are curve coefficients calibrated for different water to cement ratios.

Figure 5 and 6 show the variation of curve coefficients α_1 and α_2 with respect to water cement ratio. These coefficients were estimated using polynomial curve fitting to the second degree.

If the water to cement ratio w/c is taken as a percentage, the formulas of α_1 and α_2 can be written as follows:

For cement dose of 300 kg m^{-3}, α_1 and α_2 can be written for concrete age of 7 days and 28 days as shown in Eq. 2 and Eq. 3, respectively:

$$\alpha_1 = 4.9327\text{-}0.1014\,(w/c) + 0.0009\,(w/c)^2$$

and

$$\alpha_2 = 31.89 + 1.1115\,(w/c)\text{-}0.0093\,(w/c)^2 \quad (2)$$

$$\alpha_1 = 0.215 + 0.107\,(w/c)\text{-}0.0011\,(w/c)^2$$

and

$$\alpha_2 = 94.437\text{-}3.8225\,(w/c)\text{-}0.0389\,(w/c)^2 \quad (3)$$

Similarly, Fig. 7 and 8 show the variation of curve coefficients α_1 and α_2 with respect to water cement ratio for a cement dose of 350 kg m^{-3}. These coefficients were estimated using polynomial curve fitting to the second degree.

For cement dose of 350 kg m^{-3}, α_1 and α_2 can be written for concrete age of 7 days and 28 days as shown in Eq. 4 and Eq. 5, respectively:

$$\alpha_1 = \text{-}12.924 + 0.6025\,(w/c)\text{-}0.0059\,(w/c)^2$$

and

$$\alpha_2 = 99.837\text{-}3.9348\,(w/c) + 0.0389\,(w/c)^2 \quad (4)$$

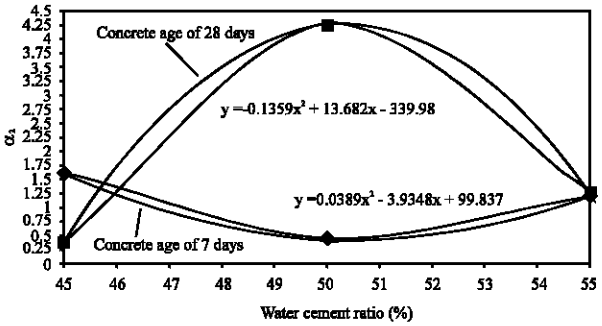

Fig. 8: Variation of the coefficient α_2 with respect to water cement ratio, cement dose = 350 kg m^{-3}

$$\alpha_1 = 13.52\text{-}0.4385\ (w/c) + 0.0046\ (w/c)^2$$

and

$$\alpha_2 = -339.98 + 13.682\ (w/c) - 0.1359\ (w/c)^2 \quad (5)$$

As an illustrated example, if the cement dose is 350 kg m^{-3} and the cement to water ratio is 50%. Then, α_1 = -12.924+0.6025 (50)-0.0059 (50)^2 = 2.451 and α_2 = 99.837-3.9348 (50) + 0.0389 (50)^2 = 0.347. Therefore, the actual strength at age of 7 days become:

$$F_{actual} = 2.451\ (F_{accelerated}) + 0.347$$

The above figures and equations show that the effect of variation in water cement ratio on the general relationship between accelerated and hardened concrete strength is small for low cement dose (i.e., 300 kg m^{-3}) and it is considerable for high cement dose (i.e., 350 kg m^{-3}), especially for 28 days compressive strength. The nonlinear relationship between w/c ratio and the ratio between strength of hardened concrete at 7 and 28 days age to accelerated one is shown in Fig. 9 and10.

From these figures, the following relationships were derived for the ratio of concrete strength at 7 days age to accelerated one and the ratio of concrete strength at 28 days age to accelerated one are given in the following equations:

i) For cement dose of 300 kg m^{-3}.

$$R_7 = 68(W/C)^2\text{-}65.067(W/C) + 17.657 \quad (6)$$

$$R_{28} = 115.04(W/C)^2\text{-}110.7(W/C) + 29.336 \quad (7)$$

ii) For cement dose 350 kg m^{-3}:-

$$R_7 = 60(W/C)^2\text{-}56.6(W/C) + 15.74 \quad (8)$$

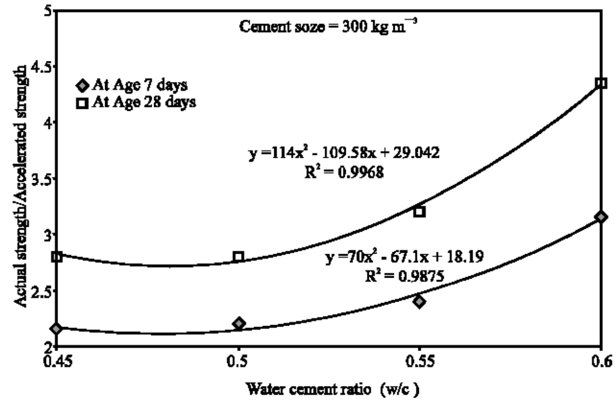

Fig. 9: Ratio of actual to accelerated strength for cement doze of 300 kg m^{-3}

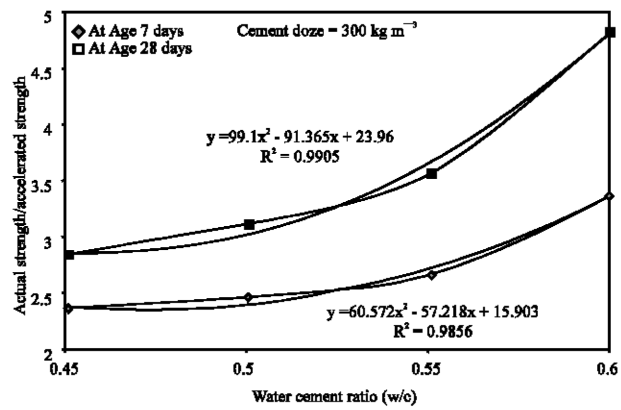

Fig. 10: Ratio of actual to accelerated strength for cement doze of 350 kg m^{-3}

$$R_{28} = 112.25(W/C)^2\text{-}104.9(W/C) + 27.372 \quad (9)$$

Where R_7 is the ratio of concrete strength at 7 days to the accelerated strength and R_{28} is the ratio of concrete strength at 7 days to the accelerated strength

These equations show that the R_7 is in the range from 2.15 to 3.15 for cement dose = 300 kg m^{-3} and from 2.4 to 3.4 for cement dose = 350 kg m^{-3}, while the range of R_{28} is from 2.7 to 4.35 for cement dose = 300 kg m^{-3} and from 2.8 to 4.8 for cement dose 350 kg m^{-3}.

The final summery of the above relationships and results are highlighted in Fig. 11 which designed for practical applications. This figure can be used to estimate the required hardened concrete strength ratio at 7 and 28 days by knowing the w/c ratio and the concrete class (i.e., cement dose in kg m^{-3}).

Case example: If w/c = 0.5 and Cement dose = 350 kg m^{-3}. If the accelerated strength is found to be 11 MPa then

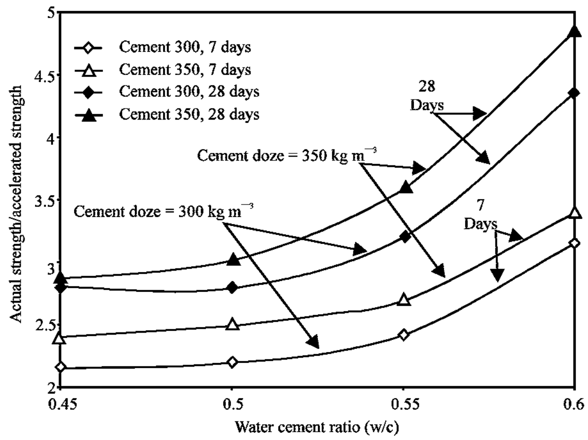

Fig. 11: Ratio of actual to accelerated strength for cement doze of 300 and 350 kg m^{-3}, respectively

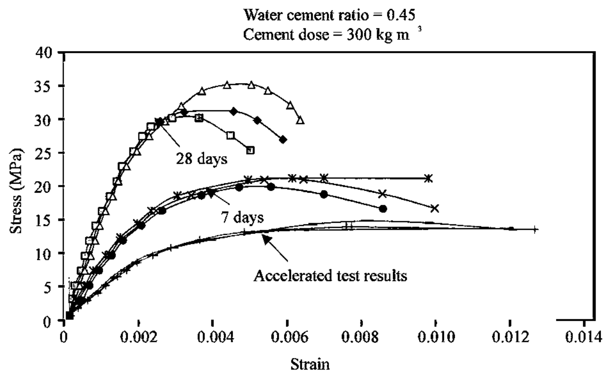

Fig. 12: Stress strain diagram of accelerated, 7-days old and 28 days old concrete cubes for water cement ratio of 0.45 and cement dose = 300 kg m^{-3}

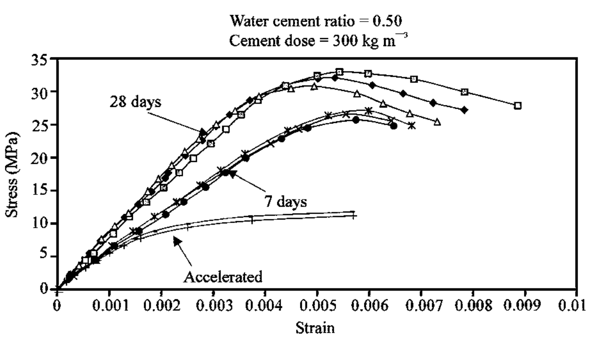

Fig. 13: Stress Strain Diagram of accelerated, 7-days old and 28 days old concrete cubes for water cement ratio of 0.50 and cement dose = 300 kg m^{-3}

from Fig. 7 we can estimate the strength ratio $Fc_{28}/Fca = 3.075$. Hence $Fc_{28} = 34$ MPa.

On the other hand Fc_{28} can be estimated more accurate from Eq. (11) such that:

$$Fc_{28} = 3.0054*(11) + 4.2435 = 37.25 \text{ MPa}$$

So the deviation is about 3.25 which form an error of about 9% which is almost acceptable for practical purposes.

The relationship between modulus of elasticity of accelerated concrete to the hardened concrete was observed for different w/c ratios. The results are shown in Fig. 8 and 9. The relationship model is found to be:

$$E_{ac} = 0.47\ E_{28} \text{ for } w/c = 0.45 \quad (10)$$

and

$$E_{ac} = 0.52\ E_{28} \text{ for } w/c = 0.52 \quad (11)$$

CONCLUSIONS

The following points are concluded based on the findings in this research, which are:

- Hardened concrete strength can be estimated from accelerated strength with reasonable accuracy.
- The relationship between hardened concrete strength and accelerated strength is affected by variation in the W/C ratio especially for high strength concrete with high cement dose.
- Modulus of elasticity of hardened concrete can be predicted from accelerated one which is = 0.49 of E_{28} days.

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