Improving the regulatory framework for the design of rigid pavements

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Abstract. The study analyses local and foreign experience and trends in the field of improving the design of rigid structures of road pavements with the aim of a significant increase in their reliability and durability. It is shown that while ensuring the necessary quality of construction and timely completion of the full list of works on the current maintenance and repair of the construction of rigid pavements, they can serve without major repairs for 50 years or more. Based on the analysis, it was found that structures with a cement-concrete coating thickness of more than 30 cm on highly stressed highways have a resource of more than 100 million standard axial impacts. One of the factors hindering the practical implementation of new solutions is the lag in the development of the theory of calculation and the difficulty in determining the parameters necessary for calculation that characterize the properties of materials, taking into account their heterogeneity and variability during the designed service life. A catalog of rigid pavement designs is proposed based on the predicted number of standard axial impacts for the design life of the structure before overhaul.

1. Introduction
A significant increase in the reliability and durability of pavement structures requires a detailed analysis of the accumulated experience, taking into account the full life cycle, including the processes of calculating and designing pavements, construction technology and organization, construction quality control, activities carried out in the process of repair and maintenance of roads.

The inconsistency of the situation lies in the fact that the design life of pavements with asphalt coatings for a long time was defined to be in the range of 10–18 years, and that of pavements with cement concrete coatings was 25–30 years. These terms were used by specialists in the process of calculating and designing pavements, when determining the total number of impacts of wheel loads, by checking the coating materials for fatigue strength, for shear in the subgrade, and for the stability of the structure against frost heaving.

Based on these terms, the requirements of the standards for building materials used in the construction of pavements were established. These terms served as the guidelines in the selection of criteria for assessing and monitoring the quality of construction of the subgrade and layers of pavement. Funds for the repair and maintenance of road surfaces were mostly planned based on the indicated terms as well.

However, many examples can be given of the fact that long before the expiration of the design service life, cracks, ruts, potholes, ledges and other damages appear on the surface of the carriageway. As a result, the need for repair occurs before the expiration of the standard terms and the necessary repair work is postponed to a later period.
As local and international experience shows, the most important feature of roads is their heterogeneity along the length of the road. This leads to the fact that at almost any object, individual sections of road surfaces are destroyed before the design service life; however, others endure much longer. According to Figure 1, 10% of asphalt concrete pavements require repair after 7 years, while 10% of cement concrete pavements require repair after 20 years.

![Figure 1. Service life of asphalt concrete (1) and cement concrete (2) pavements on German federal highways](image)

An analysis of the reasons for the difference in design and actual pavement life [1, 2] showed that the totality of all reasons can be divided into the following four groups:

- actual deviations of the values of the intensity and composition of the movement during operation from the predicted values adopted in the design process;
- the actual deviations of the parameters of the constructed structures from those provided for by the project, as well as the heterogeneity of the subgrade and materials for road pavement, often significantly exceeding the guideline values;
- deviations of the actual parameters of atmospheric processes, mainly changes in temperature and the amount of precipitation, during operation from long-term average values accepted in the calculation and design of pavement;
- deviations in the quality and terms of the actually carried out repair and maintenance measures from those stipulated by current standards and rules.

Considering the first group of reasons, one should pay attention to the technological progress and the efficiency of road transport being the most often associated with an increase in axial loads, because it is the factor that allows the most appreciably and at the lowest cost increasing the carrying capacity of vehicles and their economic efficiency. But even under limited axial loads, increasing the number of axles and developing multi-axis trucks and road trains allows raising the carrying capacity to 50 tons and more. Freight and passenger considerably change over 25–30 years, which leads to large deviations in the actual intensity and composition of traffic in comparison with those values adopted in the calculation of pavements.

The second group of reasons includes possible deviations in the design of the subgrade and pavement in comparison with the parameters adopted in the project. This applies primarily to deviations in the thickness of individual structural layers and the significant heterogeneity of the applied subgrades and building materials. It is important to emphasize that most of these deviations are completely natural and are determined by the natural features of the starting materials, the designs and capabilities of road-building machines and equipment for the production of materials and construction technology.
As a result, there are regulated tolerances for deviations of the actual structural parameters and physico-mechanical properties of the materials embedded in them. It is also impossible to exclude unregulated and unacceptable deviations that are the result of violations of technology, the use of low-quality materials and the limited information received in the process of quality control of construction.

As a result, the parameters of the implemented facility differ from those provided by the project and, accordingly, we should expect a decrease in the service life in comparison with the design values.

The third group of reasons includes a set of atmospheric effects that cause changes in temperature and humidity of the subgrade and materials in the layers of the pavement structure. The temperature and shrinkage stresses in the layers with cement depend on how temperature and humidity change, as well as the stiffness and strength of the layers with bitumen. Abnormally high temperatures over a long period can cause large-scale damage on a large part of roads with asphalt pavement due to a significant decrease in the strength of asphalt concrete layers.

The decrease in the strength of materials as a result of alternate freezing and thawing depends on how the meteorological conditions are formed in a particular year or season. The change in the deforming properties and strength of the soil base depends on the duration of the period of autumn moisture accumulation, the intensity of freezing of the soil, the number of thaws in the winter period and the temperature behavior during thawing. These processes are characterized by their own characteristics, depending on the meteorological conditions prevailing in each specific year.

A significant dependence of the strength of materials on their moisture content should be noted as well. An objective assessment of the health of the material should be based on an analysis of the relative duration of its work in the structure in a dry, moderately moist and water-saturated state.

The fourth group of reasons includes deviations from routine maintenance of the road during operation, most often due to insufficient or untimely financing. The regulations envisage the implementation of a sufficiently large number of measures, including the cleaning of the roadway from dust and snow, the uniform distribution of deicing agents on the surface of the roadway, the timely restoration of roughness, the filling of joints and cracks with mastic or bitumen, the sealing of individual irregularities and potholes, and others. The delay in these measures significantly complicates the working conditions of the structure, increases the level of stresses and increases the intensity of destruction. The presence of irregularities increases the load on the structure due to vertical vibrations of vehicles.

The delay with closing cracks and joints in the coatings contributes to their filling with mineral particles and water, which causes the formation of potholes. Untimely patched potholes a significant part of the time are filled with water and, accordingly, create a spot of excess moisture. All this as a result activates the process of accumulation of damage and reduces the service life.

From the above it follows that there is a set of objective reasons that are underconsidered in the road pavement design, which leads to a significant difference between the design and actual service life. It is important to emphasize that the degree of responsibility for premature destruction at each stage of the investment cycle “design, construction, operation” is uncertain, which cannot be considered satisfactory, since excludes targeted elimination of the destruction causes.

A detailed analysis of the results of long-term monitoring of the condition of road surfaces on roads in our country and abroad also showed that at many objects there are separate sections of roads on which the surfaces last much longer than the standard service life. This circumstance served as the basis for the formulation of a wide range of studies in the direction of a significant increase in the durability and service life of pavement.

2. Problem statement
Taking into account the general tendency to increase the service life of pavement, in 2000 the Alliance of Asphalt Concrete Pavements of the USA proposed the concept of Perpetual pavements [3]. Perpetual pavements were defined as asphalt concrete pavements designed and constructed in such a way that they could serve more than 50 years without major repairs, requiring only periodic removal and replacement of the worn part of the top layer of asphalt concrete. The following advantages of
such coatings were noted:

1. Low cost of the full life cycle costs due to the reduction of capital repairs;
2. Low loss of users due to a decrease in the total duration of time for repair works;
3. Reducing the environmental impact due to reduced material consumption and the reuse of the material from scraped off top layer.

The expert community working in the field of improving the design and construction of cement concrete pavements is also interested in increasing the overhaul life. A set of scientific studies is being carried out aimed at increasing the service life of up to 65 years.

As a result, the Long-lasting pavement direction was formed aimed at a significant increase in the durability of pavement designs proposed in the USA. Figure 2 shows an algorithm diagram for designing such structures.

One of the main new requirements is a significant increase in the thickness of pavement layers for roads with high traffic intensity. An increase in the total stiffness of the coating reduces the load on the underlying layers of the pavement and the soil base. This allows inhibiting the accumulation of damage in these layers and helps to increase the overhaul life. Evidently from the plot shown in Figure 2, the thickness of the coatings is proportional to the number of standard axial loads. At maximum axial loads exceeding 100 million, the required thickness for cement concrete pavements is 32.5 cm and 35 cm for asphalt concrete pavements.

Studies in this direction have spread in European countries [4]. In the early 2000s, a working group was created from representatives of research institutes of interested European countries (Long-Life
Pavement Group), which prepared a review report that included information on experience indicating the possibility of structures serving longer periods without repair than design lifetimes. It was decided to consider durable types of pavements as those types of pavements that will not develop significant damage in the working layer of the subgrade and base layers that require overhaul of the pavement structure. At the same time, measures to replace the top layer are considered acceptable.

It is characteristic that at present the total thickness of the layers of cement concrete pavements assigned during the design of pavements in different countries ranges from 22 cm to 31 cm (see Figure 3).

![Figure 3. Thickness of concrete coating in different countries of Europe](image)

Road users are making ever greater demands on the operational condition of roads and, as a consequence, on improving methods for designing pavements. Today, road pavements work in difficult conditions of an ever-increasing intensity of vehicle traffic, in a mode where residual deformations quickly accumulate, intensive wear of road surfaces occurs, and various types of damage appear. This leads to a decrease in the service life of the pavements. The use of structures and materials capable of increasing the service life of pavements and coatings is an urgent task.

In the Russian Federation, road design pays insufficient attention to pavement construction. The factual experience of operating a variety of road structures, with the identification of the most effective solutions, is not fully taken into account. Therefore, the choice in favor of a particular pavement design in many cases is carried out without taking into account the accumulated experience of using well-established standard designs.

Thus, there was a need to improve the existing practice of designing road structures to bring them in line with the international trend of increasing the durability and service life of road pavements.

3. Basics of proposed design methodology for rigid pavement construction

In world practice, there are two fundamental approaches to the design of pavement designs [5]. The first approach is based on calculating the parameters of the stress-strain state of the structure and comparing these parameters with the maximum permissible values. The second approach involves the appointment of parameters of typical designs based on a limited number of the most significant factors. At the same time, great importance is attached to structures tested at testing grounds or in real operating conditions. Typical pavement designs are widely used in the USA, Austria, Germany, Italy, France and other countries.
The basis for the practical account of cement concrete fatigue in structures is the test results of samples under the influence of repeated loads with a constant amplitude and frequency of loading (see Figure 4).

![Figure 4. Changes in stress during fatigue tests of concrete samples](image)

According to the results of such tests, the number of cycles necessary for the destruction of the sample at voltages of different levels is established. The stress state level in a cycle is the ratio of the maximum stress to the ultimate strength under a single loading.

On the basis of experiments, it was found that the number of cycles before the destruction of sample N can be represented as function F of the ratio of the maximum stress to the ultimate strength of concrete with single loading R:

$$N = F\left(\frac{\sigma_{\text{max}}}{R}\right)$$

In addition, it was also established that the number of loading cycles before fracture of the sample depends on the characteristics of the loading cycle. The characteristic of the loading cycle is called the ratio of the minimum stress in the cycle to the maximum value.

As a result of numerous experiments to determine the parameters of fatigue curves, a large number of models have been proposed that also take into account a number of other parameters, such as the frequency of loading, the moisture content of cement concrete, the time intervals between cycles, the rate of rise of the load, the type of aggregate in concrete, the type of cement, etc. However, characteristic of all tests was the constancy of the level of stress within one implementation. The dependencies obtained in this way served as a means for predicting the operability and designing various structures in which the parameters of the loading cycles vary significantly during their operation.

In relation to the calculation of cement-concrete coatings of roads and airfields, the empirical dependences presented in Figure 5 are most widely used. It is characteristic that a number of dependences gave fatigue coefficients greater than 1, which would seem to contradict the physical nature of the fatigue phenomenon. However, in one case this is due to the phenomenon of dynamic hardening due to short-term application of the load, (curve 3), and in the other cases (curves 1 and 2), with the design features of pavements, which are plates on an elastic base, statically indeterminable systems with a large number of extra connections.

With regard to road coatings, it is well known that the stresses caused by the passage of cars vary significantly due to differences in the carrying capacity of vehicles, uneven loading, position with respect to the edge of the roadway, condition of the subgrade, temperature regime of the coating and other factors. Figure 6 schematically shows how tensile stress can change in an arbitrary section of a cement concrete pavement under the influence of passing cars. The magnitude of the voltage at an
arbitrarily fixed point in time is a random variable, and the function of the voltage change in time can be assigned to the class of random functions.

**Figure 5.** Dependence of cement concrete fatigue coefficients on the number of load application cycles: 1) according to SNiP 11-47-80; 2) according to VSN 197-93; 3) from eq. \( K_y = 1.3 - \frac{\log N}{7} \left( 1.3 - \frac{0.5}{1 - 0.616 \cdot \rho} \right) \); 4) as \( K_y = 1.08 \cdot N^{-0.063} \)

**Figure 6.** Change in stress in cement concrete coatings under a moving car

To estimate the maximum number of load cycles for a structure undergoing a stress state characterized by an arbitrary random function, the Miner Rule hypothesis (linear summation of damage) has been widely used.

The hypothesis is based on the assumption that each load application cycle can be characterized by a unit damage, which can be defined as:

\[
\alpha_i = \frac{1}{N_i},
\]

where \( N_i \) is the number of cycles with a given level of stress and a cycle characteristic that causes the destruction of the cement concrete sample.

The process of changing the measure of damage is a function of time, and the value at each fixed point in time can be a characteristic of the current state of the pavement. The closer this value is to 1, the sooner the destruction of the pavement will occur and the less residual durability the structure has at this point in time.

The concept of a measure of damage is also introduced, for which the sum of single damage is taken for the period of interest or after a certain number of cycles of load exposure.

\[
D = \sum_{i=1}^{C} \alpha_i,
\]
where C is the number of stress repetitions for the time period of interest.

From the definition of a unit damage, it follows that in the process of structure material operation without destruction, the following inequality must be fulfilled:

\[ D < 1. \quad (4) \]

D reaching 1 means that the number of cycles of exposure to the load has reached the limit value. The specified ratio allows predicting the performance and calculating the resource structures of rigid pavement.

Therefore, the essence of the proposed methodology is, based on an analysis of the parameters of the stress-strain state of cement concrete layers in the considered pavement structure under a flow of conventional vehicles with standard axial loads, to calculate the design life in the form of the number of standard axial impacts, for example – P11.5.

4. Main results

Based on the calculations in accordance with the above methodology and accounting national experience in the design, construction, operation and diagnostics of rigid road pavements, as well as advanced foreign experience, MADI specialists developed standard GOST R “General automobile roads. Designing rigid pavement. Typical designs”.

The standard governs the parameters of rigid pavement with monolithic cement concrete pavement. The standard allows normalizing the most important parameters of the pavement design: the thickness of pavement, the type and parameters of the base, the thickness of additional layer of the base, the distance between compression joints, the diameter of pins and the distance between them. The value of the predicted number of passes of standard axial impacts for the design service life of the pavement structure is taken as the main factor determining the design parameters. As a calculated load, A-11.5 was adopted.

The fundamental principle in choosing a standard design is to predict the number of impacts of standard axial loads of the most loaded road lane for the design period of pavement. At the same time, the predicted flow, including the entire range of cars from light trucks to multi-axle road trains, is replaced by the amount of standard axial loads A-11.5 equivalent in the destructive effect.

The basis for predicting the intensity and composition of the traffic flow is the results of a feasibility study on the need for the construction or reconstruction of a highway.

The predicted composition of the traffic flow should correspond to the categories and types of vehicles in accordance with GOST 32965.

The modulus of elasticity of the soil of the working layer of the subgrade should be at least 40 MPa. For road sections with a lower modulus of elasticity of the working layer of the subgrade, it should be increased through special measures to regulate the water-thermal regime, strengthening or replacing the soil.

The assigned design service life of rigid pavement is at least 30 years. The class of concrete for tensile bending for the standard structures with cement concrete coating presented in this standard is assumed to be Btb4.4 MPa as per GOST 26633.

The material of the base layer is assigned depending on the availability of road building material in the construction area and the number of equivalent impacts of standard axial loads for the design service life of the pavement structure.

The use of typical designs of rigid road pavements will improve the quality of design, increase the reliability road pavements, increase their overhaul life and significantly reduce the cost of road users.

5. Conclusions

For an objective assessment of the advantages and possible disadvantages of the proposed structures, it is extremely important to carry out detailed quality control of construction works and regularly conduct instrumental monitoring of the state of the constructed carriageways with registration of such important characteristics as longitudinal evenness, rut depth, the number and location of cracks and other damage.
### Table 1. Parameters of typical designs of rigid pavement with cement concrete coating, depending on the resource P1.1.5

| Parameter name                                                                 | Types of pavement design |
|-------------------------------------------------------------------------------|--------------------------|
| Number of equivalent impacts of standard axial loads [mln]                   | R-70                     |
| Thickness of the cement concrete coating [cm]                                | R-50                     |
|                                                                               | R-20                     |
|                                                                               | R-5                       |
|                                                                               | R-1                       |
|                                                                               | R-0.3                     |
| ≥50                                                                               | 20–50                   |
| 20                                                                               | 5–20                     |
| 5                                                                                 | 1–5                      |
| 1                                                                                 | 1–0.3                     |
| ≤0.3                                                                             | 0.3                      |
| Thickness of the cement concrete coating [cm]                                | Hard rolled concrete      |
|                                                                               | 20                       |
|                                                                               | 18                       |
|                                                                               | 16                       |
|                                                                               | 12                       |
| Type and thickness of the base [cm]                                          | Mineral material not treated with binder |
|                                                                               | 20                       |
|                                                                               | 18                       |
|                                                                               | 18                       |
| Distance between seams [m]                                                    | Transverse seams         |
| Pin diameter [mm]                                                             | 6                        |
| Pin length [cm]                                                               | 6                        |
| Pin spacing [cm]                                                              | 5                        |
| Pin diameter [mm]                                                             | 25                       |
| Pin length [cm]                                                              | 25                       |
| Pin spacing [cm]                                                              | 5                        |
| Pin diameter [mm]                                                             | Longitudinal seams       |
| Pin length [cm]                                                              | 80                       |
| Pin spacing [cm]                                                              | 80                       |
| References                                                                     |                          |
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