DESIGN THEORY AND METHOD OF INTERLOCKING CONCRETE BLOCK PAVING FOR PORT AREAS

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Abstract

Since 1984, the interlocking concrete block pavement has been increasingly used for the paving of port areas, and corresponding studies, including the tests in laboratory and in situ, and the mechanical analysis based on the finite element method, have been conducted in P.R.China. Based on the results of the tests and analysis, the design method with multi_criteria, including deflection, rutting depth and flexural stress at the underside of semi_rigid basecourses, has been developed.

Introduction

In P.R.China, the interlocking concrete block pavement is a new type of pavement. In 1984, the concrete block paving for port areas were constructed in Huangpu harbour, Guangzhou, which is first trial application of block pavement in China. Since then, the block paving has increasingly been used in the port areas because it is more economical and has better suitability to the poor foundations than other forms of paving.

As compared with the design of highway pavements, the port paving have a lot of special features, especially in the considerations of the loads. The range of the loads carried out by port paving are very wide (from 20kN to 500 kN), and the number of load repetitions are much less than on highway pavements. In the structural design of port paving, the concentrated and heavy loads play a dominant role so as to it won't proper if the design criteria, design methods and design parameters for the highway asphalt pavements are directly used for the port paving.

In order to clarify the load spreading mechanism of interlocking block layer and to develop a structural design method of block paving suitable for port areas, author conducted the full scale plate_loading_tests in laboratory and in situ respectively in 1984-1985 and 1991-1992. On the basis of the results of the tests, a model for the mechanic analysis of block paving and corresponding computer software were developed, and in conjunction with the design experience and design custom, the design method and design nomograph for port paving,

which have been incorporated into the "Specifications of Paving for Port Areas", were developed. The following is a brief introduction of this design theory and method.

Structural Behaviour of Block Paving

Arch Effect

Forming of Interlocking The initial interlocking obtained after construction is not stable. Under the repeated loads, the permanent deformation will occur in the bedding sand layer, granular basecourse and subgrade, and the blocks will adjust themselves to a equilibrium state so as to the permanent deformation is transferred to the paving surface. Figure 1 indicates the cumulative curves of paving permanent deformation from which it can be seen that the permanent deformation increases rapidly with the increase of the load repetition during the initial loading period, and then become increasing gradually[1]. Figure 2 illustrates the relationship between p/p_0, the ratio of vertical stress on the top of the basecourse to load intensity and the depth of permanent deformation. It can be seen from Figure 2 that the maximum vertical stress decreases with the increase of the permanent deformation. Therefore, the test results in Figure 1 and Figure 2 shows that with the increase

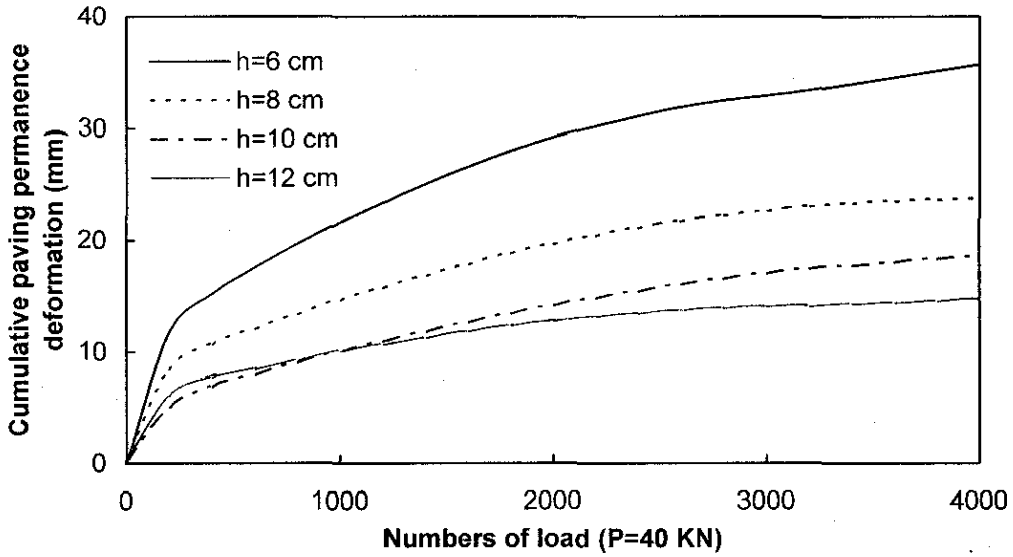

Fig. 1 Relationship between cumulative permanence deformation and load repetition

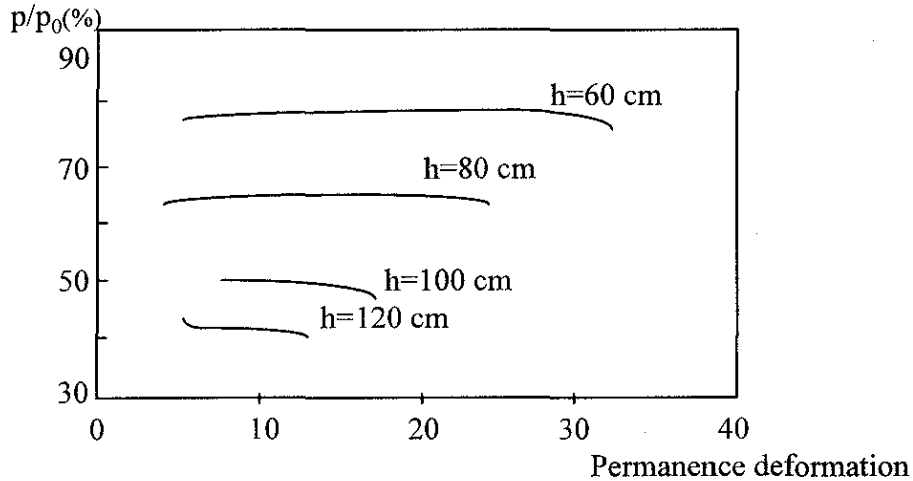

Fig. 2 Effect of permanence deformation on interlocking

of load repetition and permanent deformation, the interlocking among blocks tend to strong and then approach to stable, i.e. the improvement of the interlocking degree among blocks is accompanied with the permanent deformation.

Arch Effect The improvement and stabilising of interlocking provides a requisite condition for spreading loads. Because the blocks are very small in size, and there exist a lot of joints in the surface layer, therefore the load spreading mechanism of block layer must be different with the usual Portland cement concrete pavements and asphalt concrete pavements[2]. Obviously, the bending stresses can not be transferred across the joints, but the interlocking between blocks has an ability to transfer the vertical shear stresses. Therefore, the resistance of joints to shear is a main reason for spreading loads.

In order to clarify how the joints resist to shear stresses, it is necessary to investigate the effects of the resilient deflection of paving. As shown in Figure 3, the loading area covers 3 blocks at least, when the paving surface becomes a basin shape under load, the blocks will have slight rotation, which will be confined by the neighbouring blocks because the block layers have reached a close, equilibrium state. The constraint to the rotation produces a horizontal pushing stresses, as shown in Figure 4, and under the vertical movement trend caused by the vertical loads, the vertical friction, i.e. the resistance to shear occurs in the joints. The greater load, the greater all of the resilient deflection, the rotation and further the horizontal stresses and vertical friction, consequently, the vertical load is spread to larger area.

In the case of the crowned paving, the horizontal stresses between blocks will be more significant, as shown in Figure 5. When loading paving, the point A→A′, the corresponding resilient deflection is D_0, then

$$\Delta L = L - L_1 = D_0 * \sin\alpha \cong D_0 * \alpha$$

Figure 4 and 5 indicate that the block layer can turn the vertical loads to the horizontal pushing forces, this feature can be described as "arch", i.e. the block layer has significant "arch effect" through which loads can be spread. In the process of load spreading, the

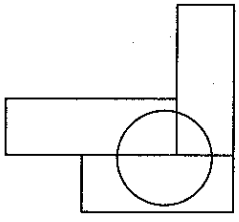

Fig. 3 Load position

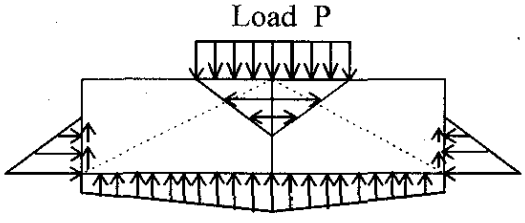

Fig. 4 Arch effect caused by slight rotation of blocks

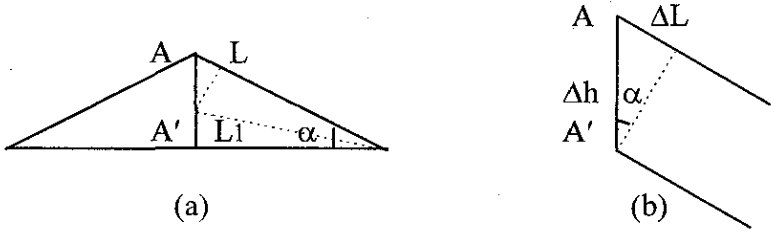

Fig. 5 Horizontal pushing force caused by crown

resilient deflection plays an important role which controls the shear strength in joints, and the spreading of load is accompanied with the resilient deflection.

Axisymmetric performance Table 1 lists an example of the measured resilient deflection basins of paving with different block thickness from which it can be seen that the block paving has an axisymmetric performance[2][3]. This finding provides a basis for the development of the proper mechanic analysis model of block paving.

Table 1 Measured resilient deflection basins of block paving laid in herringbone bond

Thick	Direction														
	0°					45°					90°				
	Distance from load centre (cm)														
	0	20	40	60	80	0	20	40	60	80	0	20	40	60	80
cm	Deflection (0.01mm)														
8	181	102	50	19	6	182	107	47	13	2	182	109	50	20	5
10	168	93	46	13	2	168	94	43	15	6	168	94	46	15	6
12	152	87	45	22	6	152	87	44	27	8	152	84	49	16	7

Shearing Performance in Joints

It can be known from the above analysis that the loads are spread through the shear strength of joints, therefore it is critical for determining the bearing capacity of block paving to clarify the shear performance of joints. Under the vertical loads, ΔD, the shear movement (deflection difference) between both sides of joint is

$$\Delta D = D_{left} - D_{right}$$

where, D_{left},D_{right} is the resilient deflection of left and right side of joint respectively. The measured relationship between τ, shear stress and ΔD, shear movement has been illustrated in Figure 6a, which can be simplified into an ideal form shown in Figure 6b, and τ_p is called as a peak shear strength.

The peak shear strength consists of the plane friction and rough friction, and in the case of block paving, the plane friction plays a dominant role. When the horizontal pushing stresses are different, ΔD_p,the shear movement corresponding to τ_p will have different feature based on which the shear failure of joints can be categorised to 2 typical modes, i.e. the fixed modulus mode and the fixed movement mode, as shown in Figure 7. The fixed modulus mode means that with the increase of the horizontal pushing force between blocks, ΔD_p increases (Figure 7a) and the shear modulus keeps constant, while the fixed movement mode means that with the increase of the horizontal pushing force, the shear modulus increases and the ΔD_p keeps constant. The test results show that the shear failure mode of joints with parallel sides is in agreement with the fixed movement mode.

The shear modulus and shear strength are relative to the horizontal pushing force, which is caused by the "arch effect" in block layer, while the "arch effect" is dependent of the resilient deflection of paving. Therefore, the resistance of joints to shear can be described indirectly with the resilient deflection of paving.

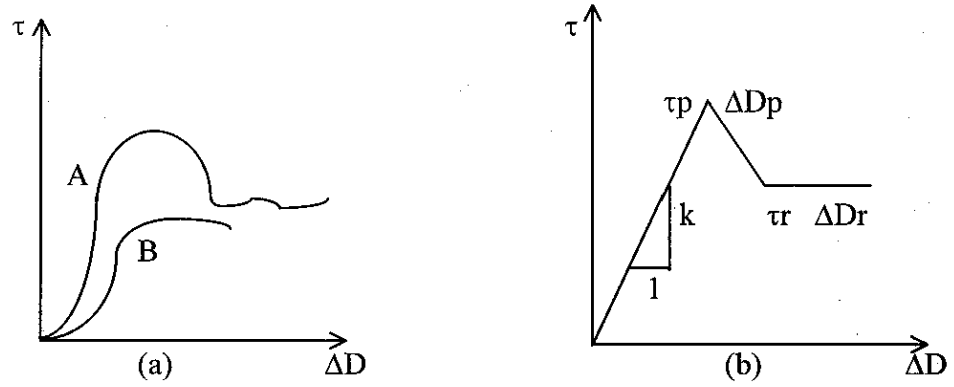

Fig. 6 Mechanic features of joints

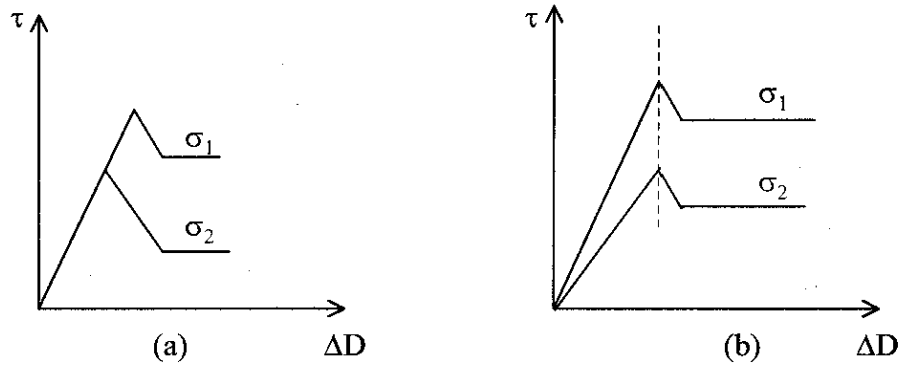

Fig. 7 Typical failure mode of joints

It can also be seen from Figure 6 and 7 that the relationship between τ and ΔD is linear when $\Delta D \leq \Delta D_p$, therefore the shear performance of joints can be described with Goodman model, i.e.

$$\tau = k_j * \Delta D$$

where, k_j is the shear modulus of joints, which is a function of the horizontal pushing force (resilient deflection).

Typical Load_Deflection Relationship

The load_deflection relationship of block paving indicates not only the mechanic performance of entire paving structure, but also particular performance of block layer. Usually, with the increase of P, the load magnitude, the deformation rate of road material commonly used will be faster and faster, but in the block paving, the "arch effect" make the horizontal pushing stress greater and shear modulus between blocks stiffer, and further make the deformation (deflection) increment become less. In fact, the features of the load_deflection relationship shown in Figure 8 are the sum of two structural behaviour, i.e. one is the behaviour of the paving foundation (basecourse and subgrade), which deflection increment is faster and faster, and another is the block layer, which will be stiffer and stiffer, with the increase of the load (or deflection). It can also be seen from Figure 8 that in the initial loading stage, the overall modulus of the paving structure increases with the increase of the load (deflection), which means that the stiffening rate of the block layer is more than the decrease rate of foundation modulus, therefore the shape of the load_deflection curve is controlled by the performance of block layer. In the medium stage, the trend of modulus

increase of paving structure becomes less so as to the load_deflection relationship approaches straight line, which means the stiffening rate of block layer is nearly same with the rate of decrease of foundation modulus. The final stage is reverse with the initial stage, in this stage, the shear movement in joints have exceeded ΔD_p.

Critical State and Critical Deflection

The critical state is corresponding to the point C in Figure 8 where the two_tail differential $\Delta^2D/\Delta^2P=0$. Using this result, the critical deflection can be determined, as shown in Figure 9, and the determined critical resilient deflection is 2.0 mm.

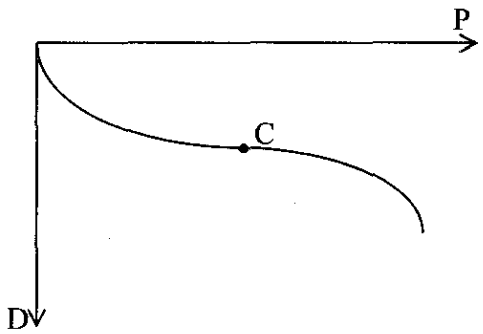

Fig. 8 Typical of load _deflection relationship

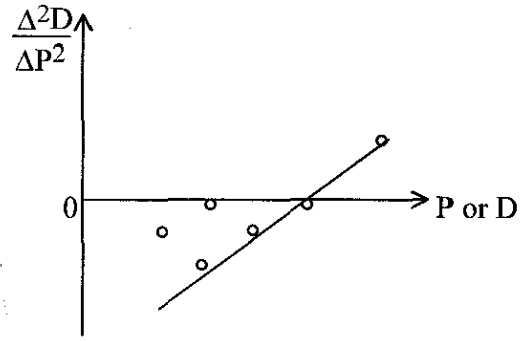

Fig. 9 Method of determining the critical deflection

Mechanic Model and Analysis Method

Mechanic Model

It is known from the above analysis that although the block layer is not geometrically axisymmetric, the deflection basins measured on paving surface exhibit the circular form. Accordingly, the block paving structure can be idealised as a space axisymmetric model (Figure 10). The following assumptions are taken for the various components of this axiymmetric structure[3]:

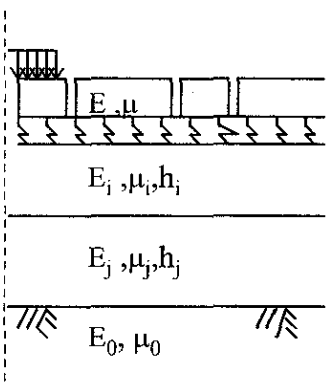

Fig. 10 Mechanic model for block pavement structure

a. The concrete blocks are an elastic material characterised by E, its Young's modulus and μ, Poisson's ratio.

b. Only shear stresses can be transferred across the joints between blocks, and the

relationship between τ, shear stress and ΔD, shear movement across the joint is assumed to follow Goodman model.

c. The bedding sand layer is represented by a set of springs.

d. The base, subbase and subgrade is a linear_elastic, homogeneous multilayer system characterised with E, resilient modulus and μ, Poisson's ratio.

e. The interface between block layer and bedding sand layer as well as between bedding sand layer and basecourse are frictionless.

Structural Analysis

Based on the analysis described above, BLKPAVE, a computer software(Finite Element Method) for the structural analysis of block paving was developed, with which the effects of joints shear modulus and the bedding sand spring coefficient on the deflection of paving have been analysed. Figure 11 illustrates an example of analysis results from which it can be seen that when the shear modulus of joints is small, the effect of changing the bedding sand coefficient on the deflection is significant, but with the increase of the shear modulus of joints, the effect of bedding sand coefficient become less.

By matching the measured and computed deflection basins, the shear modulus of joints and bedding sand coefficient can be determined. Based on the analysis of above, the shear modulus of joints is a function of the deflection. However, the deflection of paving in normal work conditions is between 1 and 2 mm, in this case, the load_deflection relationship is almost straight line, therefore the shear modulus of joints and bedding sand coefficient are treated as constant for analysing with ease, i.e. k_j, the shear modulus of joints is 20MPa, and

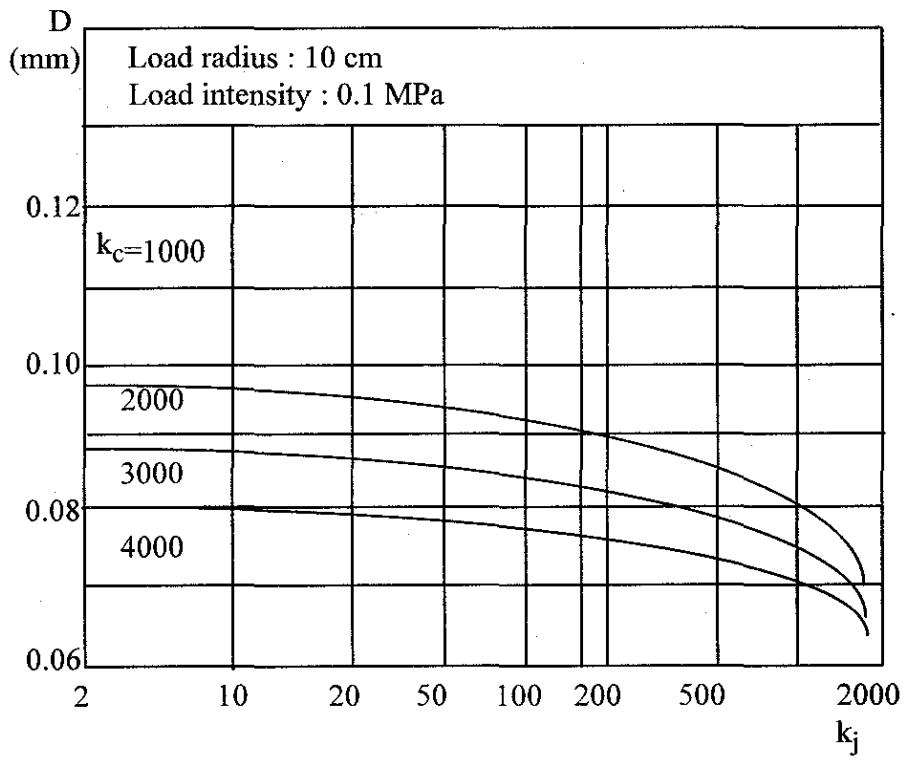

Fig. 11 Relationship of k_j, k_c and surface deflection

k_c, the bedding sand coefficient is 3000 MPa/M. The basecourse, subbase and subgrade moduli are obtained from test results, and the modulus of blocks is taken as 35000MPa.

Load Considerations

The types of vehicles for handling containers or other goods are very complex, the wheel loads are widely distributed from 20kN to 400kN, and the pressures of pneumatic tyres are between 0.30 MPa and 1.33 MPa. On the other hands, the vehicle traffic is not channelized, therefore the load considerations in highway can not be directly used in port areas.

In order to simplify the load considerations, the vehicle types and the wheel configurations were investigated based on which the vehicle loads were classified into 6 classifications, as listed in Table 2[4]

Table 2 Classifications for Operation Vehicle Loads

Load class	range of load (KN)	Standard load		
		load (KN)	contact area (cm^2)	contact pressure (MPa)
P1	30~70	50	715	0.70
P2	70~130	100	1000	1.00
P3	130~180	150	1500	1.00
P4	180~250	200	2000	1.00
P5	250~350	300	3000	1.00
P6	>350	400	4000	1.00

For the container loads, the laden rate of containers are considered, and the classification is listed in Table 3.

Table 3 Considerations of Container Loads

Storeys	Weight discount (%)	Contact pressure (MPa)	Load (KN)		
			single	column	block
1	0	2.59	76.2	152.4	304.8
2	10	4.67	137.2	274.3	548.6
3	20	6.23	182.9	265.8	731.5
4	30	7.27	213.4	426.7	853.4
5	40	7.78	228.6	457.2	914.4

Structural Design Method

Design Criteria

The different design criteria are used for the design of block paving with different base materials. For the paving structures with granular basecourse, the permanent deformation and shear failure under concentrated load along the joints are two main failure modes. The permanent deformation caused by the earlier compaction of the bedding sand layer and the accumulation of the plastic deformations in base, subbase and subgrade under the repeated loading, will deteriorate the performance of paving and will bring the adverse effects in the drainage and bearing capacity of paving. If the base, subbase and subgrade is too weak to sustain the concentrated loads, the shear stresses in joints will probably be greater than the shear strength offered by the friction between blocks, so that the shear failure will occur in the block layer, even with the individual block being punched into the bedding sand layer and basecorse. Therefore, two design criteria, i.e. rut depth to control the performance of paving and resilient deflection to control the shear failure above, are used for the design of the block

paving structure with granular basecourse.

Considerable permanent deformation will not occur in the block paving with semi_rigid base, however the fatigue cracking will occur under repeated loading, which may damage the monolithic stiffness of the base, and lead to severe rutting and shear failure of the block layer. Therefore, the maximum flexural stress under the concentrated load and the maximum fatigue flexural stress under repeated load at the underside of the basecourse bottom are considered as a criteria for the paving with semi_rigid base.

Estimation of Rutting Depth

It can be known from the test results that the accumulation of the permanent deformation depends on the magnitude of loads, the bearing_capacity of structure, the thickness of block layer as well as number of load repetitions, while the rutdepth is relative to both the accumulation of permanent deformation and the lateral distribution of vehicle loads. Based on the regression analysis of test results, the following formula is used for the estimation of the rutdepth[5]:

$$RD=961C\bullet D_0\bullet p_0^{-0.16}r_0^{-2.21}e^{(-0.24D_0-0.11h)}N^{0.265}$$

where, RD is rutdepth, in mm; D_0 is resilient deflection, in mm; p_0,r_0 is load pressure, MPa and equivalent radius of loaded areas, in cm, respectively; h is the thickness of block, in cm; N is number of load repetitions; and C is wheel configuration coefficient, C=1 for single wheel and C=1.17, 1.25 and 1.34 corresponding to h=8,10 and 12 cm for dual wheels.

Where a large number of load repetitions are applied, the rutdepth will control the design thickness of paving, therefore the various loads have to be converted into the standard load , which has been defined in Table 2. The conversion formula of loads is as follows:

$$\eta i=C_1\bullet(L_i/L_S)^{3.77}\bullet(p_S/p_i)^{0.59}\bullet(r_S/r_i)^{8.35}\bullet e^{0.92(Ls-Li)}$$

where, p_S, r_S and Ds is the pressure, radius and resilient deflection of standard load; p_i, r_i and D_i is the pressure, radius and resilient deflection of i_th load; C_1 is the coefficient having the following values: C_1=1 when converting between single wheels and between dual wheel loads; C_1=0.5530, 0.4308 and 0.3314 for h=8,10 and 12 cm when converting from single into dual wheel load respectively.

Allowable Value of Design Criteria

The allowable rutdepth is determined based on the empirical method, and it is different in different areas of port. In the road pavement of port, the allowable rutdepth is 30 mm, while in the stacking areas, the allowable rutdepth is taken as 60 mm. The allowable deflection of paving is 2 mm, as described above. The flexural strength of the semi_rigid basecourse is determined with test, which will be used for the structural design of paving in stacking areas. In the areas carrying out the repeated loads, the fatigue flexural stress at the underside of bottom will be considered, and the fatigue equation of the semi_rigid material uses the results in "Specifications for Asphalt Pavements Design", i.e.

$$\log(\sigma/S) = 0.398 - 0.11\log N$$

Design Nomograph

Using the method described above, the design nomograph for different paving with different function and with different base type can be plotted for designing with ease, and Figure 12 is an example.

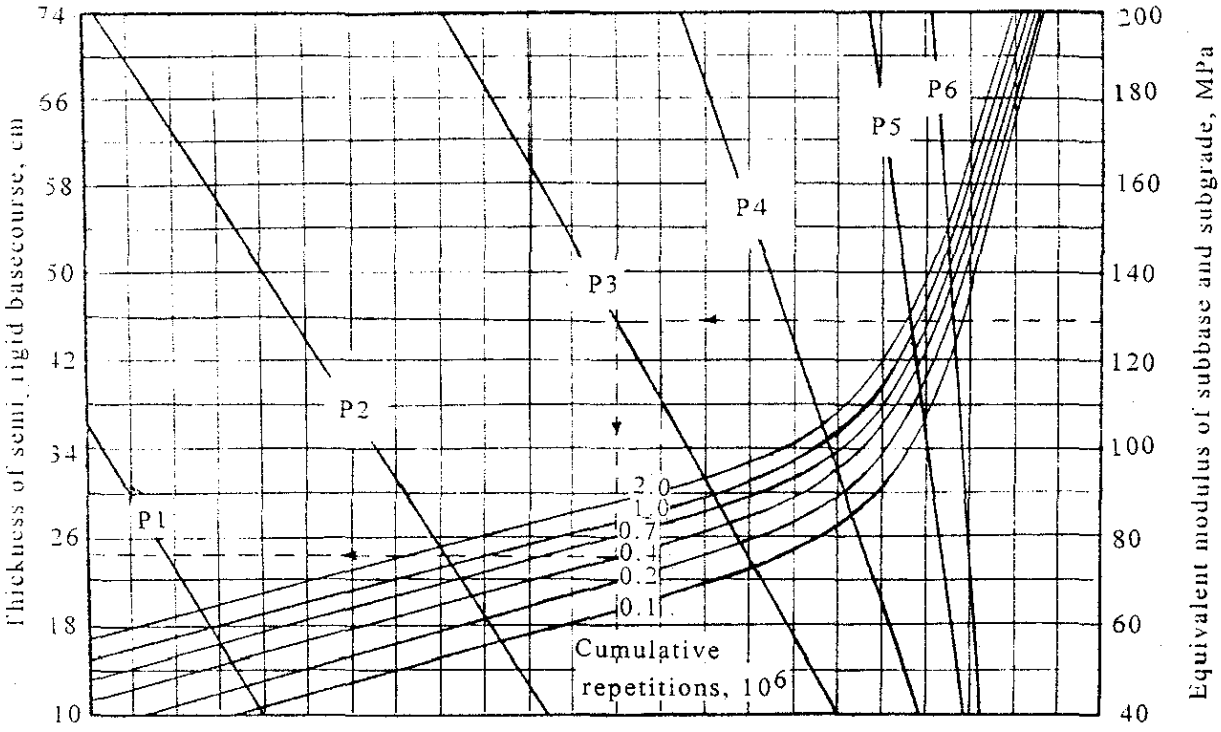

Fig. 12 Design nomograph (Semi_rigid basecourse, Operation vehicle loads)

Concluding Comments

The design theory and design method of concrete block paving is a new research field in China although in other country the researches and applications have a long history. So far, several port areas have been laid with the concrete blocks, a few trial uses have been conducted in the urban road and bridge approaches, and it is to be expected that the more and more concrete block paving will be used in both port and road engineering.

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