ESTIMATION OF $\delta T$ INPUT FOR JPCP DESIGN USING THE MEPDG

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ABSTRACT

In recent years, highway agencies have focused on adopting pavement design practices that meet agency-specified performance requirements. The American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide, Interim Edition (MEPDG) uses various material property inputs as well as construction and design feature inputs to predict performance. The permanent curl/warp equivalent temperature difference, commonly referred to as \( \Delta T \) or \( \Delta \delta T \) in rigid pavement design, is a critical input to the jointed plain concrete pavements (JPCP) design procedure, and is often difficult to estimate for a given project. The magnitude of the \( \Delta \delta T \) procedure is considered to vary with the paving weather, mix design and pavement design features. During the calibration of the MEPDG JPCP distress models, the value of the \( \Delta \delta T \) parameter was set at -10°F. While it is recognized that this assumption is not necessarily accurate for all conditions (or all projects), this was considered the optimum value yielding the closest match to field performance. This paper presents the development of a predictive model to estimate this key JPCP design parameter for a given project based on portland cement concrete (PCC) material index properties, pavement design features, and local climate parameters. The JPCP \( \Delta \delta T \) negative gradient was found to increase with an increase in temperature range at the project location for the month of construction and slab width, and also with a decrease in slab thickness, PCC unit weight, w/c ratio, and latitude of the project location. This model is valid only for use with the MEPDG Version 1.1 that was utilized in the \( \Delta \delta T \) model development.

Keywords
Rigid pavement design, MEPDG, JPCP distress prediction, climate effects, \( \Delta \delta T \), curling and warping
INTRODUCTION

The MEPDG developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A (ARA, 2004), and subsequently improved under NCHRP 1-40 A&D (ARA 2006), allows users to model the effects of project-specific climate, traffic loads, materials, design features, and construction practices mechanistically to predict pavement performance based on distress models calibrated with field sections. A majority of the field pavement data and performance data were obtained from the long term pavement performance (LTPP) database. The MEPDG is considered a significant improvement over current pavement design procedures (such as AASHTO 1993, 1998) and in November 2007 received the status of an AASHTO Interim Standard. The MEPDG Manual of Practice (AASHTO, 2008) and Local Calibration Guide (ARA, 2008) developed under NCHRP 1-40B provide guidance to State highway agencies (SHAs) that are considering implementation of the MEPDG. It is expected that SHAs will adopt locally calibrated distress models that are representative of their specific materials and design conditions.

As agencies evaluate the MEPDG and streamline efforts for implementation, the need for a wide variety of materials and design inputs is being constantly recognized. SHAs continue to face challenges in estimating material parameter inputs and understanding their impact on pavement performance. MEPDG offers the option of using level 2 inputs obtained from correlations between the primary inputs (Level 1 measured) and other parameters that are material-specific or are measured through simpler tests (ARA, 2004, 2006; AASHTO, 2008). Likewise, in JPCP design, the permanent curl/warp gradient, i.e. the $\delta T$ parameter, varies by project and is typically considered a function of the paving weather conditions, the hydration and setting properties of the PCC mix, and the design features that include the base frictional characteristics as well as the slab geometry. Since the magnitude of this parameter is not readily available during the national calibration process, this parameter was set to a value of -10 °F. The selection of this constant value was based on a very careful evaluation of the distress models and was primarily based on optimizing model predictions relative to field observations (ARA, 2004). Given the extent of information available at the time, there were no other practical alternatives. However, based on the distress model calibration developed, it is now feasible to quantify the errors in performance prediction and readjust the $\delta T$ to minimize field performance prediction errors. The readjusted $\delta T$ can be correlated to project-specific independent variables to develop a $\delta T$ model.

This paper presents the first attempt to derive an improved method to estimate $\delta T$ through a level 2 correlation model. This model was developed as a function of materials, construction climate and design parameters. The model utilizes data specific to all calibration sections (current as of the LTPP Standard Data Release Version 23.0) as well as data generated through multiple runs of the MEPDG software program for each project. Therefore, the model developed is confined for use with the specific distress calibration model as will be evident in this paper. While the model presented in this paper was developed using the MEPDG software program version 1.1, the paper also presents a procedure that can be adopted for future revisions of the MEPDG or for use in local calibration procedures.
SIGNIFICANCE OF \( \Delta T \) IN JPCP DESIGN USING MEPDG

Temperature and moisture variations through the PCC slab are considered in the calculation of the accumulated damage over the design life. Moisture/shrinkage gradients are considered through an equivalent temperature gradient. The gradients used in the analyses include a “permanent” component and “transitory” (hourly and monthly) component. A transitory curl/warp includes the effect of the Enhanced Integrated Climatic Model (EICM) computed hourly temperature profiles through the PCC slab and through changes in moisture content in the top of the slab due to changes in relative humidity. The permanent curl/warp, also modeled through an effective temperature difference through slab, and commonly referred to as the \( \Delta T \), is considered to account for the permanent curl/warp locked into the slab. Typically, the \( \Delta T \) has a negative value indicating that the locked in effective temperature gradient produces a slab deformation that causes the corners of the slab to curl upwards. The concept of built-in gradients or permanent curl/warp gradients has been discussed in several recent publications (Armaghani et al., 1987; Yu et al., 1993, Rao et al., 2001). The permanent curl/warp gradient, \( \Delta T \), develops over a short period of time after the initial paving and is affected by the following:

- Paving temperature and the temperature gradient at the time of initial set, which is affected by the heat of hydration generated as the concrete hardens and the solar radiation at the project location
- Temperature drop until the hydrating concrete reached ambient conditions, typically within 24-48 hours depending on the concrete mix used
- Strength gain characteristics of the concrete and its ability to resist deformations
- Shrinkage of the concrete which is in turn affected by the mix design, relative humidity, and wind speed at the location
- Base type, base stiffness, and the frictional resistance offered by the base layer interface
- Concrete creep effects that tend to relax the upward curl built up
- JPCP design features such as the joint spacing, dowels, etc.

Field studies (Rao et al., 2001, Wells et al., 2006) have shown that high temperatures at the time of paving, higher temperature drop during the period of concrete setting, higher shrinkage, very stiff base layers, longer joint spacing and the absence of load transfer devices tend to increase the negative value of \( \Delta T \), or causes the corners to curl upwards. The \( \Delta T \) parameter, which has been found to be very sensitive to JPCP cracking prediction, clearly is not a constant value but can vary as some of the aforementioned factors change. Note that the JPCP distress calibration models used a constant value of \(-10^\circ\text{F}\) as there was no practical means to estimate the \( \Delta T \) value for each calibration section.

BENEFITS OF \( \Delta T \) ESTIMATION

Accurate estimation of \( \Delta T \) will positively impact all aspects of pavement engineering—analysis, design, construction, quality control (QC) and quality assurance (QA), pavement management, and rehabilitation. Primarily, pavement designs can be optimized to utilize mix designs and paving seasons to provide a favorable or an allowable range of \( \Delta T \) values. Agencies could consider setting guidelines on permissible paving temperatures in their
construction specifications for typical mix designs and pavement designs. Alternatively, the same models used in the MEPDG for design and construction analyses can be used in the future management of the pavement to estimate its remaining structural and functional life. Knowing the measured values from construction, the likely range of \( \Delta T \) values predicted for a specific day of paving can be used to assist an agency in revising the expected performance of the pavement. Finally, the estimation of \( \Delta T \) can be of immense use in forensic analyses of pavements that show signs of early distresses.

MODEL DEVELOPMENT

In developing the models, a uniform set of statistical criteria were used to select independent parameters to define a relationship as well as to mathematically formulate prediction functions. The analyses examined several statistical parameters in choosing the optimal model and in determining the predictive ability of the model. In general, the optimal set of independent variables (through the Mallows Coefficient, \( C_p \)), the interaction effects (through the Variance Inflation Factor), the significance of the variable (through the \( p \)-value), and the goodness of fit (through the \( R^2 \)) were verified. The VIF and \( p \)-value were limited to 5 and 0.05 respectively.

Data Formulation Details

The following are details about the data used in the development of the model

- **Model data**: Data obtained from the 300 JPCP calibration sections, 285 LTPP and 15 non-LTPP sections.

- **Model description**: Relationship between a dependent parameter and predictor variables for dependent variable \( \Delta T \) values established by matching field performance to MEPDG predicted performance in LTPP sections used in MEPDG calibration.

- **Dependent variable type and data source**: Parameter established by trial and error for each calibration section so that predicted performance “matches” field performance for each section. The dependent variable is \( \Delta T \)

- **Independent variable type and data source**: Continuous variables from LTPP database or calibration sections.

- **Correlation**: Dependent variable generated from multiple MEPDG runs correlated to independent variables from LTPP database through simple mathematical correlation.

- **Model inference space**: Specific to MEPDG performance prediction. In other words, the MEPDG distress model calibration is built into the \( \Delta T \) predictive relationship proposed and therefore is applicable only to derive MEPDG-specific inputs. However, relative comparisons will be valid. For example, \( \Delta T \) determined from this relationship for different locations will explain the relative potential for developing excessive curling at these locations.
Generating Dependent Variable Data

Both the JPCP transverse fatigue distress model and JPCP mean joint faulting were considered for use as the basis for selecting the optimum $\delta T$ with minimized errors. However, JPCP transverse fatigue cracking prediction data correlated well with the material, climate, and design elements to develop the $\delta T$ prediction model. The procedure used to determine this value, of the dependent variable in the analysis, entailed the following steps.

**Step 1: Run MEPDG Calibration Files for a Range of $\delta T$ Values**

The transverse cracking model in the MEPDG was originally calibrated using 300 design projects at a $\delta T$ value of -10 °F (ARA, 2004, 2007). Each of these calibration files were run at $\delta T$ values of -2.5, -5.0, -7.5, -10, -12.5, and -15 °F. The number of $\delta T$ levels (six) and the range (-2.5 to -15 °F) were selected based on practical considerations of the time required to perform this analysis as well as to maintain the bounds of the predicted value within a reasonable range.

**Step 2: Compile Predicted Cracking Data for All Ages**

Field measured cracking at different ages was available for all the sections used in the calibration models. MEPDG-predicted damage and cracking data were extracted for ages corresponding to field data measurements. Table 1 shows a sample for cracking data extraction for section 01_3028.

**Step 3: Calculate Errors and Determine Optimal $\delta T$ for Each Section**

The predicted cracking for each level of $\delta T$ (as shown in Table 1) was compared against the field data to compute errors for each age. The sum of squared errors was next computed for each age and for each level of $\delta T$. Table 2 shows an example of error calculation for section 01_3028.

The minimum sum of squared error for all ages (21.56) is observed for a $\delta T$ of -10 °F in this case. The value -10 °F is therefore the dependent variable for this section. The same procedure was repeated for all 301 JPCP sections to develop a list of optimum temperatures, or dependent variables for each calibration file.

The example presented in Table 2 used a straightforward process to select the $\delta T$ value. The sum of squared errors reaches a minimum value for a value of -10 °F. However, there were cases where the sum of squared errors did not provide a clear choice for the selection of an optimal value. As shown in Table 3, scenarios A and B are assigned a value of -10 and -12.5 °F, respectively. Scenario C represents a case where the measured cracking was zero percent for all ages, and the predicted cracking also was zero at all values of $\delta T$. Scenario D represents a case where the minimum error is achieved at the bounds of the selected range (i.e., at -15 °F). A higher $\delta T$ can result in smaller errors, but the extent of data that could be appropriately included in the analyses by evaluating higher $\delta T$ values was minimal. Therefore, all cases that resulted in error trends as represented by scenarios C and D were deleted from the data set.
used for the statistical analyses. The data set used in the statistical analyses contained 147 JPCP sections.

**JPCP $\Delta T$ Gradient Model Development**

It was observed that the data generated for the dependent variable, $\Delta T$, correlated well with the material, design, and climate parameters when transformed from $\Delta T$ temperature differential to $\Delta T$ temperature gradient. This involved simply dividing the $\Delta T$ temperature differential by the slab thickness. A step-wise regression analysis and $C_p$ analyses were performed to select the variables that are correlated to the dependent variable and to select the best combination of variables to develop the model. After an iterative process to optimize the model, the equation developed to estimate the $\Delta T$ gradient variable is:

$$\Delta T/\text{inch} = -5.27805 - 0.00794 \times TR - 0.0826 \times SW + 0.18632 \times PCCTHK$$
$$+ 0.01677 \times uw + 1.14008 \times w/c + 0.01784 \times latitude$$

where

- $\Delta T/\text{inch}$ = predicted average gradient through JPCP slab, °F/inch
- $TR$ = difference between maximum and minimum temperature for the month of construction, °F
- $SW$ = slab width, feet
- $PCCTHK$ = JPCP slab thickness, inch
- $uw$ = unit weight of PCC used in JPCP slab, lb/ft$^3$
- $w/c$ = w/c ratio
- latitude = latitude of the project location, degrees

The model considers climate ($TR$, latitude), design ($SW$, $PCCTHK$), and material ($uw$, $w/c$) parameters. The model statistics are presented in Table 4. The model was developed with 147 data points and has an $R^2$ of 0.4967 percent and an RMSE of 0.3199. Table 5 provides details of the range of data used to develop the model. Figure 1 shows the predicted vs. measured for the proposed JPCP $\Delta T$ gradient model, while Figure 2 shows the residual errors. Note that the measured data here refers to the $\Delta T$ gradient determined by matching MEPDG prediction to field performance. Figure 3 shows the predicted vs. measured $\Delta T$ for the model.

Figure 4 through Figure 10 present the sensitivity analysis performed to examine the impact of varying the model parameters on its prediction. The parameters included are temperature range, slab width, slab thickness, unit weight, w/c ratio, and latitude. For each sensitivity analysis, the variable of interest was varied while holding all other variables constant at their typical values. Typical values used in this analysis were 24 °F temperature range, 12-ft slab width, 10-in slab thickness, 145 pcf PCC unit weight, 0.40 w/c ratio, and 40 degrees latitude.
The following are brief observations from these sensitivity analyses:

- For the typical values used for each of these variables, the \( \Delta T \) gradients estimated are in a very reasonable range.
- An increase in local climate temperature range increases the temperature gradient (see Figure 4). The local climate temperature range is indicative of the level of temperature drop the project location can experience. The larger the difference in the temperature between day and night (assuming paving is performed in the daytime), the larger the negative temperature gradient locked into the slab as the slab hardens within a 24-hour period.
- Wider slabs produce a larger built-in gradient (see Figure 5), as has been validated in several field studies. The total thermal expansion is larger for a longer/wider slab and, therefore, the resulting curvature of the slab induces a greater lift-up at the slab corners. The data did not show a significant effect of the slab length or joint spacing parameter.
- Thicker slabs reduce the \( \Delta T \) gradient, as shown in Figure 6. This is the expected trend, as thicker slabs, due to a greater weight, tend to restrain the corners from curling up as the concrete hardens. This figure also shows that for very thin slabs (< 8 in), the effect is reversed. The physical significance of this cannot be fully explained or supported with data. It is therefore necessary to evaluate the sensitivity to each parameter while selecting a \( \Delta T \) for each project.
- The larger unit weight of the PCC material used in the JPCP slab also reduces the magnitude of built-in gradient (Figure 7), primarily because of the restraint provided by the heavier slab during hardening.
- Lower w/c ratios have a higher rate of hydration, and therefore the PCC slab remains plastic for a shorter duration of time. Strength gain offers the slab the rigidity necessary to bear against the base and does not allow the slab corners to curl up. Therefore, lower w/c ratios tend to have higher built-in gradients, as seen in Figure 8. Further, at very low w/c ratios, the PCC mix undergoes autogeneous shrinkage, which increases the potential for higher gradients in the slab.
- Figure 9 and Figure 10 show the effect of latitude on predicted \( \Delta T \) gradients. The United States lies between 30 and 50 degrees latitude in the northern hemisphere. The full range of latitudes is covered in Figure 9. While this plot might appear to show \( \Delta T \)’s high degree of sensitivity to the latitude parameter, for routine predictions using this model, the temperature range is a critical input. In other words, a given maximum temperature in the southern US could have a much different temperature range relative to a location in the northern US with the same maximum temperature. Therefore, the latitude parameter has to be evaluated combined with the temperature range parameter as shown in Figure 10. The predicted \( \Delta T \) for several locations in the US are presented.

** USING THE JPCP \( \Delta T \) MODEL **

In using the \( \Delta T \) model, it is important to understand that the \( \Delta T \) determined is not necessarily the actual \( \Delta T \) built into the field slab. This model simply provides an input value that is most likely produce the best performance prediction.
An example illustrating the use of the JPCP \textit{deltaT} model is provided using the LTPP SPS-2 section 04_0213 located in Maricopa County, AZ, and constructed in July 1993.

The latitude, design, and material inputs required for the \textit{deltaT} prediction model can be obtained from the MEPDG inputs:

- \textit{Latitude} \: \: \: 33.45° North
- \textit{PCC thickness} \: \: \: 8.3 inches
- \textit{Slab width} \: \: \: 14 feet
- \textit{PCC unit weight} \: \: \: 145.3 lb/ft$^3$
- \textit{PCC w/c ratio} \: \: \: 0.365

The temperature range input to this model is the difference between the mean monthly maximum and minimum temperatures for the month of July from historical climate data records (as climate data included in the MEPDG). If the user does not have this information readily available, the data to compute the temperature range can be determined from the output file of the MEPDG analysis of this section. The output file (say, titled “04_0213.xls”) contains a worksheet titled “Climate” with key climate data for the specific location (or the virtual climate station created). This worksheet includes the monthly climate summary with minimum and maximum temperature by month for all years of data used under the headings “Min. Temp.(°F)” and “Max. Temp.(°F)” respectively.

For the month of July, the average minimum and maximum temperatures are 73°F and 111.7°F respectively. The difference between these temperatures is 38.7°F.

Using these inputs, the \textit{deltaT} gradient can be calculated as -1.7457138 °F/inch. For the slab thickness of 8.3 inches, this is equivalent to a \textit{deltaT} of -14.5 deg F. This value is significantly higher than the default -10 °F/inch. This input can be revised in an MEPDG file and reanalyzed to evaluate the predicted transverse cracking performance.

**ACKNOWLEDGEMENT**

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REFERENCES


### Table 1. Summary of field measured distress and predicted distress for section 1_3028.

<table>
<thead>
<tr>
<th>Pavement age</th>
<th>Measured field cracking, percent</th>
<th>Predicted cracking, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DT = -15</td>
</tr>
<tr>
<td>20.31507</td>
<td>0</td>
<td>20.8</td>
</tr>
<tr>
<td>21.84384</td>
<td>0</td>
<td>26.9</td>
</tr>
<tr>
<td>26.52329</td>
<td>4</td>
<td>48.9</td>
</tr>
<tr>
<td>28.87123</td>
<td>4</td>
<td>57.7</td>
</tr>
<tr>
<td>32.72329</td>
<td>8</td>
<td>70.1</td>
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</table>

### Table 2. Error calculations for section 1_3028.

<table>
<thead>
<tr>
<th>Pavement age</th>
<th>Measured field cracking, percent</th>
<th>Squared error calculation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DT = -15</td>
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<tr>
<td>20.31507</td>
<td>0</td>
<td>432.64</td>
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<tr>
<td>21.84384</td>
<td>0</td>
<td>723.61</td>
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<tr>
<td>26.52329</td>
<td>4</td>
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<tr>
<td>28.87123</td>
<td>4</td>
<td>2883.69</td>
</tr>
<tr>
<td>32.72329</td>
<td>8</td>
<td>3856.41</td>
</tr>
<tr>
<td>Sum of squared errors</td>
<td></td>
<td>9912.36</td>
</tr>
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</table>

### Table 3. Determining optimal \( \Delta T \).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sum of squared errors</th>
<th>( \Delta T ) at minimum error, °F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
<td>12.5</td>
</tr>
<tr>
<td>A</td>
<td>19824.72</td>
<td>420.7</td>
</tr>
<tr>
<td>B</td>
<td>5.39</td>
<td>2.6</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>12600.71</td>
<td>13032.5</td>
</tr>
</tbody>
</table>
Table 4. Regression statistics for JPCP $\Delta T$ model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>DF</th>
<th>Estimate</th>
<th>Standard error</th>
<th>t-value</th>
<th>Pr &gt; t</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>-5.27805</td>
<td>1.06943</td>
<td>-4.94</td>
<td>&lt;.0001</td>
<td>0</td>
</tr>
<tr>
<td>TR</td>
<td>1</td>
<td>-0.00794</td>
<td>0.00396</td>
<td>-2</td>
<td>0.047</td>
<td>1.86047</td>
</tr>
<tr>
<td>SlabWidth</td>
<td>1</td>
<td>-0.0826</td>
<td>0.03432</td>
<td>-2.41</td>
<td>0.0174</td>
<td>1.07141</td>
</tr>
<tr>
<td>PCCTHK</td>
<td>1</td>
<td>0.18632</td>
<td>0.0195</td>
<td>9.55</td>
<td>&lt;.0001</td>
<td>1.0642</td>
</tr>
<tr>
<td>UW</td>
<td>1</td>
<td>0.01677</td>
<td>0.00669</td>
<td>2.51</td>
<td>0.0133</td>
<td>1.22792</td>
</tr>
<tr>
<td>WC</td>
<td>1</td>
<td>1.14008</td>
<td>0.2914</td>
<td>3.91</td>
<td>0.0001</td>
<td>1.14857</td>
</tr>
<tr>
<td>Latitude</td>
<td>1</td>
<td>0.01784</td>
<td>0.0072</td>
<td>2.48</td>
<td>0.0144</td>
<td>1.85265</td>
</tr>
</tbody>
</table>

$R^2$ | RMSE | N |
--- | --- | --- |
0.4967 | 0.3199 | 147 |

Table 5. Range of data used for JPCP $\Delta T$ model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range</td>
<td>21.2</td>
<td>64.5</td>
<td>47.4</td>
</tr>
<tr>
<td>Slab width</td>
<td>12.0</td>
<td>14.0</td>
<td>12.5</td>
</tr>
<tr>
<td>PCC thickness</td>
<td>6.4</td>
<td>14.3</td>
<td>9.6</td>
</tr>
<tr>
<td>Unit weight</td>
<td>134</td>
<td>156</td>
<td>147</td>
</tr>
<tr>
<td>Water cement ratio</td>
<td>0.27</td>
<td>0.72</td>
<td>0.46</td>
</tr>
<tr>
<td>Latitude</td>
<td>27.93</td>
<td>49.60</td>
<td>39.58</td>
</tr>
</tbody>
</table>
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Figure 4. Graph. Sensitivity of predicted deltaT to temperature range during month of construction.

Figure 5. Graph. Sensitivity of predicted deltaT to slab width.
Figure 6. Graph. Sensitivity of predicted $\Delta T$ to slab thickness.

Figure 7. Graph. Sensitivity of predicted $\Delta T$ to PCC slab unit weight.

Figure 8. Graph. Sensitivity of predicted $\Delta T$ to PCC w/c ratio.
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