

Keywords: sand deflation; consolidation; physic-chemical method; impregnation; protective crust; capillary forces; gravitational forces; solvation layer; humidity; specific consumption; concentration

Makhamadjan MIRAKHMEDOV

Tashkent State University of Transport

Temiryulchilar 1, 100167, Tashkent, Uzbekistan

Corresponding author. E-mail: mirakhmedovm@mail.ru

THEORETICAL BASES OF IMPREGNATION WITHOUT PRESSURE OF MELIORANTS AND THE APPLICATION OF THEIR FEATURES IN PRACTICE OF FIXING MOBILE SANDS

Summary. Desert sand is subject to deflation, which during the construction and operation of railways in the sandy desert leads to the filling of the railway track with sand and erosion of subgrade. To prevent this phenomenon, the surface of the sand is fixed with a binder, which is sprayed onto a deflated surface. The penetration of the working composition of the binder due to the characteristics of grinding is accompanied by an uneven distribution of the substance, which is proposed to characterize the saturation coefficient. Peculiarities of the interaction of the binder and sand from which the protective crust is formed are revealed, which made it possible to change the nature of the impregnation. Pre-wetting allows to reduce the pore space of sand, change the nature of the transfer of the substance when impregnated into the capillary, and increase the uniformity of impregnation, which as a result allows to obtain a resource-saving solution when fixing the movement of sand.

1. INTRODUCTION

1.1. The urgency of the problem

The transport communications of the world, in particular, railways and roads, are developing steadily. However, owing to the need for industrial development, they are built in difficult environmental conditions, for example, in mountains and deserts, in particular in sandy deserts [1 - 5]. Roads, under these conditions, are adversely affected by climatic events, such as deflation. Deflation causes the roadbed to be blown, and the sand carried as a result of deflation is deposited on the upper structure of the path, saying that the path is entered by sand [6 - 9]. Blowing and drifting are, therefore, manifestations of deflation, its result. These manifestations seriously reduce the traffic safety of vehicles, especially with a steady increase in speed train traffic (Figs. 1, 2).

The sand drift fixation in its arsenal has [6, 7] some biological and technical methods. Sharing biological and technical methods forms a combined method [2, 5].

Therefore, in the sandy deserts, the study of the negative effect of deflation on the safe construction and operation of communications (roads and railways) and the improvement of the technology to protect them from moving sands is an urgent task [10-13].

Technical methods consist of mechanical method, as well as physical and chemical methods [14, 18, 27].

The latter are used in emergency situations when it is necessary to take measures to halt the rapid deflation.



Fig. 1. Sandy drift of a railway track near the station Altynkol (Kazakhstan)
(Photo: Mirakhmedov M., 2012)



Fig. 2. SKM500 sand truck in Saudi Arabia
(photo: Plasser & Theurer)

The mechanization of sand consolidation work became possible with the development of a physicochemical method. A variety of chemical materials for bonding sand grains have been recommended: heavy oil [27, 30], various polymers, bitumen emulsion, etc. [17].

The mechanical method is implemented by installing various barriers: low barriers made of local plant waste (reeds, palm leaves, etc.), which are buried in the sand in rows or in the form of a checkerboard with cells [28], as well as high fences made of various materials (boards, stone, plastic etc.) [9, 17]. As a promising biological method, one can point to research on the creation of a layer of biomass on the surface of the sand [28, 29].

Each method has its own field of application, depending on a number of climatic and morphological features of the area, the protected object. From an economic point of view, it is important that costs are kept to a minimum. Therefore, when choosing a method of protecting an object from sand, preference should be given to waste or local secondary products.

Furthermore, these methods are used, primarily, to improve the efficiency of agroforestry work, i.e. sowing and planting.

1.2. Identification of promising areas of research

There are several methods for fixing moving sands. As a radical measure to achieve a short-term, but immediate result, first, some authors resorted to the physicochemical method (PhChM) of sand fixation [14, 15].

The essence of PhChM is to implement a technological method of spraying a binder on a fixed sand surface with garden sprayers (Fig. 3).



Fig. 3. Side blast sprayers: OVG-2006B and “Master” with drop-down consoles

The liquid without pressure moves into the sandy substrate, permeates it and forms a specific building material - a knitted sand crust, i.e. the binder plays the role of improver of sand, improving its physic mechanical properties, possessing a property that provides stability against the destructive effect of the flow of sand carried by the wind, i.e. wind sand flow [16, 17]. The properties of the crust depend on the properties of its constituents and the features of their interaction, which are manifested

in the process of impregnating the sandy substrate with a binder, stabilizing the state of the deflated surface. Owing to these circumstances, it seems important to reveal the features of pressure-free impregnation, to create the theoretical foundations of impregnation and to propose a resource-saving technological solution in the matter of fixing by impregnation of mobile sands.

2. BASIC TERMS AND CONDITIONS OF NON-PRESERVATED IMPLEMENTATION OF SAND SUBSTRATE BY BINDING SUBSTANCES

To date, ideas about the mechanism of sand impregnation with chemical improver do not fully reveal the essence of the phenomenon. Therefore, it becomes necessary to conduct a more detailed theoretical study and summarize the results of previously conducted experiments [16, 18].

For completeness of determining the law of motion of a chemical reagent in sand, the conversion function is not applicable to the vertical impregnation of water into real soils, and the experimental results do not completely coincide with the measured distribution of water in the soil [17, 18].

It is known that impregnation occurs under the influence of gravitational and capillary forces. It is also known that the influence of gravitational forces can be neglected, if and only if the potential energy of the field of capillary forces referred to a unit of liquid is greater than the potential of the field of gravity $\psi \gg \psi_g$. According to A.V. Lykov, this is true when the internal size of the channel through which the fluid moves has a size of less than 10^{-2} mm [19]. Otherwise, the mass of the impregnated liquid cannot be neglected. Therefore, to establish the predominant influence on the impregnation process of a particular field of force, it is necessary, first, to determine the internal diameter of the channel formed between the particles of the substrate.

2.1. Hydrodynamic approach to solving the problem of impregnating sand with a binder

Imagine fluid transfer as a filtering process. It is fair to assume that the solution to the filtering problem can be approached from the standpoint of the external and internal problems of hydrodynamics, i.e. present as a mixed problem of hydrodynamics [17, 18, 21]. In fact, it can be assumed that the flow moves in irregularly shaped channels formed by the gaps between the particles of the layer (the position of the internal problem of hydrodynamics). On the contrary, it can be assumed that the flow flows around particles of a layer of sand encountered on the way (the position of the external problem of hydrodynamics). Mixed tasks involve the combination of two representations for the purpose of convenience of calculation [22 - 26]. There is a certain degree of idealization, i.e., suppose that the main parameters of the problem have the following form:

- specific surface of the particles in a unit volume of the layer s_{sk} ;
- porosity or fraction of free volume ($\varepsilon = (\rho_t - \rho_j)/\rho_t$);
- grains of sand are a spherical body with an equivalent diameter (d_e).

The experiments will be carried out taking into account the similarity criteria in a vessel with a cross-section S , which is filled with sand to a height H . The volume of sand in the vessel $V = S \cdot H$. Then the surface of the grains can be defined as $F_p = V \cdot s_{sk} = S \cdot H \cdot s_{sk}$, and the volume of the solid phase (sand particles) in the vessel according to the formula $V_p = V - V_n = S \cdot H \cdot (1 - \varepsilon)$, and the volume of the solid phase (sand particles) in the vessel according to the formula $V_p = V - V_n = S \cdot H \cdot (1 - \varepsilon)$. Taking into account the similarity criteria, we have the volume of sand, the surface of the particles, and the volume of the solid phase, where V_n - is the pore volume.

The total resistance of the layer of sand grains is as follows (1):

$$\Delta p = (\lambda H / d_e) \left(\frac{\rho \cdot S^2}{2} \right), \quad (1)$$

where λ – is the total coefficient of friction resistance and local resistances; Δp – is the total resistance of the granular material; and d_k – equivalent diameter of polydisperse channels granular material.

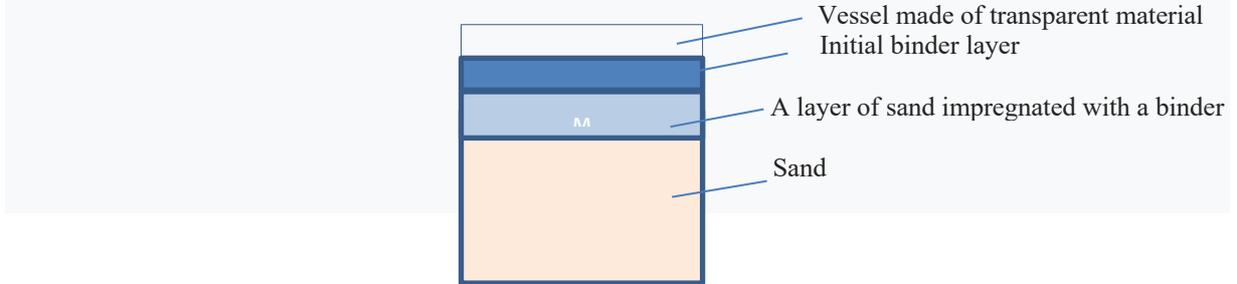


Fig. 4. Binder impregnation sand model

From the standpoint of the internal problem of hydrodynamics, the diameter of the channel, as is known, is as follows (2):

$$d_k = \frac{4\varepsilon}{s_{sk}}, \text{ m} \quad (2)$$

where s_{sk} – is the specific surface m^2 / m^3 .

Determination of the specific surface area presents known difficulties. To overcome this difficulty, we will try to solve the problem by jointly considering the external and internal problems of hydrodynamics. Suppose that there are particles of arbitrary shape in the vessel, and then the volume of one particle is as follows (3):

$$v_c = \frac{V_c}{n} = \frac{SH(1-\varepsilon)}{n}, \quad (3)$$

The volume of one particle based on its geometric shape can also be expressed as the volume of the ball $v_c = \frac{\pi d_e^3}{6}$. Then the ratio of the surface of the particle to its volume is as follows (4):

$$\frac{f_c}{v_c} = \frac{SHs_{sk}}{n} \times \frac{n}{SH(1-\varepsilon)} = \frac{s_{sk}}{1-\varepsilon}. \quad (4)$$

At the same time, $\frac{f_c}{v_c} = \frac{\pi d_e^2}{F} \times \frac{6}{\pi d_e^3} = \frac{6}{F d_e}$. Equating expression to (4) we obtain a formula for determining the specific surface (5):

$$s_{sk} = \frac{6(1-\varepsilon)}{F d_e}, \quad (5)$$

where F is the shape factor of the particles, given in reference books.

Substituting (2) in (5), we obtain the formula (6):

$$d_k = \frac{2\varepsilon}{3(1-\varepsilon)} F d_e. \quad (6)$$

Taking from the directory $F = 0.9$, porosity coefficient $\varepsilon = 0.3-0.45$ (the sand porosity of the Kulsary deposit [16], for example, is 44%), and the predominant fraction of sand in its granulometric composition $d = 0.14$ mm, it is possible to obtain an equivalent channel diameter equal to $d_k = (3.2-6.86) \cdot 10^{-2}$ mm $> 10^{-2}$ mm. So, strictly speaking, the influence of gravity cannot be neglected. This circumstance limits the idealization of the process of impregnation and replacement of real sand with capillary tubes. This means, first of all, that the study of the process of pressure less impregnation of desert sand with a binder should be carried out on physical models. This is all the truer if we take into account that the particle size distribution of the moving desert sands is also represented by the particle size distribution in a rather wide range of particle changes from 0.05 to 0.25 mm.

2.2. Features of impregnation

From the condition of preservation of the substance (liquid) before and after impregnation, the volume of impregnated liquid (Q) should be equal to the pore volume of the substrate in the impregnated layer (Q_I), i.e. $Q=Q_I$. From the condition of maintaining the volume of liquid before and

after impregnation, the volume of impregnated liquid should be equal to the pore volume of the substrate in the impregnated layer $Q_1 = Q_2 \cdot \varepsilon$, where Q_2 – volume of sand soaked in liquid and ε – bulk porosity. Assuming equal to the area of sand and the area impregnated with a chemical reclaimant, we obtain (7):

$$\delta = h_k / \varepsilon, \quad (7)$$

where δ – is the initial liquid layer above the sand surface, mm.

With free impregnation of sand with multicomponent, non-Newtonian fluids, the impregnation depth will be greater than the theoretically possible value $(h_k) > \delta/\varepsilon$. From the point of view of resource saving, excess consumption of chemical reclaimant $q_i > q_{\max}$ above the maximum is not acceptable.

$$\delta = h_k \cdot k_n / \varepsilon, \quad (8)$$

where k_n – is the proportionality parameter, called the coefficient volume of sand saturation with chemical ameliorant.

Always with free sand soaking with multi-component, non-Newtonian liquids, the depth of impregnation will be more than the theoretically possible value of $h > \delta/\varepsilon$; close to and more than $k_n < 1$, units indicate that the sand saturation $k_n \geq 1$ limit has come under these conditions and the initial volume of the chemical ameliorant has not fully soaked. From the point of view of resource saving, excess consumption of chemical reclaimant $q_i > q_{\max}$ above the maximum is not acceptable. From a technological point of view, the excess consumption of chemical improver $q_i > q_{\max}$ more than the maximum is not acceptable from the point of view of resource saving. Those study of the construction and technological characteristics of the protective layer should be in the range of values of $k_n \leq 1$, so that $q_i \leq q_{\max}$. The transfer of emulsions is accompanied by selective wetting of the sand grains with water. A thin film of a liquid is formed, and the dispersed phase of a chemical improver consisting of emulsified particles (according to [15, 22]) is transferred cork.

When impregnated with solutions and multicomponent liquids [16], the pore size narrows during the impregnation process, and as a result, the fluid front movement is unstable owing to selective adsorption of the dispersed chemical ameliorant surface particles to the hydration layer, which diffuse from its volume. This phenomenon was confirmed in other works [15 - 17]. As a result, this leads to a decrease in the radius of the smallest passages between contiguous particles and a change in the nature of the transfer from the predominantly gravitational to the capillary. Thus, a quite unambiguous evidence of the informative value of the saturation coefficient for revealing the nature of the impregnation was obtained. Its values, calculated over the whole range of variation of factors close to unity ($k_n < 1$), mean that this binder does not separate when penetrating into the sand, the pore space does not narrow, and the process proceeds under the predominant influence of the field of gravity. If the value of the saturation coefficient is less than unity ($k_n \leq 1$), and changes in the range of variation of factors $k_n \approx 1$, then this means that this binder, when penetrating into the sand, separates, and the impregnation process occurs when the pore space narrows under the predominant influence of the capillary field.

From a technological point of view, these circumstances determine the choice of mode of impregnation and the consumption of a chemical improver. Obviously, for emulsions, the maximum flow rate is determined $k_n \sim 1$ by the value of the saturation coefficient, whereas for solutions and high-molecular substances $k_n \leq 1$. In all cases, $k_n < 1$ values close to one indicate that the maximum consumption of the chemical ameliorant is achieved. Excess consumption $k_n > 1$ is not allowed. With this in mind, a classification has been proposed, which makes it possible to identify the maximum level of consumption of a chemical ameliorant in the study of new types of it and to develop on their basis new technologies for fixing moving sands (Table 1).

This circumstance also suggests the idea of using the nature of the characteristic of sand impregnation with binders to increase resource saving and reduce the cost of the method. To do $k_n > 1$ this, reduce the size of the channel formed between the particles of a sandy substrate. For example, soak sand when wet, i.e. in the rainy season or after artificial humidification.

Table 1

The nature of the impregnation

The nature of the impregnation	Type of binder	Values of saturation
Without separation of the binder	emulsion	$0.95 < k_n < 1$
With the separation of the binder	multicomponent	$0.55 < k_n < 0.95$
	solutions	$0,65 < k_n < 0,95$
Saturation limit corresponding to		$q > q_{max}; k_n > 1$

The use of locally produced binders in sands of a wet state as a result of reducing the pore space of the substrate will lead to a change in the nature of the impregnation from predominantly gravity to predominantly capillary, which will lead to a decrease in the rate of penetration of the binder into the sand and increase the uniformity of impregnation composition and its specific consumption, and as a result, obtaining a number of alternative resource-saving technological solutions, such as repetitions of mobile sands by a physicochemical method.

3. CHOICE CRITERIA FOR EVALUATING THE STRENGTH OF A PROTECTIVE LAYER

From the analysis of literature and regulatory sources, the requirements for anti-deflation protective coatings were established: fast elastic deformation modulus $E_1 < 8 \times 10^6$ Pa, slow elastic deformation modulus $E_2 < 1,1 \times 10^6$ Pa, equilibrium elastic modulus $E < 4,4 \times 10^6$ Pa, and the highest plastic viscosity $\eta > 1.05 \times 10^6$ Pa s [14]. In some studies, it is noted that the main criteria for evaluating the optimal structure of the protective layer can also be shear deformations: elasticity λ , static plasticity, and the period of true plastic relaxation [17]. Thus, the state of the protective crust is evaluated by many indicators. Only to clarify the possibility of implementing the main technological method of the physicochemical method of fixing sand - impregnation of a binder and obtaining a stable protective crust, it is necessary to conduct a sufficiently large amount of experimental research. In addition, the whole variety of physico-mechanical characteristics and parameters can be expressed in a generalized form by plastic strength $P_m > 3 \times 10^3$ Pa [18]. Given these circumstances, the study was proposed to be carried out in two stages: at the first stage, the possibility of using one or another binder with respect to the degree of impregnation and plastic strength is assessed, then, with a positive result, at the second stage, an in-depth study of the properties of the protective peel is done.

4. RESULTS AND ANALYSIS

As a result of experimental work performed in laboratory conditions, the compositions and possible concentrations of binders were determined. To increase the plasticity of the obtained protective coating based on dextrin, it was modified with gossypol resin (1 part to 4 parts of dextrin), dissolved in water in the presence of sodium hydroxide (1 part to 6 parts of dextrin), and the concentration of dextrin in the aqueous solution was 2-2.2%. The concentration of polymer adhesive in an aqueous binder solution was 1.5%.

The research results showed that the impregnation begins at a moisture content of less than 22%. The maximum humidity at which the impregnation reaches its maximum depth ranges from 20-21%.

Protective crusts were obtained by spraying the solution on dry and wet sand. At the same time, the specific consumption varied from 0.5 to 3 l / m².

Furthermore, the recommended construction and technological parameters of the protective peel, in particular, plastic strength, specific consumption of the solution, and concentration of binders were estimated (Tables 2 - 4).

It was found that on wet sand, a crust with desired properties is obtained at a lower consumption of binder; this is apparently due to the nature of its distribution in depth and depends on the speed of impregnation.

Table 2

The dependence of the depth of impregnation of solutions on time
(specific consumption of binders in dry sand 3.0 l / m²)

Impregnation Methods	Time from the start of impregnation, s	The depth of the layer from the surface of the peel, mm	
		Dextrin	KP-001 Adhesive
On air-dry sand (3-5%)	0	0	0
	1	6	7
	2	10	12
	3	11	11
	4	11	11
In the wet sand (20%)	0	0	0
	60	6	7
	120	9	10
	180	12	13
	300	15	15
	420	20	20
	480	20	20

Table 3

Construction and technological characteristics of the protective pee

Binder based on:	h (mm), P_m (Pa x 10 ³), q (l/m ²)				
	On air-dry sand			In the wet sand, W = 20%	
	h	P_m	q	h	q
dextrin	5		3	5	1,5
KP-001 Adhesive	5	4,2-4,5	3,2	5	1,5

Table 4

Recommended concentrations and specific costs of working compositions of binders (solutions)

Type of binder	The concentration of binder, %	The plastic strength of the peel, P_m , kPa		Specific consumption of a binder working concentration solution q , l / m ²	
		obtained in the sand		sand	
		air dry	wet	air-dry	wet
Dextrin solution	2,2	4 -4,5	2,7-3	3,2-3,5	1,5
Adhesive solution KP-001	1,5	1,5	3-5	3,0-3,3	1,5

In prices for April 2018, a comparison was made of the economic efficiency of the proposed methods of sanding with the six methods that were most widely used.

Compared with gossypol emulsion-based formulations, which are the most economical of the known ones, the savings per 1 ha when using the composition of a binder solution based on dextrin will be 1225 thousand soums, and when using a binder solution based on polymer glue - 1575 thousand soums. Compared with reed cells used in Uzbekistan, savings per 1 ha when using the composition of a binder solution based on dextrin will be 5646 thousand soums, and when using a binder solution based on polymer glue - 5996 thousand soums.

Pilot implementation of the research results was carried out during 2015-2016. on sandy sections of the Navoi-Uchkuduk-Misken line of the railway of JSC "Uzbekistontemiryollari": in 2015, on the section Km 273 PK0 + 00 - PK5 + 00; in 2016 - Km 274 PK 0 + 00 - 2 + 50 with fixing the dry and wet sands with the obtained compositions by processing strips.

The industrial implementation of the research results fully confirmed the effectiveness of the application of the developed solution compositions and the proposed technology. Protective crusts obtained on sections of the Navoi-Uchkuduk-Misken railway line had technological characteristics (strength $P_m \geq 2.5$ kPa, $h \geq 5$ mm), ensuring their resistance to the effects of wind-sand flow during the year. As a result of the introduction of new compositions and new technology, a 60% reduction in labor costs was achieved due to the complex mechanization of work, as well as 50% savings in materials by reducing the specific consumption of the working composition and the concentration of binder by 15%.

5. CONCLUSIONS

1. The physico-chemical method of fixing movable sand, carried out by the use of various binders, is aimed at forming a protective crust in the upper layer of sand. In the formation of the structure of the crust and its physical and mechanical properties, the impregnation of sand with the working composition of the binder is important, which can be considered as the pressureless movement of the substance in the porous body of the sandy substrate. Then, the impregnation process can be formulated as a hydrodynamic problem.
2. A joint consideration of the hydrodynamic problem from internal and external positions, taking into account the particle size distribution of medium and well-sorted sand, yields the equivalent pore space diameter for real moving sands, which made it possible to state, as a result, that the impregnation occurs under the predominant influence of gravitational forces. To ensure uniformity of impregnation and more complete saturation of the pore space with an astringent, it is necessary that the impregnation occurs under the predominant influence of capillary forces.
3. To achieve the capillary nature of the binder impregnation, it is proposed to moisten the sand in a natural or artificial way. Then, the solvate layer of the moisture film increases while decreasing the pore space of the sand. At the same time, the concentration of the substance in the working composition and its specific consumption also decrease, which opens up the prospect of creating a number of alternative resource-saving technological solutions for fixing the moving sands with the physicochemical method.
4. An express method is proposed for studying the possibility of using binders to create sand-protective crusts, based on a scientifically based reduction in the number of studied characteristics to two — the thickness of the crust and its plastic strength.
5. The factor of sand moisture has been identified as a source of reducing binder consumption for obtaining a protective crust by 10-15% and increasing the period of time suitable for sandblasting, which allowed to improve the technology of sandblasting by introducing the preliminary wetting of the sand base.
6. Developed compositions for fixing movable sand were based on locally produced binders - dextrin and adhesive KP-001:
 - dextrin - 2.2%; NaOH - 0.4%; HS (plasticizer) - 0.6%; water - 96.8%.
 - adhesive KP - 001 - 1.5%; water - 98.5, providing the required resistance of the resulting protective crust to the wind-sand flow.
7. As shown by the calculations of technical and economic efficiency, the use of the developed formulations of binder solutions to obtain a protective crust and improved sandblasting technology can reduce labor costs by 60%, get a decrease in binder consumption by 50%, and increase seed germination of sand-loving plants (phytomelioration) by 15%.

Reference

1. Laity, Julie J. *Deserts and Desert Environments: Volume 3 of Environmental Systems and Global Change Series*. John Wiley & Sons. 2011. No. 49. P. 2-7. ISBN: 978-1-4443-0074-1.

2. Pye, K. & Tsoar, H. *Aeolian Sand and Sand Dunes*/ Springer, 2009.
DOI: 10.1007/978-3-540-85910-9.
3. Dong, Z. & Chen, G. & He, X. & Han, Z. & Wang, X. Controlling blown sand along the highway crossing the Taklimakan Desert. *J. Arid Environ.* 2004. No. 57. P.329-344.
DOI: 10.1016/j.jaridenv.2002.02.001.
4. Han, Z. & Dong, Z. & Wang, T. & Chen, G. & Yan, Ch. & Yao, Z. Observations of several characteristics of aeolian sand movement in the Taklimakan Desert. *Science in China Series D: Earth Sciences*. January 2004. Vol. 47. No. 1. P. 86-96.
5. Jabbar Ali Zakeri. Investigation on railway track maintenance in sandy-dry areas. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*. 2012. Vol. 8. No. 2. P. 135-140.
6. Hagdorn, M. & Busche, D. & Draga, M. *Les sables éoliens, modélés et dynamique. La menace éolienne et son contrôle*. Bibliographie annotée. Deutsche. GesTechnZusammenarbeit (GTZ). *Schifftereibe*. Vol. 122. 1984. No. 1. 758 p.
7. Khalaf, F.I. & Al-Ajmi, D. A eolian processes and sand encroachment problems in Kuwait. Kuwait Institute for Scientific Research. *Geomorphology*. 1993. Vol. 6. No. 2. P. 111-134.
8. Heffernan, M. (2010) *Engineering Earth - the Impacts of Mega engineering Projects*. Springer Netherlands. Chapter Shifting Sands: the Trans-saharan Railway.
DOI: 10.1007/978-90-481-9920-4.
9. Raffaele, L. & Bruno, D. & Fransos, F. Pellerey Incoming windblown sand drift to civil infrastructures: a probabilistic evaluation. *J. Wind Eng. Industrial Aerodynamics*. 2017. No. 166. P. 37-47. DOI: 10.1016/j.jweia.2017.04.004.
10. Plaza, J.S. & Barcel, M.L. & P.R. de Lema Tapetado. Sand and wind: an outline of the study of éolian action on infrastructure with reference to Haramain high speed railway, Makkah-Al-Madinah. *Rev. Obras Publicas*, 2012. No. 159. P. 7-36. Available at:
http://ropdigital.ciccp.es/detalle_articulo.php?registro=19202&anio=2012&numero_revista=3537.
11. Zakeri, J.A. & Forghani, M. Railway Route Design in Desert Areas. *American Journal of Environmental Engineering*. 2012. Vol. 2. No. 2. P. 13-18. DOI: 10.5923/j.ajee.20120202.03.
12. Hewitt, T. Designing a heavy haul desert railway: lessons learned. In: *11th International Heavy Haul Conference*, (IHH 2015). Operational Excellence. Perth, Western Australia. P. 228-237.
13. *Rail - первая железная дорога ОАЭ. Железные дороги мира*. № 6. 2016. [In Russian: *Rail - UAE's first railway. World Railways*. 2016. No. 6. Available at:
<http://railknowledgebank.com/Presto/content/Detail.aspx>.
14. Freer, R.J. & Hewish, F. & Ghataora, G.S. & Niazi, Y. Stabilization of desert sand with cement kiln dust plus chemical additives in desert road construction. In: *Proceedings of the ICE - Transport*. 1999. Vol. 135. No. 1. P.29-36.
15. Kok, J.F. & Parteli, E.J.R & Michaels, T.I. & Karam, D.B. *The physics of wind-blown sand and dust*. Rep. Prog. Phys. No 75. 2012. P. 106901. DOI: 10.1088/0034-4885/75/10/106901.
16. Mirakhmedov, M.M. & Muzaffarova, M. Methodological aspects of the development of resource-saving technologies of shifting sands fixation. In: *19 Internationale*. Weimar: Bauhaus-Universität. 2015. P. 2-1203 – 2-1209.
17. Мирахмедов, М. *Основы методологии организации пескозакрепительных работ и защита природно-технических объектов от песчаных заносов*. Ташкент: Фан ва технологиялар. 2016. 248 с. [In Uzbekistan: Mirakhmedov, M. *Fundamentals of the methodology of organizing work on fixing sand and protecting natural and technical objects from sand drifts*. Tashkent: Science and technology].
18. Mirakhmedov, M. & Muzaffarova, M. Integrated Solution to the Problem of Resource-Saving Fixing of Moving Sands. *Civil Eng Res J*. 2019. Vol. 7. No. 5. P. 555723.
DOI: 10.19080/CERJ.2019.07.555723.
19. Лыков, А.В. *Тепломассообмен*. 2-е изд., перераб. и доп. Москва: Энергия, 1978. 480 с. [In Russia: Lykov, A.V. *Heat and mass transfer*. 2nd ed., Moscow: Energy].
20. Зотов, К.В. & Кучурина, Т.Н. *Основы моделирования массопереноса в пористой среде. Учебное пособие*. Часть 1. СПбГУ. 2014. 34 с. [In Russian: Zotov, K.V. & Kuchurina, T.N.

- Fundamentals of modeling mass transfer in a porous medium. Tutorial. Part 1.* St. Petersburg State University].
21. Pabst, W. & Gregorova, E. *Characterization of particles and particle systems.* ICT Prague. 2007. 122 p.
 22. *L'eau et les sols - Hydrodynamique des milieux poreux.* Available at: <https://www.edx.org/course/leau-et-les-sols-hydrodynamique-des-milieux-poreux>.
 23. Reichardt, K. & Timm, L.C. & Dourado-Neto, D. The recent similarity hypotheses to describe water infiltration into homogeneous soils. *Scientia Agricola.* 2016. Vol. 73. No. 4. Piracicaba, Brazil. Available at: <http://dx.doi.org/10.1590/0103-9016-2015-0364>.
 24. Cheremisinoff, N.P. *Liquid Filtration.* Butterworth-Heinemann. 28.07.1998. 319 p. Available at: https://books.google.com/books/about/Liquid_Filtration.html.
 25. Nicholas, P. Cheremisinoff. *Liquid Filtration.* Butterworth-Heinemann. 28 Juet 1998. 319 p. Available at: https://books.google.com/books/about/Liquid_Filtration.html.
 26. Takahiro Nomura, Noriyuki Okinaka, Tomohiro Akiyama. Impregnation of porous material with phase change material for thermal energy storage. *Materials Chemistry and Physics.* 15 June 2009. Vol. 115. Issue 2-3. P. 846-850. Available at: <https://doi.org/10.1016/j.matchemphys.2009.02.045>.
 27. Kerr, R.C. & Nigra, J.O. *Eolian Sand Control.* Arabian American Oil Company. 1952.
 28. Lima, I.A. & Araújo, A.D. & Parteli, E.J.R. & Andrade, J.S. & Herrmann, H.J. Optimal array of sand fences. *Scientific Reports.* 2017. No 7. P. 45148.
 29. Chen, L. & Zuoming, X. & Chunxiang, H. & Dunhai, L. Man-made desert algal crusts as affected by environmental factors in Inner Mongolia, China. *Journal of Arid Environments.* 2006. Vol. 67. No. 3. P.521-527.
 30. Zhou, X. & Zhao, Y. & Belnap, J. & Zhang, B. & Bu, C. & Zhang, Y. Practices of biological soil crust rehabilitation in China: experiences and challenges. *Restoration Ecology.* Pub Date: 2020-03-31. DOI: 10.1111/rec.13148doi:10.1111/rec.13148.
 31. Мирахмедов, М. *Закрепление подвижных песков тяжелыми нефтями.* Автореф. дисс. канд. техн. наук. Ташкент: 1975. ТПИ. 49 с. [In Russian: Mirakhmedov, M. *Consolidation of mobile sands with heavy oils.* Thesis of diss. for the degree of candidate of technical sciences. Tashkent: 1975. TPI].

Received 15.04.2019; accepted in revised form 25.11.2020