ENVIRONMENTAL INFLUENCES ON WARPING AND CURLING OF PCC PAVEMENT

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ABSTRACT

This research was conducted to analyze the influence of moisture content in concrete pavement slabs on warping and curling of Portland Cement Concrete (PCC) pavement. To do this, temperature and deflection data measured in an instrumented test runway pavement at the Denver International Airport [1-3] was used. Variation in temperature gradient over the slab thickness was computed and plotted against time, for both the summer and the winter. Deflections of the PCC slabs and the base layer were compared to identify gaps between the two layers caused by slab warping and curling. It has been found that such gaps physically exist and that the magnitude of the gaps varies with time as temperature gradient does. The gap magnitude at various locations within the slabs, together with the temperature gradient, was plotted on the same time scale. This has made it possible to quantify the influence of moisture gradient in the equivalency of temperature gradient on slab warping. As expected, the equivalent temperature gradient of moisture content also varies with time and is dependent on the day of the year and the hour of the day. Based on the available data, this value varies in the neighborhood of 0.10 to 0.27 (^{o}C/cm), which is about half of the maximum positive temperature gradient (when the bottom of the slab has a lower temperature than the top of the slab) in the summer and close to the maximum positive temperature gradient in the winter. The analysis has also proved the fact that the existence of moisture gradient strengthens the effect of negative temperature gradient (when the bottom of the slab has a higher temperature than the top of the slab), but weakens the effect of positive temperature gradient.

INTRODUCTION

Several factors contribute to the curling and warping of PCC pavement slabs. These include construction warping that is formed during the curing period of the concrete, curling that is caused by temperature gradient along the pavement thickness, and warping that is caused by moisture gradient along the pavement thickness. Among these three types of curling and warping, construction warping is permanent and the other two types vary daily as environmental factors change. This paper is focused on the daily changes of slab curling and warping using the measured in-situ pavement data at the Denver International Airport.

It is well known that PCC pavements warp due to the combined effect of temperature and moisture. The effect of temperature on slab warping has been discussed in detail in various technical reports [4, 5]. However, few reports are available on the effect of moisture on PCC pavements. People have realized that warping of the PCC slab can be partially attributed to the existence of a moisture gradient over the thickness of the slab. However, how much this moisture gradient could be and how much it could contribute to slab warping remain unknown due to the difficulty in moisture content measurement in concrete pavement slabs.

People have successfully used the Time Domain Reflectometry (TDR) gages to measure moisture content in soils [6, 7]. Considering the similarities in concrete and soil materials, the FAA Technical Center installed 46 TDR gages in their test runway in both the slab and the soils [1, 2]. While the reliability and calibration of the moisture content data is still under investigation, the temperature data measured using thermocouples embedded in the same slabs was found to be in pretty good quality. On the other hand, the embedded multidepth LVDT (MDD) gages in the same test slabs have made it possible to monitor the deformation of the slabs continuously.

Of the three related parameters (temperature, moisture, and slab warping), temperature has been accurately measured. The idea of this research is that as long as the status of slab warping can be defined, it is possible to quantify the influence of moisture content on slab warping, at least approximately.

During a 24 hour period on a normal day (no rain or other surface water), the shape of a PCC slab varies between upward and downward warping. Therefore, there should be two transition points when the slab is closest to its flat position. If there were no moisture gradient, such transition state would occur when temperature gradient were zero. Because moisture gradient does exist, the reason why the slab is close to flat is that the warping caused by the temperature gradient is compensated by the one in the opposite direction caused by the moisture gradient.

At this point, the moisture gradient is equivalent to the temperature gradient, which can be easily computed using the test data. It should be pointed out that the equivalency of moisture gradient to temperature gradient thus obtained is an approximate value since moisture gradient also varies with time, as does the temperature. However, this value is relatively reliable because the magnitude of moisture gradient variation is expected to be much lower than that of temperature gradient variation. In addition, this value can be used to obtain more accurate equivalency of moisture gradient once reliable moisture content data is available.

LOCATION OF THE MDD GAGES AND THERMOCOUPLES

Figure 1 shows the horizontal locations of thermocouples and MDD gages installed in the runway. In this figure, the MDD gages are numbered from 1 to 10, and the thermocouple location is depicted by the corresponding table names in the Oracle database: “TA2”, “TB3”, and “TC3”, respectively. Here the first letter of the table name represents ”Thermocouple” and the other two characters designate the horizontal location of the slab within and below which the thermocouples were embedded.

At each of the horizontal thermocouple location, either eight or nine thermocouples were embedded in the PCC slab. The eight thermocouples were equally spaced through the thickness of the slab and the additional one, if applicable, was embedded close to the top surface of the slab. Figure 2 shows the thermocouples embedded in slab B3 as an example of the vertical locations of the thermocouple arrangement. Twenty-two more thermocouples were embedded at specific depths below the PCC slab. Each MDD gage has 4 LVDT modules embedded at the following locations: mid-layer in the PCC pavement slab, the bottom of the cement treated base, the bottom of the lime-treated subbase, and 30cm (12 inches) below the top of the subgrade. The measured displacement is in terms of the relative movement between the LVDT module and the anchor, which is fixed at the depth of 3.05m (10 feet) from the top surface of the PCC slab. The exact location of the gages is listed in Table 1 and 2. This information is also available online from the Federal Aviation Administration World Wide Web site [1].

MECHANISM OF MOISTURE INDUCED SLAB WARPING

Slab concrete is usually drier at the top part than at the bottom except for when there is surface water. Similar to the definition of temperature gradient, moisture gradient is defined as the differential moisture content between the bottom surface and the top surface of the PCC slab, divided by the slab thickness. With this definition, positive moisture gradient exists when the lower part of the slab is moister than the top part, which is the normal case, and negative moisture gradient exists when the lower part of the slab is drier than the top part. When moisture gradient exists, the part of the slab with less moisture content tends to shrink, causing part of the slab to uplift. Additional stress is then induced by the moment couple formed by the support from the base layer and the self-weight of the slab.

When the PCC slabs are subject to positive moisture gradient, they tend to warp upward and tensile stresses are induced at the top of the slabs. When negative moisture gradient exists, the slabs tend to warp downward and tensile stresses are induced at the bottom of the slabs.

On the other hand, when the PCC slabs are subject to negative temperature gradient, they also tend to warp upward since the lower part of the slabs expands more than the top part of them. Similarly, tensile stresses are induced at the top of the slabs in this case. When the temperature gradient is positive, the slabs tend to warp downward and thus inducing tensile stresses at the bottom of the slabs.

Slab warping is induced by both moisture gradient and temperature gradient. The effect of warping is reduced when the two values have opposite signs, and enlarged when they have the same sign. In order to compare the effect of the two factors quantitatively, one has to be converted to the other. Since temperature gradient has been widely used and since its theory and measurement techniques are well developed, it is reasonable to convert moisture gradient to temperature gradient for analysis.

Compared with moisture gradient, temperature gradient varies with larger magnitude. During a 24-hour period, temperature gradient varies between positive values in the afternoon and negative ones during the night but moisture gradient remains positive on a normal day. Therefore, the addition of moisture gradient actually enlarges the warping effect on PCC slabs in the night and reduces it during the day.

TEMPERATURE GRADIENT

Figure 3 a) and b) show temperature gradient versus time curves. Figures 4 a) and b) were plotted for a look on how temperature gradient changes during a 24-hour period. These figures were plotted using data from the "TB3" and "TC3" tables in the Oracle database, which were collected by the thermocouples embedded in slabs B3 and C3 (Figure 2). It can be seen from the figures that temperature gradient in the concrete slab changed greatly and two zero temperature gradient occurred during a 24 hour period. The maximum temperature gradient was about 0.52 (^{o}C/cm) between August 25 and 29 1997, and about 0.31 (^{o}C/cm) between January 10 and 14 1996. Figure 4 also indicates that there is significant temperature variation in top part of the slab. The curves are not even close to be linear. This means that bilinear gradients should better approximate temperature gradients in a slab than simple linear approximations throughout the slab thickness.

GAPS BETWEEN PCC SLABS AND THE BASE LAYER

In order to quantify the effect of moisture gradient, a better understanding of slab warping is necessary. A frequently asked question is: does a PCC pavement slab really warp? If we consider the fact that slab warping is always constrained by the self-weight of the slab, the question becomes whether this constraint is strong enough to hold the slab as flat as when it was constructed. This question can be easily answered with the in-situ test data of the test runway at the Denver International Airport. As previously mentioned, each of the ten MDD gages embedded within and below the PCC slabs at the test site has 4 LVDT modules including one embedded in the PCC slab and one in the cement treated base layer. Assuming that the compressibility of the two layers can be neglected, the difference between the measured deflections of the two LVDT modules represents a gap between the two layers [8]. Gage data was analyzed for each of the three typical locations: slab interior, slab edge, and slab corner. The gap versus time curves are shown in Figure 5.

In Figure 5 the horizontal scale represents time and the vertical axis on the left side shows the magnitude of the gaps that vary with time. The gaps were computed as the relative displacement between the LVDT modules and the anchor [8]. These gap versus time curves have revealed the following facts:

- The gaps between the two layers physically exist and exhibit clear daily cycles, as do the temperature curves.
- The gap curve for the slab edge location basically follow the trend of the gap curve for the interior slab location, but is influenced by the one for the slab corner location. As expected, when the gap at the interior reaches the maximum peak, the one at the slab corner becomes the minimum, and viceversa.
- The maximum peak of the gap between the slabs and the base layer occurred between 14:00 and 16:30 at the slab interior, at about 6:30 A.M. at slab edges and corners.
- The magnitude of the maximum gap at the interior and edges of the slabs during those days was about 0.08 to 0.13 mm (3 to 5 mils). The magnitude of the maximum gap at the corners of the slabs during those days was about 0.38 to 0.64 mm (15 to 25 mils). This means that the gaps at the corner of the slabs are about 5 times of those at other locations.
- There seems always a gap between the slab and the base layer. If the interior slab is contacted with the base layer, there must be a gap at the edges and corners of the slab. For this reason, a slab is never absolutely flat since its first warping occurred.
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CORRELATION OF TEMPERATURE GRADIENT AND GAPS

Although the slab is not absolutely flat, it changes its shape between downward warping and upward warping everyday. Therefore, there should be a transition moment when the slab is close to its flat state. This transition state is the one when gaps between the PCC slab and the base layer at all the three typical locations (interior, edge, and corner) are close to zero. For this analysis, the gaps and the temperature gradient are plotted in the same figure on the same time scale, as shown in Figure 5. The following are the observations:

- The close flat state of the slab does not occur at the same time as the zero temperature gradient state does. This proves the fact that slab warping is induced by both temperature gradient and moisture gradient.
- Both the zero temperature gradient state and the close flat state of the slab occurred in daytime. The later occurred between the period of the two zero temperature gradient states. This proves the fact that moisture gradient reduces the influence of temperature gradient in daytime.

The close flat state is a typical warping state since the effect of moisture gradient should be equal to that of temperature gradient in magnitude but in the opposite direction at this moment. Hence the time when the slab is at its close flat state is determined in the figures where all the gap values are close to zero. The temperature gradient values, which is equivalent to the moisture gradient in value at this time, at the determined time was then measured in the same figure. Tables 3 and 4 show some of these measured values.

From the tables it is clear that the equivalency of moisture gradient to temperature gradient at the time when the slab was close to flat varies between 0.10 and 0.27. The larger value occurred in the late morning or early afternoon when the temperature was on the rise. The smaller value occurred in the late afternoon when the temperature was decreasing.

Notice that the above equivalent temperature gradient of moisture gradient is at the same level as the maximum and minimum daily temperature gradient. Table 5 shows the daily peak values of the temperature gradient. It can be seen from Table 5 that the high value of the equivalent temperature gradient of moisture gradient is about half of the daily maximum of the temperature gradient in the summer, and is about the same as the daily maximum of the temperature gradient in the winter. The low value of the equivalent temperature gradient of moisture gradient is about the same as the daily minimum of the temperature gradient in both the summer and the winter.

Since the high value of the equivalent temperature gradient of moisture gradient occurred in the late morning or early afternoon, which is the time when the maximum temperature gradient occurred. It is suggested that the measured or modeled temperature gradient be reduced by a factor of 0.5 when it is used to computer additional environmental stresses in the summer. The stresses thus computed are actually the ones induced by the combined effect of temperature and moisture content. For the winter case, environmental factors induced stresses are more likely compensate with each other and additional stresses hence need not be computed. On the other hand, the low value of the equivalent temperature gradient of moisture gradient can be expected to occur at the same time as the minimum temperature gradient occurred. Therefore, a factor of 2 needs to be multiplied to the daily minimum peak of temperature gradient when environmental factors induced stresses are to be computed. In this way, the contribution of moisture gradient, which is equivalent to that of temperature gradient, is considered.

By taking into account the effect of moisture gradient, both the over estimated tensile stresses at the bottom of the PCC slab when the daily temperature is high and the under estimated tensile stresses at the top of the PCC slab when the daily temperature is low can be compensated. The later situation is useful in explaining the on-site observation of corner cracking initiated from the top of the slabs.

CONCLUSIONS

This paper used the Denver test data to analyze the influence of moisture content on slab warping of PCC pavement. It was found that the equivalent temperature gradient of moisture gradient varied between 0.10 and 0.27 ^{o}C/cm. When temperature gradient is used to analyze the combined effect of temperature and moisture content, it should be multiplied by a factor to compensate the influence of moisture content. The value of this multiplier is season and time dependent, as the magnitude and direction of slab warping induced by moisture gradient do. According to the gap and temperature gradient curves, a few values of the multiplier are suggested. A multiplier of 0.5 is suggested for the measured or modeled positive temperature gradient when additional stresses at the bottom surface of the slab are to be computed for the afternoon in the summer. A multiplier of 2 is suggested to compensate the influence of moisture content when negative temperature gradient is to be considered to compute the tensile stresses at the top surface of the slab for the night in both the summer and the winter. For the winter and afternoon case, the two environmental factors compensate their influences with each other and the environmental factors induced additional stresses can be ignored.

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NOTATION

DEN --- Three letter code for the Denver International Airport

KEYWORDS

PCC pavement, concrete, moisture content, temperature gradient, airport, deflection, LVDT