Field Investigations on Temperature Differentials and Curling Strains in High Volume Fly Ash Concrete Pavement

Aravindkumar Harwalkar and Dr.S.S.Awanti

Abstract: In this study an attempt has been made to establish temperature profiles across different thicknesses for pavement quality high volume fly ash concrete (PQHVFAC) and conventional concrete (PCC). To accomplish this three small square slabs each for PQHVFAC and PCC were cast. Also two instrumented pavement test sections, one of PQHVFAC and another of PCC, were constructed adjacent to small square slabs. A total number of 32 sensors consisting of 20 thermistors and 12 number of vibrating wire strain gages have been used. Three dimensional finite element analysis (3DFE) using ANSYS software was carried out to determine the curling stresses and strains. Also parametric study using 3DFE analysis and Westergaard-Bradbury's technique was carried out. The temperature profiles across the different thicknesses of both types of concrete were non linear. The values of temperature differentials were higher for PQHVFAC than PCC. Both 3DFE and classical approaches give conservative estimate of curling strains.

Index Terms: Curling stress, Nonlinear temperature profile, Pavement quality high volume fly ash concrete, 3DFE analysis.

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1. INTRODUCTION

Nature of temperature distribution across the thickness of concrete pavement is an important factor for the design of rigid pavements. Due to temperature differential (difference in temperature between top and bottom of slab) and restrain on slab due to its weight or boundary conditions, curling stresses are induced in the pavement. Even though the thermal conductivity of the material is low, the daily variations in the temperature have got significant effect on stresses in concrete pavement. The distribution of temperature and curling stresses in rigid pavement is dependent on the material properties mainly coefficient of thermal expansion and Young's modulus of elasticity of concrete. Apart from that it is dependent on ambient conditions such as air temperature, moisture and wind conditions. Majority of literature available on measurement of temperature differential and curling stresses till date, are on conventional concrete pavement without mineral admixtures.

Study on curling stresses in conventional concrete has been carried out since 1920s. Westergaard's [1] approach based on linear temperature gradient has been widely used in estimating the values of curling stresses. Bradbury [2] developed the equations for a slab with finite dimensions using Westergaard's analysis. Nonlinear temperature distribution in concrete pavements based on field investigations has been reported in literature [3], [4] and [5]. The temperature profile has been given by 3rd order polynomial or quadratic equation in literature [6], [7] and [8].

Earlier it was reported that difference in curling stresses between that due to linear and nonlinear temperature gradient is small [9]. But pronounced effect of nonlinear temperature distribution has been emphasized in the recent literature [6], [7] and [10]. Several 3DFE models have been developed by researchers [8], [10] and [11] for estimating the curling stress values in concrete pavement. The 3DFE models can easily incorporate the non linear temperature distribution in the analysis. As per the published literature a limited study has been reported on temperature distribution in high volume fly ash concrete pavements.

2. RESEARCH SIGNIFICANCE AND SCOPE

In the current work an attempt has been made to establish temperature profiles across the different thicknesses of pavement quality high volume fly ash concrete (PQHVFAC) and conventional concrete (PCC). In the first stage mix proportion of PQHVFAC with optimum cement replacement level was finalized from trial mixes in the laboratory. Also mix proportion of PCC which gave equivalent flexural strength to that of PQHVFAC was established. In the second stage test stretches of PQHVFAC and PCC were constructed to study the field response. Temperature variations across the different thicknesses of concrete slabs of both categories were measured for winter and summer seasons by embedding thermistors in small square slabs. A total number of 20 thermistors have been used. Strains were measured using 12 number of embedded vibrating wire strain gages. Analysis for curling stresses due to field measured temperature differentials was carried out using 3DFE analysis and classical solution of Westergaard-Bradbury. For 3DFE analysis ANSYS software has been used. 3DFE results for curling stresses were compared with the results of other softwares

- *Aravindkumar Harwalkar is currently Associate Professor in Department of Civil Engineering, P.D.A.College of Engineering, Gulbarga, Karnataka State, India. Tel.:+919449775788; Fax: +91(8472)255685; E-mail: harwalkar_ab@yahoo.co.in*
- *Dr.S.S.Awanti is currently Professor and Head, Department of Civil Engineering, P.D.A.College of Engineering, Gulbarga, Karnataka State, India. Tel.: +919448257587; Fax: +91(8472) 255685;* E-mail: ssawanti@yahoo.co.in

mentioned in the literature [10]. Analyzed results of curling strains from 3DFE analysis were compared with the field data.

3. LABORATORY INVESTIGATIONS

3.1 Materials

The ordinary Portland cement from single batch has been used in the present investigation. The coarse fraction consisted of equal fractions of crushed stones of maximum size 20mm and 12mm. In PQHVFAC low calcium fly ash satisfying the criteria of fineness, lime reactivity and compressive strength requirements [12] has been used for cement replacement. Fine aggregate used was natural sand with maximum particle size of 4.75mm. Polycarboxylic based superplasticizer has been used as high range water reducing admixture (HWRA) to get the desired workability. The optimum dosage of superplasticizer for each type of concrete was fixed by carrying out compaction factor tests.

3.2 Mixture Proportions

A minimum grade of M30 which results in a minimum static flexural strength of 3.8N/mm^2 has been specified for pavement quality concrete by Indian Roads Congress [13]. Trial mixes were developed to achieve M35 grade PQHVFAC at cement replacement of 60%, which was the optimum replacement percentage with water to cementitious ratio of 0.3. Water to cementitious ratio utilized in the investigation i.e., 0.3 was the lowest value that could be used from the limitation of reduction in water content that can be achieved using HWRA and usage of conventional means of mixing and compaction. For conventional PCC pavement segment and small square slabs, control concrete mix proportion which gave similar static flexural strength as that of PQHVFAC was determined. Mixture proportions of the two types of concrete are shown in Table 1.

3.3 Static Test Results

Cube specimens of size 150mm×150mm×150mm were used for determining compressive strength. For static flexural strength, prism specimens of size 75mm×100mm×500mmh have been used. Prism specimens were tested under one-third point loading with an effective span of 400mm. All the strength properties were determined after a curing period of 28days. It was observed that high volume fly ash concrete showed improved behavior with respect to relation between flexural and compressive strength when compared with conventional concrete. The values of moduli of elasticity were established by pulse wave velocity technique. The cube compressive strengths, flexural strengths and moduli of elasticity for the two types of concrete are tabulated in Table 2. Using the results of CBR test and codal provisions [14] the value of modulus of sub-grade reaction was estimated as 0.09N/mm^3. The values of coefficient of thermal expansion and Poisson's ratio mentioned in the literature [13] for PCC i.e., $10\times10^{-6}/\ ^0$C and 0.15 respectively have been used for PQHVFAC for 3DFE analysis.

4. FIELD INVESTIGATIONS

In the current work temperature measurements have been carried out from January 2011 to June 2011 covering winter and summer seasons. Temperature measurements were done in three PQHVFAC small slabs of size 500×500mm and thicknesses 150mm, 200mm and 300mm. Also measurements were done in three conventional PCC small slabs of plan size 500mm×500mm and thicknesses 150mm, 200mm, and 250mm. A Plain jointed concrete pavement test stretch of size 3.5m×18.0m×0.2m was cast adjacent to small slabs. The test stretch consisted of two segments, each of length 4.5m, for PQHVFAC and two segments, each of length 4.5m, for PCC. Pavement test stretch was constructed to measure the wheel load response at a later stage. Thermistors (embedded type) were used for measurement of temperature distribution across the thickness of small slabs. Vibrating wire strain gages were installed in pavement slabs to measure the strain values. For 150mm thick small square slabs 3 thermistors (at depths 38mm, 75mm and 112mm from top) and for 200mm thick small slabs 3 thermistors (at depths 50mm, 100mm and 150mm from top) have been used for each type of concrete. For 300mm thick PQHVFAC small slab, 4 thermistors (at depths 50mm, 100mm, 200mm and 250mm from top) and for 250mm thick PCC small slab 4 thermistors (at depths 50mm, 100mm, 150mm and 200mm from top) have been used. Hence a total number of 20 thermistors have been installed to establish the nature of temperature gradient in both PQHVFAC and PCC. A total number of 12 vibrating wire strain gages were installed in the test stretch of the pavement (six numbers in PQHVAFC stretch and six numbers in PCC test stretch). They were installed at 3 locations i.e.; at edge, interior and corner. At each location 2 strain gages i.e.; one at 40mm from top of slab another at 40mm from bottom were used. A typical plan lay out of vibrating wire strain gages in the pavement stretch is shown in fig. 1. Data from all these sensors were acquired continuously by an automatic data logger. Temperature data along with strain values have been acquired continuously at a triggering time of 30 minutes. Temperature data and strain data were collected after a curing period of 28 days. Ponding method of curing was adopted for small slabs and test stretch as well.

4.1 Casting of Pavement Test Stretch:

Granular material belonging to WBM Grade 2 classification [15] was used as sub base for the pavement slab. A thickness of 75mm was used for sub base layer and a degree of compaction of 98% was maintained for granular sub base. A polythene sheet was provided between granular sub base and the pavement slab to reduce the frictional stresses. For the test stretch of pavement contraction joints were provided at a spacing of 4.5m. Joint cutting for the pavement stretch was done after 24hours from casting time since the final setting time of PQHVFAC was higher than that of PCC. Depth of saw cutting for contraction joints was maintained as 0.25 times the thickness of slab. Surface vibrator was used for compaction with the exception of location of gages.

Boxes of 0.5m×0.5m×0.2m were used for casting at the locations of strain gages. Specially prepared cover blocks were used for placing the bottom gages at the required depths. Axes of all the gages were aligned along the length of the pavement. The orientation of all the gages and depth of placement of top gages was ensured by using two Ø10 reference bars. The reference bars were removed immediately after compaction of concrete. Placing and compaction of concrete was done in boxes first. Boxes were immediately removed after casting which is followed by concreting in the remaining stretch of pavement. During the casting precaution was taken so that joint is not formed between the concrete cast in the box and the remaining stretch of concrete. A typical view of placing the vibrating wire strain gages in pavement slab is shown in fig. 2.

TABLE 1. MIXTURE PROPORTIONS OF CONCRETE

Mixture Components	PQHVFAC	PCC
Cement (OPC 53 grade) in kg/m^3	176	440
Class F fly ash in kg/m^3	264	0
Water in kg/m^3	132	154
Superplasticizer in liter/m^3	3.5	9.9
Saturated surface dry sand in kg/m^3	858.2	871.0
Saturated surface dry coarse aggregate in kg/m^3	1059	1059

TABLE 2. MECHANICAL PROPERTIES OF CONCRETE

Property of concrete/ Type of concrete	28 day characteristic cube compressive strength in MPa	28 day characteristic static flexural strength in MPa	Modulus of Elasticity in GPa
PQHVFAC	40.8*	5.3*	42.0*
PCC	56.3*	5.5*	47.0*

** Mean value of six specimens*

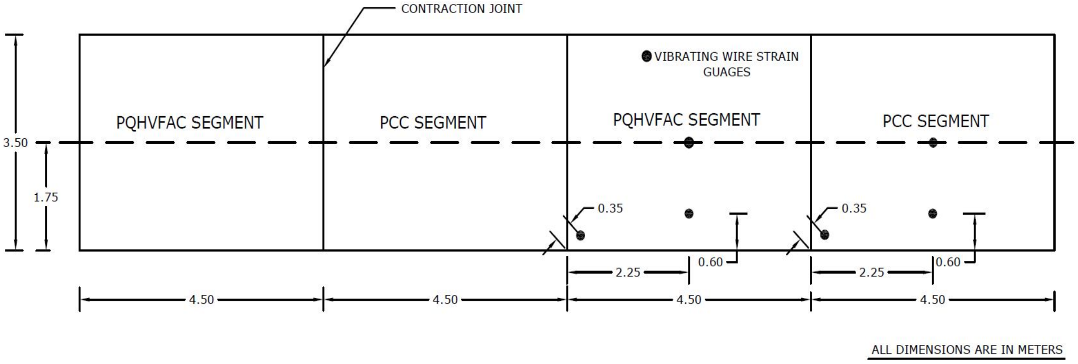

FIGURE 1. LAY OUT OF VIBRATING WIRE STRAIN GAGES IN PAVEMENT TEST STRETCH

FIGURE 2. PLACING OF VIBRATING WIRE STRAIN GAGE IN PAVEMENT TEST STRETCH

4.2 Casting of Small Square Slabs for Measurement of Temperature Distribution:

Casting of small square slabs for measurement of temperature was done in the boxes of plan size 0.5m×0.5m and the required thicknesses. To maintain similar conditions for comparative studies on temperature variation in different thicknesses of concrete, thermistors were embedded in separate concrete prisms instead of placing in the pavement test stretch for 200mm thick concrete also. Thermistors were placed at predetermined depths at the center of the prism during placing of concrete. Granular sub base, similar to that of pavement slab, was provided for the prisms. Also similar exposure conditions were maintained for both test stretch and small slabs. Boxes were removed after the initial setting time of concrete. Strain gages and thermistors were calibrated in the laboratory before embedding in concrete.

5. RESULTS OF FIELD INVESTIGATION

5.1 Measurement of Temperature Differentials

Peak positive temperature differentials i.e., temperature at the top being higher than at the bottom (PPTD), were obtained in the noon. Peak negative temperature differentials i.e., temperature at the bottom being higher than at the top (PNTD), were obtained in early morning. Both types of concrete, attained peak temperature differentials at similar timing. Maximum PPTD value was recorded on 5 May 2011 at 1.30PM for PQHVFAC and for PCC it was recorded on the same day at 3.00PM. A typical variation of temperature in all the thermistors on 5 May 2011 for 200mm thick prisms for PQHVFAC and PCC is shown in fig. 3 and 4 respectively. Maximum and minimum air temperatures on the day were 42.1^{0}C and 24.5^{0}C respectively. The peak PNTD values were almost half of the PPTD values. Hence it is the maximum PPTD value which will govern the design of rigid pavements. The variations of positive and negative temperature differential between top and bottom thermistors in case of PQHVFAC and PCC for the two seasons are shown in figures 5 and 6 respectively. Best fit temperature distribution curves for maximum PPTD, PNTD for PQHVFAC and PCC for different thicknesses are shown in fig. 7 to 10 respectively. Temperature distributions in all the cases were nonlinear. Natures of temperature profiles across the particular thickness for PPTD values on all the days were similar. Maximum PPTD for PQHVFAC was higher than that for PCC for all the thicknesses. There maximum PPTD value for 300mm thickness has shown slight decrease when compared with that of 250mm thick slab in case of PQHVFAC. In case of PCC maximum PPTD values for 250mm and 200mm thicknesses were identical. For 150mm thick prism values of maximum PPTD and PNTD were nearly half of the corresponding values for higher thicknesses in both types of concrete. Variations of PPTD and PNTD values (determined from established temperature profiles) with different thicknesses of concrete are shown in fig. 11.

5.2 Curling strain measurement:

Curling strain values were also recorded at an interval of 30 minutes simultaneously with temperature values. Vehicles with different axle configurations were allowed to move on the pavement, only when wheel load strains were to be measured. With this it was possible to measure exclusively, strains due to temperature effects (neglecting the contribution of other climatic factor such as moisture gradient). Strain values showed higher variation at the corner (top) and the interior (top) locations for PQHVFAC for both PPTD and PNTD. For conventional concrete higher variations in values of strains were observed at the interior and edge locations. The recorded curling strain values varied between -15µ and +15µ (- sign indicating compressive strain and + sign indicating tensile strain).During a day the attainment of peak value of strain and peak value of the temperature differential (either positive or negative) was not simultaneous for both types of concrete. Attainment of peak temperature differential was lagging by 1 to 4 hours with the timing of attainment of peak value of strain.

6. ANALYSIS FOR CURLING STRESSES AND STRAINS

3DFE analysis was carried out to estimate the values of curling stresses and corresponding strains. ANSYS software [16] has been used for the analysis. 3-D brick element having eight nodes i.e., SOLID45 has been used to model the pavement slab. The slab is assumed to be founded on a dense liquid foundation. Hence COMBIN14 spring elements were used to model the base material. The effective normal stiffness of the spring element was calculated by multiplying modulus of sub grade value with influencing area of the element. For analysis, one pavement segment between contraction joints i.e., of size 3.5m×4.5m×0.2m has been considered. CONTAC174 interface element which can support Coulomb and shear stress friction has been used for representing the interfacial behavior between slab and the base material. Since polythene sheet was provided between the pavement slab and the sub grade, a low value of 1.2 has been used for the friction factor in the analysis. A typical meshed pavement model is shown in fig. 12.

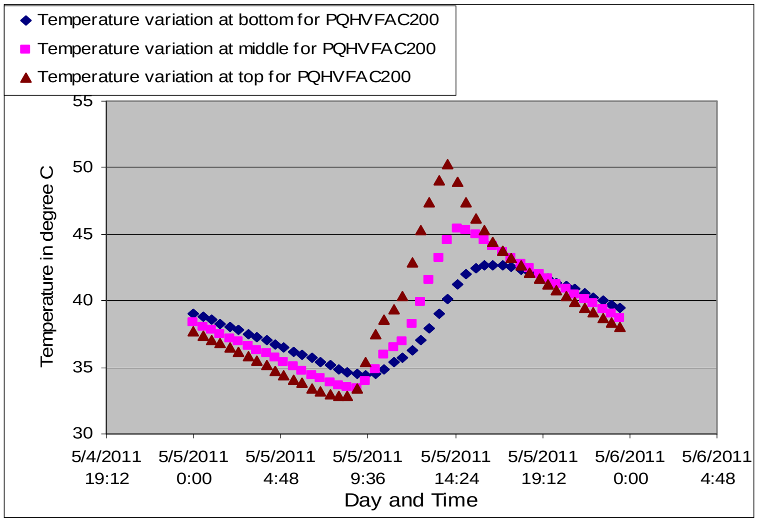

FIGURE 3. TEMPERATURE VARIATION IN 200MM THICK PRISM OF PQHVFAC ON MAY 5, 2011

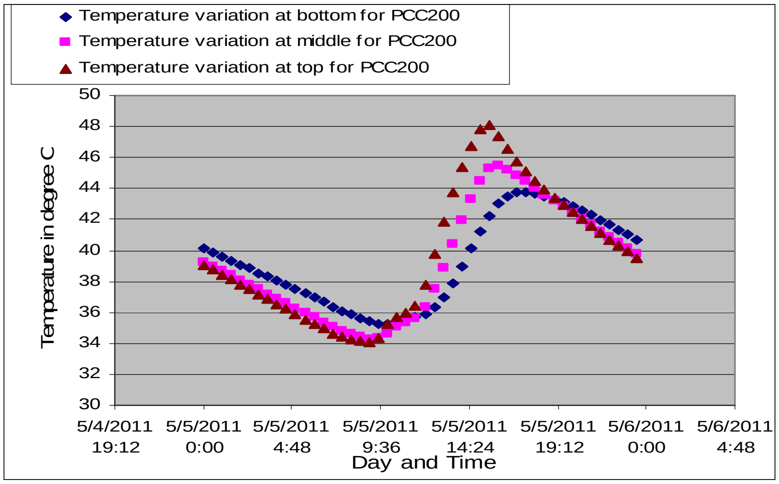

FIGURE 4. TEMPERATURE VARIATION IN 200MM THICK PRISM OF PCC ON MAY 5, 2011
(NOTE: THE PATTERN OF DATE IN THE GRAPH IS MONTH/DAY/YEAR)

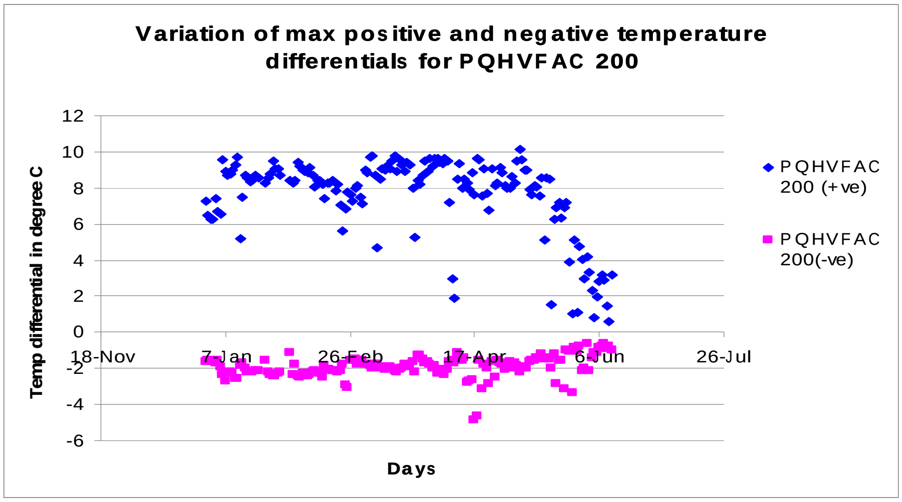

FIGURE 5. VARIATION OF MAXIMUM POSITIVE AND NEGATIVE TEMPERATURE DIFFERENTIALS FOR 200MM THICK PQHVFAC
(NOTE: NEGATIVE SIGN IN THE FIGURE INDICATES ONLY ABOUT THE FACT THAT TEMPERATURE DIFFERENTIAL IS A NEGATIVE TEMPERATURE DIFFERENTIAL)

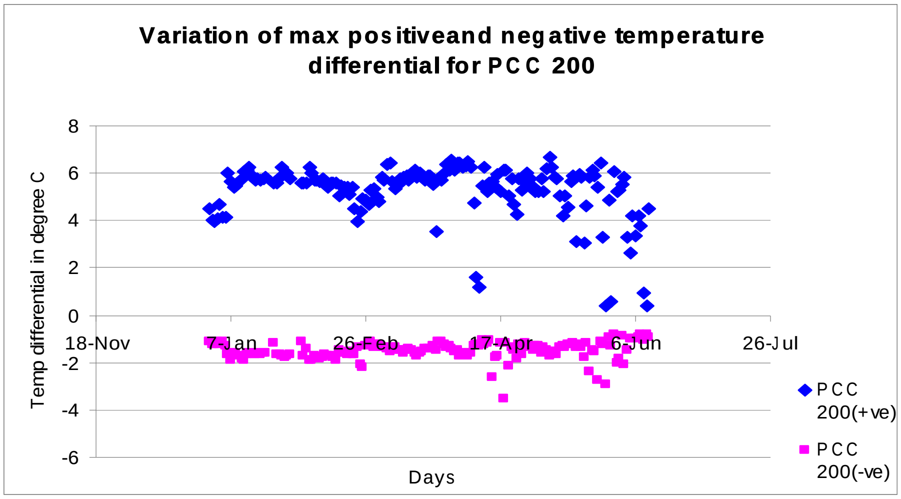

FIGURE 6. VARIATION OF MAXIMUM POSITIVE AND NEGATIVE TEMPERATURE DIFFERENTIALS FOR 200MM THICK PCC
(NOTE: NEGATIVE SIGN IN THE FIGURE INDICATES ONLY ABOUT THE FACT THAT TEMPERATURE DIFFERENTIAL IS A NEGATIVE TEMPERATURE DIFFERENTIAL)

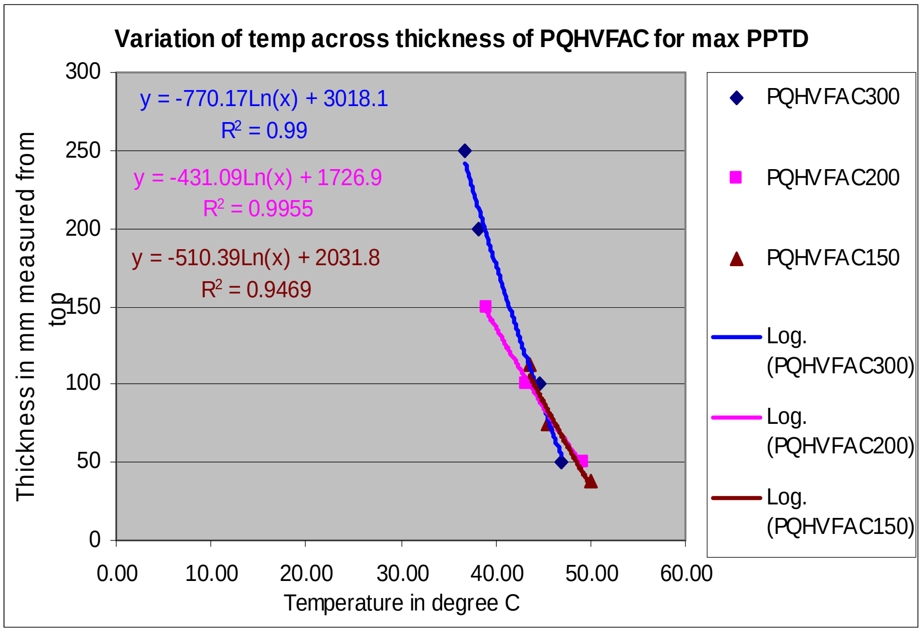

FIGURE 7. TEMPERATURE PROFILE ACROSS DIFFERENT THICKNESSES OF PQHVFAC FOR MAXIMUM PPTD

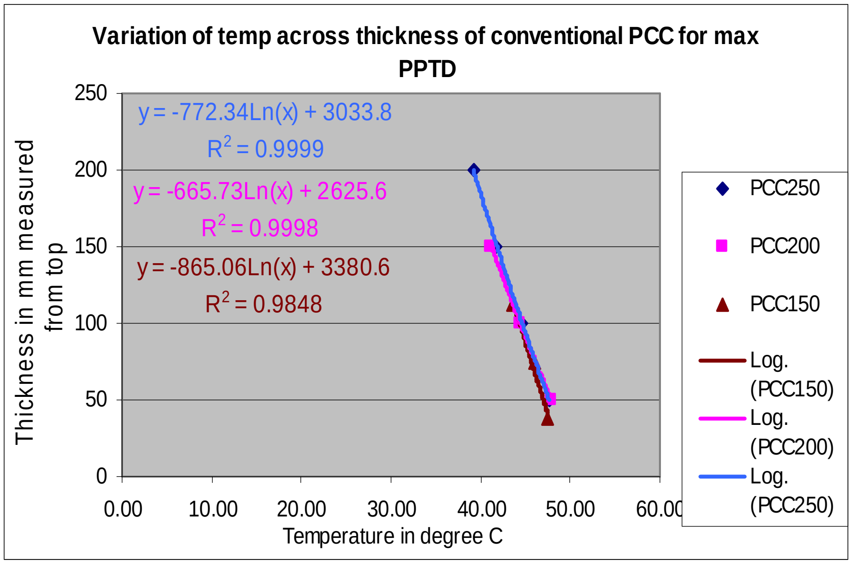

FIGURE 8. TEMPERATURE PROFILE ACROSS DIFFERENT THICKNESSES OF PCC FOR MAXIMUM PPTD

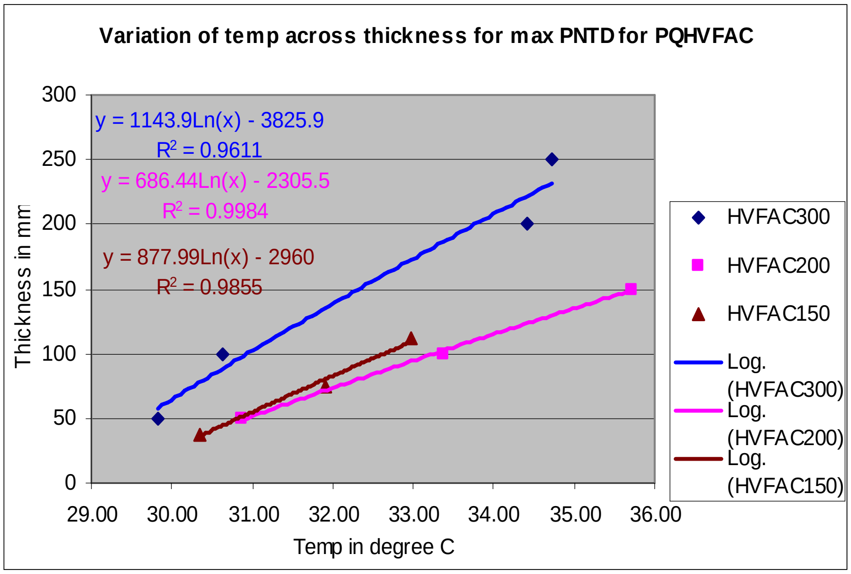

FIGURE 9. TEMPERATURE PROFILE ACROSS DIFFERENT THICKNESSES OF PQHVFAC FOR MAXIMUM PNTD

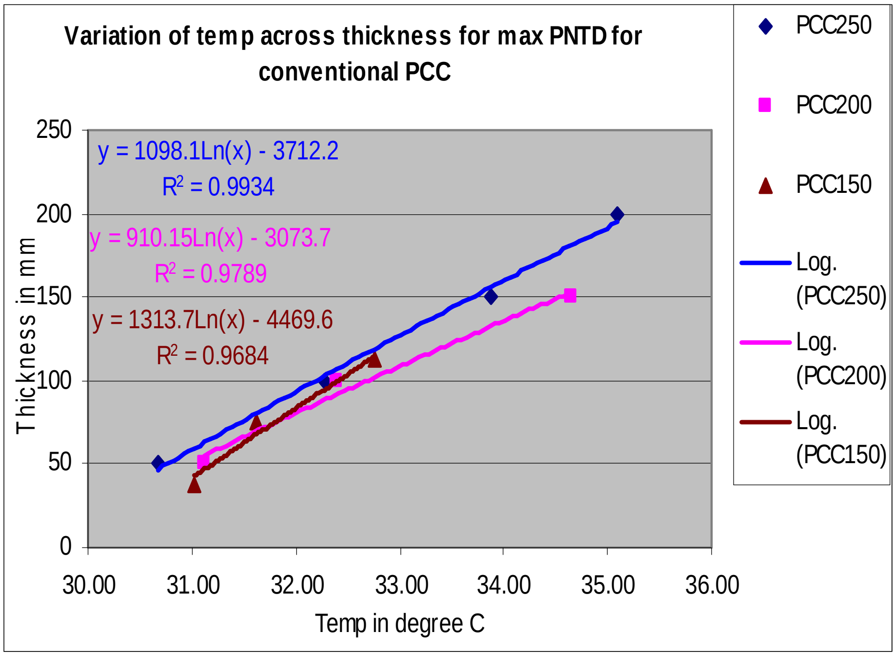

FIGURE 10. TEMPERATURE PROFILE ACROSS DIFFERENT THICKNESSES OF PCC FOR MAXIMUM PNTD

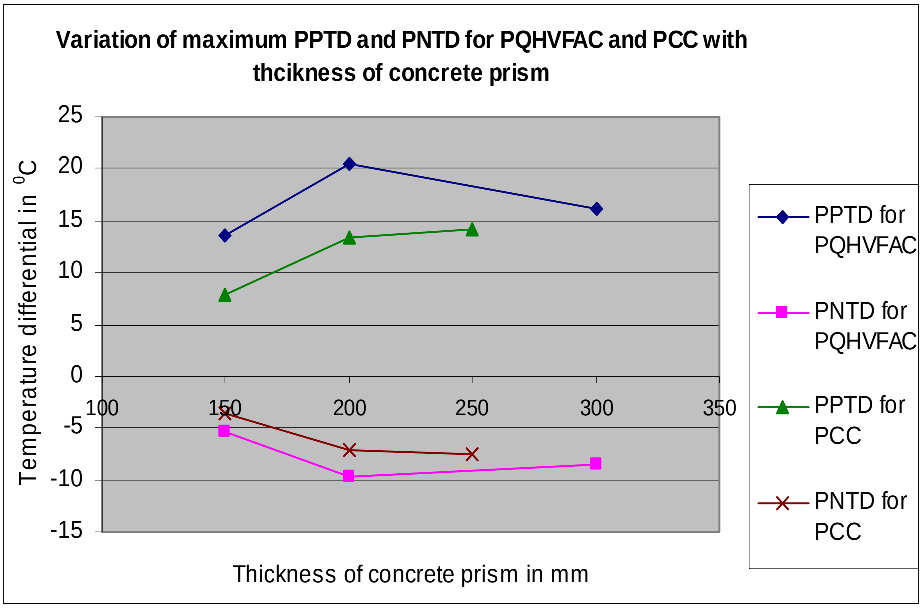

FIGURE 11. VARIATION OF PPTD AND PNTD WITH THICKNESS OF CONCRETE

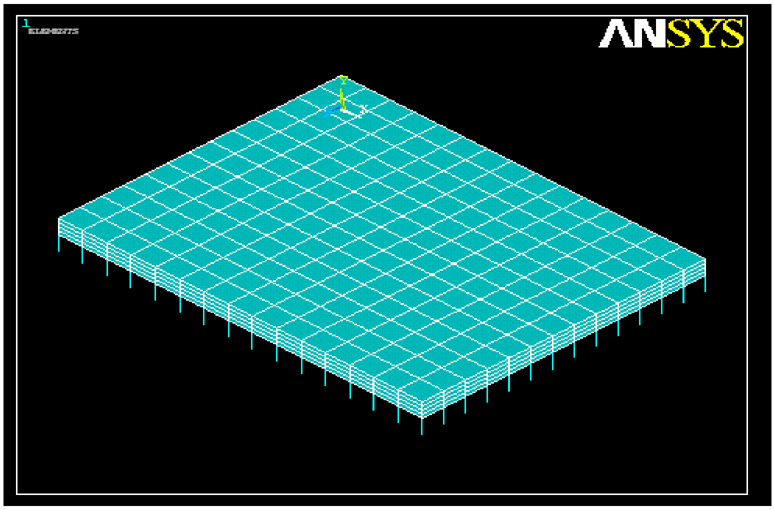

FIGURE 12. MESHED PAVEMENT MODEL

For analysis PPTD values of 20.4^{0}C and 13.4^{0}C have been used for PQHVFAC and PCC respectively. These values of PPTD were calculated from the respective temperature profiles. Temperature values at different depths determined from respective temperature profiles for 200mm thickness were applied on the elements for both types of concrete. Self weight of pavement slab and the interfacial contact with the base were the only restrains used in case of analysis for curling stresses and strains. Analysis was also carried out for linear temperature gradient between top and bottom temperature values using 3DFE and Westergaard-Bradbury techniques. From 3DFE analysis maximum longitudinal strains were -36.3µ and +36.4µ for PQHVFAC at the level of top and bottom strain gages respectively. The maximum strain locations were edge and interior in the analysis. The corresponding maximum recorded strain values were -9.1µ and +13.8µ. 3DFE analysis gave maximum strain values in PCC as -23.9µ and +24.0µ at the level of top and bottom gage respectively at edge and interior locations. The corresponding recorded maximum values of strains in PCC were -15.2µ and +1.3µ. It was observed that strain values obtained from 3DFE analysis matched with the recorded values qualitatively at all the locations except at corner bottom for PQHVFAC. For PCC, measured and analyzed values do not match qualitatively at bottom locations of interior and corner portions of the pavement segment. The magnitudes of recorded strain values were lower than the analyzed values. This may be due to partial restrains generated on the side faces of the slab in the field. 3DFE analysis predicts the location of neutral axis at mid depth. But from the field data it was observed that neutral axis is not at mid depth of the slab. This gives an indication of the presence of axial thrust on the pavement slab apart from flexure.

Curling stress values obtained by 3DFE analysis for non linear temperature gradient and linear temperature gradient are tabulated in Table 3. A typical nodal principal stress contour for PQHVFAC slab for non linear temperature gradient is shown in fig. 13. Curling stresses obtained by 3DFE analysis were of similar magnitude to that reported in the literature [10] for similar conditions using different softwares. 3DFE analysis resulted in higher curling stresses for nonlinear temperature gradient when compared to that for linear temperature gradient. In case of PQHVFAC increase in curling stress value was 9.2% for nonlinear positive temperature gradient. Corresponding increase in case of PCC was 5.3%.

7. PARAMETRIC STUDY FOR CURLING STRESSES

PQHVFAC pavement segment has been analyzed for curling stresses in different thicknesses for the linear temperature gradient of 0.102^{0}C/mm and gravity loading using ANSYS and Westergaard-Bradbury technique. Results are shown in fig. 14. It can be seen that Westergaard-Bradbury technique results in over estimate of curling stresses especially for higher thicknesses of pavement slab. This may be due to some simplifying assumptions made and ignoring restrain due to interfacial contact in the classical approach. Also it can be seen that for a given temperature gradient curling stress value decreases with increase in thickness and for thickness above 250mm the rate of variation of curling stress decreases.

TABLE 3. MAJOR PRINCIPAL CURLING STRESS VALUES IN CONCRETE

Parameters	Thickness of Concrete in mm	Maximum PPTD in ^{0}C	Major principal curling stress values^c in MPa		
			By 3DFE analysis		By Westergaard-Bradbury approach
			For nonlinear temp. profile	For linear temp. profile	
PQHVFAC	200	20.4	+3.21	+2.94	+3.89
PCC	200	13.4	+2.37	+2.25	+2.77

^{c} *Tensile curling stresses are indicated by +ve sign.*

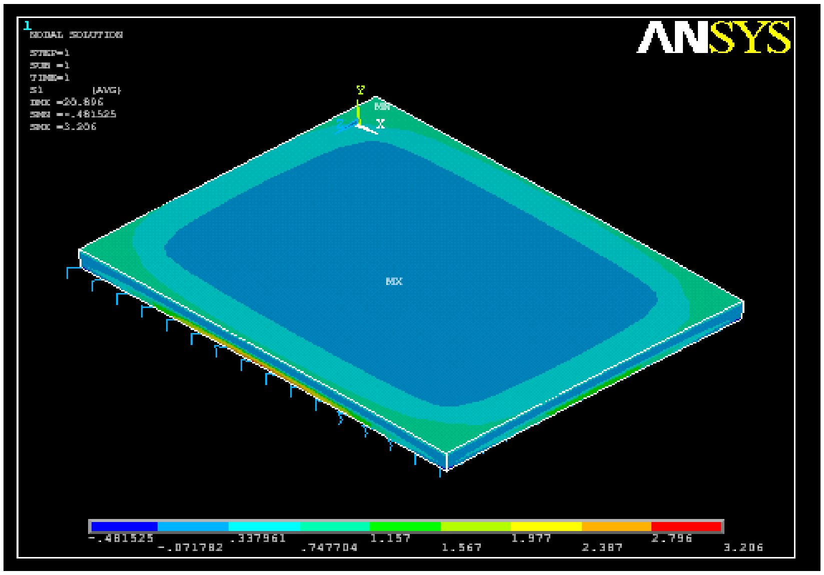

FIG. 13. NODAL PRINCIPAL STRESS CONTOUR FOR NON LINEAR TEMPERATURE GRADIENT FOR PQHVFAC

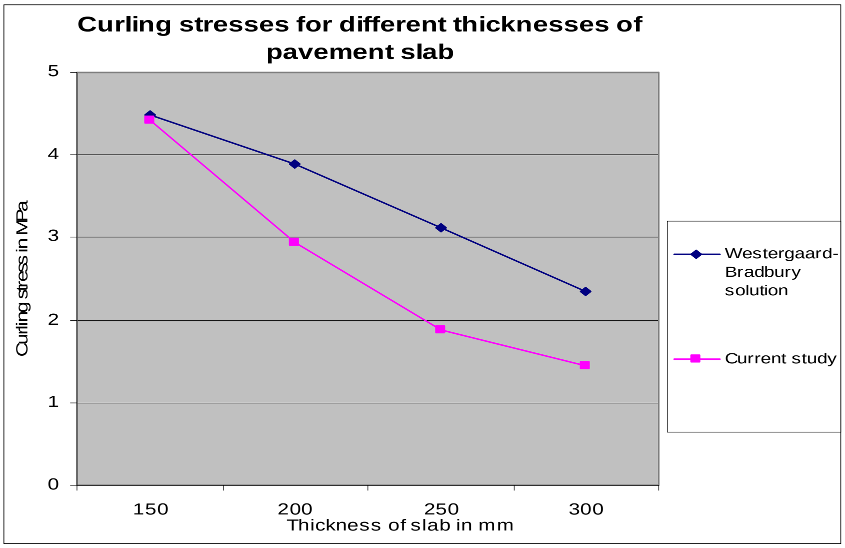

FIGURE 14. PARAMETRIC STUDY FOR CURLING STRESSES

8. CONCLUSIONS

Based on the results following conclusions were drawn:

1. High volume fly ash concrete with 60% cement replacement by low calcium fly ash can be used for construction of rigid pavements.
2. The temperature distributions across all the thicknesses of slabs are non linear for both PQHVFAC and conventional concrete. The natures of distributions are typically logarithmic for both types of concrete.
3. The PPTD and PNTD values are higher in case of PQHVFAC than PCC for similar exposure conditions. The PPTD values showed a percentage increase of 52.2 and 72.2 for 200mm and 150mm thickness respectively. The percentage increase in PNTD values are 34.7 and 50.0 for 200mm and 150mm thick prisms respectively.
4. The maximum PNTD values were half that of maximum PPTD values for both PQHVFAC and PCC. This phenomenon may be due to slab surface temperature being always higher than the air temperature during day time.
5. The values of positive temperature differentials are dependent on thickness of slabs. The maximum PPTD values for 150mm thick slab are about 50% that for higher thickness slabs.
6. The temperature profiles established in this study will be a useful data for design of rigid pavements with PQHVFAC and PCC.
7. Attainment of peak temperature differential and peak thermal strain is not simultaneous. Analyzed longitudinal strain values match qualitatively with that of recorded strains at majority of locations for thermal loading, for both types of concrete. Both 3DFE analysis and classical approaches give conservative estimate of curling strain values.
8. Westergaard-Bradbury approach gives overestimate of curling stress values.
9. Non linear temperature gradient results in higher curling stresses.
10. 3DFE technique using ANSYS provides a versatile technique in analyzing pavement slab for thermal stresses due to different kinds of temperature profiles.

9. ACKNOWLEDGMENT

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