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FULL LENGTH ARTICLE

Compressive strength prediction of Portland cement concrete with age using a new model

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Abstract Based on the existing experimental data for compressive strength values of different concrete mixes, a statistical analysis for the gathered data was conducted. The analysis revealed a model for predicting the compressive strength of concrete mixes at any age with the help of two constants (A) and (B) that are considered as a characteristic property for a concrete mix. The constant (A) is introduced as a rate of strength gain constant whereas, (B) is introduced as grade of strength constant.

Once the values of constants (A) and (B) are defined for a concrete mix, the compressive strength at any age could be simply predicted without collecting data at that age. The values of (A) and (B) could be determined by one of two methods. Solving two simultaneous equations at two different ages while performing either design or trial concrete mix is a method that could be used to define the two constants. Other method is based on concrete strength at 28-day age. The proposed model was studied for different concrete mixes. The study covered some parameters including the influence of, mineral admixtures as a partial replacement of cement, metakaolin, nano silica fume, curing in water or lime and the effect of curing temperature.

The analysis reveals that mixes containing no admixtures, mixes containing silica fume and cured at normal temperature, mixes containing nano silica and cured in water are following with high accuracy the proposed model.

Introduction

Compressive strength of concrete is one of the most important and useful properties. As a construction material, concrete is employed to resist compressive stresses. While, at locations where tensile strength or shear strength is of primary importance, the compressive strength is used to estimate the required property.

Common trend in concrete technology is to use compressive strength as a quantitative measure for other properties of hardened concrete [1].

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It is well known that, immediately after mixing cement based materials, the hydration process takes place. CSH is the compound resulting from hydration and it gives concrete its strength.

Cement based materials develop strength with continued hydration. The rate of gain of strength is faster at start and the rate gets reduced with age [1]. In spite of considering the 28-day compressive strength for design purposes, actually concrete develops strength beyond 28 days as well. Most codes of practice do not consider the increase of strength beyond 28 days for design purposes [ACI [2], ECP [3], . . .].

British code gives modification factors for permissible compressive strength as 1.0, 1.10, 1.16, 1.2 and 1.24 for 1, 2, 3, 6, and 12 months as minimum age of member when full design load is applied whereas, for high strength concrete, British code allowed to add 0, 4.2, 5.5, 7.7 and 10.2 MPa over the permissible strength at 28 days for 1, 2, 3, 6 and 12 months, respectively.

Many a time it may be necessary to estimate the strength of concrete not only at an early age but also at later ages [1]. Many research workers have attempted to estimate the strength of concrete at 1, 3 or 7 days and correlate to 28-day strength. Numerous research works have provided certain relationships. For instance;

In Germany, the relation between 28-day strength f_{c28} and the 7-day strength, f_{c7} is taken to lie between [1],

$$f_{c28} = 1.4f_{c7} + 150 \text{ and } f_{c28} = 1.7f_{c7} + 850\,(f_c) \text{ is being expressed in psi} \quad (1)$$

Another formula was proposed as follows:

$$f_{c28} = K_2(f_{c7})^{K_1} \quad (2)$$

where, f_{c7} and f_{c28} are the strengths at 7 and 28 days, respectively. K_1 and K_2 are the coefficients which are varied for different cements and curing conditions. The value of K_1 ranges from 0.3 to 0.8 and that of K_2 from 3 to 6 [1].

Earlier ECP [3] considered compressive strength gain as a parameter of age through the coefficients for ordinary Portland cement concrete strength as 0.4, 0.75, 1.0, 1.176 and 1.33 for 3, 7, 28, 90 and 360 days age, respectively. Whereas, for rapid strength Portland cement concrete those values were given as 0.556, 0.8363, 1, 1.111 and 1.176 for 3, 7, 28, 90 and 360 days, respectively. But with issuing the last version of ECP [3], the coefficients considering the variation of compressive strength with age had been omitted.

In the history of concrete technology, Abrams' formula [4] was the first one describing the dependence of concrete strength on water cement ratio. Abrams suggested a mathematical relationship between concrete strength and water/cement ratio as:

$$f_c = \frac{A}{B^x} = AB^{-x} \quad (3)$$

where (f_c) is the compressive strength of concrete; A and B are experimental parameters for a given age, material and curing conditions; and (x) is water/cement ratio by mass.

For an average Portland cement concrete cured under normal temperature and moisture, Abrams gave the relationship between compressive strength and water/cement ratio as [5];

$$f_{c7} = \frac{63.45}{14^x} \quad \text{and} \quad f_{c28} = \frac{96.55}{8.2^x} \quad (4)$$

where, f_{c7} and f_{c28} are the strengths in MPa at 7 and 28 days, respectively. Moreover (x) is the water/cement ratio.

To consider the use of mineral admixtures in concrete, many studies have shown that when the water/binder ratio is used instead of water/cement ratio as basis for mix design; strength prediction becomes more accurate [5,6].

The water binder ratio takes the following shape;

$$x = \frac{w}{c + kf + s} \quad (5)$$

where x is water/binder ratio; w is water content; c is cement content; f is fly ash content; s is granulated blast furnace slag (GBFS) content and k is an efficiency factor.

Beside Abrams' formula, the power formula is considered as one of the most useful formulae in the field of concrete technology. It takes the following form [4]:

$$f_c = Ax^{-B} \quad (6)$$

where (f_c) is the compressive strength; A and B are experimental parameters for a given age and x is the water/cement ratio.

Implementation of either Abrams' formula or power formula to predict the concrete strength at any age requires collecting a lot of data at that age, then build a specific formula, and using a time factor (a function of age) multiplied by specific age strength (usually 28 – day strength) to estimate the strength at a given age.

Yeh [7] proposed two novel methodologies, parameter – trend – regression and four – parameter – optimization methodology to extend Abrams' formula and the power formula to any given age without collecting data at that age. The proposed model is a generalization of Abram' formula and the power formula, respectively, to be;

$$f_{c,t} = \frac{A_t}{B_t^x} = A_t B_t^{-x}$$

$$f_{c,t} = A_t x^{-B_t} \quad (7)$$

where ($f_{c,t}$) is the concrete compressive strength at age t days; (A_t) and (B_t) are experimental parameters depending on age and (x) is the water/binder ratio [7].

Early age strength prediction in concrete is very useful in reducing construction cost and ensuring safety. Furthermore, early age strength prediction has several practical applications. It can be used to determine safe stripping time, prestressing application or post – tensioning time, to monitor strength development, particularly when concreting in cold weather, to check serviceability conditions or compliance criteria, to ensure construction safety and, generally to estimate the quality of construction and potential durability [8].

Moreover prediction of concrete strength at late ages is being significant from both technical and economical points of view. For instance, when considering the actual strength values at which the structure is being subjected to full load, materials safe could be achieved as considered by BS in the track of minimizing the pollution.

Concrete compressive strength is influenced by many factors including, water/cement ratio, cement content and properties, aggregate type and its properties, etc. This paper introduces a simple mathematical model that can help predicting the compressive strength for a specified concrete mix at any