STRUCTURAL STUDY OF ASPHALT CONCRETE OVERLAYS ON THE EXISTING PORTLAND CEMENT CONCRETE PAVEMENT

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Abstract: Asphalt concrete (AC) overlay is an important measure in the rehabilitation of Portland cement concrete pavement (PCCP). This paper conducts a comprehensive study of AC overlay on PCCP with mechanics analysis, anti-cracking measures, laboratory research, test-road surveys, construction techniques and design methods. Finite element method is used to analyze the load stress and the temperature stress, the deflection difference at slab joints and the effects of the anti-cracking interlayer. Large-scale fatigue equipment has been used to carry out the full-size indoor experiments to study the fatigue response of this pavement structure under repeated loads. Test roads are built by using different types of anti-cracking measures in order to find the optimum way to prevent reflection cracks. On summary of theoretical analysis, test results and the other existing research conclusions, three design indices are presented and the design method is recommended.

The asphalt concrete (*AC*) overlaying is a common maintenance measure for the Portland cement concrete pavement (*PCCP*). There are two main functions for this work: The first one is that the service functions of the road surface, such as anti-skidding function and pavement evenness, can be quickly restored. The second one is that the pavement can be strengthened and the road bearing capacity can be raised. At present, PCCP has found wider and wider application in China with a total completed mileage of about 70000 km. However, many of the concrete pavements have been damaged due to the rapid increases of the traffic volume and the vehicle load in the recent years. And these roads need badly rehabilitation and strengthening. Under the influence of cracks and joints of the existing PCCP, AC overlay usually results in reflection cracking. Accordingly, it is very important to control the reflection cracking in the structural design of AC overlays on PCCP. There are, till now, no specifications for the designing method on this kind of pavement in China, and the designing work can only be done with the reference of foreign methods like *AASHTO*, *AI* and *ARE* in the United States, and *Ta*[1] in Japan. However, there is a great difference between these empirical methods and the conventional theory in China, and they cannot be directly used in the design. Therefore, it is of great significance to carry out the structural study of AC overlays on the existing PCC pavements and to perfect its theoretical system. This paper conducts its structural study of AC overlay on the existing PCCP with mechanical analysis, indoor tests, experimenting road tests, designing methods and construction techniques.

1. ANALYSIS FOR LOAD STRESS

There is a weak-point on the slab joints of the entire pavement during the AC overlaying. This is because the reflection cracks can be easily produced after the stress at the upper *AC* layer of the joints is concentrated to make it in the disadvantageous stress state under vehicle loads. Using finite element method (FEM) to analyze the AC stress and displacement under the vehicle load, theoretical basis for the designing method can be developed.

1.1 Computation Mode

The characteristics of AC overlay on the existing PCCP lies in that there are continuous media such as subgrade, base and AC layer, while there is continual breaking at the joints of *PCC* slabs and there is a smaller rigidity between the base and the AC layer but a greater rigidity of *PCC* slabs. In order to make it easy to do the theoretical analysis, the following presumptions are adopted: smooth contact of *PCC* slabs and the subgrade; complete continuation of *PCC* slabs and *AC* layers; a required width of the joints without transferable load; semi-space elastic subgrade (E subgrade); and elastic materials of all the layer with E and μ characteristics.

As the vehicle load acts only on some parts and there are longitudinal and transverse joints in PCCP, it is more reasonable to set up three-dimensional model. The load is the double-wheel axial load with the axis weight of $100KN$[2]. During the analysis with FEM, the three-dimensional eight-node isoparametric element is used, and the truss element is also used to imitate the smooth contacting condition between the subgrade and slabs (see Fig.1 for the computation of pavement structure).

1.2 Analysis for Critical Load Positions

To prevent reflection cracks from AC overlay, the selection of the critical load positions should be done under the most disadvantageous state of stress and displacement in *AC* overlay. The load conditions can be determined by the consideration of the double-wheel load and axial load, the deviation load (that is: the critical load distribution along the joint) and the centric load (the symmetric load distribution on the junction) in load distribution. As there may be new division of vehicle lanes after the surface is covered by AC, the range of the load action may be increased and the vehicles may also be running along the longitudinal joints. The following load conditions have been considered during computation (see Fig.2): The first condition is that when the load acts on the longitudinal joint of the slabs (see ① of the graph), the load on the adjacent slabs may be transferred from one slab to another, in which the wheel load is computed with 5 load positions and the axial load is computed with 7 load positions. The second condition is that when the load acts on the transverse joint of the slabs (see ② of the graph) and moves from the slab center to the slab edge, the wheel load is computed, with the consideration of the two adjacent slabs, with 8 load positions and the axial load is computed with 3 load positions. The third condition is that when the load acts on the corner of the slab, only the wheel load is computed with the consideration of the four adjacent slabs, among which there three deviation load conditions and three centric load conditions.

The computation results have shown that when AC overlay is thinner (within 12 cm), the overlay will be mostly compressed and there will be a greater shear stress, which indicates that the generation of the reflection cracks has something to do with the shearing damage from the vehicle load. The damage appears in two aspects: there is a greater shear stress in AC overlay above the joints and there is a greater deflection difference at slab joints. When the load acts on the slab corner, there will be a greater shear stress and deflection difference on both the longitudinal and transverse joints. And there is little difference of the computation results between the wheel load and the axial load.

Through the all-round comparison, the load position of the greatest shear stress is that the wheel load acts upon the edge of transverse joint, and the load position of the greatest deflection difference is that the axial load acts upon the edge of transverse joint. As to the stress fatigue, one transit from the transverse joint equals to two transits from longitudinal joint. Accordingly, the final selection of the critical load position is the wheel load that acts upon the center of the transverse joint (see Fig.3). At this point the largest deflection position on *AC* surface is on the center of the single-wheel load (see Point 1 in the graph), the largest deflection position at slab top is on Point 2 of the graph, the largest deflection difference position is on the internal edge of single-wheel load at the joint (see the difference at Point 2 and Point 4 for deflection), and the greatest shear stress is on the bottom of *AC* layers (see Point 3 of the graph).

1.3 Analysis for Stress and Displacement Regularity

The following is to analyze the variation of computing parameters on the influence of computation results. There is a smaller influence of the slab size (the usual size: 4.5m x 5m) on the computation results of the interior shear stress of *AC* layers, surface deflection and the deflection difference at slab joints. The deflection difference decreases with the increases of AC modulus E_a, AC layer thickness h_a, slab modulus E_c, slab thickness h_c and base modulus E_s. Fig.4 shows the variation of the deflection difference with h_c in the condition of different h_a values and Fig.5 shows the variation with h_a in the condition of different E_s values. The shear stress of *AC* layers above the joints decrease with the increases of h_a, h_c, E_c and E_s, and increase with the increase of E_a. In the usual changing range of all the parameters, h_a and E_s are the two influential variables that affect the computation results, E_c and E_a, and do not produce remarkable influence on the results. And there is very weak influence of plate thickness h_c on the results with linear characteristics.

The shear stress on *AC* layers and deflection difference decrease with the increase of h_a, which fully shows that the increase of AC thickness can prevent the pavement from shearing damage. However, the surface deflection of AC layers increases with h_a to its maximum value first and then gradually decreases, the changes of which are obviously different from those of the flexible pavement (see Fig.6). The main reason is that the slab has a greater rigidity while the AC layer has a smaller modulus, and the compressive deformation will be produced on *AC* layers under the load.

1.4 Practical Computation Method

In order to make designing work convenient, the following parameters [3] are selected to compute the shear stress and deflection difference, which are: the slab size = 4.5m x 5m, E_a = 1500 MPa, E_c = 30000 MPa, h_a = 4,6,8,10,12,14, and 16cm, h_c = 18,20,22,24,26 and 28cm, E_s = 100,125,150,175,200,250 and 300 MPa. Tab1 lists some computation results of the shear stress when h_c=20cm. Through the regression of the computation results, the regression formula of the shear stress is:

$$\tau_{yz} = (2.8761 - 0.02023h_c)E_s^{-0.168} \cdot 0.93^{h_a} \tag{1}$$

The following formula is adopted for the regression of deflection difference:

$$\Delta w_{12} = A_0 - A_1 h_a + A_2 h_a^2 - A_3 E_S + A_4 E_S h_a - A_5 \times 10^{-3} E_S h_a^2 + A_6 \times 10^{-4} E_S^2 - A_7 \times 10^{-5} E_S^2 h_a + A_8 \times 10^{-6} E_S^2 h_a^2 \tag{2}$$

In the formula, the unit of Δw_{12} is 10^{-5}cm, and the values of the regression coefficients for

A_0 ,A_1 ... A_8 can be found in Table 2.When h_c is not 20, 24, 28cm, the linear interpolation can be done. The computation errors in the regression formula can be controlled within 2%.

Table 1. Some Computation Results of the Shear Stress when h_c=20cm (MPa)

Es \ ha	4cm	6cm	8cm	10cm	12cm	14cm	16cm
100	0.8982	0.7604	0.6232	0.5479	0.4728	0.4120	0.3513
125	0.8646	0.7349	0.6060	0.5332	0.4606	0.4016	0.3425
150	0.8329	0.7104	0.5880	0.5182	0.4482	0.3906	0.3328
175	0.8064	0.6900	0.5741	0.5062	0.4382	0.3820	0.3255
200	0.7817	0.6706	0.5596	0.4938	0.4279	0.3727	0.3174
250	0.7404	0.6382	0.5361	0.4735	0.4108	0.3567	0.3024
300	0.7061	0.6112	0.5162	0.4563	0.3963	0.3448	0.2931

Table 2. Regression Coefficients for Deflection Difference

h_c (cm)	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
20	351.8	27.20	0.7481	0.7789	0.07559	2.3084	8.8783	9.2487	2.8176
24	317.2	22.94	0.5884	0.6904	0.05892	1.5112	8.4867	7.3651	1.6365
28	301.1	24.18	0.7264	0.7209	0.08524	3.2447	9.931	21.4092	5.8680

2. ANALYSIS FOR TEMPERATURE STRESS

As the pavement is in the natural environment and is influenced with the continual temperature changes, the temperature inside the pavement also changes, producing its internal stress. During the analysis, the computation results[3] of the thermal analysis on the *RCC-AC* compound pavement are directly used. According to the recommended maximum gradient values of *RCC-AC* temperature, FEM is used for the temperature stress analysis of the *AC* overlay on *PCC* slabs.

Through the computation of three-dimensional finite element model and two-dimensional finite element model, it has been found that there is a small difference of the temperature stress in the two cases, but the computation can be simplified with the two-dimensional model.

Under temperature load, the concentrated stress can be produced in AC overlay above the slab joint. In the temperature-decreasing condition, the maximum value of tensile stress will be in the middle of the slab joint at *AC* bottom, and greater shear stress will appear in the interlayer of AC layer and PCC slab at the same time. The reason why the stress is concentrated is that there is restraint between *AC* layers and *PCC* slabs. When the temperature decreases, not only the self-contraction of *AC* produces greater tensile stress, but also the contraction of slabs makes the AC stress greater. The computation shows that when there is temperature difference (temperature gradient) in the depth of the pavement, the internal stress may be produced inside the pavement structure. And the uniform temperature changes can also cause the interior of AC layer to have greater stress, which shows the different regularity of the temperature influences on the four-side free slab on an elastic base. The greater the temperature decreases and the greater the negative temperature gradient, the greater the tensile stress produced from the interior of AC layer. In terms of values, the stress caused by the temperature load is greater than that from vehicle load. This indicates that the temperature load is also one of the main reasons why the reflection cracking can be produced in *AC* overlay.

The asphalt mix is a kind of viscoelastic material with the phenomena of creepage and stress relaxation. Some amount of stress from the temperature load may be lost and some may be accumulated. According to the *Boltzmann* superposition principle [4], FEM can be used to compute the temperature stress when the relaxation influence is considered. In computation, the temperature-decreasing process should be divided into several sections first and then the temperature magnitude in each section and the relaxation modulus of AC can be computed. Accumulating the temperature stress computed with FEM can obtain the stress when the temperature decreases to the end. The computation results show that after the relaxation influence is considered there will be a great decrease of the stress concentration in AC layers. These computation results are closer to the actual conditions, but there will be a rapid increase of the computation work.

3. MECHANICAL ANALYSIS FOR ANTI-CRACKING INTERLAYER STRUCTURE

To prevent or postpone the occurrence of reflection cracking, the anti-cracking interlayer is often constructed between the existing PCCP and the AC overlay, namely *SAMI* structure. The interlayer is mainly the materials like geotextile, geogrid, water-proof felt made of modified asphalt, modified asphalt sand, special AC and macadam asphalt. The thickness of the interlayer is small, ranging 0.2 ~0.3cm, which will result in great changes of the materials' mechanical performance and characteristics. These materials are of two classes: The first class is the modified asphalt sand and special AC, etc, which can remain their own characteristics in the pavement structure because they are thicker. During the computation, they are treated in the same way as the elastic materials with three-dimensional element. The second class is the geo-textile things. As their thickness is relatively small, they are not taken as a dependent structural layer in the pavement and cannot remain their own mechanical characteristics, hence are not considered as isotropy materials. As they can withstand greater tensile stress in the horizontal direction, have a smaller rigidity in the longitudinal direction and cannot be deformed and sheared, their mechanical characteristics is similar to that of memebrane.

3.1 Analysis for the First-class Interlayer with Three-dimensional Element

The three-dimensional element should be used to treat the thicker interlayer. If the modulus is small in the interlayer, 50MPa is taken, and 1cm is taken as its thickness. The computation results have shown that after the placing of interlayer between *AC* and *PCC*, there is a great change of stress and displacement in *AC* under vehicle load, an obvious decrease of shear stress at the joints of *AC*, a weakening of stress concentration and a reduction of deflection difference at slab joints. But the deflection on *AC* surface become greater, which is due to the smaller rigidity in the interlayer and thus the compressive deformation under longitudinal load. Without the interlayer, there is a uniform change of deflection values at the bottom of *AC* layers, especially right under the wheel load. This shows that *AC* layers have their rigidity and no displacement will take place in the smaller range. When the interlayer is built, the deflection value may suddenly increase right under the wheel load, which is because the anti-deforming capacity of pavement becomes weak and deflection range becomes smaller (see Fig.7, in which the horizontal axle l indicates the distance from the center of load position to the calculation point at the transverse joint.)

3.2 Analysis for the Second-class Interlayer with Plane Membrane Element

As the geo-textile things in the anti-cracking interlayer have a smaller thickness with the similar characteristics as that of membrane, they cannot withstand shear force and deformation, but only tensile stress. In the pavement structure, they can change the mechanical characteristics in the horizontal direction at the bottom of *AC* layers. The geometric formula of membrane [5] is:

$$\varepsilon_x = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 \tag{3}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 \tag{4}$$

According to the above geometric formula, the element stiffness matrix can be set up to conduct FEM analysis. The computation results show that there is no obvious influence on AC stress and displacement on the whole after the interlayer place, and there will be a decrease of shear stress and deflection difference (see Fig.8) at the joints. This is because there is a great modulus of the AC material and PCC material and the geo-textile things have smaller modulus and thickness. Thus there is a small change of the whole element rigidity after the element rigidity of geo-textile things is increased, and there is not a great solution change in the end. After placing the interlayer, there are some changes of tensile stress, shear stress and deflection difference on *AC* layers. Only the deflection values at the bottom of *AC* layers have almost no change, which is because the geo-textile things are taken as plane model in the computation and the vertical mechanics contribution in the vertical direction are omitted in the supposition.

4. INDOOR TESTS

With the help of large-scale fatigue equipment and through indoor full-size tests, there can be studies on the mechanism from the reflection cracking when AC overlay is built on the existing PCCP, the fatigue process, and the anti-cracking effect when the geo-textile things are done. And the methods for designing parameters can be studied and determined.

4.1 Test Schemes

The lime-soil base should be constructed in the trough in the 6m x 18m test room, and then 2m x 2m concrete slabs should be made. After that, there are two measurements: firstly measuring the deflection difference at the slab joints and secondly doing the same measurement when the AC overlay is built. When these have been done, the vertical load should be exerted on *AC* surface at the one side of the slab joint with a frequency of 60 times/min and load grades of 50KN, 100KN, and 200KN. During the tests, cracking occurrences and extension processes should be observed and taken down, and the regularity for the applied load numbers of deflection difference should be measured. When the reflection cracking takes place throughout *AC* surface, the test should be stopped. The parallel comparison tests can be used to show the anti-cracking effect of the geo-textile things.

In the dynamic load-applied equipment, *WPS*-500 pulse fatigue testing device is used, and the deflection is measured with the displacement sensor and micro-strain automatic monitor. WPS-500 device is composed of three parts: the main machine, the control carbet and the force-applied hammer, the last part of which is essentially a hydraulic pressure piston (see Fig.9)

4.2 Test Conclusions

①The reason for the occurrence of asphalt cracks and its extension is rather complicated. They result sometimes from the action of the direct shearing damage of load, sometimes from the accumulated fatigue damage, and sometimes from the stress concentration from the crack tip under the applied load. All these factors may produce cracks and extension.
②Through the comparison of the deflection difference before and after the AC overlaying, it has been found that the AC overlay on the slabs can strengthen the working performance of the whole pavement, raise the load-transmission capacity of slabs and reduce the deflection difference at slab joints from vehicle load.
③During the earlier stage of fatigue tests, the load-transmission capacity, with the increase of applied load numbers and the gradual development of reflection cracks, will decrease, and the deflection difference of slab joints will become greater and greater. The regression analysis for the test data shows that the rising regularity can go with the linear formula $\triangle W = a + KN$. In it, a is the initial deflection difference before the load action ($N = 0$), K is the rising rate of deflection difference which has something to do with the magnitude of the exerted load and the thickness of the AC overlay, and N is the applied load numbers. When the deflection difference increases to the equal value of deflection difference before AC overlaying, the pavement is considered to be damaged, and there are reflection cracks throughout *AC* layers. At this time, even if there is continuous load increase, the deflection difference will not be obviously increased. At the later stage of tests, the regression formula between deflection difference and applied load numbers will be quadric parabola.
④The comparison of fatigue tests through placing geo-textile as anti-cracking interlayer and directly AC overlaying shows that the geo-textile things cannot prevent the occurrence of reflection cracks, but can delay their development. This is because the geo-textile things can absorb and diffuse stress, enlarge the stress distribution range, reduce its concentration, stop the new occurrence of cracks, prevent the original crack extension and undertake the cooperative work of some horizontal stress, and jointing slabs and *AC* layers.
⑤During the tests, the stress and displacement under the load action on *AC* layers are also measured. The comparison of the theoretical computation indicates that the base modulus under the plates and the revised formula have great influence on their coincidence, and there will be great difference [6] between the theoretical values and the actually-measured ones if the existing formula is used.

5. TEST ROAD AND CONSTRUCTION TECHNIQUES

5.1 Types of the Test Road Section

The test road is Qufu ~ Taian section of the national trunk highway 104. The work is done together with the actual reconstruction of the existing PCCP. The test road section is of six types: ①directly overlaying 9cm-thick AC on PCCP (5cm-thick coarse AC and 4cm-thick medium-grained AC); ②constructing *Trevia* geotextile on PCCP with 6cm-thick AC on the upper layer (4cm-thick medium-grained and 2cm-thick fine-grained); ③laying 1m-wide domestic non-woven geotextile on the PCCP joints with 6cm-thick AC on the upper layer; ④laying 1m-wide domestic woven geotextile on PCCP joints with 6cm-thick AC on the upper layer;⑤firstly laying 15cm-thick cement-stabilizing crushed stones on PCCP, secondly cutting cracks every 20m apart and then laying 90cm-wide glass-fabric cloth on the cracks with 6cm-thick AC on the upper layer; ⑥ laying 90cm-wide glass-fabric cloth every 5m apart on the cement-stabilizing crushed stones corresponding to PCCP transverse joints with 6cm-thick AC on the upper layer. The purpose of constructing different types of test roads is to get thorough observation of the roads and carry out comprehensive comparison. Through the work, not only the method to control the reflection cracks can be found, but also the best one can be chosen under the certain conditions. The test road has been in service for two years. Through surveys it is found that the method adopted in 2nd type test road is the most effective to prevent reflection cracking, for the fact there is no reflection cracks till now. The method on the 5th type test road shows a relative poor effect. However there need to be long-period observation in the future.

5.2 Judgement and Treatment for Cavity under Slabs

It is subjective and sometimes even inaccurate to judge existence of the cavity possibility under plates through observation. Very often, this observation may be affected by such factors as the joint load-transmission capacity and base situation. It is better to establish, with the help of approximate beam method [7] in the elastic base slab computation, a relationship formula between the deflection difference at the slab center and the deflection difference at the slab edge under standard load [2]. According to the ratio value K_a of the two, whether there is the existence of cavity under slabs can be judged, that is:

$$K_a = \frac{W_A}{W_C} \geq \frac{4}{1+a} \quad \frac{f_e(\lambda_l)}{f_m(\lambda_l)} \tag{5}$$

In the formula:

W_A ---- the practically-measured deflection value at the slab transverse joint center under the standard axial load,

W_C ---- the practically-measured deflection value at the slab center when the standard load acts upon the slab center,

a ---- load transmission coefficient, the ratio of shear stress on both sides when the load acts upon the joint,

$f_e(\lambda_l)$ ------ function, $f_e(\lambda) = \dfrac{sh2\lambda - \sin 2\lambda}{ch2\lambda + \cos 2\lambda - 2}$

$f_m(\lambda_l)$ ------ function, $f_m(\lambda) = \dfrac{ch\lambda + \cos\lambda + 2}{sh\lambda + \sin\lambda}$

λ_l ---- the converted length of slab length , $\lambda_l = \dfrac{l}{s}$, l is the slab length and $s = \sqrt[4]{\dfrac{E_C h^3}{3K}}$

K ---- the reflection coefficient for *Winkler* subgrade.

When all the above can be met in the formula, there is cavity possibility under the measuring slab edge.

Drilling and mortar jacking [6] can be adopted for the treatment of the problem. The mortar-jacking material should be good in flowing and high in strength. The experiment has shown that cement coal-ash mortar meats the above requirement. The mortar material can be made up of the ratio of 1:0.49:0.46:0.006 (cement, coal-ash, water and early strength agent). The compression strength after seven days can reach 5*MPa*. Besides, the cement coal-ash mortar has the advantage of being small in contraction, economical in cost and convenient in construction.

The construction equipment includes a drilling machine, mortar-making equipment, mortar-jacking equipment and fastening device for jacking-machine head. With high pressure, the material can be jacked into the bottom of the concrete slab. In order to fasten the mortar-jacking head onto the hole, a new kind of self-expansion mortar-jacking head has been developed on the principle of expansion bolt, which has the function of fastening and sealing, and is easy to be assembled and disassembled and very high in efficiency. The procedures of mortar jacking under the slabs are: positioning – drilling – mortar-making – mortar jacking –hole-sealing – maintenance – defection check.

5.3 Construction Techniques

Before the construction of AC overlay, there should be treatment for the existing PCCP, such as removing the broken slabs. After the treatment of the base, the concrete slabs should be newly constructed or the prefabricated concrete slabs should be laid on it. There should be special treatment for cracks, joint damage, cavity under the slabs, plate-overlapping and plate-corner damages. Only if all the slabs can firmly lie on the base, can the AC overlay work well. And the stable base is the key to the prevention and the delays of reflection cracking.

Before laying geotextile on PCCP, there should be thorough cleaning for the pavement before spraying adhesive asphalt, the quantity of which should be determined according to the test. The commended quantity is, when PCCP is completely dry, 1.087~ 1.631 litre/m^2 of ordinary emulsified asphalt or 0.9~ 1.2kg/m^2 of ordinary hot asphalt. The asphalt-spraying vehicle can accurately control the asphalt quantity to be sprayed. The asphalt temperature should be controlled within the limit so as not to burn down the geotextile, the proper temperature of which ranges from 54℃ ~ 71℃. The full-width geotextile should be paved by specialized equipment or converted equipment. Sometimes, the work can be done by hand if the mechanical things are not available. The laying work for geotextile should be smooth and flat with an overlapping width of no more than 10cm ~15cm. When the geo-textile is laid, it should be paved immediately with hot AC. The temperature of the AC should not be higher than 160℃. In order to prevent the asphalt-soaked geotextile from adhesion to the paver or other equipment, sand or stone chips can be sprayed over it. When AC cannot be paved after the geotextile laying work, sand can still be used to spray over it with the quantity of 0.81kg/m^2 ~1.10kg/m^2. At this time, tire roller should be used to compact the pavement and the traffic on that section should be in control.

The technical requirements of AC, the AC mixture design, mixing and paving work are almost the same as the construction for the ordinary AC pavement. The only difference is that when the compact work is done, the proper tonnage of the roller should be determined according to the thickness of asphalt layer to prevent the asphalt mixture from secondary fining due to the vibration.

6. DESIGNING METHOD

There are three kinds of damage after the AC overlaying on PCCP: the cracks in slab due to fatigue, the separation of *AC* overlay from PCCP and the reflection cracking in *AC* overlay. The bending stress index at the slab bottom can be used to control the first damage. The shear stress of the interlayer between AC overlay and PCCP can be used to control the second damage. The reflection crack is the main damage when the existing PCCP is overlaid with AC. The effective method to control this damage is closely related to the factors that cause the damages. The research work has shown that under the action of both temperature load and vehicle load, the stress may be concentrated at the PCCP joints.

What's more, as great deformation and stress exist in the AC overlay, the load stress and temperature stress act repeatedly upon them, resulting in a lot of damage because of the accumulated fatigue.

According to the causes of the reflection cracks, three methods can be adopted to control the damage: the shear stress in *AC* overlay above slab joints, deflection difference at slab joints and the tensile stress in *AC* overlay under disadvantageous load. The first two methods can prevent the shear damage from vehicle load, and the last method can control the damage from tensile stress in *AC* layers when the temperature is decreased.

6.1 Taking the Bending Stress at Slab Bottom as a Control Index

The computation for tensile stress under slabs involves in the consideration of vehicle load and temperature load. The determination for the base modulus under slabs should be done according to different conditions in the computation. The formula for calculating load stress [1] is:

$$\sigma_p = (1.0099 - B_1 h_a) k_r \cdot k_f \cdot k_c \sigma_{ps} \tag{6}$$

In the formula:

- σ_p ---- fatigue stress of load;
- k_f ---- fatigue stress coefficient in the consideration of accumulated load ;
- k_r---- stress conversion coefficient in the consideration of joint load-transmission capacity;
- k_c ---- comprehensively revised coefficient in the consideration of dynamic load and over-load;
- B_l ---- coefficient of the asphalt layer influence on the tensile stress under slabs, which can be computed through three-layer elastic layer theory;
- h_a ---- thickness of AC overlay;
- σ_{ps} ---- tensile stress under slabs when the standard axial load acts upon the critical load position.

The temperature stress should be calculated according to the following formula:

$$\sigma_t = k_t (1 + B_2 h_a) \sigma_{tm} \tag{7}$$

In the formula:

- σ_{tm} ----temperature warping stress at the slab edge center when the temperature gradient is greatest;
- k_x ---- temperature stress coefficient in the consideration of the temperature non-linear distribution along the slab thickness, which is determined according to factors like slab-length L, slab-thickness h_c ,etc ;
- k_t ---- revised coefficient in the consideration of fatigue;
- B_2 ---- coefficient of the influence of the AC overlay on the temperature stress he slat tab edge center, which can be computed through FEM [1].

Firstly, the axial load should be converted into standard axial load, and the preliminary estimation for asphalt layer thickness should be done. Then the temperature fatigue stress and load fatigue stress should be computed. When the sum of the two is no greater than 103% of the actual PCC flexural strength, but no lower than 95% of it, the preliminary estimation thickness of AC overlay can be taken as the final thickness. Otherwise, the preliminary estimation thickness should be changed and more computation should be done until the satisfactory thickness is achieved. The design thickness of AC overlay should not be thinner than 5cm.

6.2 Taking the Deflection Difference at Slab Joint as a Control Index

The definition of the permitted deflection difference Δw_R is the greatest deflection difference at the slab transverse joints under the standard axial load in the most disadvantageous season of the end of the service year for the AC overlay on PCCP. It can be determined with the following formula [8]:

$$\Delta w_R = (1 - 0.002h_a)\,\Delta w_1 \tag{8}$$

In the formula, Δw_1 is the deflection difference before the AC overlaying. It is required that $\Delta w_R < 0.05$mm.

The thickness of the AC overlay should be determined with the following formula:

$$\Delta w = k_{wr} \cdot k_{wc} \cdot \Delta w_{12} \leq \Delta w_R \tag{9}$$

In the formula:

Δw ---- computed deflection difference;

k_{wr} ---- revised coefficient of deflection difference in the consideration of the base types and subgrade condition;

Δw_{12}---- the deflection difference at the slab joint when the standard load acts upon the critical load position, which can be computed by using FEM (see Table 1 for regression formula).

6.3 Taking Shear Stress in *AC* Overlay above Slab Joint as a Control Index

The determination for the permitted values of shear stress can be found in the methods for urban road pavement design in China [9]:

$$\tau_R = \tau_{max}/k \tag{10}$$

In the formula:

τ_{max}----the AC strength of the once shearing damage, $\tau_{max} = c + \sigma_a \mathrm{tg}\,\phi$;

c, ϕ ---- the AC cohesive strength and internal friction angle;

σ_a ---- the effective normal stress at the computation spots;

k ---- the coefficient of the structural strength during the road resistance against shear force, which has something to do with two factors: the repetitive load numbers and the highway grade.

The computation for the AC overlay thickness by taking shear stress as the design method should be done according to the following formula:

$$\tau = k_{sr} \cdot k_{sm} \cdot \tau_{yz} < \tau_R \tag{11}$$

In the formula:

k_{sr} ---- the conversion coefficient of shear stress in the consideration of the anti-cracking interlayer. When there is no interlayer, k_{sr} = 1. Otherwise k_{sr} is determined by the interlayer thickness and modulus.

k_{sm} ---- the conversion coefficient of shear stress in the consideration of the joint load-transmission capacity;

τ_{yz} ---- the shear stress when the standard load acts upon the critical load position (computed with formula 1).

The actual computation results have shown that there is different thickness of the AC overlay if the different designing methods are adopted. During the designing work, the selection of a controlling method should be made according to the specific condition. The other methods can be used for checking work. The AC mixture design can be done according to the usual method.

7. CONCLUSIONS

① This paper carries out a mechanical analysis for the AC overlay on the existing PCCP by using FEM. The emphasis of the paper is to compute the shear stress of *AC* overlays above the joints and deflection difference at slab joints, analyze the critical load positions and the affecting regularity of the design parameters, and provide regression formulas within the normal design parameters. All these can be used as references for designing work.
② For the temperature stress of the AC overlays, there is no great difference in the computation results between the two-dimensional FEM model and the three-dimensional FEM model, but the computation has been very much simplified. In terms of values, the internal stress in the *AC* overlay from the temperature load is greater than that from the vehicle load. When the AC relaxation behavior considered, the temperature stress value will be decreased.
③ When the anti-cracking interlayer is placed between AC overlay and PCCP, the two kinds of element models are used, according to the mechanical characteristics of the interlayer, to analyze the changes of stress and displacement in *AC* overlayer. The computation has shown that the anti-cracking interlayer can reduce the damage from the vehicle load, and decrease the deflection difference and AC shear stress. However, there are great differences in the computation results with the two models.
④ Large-scale fatigue equipment has been used to carry out the full-size fatigue tests for AC overlay on PCCP, and analyze the process and causes of the generation, development and damage of reflection cracks. In the end, the relationship between the deflection difference at slab joints and the applied load numbers has been obtained. Through the comparison tests, the effect of the anti-cracking interlayer of geo-textile things has been checked. Now, it is clear that although the geo-textile things cannot directly prevent the occurrence of reflection cracks, they do delay and even stop the further development of the cracking process.
⑤ The method to prevent reflection cracks is to be found through the construction of different types of test roads, and now the best method is also to be found under the certain conditions. The judgement formula and treatment method for the cavity under slabs has been achieved. The important technical problems in the mortar jacking technique under slabs have been successfully solved. And extensive studies for the AC overlaying technique and geotextile construction have been conducted.
⑥ Through the analysis for the damages of AC overlay on the existing PCCP, different designing indexes have been proposed and the computation methods for the thickness of AC overlay have been provided.

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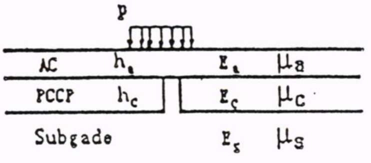

Fig.1 Calculating diagrammatic illustration of AC overlay on PCCP

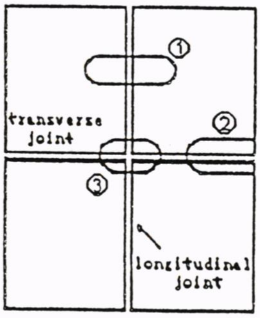

Fig.2 Distribution of the vehicle load position

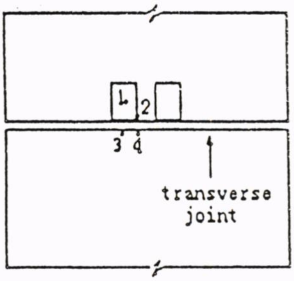

Fig.3 The critical position of load

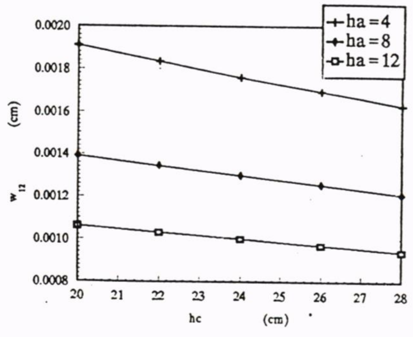

Fig.4 Variation of the deflection difference w_{12} with h_c

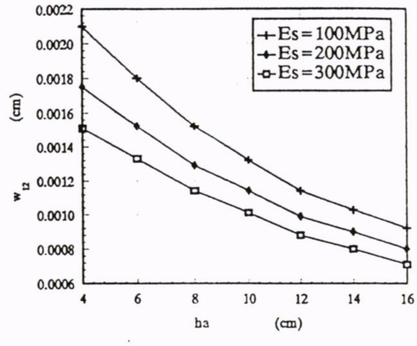

Fig.5 Variation of the deflection w_{12} difference with h_a

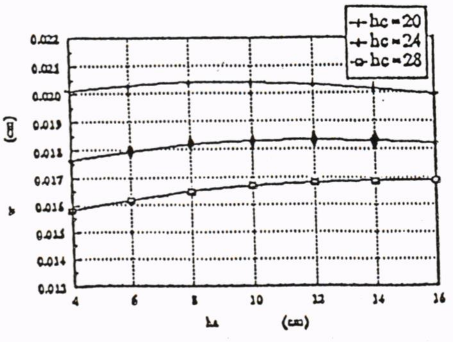

Fig.6 Variation of AC surface deflection w with AC thickness h_a

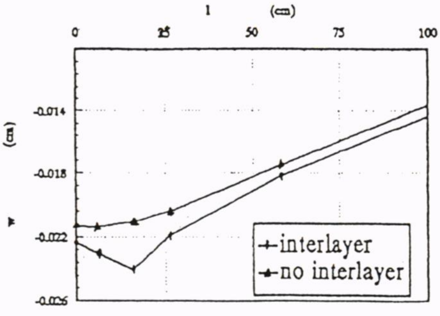

Fig.7 Comparison of the deflection on AC surface without anti-cracking interlayer to the deflection with anti-cracking interlayer

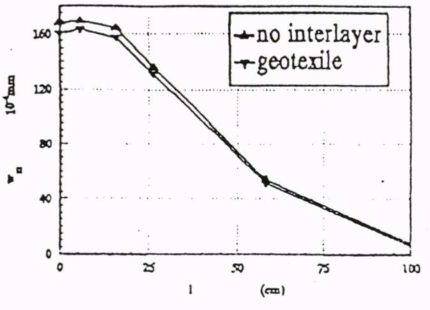

Fig.8 Comparison of the deflection difference without anti-cracking interlayer to the deflection difference with geotexile interlayer.

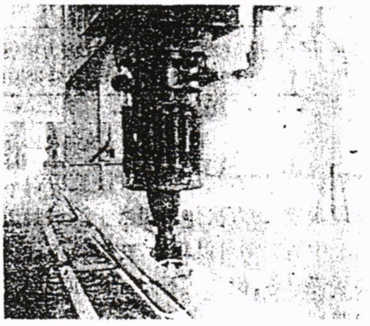

Fig.9 The force-applied hammer of WPS-500 device