THERMAL STRESS ANALYSISOF RCC-AC COMPOSTTE PAVEMENT

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abstract:In this paper, the three dimensional isoparametric finite element method is used to analyze the thermal stress of Roller Compacted Concrete and Asphalt Concrete (RCC-AC) composite pavement, in which both the perfect smooth and full friction are developed at the interface between RCC and foundation. The results show that the main influence factors for thermal stress are Thickness (h_c) , Thermal gradient (T_g) and Coefficient of Thermal Expansion (α_c) . The thermal stress calculation method provided can be used by designers.

1. INTRODUCTION

In the structure of RCC-AC composite pavement , due to a larger size of the RCC slab than that of ordinary concrete slab and an overlying AC layer , its thermodynamic properties have been greatly improved. Therefore, a study should be necessary to be carried out on its thermal stress. Generally, the thermal stress of the RCC slab can be divided into two types, ie, warping stress derived from the different temperature between top and bottom of the slab; shrinkage stress or thermo compressive stress derived from the uniform increase or decrease of temperature, which leads to thermal expansion or shrinkage. The paper presents a deep study on the warping stress .

In view of the trend of continously increase of thickness of the RCC slab and the remarkable effects on the calculation result from the different assumption-thin slab or thick slab, in practical highway construction , three dimensional isoparametric finite element method is adopted to calculate thermal stress of RCC-AC composite pavement.

2. FUNDAMENTAL PROBLEMS

The following several factors should be taken into consideration when eight-node three dimensional isoparametric finite element method is applied to calculate the thermal stress of RCC-AC composite pavement built over elastic semi-infinite subgrade.

2.1 Material Model

In the RCC-AC composite pavement structure, when there is a very small temperature gradient for subgrade and a smooth interface between the RCC slab and subgrade, its thermal strain can be ignored. Thus the used materials can be seen as isotropic linear elastic material.

Thermal properties of subggrade should be considered when there is a continuous interface .The RCC slab is an isotropic thermoelastic material, with its Elastic modulus of concrete (E_c), Poisson's ratio(μ_c) and coefficient of thermal expansion (α_c) varying with temperature, but in general, the variation is negligible . The values of E_a, μ_a, α_a of the overlying AC layer vary with temperature considerately and show a notable non-linearity. However ,because of the small value of E_a/E_c as well as the small thickness of AC in most cases, no much influence on the thermal stress of the RCC slab, which results from the variation of material parameters, will be produced. Therefore, material parameters of the RCC slab and AC layer can be seen as constant .

Make sure to consider the influence of temperature in stress calculation ,as shown in the following formula.

$$\{\sigma\} = [D][\{\varepsilon\} - \{\varepsilon_0\}] \tag{1}$$

In which

$$\{\varepsilon_0\} = \alpha\Delta T\{1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0\}$$

[D]=elasticity matrix of RCC plate

2.2 Boundary Condition

As the tie bars and the dowel bars are seldom used in RCC pavement construction ,the RCC slab can be viewed as a slab with free constrain for four edges ,based on elastic foundation. Practice shows that the AC layer laid over the RCC slab could hardly deal with the problems of reflection crack by increasing its thickness and joints of the RCC slab would surely come to the top through AC, sooner or later, so AC layer shares the same calculation size with free ambient constrains.

To meet need of construction and design, both the smooth and full friction inerface conditions between RCC plate and foundation are calculated and analyzed. The interface between RCC and AC is seen as continous in the light of requirements and measures taken in construction. Only positive temperature gradient (the temperature of the top of the slab is higher than that of the bottom)is considered, where self-weight of the RCC slab is not considered.

According to the study of temperature field , the temperature gradient of RCC, which is non-linear, tends to show a linear property with the overlying of AC layer above 4cm .Therefore ,linearity is used in the study of the thermal stress.

2.3 Calculation Scope and Element Division

It should be noted that finite dimension is used in the application of finite element method, though subgrade is taken as semi-infinite. To determine the influence on calculating results resulted from the scope of subgrade , let the size of RCC slab be 12m × 5m × 0.24m, taking advantage of its characteristic of symmetry, we take 1/4 the size for calculation , with the width of subgrade ranging from 2.5m, the length from 6m to 10m, and the depth from 3m to 7m, to enable the convergence of the maximum thermal stress , as shown in Table 1.When the thickness increases from 6m to 7m, the stress only decreases by 0.08% and 0.2% at the adge and middle of the slab respectively.

Table 1 The influence of subgrade depth on the thermal stress at the bottom of the slab

Depth(m)		3	4	5	6	7
σ_x (MPa)	Middle of slab	4.56843	4.56209	4.55687	4.55345	4.55136
	Edge of slab	4.36483	4.35997	4.35456	4.35024	4.34695

Element division also has an influence on the maximum thermal stress at the bottom of the slab , and its density should match with the field of stress. In view of the uniform distribution of the thermal load in the slab, and of coordination between element sizes , approxmately same element density along the length of the slab and the width of the slab and increased density along the thickness of the slab are used, with the solutions converged ,which is shown in Table 2.The density of element of subgrade along the depth has little influence on the thermal stress at the bottom of the RCC slab. It can be seen from Table 2 that the augment of density of element along the depth of the slab gives rise to a great effect on the thermal stress. When the element division is 17×7×8m ,the solutions to the problems has already converged , which will become the standard for the following calculation.

Table 2 The influence of element division on the thermal stress

Element division (x、y、z)	Middle of slab (MPa)		Edge of slab (MPa)	
	σ_x	σ_y	σ_x	σ_y
15 × 6 × 6	2.26902	1.81423	2.19930	1.73785
15 × 6 × 7	2.28626	1.82721	2.21631	1.75096
17 × 7 × 8	2.29885	1.82218	2.20540	1.73533
20 × 8 × 6	2.26871	1.77591	2.15769	1.67347

3. ANALYSIS OF THE THERMAL STRESS OF THE RCC SLAB

As stated above ,two kinds of contact conditions between the RCC slab and subgrade, continous and smooth ,are to be considered in the calculation of the thermal stress .

3.1 The Smooth Contact Condition

To achieve smooth contact between layers, special element such that $\tau_{zx} = \tau_{zx}=0$ is introduced between the RCC slab and subgrade. To aim at finding out its general law, let E_c be 34000 MPa, E_s be 200MPa, h_c be 24cm, T_g be 1℃/cm α_c be 1×10^{-5}/℃, the length of the slab be 12m , the width of the slab be 5m , when the temperature gradient remains the same , the solutions to the different surface temperature of the slab are shown in Table 3.

Table 3 Thermal stress at the bottom of the RCC slab with different surface temperature

RCC Surface Temperature ℃	Middle of slab		Edge of slab	
	σ_x	σ_y	σ_x	σ_y
24	4.57823	3.74109	4.37220	3.52063
44	4.55136	3.73253	4.34695	3.51358
Relative error(%)	0.59	0.23	0.58	0.20

Table 3 shows that thermal stress is only related to the temperature gradient and has nothing to do with the values of temperature. Furthermore, it is the warping stress that is discussed here ,then it also provides an indirect verification of the realization of the smooth contact between layers.

The elements that influence the warping stress are E_c ,h_c E_s ,A, B , T_g , α_c et c. As the influence of T_g and α_c , on the thermal stress turns to be linear , let T_g be 1℃/cm , α_c be the 1×10^{-5}/ ℃ for the sake of convinience. When it comes to the influence of E_s, E_c , h_c on the warping stress ,let the plan size of the slab be 12×15 m.

3.1.1 Influence of E_s on the stress

σ_x (hereafter σ_x standing for the warping stress value at the central bottom point of the edge of the slab) varies with E_s, as shown in Table 4. σ_x decreases a little with the increase of E_s . Taking E_s with a value of 200MPa as a standard value ,its relative error can hardly reach 0.5% within the scope generally used .Therefore let E_s be 200MPa in the following development of design graph because so little error can easily satisfy the requirement on precision in engineering design work .

3.1.2 Influence of E_c on the stress

Let E_s be 200MPa, σ_x increases with the increase of E_c and presents a linear relation with E_c, Let the thickness of the slab (h_c) be 20cm and 30cm , when the value of E_c is risen from 28000MPa to 38000M Pa, σ_x goes up by 36.64% and 36.47% respectively, from which we can see that their extent of rise remains fundamentaly same although there exists an obvious difference the values of σ_x .

3.1.3 Influence of h_c on the stress

Since T_g remains the previous value, σ_x increases with the increase of h_c. Let E_c be 28000MPa and 38000MPa, when h_c increases from 20cm to 30cm, σ_x rises by 49.74% and 49.54%. Hence the influence of h_c on σ_x is similar to that of E_c on σ_x

Table 4 Influence of E_s on the thermal stress

E_c	h_c (cm)	E_s	σ_x (MPa)	Relative error(%)
30000	20	100	3.22508	0.4
		200	3.21163	0
		300	3.20586	-0.2
38000	20	76	4.11032	0.5
		95	4.10587	0.4
		200	4.08976	0
36000	24	120	4.64544	0.2
		144	4.64239	0.1
		200	4.63605	0

3.1.4 Influence of Plan Size of Slab on the stress

Let the width of the slab be 4.5m, Ec be 34000MPa, E_s be 200MPa, when the length of the slab increases from 4.5m to 18m, the corresponding warping stress in the middle of the slab and at the edge bottom of the slab is shown in Fig . 1, from which it can be seen that the length of the slab has little influence on σ_y. σ_x in the middle of the slab shares t0he similar relation with the length of the slab with that of the edge bottom of the slab .When the length ranges from 4.5m to 7.0m, σ_x varies greatly with it (σ_x in the middle of the slab increases by 38.3%, σ_x at the edge bottom of the slab by 38.15%) .The maximum value of σ_x occurs when the length reaches 9m. However when the length of the slab is above 14m ,the reduction extent of σ_x with the increase of the length of the slab is very small. If the length of the slab rises from 15m to 18m, σ_x only decreases by about 0.8%. Variations of σ_x at the slab edge with the length is shown in Fig. 2, with the with being 4.5, 5.0, 6.0m, from which we know that its law is similar to that of the above conditions.

The following two conclusions can be drawn from Fig. 1 and Fig. 2. One is that influence of the slab length on σ_x varies with the direction; the other is that there exists a maximum value and steady value for σ_x with the variation of the length of the slab.

3.2 The Continous Contact Condition

When the continous interlayer contact condition is used, the thermal properties of subgrade bas little influence on the warping stress at the bottom of the RCC slab. So subgrade is viewed as elastic material in the calculation .But when the interlayer contact condition is contionus, it will bring forth great influence. Without considering the thermal properties of subgrade ,the thermal stress at the bottom of the slab decreases with the increase of the surface temperature of the RCC slab .When the surface temperature goes up from 24℃ to 64℃, σ_x at the slab edge decreases by 48.31%, which is due to the horizontal restrain from the subgrade at the bottom of the RCC slab. The above phenomenon does not accord with the fact. In reality , the base course of RCC is generally built with granular material stablized with inorganic binding material. According to relevant study, for the materials such as sand gravel stablized with lime and soil, sand gravel stablized by lime and flyash, sand gravel stablized with cement with content of granular material above 75%. their linear expansion coefficient is close to that of cement concrete for which the base course linear expansion coefficient is determined by that of the RCC slab. With base course seen as thermal-elastic material, when the surface temperature of the RCC slab varies, its thermal stress remains unchanged and

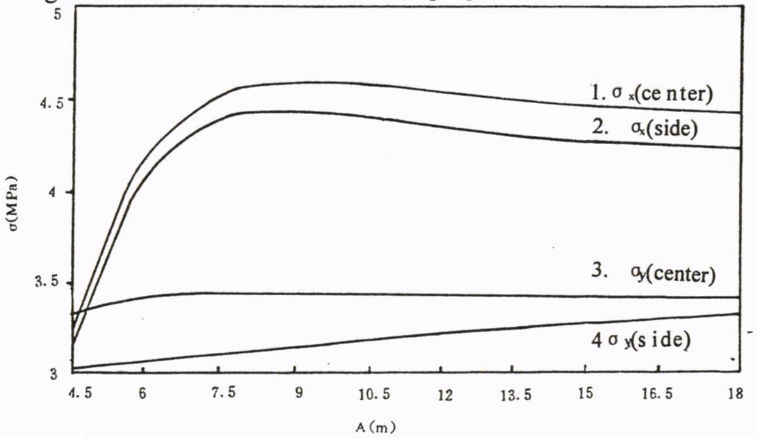

Fig.1 Influence of the plan size of the RCC slab on thermal stress

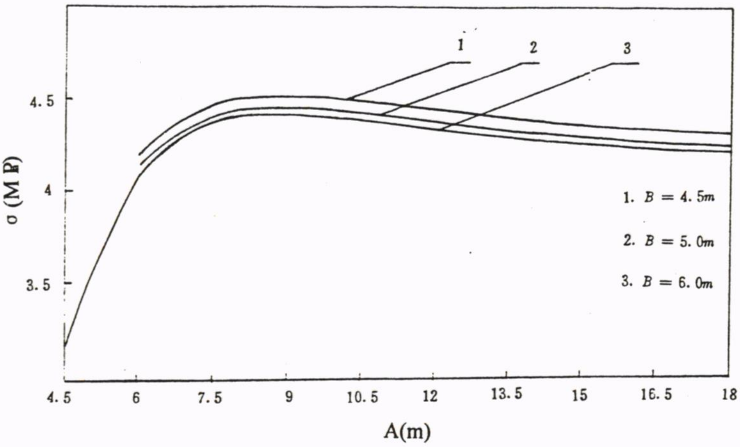

Fig.2 Influence of variation of the width of the slab on thermal stress

approaches that for smooth interface contact condition. When the parameters for calculation are unchanged, the thermal stress at the edge of slab are 4.37MPa, and 4.197MPa, for the continous and the smooth respectively, in which the former makes up 96% of the latter. While the calculation on the continous interlayer contact is carried out, whose results approach that of the smooth, too many parameters in it will bring forth difficulty in drawing the nomograph. So the result of the smooth interlayer contact multplied by 0.96 can be taken as that of the continous one. In the study of design method, due to the small proportion of the thermal stress made up in the total stress, one nomograph could be used to calculate thermal stress for both smooth and continous interface contact conditions in practical application.

4. ANALYSIS ON THERMAL STRESS OF RCC-AC COMPOSITE PAVEMENT

Overlying of AC layer on the RCC slab is equivalent to the increase of the thickness or value of Ec of the RCC slab. While both the temperature gradient and hc remains unchanged, although the overlayer of AC will lead to increase at the bottom of the slab, the temperature gradient of the RCC slab decreases remarkably with the overlying of AC. Thus, the thermal stress of the RCC pavement with AC layer is less than that of no AC layer.

While study the influence factors of thermal stress at the bottom of the RCC slab, besides the RCC slab itself, many other factors such as thickness of AC, hc, α_c should be taken into account. To find out its general law, let the size of the RCC slab be 12 × 5 × 0. 25m, Ec be 30000 MPa, μ_a be 0.25 and the smooth interface contact between the slab and subgrade is adopted.

As stated above, α_c presents a linear relation with the thermal stress at the bottom of the RCC slab, and the same is also true with α_a for example, let ha be 4cm, α_c be 1× 10^{-5}/ ℃ when α_a increases by one hundred percent and two hundred percent, σ_x at the edge of the slab increases by 1.30% and 2.68% respectively. Some study shows that linear expansion coefficient of asphalt concrete is about two times that of ordinary cement concrete, and 1.5 times that of RCC, based on which α_a takes 2×10^{-5}/℃ in the following analysis.

When ha=4cm and Ea increases to 1200MPa and 1400MPa from 1000MPa, σ_x at the edge of the slab increases by 0.43% and 0.86% respectively, which shows a linear relation. Meanwhile there is a little variation of σ_x derived from change of Ea Therefore, Ea takes 1200MP_a in the following calculation.

With hc , Ec unchanged, σ_x increases with the increase of ha. Let hc be 22cm Ec be 30000MPa, when ha ranges from 4cm ,8cm to 12cm , σ_x increases by 2.66%,5.819% and 9.45%,respectively , compared with that of h_a=0, but the extent of increase reduced because the contribution of AC layer is cut down owing to the high rigidity of RCC .

The same law is true with the continous contact condition between the slab and subgrade.

5. PRACTICAL CALCULATION METHOD OF THERMAL STRESS

The three-dimensional isoparametric finite element method provides the analysis of thermal stress of RCC-AC composite pavement with a relatively ideal way. However it is necessary to explore and develop a practical method that would also meet the requirement on both precision and practical use , because the direct application of the above method will bring about lots of inconvenience for engineering design.

5.1 Thermal Stress Calculation of RCC

In the thermal stress calculation method in use at the present for highway cement concrete pavement ,calculating formula of stress coefficient put forward by Bradbury in 1938 is used to analyze thermal stress of slab with finite size over subgrade . In the method there is an assumption that sees the slab as thin slab, which does not conform to reality. The thermal stress calculating results of three dimensional isoparametric finite element method also approve so. With the plan size of the slab being 12 × 5m , Ec ranging from 28000MPa to 38000MPa, h_c ranging from 20cm to 30cm , the result obtained from 72 data shows that its general trend is close to that of conventional warping stress coefficient , but presents not a curve but a banding shape within the scope of A/L(B/L) commonly used. When the width of the slab ranges from 4.5m to 6.0m and the length of the slab from 4.5m to 18m ,with Ec,Es, hc unchanged, the coefficient of the warping stress is shown in Fig. 3 . It can be seen from Fig. 3 that there exist many problems in the coefficient of warping stress, namely, the same A/L(B/L) will have different Cx (Cy), which should be impossible according to theoretical analysis. In view of this inadequacy ,we take drawing the nomograph of the thermal stress at the edge of the slab directly as the choice.

The values of calculating parameters used in drawing nomograph of the thermal stress are shown as follows.

hc=20,22,24,26,28,30cm
Ec=28000,30000,32000,34000,36000,38000MPa
$\mu_c=0.5$, Es=200MPa
Plan size the slab A × B=12×5 m
Temperature gradient Tg=1℃/cm
Linear expansion coefficient $\alpha_c = 1 \times 10^{-5}$/℃

The calculating results obtained are used to draw Fig. 4. That set Es be $200MP_a$ has already been verified in the thermal stress analysis. According to study, the length of the RCC slab generally ranges from 10m to 15m. When the width of the slab ranges from 4.5m to 6.0m and the length of the slab is above 10m, σ_x decreases with the increase of the length of the slab. If the length of the slab increases to 12m from10m, σ_x decreases by 1.71% ; if the length of the slab increases to 15m from 12m, σ_x decreases by 1.75%. When the width of the slab is more than 5m, 1m increase of the width results in 1.42% increase of σ_x. The above variations are small, by and large. Considering the accordance between the thermal stress and load stress, finally, let the length of the slab be 12m and the width be 5m.

5.2 Thermal Stress Calculation of RCC-AC Composite Pavement

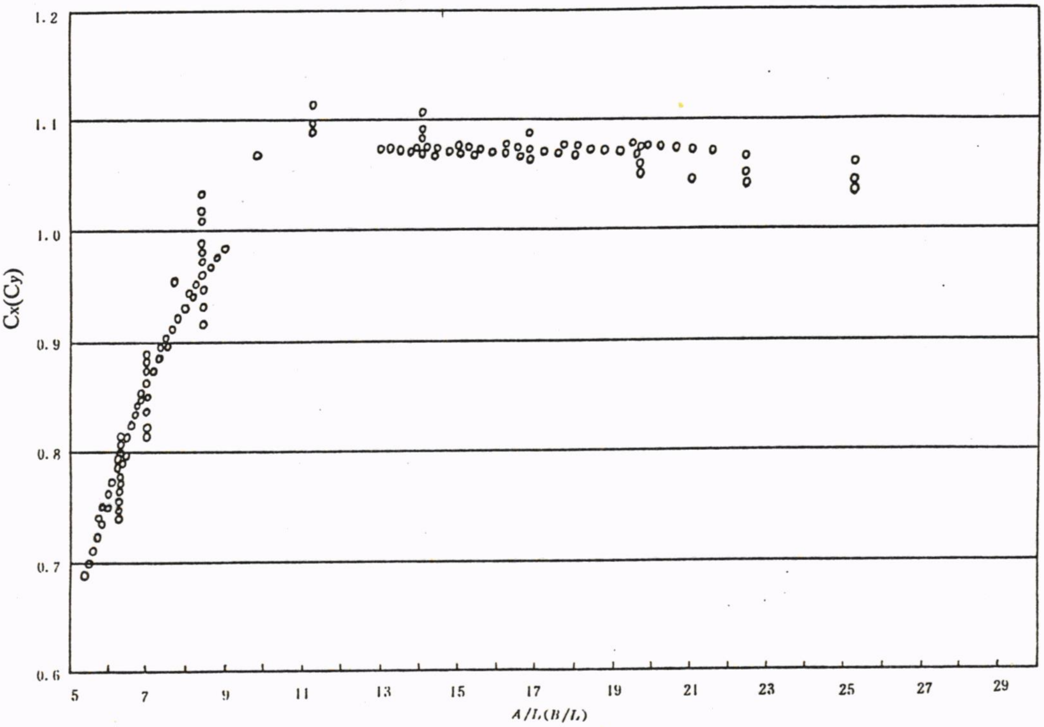

Fig.3 The graph for coefficient $C_x(C_y)$

After the RCC slab is overlaid with AC layer, two major calculating parameters h_a and E_a, are introduced, which brings about great diffculty in drawing nomograph. It can be seen from the thermal stress analysis of RCC-AC composite pavement that the variation of Ea in the scope commonly used has little influence on σx, so let Ea be 1200MPa. Only variation of h_a is considered in studying the influence of the AC layer on the thermal stress at the bottom of the RCC slab. Parameters used are shown as follows:

E_c=30000, 32000, 34000, 36000, 38000MPa
h_c=20, 22, 24, 28, 30cm
μ_c=0.15, Es=200MPa, =0.3, $\alpha_c = 1 \times 10^{-5}$/℃
ha=0,4, 8, 12cm
Ea=1200MPa, μ_a=0.25, Tg=1℃/cm, $\alpha_a = 2\times 10^{-5}$/℃

The calculating results are regressed based on the following formula.

$$\sigma_x = \left(1 + B'h_a\right)\sigma_{ox} \tag{2}$$

Where σ_x—thermal stress at the bottom of the RCC slab of the RCC-AC composite pavement;
B`—influence coefficient of h_a:
σ_{ox}—thermal stress at the bottom of the RCC slab when ha=0

The regressive relative coeffi-cient of the above formula ranges from 0.997 to 0.998.

To make application easier, the nomogram is drawn, as shown in Fig. 5.

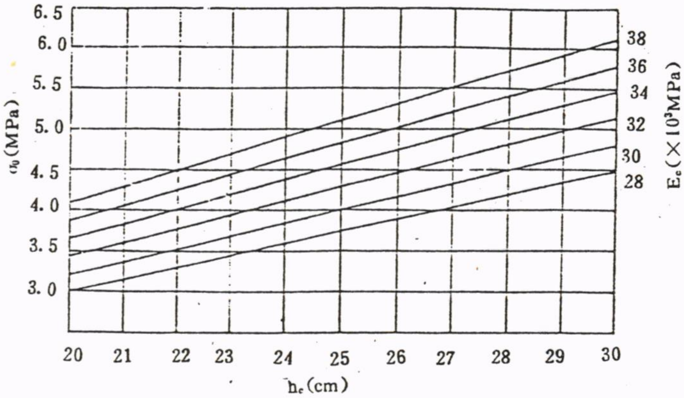

Fig .4 The calculating graph for thermal stress of the RCC

5. CONCLUSIONS

(1) The three dimensional isoparametric finite element method has been used to analyse the thermal stress of RCC-AC composite pavement. Its calculating results show that main influence factors on thermal stress include hc, Tg and α_c in which Tg, α_c, seen as constant in drawing nomograph, is in directly proportional to thermal stress. When plan size of the slab is less than 7m, thermal stress increases comparatively with the increase of the length of the slab and reaches the maximum at about 9m; when the length of the slab is more than or much too more than 12m, the thermal stress is tapering off gradually and tends to be stable.

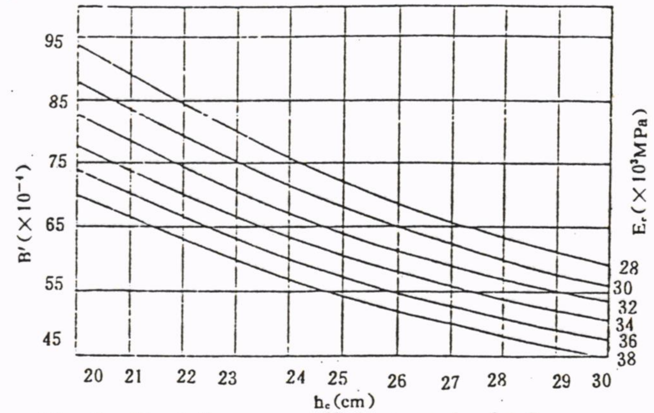

Fig. 5 The influence coefficient graph of AC layer on the thermal stress of the RCC

(2) The extent to which the interlayer contact condition between the RCC slab and subgrade has influence on the thermal stress, at the bottom of the RCC slab, is up to the calculating model of base-course materials. When subgrade is only viewed as elastic materials, there is a great variation of influence on thermal stress for perfect smooth interlayer contact and continous one, the former greater than the latter. If subgrade seen as thermal elastic material, thermal stress for both interlayer contact conditions becomes closer to each other.

(3) Case study shows that the nomograph of thermal stress of the RCC slab and the graph of influence coefficient of AC layer developed has relatively high precision and can satisfy the need of practical application.

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