Model to Predict Plastic Shrinkage Cracking of Freshly Placed Concrete

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Abstract: This paper presents a statistical model that can predict occurrence of plastic shrinkage cracking of freshly placed concrete based on the bleeding water of concrete and environmental conditions to which the concrete is subjected. In the analysis, simplified version of Menzel's formulae is used in estimating the evaporation rate based on the environmental conditions while self-weight consolidation model is used in estimating the bleeding of concrete. Test results of occurrence or nonoccurrence of plastic shrinkage cracking of 48 specimens of different concrete mixes tested under different environmental conditions (evaporation rate) are used in developing a binomial logistic regression model for the prediction. Resulted formulae indicate over 95% confidential interval accuracy in predicting occurrence of plastic shrinkage cracking of concrete. The two-variable used in the prediction, bleeding of concrete (mixing variable) and environmental conditions (evaporation rate) have shown strongly correlated for the occurrence of plastic shrinkage cracking of concrete.

Keywords: Plastic Shrinkage Cracking, Evaporation rate, Bleeding of concrete, Regression model

1. INTRODUCTION

Plastic shrinkage cracking, though, is not considered to have significant influence on the structural behavior, nonetheless, present a server threat to the durability performance of concrete structures. Shrinkage of the paste during the plastic stages mainly due to evaporation of surface water causes concrete surfaces to dry significantly with respect to the underlying concrete layers that are still under wet conditions. Restrain provided by the underlying layers to the shrinking layers on the top develop strain gradient across the section causing tensile stress to develop on the surface of concrete. If the concrete has not developed sufficient strength at the time of drying, occurrence of plastic shrinkage cracking become inevitable. As drying is primary requirement for cracking plastic shrinkage cracking can is only possible after the evaporation of the surface water. Often plastic shrinkage cracks occur parallel to each other running into several feet or as randomly orientated cracks (polygonal) of few centimeters. These cracks are usually wide at the top of the surface and considered shallow and confined only to the dry layers that has not developed sufficient strength at the time of crack development. However, there are records of deep cracks due extreme evaporation conditions and unfavourable material usages and cracks that were originally developed as shallower and narrower shrinkage cracks to develop as wide open cracks due to subsequent buildup of drying shrinkage strain on them. There are also records of fully penetrating shrinkage shrinkage cracks.

Fig. 1 shows the schematic view of cumulative bleeding water accumulated on the surface and drying due to constant evaporation rate. Intersection of the two curves is known as air entry point. It is after this air entry point that concrete drying will start and surface tension will start to develop. Drying due to evaporation cannot be supported indefinitely by bleeding water. This is why, complementing bleeding water by early curing, covering up the concrete and use of curing agent to reduce evaporation have become effective means to mitigate shrinkage of cracking of concrete. Developing sufficient surface tension at the point of air entry is another effective means to mitigate plastic shrinkage cracking. It has been found that the use of fibers reinforcements like acrylic fibers can strengthen drying surface and mitigate effects of plastic shrinkage cracking. It should now be clear that strength of concrete paste and local straining sustained due to restrained conditions are other two important consideration for the plastic shrinkage cracking of concrete. However, modeling all these interrelationships identified as bleeding, evaporation and tensile strength development and strain development in the paste due to
restrain conditions at the air entry point, to predict plastic shrinkage cracking is considered enormously difficult task. In this study 48 different concrete samples subjected to different environmental conditions under restrained conditions to simulate actual site conditions were tested for occurrence or non occurrence of plastic shrinkage cracking. Results were then used in binomial logistic regression model to make predictions for plastic shrinkage cracking. Bleeding water of the mix and evaporation rates are considered independent variables of the model while plastic shrinkage cracking of the testing samples is considered the dependent variable in formulating the regression relationship for plastic shrinkage cracking. Although, it is not apparent tensile strength have been accounted, it can be argued that that since the model uses presence and absence of plastic shrinkage cracking of the 48 test specimens to calibrating the statistical model tensile strength is invariably accounted in the prediction.

![Figure 1 Schematic View of Concrete Drying Process](image)

1.1. Evaporation

As described in the previous chapter evaporation is one of the main variable considered for the prediction. There are many hydrological models to evaluate surface water evaporation. Bleeding water evaporation from the surface of concrete is considered no different pan evaporation. Menzel's formula and derivation of it with vapor pressures replaced by surface temperature and air temperature is preferred choice for the evaporation of bleed water from the concrete surface. Although it is usual to consider the surface temperature and air temperate to be identical, formulae provide option to consider different surface temperatures when surface record higher temperature to atmospheric temperature as a result suns radiation or excess energy deliberated by the hydration heat. The simple equation that was introduced by Uno with vapor terms replace by temperatures is given below. This is the same formulae that is currently being recommended by the American Concrete Institute’s (ACI) recommendation as single variable to control cracking. Figure 2 shows a chart developed by Precast Association (PCA) and published by ACI which is popularly used in the practice to calculate the rate of evaporation. However, it must be noted that this can only predict the relative magnitude of the environmental conditions to cause plastic shrinkage cracking in concrete mixers and not the real potential for plastic shrinkage cracking of concrete which is greatly influenced by the by both the properties of concrete mixers and evaporation. Nonetheless experimental investigation strongly suggested that this formulae is quite capable of handling the evaporation of bleeding water from the surface of concrete as long as water is available at the surface including early age of drying when no visible surface water happen to exist.

\[ E = 5 \times 10^{-6}(V + 4)[(T_c + 18)^{25} - \left(\frac{R_h}{100}\right)(T_c + 18)^{25}] \quad \text{Equ. (1)} \]
1.2. Bleeding

The accumulation of water over a period of time at the surface of freshly mixed cement paste, mortar, or concrete is known as ‘bleeding’. This is considered by many as one of the major factors that influence the occurrence of plastic shrinkage cracks of freshly placed concrete and thus the major contributor to plastic shrinkage cracking. Bleeding water accumulated on the surface depends largely on the mixing variables and the thickness of the slab or surface area to concrete volume ratio. It seems that current standards on plastic shrinkage cracking either overlook bleeding water accumulated on the surface or assumes certain minimum water would anyway be available on the surface. However, experimental investigations have shown that the bleeding water depends on the mixing variables and is most of the time become less than the evaporation rate of most of the tropical climatic conditions at times plastic shrinkage cracking is considered is most likely. In this study bleeding water is considered the other main variable, aside evaporation of surface water in the prediction of the plastic shrinkage cracking of concrete. There are different model to predict bleeding water of concrete explained based on mixing variable and among them self-weight consolidation model is shown to predict the initial bleeding and subsequent cessation of bleeding more effectively than the sedimentation based models. Detail of the derivation of self-weight consolidation model can be found elsewhere. Equation (1), Equation (2) and Equation (3) below provide the numerical solution of the self-weight consolidation model based on finite difference method.

\[ h_0 = h_{eq} - \int_0^{z_0} [1 + e(z,t)] \, dz \]  

Where \( h_0 \) is the initial height of the cement paste, \( h_{eq} \) is equivalent height of the cement paste, \( e(z,t) \) is the void ratio at time \( t \)

The \( \beta \) and \( K_0 \) in the above equation depend on the mixing variables and slab thickness is governed by the rate and amount of bleeding. After a comprehensive experimental study encompassing all mixing variables including W/C ratio, aggregate influence, cement type and slab thickness \( \beta \) and \( K_0 \) for given mix is expressed with respect to reference mix is given in the equation (4) and (5). Subscript of the coefficients of variation referred the mixing variables considered in the analysis which include water cement ratio, relative fineness of fine aggregates, relative coarse fraction, thickness of the slab, and Cement type.
3.1. concrete to mixing variables on plastic shrinkage cracking of concrete. 

Table 1, along with the results of the model was conducted to aggregate, mixing the include rates conditions based concrete different The experimental investigation of this study involves testing mixers of different mix proportions and validating the model it is found that the formulated logistical regression model can predict occurrence environmental conditions both have significant influence on the plastic shrinkage cracking of concrete. 

3. METHODOLOGY

The experimental investigation of this study involves testing mixers of different mix proportions under different evaporation rates. Changing mixing variable primarily involve changing the bleeding rate of concrete and early strength development. Mixers were then tested under different environmental conditions based on actual records of the different environmental parameters simulating evaporation rates between 0.3 kg/m² to 1.2 kg/m². The main variable considered for mixing in the investigation include W/C ratio, Cement content, workability, and cement type while for the environmental conditions different combinations of air temperature, humidity and wind velocity was used. To explain the bleeding water based on mix variables, a separate study was conducted to find the influence of mixing variable on bleeding water. As w/c ratio, water content, cement type and fineness of fine aggregate, coarseness of coarse aggregate and slab thickness of the concrete mix is considered to influence bleeding water collected on the surface, the standard test for determine the bleeding water was conducted to formulate the bleeding water of concrete mixes based on self-weight consolidation model.

3.1. Experimental Setup

Table 1, along with the results of the lowest evaporation rate at which the particular mix has sustained plastic shrinkage cracking, shows the different mixes that have been tested to identify the effect of mixing variables on plastic shrinkage cracking of concrete. In table one mixes are arrange according to the main variables studied that include Cement type, W/C ratio, Workability and Thickness of the concrete cast. Two slab thicknesses; 100mm; 150mm, three cement types; Ordinary Portland.

\[ K_0 = K_{o,ref} \cdot \lambda_{Ko,w/c} \cdot \lambda_{Ko,ff} \cdot \lambda_{Ko,crs.frac} \cdot \lambda_{Ko,H} \cdot \lambda_{Ko,cem} \]
\[ \beta = \beta_{ref} \cdot \lambda_{\beta,w/c} \cdot \lambda_{\beta,ff} \cdot \lambda_{\beta,crs.frac} \cdot \lambda_{\beta,H} \cdot \lambda_{\beta,cem} \]

Coefficient of correlation \( \lambda \)'s for \( \beta \) and \( K_0 \) found by calibration of test experimental results for each of the variable are shown equation (6) to (16). Full details of the determination of these coefficient can be found elsewhere.

\[ \lambda_{Ko,w/c} = 0.0102e^{0.0792 w/c} \]
\[ \lambda_{Ko,H} = 0.0052H-0.0298 \]
\[ \lambda_{Ko,crs.frac} = 0.0542(\text{Agg size})+0.125 \]
\[ \lambda_{Ko,cem} = 0.1422e^{0.0049.cem} \]
\[ \lambda_{Ko,ff} = -0.0077.ff + 1.3209 \]
\[ \lambda_{\beta,w/c} = 103.89e^{-0.08 w/c} \]
\[ \lambda_{\beta,H} = 0.0056H+0.1989 \]
\[ \lambda_{\beta,crs.frac} = -0.029(\text{Agg size})+1.4702 \]
\[ \lambda_{\beta,cem} = 537.6e^{0.015.cem} \]
\[ \lambda_{\beta,ff} = 0.0155.ff + 0.088 \]

2. RESEARCH SIGNIFICANCE

Current recommendation for the prediction of plastic shrinkage cracking is based only on evaporation rate only. Although there are numerical approaches, it is extremely time consuming. The results of numerical solutions doesn’t necessarily warrant reliable prediction due to complications in modeling due to unavailability of reliable data for critical parameters for the plastic state of concrete. Solution procedure outlined in this paper present binomial logistic regression analysis based solution for the prediction of plastic shrinkage cracking. Basic variable consider in the analysis include both the evaporation and bleeding. This also include data from 48 number of mixes subjected to different environmental conditions with occurrence or non-occurrence of plastic shrinkage cracking. After validating the model it is found that the formulated logistical regression model can predict occurrence and non-occurrence of plastic shrinkage cracking at 95% accuracy and that the bleeding water and environmental conditions both have significant influence on the plastic shrinkage cracking of concrete.
cement; Fly ash; Portland limestone cement, three w/c ratios; 0.45; 0.55; 0.65; and three Cement content; 350kg/m³; 400kg/m³; and 450kg/m³; are considered in the experimental investigation. All mixer designation were tested for evaporation rates 0.3 0.6. 0.9 and 1.2 kg/m²/hr. making the total number of mixes test 48. Names given in the table identify variables involved in the mix starting from w/c ratio, cement content, thickness and the cement type. For example the W/C-0.55 /400 kg/m³/100thk /opc means that this mix is having water cement ratio of 0.55, 400 kg/m³ of OPC cement for 1m³ of concrete and is cast into 100mm thick slab. Testing arrangement used in the investigation is shown in Figure 2. Experiment was conducted in specially designed environmental chamber that can regulate evaporation rate by regulating temperature, humidity, and wind velocity. All specimens were subjected to 250W/s radiation using incandescent light. Details of the concrete mold with arrangement to introduce cracks are shown in Fig. 3.

Table 1 Mixer designation and their minimum evaporation rate at which cracks recorded.

<table>
<thead>
<tr>
<th>Code</th>
<th>Variable</th>
<th>Evaporation Rate at which It Cracks</th>
<th>Possibility of cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C-0.55/400 kg/m³/100thk/opc</td>
<td>Cement type</td>
<td>0.9ER</td>
<td>PLC&gt;OPC&gt;FLY-ASH</td>
</tr>
<tr>
<td>W/C-0.55/400 kg/m³/100thk/plc</td>
<td>w/c ratio</td>
<td>0.6ER</td>
<td>Higher w/c ratio reduces potential</td>
</tr>
<tr>
<td>W/C-0. 55/400 kg/m³/100thk/fly ash</td>
<td>Workability</td>
<td>1.2ER</td>
<td>Higher cement content reduces potential</td>
</tr>
<tr>
<td>W/C-0. 65/400 kg/m³/100thk/opc</td>
<td>Slab thickness</td>
<td>0.6ER</td>
<td>Higher thickness reduces potential</td>
</tr>
<tr>
<td>W/C-0. 55/400 kg/m³/100thk/opc</td>
<td>Slab thickness</td>
<td>0.6ER</td>
<td>Higher thickness reduces potential</td>
</tr>
<tr>
<td>W/C-0. 45/400 kg/m³/100thk/opc</td>
<td>Slab thickness</td>
<td>NO CRACK</td>
<td>Higher thickness reduces potential</td>
</tr>
</tbody>
</table>

Figure 2  Actual experimental set up

Figure 3  Dimension and detail of the concrete mold
4. RESULTS AND ANALYSIS

Table 1 shows the summary of results of experimental investigation based on the lowest evaporation rate at which the cracks have developed in the mix. Results indicate that the higher cement content at constant water cement ration, higher slab thickness reduces potential of plastic shrinkage cracking same w/c ratio at different cement content is indifferent to plastic shrinkage cracking. Comparing cement type blended cement with 15% replacement of clinker with fly ash is found considerably better than OPC while PLC with 15% limestone is considered mostly vulnerable for plastic shrinkage cracking of concrete.

Based on the test results, binomial logistic regression model with bleeding and evaporation as independent variables, cracking as dependent variable has then been developed to predict the occurrence of plastic shrinkage cracking of concrete. The value of the observational (dependent) continual variable for jth case is considered as Zj as shown in the equation 17 which in this case is occurrence of plastic shrinkage cracking.

\[ Z_j = b_0 + b_1X_{i1} + b_2X_{i2} + \cdots + b_nX_{in} \] \hspace{1cm} (17)

\( X_i \) is the jth predictor for the ith case
\( b_j \) is the jth coefficient

Probability of occurrence of plastic shrinkage cracking is given by equation 18.

\[ P_j = \frac{1}{1+e^{-Z_j}} \] \hspace{1cm} (18)

\( P_j \) is the probability the jth case experiences of the event of interest which is in this case plastic shrinkage cracking of concrete.

Table 2 shows the sensitivity analysis results of the calibrated model based on test results. Values in the Table 2 show strong correlation between dependent variable (the plastic shrinkage cracking) and its independent variables evaporation rate(ER) and bleeding rate (BV). Equation derived for the probability of cracking is shown in equation 19.

\[ \ln \left( \frac{P}{1-P} \right) = 16.969(ER) - 0.018(BV) - 8.150 \] \hspace{1cm} \text{ER- evaporation rate (kg/m}^2\text{.h)}

\[ P = \frac{e^{16.969(ER) - 0.18(BV) - 8.150}}{1+e^{16.969(ER) - 0.18(BV) - 8.150}} \] \hspace{1cm} \text{BV- bleeding volume (ml)}

<table>
<thead>
<tr>
<th>Variables</th>
<th>B</th>
<th>Sig.</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>evaporation</td>
<td>16.969</td>
<td>.014</td>
<td>2.343E7</td>
</tr>
<tr>
<td>bleeding</td>
<td>-.018</td>
<td>.022</td>
<td>.982</td>
</tr>
<tr>
<td>Constant</td>
<td>-8.150</td>
<td>.026</td>
<td>.000</td>
</tr>
</tbody>
</table>

Table 2 Sensitivity analysis of the dependent and independent variables.
5. CONCLUSIONS

Combining evaporation with bleeding based on binomial logistic regression model show 95% accuracy in predicting plastic shrinkage cracking of concrete. Based on observed test results, it is suggested that the current ACI standard recommendation of 1 kg/m²/hr is grossly inadequate as precautionary measure against plastic shrinkage cracking. If one requires precautionary measure based on evaporation rate along, 0.5 kg/m²/hr evaporation rate is considered more appropriate. This study has also identified that evaporation based on Menzel’s formula and bleeding based on self-weight consolidation model is accurate in modelling the two main independent variables of plastic shrinkage cracking of concrete. Binomial logistic regression formulae derived in this study (equation 19) with the cut-off probability of 0.5 and above, proved to be reliable method to predict plastic shrinkage cracking of concrete.

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