APPLIYING EARLY CONCRETE COMPRESSIVE STRENGTH PREDICTION IN INFRASTRUCTURE CONSTRUCTION; CASE STUDY

S.R.DAREGHOLI
Civil engineer, Mahab Ghodss Consultant Co., Iran

H.HOSSEINZADEH
Hydraulic structural engineer, Mahab Ghodss Consultant Co., Iran

ABSTRACT

Now-a-days using concrete in various structures, especially infrastructures, is one of the most affordable, reliable and popular methods in all around the world. Accordingly, the cement consumption is an important criteria to evaluate the development of a country. The importance of quality of concrete is an undeniable factor in durability of structures. Compressive strength is an indicator of utmost significance for acceptance of concrete quality and most of the other parameters such as tensile strength and durability are often a function of characteristic compressive strength of concrete. The issue of fluctuation of concrete compressive strength values is common in construction. Since design of structures is usually based on 28 or 90 days compressive strength, prediction of final strength of concrete by use of 7 days strength is remarkably helpful for recognizing defective concrete and reacting properly for modification. Late detection of problem not only will take a lot of time, but it also imposes extra cost to project. Purpose of this paper is deriving mathematical equations in order to predict compressive strength of concrete in older ages during construction of a dam site that it can help to modify procedure of execution and reduce costs and time of project significantly.

***Keywords** : Concrete, Compressive Strength, Strength Prediction, Quality Control, Mathematical Model, Regression*

1. INTRODUCTION

Concrete is a popular construction material that is used in all around the world. Low cost, availability of constituents, workability, durability and appropriate compressive strength are the advantages of concrete. However, these advantages seriously depend on the optimum mix design and placing and curing quality. Quality control of concrete is made at three stages, control of properties of the constituents (water, cement and aggregates), tests on fresh concrete and test on hardened concrete(compressive, tensile and bending strength tests).[1]

In construction industry, strength is a primary criterion in selecting a concrete for a particular application. Concrete used for construction gains strength over a long period of time after pouring it. The characteristic strength of concrete is defined as the compressive strength of a sample that has been aged for 28 days or 90 days depending the designated load patterns during construction and operational periods.

Neither waiting 28 days from such a test would cause lots of delays in construction process, nor neglecting it, would effect on the quality control process of concrete in large construction sites. Construction loading is one of the most intensive stage of a structure's life. Premature removal of formwork, lifting or moving of precast concrete or large construction live loads can cause cracking or other damages. In structures with mass concrete that are investigated in this paper, even if a structure does not show any defects during the construction stage, it is possible to encounter defects and damages during operational period. Therefore, early and reliable prediction for the strength of concrete would be very important in order to make decisions. Because repairing, retrofitting and additional necessary tests of hardened concrete are so time consuming and expensive, taking proper actions among construction for satisfying acceptance criteria is an issue of utmost importance.

Accordingly, prediction of concrete strength has been an active area of research and a considerable number of studies have been carried out. Many attempts have been made to obtain a suitable mathematical model which is capable of predicting strength of concrete at various ages with acceptable accuracy. The aim of this study is achieving to an equation by statistical analyzing of 175 compressive test results through mathematical regression model in order to predict the concrete characteristic strength by use of early age results and using them to making practical site decisions and making early appropriate modification in concrete production, transportation and placing to avoid financial damages.

There are some mathematical relationships in previous studies that are developed and can predict 28 days strength form 7 days results. Mentioned studies have shown that developed equations are different from one construction site to another, because of the different characteristics of materials that have been used. It is necessary to analysis the generated concrete strength data in every construction site, especially in mega projects, and develop appropriate equations to that specific construction site.

ACI committee 209 [9] suggested Equation 1 for prediction of compressive strength of standard concrete specimen (cylinder; diameter 150mm; height 300mm) made with ordinary Portland cement (Type I) which is moist-cured and tested in a standard condition as mentioned in ASTM C 192-00 [10] and ASTM C 39-99 [11]

$$f_{ct} = f_{c28}\left(\frac{t}{4 + 0.85t}\right) \qquad ...(1)$$

Where fct is compressive strength at age t-days and fc28 is compressive strength at age of 28 days.

Hamidzadeh et al. 2006, GMDH-type neural networks base on some experimental data in order to model and predict compressive strength of 42-days. The aim of such modelling is to show how compressive strength of 42-day change with the variation of Compressive strength of 7 and 28 days old. In the other study Zain et al., 2008 has used non-linear regression equation for the prediction of concrete compressive strength at different ages. But they have used different concrete mix designs for developing their equations. They showed non-linear regression is a reliable method to developing concrete equations. Khashman and Akpinar, 2017, used artificial neural network (ANN) model to predict and classify the compressive strength of different concrete mixes into low, moderate or high strength and suggest to use it instead of traditional destructive compressive strength tests. Hasan and Kabir, 2012, developed a simple mathematical model based on concrete's nature of strength gain to predict the compressive strength of concrete at 28th day from early age results. The model is a simple equation (a rational polynomial) that consists of two constants and one variable which is the age of concrete in days. Hossein Akbarzadeh Kasani, 2016, proposed new linear and power relations for estimating 28 and 42 days strength values by analyzing on 382 datasets of ordinary Portland cement concrete.

In large scale construction plants, especially in dam construction, using a particular mix design for a large amount of concrete is very common. This paper developed mathematical equations in order to predict compressive strength of a particular mix design (with compressive strength of 30 MPa) that is used in spillway and water intake structures of KANISIB reservoir dam in West Azerbaijan province in Iran. Case study concrete compressive strength results and on field decisions making to manage appropriate production of the concrete in large sites are the basis of this research.

1.1 Case study

In this study, data of Kanisib reservoir dam project has been used. This project is located near Piranshahr, western Azerbaijan province, Iran (Fig.1). This dam is designed for the aim of providing agriculture and water transmission to Urmia Lake through a conveyance tunnel with volume of 52 cms. Dam reservoir capacity is almost 330 MCM.

Kanisib dam is a clay core embankment dam with height of 65 meters and volume of earth filling is 2500000 m^3. The flood evacuation system consist of a concrete spillway with stilling basin which the volume of concrete work for this

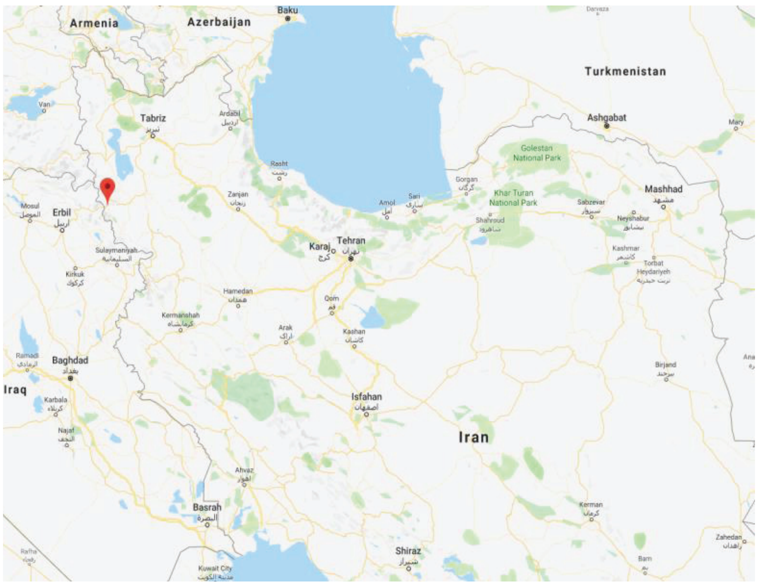

Figure 1 : Location of KANISIB dam in northwest of Iran

structure is about 850000 cubic meters. In this project an intake tower with height of 44 meters and concrete volume of 1600 cubic meter has been considered in order to provide the environmental irrigation demand of downstream and evacuate the reservoir and sediments in critical situations. Concrete production system consist of two batching plants with production capacity of 120 cubic meters per hour.

One of the most important factors in strength growth of concrete is the type and amount of used cement in mix design. In this project, Portland Pozzolana Cement (PPC) has been used. The presence of pozzolans will definitely effect on the strength growth. In other words, the growth rate of concrete strength with Ordinary Portland cement (OPC) is quite different from concrete with PPC.

Number of 175 series of specimens have been provided during executing almost 19000 cubic meters of concrete in spillway and water intake structures.

Each groups of specimens for a concreting section contains 6 standard cylindrical samples (d=150mm and h=300) that 2 of them will be broken after 7 days, next 2 samples will be tested after 28 days and the compressive strength for the rest of specimens would be determined after 90 days. All parts of Inspection Testing Plan (ITP) has been carried out according to ACI 318.

Figure 2 : (a) Spillway of KANISIB reservoir dam, April 2019. (b) Water intake tower of KANISIB reservoir dam, February 2019

1.2 Method

The strengthening of concrete is a complex process involving many external factors. A number of improved prediction techniques have been proposed by including empirical or computational modeling, statistical techniques and artificial intelligence approaches. Many attempts have been made for modeling this process through the use of computational techniques such as finite element analysis. While, a number of research efforts have concentrated on using statistical methods especially regression models to improve the accuracy of predictions. Statistical models have the attraction that once fitted they can be used to perform predictions much more quickly than other modeling techniques, and are correspondingly simpler to implement in software. Apart of its speed, statistical modeling has the advantage over other techniques that it is mathematically rigorous and can be used to define confidence interval for the predictions. This is especially true when comparing statistical modeling with artificial intelligence techniques. Statistical analysis can also provide insight into the key factors influencing 28 days and 90 days compressive strength through correlation analysis. For these reasons statistical analysis was chosen to be technique for strength prediction of this paper. Five different types of functions, including exponential, linear, logarithmic, polynomial and power had been tried for fitting data and eventually polynomial one had been chosen for predicting of concrete characteristic strength by use of early age results.

The polynomial models can be used in those situations where the relationship between study and explanatory variables is curvilinear. Sometimes a nonlinear relationship in a small range of explanatory variable can also be modeled by polynomials. The kth order polynomial model in one variable is given by:

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + ... + \beta_k x^k + \varepsilon_0 \quad (2)$$

A sufficient number of tests are needed to indicate accurately the variation in the concrete produced and to permit appropriate statistical procedures for interpreting the test results. Statistical procedures provide a sound basis for determining from such results the potential quality and strength of the concrete and for expressing results in the most useful form. A strength test result is defined as the average strength of all specimens of the same age, fabricated from a sample taken from a single batch of concrete. A strength test cannot be based on only one cylinder; a minimum of two cylinders is required for each test. Concrete tests for strength are typically treated as if they fall into a distribution pattern similar to the normal frequency distribution curve illustrated in Fig. 1.

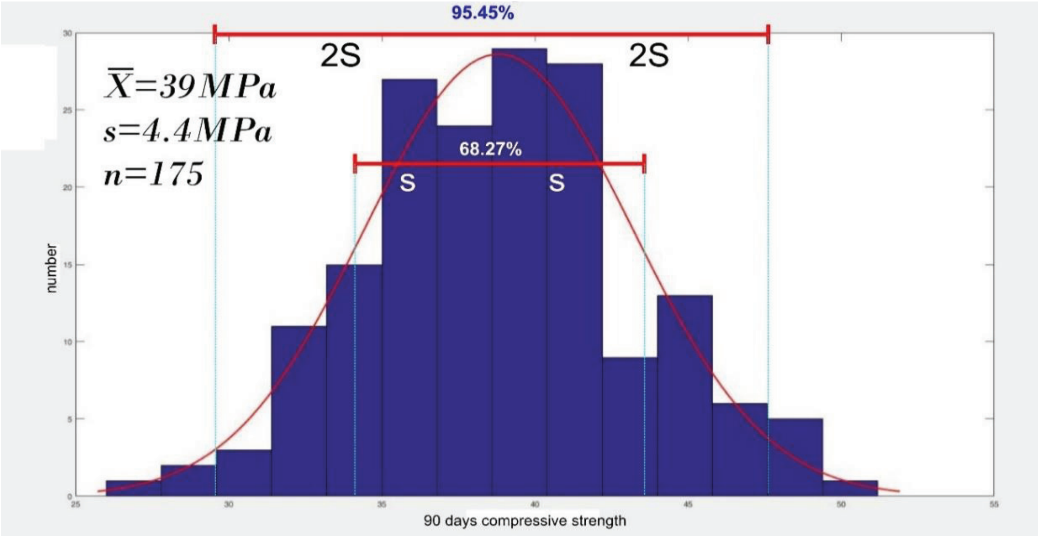

Figure 3 : Normal distribution of 90days compressive strength

The normal distribution can be fully defined mathematically by two statistical parameters, the mean and standard deviation. These statistical parameters of the strength can be calculated as shown below:

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{1}{n}\sum X_i = \frac{1}{n}(X_1 + X_2 + \cdots + X_n) \tag{3}$$

Xi is the i-th strength test result, n is number of test results.

$$s = \sqrt{\frac{n\sum_{i=1}^{n} {X_i}^2 - \left(\sum_{i=1}^{n} X_i\right)^2}{n(n-1)}} = \sqrt{\frac{\sum_{i=1}^{n} {X_i}^2 - n\bar{X}^2}{n-1}} \tag{4}$$

Where "s" is the sample standard deviation, n is number of strength test results. So $\bar{X}$ = 39 MPa and s = 4.4MPa.

As it is shown in Figure 4 and based on above calculation the probability of reaching to characteristic compressive strength by the selected mix design is about 95%.

One of the primary purposes of statistical evaluation of concrete data is to identify sources of variability. This knowledge can then be used to help determine appropriate steps to maintain the desired level of control. Several different techniques can be used to detect variations in concrete production, materials processing and handling, and contractor and testing agency operations. One simple approach is to compare overall variability and within-test variability, using either standard deviation or coefficient of variation, as appropriate, with previous performance.

Table (1) gives the standards of control which are appropriate for concrete having specified strengths up to 35 Mpa (5000 psi). This standard of control were adopted based on examination and analysis of compressive strength data by ACI Committee 214 [13] and ACI Committee 363 [14]. The strength tests were conducted using 150 × 300 mm (6 ×12 in.) cylinders. According to above calculation the standard deviation is equal to 4.4, so base on following tables, it is obvious that the variability of the results should be controlled more. Variations in strength test results can be traced to two different sources:

1. Variations in testing methods that is estimated by the within-test variation based on differences in strengths of companion (replicate) cylinders comprising a strength test result. The within-test variation is affected by variations in sampling, molding, consolidating, transporting, curing, capping, and testing specimens.

2. Variations in the properties or proportions of the constituent materials in the concrete mixture, variations in the production, delivery or handling procedures, and variations in climatic conditions. Once a desirable mixture has been formulated in the laboratory, field testing with production-sized batches is recommended. Quite often laboratory trial batches have exhibited a strength level significantly higher than that which can be reasonably achieved in production. Actual field water demand, and therefore concrete yield, has varied from laboratory design significantly. Ambient temperatures and weather conditions have affected the performance of the concrete. Practicality of production and of quality control procedures have been better evaluated when production-sized trial batches were prepared using the equipment and personnel that were to be used in the actual work [14].

Table 1 : Evaluation of standard deviation for compressive strength

Class of operation	Overall variation				
	Standard deviation for different control standards (Mpa)				
	Excellent	**Very good**	**Good**	**Fair**	**Poor**
General Construction Testing	Below 2.8	2.8 to 3.4	3.4 to 4.1	4.1 to 4.8	Above 4.8
Laboratory Trail Batches	Below 1.4	1.4 to 1.7	1.7 to 2.1	2.1 to 2.4	Above 2.4

The acceptance criteria of this project is based on ACI committee 318 [15]. When a concrete production facility has a suitable record of 30 consecutive tests of similar materials and conditions expected, once the sample standard deviation has been determined, the required average compressive strength, when the f'c is less than 35 Mpa, will be obtained from the larger value computed from Eq. (5) and (6) .

$$\bar{X} = f'_c + 1.34s = 30+1.34\times4.4=35.9 < 39MPa \quad (5)$$

$$\bar{X} = f'_c + 2.33s-3.5 = 30+2.33\times4.4-3.5=36.8 < 39\ MPa \quad (6)$$

Equation (5) is based on a probability of 1-in-100 that the average of three consecutive tests may be below the specified compressive strength fc′. Equation (6) is based on a similar probability that an individual test may be more than 3.5 Mpa below the specified compressive strength fc′. Therefore, for accepting the quality of poured concrete following equations shall be satisfied:

$X1>f'c$ and $X2>f'c$ and $X3>f'c$

If not

Average $(x1,x2,x3)>f'c$ and $Xmin>f'c-3.5$ Mpa

1.3 Results

In order to find out the strength gaining pattern of the concrete with age, strength versus day curve was plotted for every single set of specimen test data. It was observed that every curve follows a typical pattern. Figure 5 is a representative figure showing the strength gaining pattern with age of concrete for average of all results.

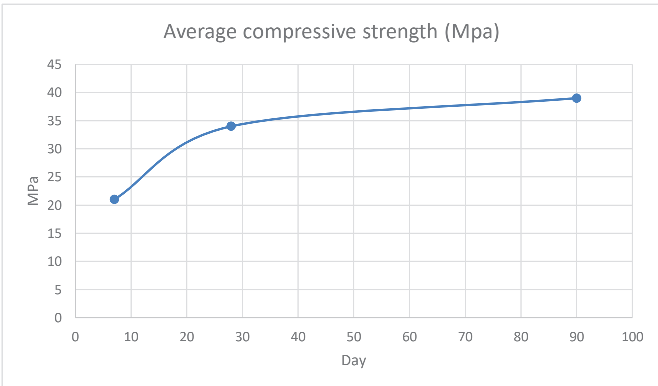

Figure 4 : Average compressive strength based on age of specimens

Excel curve fitting tool was used to plot these data and also for the analysis purposes. By means of this tool 3 equation have been derived in order to predict the 28 and 90 days strength from earlier test results.

First developed equation can be used for estimation of 28 days compressive strength by use of 7 days strength.

$$y = -0.0037x^3 + 0.2441x^2 - 4.3762x + 51.991 \quad (7)$$

Where 'y' is 28 days and "x" is 7 days compressive strength.

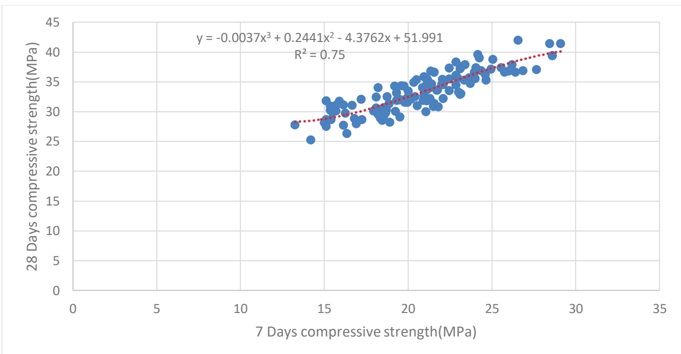

Figure 5 : Estimation of 28 days compressive strength by use of 7 days strength

Correlation coefficient is the analysis criterion for fitting polynomial function. The analysis for predicting 28 days compressive strength base on 7 days strength has shown that increasing the order of polynomial has not any significant effect on the increasing of correlation coefficient. So 3rd order polynomial with correlation coefficient of 0.75 has been selected for developing the equation. Due to the high standard deviation (S = 4.4) of used data it is not possible to reach higher correlation coefficient. The most frequency of data is related to 7 days compressive strength between 20 and 25 MPa and for 28 days compressive strength between 30 and 35 MPa.

Second developed equation can be used for estimation of 90 days compressive strength by use of 7 days strength.

$$y = -0.0031x^3+0.2127x^2 - 3.8082x + 53.879 \quad (8)$$

Where 'y' is 90 days and "x" is 7 days compressive strength.

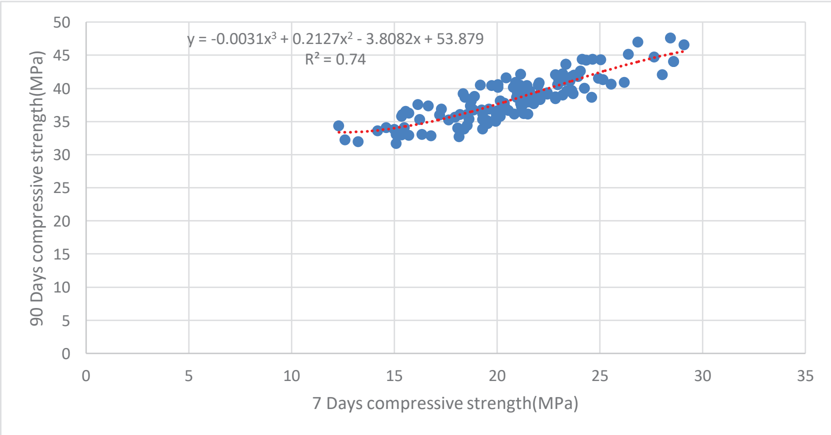

Figure 6 : Estimation of 90 days compressive strength by use of 7 days strength

Derived correlation coefficient for the relation between 7 and 90 days strength is 0.74 and is almost equal to the previous one. The most frequency of data is related to 7 days compressive strength between 20 and 25 MPa and for 90 days compressive strength between 35 and 40 MPa. Using of PPC has an effect on the rate of strength growth from 28 days to 90 days that will be illustrated in the next equation.

Third developed equation can be used for estimation of 90 days compressive strength by use of 28 days strength.

$$y = 0.0009x^3 - 0.0723x^2 + 2.5884x - 1.4065 \quad (9)$$

Where 'y' is 90 days and "x" is 7 days compressive strength.

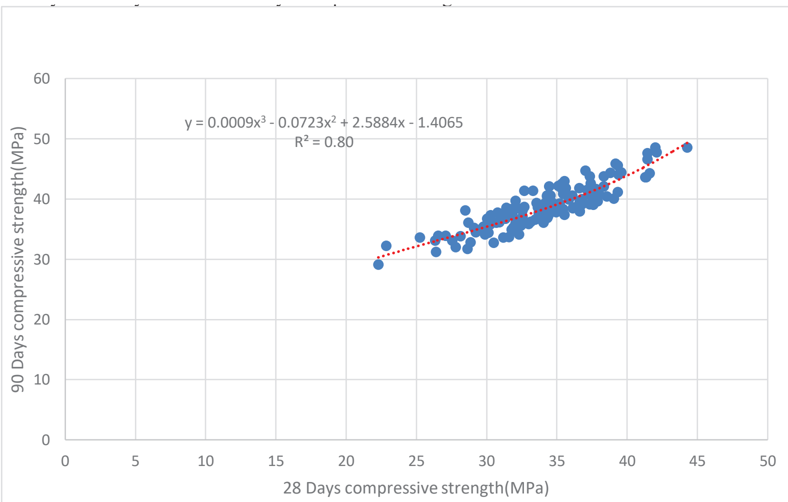

Figure 7 : Estimation of 90 days compressive strength by use of 28 days strength

Correlation coefficient for Equation 9 is equal to 0.8. Compressive strength growth from 28 to 90 days is mostly because of the role of existing pozzolans besides remaining cement hydration, which cause smaller rate of growth rather than first 28 days. The most important reason for getting higher correlation coefficient in Equation 9 is the lower level of changing rate of strength growth from 28 to 90 days.

Linear correlations corresponding to Figures 6, 7 and 8 are summarized in Table 2. Also these figures are the best fitted polynomial relations and the correlation coefficient is about 0.75 to 0.8.

Table 2 : Fitted polynomial relations for prediction of compressive strength in older ages

Developed equation	Equation No.	Data Length	R2 (Correlation Coefficient)
$F_{28} = -0.0037 (f_7)^3 + 0.2441(f_7)^2 - 4.3762(f_7) + 51.991$	7	175	0.75
$F_{90} = -0.0031 (f_7)^3 + 0.2127(f_7)^2 - 3.8082(f_7) + 53.879$	8	175	0.74
$F_{90} = 0.0009 (f_{28})^3 - 0.0723(f_{28})^2 + 2.5884(f_{28}) -1.4065$	9	175	0.80

2. CONCLUSIONS AND PRACTICAL NOTES

According to the test results, it is possible to estimate the final compressive strength of produced concrete in site accurately after 7 days. It will help us in various ways to increase the quality of execution that are explained in following paragraphs.

1. Finding out deficiencies in producing, conveying or pouring concrete:

   After 7 days, when the initial compressive strength of concrete is determined, final strength will be predicted by use of derived equations. This can help us to understand deficiencies in producing, conveying or pouring concrete and make proper decision in order to amend the situation. Humidity of materials, required water of mix design, batching calibration and quality of cement and additives are common reasons that affect compressive strength of concrete. Control and modification of each of them can prevent from financial and time losses in project.

2. Retrofitting defected structure

   In such a structures that concrete should be poured in several lifts because of various considerations, if one single lift couldn't reach to characteristic strength, according to different references, it will be accepted if it could pass some criteria. In this paper, the acceptance criteria of ACI committee 318 is used to evaluate the quality of concrete. For instance in 8th lift of one of our structures the 7 day compressive strength was 13 Mpa and the 28 days strength was 20 Mpa, according to Equation 9 the predicted 90 days compressive strength will be 28.5 Mpa. So we decided to use another mix design with higher amount of cement in order to increase strength of next two lifts and pass the acceptance criteria. If we couldn't use developed equations, this deficiency would continue and finally it could impose lots of costs for destructing or rehabilitation of the structure.

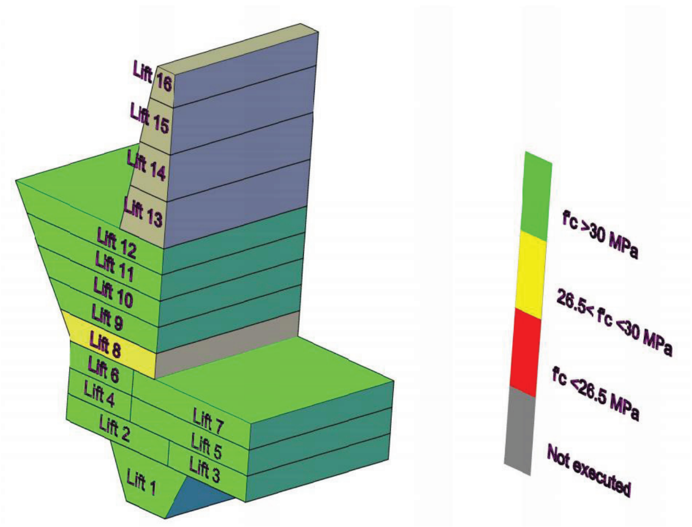

Figure 8 : Compressive strength of one of the spillway Walls

3. Periodic control of materials:

   Concrete contains different materials, the amounts of aggregates are more than other ingredients. So both of the fine and coarse aggregates shall be test periodically. In most of huge construction plants, especially in dam sites, most of the required materials are provided from near borrow pits. One of the main reasons of differences in concrete strength is alternation of material's property with the initial materials that mix designs have been produced by them. In other words, changing in quality of material can cause this issue.

4. Additives and cementitious material:

   Because probability of variation in quality of additives and cementitious material it is necessary to have a systematic approach for testing products and components Inspection Test Plan (ITP). There are several reasons why the quality of additives and cementitious materials is volatile, differences in raw materials, changing produce procedure and how to store them. Due to significant cost of the experiments, duration of these tests varies from one to several month in accordance with the technical specifications of the project.

In case of short-term compressive strength loss and after estimating final strength by use of derived equations, if the predicted strength wouldn't reach to required amount and the reason was unknown, controlling the quality of cementitious materials and additives can help us to recognize the reason and prevent from producing and implementing defective concrete.

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