Experimental Study on After-Mixing Temperature Control of Concrete in Batching Plant Production

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Abstract. Calculation of the concrete temperature in production phase is an important parameter to control the concrete quality, confining inconsistencies, and costly corrections. In order to obtain after mixing temperature of concrete, the before mixing temperature and weight of the constituent material as well as the moisture contents of the aggregates are collected. Using heat balance equilibrium of the concrete material is an easy and widely used method to calculate after-mixing temperature of the concrete. ACI 306R-10 has presented an equation to calculate the concrete temperature based on thermal equilibrium of the constituents. To evaluate the performance of the equation in estimation of the concrete temperature an experiment is conducted. In the experimental site test results of the output from a batching plant is recorded and graphed. The results of the after induction temperature were calculated using the formula presented in ACI. However, the proposed equation predicts smaller temperature values compared to the actual ones. In the final step the reasons for deviation in the results was discussed and an equation is derived to calculate the concrete temperature for post-mixing stages. The obtained equation was tested on other data and the results show that the method could predict the results reliably.

1. Introduction

Controlling of the fresh concrete temperature to remain within the specified range stated in standards and codes is an important factor for obtaining quality concrete in hot and cold weather concreting [1]. For large-scale concrete production, the cementitious paste is mixed together with fine and coarse aggregate in batching plant. The weight and the thermal data of aggregate, concrete, water and other ingredients are measured and recorded to obtain an estimation of the fresh concrete temperature at the batching plant output. Batching plant is a set of equipment which is used for proportioning of the materials [2]. Various methods and techniques are available for temperature control of the produced concrete. Concrete thermal conditions were controlled in accordance with the project requirements and the recommendation of the regulations [3]. Obviously, correct estimation of the concrete temperature will lead to more accurate results as well as a reduced correction costs.

Heat evolution in concrete is a very complex process involving some material and environmental variables that is controlled by interactions among other factors. The heat evolution over time can be separated into four distinctive stages including pre-induction, induction, strength gain, and steady state steps. Fresh concrete temperature can be inspected while discharging from batching plant, before delivery, and after placement. However, the concrete temperature can be regulated just by controlling the temperature of the constituent in before-mixing condition in batching plant and through controlling the temperature of its components [4]. For producing concrete in research and execution phase, several tests are conducted on the ingredients to evaluate their interaction in the final mix. However, the temperature of the fresh concrete is a parameter that has not been studied as broadly as other aspects.
It can be due to the large dependency of the fresh concrete temperature to the ambient condition and high variability due to environmental factors. The heat evolution steps of concrete are presented in Table 1.

| Heat evolution stage | Period * | Source of thermalization | Effect in temperature | Stage in production phase |
|----------------------|----------|--------------------------|------------------------|---------------------------|
| Pre-induction        | From initiation time ~10 min | Reaction in aluminate, ferrite and silicate phases | Sharp increase in temperature | At concrete mixer |
| Induction            | ~10 min–~4 hrs. during microstructure formation | Not much hydration takes place | Lower trend compared to pre-induction | Transportation and placement |
| Strength gain        | ~4hrs–24hrs | Reaction of the calcium silicates | Increase in temperature | In the formworks |
| Steady state         | ~24hrs–∞ and continues for years or even decades | Formation of monosulphate | Temperature stabilization | In the formwork and after formwork removal |

* Depends on multiple factors such as cement type, admixtures, and w/c.

Cement hydration is an exothermic reaction and is release of energy in the form of heat. Hydration heat is greatly contributed to the chemical behaviour of the compounds, and could be determined by multiplication of the heat of hydration of the individual pure compounds into their mass proportions [6]. The total amount of the released dehydration heat is an indicator of the reactivity of concrete components. Moreover, it determines the setting and hardening characteristics of concrete at the early age of the cement paste [6]. The temperature variation of concrete due to hydration is largely varied by the constituent materials, mix proportioning and ambient parameters [7]. Calcium is the major constituent of Portland cement and development of total heat is dominated by the calcium contents in the mix [3]. Higher dehydration heat as a result of higher chemical reactivity of the cement contents may result in undesirable durability problems like cracks and shrinkage in the concrete [8,9]. The reaction between cementitious materials and water is the main source of dehydration heat. Cementitious products form the glue to hold concrete ingredients together. These materials include traditional Portland cement and by-product of industrial processes such as silica fume, fly ash, ground granulated blast furnace slag (GGBS), and limestone fines. The industry by-products are mixed either in cement production phase or combined at concrete mixer. Controlling of the type and amount of cementitious materials is an effective temperature control solution for limiting temperature rise in concrete that are sensitive to temperature variations [10]. Several researches have been conducted on the effects of temperature on the fresh concrete properties with a variety of results [11]. Several standards and specifications are contributing to the influence of cold and hot weather in properties of early age concrete and to prevent the damages caused by variation in temperature due to thermal factors. As stated in ACI 305.1-06, the concrete production temperature shall be controlled in a way that the maximum temperature at the discharge stage will not exceed maximum allowable concrete temperature specified in the standard. Hence, it is of great importance to provide cost-effective solutions for on-site concrete production. Several methods are introduced for controlling the concrete temperature in practical applications such as artificial heating or cooling of raw materials – pre-heating or pre-cooling – and providing suitable curing condition – post heating or post cooling – [12-13]. One should consider the cost-effectiveness of the adopted additional precautionary measures.
The applied precaution actions are aimed to be served with minimum cost and maximum benefit as dual objectives. The great share of these precaution actions are applied in on-site concrete production system [14-15]. Some recommendations on fresh concrete temperature are shown in Table 2.

Table 2. The temperature inspection and testing recommendation in standards and codes

| Standard | Number | Fresh concrete delivery temperature | Inspection/ test | Minimum frequency |
|----------|--------|-------------------------------------|------------------|------------------|
| ACI      | 305    | Min (˚C) Max (˚C)                   | ASTM C1064       | ASTM C94 /C94M   |
| BS EN    | 206    | 5                                   | Measure temperature | Periodical and when new batch or load arrival |
| ACI      | 306    | 13                                  | ASTM C1064       | ASTM C94 /C94M   |

Although, up to the present time, a great number of researches have been carried out by numerous investigators with respect to the chemical and mechanical properties of concrete and effect of the ingredients on the behaviour of concrete, thorough literature survey shows that gaps of knowledge exist on fresh concrete temperature, especially in on-site concrete production system. In this paper, the thermal parameters of the concrete ingredients are investigated separately and the effect of each component and interaction with the ambient temperature is detailed. Batching plant is the only stage in which control can be applied on the produced concrete. Hence the focus in this study is on the effect of batching plant system on the concrete component temperature, and the influence of the components of the batching system on the concrete temperature. The results of the measurement of the temperature of concrete and concrete constituents are provided in a batching system. Finally, an example of a real case batching plant is brought up. The research suggests a more accurate estimation of the concrete temperature for manual medium-sized batching plant systems. By collecting and recording the weight and the thermal data of the aggregate, concrete and water, the fresh concrete temperature is reached at the batching plant output.

2. Material and methodology

In order to evaluate the quality of the material used in this experiment, several tests were carried out. Table 3 shows the summary of the conducted tests for quality control of the materials. In the first steps, several chemical and physical analyses were conducted on concrete constituents. The particle size gradation was in accordance to ASTM/C136-01, which represents the sieve analysis of the fine and coarse aggregates [16]. Degradation of the resistance was determined using ASTM/C131 for large size coarse aggregate [17]. The soluble sulphate content of the fine and coarse aggregates was determined according to ASTM/C1524 [18]. Accordingly, an investigation was made to study the potential harm of the organic impurities included in the aggregate according to ASTM C40 [19]. The potential alkali reactivity test according to ASTM C1260 was made on aggregates [20]. The test was made using the type I Pozzolan Portland cement of Oromieh factory (Iran) with maximum pozzolan content of 15%.

The concrete samples were made using the mix shown in Figure 1. The specific gravity and fineness modulus of sand are 2.51 and 3.12, respectively. The maximum aggregate size was 25.4 mm. To provide the required water-to-cement ratio (W/C) of 0.35, super-plastizer was used. The data are collected from a half-cube meter batching plant during a six-month period. The collected variables include temperature, weight and moisture content of fine and coarse aggregates, cement’s temperature and weight, mixing water temperature and weight, temperature and weight of micro silica and added water to micro silica, specific gravity under a saturated surface-dry condition (SSD) of aggregates. The view of the batching plant is shown in Figure 2.
ACI 306R-10 has proposed a formula based on heat balance equilibrium of the concrete material to calculate pre- and post-mixing temperature of the concrete. The weights, temperature of the constituents as well as the moisture content of the aggregates are used in this equation.

\[
T = \frac{0.22(T_cW_c + T_sW_s + T_wW_w) + T_cW_c + T_sW_s + T_wW_w}{0.22(W_c + W_s + W_w) + W_c + W_s + W_w}
\] (1)

Where \(T_c, T_s, T_w\) are temperature of concrete, coarse aggregate, cement, fine aggregate, mixing water, respectively. \(W_c, W_s, W_w, W_{sw}, W_{sw}\) are weight of SSD of coarse aggregate, cement, SSD of fine aggregate, mixing water, free water on fine aggregate, and free water on coarse aggregate, respectively. The specific heat of the cement and aggregates are assumed 0.22 kcal/(kg C).

3. Experimental results and discussion

In the following the results of the experimental case study for evaluation of the concrete constituents as well as the test carried out on the concrete are presented. Furthermore the temperature variation of the fresh concrete is discussed as possible reasons for variation of the temperature in the after mix concrete is discussed.

3.1. Material tests

Figures 3-4 show the grading results of the aggregate obtained from sieve analysis. The maximum expansion of the aggregates in the concrete samples at the age of 4, 7 and 16 days was 0.016, 0.04 and 0.112, respectively, which means the potential alkali reactivity of the aggregates was not significant. The fineness modulus of the fine aggregate is 3.79 with a specific gravity of 2.602 and silt and clay content of 0%. The results show that using silica fume has effectively improved the concrete mixture to recover the loss of required finer particles in sand.
In order to analyse the quality of the constituent material in the concrete, several tests have been conducted that are shown in Table 3.

**Table 3.** Materials and their conformance to the specifications and codes

| Material          | Code and specification | Reference | Subject                    | Test results                                | Frequency          |
|-------------------|------------------------|-----------|----------------------------|---------------------------------------------|--------------------|
| Cement            | ASTM C595              | [21]      | Cement standard tests      | Fineness: 3588 (cm²/gr)                     | Each shipment/     |
|                   |                        |           |                            | Setting time: 107 and 220                   | every 1000 ton     |
|                   |                        |           |                            | for initial and final, respectively         |                    |
|                   | ASTM C204              | [22]      | Cement test                | Autoclave expansion: 0.05                   |                    |
| Micro silica      | ASTM C1240             | [23]      | Micro silica test          | Checking of the product data sheet          | Every shipment     |
| Aggregates        | ASTM C33               | [24]      | Concrete technical         | Checking of the product data sheet          | Every source       |
|                   | ASTM/C136              | [25]      | sieve analysis             | Fulfilled                                   |                    |
|                   | ASTM/C117              | [26]      | Material passing the       | -                                           | Every two week     |
|                   | C1524                  | [18]      | 0.075mm                    | Figure 3 and 4                              | Every month        |
|                   | C131                   | [18]      | Abrasion                   | 0.003%                                      | Change of material |
|                   |                        |           |                            | 19.95%                                      | source             |
|                   | C127                   | [27]      | Specific gravity           | 2.602 gr/cm³                                | Every month        |
|                   | C123                   | [28]      | Lightweight particles in   |                                            | Every month        |
|                   | C142                   | [29]      | Clay lumps and friable     | 0%                                          | Every month        |
|                   | C127                   | [30]      | Water absorption           | 0.855%                                      | Every two weeks    |
|                   | C40                    | [19]      | Organic Impurities         | 0%                                          | Every month        |
|                   | C88                    | [31]      | Weight loss during         | 0%                                          | Every change in    |
|                   |                        |           | sulphate                   |                                             | source             |
| Water             | ASTM D516 and AASHTO   | [32,33]   | Test for quality of water  | SO4, ppm 1000; Cl, ppm 500; Compressive     | Every new source   |
|                   | T26                    |           |                            | strength; Time of set                        |                    |
| Super plasticizer | ASTM C 494/C           | [34]      | Chemical Admixtures for    | As per data sheet                           | Each shipment      |
| (SF40)            |                        |           | concrete                   |                                             |                    |
| Concrete          | ASTM C1260             | [20]      | Expansion                  | Expansion of 0.016, 0.04, and 0.112 in 4th,| Every new source   |
|                   |                        |           |                            | 7th and 16th, respectively.                |                    |

Figure 3. Sieve analysis of the aggregates (a) coarse aggregates (b) fine aggregate
The chemical composition of the cement and water are important in hydration heat release and the heat convection parameters of the concrete. Table 4 shows the chemical composition of the used cement and water in the experiment.

**Table 4.** The chemical composition of the cement and water used in the experiment

| Compound     | Amount | Compound                           | Amount          |
|--------------|--------|------------------------------------|-----------------|
| SiO₂         | 26.83  | Total Dissolved Solids (TDS)       | 267 mg/lit      |
| Al₂O₃        | 5.25   | Turbidity                          | 0.6 NTU         |
| Fe₂O₃        | 2.80   | PH                                 | 7.9             |
| CaO          | 58.97  | Salinity                           | 0.3%            |
| MgO          | 1.88   | Conductivity                       | 558 K₂O         |
| Na₂O         | 0.59   | Hardness                           | 320 mg/lit      |
| K₂O          | 1.02   | Alkalinity test with phenolphthalein (P-ALK) | 0 |
| SO₃          | 1.75   | Alkalinity test with methyl orange (M-ALK) | 280 |

3.2. *Analysis of the temperature data*

Figure 4 shows the variation of the ambient temperature with the measured concrete temperature obtained from the output of the batching plant. The obtained data are collected within the period of six month in the temperature range of -3°C to 15°C. The plot of the temperature variation versus the ambient temperature is following a similar pattern as shown in Figure 4. However, the concrete temperature of the fresh concrete in batching plant output is higher than the ambient temperature and it was kept within 11°C to 23°C range.

![Figure 4. The concrete temperature versus the ambient temperature](image)

The data for the materials before mixing includes the weights, temperature of the constituents and the moisture content of the aggregates as well as after mixing data including the final temperature of the produced concrete are recorded for this experiment. The after mixing temperature of the produced concrete was calculated for all available samples. The recorded temperature obtained from the site measurement of the batching plant output and the value calculated from the recorded weight, temperature and moisture of the constituent using the Eq. (1) are plotted for the comparison purpose. Figure 5 shows the results for calculated and actual results of the concrete.
As shown in Figure 5, there is discordance between the results obtained from the actual concrete temperature and the values obtained from Eq. (1). For both plots, the pattern of the trend are similar but the values obtained using ACI 306R-10 tend to be almost 3°C lower in the concrete samples than their actual temperature. A concrete sample C35 with zero silica fume was also used to confirm the results obtained by C55 concrete. It is shown that there is not a significant change in the results obtained from both concrete mixtures in the final temperature using Eq. (1). In the following subsection an investigation is conducted to illuminate the discrepancy obtained from the results using two methods.

3.3. Discussion on the results

As shown in Figure 5, the actual temperature of the concrete is higher than the calculated value using Eq. (1). It can be observed from the figure that the variation is independent of any of the variables presented in Eq. (1) including weight, moisture and temperature of the constituent material. The possibility of such a variation in temperature was also mentioned in other references such as [3,35,36]. The offset of almost 3°C in the trends of the plots supports involvement of other thermal parameters in the system. The discordance in the measurement and the calculated values of the concrete temperature could be as a result of the time required for heat transfer from the aggregates, specifically coarse aggregate, to the surrounding constituents to reach a thermal equilibrium. To investigate the effect of the required time to reach thermal equilibrium, a study was conducted. Coarse aggregate are assumed as spherical shape with diameter of 15 mm. The diameter is obtained by the grading distribution of the coarse aggregates in the sieve analysis shown in Figures. 3-4. Using the lumped capacitance method for transient conduction, the time for reaching isothermal equilibrium after imitation of exothermic reaction can be calculated. In the first step, the Biot number is calculated for the thermal system using Eq. (2). The Biot number is defined as the ratio of conduction resistance to convection resistance and imply that the external resistance associated with convectional heat transfer is dominant [37].

\[ B_i = \frac{hL}{k} \]  \hspace{1cm} (2)

Since the calculated Biot number is less than 0.1 the lumped capacitance method is valid for the present setup [38]. The required time to reach bulk fluid temperature can be calculated using Eq. (3),

\[ t = \frac{\rho V_c}{hA_s} \ln \frac{\theta_i}{\theta} \]  \hspace{1cm} (3)

Where \( \rho \) and \( V_c \) are density and volume of the assumed coarse aggregate, respectively. \( h \) and \( A_s \) are the convection heat coefficient of the concrete and outer surface area of the assumed coarse aggregate, respectively [39]. \( \theta_i \) and \( \theta \) are the difference between initial object temperature \( T_i \) and bulk fluid temperature \( T_\infty \) and difference between object temperature \( T \) and bulk fluid temperature \( T_\infty \).
at time $t$. The temperature of the coarse aggregates gradually increases to reach the bulk concrete temperature. Using Eq. (3) the required time for the constituent materials to reach the isothermal temperature is calculated. In 705 seconds all constituent materials reach after mix isothermal temperature. On the other hand, the required operation time for charge, mixing, sampling and temperature measurement in a batching plant specification is shown in Table 5. As shown in Table 5, the initiation time of the process till the temperature measurement of the produced concrete is almost 310 seconds. The obtained data shows that the operation time is lower than the time required to isothermal temperature. As a result the recorded temperature is accordingly lower than the one obtained from the temperature of the constituent in thermal equilibrium. The result can demonstrate the variation of the before mix and after mix temperatures.

| No. | Task name                                           | Duration (second) |
|-----|----------------------------------------------------|-------------------|
| 1   | Charging and mixing of the concrete constituents   | 90                |
| 2   | Discharge the mixer                                | 10                |
| 3   | Sampling and transfer for testing.                 | 20                |
| 4   | Concrete temperature measurement (2-5 min based on ASTM 1064) | 190               |
|     | Total                                              | 310               |

On the other hand, the obtained thermal offset might be due to other reasons amongst which probably the most important is development of hydration heat. Hydration heat is greatly contributed to the chemical compounds of the concrete constituents. Although, in this experiment, using pozzolanic cement in concrete mixtures can slightly decrease the peak amplitude of temperature and delay the temperature rising profiles, the variation is insignificant in the temperature of Portland pozzolanic cement [36]. Furthermore, the researches show that the influence of the silica fume in hydration heat is negligible [36]. Eq. (1) is based on the thermal balance among constituents in the whole medium with the assumption that all phases of the material are in thermal equilibrium. In the above assumption the effect of parameters such as hydration heat, viscous dissipation and mechanical work is neglected [3,40]. Even though the equation is obviously not sufficiently accurate to predict the after mixing concrete temperature with a high degree of confidence, it does provide a substantial insight into the output temperature. In order to obtain a more accurate estimation of the temperature it is necessary to include the effect of those missing factors in the equation. Accordingly, a nonlinear regression was performed to derive constants of the equation from the experimental data. Figure 6 shows the plot of the nonlinear regression of the data.

Figure 6. Plot of the nonlinear regression of the experimental data and data from Eq (4)
Based on the findings of the nonlinear regression a modified equation is derived by combining the Eq. (1) and the extracted constants as per below.

\[
T = \frac{0.22(T_w W_w + 0.45T_s W_s + T_c W_c) + T_L W_L + T_a W_a + W_w + W_s + W_c}{100}
\]  

(4)

The results indicate that the proposed equation is capable of estimating the actual temperature with a higher accuracy than the original one. This study deals with a specific mix design of concrete [41-42]; however future study need to expand the scope to cover more other mix designs [43].

4. Conclusions

Controlling of the before-mix temperature of the concrete constituents is a simple solution to the quality problems raised by temperature inconsistencies in concrete. Several methods are introduced for controlling of the concrete temperature to the pre-determined profile in practical applications that include heating or cooling of raw materials and providing suitable curing condition. The after mixing temperature of concrete can be estimated by analysis of the before mixing temperature and weight of the constituent material as well as the moisture contents of the aggregates. ACI 306R-10 has presented an equation to calculate the concrete temperature based on thermal equilibrium of the constituents. In a case study, the data of a batching plant was collected for 120 different batches within six-month period. The required quality control tests are carried out for the concrete constituents and the output concrete of the batching plant. The result was checked by the acceptance criteria introduced by the presented standards and specification. In the next step the recorded data for the temperature, moisture and weight of the materials was put into the equation introduced by ACI to check the after mix concrete temperature. It was seen that there is a gap between the measurement of the actual temperature of the batching plant output and the calculation of the value obtained by the proposed equation. To study the reason for such a variation in the results, the heat parameters was investigated and potential reasons for the discordance were discussed. Finally, the relation between the measurement and calculation results is given by a nonlinear regression. An equation is introduced to calculate the after mix temperature of concrete with a better accuracy and precision. The obtained results show that the obtained equation can estimate the fresh concrete temperature with higher accuracy.

5. References

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