Influence of Type and Thickness of Cement-Concrete on the Calculation of Rigid Road Surfaces with Asphalt-Concrete Pavement

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Abstract. The article is based on the example of calculations of options for hard pavements with asphalt concrete pavement according to regulatory documents in force in the Russian Federation, the results of a study on the dependence of the thickness of the cement concrete layer on the quality of the cement concrete mix are presented in this article. A comparison was made of the thickness of cement-concrete slabs, obtained as a result of calculation according to our "Guidelines for the design of rigid pavements" with similar designs recommended by the "Road Design Guide" of the state of California. Conclusions are drawn on the need to improve the methods of calculating rigid pavements in the Russian Federation, allowing to take into account more parameters, including those associated with new technologies for the preparation of cement-concrete mixture and its paving.

1. Introduction

The main structural element of a hard pavement is a cement-concrete slab (monolithic or prefabricated), from which the pavement or base is made. It is with cement-concrete that the main advantages of a hard pavement are correlated: strength and durability [4]. Therefore, one of the basic calculations of a hard pavement is the calculation of the thickness of the cement-concrete slab. In this article, on the basis of the example of calculations of rigid pavement with asphalt-concrete pavement and cement-concrete foundation, the methods for calculating a cement-concrete slab using methods used in the Russian Federation and in the United States of America are considered.

2. Current importance

Currently, due to the increasing traffic intensity on the country's roads, increasing the carrying capacity of vehicles, as well as increasing the standard service life of pavements, the problem of preferable use of rigid pavements in the construction and reconstruction of highways is becoming more and more apparent. Research of many modern scientists is devoted to this problem: V. Silyanova [8], A.P. Vasiliev [9,10], B.S. Radovsky [6,7], E.T. Savchenko [11], I.E. Ilina [12], A.P. Vinogradov [13] and others. Therefore, the methods of calculating hard pavements, the determination of factors affecting the thickness of the cement-concrete layer, durability and structural strength are of interest.
3. Formulating the problem
In the Russian Federation, the calculation of rigid pavements is carried out according to the “Guidelines for the design of rigid pavements”. Many parameters are taken into account in the calculation: traffic intensity, loads, road category, road-climate zone, etc. [5]. As well as the calculated and regulatory characteristics of cement concrete, from which the bearing layers are arranged.

The method of calculating rigid pavement surfaces of the American Association of State Highway and Transportation Officials (AASHTO) [14] has become widespread abroad. This technique or its analogues are actively used in North and South America, as well as in some countries of Europe and Asia [7].

As part of this work, we will calculate the thickness of the cement-concrete base for hard pavement type with asphalt-concrete pavement using cement-concrete of various strength. And also compare the results with the thickness of the cement-concrete slab recommended method AASHTO.

4. Theoretical section. Examples of calculating road surfaces with asphalt-concrete pavement
We give examples of the calculation of rigid pavement in the Krasnodar region in accordance with the "Guidelines for the design of rigid pavement" and compare the resulting design with the structures used in the United States.

The initial data for the calculation is the following:
- Calculated axle load 115 kN (GOST R 52748-2007 "Public roads. Regulatory loads, load calculation schemes and approximation dimensions").
- Accordingly, the calculated load on one wheel \( Q = 57.5 \) kN.
- The number of applications of the calculated load for 25 years per one lane of the carriageway is \( N_{sum} = 15 \) million. The formula calculation is carried out by checking the tensile strength of the coating during bending.

System No. 1:
- The coating is two layers of asphalt-concrete, the upper one of fine-grained grade 1 with bitumen brand: BND 60/90 \( E = 4500 \) MP, the thickness is \( h = 6 \) cm, the lower one is coarse-grained with bitumen brand BND 60/90 \( E = 2800 \) MPa, with a thickness of \( h = 12 \) cm.
- Base - concrete class Btb 4.4; \( E_1 = 36000 \) MPa; thickness \( h_1 \) must be determined by calculation.
- Additional base - crushed stone 40-80, \( E_2 = 450 \) MPa, \( h_3 = 25 \) cm.
- Additional base - medium sand, \( E_3 = 120 \) MPa, \( h_4 = 50 \) cm.
- The soil of the roadbed is light loam, \( E_4 = 34 \) MPa.

The calculated load on the wheel, taking into account the dynamics \( Q_{dp} = 57.5 \times 1.3 = 74.75 \) kN, at a pressure of \( p = 600 \) kPa, the diameter of the calculated print is \( D_{tire} = 0.398 \) m.

The overall module of the structure under the concrete slab is calculated using the M.B. Korsunsky approximation formula:

\[
E_{eq} = \frac{E_i}{0.71 \left( \frac{E_i^{(i+1)}}{E_i} \right)^{\frac{1}{3}} \arctg \left( \frac{1.35 \times h_i}{D_{tire}} \right) + \frac{E_i}{E_i^{(i+1)} + 2 \pi \arctg \frac{D_{tire}}{h_i}}} 
\]

where the conditional diameter of the stamp in the layer-by-layer reduction of a two-layer half-space to a uniform one is taken to be equal to \( D_{tire} = 0.50 \) m; index \( i \) refers to the upper layer of the successively considered two-layer systems, and index \( (i + 1) \) refers to the base below it. Consistently applying the formula, we find:
- equivalent module at the surface level of additional sand base \( E_{eq} = 76.18 \) MPa,
- equivalent module at the surface level of additional sand-gravel base \( E_{eq} = 152.32 \) MPa.

Therefore, the total construction module under the cement concrete slab is \( E_0 = 152.32 \) MPa. The coefficient of transverse deformation of the equivalent base under the slab becomes \( v_0 = 0.30 \). Now it is necessary to determine the bending stress of the concrete slab and calculate the required thickness, based on the strength of the concrete.
We find the calculated tensile resistance of concrete to bending. According to the formula, the coefficient of concrete fatigue at repeated loading is determined by the dependence

\[ K_{fat} = 1.08 \cdot (\sum Np) - 0.063 \]  

(2)

In fact, this coefficient \( K \) is the value of the ratio of stress to strength, at which the sample tested for fatigue withstands \( \sum Np \) repeated load applications.

We calculate the fatigue coefficient \( K_{fat} = 1.08 \cdot (15 \cdot 106) - 0.063 = 0.441 \)

This means that the margin for concrete fatigue should be at a given total number of load applications (15 million) not less than \( 1 / 0.441 = 2.27 \).

\[ R_{bt} = 4.4 \cdot 1.2 \cdot 0.441 \cdot 0.95 = 2.212 \text{ MPa} \]

The slab must be of such thickness that the tension in it from bending stretching is less than 2.212 MPa. We set the plate thickness to 23 cm.

According to the formula (5a), we calculate the elastic characteristic of the plate at \( h = 0.23 \text{ m} \), \( E = 36000 \text{ MPa} \), \( v = 0.20 \), \( E_0 = 164.43 \text{ MPa} \), \( V_0 = 0.30 \).

We obtain \( L_e = 0.7595 \text{ m} \). In this case, the radius of a wheel print with a load \( Q = 74.75 \text{ kN} \), with a pressure of \( p = 600 \text{ kPa} \), is \( c = 0.199 \text{ m} \).

The design concrete resistance \( R_{bt} \) class \( B_{tb} = 4.4 \) stretching when bending according to the formula:

\[ R_{bt} = B_{tb} \cdot K_{np} \cdot K_{fat} \cdot K_F \]

(3)

Where \( B_{tb} \) - concrete class tensile bending; \( K_{np} \) - the coefficient of strength with time; for concrete of natural hardening for areas with a temperate climate.

\( K_{np} = 1.2 \); \( K_{fat} \) is the coefficient of concrete fatigue upon repeated loading calculated by us above;

\( K_F \) - coefficient taking into account the effects of alternate freeze-thaw, equal to 0.95.

The Gorbunov-Posadov formula is implemented in order to find the load. And to theoretically calculated load, we introduce several coefficients:

\[ \sigma = \frac{K_I \cdot K_{con} \cdot K_{pin}}{K_t} \cdot \sigma_{gp} \]

(4)

Where \( K_I \) is the coefficient taking into account the influence of the location of the load; for unreinforced coatings \( K_I = 1.5 \);

\( K_{con} \) is the coefficient which takes into account the working conditions; \( K_{con} = 0.66 \); \( K_{pin} \) - coefficient taking into account the effect of pin connections on the conditions of contact of the plates with the base; in the presence of transverse seams of pins \( K_{pin} = 1 \); \( K_t \) - the coefficient which takes into account the effect of temperature warping of the plates, determined by the table depending on the road-climatic conditions and the thickness of the plate, for the natural conditions of these conditions.

We receive the load calculation result:

\[ \sigma = \frac{1.5 \cdot 0.66 \cdot 1}{0.73} \cdot 1.407 = 1.908 \text{ MPa} < R_{bt}^{calc} = 2.212 \text{ MPa} \]

(5)

The calculation is finished. We have calculated a plate thickness of 23 cm.

System No. 2:

The coating is two layers of asphalt-concrete, the upper one of fine-grained grade 1 with bitumen brand BND 60/90 \( E = 4500 \text{ MP} \), the thickness is \( h = 6 \text{ cm} \), the lower one is coarse-grained with bitumen brand BND 60/90 \( E = 2800 \text{ MPa} \), and \( h = 12 \text{ cm} \) thick.

Base - concrete class Btb 3,2; \( E_1 = 30000 \text{ MPa} \); thickness \( h_1 \) must be determined by calculation.

All other data remains the same.
We carry out the same calculations as in the first variant, but for concrete of class Btb 3,2. And as a result we get a cement concrete slab with a thickness of 26 cm.

Then we make the calculation of asphalt concrete pavements on concrete foundations, which must be "produced according to two conditions:
* crack resistance of asphalt concrete pavement in the coldest month of winter;
* strength - the ultimate resistance of the coating and the base to repetitive loads from motor vehicles "[1].

The thickness of the asphalt concrete pavement is also determined by the "Guidelines for the design of rigid pavements."

![Figure 1. An example of two pavement designs, calculated according to Russian standards:](image)

- a) 1 - a two-layer coating of asphalt-concrete with thickness h = 6 + 12 cm;
- 2 - cement-concrete base h = 23 cm;
- 3 - base of crushed stone h = 25 cm;
- 4 - sand base h = 50 cm;
- 5 - roadbed from light loam
- b) 1 - two-layer coating of asphalt-concrete with thickness h = 6 + 12 cm;
- 2 - cement-concrete base h = 26 cm;
- 3 - base of crushed stone h = 25 cm;
- 4 - sand base h = 50 cm;
- 5 - roadbed from light loam

So, the calculations made allow us to draw the following, quite expected conclusion: with a decrease in the strength characteristics of concrete, the thickness of the cement concrete increases.

Now we will compare the structure calculated by us with those structures that are used in the United States of America for roads with traffic of similar intensity. Here for many years the calculated load on the wheel was 40 kN (80 kN per single axis). The total number of applications of 15 million axial loads of 115 kN corresponds approximately to 15 × 10^6 × (115/80) = 64 × 10^6 applications of single axes of 80 kN. This is quite heavy traffic.

We investigate what the California Road Design Guidelines recommends for such a load [15, 16].

The passage of 64 million axles with a load of 80 kN corresponds to the California Traffic Index (TI - Traffic Index) TI = 14.75.

There are two options for thick pavement. The first of these refers to the construction with lateral support (lateral support) along both longitudinal seams, when, firstly, the plate is connected to the adjacent plate of the roadway with steel anchors, and secondly, it is connected by steel pins to the concrete shoulder or has a wider plate. The second value relates to a structure that does not have lateral reinforcement on both sides, and it can be seen that in this case the plate should be 3 cm thicker [6].

From this it is seen that for such a load in Southern California on the loamy soil of the roadbed it is recommended to design the following road pavement:
- cement-concrete coating – 27 cm or 30 cm (we have 23 cm);
- additional base of crushed stone of the second class - 21 cm (we have calculated - crushed stone 25 cm + 50 cm - sand).

We see that in the United States the thickness of cement concrete pavements is greater than that obtained when calculating in accordance with the standards adopted in Russia.

Figure 2. Examples of typical hard pavement designs in California:

1 - cement concrete floor with seams and pins in the seams;
2 - continuously reinforced coating without transverse seams;
3 - lean cement concrete base;
4 - base of hot dense asphalt concrete with a maximum grain size of 19 mm;
5 - additional base of crushed stone of the second class with a maximum particle size of 70 mm, which can contain up to 50% of crushed old asphalt concrete or cement concrete;
6 - subgrade of fine dusty sand, silty sandy clay or dusty loam with a plasticity number less than 12.

5. Practical significance. Suggestions
The difference in the calculated thickness of the cement-concrete layers obtained in calculating rigid pavement using various methods is fully explained by different approaches to the solution of the problem. The methodology proposed by AASHTO relies mainly on the experience of building hard-surface roads that they have accumulated over the years, as well as building experimental plots at research sites. Due to this, most of the parameters used in the calculations are obtained not so much by theoretical as by empirical method. Moreover, these parameters are constantly updated. In the Russian regulatory documents, in the same “Guidelines for the design of rigid pavement”, there are also parameters that are obtained empirically. But they have been studied many years ago and do not always reflect the current state of things.

Take, for example, our calculations. We found out that the thickness of the cement-concrete layer of rigid pavement depends on the quality of the cement-concrete used in its design. However, the methods for preparing the concrete mix and its quality have changed over time. The modern approach to the production of concrete provides for the improvement of their rheological properties through the use of various effective complex modifiers that can provide high strength and durability. Modifiers are quite versatile in their application, they are suitable both to increase the strength and density of concrete, and to improve its water resistance. Thanks to them, the amount of water in the mixture can be reduced by 30%, and at the same time the mixture will retain its mobility, which allows to obtain concrete with a slight shrinkage. That is, modern cement concrete differs from traditional cement concrete, which was used in the construction of roads in the 50-80s of the last century. However, in modern calculations of rigid pavements used in Russia this is not taken into account.
6. Conclusion
The advantages of a rigid pavement over a pavement of a non-rigid type are generally known. These include: a large bearing capacity, durability, increased resistance to aggressive media [3]. However, at present, in accordance with our regulatory documents, we use the theoretical base of 50-70 years ago, which does not fully take into account modern technologies for the production and laying of cement-concrete mixtures, for calculating hard pavement.

In other words, we can say that the method of calculating rigid pavements in our country currently lags far behind the existing realities and does not take into account the diversity of the changes taking place. To eliminate this lag, it is necessary to return to a comprehensive solution of the problem by calculating rigid pavements. It should be based both on theoretical studies that take into account new building materials and construction methods, as well as practical experience in modern construction of structures, including experimental ones. This in turn will make it possible to more effectively use rigid pavement for solving such tasks as increasing the strength of pavements for their durability and resistance to negative environmental influences.

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