Prospects for estimating the pavements structural capacity based on rolling wheel deflection

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Abstract. This article contains the results of the study of elastic deflection of semi-rigid pavement defined by the method of a rolling wheel (RWD) under different axial loads. For the investigations, an exclusive mobile complex was developed, allowing measurements to be made in a motion for various axial loads from 100 to 250 kN. It has been observed that the dynamic method of testing a semi-rigid pavement with a rolling wheel with different load levels allows determining non-linear characteristics of the deformation curve and deformation features of the package of asphalt concrete layers with appropriate loads, that cannot be done with the standard method of estimating the elastic deflection under a load of 100 kN. The results of the study can be used to develop criteria for assessing the strength, reliability, and deformability of semi-rigid pavement. It is possible to determine the likelihood of a joint failure-free operation of a rigid base and non-rigid layer with a resource forecast and the feasibility of its cold recycling.

Keywords: recycling, elastic deflection, reliability, residual service life, rolling wheel deflection method, semi-rigid pavement

1. Introduction

Nowadays, more and more attention regarding the practice of repair and reconstruction of roads is being paid to the reuse of materials of the structural layers of old pavements, in connection with which both technological and material research methods of increasing the reliability and efficiency of their regeneration processes are being developed.

Technological solutions for the regeneration of exploitation ability in terms of the life cycle of pavements (layers) have their advantages and disadvantages in terms of their implementation and achievement of maximum technical and economic efficiency indicators. Recently, cold pavement...
regeneration technologies, both through the central asphalt concrete plant and in-situ, have become
very popular [1, 2].

Most often, bitumen emulsions or foamed bitumen are used as a regenerating substance or a binder
[3–6], in the proportions determined at the design stage of the composition of cold mixes. Portland
cement, fly ash or quicklime are added to increase the stability of cold mixes and achieve higher
structural characteristics of concretes prepared on their basis in road pavements.

In most cases, to increase the reliability of the newly constructed in this way pavements, the
reinforcement layers are made from hot and warm asphalt concrete mixes, or protective layers (from
floated emulsion-mineral mixes, in the form of surface dressing, impregnations, etc.).

The most important stages of the cold pavement recycling system are its diagnostics with the
development of optimal methods for regenerating the properties of the materials of the old structural
layers and making a new design [7]:

- collection of initial data (historical data, service life, traffic volume, types of traffic loads, etc.);
- preliminary studies and selection of pavement sections with an identical condition;
- detailed studies of the pavement condition on the equal sections;
- the primary design of new pavement based on the predicted properties of the regenerated
  materials of the structural layers;
- laboratory design of the compositions of the regenerated materials for designing structural
  layers of new pavement;
- final design and calculation of the new pavement;
- technical and economic analysis of options for cold recycling of an existing pavement.

The primary indicator that currently determines the structural strength of existing pavement in the
process of diagnostics is elastic deflection. This is due to the simplicity of the experiment and great
difficulties in the experimental evaluation of stress fields and deformations of a real road structure.

As a result of the combined effect of traffic loads and weather and climatic factors, stress and strain
occur in the structural layers of the pavement. The durability of the whole structure depends on the
magnitude of these stresses and the reaction of payment layer materials to them. The ability to
accurately estimate stresses and deformations during the entire service life of pavement at the design
stage is the crucial point of most modern methods of its design and calculation.

The stresses and deformations that occur in the structural layers of the pavement, due to the
complexity of the properties of the materials from which they are constructed, depending on many
factors, including the load time and temperature. Calculating them analytically requires solving many
equations. It can be reasonably stated that at present, it is theoretically impossible, with a high level of
convergence, to perform calculations of the pavement resource during its life cycle.

Due to the described difficulties of accurately determining stresses and deformations by calculation
over decades, most countries have used empirical pavement design techniques that were based on
experimental results (such as AASHTO road tests in the USA in 1962, 1965), or the long-term
observations for the behavior of various pavements during the whole period of their service. Many
pavement calculation schemes adopted abroad are based on methodologies centered around these
studies, and the lack of theoretical ideas about the stress-strain state is compensated for by a massive
amount of experimental data. For example, even in the USA, only in 2002, pavement calculation
methodologies that did not directly consider research data were developed [8].

Empirical dependencies in the form of equations, graphs, nomograms, link some measured
indicators of the pavement (most often the value of the elastic deflection on the surface of the road)
with the service life. Generally, these dependencies are poorly correlated with the results beyond the
limits of the data used for developing.

In many countries, so far, the design criterion assumes that the road structure meets the
requirements of strength and reliability in terms of the elastic deflection [9-11]. The value of the
minimum total required module of elasticity of the structure is calculated by empirical dependencies
on the traffic volume at the end of the service life, or on the total number of load applications over the
entire service life. Only elastic deflection can be tested experimentally in a simple and accessible way.
The value of deflection on the road surface is taken as its vertical deformation under the applied static or dynamic load. The most sophisticated measuring instruments record vertical deformations at many points, which makes it possible to obtain the outlines of a “deflection bowl”. The “deflection bowl” is the area of the layer that is deformed when a load is applied.

All tools used to determine the deflection on the layer can be divided into two categories:

- Static;
- Dynamic.

The primary tool for the static determination of the elastic deflection is the lever-type deflection indicator, or “Benkelman beam”. Among the dynamic methods, there are tools operating on the principle of the vibration load application and the principle of a falling load or rolling wheel.

2. Studies of the pavement elastic deflection

Despite quite complicated methods of bringing the measured values of elastic deflection to standard conditions, very often they are not enough for proper application of design solutions for major repairs and reconstruction, since it is difficult to calculate the residual service life of materials of structural layers, their resistance to deformations under the influence of modern traffic loads. Fig. 1a shows an example of a typical (phenomenological) curve (model) of changes in deflection during the pavement life cycle when the development of defects may not occur predictably, but rather incrementally while ensuring the required strength indicators, determined based on the estimated value of the elastic deflection.

In this regard, there is also a difficulty with a reasonable choice of areas that are most suitable for cold recycling of pavements. The situation is even more complicated when the bases are composed of materials containing mineral binders (concrete of varying strength, reinforced materials), for so-called semi-rigid road structures with non-rigid (usually asphalt concrete) layers and with rigid (reinforced by mineral binders) base layers.

This is primarily due to the accumulation of infrastructural damageability in the asphalt concrete layers and layers reinforced with mineral binders. Damageability is the accumulation of defects in the structure of the material of the pavement structural layer in the course of its operation that leads, when there are too many defects, to unacceptable deformation or destruction. The development of damageability takes place in three stages and leads to a decrease in the strength and deformation characteristics of the materials of the road construction layers:

1. The destruction at the micro-level and sub-micro level, which cannot be fixed based on existing methods and tools.
2. The formation of micro-defects and the development of infrastructural damageability, which can be set with special tools and pursuant to observations for several years.
3. The development of macro-defects which can be recorded visually (i.e., defects that are visible on the layer).

By area of coverage, all three stages are uneven. Therefore, it is important to have appropriate monitoring in order to identify priority areas for prevention and proper repair.

Thus, the existing method of assessing the strength of pavement by measuring deflections and determining the module of elasticity is quite simple, however, it is often ineffective in terms of taking into account the actual service life reserve, and does not allow for simple and adequate dependencies linking the module of elasticity of the pavement with indicators of operational condition pavement such as cracking (Fig. 1b), roughness (Fig. 1c), rutting (Fig. 1d), etc. [12].

Diagnostic methods based on visual fixation of defects and measurement of elastic deflection only state the actual condition of the pavement but do not allow determining the reason for the defects that have appeared and the forecast of their development over time, which makes it difficult to assign the type and term of repair correctly. Errors may be even higher in the study of semi-rigid pavement. Another disadvantage of existing methods for estimating deflections, especially when assessing the strength of pavements with increased reliability (including semi-rigid), is often a small value of deflections from a standard load of 100 kN (within the experimental error).
It is known that one of the most effective ways to determine the elastic deflection of pavement is to dynamically measure from a rolling wheel (RWD) [13–17], as the vehicle's effect on the pavement is simulated to the maximum. This method allows obtaining much more information about the characteristics of the road surface. We have developed a mobile complex that allows measurements to be made in a motion for various axial loads from 10 to 25 tons (Fig. 2) based on a laser Doppler measurement system.

**Figure 1.** Features and results of the elastic deflection study

**Figure 2.** Mobile Measuring Complex (RWD)
However, even this method of direct measurement of the deflection is insufficient for assessing the actual reliability of the pavement and determining the optimal terms of maintenance and repair which is the most crucial element of the pavement management system. Corresponding post-processing of the obtained data of evaluating vertical deformations is required. This is since the decrease in the module of elasticity of structural layers from rigid (elastic) and non-rigid (viscoelastic) materials, for example, due to an increase in infrastructural defects, affects the durability of pavement, including elastic deflection, to varying degrees.

Fig. 3 shows the dependence obtained by carrying out calculations from which it can be seen that if the module of elasticity of the thick rigid foundation due to the accumulation of infrastructural damage decreases by 2–2.5 times, this will lead to an increase in the amount of pavement elastic deflection in 1.6–2.3 times, whereas, and if the module of the upper non-rigid layers is also decreased by the same value, compared to the base, thickness will increase by 1.2–1.25 times. The calculations were made according to the dependencies developed by Korsunsky based on the fundamental solutions of Burmister, Kogan and others for the evaluation of stresses and deformations in multilayer structures. In this case, if you operate only with the value of elastic deflection from a standard load of 100 kN, it is impossible to identify the cause of the defects and, especially, to predict their development.

![Figure 3. Change of the elastic deflection of the semi-rigid pavement](image)

With a higher increase in damage and decrease in the module of rigid layers, the deflection can rise avalanche-like. If the pavement structure has deviations from the quality of materials or the quality of its structure, then the effect may be even higher.

The process of assessing the reliability of such pavements is hampered due to their high structural strength, when the value of elastic characteristics, for example, elastic deflection, is insignificant when tested with standard loads (e.g., 100 kN).

Currently, the calculations of road structures are mostly focused on the fact that the pavement is represented as a half-space (and a multi-layer one) of a certain rigidity (elasticity) [18–23]. At the same time, the disadvantage of the elastic half-space model is that it does not limit, for example, the load-carrying capacity of the compressible zone at the base of the road structure. In actual conditions of interaction between the pavement and the base, the base and the soil of the subgrade under the
influence of dynamic traffic loads, the load-carrying capacity of the structure is limited, and this feature significantly influences the nature of contact stress distribution and, consequently, the accuracy and efficiency of models for assessment reliability and durability of the pavement.

With an unlimited load-carrying capacity of a multi-layered rigid (elastic) half-space, the increase in the calculated value of the deflection occurs almost linearly, where the deflection value is directly proportional to the value of the actual load. This does not consider the features of semi-rigid pavement combining rigid bases and non-rigid upper layers. Because of this, there are often failures in the design and calculation of pavements, when, regardless of the material type of the structural layer, the strength of the pavement increases only based on the value of the module of the elasticity and thickness of the layers. This is fundamentally wrong for real road structures and especially for semi-rigid pavements when calculating their reliability and durability, establishing their residual life.

In order to increase the efficiency and confidence of studies of the strength and reliability of semi-rigid pavements, rolling wheel tests (RWD) were carried out with fixing elastic deflection for three design axial loads: 13, 17 and 21 tons (Fig. 4) in 2018 on the non-stop traffic highway (the year of pavement is 2007) on an area of 5 km at a design temperature of asphalt concrete pavement about 20 °C.

Fig. 5 presents the data of the results of studies of elastic deflection determined by the rolling wheel method, for individual sections (1–6) in the form of flow diagrams in the coordinates of "load-deflection".

As shown by the results of statistical processing of experimental data with a large proportion of correlation ($R^2 \geq 0.95$), the value of the elastic deflection of a semi-rigid pavement ($i_{el}$) depends on the value of the axial load ($P_i$) with the subordination of the X reciprocal linear regression model (reciprocal X model) of the form:

$$P_i = a - \frac{b}{i_{el}},$$

where $a$ and $b$ are the coefficients of the model, in case of $i_{el} \to \infty, P_i \to P_{\text{max}} = a$.
Thus, the development of dynamic deflection (from the real vehicle wheel, including the loads above the standard, equal to 100 kN) does not occur in the dependence close to linear, but has pronounced (characteristic) levels that can be captured when building correlation dependencies of the form (1) for various loads (the parameters of correlation dependencies for average values of samples of elastic deflection values for the studied areas are presented in Table 1):

1. The level of growth of linear elastic deformation (instantaneous elastic) which may occur, for example, due to: the presence of serious inconsistencies in the strength of the base (low resistance) and the thickness of the layer (small thickness); the presence of defects at the boundary between the separation of a rigid base and a non-rigid upper layers; compressing a package of non-rigid layers; experimental error.

2. The level of axial load (dynamic elastic deflection) at which the deformation curve transitions to a non-linear stage that is caused by the base reaction and non-rigid layer properties.

3. The level of non-linear growth of vertical deformation considering the reaction of a semi-rigid pavement to a disturbance from the traffic load of various value.

4. The level of maximum axial load \( P_{\text{max}} \) above which the increase in deformation can occur unpredictably and can lead to disruption of the pavement continuity, even with a small number of impacts of traffic loads of this level.

![Figure 5. “Box-and-whiskers” diagrams for research results by sections](image)

| Table 1. Results of the elastic deflection study |
|-----------------------------------------------|
| **Section No.** | **Average sampling elastic deflection value (0.01 mm) for loads, t** | **Parameters of correlation dependence (1)** |
|                 | 13       | 17       | 21       | a       | b       |
| 1                | 46.29    | 54.45    | 71.41    | 35.80   | 1045.10 |
| 2                | 39.58    | 50.48    | 69.65    | 31.53   | 733.42  |
| 3                | 46.40    | 53.14    | 76.85    | 32.98   | 898.09  |
| 4                | 38.27    | 49.51    | 69.18    | 30.88   | 685.16  |
| 5                | 48.79    | 53.62    | 68.95    | 39.76   | 1272.46 |
| 6                | 42.20    | 52.97    | 68.41    | 33.78   | 880.06  |
Taking into account the fact that the measurements were made on the highway with the same design structure, the variation of values is quite high: the calculated minimum value ($P_{\text{max}}$) is 30.88 tons, and the maximum value is 39.76 tons, the difference between which is almost equal to the standard axial load of 10 tons. From the presented data, for semi-rigid pavements (pavements of increased deformability), elastic deflection under a load of 10 tons is not very meaningful for assessing reliability and durability.

This is since under a standard load of 10 tons, the development of deformation occurs in the linear elastic stage when the reaction of the rigid base practically does not affect its connection with the subgrade soil. Deformations of the package of asphalt concrete layers insignificantly affect the elastic deformation value with spreading of the deflection bowl over a larger area. As shown in Fig. 3, semi-rigid pavement is more sensitive to an increase in damage (as a result, a module reduction) in the concrete base layers than in asphalt concrete pavements, in terms of evaluation, for example, of the load-carrying capacity of such road structures. In this connection, in order to assess the suitability of rigid bases for further use in the process of reconstruction and repair of roads, which is also essential when performing pre-design diagnostics of pavements while developing solutions for cold recycling of structural layers, tests should be performed at loads that exceed standard loads of 100 kN in 1.5–2 times. Only in this case, the entire pavement together with the soil starts to resist, and therefore, the non-linearity of the deformation process manifests itself, which is associated primarily with a non-linear change of the pavement reaction module (to a higher degree of a rigid base on the unpaved half-space).

Thus, the value of the maximum load ($P_{\text{max}}$) can be used to assess the ability (reliability) of semi-rigid pavement as a whole, and to a higher degree of the rigid base, to the accommodation of heavy traffic loads, including their cyclic effects.

Pavements in many countries are mostly designed based on existing methodologies focused on calculations of the model of a layered elastic system, which allow calculating stresses and deformations at any point of the structure. With such an analysis, it is assumed that the materials of the pavement layers are uniform, isotropic, and linearly elastic. Mathematically, this model is based on the theory of elastic layers developed by Boussinesq in the late 19th century [24]. This model is grounded on very simple mathematical dependencies; however, it requires accepting many significant assumptions, which negatively affects the accuracy of the calculations. The main ones are the following:

- layers are continuing in the longitudinal direction;
- the bottom layer (subgrade soil) has an unlimited thickness;
- layer materials are active only in the elastic stage.

Under such conditions, the increase in the pavement reaction module ($R_p$) to the disturbance by the traffic load is continuously growing.

However, a completely different situation is observed with an actual pattern of deformation of semi-rigid pavement. Fig. 6 shows the dependencies connecting the pavement reaction module (N/m) with the value of axial load and elastic deflection concerning the correlation dependences indicated in Table 1. As is evident from these dependencies, when it is built in the indicated axes, there is some extremum of the values of the pavement reaction module. This maximum unambiguously suggests the transition of the road structure to a non-linear state with an appropriate deformation (stress).

Based on the maximum values of the pavement reaction, it is possible to determine the value of axial (wheel) load ($P_j$) and vertical deformation ($d_j$) corresponding to this extremum (Table 2). The load value corresponds to the moment when the deformation of the layer ceases to be elastic-linear and subsequently develops non-linearly.

Thus, we have one of the essential points of the pavement deformation curve, which shows the moment (according to the load (deformation)) when it ceases to be deformed in the elastic stage, i.e. deformations cease to be recurrent, and damage starts to accumulate in the structure of structural layers and their durability decreases.
Table 2. Results of the maximum axial load calculation ($P_e$)

| Parameter                  | Value of the parameter for section No. |
|---------------------------|----------------------------------------|
| Axial load ($P_e$), kN    | 18.0 16.0 16.5 15.5 20.5 17.0          |
| Maximum deformation ($d_e$), mm | 1.53 1.69 1.51 1.73 1.55 1.62 |

The above dependencies indicate that the deformation of the semi-rigid pavement under the traffic load is mainly non-linear. With an increase in the traffic load to a level of about 15-20 tons per axis (for the sections considered), pronounced deformations appear, primarily due to the properties of a non-rigid asphalt concrete pavement and the subgrade soil, which are transited from the actual load to a non-linear stage when corresponding strengths are achieved. In this case, considering the accumulation of residual deformations in the subgrade soil, there is, as mentioned above, the accumulation of damage in the asphalt concrete pavement layers and concrete base.

Thus, the dynamic method of pavement testing with a rolling wheel with different load levels allows determining non-linear characteristics of the deformation curve and deformation features of the package of asphalt concrete pavement layers with appropriate loads, including their cyclic strength under the conditions of actual traffic loads [25]. Such studies with only a large proportion of approximations can be performed using the standard method for determining the elastic deflection under a load of 100 kN.

3. Conclusion

Nowadays, more and more widely old materials of pavement constructive layers are reused for their reconstruction and repair, both with their processing and regeneration of properties and in the form of undisturbed structures and as separate elements of new road structures. In this regard, to assess the technical and economic characteristics of such projects and increase their efficiency, much attention is paid to the assessment of the residual resource of old pavements.

In many countries, the design criterion, which determines the strength and reliability of the pavement, implies compliance with the requirements for the elastic deflection value. The value of deflection on the layer surface is taken as its vertical deformation under the applied static or dynamic load.

However, despite quite complicated methods of bringing the measured values of elastic deflection to standard conditions, very often they are not enough for proper application of design solutions for major repairs and reconstruction, since it is difficult to calculate the residual life of materials of structural layers, their resistance to deformations under the influence of modern traffic loads.

In order to increase the efficiency and reliability of studies of the strength and reliability of semi-rigid pavements (structures of increased strength), rolling wheel tests (RWD) were carried out with fixing elastic deflection for three design axial loads: 13, 17 and 21 tons.
According to the results of the study, it was found that when testing semi-rigid pavements with elastic deflection fixation with at least 2–3 different axial loads in the range over 10 to 20 tons, it becomes possible to establish the non-linear characteristics of the deformation curve and deformation features of the package of asphalt concrete layers with the corresponding loads that cannot be done with the standard method for determining the elastic deflection under a load of 10 tons.

Thus, when developing criteria for assessing the strength, reliability, and deformability of semi-rigid pavement, it becomes possible to estimate the likelihood of a joint failure-free operation of a rigid base and non-rigid layer with a resource forecast and the feasibility of its cold recycling, which is the direction for future research.

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