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Design of modular removable road pavement slabs for the agro-industrial complex

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Abstract. The article deals with the justification for the design of a modular removable road pavement plate (slab) intended for high-speed construction of road sections and access roads to various objects of agricultural infrastructure under difficult off-road conditions. The proposed designs can be widely used in the rehabilitation of motor roads in the agricultural areas of eliminating the consequences of natural calamities, accidents and disasters in transport communications, at agricultural industry facilities, as well as for the deployment of road service enterprises.

1 Introduction

Existing ways to restore motor roads in the areas of eliminating the consequences of natural calamities, accidents and disasters require large material costs and are very time-consuming.

Timing of liquidation work and providing the population in distress with basic necessities will be directly related to the freight transport logistics, which finishing component is provided by road transport. Early recovery or expansion of the motor road network in the areas of eliminating the consequences of natural calamities and accidents will require passage of vehicles lacking off-road capability, with the estimated single axle load of 100 kN.

This problem can be solved by using a modular removable road pavement (MRRP), manufactured taking into account the current development level of polymeric materials and petrochemical industries, as well as experience of applying fiberglass in civil engineering .

One of the requirements for MRRP elements is to minimize their mass in order to enable manual loading and unloading along with installation work. This requirement can be implemented in two ways: by using construction materials of the lowest possible density with the required compression and bending strength characteristics, and by optimizing the element itself according to its plan dimension and thickness. To meet the challenge of MRRP constructing, a design model justification for the MRRP plate operation under conditions of the required speed of traffic flow is indicated.

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2 Materials and methods

Based on the requirements [10, 11] for the design state of underlying subgrade, the features of soil behavior under load can be formulated as follows:

1. When soil moisture is $W_{\text{отн}} = 0{,}9$, the soil is in a high-plastic or fluid-plastic state, close to the state of soil mass, which is not compactible. Internal friction and adhesion of soil, i.e. its shear resistance is negligible.

2. Low-compressible high-plastic or fluid-plastic soil is underlain by a more rigid base.

The above-mentioned state of underlying subgrade is most consistent with the estimated models of Winkler-Fuss N.I. and Sinitsyn A.P.

The Winkler-Fuss N.I. model possesses properties of local elasticity, characterized by the modulus of subgrade reaction (c). Subsidence of the underlying subgrade (ℓ) is proportional to the current load (P).

$$\ell = \frac{\mathrm{P}}{\mathrm{c}}. \tag{1}$$

Studies of this model show its applicability to the calculation of modular pavement structures under the conditions considered above. Thus, I.I. Cherkasov [12] indicates that the foundation modulus method is the more consistent with reality, the more the properties of subgrade soils approach water properties, i.e. the less the soil shear resistance is. N.N. Maslov [13] notes that plastic clay soils, due to the development of water-colloidal films, have no mineral contact between particles, which makes friction and structural cohesion forces close to zero. Consequently, the adopted design state of soil corresponds to the conditions of reliable and adequate application of the model under consideration.

In addition, the smaller the size and depth of the foundations (in our case, plate settlement) are, the better results the method of subgrade reaction modulus gives. V.A. Florin [14] considers it permissible to use the model in calculating beams when their height is less than (0.25-0.2) length, and the flat cross-section hypothesis is preserved. Installation of MRRP made of polymeric materials when restoring motor roads also meets the above conditions, since pavement elements are placed on the underlying subgrade surface, and the ratio of their height to length amounts to (0.05-0.04).

In [15] it is indicated that the Winkler-Fuss model is characteristic of compressing thin layers of loose or liquefied soil lying on a rigid foundation, which also meets the operating conditions for modular road pavement bases.

The above-mentioned competent evidence from eminent specialists allow to consider the subgrade reaction modulus hypothesis applicable to characterize the underlying subgrade design model when installing MRRP of polymeric materials.

The model of A.P. Sinitsyn [16] represents the finite thickness residual deformable layer, characterized by the modulus of subgrade reaction, lying on the surface of an elastic half-space. By its nature, the model of A.P. Sinitsyn corresponds to the operating conditions of soils in modular paving bases, but differs from the subgrade reaction modulus hypothesis by significantly less developed calculation methods for beams and slabs (especially in relation to dynamic calculations).

For this reason, the Winkler-Fuss model (hypothesis of subgrade reaction modulus) is adopted as estimated model of the underlying subgrade. The said conclusion is based on a comparison of estimated base properties with research results [12-16].

As a design strength index of the underlying subgrade, the value of deformation modulus $\mathrm{E}_0 = 60$ kg/cm^2 is accepted.

Calculate its corresponding value of the modulus of subgrade reaction [16]

$$c = 0{,}28 \cdot \sqrt[3]{\frac{вE_0^4}{(1-\mu_0^2)^4 EI}} \cong 1, \text{ (kg / cm}^3\text{)} \qquad (2)$$

where в is the carriageway width, cm;
E and E_0 are the plate and base elasticity moduli, MPa;
μ_0 is Poison's ratio for the plate and base;
I is the plate's moment of inertia.

Slab design must ensure installation of the strip-type and solid-type carriageway coverings. Accordingly, in substantiating slab structural dimensions, first and foremost, it is necessary to be based on the carriageway overall dimensions, which depend on geometric characteristics of the loads and on the required performance indicators of motor roads. Type of carriageway is selected based on composition analysis of the possible traffic expected in this area.

The proposed methodology for structural design of MRRP plates comprises the following steps:

1) determination of the width of a modular removable road pavement slab;
2) determination of the length of a modular removable road pavement slab;
3) determination of the thickness of a modular removable road pavement slab, ensuring its structural strength.

3 Results

Step 1. Width of an MRRP plate is calculated based on the desired width of carriageway. The required width of a strip-type carriageway is determined considering the wheel track of the estimated vehicle (k), wheel imprint diameter (D) and size of the safety strip marking (y), which should secure the vehicle against road departure when its trajectory deviates from a straight line (Fig. 1).

To that end, the following relation is used:

$$в = D + 2x, \qquad (3)$$

where $в$ is the width of an MRRP slab, cm;
D is the estimated tire print diameter, cm;
x is the distance from the plate edge to the tire print edge, cm.

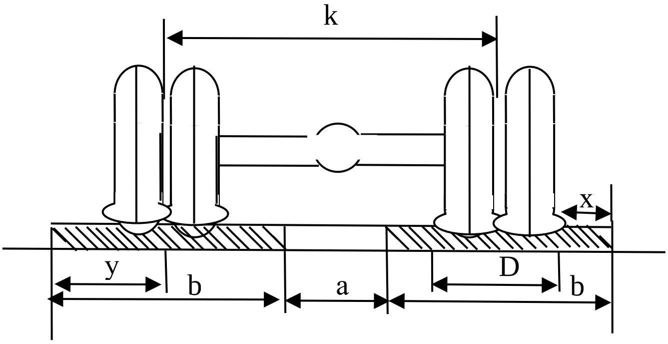


Fig. 1. Scheme for determining width of an MRRP slab.

Width of the safety strip marking (y) is calculated by the formula:

$$y = \frac{D}{2} + x, \tag{4}$$

$$x = 4{,}5\sqrt{V}, \tag{5}$$

where V is the required speed of design load on the road section under restoration, km/h.

Determining the x value functional dependence on V, taking into account characteristics of state-of-the-art and forward-looking vehicles types (Fig. 2). Apparently, this dependence (6), in contrast to the formula (5), will be non-linear.

Table 1. Dependence of the distance from the carriageway edge to the vehicle's wheel imprint on the vehicle speed.

V, km/h	x, cm	V, km/h	x, cm	V, km/h	x, cm
12	16	11	15	10	14
13	16	18	19	26	23
18	19	23	22	31	25
11	15	28	24	23	22
15	17	10	20	34	26
17	19	30	25	17	19
14	17	28	24	15	10
20	20	15	17	15	17
23	22	24	22	10	14
10	14	10	14	36	27
16	18	19	20	33	26
25	23	26	23	15	17
27	23	16	18	35	27
19	20	32	25	28	24
22	21	34	26	13	16

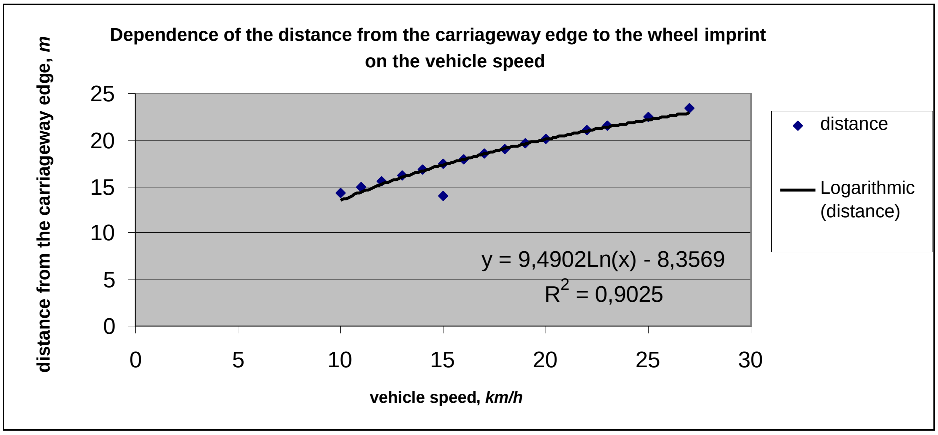


Fig. 2. Dependence of the distance from the carriageway edge to the wheel imprint on the vehicle speed.

Equation for the dependence of the distance from the carriageway edge to the vehicle's wheel imprint is calculated by the formula:

$$x = 9{,}4902\mathrm{Ln}(V) - 8{,}3569 \tag{6}$$

The results obtained in experimental studies [17, 18] made it possible to establish a statistical link between the distance from the slab edge to the tire imprint edge and the speed of kamAZ-53501 motor vehicle (Table 1).

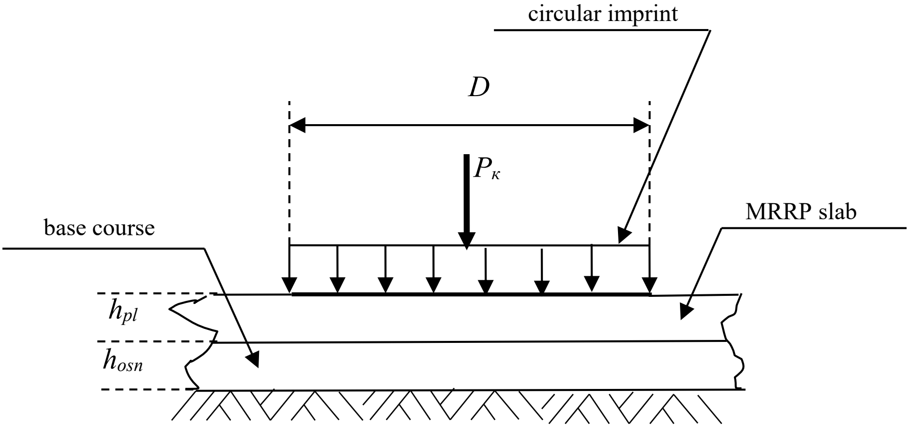
As already mentioned, MRRP should provide a possibility for both solid-type and strip-type pavings.

In case of a strip-type carriageway, an additional calculation of the wheel track spacing width is required, securing a vehicle (trailer) with a narrow wheel track against pavement departure. Wheel track spacing is assigned based on a condition to satisfy the following inequality:

$$\mathrm{a} \leq k - 2\mathrm{y}, \tag{7}$$

where a is the width of the wheel track spacing, cm;
k is the wheel track of a vehicle or a trailer having the largest wheel track, cm.

As a design scheme for loading an MRRP plate with a design vehicle wheel, a circular imprint of diameter *D* transmitting a uniformly distributed load by value *P* (Fig. 3) is adopted.



H_{pl} – slab thickness; h_{osn} – base thickness.

Fig. 3. Schematic diagram of MRRP slab loading.

Values for the P_k-wheel design specific pressure on the pavement and design diameter *D*, corrected to the wheel imprint circle of the estimated load on the pavement surface, are selected according to parameters of the estimated vehicle types based on the composition analysis of possible traffic.

Standard static load of 100 kN on the single axle of a design vehicle is used as the estimated load.

Value P_k is taken to be equal to the inflation pressure in wheel tires of the estimated load. Design tire print diameter *D* is determined by the following relationship:

$$D = \sqrt{\frac{4Q_{\mathrm{rasch}}}{\pi \times \mathrm{P}_k}} \cdot K_D, \tag{8}$$

where Q_{rasch} is the design value for the load transmitted by the wheel to the coating surface, N;
P_k is the design vehicle wheel tire pressure, N/cm^2;
k_D is the dynamic load factor.

Design value for the load is calculated by the following relationship:

$$Q_{\text{rasch}} = \frac{\text{P}}{m}, \tag{9}$$

where *P* is the design vehicle axle load, kN;
m is the number of wheels on the design vehicle axle.

Wheel load is determined considering the calculated axle load value, taken to be equal to 110 kN.

Step 2. Length of MRRP slab is calculated based on the width of the solid-type carriageway paving, and set taking into account the largest front or rear wheel track of the estimated vehicle, wheel imprint diameter and size of safety strip markings (Fig. 4). Safety markings (*y*), similar to the strip-type pavement, should secure the vehicle against road departure when its trajectory deviates from a straight line.

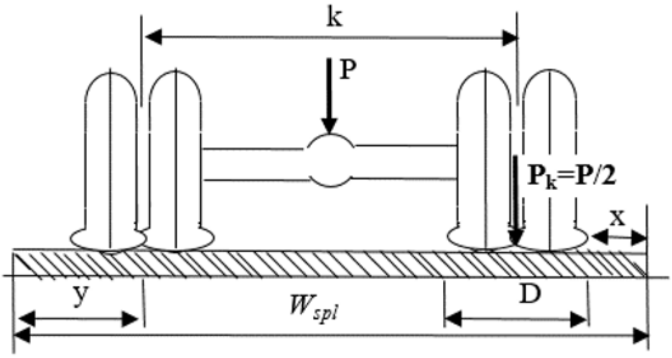


Fig. 4. Scheme for determining carriageway width of the solid-type pavement (MRRP plate length).

$$в_{\text{spl}} = k + 2\text{y}, \tag{10}$$

where $в_{spl}$ is the carriageway width of the solid-type paving (MRRP plate length), cm;
k is the largest wheel track of a car or a trailer, considered to be the design one as part of the military traffic, cm;
y is the width of safety strip marking to prevent wheel exit when the car and trailer "wobble" along the carriageway, cm.

Safety strip width for the solid-type pavement is determined taking into account the value of *x*, which is calculated in the same way as for the strip-type pavement.

Step 3. Thickness of modular removable road pavement plates is determined on the wheel loads effect.

In this case, it is necessary to calculate bending moments for the plate used in both solid-type and strip-type pavements, and then determine structural thickness of the plate, considering its reinforcement, by the value of the largest moment.

Pavements are calculated taking into account their degree of reliability (probability of failure-free structural behaviour during the intended life).

For slabs used in strip-type paving, the calculation is made according to the condition of the slab body material bending resistance in the center

$$k_{\text{pr}} \le \frac{R_{\text{rasch}} \cdot W_{\text{pl}}}{\text{M}_{\text{x(y)}}}, \tag{11}$$

where R_{rasch} is the slab design resistance when bending, Pa;
W_{pl} is the slab moment resistance, mm^3;
$M_{x(y)}$ is the bending moment in the slab center when exposed to design load, N/m.

Slab moment resistance (W_{pl}) is calculated according to the following relation:

$$W_{\mathrm{pl}} = W_{\mathrm{pr}} + W_{\mathrm{tr}}, \tag{12}$$

where $W_{\mathrm{pr}}$is the slab body moment resistance, mm^3;

W_{tr} is the moment resistance of the slab rib stiffeners, mm^3.

Bending moment ($M_{x(y)}$) is determined when applying load in the slab center (Fig. 5).

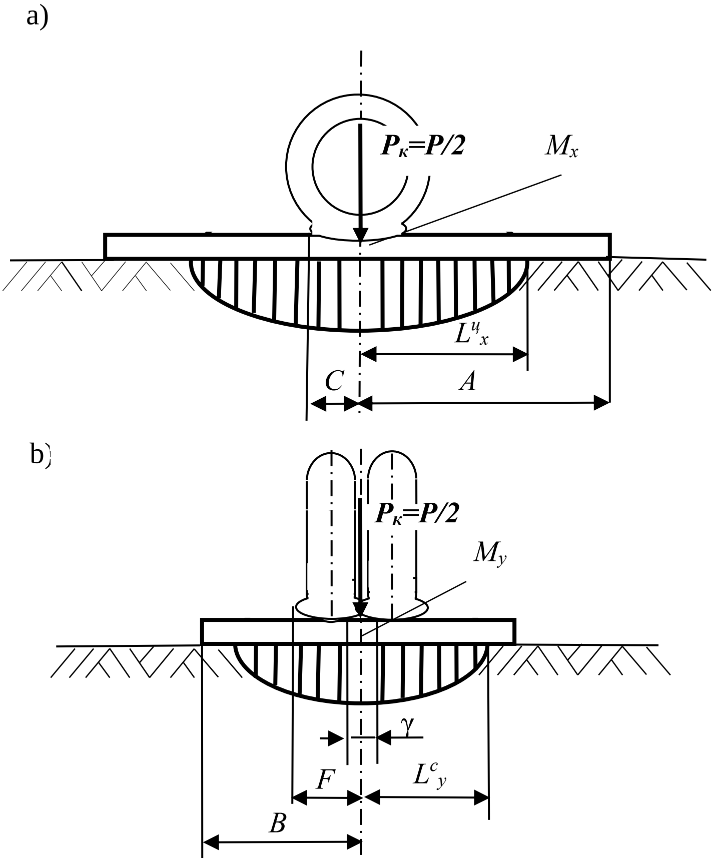


Fig. 5. Design diagram of the MRRP slab stress for strip-type pavements; a) in the longitudinal direction; b) in the transverse direction.

Design length $L^c{}_x$ and width $L^c{}_y$ of the base resistance diagrams are determined by the formulas:

$$L_{\mathrm{x}}^{c} = 2{,}5 l_{\mathrm{y}}^{\mathrm{x}} + C; \tag{13}$$

$$L_{\mathrm{y}}^{c} = 2{,}5 l_{\mathrm{y}}^{\mathrm{y}} + F; \tag{14}$$

where *C* and *F* are the wheel imprint's half-length and half-width, referred to neutral line of the plate, m;

$l_{\mathrm{y}}^{\mathrm{x}}$ and $l_{\mathrm{y}}^{\mathrm{y}}$ are the plate's elastic characteristics in the longitudinal and transverse directions, m.

Slab elastic characteristic is determined by the dependence:

$$l_{\mathrm{y}} = \sqrt{\frac{6\sum \mathrm{M}}{\sigma_{\mathrm{Dop}}}} \cdot \sqrt[3]{\frac{\mathrm{E}(1-\mu_{\mathrm{o}}^{2})}{6\mathrm{E}_{\mathrm{o}}(1-\mu^{2})}}; \tag{15}$$

where $\sum \mathrm{M}$ is the sum moment from current external forces, N/m;
σ_{Dop} is the allowable bending stress in the slab, kg/cm^2;
E and E_o are the slab and base elasticity moduli, MPa;
μ and μ_o are the Poison's ratios for slab and base;
h_{pl} is the slab thickness, m.

For a double-wheel support with the γ-distance between imprints of coupled wheels (Fig. 6)

$$C = 0{,}87\, r + 0{,}5\omega; \qquad 16)$$

$$F = 1{,}15\, r + 0{,}5\omega + 0{,}5\gamma, \tag{17}$$

where r is the wheel imprint radius, m;
ω is a geometric characteristic characterizing ellipsoidal shape of the wheel imprint (Fig.6).

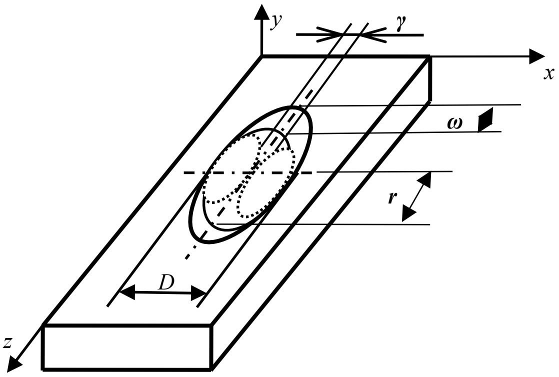


Fig. 6. Design diagram of the wheel imprint.

Values L^c_x and L^c_y are limited by slab dimensions, with $L^c_x, \leq A$ (Fig.5 a), $L^c{}_y \leq$ B (Fig.5 b);

Bending moment in the strip-type paving slab center in the longitudinal and transverse directions is determined according to the following relationships:

a) in the longitudinal direction

$$\mathrm{M}_{\mathrm{x(y)}} = 0{,}159\mathrm{P}\left(\frac{L^c_{\mathrm{x}}}{L^c_{\mathrm{y}}} G_{\mathrm{C}} + \mu \frac{L^c_{\mathrm{y}}}{L^c_{\mathrm{x}}} G_F\right); \tag{18}$$

b) in the transverse direction

$$\mathrm{M}_{\mathrm{y(x)}} = 0{,}159\mathrm{P}\frac{L^c_{\mathrm{y}}}{L^c_{\mathrm{x}}} G_F, \tag{19}$$

where G_C and G_F are imprint size influence coefficients in the longitudinal and transverse directions.

In accordance with [19,20] these coefficients are calculated using the following formulas:

$$G_{\mathrm{C}} = 1 - 1{,}136\frac{\mathrm{C}}{L^c_{\mathrm{x}}}, \tag{20}$$

$$G_F = 1 - 1{,}136\frac{F}{L_{\mathrm{y}}^{c}}. \tag{21}$$

Number of reinforcing rovings in the slab is determined on the basis obtained in the study of the following empirical formula:

$$\mathrm{y} = 0{,}1441\mathrm{x}^2 - 223{,}5\mathrm{x} + 86856 \tag{22}$$

Table 2. Influence of the number of rovings on the slab strength.

σ, MPa	**n, pcs**	**σ, MPa**	**n, pcs**	**σ, MPa**	**n, pcs**
749	300	766	385	738	599
756	250	775	328	732	649
759	236	767	381	740	583
766	214	783	290	699	959
755	254	785	284	752	490
747	310	765	393	727	693
756	248	766	389	700	954
760	231	776	324	772	349
749	292	767	376	739	595
746	321	760	430	727	694
775	194	749	510	722	204

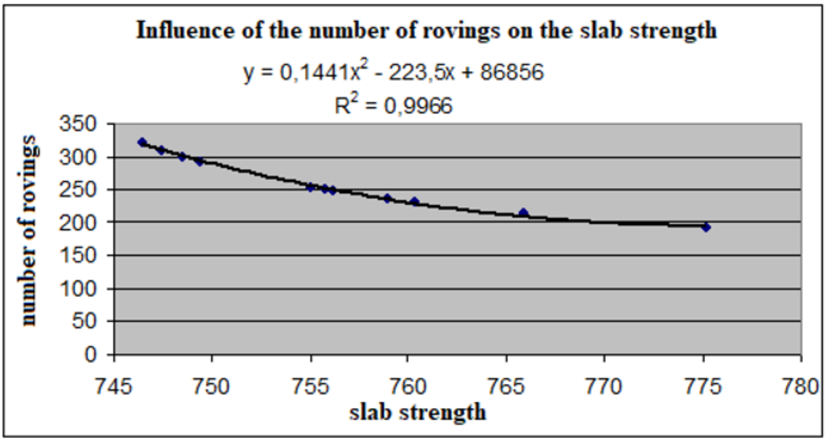


Fig. 7. Influence of the number of rovings on the slab strength.

This dependence of change in the plate bending resistance on the number of rovings is based on the experimental results, which are shown in Table 2, and the function graph is shown in Fig. 7.

Slab structural thickness is determined by the following dependence:

$$h_{\mathrm{pl}} = \sqrt{\frac{6k_{\mathrm{pr}}\mathrm{M}_{\mathrm{x(y)}}\cdot\beta}{\text{в}\times R_{\mathrm{rasch}}}}, \tag{23}$$

where β is the design strength magnification coefficient of the polymer material through its reinforcement with rovings in the longitudinal and transverse directions ($\beta = 1{,}2 - 1{,}3$).

Thus, the proposed methodology for slab structural calculations allows for its design taking into account the properties and strength characteristics of modern construction materials.

4 Conclusion

Modular removable pavements provide an opportunity to rehabilitate roads rapidly with a relatively small amount of linear preparatory work.

The advantages of such coverings lie in the possibility to build them manually without using cargo handling equipment by a four-person work crew. A valuable benefit of such pavements is also the possibility of their installation on waterlogged subgrade soils during the liquidation of consequences of natural disasters on transport communications, at oil and gas industry facilities.

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