STUDY OF SHEARING STRENGTH OF BRIDGE DECK WATERPROOF MEMBRANE

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Abstract: Based on indoor shear test and theoretical analysis and calculations, the effect on interlayer shearing strength of types of waterproof membrane, amount of membrane, vertical stress, shearing ratio are discussed in the paper. Then, the interlayer shearing strength of two kinds of waterproof membranes, CR and APP corresponding with actual running speed are obtained.

Key Words: waterproof material, shear test, inter-layer shearing strength

A large number of indoor shear tests have been carried out in order to determine the anti-horizontal shearing ability of waterproof layer and to set up the corresponding shearing indices for correctly choosing the waterproof layer, instructing design and construction, evaluating the coherence between asphalt pavement and waterproof layer as well as the coherence between bridge deck and waterproof layer, and evaluating the effect on the interlayer coherence of deck preparatory condition. Two types of waterproof materials, namely liquid membrane and sheet are chosen in the test. Indoor shear test is done at normal temperature (25℃) and the effect on interlayer shearing strength of different types of waterproof membrane, amount of membrane, vertical stress, shearing ratio are discussed . The LLM testing system self-developed by Xi'an Highway University is used for the test.

1. TEST PLAN OF INTERLAYER SHEAR TEST

It can be seen from theoretical analysis and past research results that the main factors affecting interlayer shearing strength are: the types and amount of waterproof material, vertical stress and shearing ratio applied by LLM testing system, test temperature, etc. Based on these factors the test plan is drawn as follows.

(1) Choose different membrane and amount in shear test to determine the optimum membrane content;

(2) With one or two waterproof materials with higher shearing strength, shear test is done at the optimum content, in which different vertical loads are applied to determine the relation between interlayer shearing strength and vertical load;

(3) The same as (2), the shearing ratio with the other test parameters is varied, the remaining are the same, shear test is carried out to determine the variation law of inter- layer shear strength with shearing ratio;

(4) Shear test is done at different temperatures to determine the effect of temperature on interlayer shear strength.
CR and PU are chosen for the liquid membrane type and APP and EPDM sheet for the sheet type of waterproof materials.

2. TEST RESULTS AND ANALYSIS

When PU and EPDM are used as waterproof materials, the asphalt concrete specimen are easily separated from waterproof layer due to a slight external force from moving the specimen, which shows that there is a lower interlayer shearing strength. This may result from lack of sufficient tests or product brand. Therefore, it is difficult to draw a positive conclusion of whether PU and EPDM can be used as bridge deck waterproof materials.

2.1 Optimum content of CR

The method of "laying fiberglass two times and painting CR six times" is used in the formation of waterproof membrane. The specific procedures are: paint base CR on the dry and flat surface of cement concrete first; when base CR dried, paint the first layer of CR and lay first layer of fiberglass at the same time as the second layer of CR is painted; when the CR dries, paint the third layer of CR on the dried CR surface; when the surface dries, paint the fourth layer of CR and lay another layer of glass-fiber at the same time; then comes the fifth layer of CR after which the sixth layer of CR is applied

Shear test results are shown in Table1, in which vertical stress is 0.2MPa, shearing ratio 3.5mm/min and test temperature 25℃. Variation of interlayer shear strength τ_{max} with the content increase of CR is shown in Fig.1. It can be seen from shear test results that the peak value of τ_{max} occurs at the content of around 2.3kg/m^2 of CR, on whose left side there is a slower increase but on whose

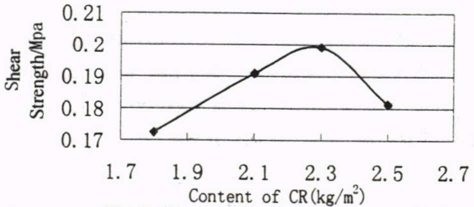

Fig.1 Shear Strength and Content of CR

right side there is a sharper decrease. Considering the variation caused by roughness of bridge decks in construction, let the optimum content of CR ranging from 2.25kg/m^2 to 2.33kg/m^2. Take lower content for bridge decks with high roughness and take higher content for bridge decks with low roughness.

Table 1 Shear Test Results of CR

Items	Contents of CR (g/cm^2)			
Total content	1.8	2.1	2.3	2.5
τ_{max} (MPa)	0.1725	0.1909	0.1992	0.1813

2.2 Effect of vertical stress on interlayer shear strength (τ_{max})

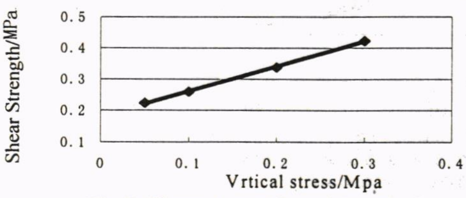

Fig.2 Shear strength and Vertical strength/CR

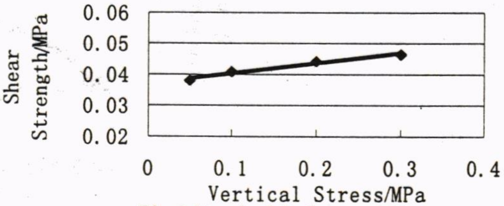

Fig.3 Vertical Stress and Shear Strength/APP

A comparison between CR and APP is made in terms of effect of σ_z on τ_{max} and the variation scope and shear test results are shown in Fig 3 and Table 2, in which shearing ration and test temperature of CR is 10mm/min and 25℃ respectively, and those of APP are 3.5mm/min and 25℃. Based on these data regressions are made.

Table 2 Effect of σ_z on τ_{max}

σ_z(MPa)		0.05	0.1	0.2	0.3
τ_{max} (MPa)	CR	0.223	0.2588	0.338	0.4228
	APP	0.0308	0.0409	0.0442	0.0464

$$CR \qquad \tau_{\max} = 0.1804 + 0.8013\sigma_z \qquad (R=0.99) \qquad (1)$$

$$APP \qquad \tau_{\max} = 0.0371 + 0.0327\sigma_z \qquad (R=0.97) \qquad (2)$$

Variations of shear strength of CR and APP with displacement are shown in Fig. 4 and Fig.5. It can be seen that the variation of shear strength of CR and APP with displacement is basically the same i.e shear strength increases with the increase of displacement at the beginning and when displacement reaches a certain value, the peak value of shear strength occurs, which shows that the interlayer structure has been destructed. With shear strength decreasing, the data following the peak value of shear strength fluctuate around a certain level is supposed to be caused by interlayer friction.

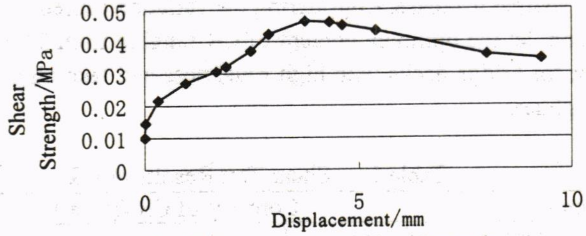

Fig.4 Displacement and Shear Strength

APP, σz=0.3MPa, V=3.5mm/min

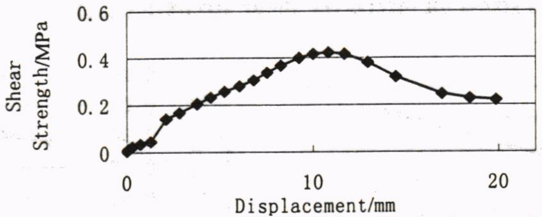

Fig. 5 Displacement and Shear Strength

CR, σ_z=0.3MPa, V=10mm/min

2.3 Effect of shearing ratio on shear strength

Vary shearing ratio, with vertical stress of 0.1MPa (CR), vertical stress of 0.2MPa (APP), and test temperature at 25℃, to study the effect of shearing ratio on shear strength. Shear test results are shown in Table 3.

Table 3 Shearing ratio and shear strength

Shearing ratio (mm/min)		3.5	7	10	20	28	50
τ_{max}	CR	0.1912	0.2387	0.2588	0.41	0.4773	0.5801
	APP	0.0442	0.0528	0.082	0.1597	0.1715	0.2598

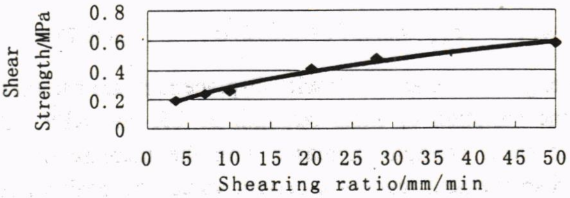

Fig.6 Shearing ratio and Shear Strength/CR

The regression equation obtained from the above two groups of data proves to be a curve of power function, as shown in Fig.6 and Fig 7. The regression equations are shown as follows:

$$CR \qquad \tau_{max}=0.1031V^{0.4} \qquad (R=0.98) \tag{3}$$

$$APP: \qquad \tau_{max}=0.016V^{0.72} \qquad (R=0.97) \tag{4}$$

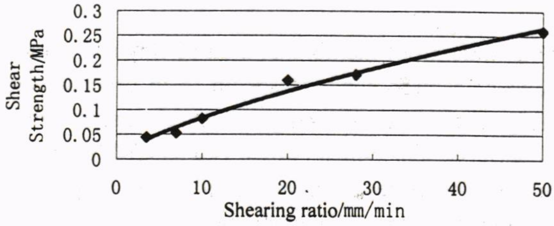

Fig.7 Shear strength and shearing ratio/APP

2.4 Effect of temperature on interlayer shear strength

Hot asphalt is used as interlayer binder in shear test at different temperatures to study the effect of temperature on interlayer shear strength. The test results are shown in Table 4.

Table 4 Effect of temperature on shear strength

Temperature	15	25	35	60
τ_{max}(MPa)	0.6170	0.4119	0.2764	0.1348

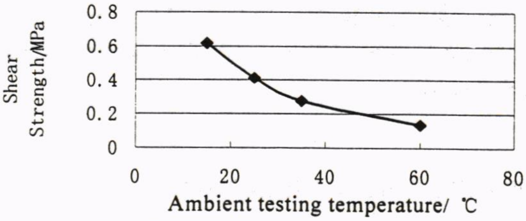

Fig.8 Shear Strength and ambient testing temperature

Test results indicate that τ_{max} at 60℃ equals 1/5 that of 15℃, which means interlayer shear strength decreases greatly (1/6～1/4 that of normal temperature) at high temperature. The ratio of τ_{max} at 60℃ and τ_{max} at 25℃ is about 1/3(the exact value is 0.3273).

The regression curve shown in Fig.8 proves to be a curve of exponent function.

The regression equation is shown as follows:

$$\tau_{max}=0.9639 \cdot 0.9671^{T} \qquad (R=0.98) \tag{5}$$

Where: T= temperature (℃)

2.5 Effect of preparatory condition of bridge deck on shear strength

In the shear test using APP as waterproof membrane, a bit of clay and some water are put on the upper surface of a group of cement concrete specimen in order to study the effect of preparatory condition of bridge deck on shear strength. Test result shows that interlayer shear strength with clean and dry surface of specimen (which is 0.0442MPa) is 19.78% higher than that with dirty and wet surface. Therefore, much attention should be paid to keep dry, clean and even during the construction of waterproof membrane.

2.6 Interlayer distress characteristics

In shear test with APP as waterproof membrane, the inter-layer distress occurs between APP and cement concrete specimen, however the cohesion between APP and asphalt concrete pavement still remains a good condition. As for CR, the interlayer distress occurs between CR and asphalt concrete pavement, but the cohesion between CR and cement concrete specimen is in a good condition. This shows that effort should be made to increase the cohesion between APP and bridge deck of cement concrete where APP is used as waterproof membrane and effort should be made to increase the cohesion between CR and asphalt concrete pavement where CR is used. The same is true with checking computations of shear stress. Shear strength between APP and bridge deck should be used checking index where APP is applied, and shear strength between CR and asphalt concrete pavement should be used as checking index where CR is used.

3. DETERMINATION OF INTERLAYER SHEAR STRENGTH

Analysis of shear test results shows that shear strength is affected by temperature, shearing ratio, vertical stress, the type and content of waterproof membrane, etc. To set up interlayer shear strength index for practical use on the basis of indoor test, the above factors must be taken into account comprehensively.

3.1 Temperature

As we all know that the temperature of asphalt pavement is different from air temperature, and that the internal temperature of asphalt pavement varies with depth. A Japanese named Takayuki believes that the relation between the highest internal temperature (τ_{max}) of asphalt pavement and the temperature of surface of pavement Ts can be expressed as follows.

$$T_{max}=mT_s+b \tag{6}$$

Where: m, b = as shown in Table 5, coefficients related to thickness of pavement

Table 5 Coefficient m, b

h (mm)	25	20	15	10	5
m	0.802	0.804	0.854	0.918	0.980
b	1.702	1.401	0.688	0.303	0.798

The thickness of asphalt concrete layer used in cement concrete bridge deck generally ranges from 5cm to 10cm. From (6) we can get:

$$T_{max}=0.980Ts+0.798 \tag{7}$$

In China the highest temperature of asphalt concrete pavement in summer time can reach 60 ℃ and can keep this high temperature for more than two hours. Considering the most unfavorable condition, let Ts be 60℃. Then

$$T_{max}=0.980\times60+0.798=59.6(℃)\approx60(℃)$$

It can be seen from shear test results that when temperature increases from 15℃ to 60℃, T_{max} decreases by about 80%. Therefore shear strength at 60℃ should be used for determination of the allowable interlayer shear strength, i.e. shear strength at 60℃ is 1/3 as much as that of 25℃.

3.2 Vertical stress

Shear test results show that τ_{max} increases nearly linearly with the increase of σz. So it is believed that interlayer shear strength suits Mohr-Coulomb's theory, i.e. when $\tau \leqslant C+\sigma_z \mathrm{tg}\phi$, inter-layer distress wouldn't occur. Herein c refers to the horizontal cohesive force between asphalt pavement and waterproof membrane and ϕ refers to internal friction angle. From (1) and (2), then

$$C_{CR}=0.1804; \qquad \varphi_{CR}=arctg0.8013=38.71°$$

$$C_{APP}=0.0371; \qquad \varphi_{APP}=arctg0.0327=1.87°$$

Materials on the interlayer surface of flooring are similar to granular materials. The shear strength mainly comes from two aspects, namely, c, the cohesive force between waterproof membrane and asphalt pavement or bridge deck and σ_z tgϕ, the friction force caused by penetration of aggregate into waterproof membrane as well as friction between contacting layers, namely

$$\tau_{max}=f(c,\varphi)=c+\sigma_z \bullet tg\varphi \tag{8}$$

Where: C= cohesive force (MPa), related to shearing ratio, c= c(v);
ϕ= internal friction angle, related to inter layer cohesion condition;
σ_z= vertical stress (MPa)

We can therefore apply c=c(v) to (8), so that

$$\tau_{max} = c(v)+ \sigma \tag{9}$$

In China the structure design of asphalt concrete flooring is the same as that of pavement structure, in which BZZ-100 is standard axle load and vertical stress is 0.7Mpa. Therefore $\sigma_z$tgϕ= 0.7 tgϕ= 0.5609 MPa for waterproof membrane of CR, and $\sigma_z$tgϕ= 0.7 tgϕ= 0.0229 MPa for waterproof membrane of APP.

3.3 Shearing ratio

Under practical vehicle load, instantaneous stress (strain) occurs inside the pavement. This response is affected by various factors. Site tests of strain at the bottom of the asphalt concrete layer in three-layer system pavement have been conducted by Hunan University and Highway Bureau of Henan Province. Testing results show that when the vehicle of model Jie Fang CA10B is running at mediate speed (48km/h), time of applying load to the bottom of asphalt pavement for front and rear tire is 0.05 and 0.083 respectively. According to some analysis, considering the thickness of asphalt layer, the time for applying tire load once (to) can be calculated as follows.

$$lgt_o=lg0.3/v+0.0004h \tag{10}$$

Where: to = time of tire load (s);
v = vehicle speed (m/s);
h = the distance of asphalt layers from pavement surface (mm)

Table 6 Tire loading time

V	km/h	120	100	80	70	60	50	40	30	20	10	5
	m/s	33.3	27.8	22.2	19.4	16.7	13.9	11.1	8.3	5.6	2.8	1.4
t_0 (s)		0.009	0.011	0.014	0.016	0.019	0.023	0.028	0.038	0.056	0.112	0.224

When the thickness of asphalt concrete flooring in cement concrete bridge deck is 5cm, the loading times for different vehicle speeds are shown in Table 6.

Table 7 Shearing ratios at different vehicle speed

V(km/h)	120	100	80	70	60	50	40	30
V (mm/min)	433	354	278	243	205	169	139	102

When subject to instantaneous load, the relative displacement between the bottom layer of asphalt concrete pavement and cement concrete bridge deck is approximately 0.0065cm. From relative displacement and tire loading time (see in Table 6), we can have shearing ratios at different vehicle speeds as shown in Table 7.

According to sharing test, $\tau_{\max}$ increases with the increase of shearing ratio, which forms power function curve. The regression equations are shown in formula (3) and (4). Based on analysis, we have

$$\tau_{max} = f(c, \phi) = c(v) + \sigma_z \bullet tg_\varphi \tag{11}$$

In (11) $\tau_{\max}$ is just related to C and shearing ratio. So it's believed that with the increase of shearing ratio, the increase of $\tau_{\max}$ just results from the increase of C. As for the CR waterproofing membrance, in order to obtain C values with the different V values, equation (1) can be changed to $C = \tau_{max} - 0.8013\sigma_z$. As it can be known from the section 2.3, τ_{max} is the interlayer shearing strength with the different V values under the vertical stress of 0.1 Mpa . Through calculation, the variation of C is shown in Table 8.

Table 8 C at different shearing ratios

Shearing ratio (mm/min)		3.5	7	10	20	30	50
C (Mpa)	CR	0.110	0.1586	0.1804	0.3299	0.3972	0.5
	APP	0.0371	0.0463	0.0755	0.1532	0.165	0.2533

The regression equation obtained from regression analysis of above two groups of date is shown as follows.

$$CR \qquad C = 0.05V^{0.59} \qquad (R = 0.99) \tag{12}$$

$$APP \qquad C = 0.128V^{0.77} \qquad (R = 0.97) \tag{13}$$

The above two regression curves, which are all exponent curves, can be expressed in following formula.

$$C = A \bullet V^B \tag{14}$$

Where: C= cohesive force at a certain shearing ratio (MPa);
V= shearing ratio (mm/min);
A, B= regression coefficients

Modification coefficient kv of shearing ratio can be introduced here, defining as the ratio of the interlayer cohesive force cv at arbitrary shearing ratio and the interlayer cohesive force C3.5 at shearing ratio of 3.5mm/min, namely

$$K_v = \frac{C_v}{C_{3.5}} = \frac{A \cdot V^B}{A \cdot 3.5^B} = (\frac{V}{3.5})^B \qquad (15)$$

It is found that the regression coefficient A doesn't play any role and only B needs to be discussed in which B regressed from different waterproof membranes varies. The modification coefficients kv of c at different vehicle speed from (15) and Table 6 are shown in Table 9.

Table 9 Kv at different vehicle speed

V (km/h)		120	100	80	70	60	50	40	30
K_v	CR	15.61	14.45	13.21	11.89	10.44	8.84	8.84	6.98
	APP	40.29	36.31	32.19	27.92	23.46	18.74	18.74	13.66

3.4 Determination of interlayer shear strength

Based on above calculation and analysis, the corresponding interlayer shear strength τ_{max} under actual vehicle load is obtained as shown in (16), in which effect factors such as temperature, vertical stress, shearing ratio, etc are considered comprehensively.

$$\tau_{max} = K_t \cdot (K_v \cdot c + \sigma_z \cdot tg\varphi) \qquad (16)$$

Where: k_t= modification coefficient of temperature, when the temperature is 25℃ and 60℃, the value of k_t is 1.0 and 0.3273 respectively.
k_v= modification coefficient of shearing ratio, see Table 9;
σ_z= vertical stress, 0.7MPa for general use;
c, ϕ = inter-layer cohesive force, infernal friction angle from shear test.

Table 10 Inter-layer shear strength of different waterproof membrane

V(km/h) Type of Membrane	120	100	80	70	60	50	40	30
CR	0.7507	0.7086	0.6635	0.6155	0.5629	0.5047	0.5047	0.4372
APP	0.4413	0.3985	0.3541	0.3081	0.2601	0.2093	0.2093	0.1546

At the most unfavorable temperature of 60℃, the corresponding shear strength of CR and APP at different vehicle speeds under the standard axle load BZZ-100 from (16) is shown in Table 10.

4 . CONCLUSIONS

4.1 When CR is used as waterproof membrane of bridge deck and the construction method of "laying fiberglass twice and painting CR six times" is adopted, the optimums content of CR ranges from 2.25kg/m^2 to 2.33kg/m^2.

4.2 It's found from indoor shear test that the influence laws of vertical stress, shearing ratio and temperature on interlayer shear strength accord with linear, power function and exponent function relations respectively.

4.3 Through analysis of interlayer shearing distress characteristics, the shear strength between APP and bridge deck should be chosen as checking index when shearing stress is to be checked. As for CR the shear strength between CR and asphalt pavement should be used as checking index.

4.4 Based on a comprehensive analysis of effects on inter layer shear strength of temperature, vertical stress, shearing ratio and type of waterproof membrane, the corresponding calculation formula of shear strength under actual vehicle load at most unfavorable temperature of 60℃ is obtained for the bridge deck waterproof membrane, namely $\tau_{max} = 0.3273(Kv \cdot c + \sigma_z tg\phi)$. Then the corresponding interlayer shear strength at different vehicle speeds for CR and APP is given.

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