До теперішнього часу практично не існує експериментальних досліджень дренажних споруд. Об'єктом представленого дослідження є дорожня конструкція з поперечним дренажем мілкого закладання, яка влаштовується на перезволожених ділянках автомобільних доріг. З метою визначення інтенсивності водовідведення дренажної конструкції, в залежності від властивостей матеріалів-наповнювачів, на спеціальній моделюючій установці дорожньої конструкції проводився експеримент.

Параметри установки дозволяють влаштовувати конструкцію, що відповідає реальним натурним умовам – параметрам III категорії автомобільної дороги та дослідити процеси формування фільтраційного потоку в дренажній траншеї, що неможливо на реальних об'єктах.

На лабораторній установці проводилися дослідження умов роботи дренажних конструкцій: шару із щебню фракцією 20–40 мм та двох типів поперечних дренажів мілкого закладання з різних матеріалів-наповнювачів в траншеї. У процесі проведення ряду експериментальних досліджень проводилося вимірювання об'єму відведеної води з траншеї, часу відведення. За результатами досліджень, на основі методів математичної статистики побудовано уніфіковані рівняння кореляційно-регресійної моделі щодо режиму роботи дренажної конструкції в залежності від початкової вологості ґрунту земляного полотна.

За отриманими результатами експериментальних досліджень визначено один з основних показників роботи конструкцій дренажів мілкого закладання, який залежить від властивостей матеріалів-наповнювачів траншей – інтенсивність водовідведення. Встановлено, що дренажна конструкція з щебеневим ядром в траншеї працювала в одному режимі сформованого потоку на відміну від конструкції з полівінілхлоридною трубою, обсипаною крупнозернистим піском. Робота конструкції з трубою за інтенсивністю водовідведення поділяється на короткочасний та тривалий режим. Отримані регресійні залежності дозволяють зробити прогноз щодо кількості відведеної води запропонованими дренажними конструкціями за певний проміжок часу для натурних умов

Ключові слова: дорожня конструкція, дренуючий шар, дренаж мілкого закладання, полівінілхлоридна труба, щебеневе ядро

UDC 625.7/.8
DOI: 10.15587/1729-4061.2020.203551

THE INTENSITY OF WATER REMOVAL FROM SHALLOW DRAINAGE SYSTEMS CONSIDERING THE PROPERTIES OF FILLER MATERIALS

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Received date 30.03.2020
Accepted date 19.05.2020
Published date 19.06.2020

1. Introduction

The main signs of insufficient water drainage include a decrease in strength and load-bearing capacity of the road structure because of overwetting and significant reduction of the modulus of elasticity of soil and layers of the road pavement base arranged of coherent soils.

When designing roads in overwetted areas, two main problems must be solved: prevent water from entering to infiltrate and ensure its rapid drainage. If drainage structure is designed and arranged of low-quality materials with low drainage intensity, it, on the contrary, contributes to excessive moisture accumulation, causes damage to the road pavement, and premature deterioration of road-service quality (RSQ).

In order to prevent or minimize future damage and improve RSQ, it is necessary to arrange drainage systems of appropriate and high-quality materials. Appropriate drainage is an important element of road design due to which the required level of strength characteristics and the cost to quality ratio is achieved. The drainage system reduces the costs of road maintenance and, accordingly, can significantly reduce future overhaul and reconstruction work volumes.

The above-mentioned forms a scientific issue of the day: determining the efficiency of underground drainage structures proceeding from water drainage intensity. Appropriate experimental studies of the operation of shallow drainage systems (SDS) constructed of various materials make it possible to determine the volume of water removed and time of its removal and make rational design decisions.

2. Literature review and problem statement

Depending on design objectives, the proposed SDS types should provide proper and long-term RSQ. Detailed consideration of all RSQ aspects, the study of physical and functional properties based on qualimetry methods are given in [1, 2]. The relationship between the condition of the elements of road structures (in particular, underground drainage structures) and surface drainage structures significantly affects the costs of road construction. The issue of the significance of the impact of drainage structures, especially underground ones, on RSQ remains unsolved. It is very difficult to assess their condition and efficiency. This can be done by means of visual inspection but the problem is in the fact that there may be several causes of deformation of the road covering and the road structure as a whole.

Moistening dynamics in road structures during the annual cycle significantly affect design decisions and road maintenance. Moisture regime of a road section in Sweden was studied in [3] by the method of electric tomography. The testing of samples of pavement base layers with different humidity levels by the method of acoustic emission was proposed by Chinese researchers in [4]. These results form a basis for making changes in pavement design in conditions of climate change. Even though the number of in-field studies of moisture regime of road structures applying non-destructive methods is increasing, similar approaches to monitoring operation of drainage structures were not proposed.

Importance of shallow drain (SD) operation, consequences of their poor drainage, impact on traffic safety, and inter-repair time are described in detail in [5, 6]. However, no approaches have been proposed to improve the work of SDS, peculiarities of the use of filler materials depending on drainage intensity have not been taken into account.

Peculiarities of operation of surface drainage structures in a complex with SD which work on the principle of drying were considered in [7]. Their negative impact on the roadside environment was analyzed. In order to improve environmental safety, the authors proposed to use absorbing drainage layers. There is a controversial issue regarding the stress-strain state (SSS) of such a road structure which is weakened by over moistened base. Shallow drainage is arranged in the working zone of the road structure where there is an imposition of two types of the greatest loading: from moving vehicles and own weight of the structure.

The definition of SSS of a road structure with a transverse tubular SD as an atypical structure was presented in [8]. According to the strength characteristics, the feasibility of using drainage pipes was determined. It would be necessary to consider in [8] SSS features of road structures with drainage having a crushed stone core which would make it possible to more reasonably determine the feasibility of using tubular drainage structures.

A decrease in bearing capacity of the roadbed soil is determined by the accumulation of moisture from heavy, prolonged rainfalls leaking through potholes, cracks in the road surface, nonconsolidated roadsides, and slopes. The importance of ensuring intensive drainage of SD in the climate of India in order to prevent the development of deformations on the road surface was considered in [9]. The drawback of this study is the lack of observations and analysis to determine the drainage capacity of the proposed structures.

Several methods of preventing moisture penetration into the road structure were considered in [10] taking into account parameters of the transverse and longitudinal profiles of the road and arrangement of drainage structures. The results of long-term field tests on Australian roads to study the migration of infiltration moisture in the layers of pavement were presented. The study was conducted on road structures without drainage. Given the fact that SDs are underground structures, the effectiveness of their work in such conditions is quite difficult to determine and requires many clarifications. This relates to peculiarities of obtaining results both in field conditions because of duration and weather conditions of their conduction and in theoretical studies because of certain assumptions.

The study analysis necessitates the use of full-scale experimental models with a possibility of visualization. This task is quite difficult, because SDs are underground structures and it is impossible to study processes of formation of filtration flows in drainage trenches of real objects.

3. The aim and objectives of the study

This study objective is as follows. Based on experimental studies, determine the intensity of drainage with transverse SDs built from various filler materials.

To achieve this goal, it is necessary to solve the following tasks:

– to study work of two types of SDS with different filler materials of the drainage trench in terms of drainage intensity;

– based on the results of experimental data, construct and study regression models of work of each SDS;

– to determine conditions of operation of each variant of the drainage trench design and their influence on the drainage intensity.

4. Materials and methods of experimental studies

The presented studies are based on an experiment conducted at the Educational and Scientific Laboratory of the Department of Transport Construction and Property Management at the National Transport University (Kyiv, Ukraine) using a special modeling installation of road construction. The installation parameters have allowed us to arrange one running meter of a road structure (a 0.5 road width from its axis in a cross-section) according to real full-scale conditions for roads of technical categories III and IV. The installation dimensions are 1.0×4.0×1.5 m. The front wall of the installation is made of organic glass which makes it possible to directly observe the formation of filtration flows in the drainage trench (Fig. 1, 2). Typical structures of transverse SDs of various filler materials were used in the study.

At the bottom of the installation, there is a 5 cm thi cmck layer of sand covered with a layer of geosynthetic material (GSM). Roadbed (RB) of loamy sand with a total thickness of 55 cm was poured on the sand in layers and compacted. The upper layer of the RB soil corresponds to the slope (25 ‰) of the carriageway.

In the upper layer of the soil, a rectangular drainage trench 0.20 m deep and 0.25 m wide lined with GSM along its perimeter was arranged. The slope of the trench bottom was taken equal to the slope of the upper soil layer.

Studies of operating conditions of two types of SDS arranged of different trench filler materials were conducted at the laboratory installation to determine drainage intensity.

A perforated PVC pipe pre-wrapped with GSM (with an overlap of 0.1 m) was laid on the bottom of the SDS 1 trench over the GSM layer covering the trench perimeter. The GSM cover of the pipe was sewn with a synthetic thread. The drainage pipe was tightly filled with washed coarse-grained quartz sand with a grain size of 2–3 mm. The filtering crumbs were covered with the GSM side edges with an overlap of 30 cm and fixed with wooden pins with a step of 0.25 m. The SDS 1 with the PVC pipe is shown in Fig. 1.

In SDS 2, a 0.05 m thick layer of washed crushed stone of 5–10 mm fraction was laid in the trench, covered with GSM, and the next 0.2 m thick layer of washed crushed stone of 20–40 mm fraction was laid up to the trench top. The crushed stone core was also covered with the GSM side edges with a 30 cm overlap and fixed with wooden pins with a step of 0.25 m. The SDS 2 with a crushed stone core is presented in Fig. 2.

The trench and RB were covered with GSM and a 0.12 m thick drainage layer of washed crushed stone of 20–40 mm fraction was arranged. Arrangement of the crushed stone layer was determined by the fact that it has a compact, porous structure with filtration coefficient of 200 m/s and does not stop water that makes it possible to more effectively study the operation of the drainage trench and determine the effectiveness of its work in terms of drainage intensity.

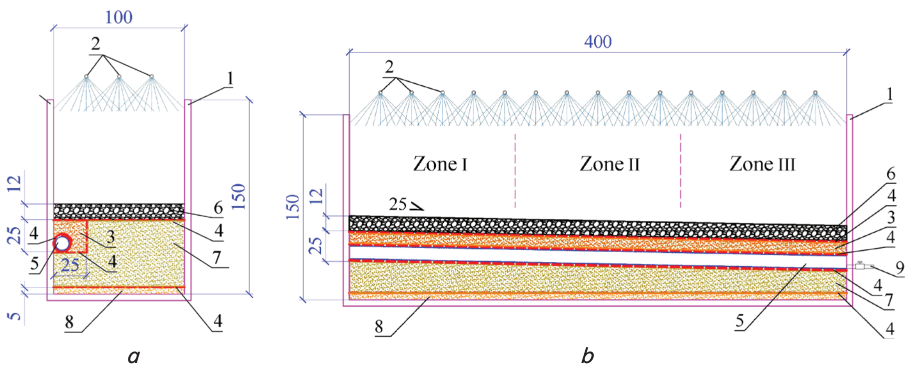

Fig. 1. Experimental installation with an SDS 1 having a PVC pipe: *a* – end plane; *b* – lateral plane; I, II, III – respective measurement zones; 1 – the housing of the experimental installation; 2 – rainfall simulation system; 3 – a filler of the drainage trench: washed quartz sand with the grain of 2–3 mm fraction; 4 – an interlayer of GSM; 5 – 100 mm dia. PVC drainage pipe with holes; 6 – drainage layer: washed crushed stone of 20–40 mm fraction; 7 – soil: dusty loamy sand; 8 – layer of fine-grained sand; 9 – outlet (a tap); 10 – the front wall of the experimental installation body of plexiglass (10)

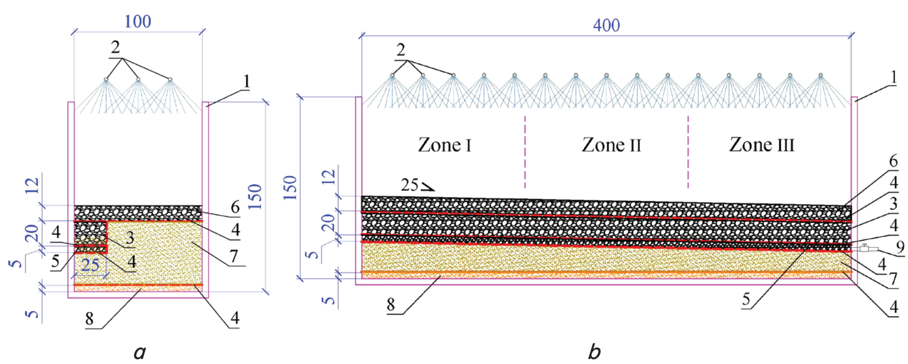

Fig. 2. Experimental installation with SDS 2 from a crushed stone core: *a* – end plane; *b* – lateral plane; I, II, III – respective measurement zones; 1 – the housing of the experimental installation; 2 – rainfall simulation system; 3 – a filler of the drainage trench: washed crushed stone of 20–40 mm fraction; 4 – a layer of GSM; 5 – a filler of the drainage trench: washed crushed stone of 5–10 mm fraction; 6 – drainage layer: washed crushed stone of 20–40 mm fraction; 7 – soil: dusty sand; 8 – layer of fine sand; 9 – outlet (a tap); 10 – the front wall of the experimental installation body made of plexiglass

5. Results obtained in the study of drainage intensity in shallow drainage systems

5. 1. The results of experimental studies of SDS of two types with various filler materials in the drainage trench

In order to determine the duration and amount of moisture removal from the soil of the SD road base, the amount of water that will fall on 4 m^2 of the surface of the laboratory road structure installation was determined. The amount of water corresponded to the amount of rainfall of 5 % supply. Meteorological data were used for the calculation: intensity i_{zd5} of rainfall of 5 % supply and duration T_3 of 5 % supply according to [11]. The amount of heavy rainfall of 5 % supply (q_{zd5}), m^3 per 4 m^2 was determined from dependence $q_{zd5}=i_{zd5}\cdot T_3\cdot 4\cdot 10^{-3}$. For the conditions of the Kyiv region, the amount of heavy rainfall of 5 % supply is $q_{zd5}=25$ l per 4 m^2.

This determined amount of precipitation poured on the surface of the drainage layer using a system of rainfall simulation (Fig. 1, 2) which provided a uniform distribution of moisture over the laboratory installation area.

When carrying out each experiment, the humidity of the RB soil was measured before moistening (Table 1).

Table 1

Experimental measurements of roadbed moisture before moistening (I, II, III are corresponding zones on the experimental installations)

Experiment date	Soil moisture W, %			
	Zone I	Zone II	Zone III	Mean value
SDS 2 with a core of crushed stone				
11.02.2020	14.5	13.2	12.3	13.2
12.02.2020	13.1	12.9	13.1	13.1
14.02.2020	13.5	12.5	13.1	13.0
SDS 1 with a PVC pipe				
17.02.2020	12.4	10.2	11.5	11.4
19.02.2020	12.2	9.7	11.9	11.3
21.02.2020	10.8	10.6	11.5	11.0

Based on the obtained experimental data, a field of correlation between the amount of filtered water and the time of its filtration for each of the studied drainage installations was constructed.

Fig. 3 shows the field of correlation between the amount of filtered water and the time of its filtration for the SDS 1 with a PVC pipe. Points correspond to the results of experimental measurements.

It was found in the experiment with the SDS 1 that after the water flow was formed in the trench and the main part of the water was drained, the SDS 1 continued to drain water in the form of drops for another 3 hours. Therefore, the total volume of water drained by this structure has increased according to Table 2.

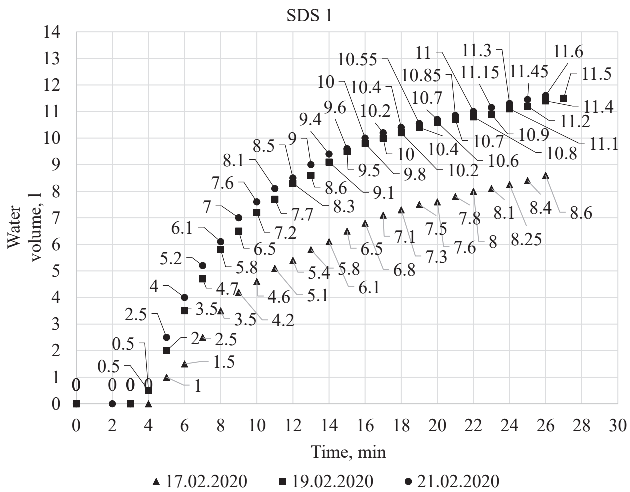

Fig. 3. Field of correlation between the amount of filtered water and the time of its filtration according to experimental measurements for the SDS 1: 17.02.2020; 19.02.2020; 21.02.2020 are the study dates

Table 2

The total volume of water drained from the SDS 1

Experiment date	The volume of water coming to the structure $Q_{tot.}$, l	The volume of water drained from the formed flow Q_{drain}, l	Time of water flow formation t_{form}, min	The total volume of drained water $Q_{drain.tot.}$, l	Total time of water drainage $t_{drain.\ tot.}$, min
17.02.2020	25	8.6	26	10.6	206
19.02.2020	25	11.5	27	13.5	207
21.02.2020	25	11.8	26	15.8	206

Fig. 4 shows the field of correlation between the amount of filtered water and the time of its filtration for the SDS 2 with a crushed stone core. The points correspond to the results of experimental measurements.

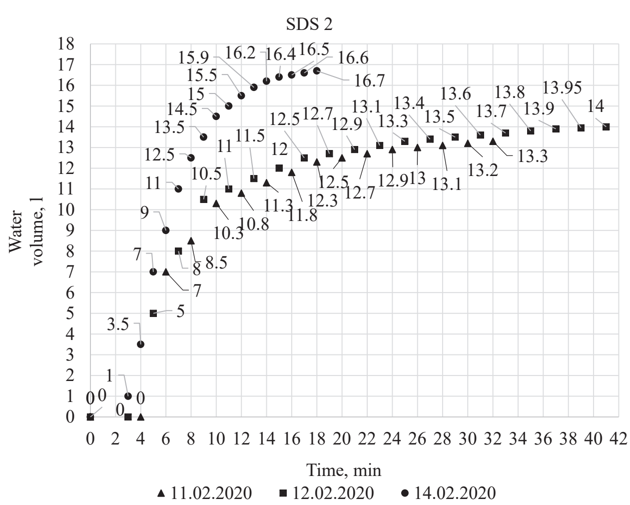

Fig. 4. Field of correlation between the amount of filtered water and the time of its filtration according to experimental measurements for SDS 2; 11.02.2020; 12.02.2020; 14.02.2020 are the study dates

It was found in the experiment for SDS 2 that the water flow was formed in this installation trench almost immediately after the end of the water supply. The time of flow formation coincided with the total drainage time. The total volume of water drained by this structure is given in Table 3.

Table 3

The total volume of water drained from SDS 2

Experiment date	The volume of water coming to the structure $Q_{tot.}$, l	The volume of water drained from the formed flow Q_{drain}, l	Time of water flow formation t_{form}, min	The total volume of drained water $Q_{drain.\ tot.}$, l	Total time of water drainage $t_{drain.\ tot.}$, min
11.02.2020	25	13.3	32	13.3	32
12.02.2020	25	14.0	41	14.0	41
14.02.2020	25	16.7	18	16.7	18

At the next study stage, the mathematical processing of the experimental results was performed in order to unify them and establish patterns between the main parameters of the studied drainage systems.

This will make it possible to predict their performance in time and space under the influence of various factors.

5. 2. Mathematical processing of the results obtained in experimental studies of the performance of shallow drainage structures

Analysis of the correlation fields between the amount of filtered water and its filtration time for the studied shallow drainage structures obtained on the basis of experimental data (Fig. 3, 4) has allowed us to hypothesize the presence of a correlation or functional relationship between these two quantities.

The choice of the structure of the regression equation, which depends primarily on the distribution of experimental data and analysis of their correlation fields, is an important point for the correlation-regression analysis of the experimental data [12, 13].

The regression equation should be chosen to describe as accurately as possible the distribution of experimental data and minimize squares of discrepancies between experimental and calculated regression equation values of the studied parameters.

Since the operation of both drainage systems features a much more slower growth of the value of the function characterizing the amount of drained water with an increase in values of time t than at small values and eventually reaches a stationary mode corresponding to an asymptotic approximation of the function to some line, it can be hypothesized that the regression equation must be sought in a form of a hyperbolic function like:

$$\hat{Q}(t) = a + \frac{b}{t}, \qquad (1)$$

where $\hat{Q}(t)$ is the calculated amount of drained water (in relation to the initial volume); t is drainage time, min; a, b are dimensionless regression parameters.

The coefficients a and b included in the regression equation (1) were determined on the basis of the method of least squares (MLS) from the formulas given in [13]:

$$b=\frac{n\sum\frac{Q_i}{t_i}-\sum\frac{1}{t_i}\cdot\sum Q_i}{n\sum\frac{1}{t_i^2}-\left(\sum\frac{1}{t_i}\right)^2}, \qquad (2)$$

$$a=\frac{1}{n}\sum Q_i-\frac{b}{n}\cdot\frac{1}{t_i}. \qquad (3)$$

To estimate the strength of the relationship between the studied parameters, coefficient of pair correlation was calculated from the following formula:

$$R=\sqrt{1-\frac{\sum\left(Q_{i.}-\hat{Q}_i\right)^2}{\sum\left(Q_i-\bar{Q}_{i.}\right)^2}}. \qquad (4)$$

The significance of the regression parameters was estimated by Fisher's F-criterion for the accepted level of significance α comparing its critical (tabular) value F_{tab} with the actual value F_{fact} determined from the formula:

$$F_{fact}=\frac{R^2}{1-R^2}\cdot\frac{n-m-1}{m}, \qquad (5)$$

where m is the number of parameters at the factorial criterion; n is the number of observations.

The average error of approximation of experimental data by correlation-regression dependence was determined from the formula:

$$\bar{A}=\frac{1}{n}\sum\frac{Q_i-\hat{Q}_i}{Q_i}\cdot 100\ \%. \qquad (6)$$

After determining the required regression parameters, a direct calculation was performed for each drainage structure taking into account specifics of different filler materials.

As an example, below is the procedure of finding the regression equation for one of the experiments with the SDS 2 (experiment date: 11.02.2020).

Similarly, parameters of the regression model were determined for the rest of the experiments with the SDS 1 and 2. The results of the correlation-regression analysis of all experimental data are presented in Table 5 and Fig. 5.

Based on the constructed regression dependences, it is possible to predict the amount of drained water by means of the proposed drainage structures for a certain period of time. In order to unify the equations given in Table 5, the dependence of the mode of operation of drainage structures on initial humidity W_{RB} was found.

Table 4

Calculation table for finding parameters of the regression model

Experimental data			Calculation data					
Measurement No i	Drainage time, t_i	Quantity of the drained water, Q_i	$1/t_i$	$1/t_i^2$	Q_i/t_i	$\hat{Q}_i$	$\left(Q_i-\hat{Q}_i\right)^2$	$\left(Q_i-\bar{Q}\right)^2$
1	4	0	0.25	0.0625	0	0.0423	$1.8\cdot10^{-3}$	0.1882
2	6	0.28	0.1667	0.0278	0.0467	0.2335	$2.2\cdot10^{-3}$	0.0237
3	8	0.34	0.125	0.0156	0.0425	0.3291	$1.2\cdot10^{-4}$	0.0088
4	10	0.412	0.1	0.01	0.0412	0.3865	$6.5\cdot10^{-4}$	0.0005
5	12	0.432	0.0833	0.0069	0.0360	0.4247	$5.3\cdot10^{-5}$	0.000003
6	14	0.452	0.0714	0.0051	0.0323	0.4521	$3.5\cdot10^{-9}$	0.0003
7	16	0.4720	0.0625	0.0039	0.0295	0.4725	$3.0\cdot10^{-7}$	0.0015
8	18	0.4920	0.0556	0.0031	0.0273	0.4885	$1.2\cdot10^{-5}$	0.0034
9	20	0.5	0.05	0.0025	0.0250	0.5012	$1.5\cdot10^{-6}$	0.0044
10	22	0.508	0.0455	0.0021	0.0231	0.5117	$1.3\cdot10^{-5}$	0.0055
11	24	0.516	0.0417	0.0017	0.0215	0.5203	$1.9\cdot10^{-5}$	0.0067
12	26	0.52	0.0385	0.0015	0.0200	0.5277	$5.9\cdot10^{-5}$	0.0074
13	28	0.524	0.0357	0.0013	0.0187	0.5340	$1.0\cdot10^{-4}$	0.0081
14	30	0.528	0.0333	0.0011	0.0176	0.5395	$1.3\cdot10^{-4}$	0.0089
15	32	0.532	0.0313	0.0010	0.0166	0.5442	$1.5\cdot10^{-4}$	0.0096
Total	270	6.5080	1.1904	0.1461	0.3980	6.5080	$5.26\cdot10^{-3}$	0.2770

Results of calculation of the correlation-regression model parameters from formulas (1)–(6)

Equation of the correlation-regression model	Coefficient of correlation	Coefficient of determination	Mean error of approximation	Value of Fisher's criterion at α=0.05	
				Critical value	Actual value
$\hat{Q}(t)=0.6159-\frac{2.2944}{t}$	0.9325	0.8809	2.72 %	4.3009	162.72

Table 5

The results of the correlation-regression analysis of experimental data

Experiment No.	Equation of the correlation-regression model	Coefficient of correlation	Coefficient of determination	Mean error of approximation, %	Value of Fisher's criterion at α=0.05	
					Critical value	Actual value
Structure 1						
1	$\hat{Q}(t)=0.356-\frac{1.3924}{t}$	0.9325	0.8809	9.3	4.3009	162.72
2	$\hat{Q}(t)=0.4958-\frac{1.8178}{t}$	0.9674	0.9358	10.85	4.3009	320.83
3	$\hat{Q}(t)=0.5064-\frac{1.82}{t}$	0.9746	0.9498	3.96	4.3009	416.24
Structure 2						
1	$Q(t)=0.6159-\frac{2.2944}{t}$	0.9905	0.981	2.72	4.6672	671.81
2	$Q(t)=0.6052-\frac{1.8677}{t}$	0.9971	0.9942	4.62	4.4139	3111.14
3	$Q(t)=0.8158-\frac{2.5108}{t}$	0.9916	0.9832	12.35	4.6001	821.19

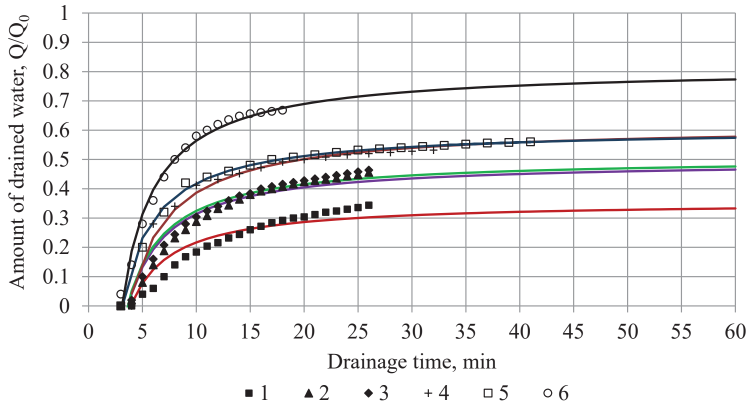

Fig. 5. Approximation of experimental data by regression dependences (points: experimental data, solid lines: regression curves): SDS 1, W_{RB}= 11.4 % (1); SDS 1, W_{RB}= 11.3 % (2); SDS 1, W_{RB}= 11.0 % (3); SDS 2, W_{RB}= 13.2 % (4); SDS 2, W_{RB}= 13.1 % (5); SDS 2, W_{RB}= 13.0 % (6)

The following is an example of a search for one of the polynomial dependences for the SDS 1, in particular, $a(W_{RB})$. Experimental measurements of humidity W_{RB} are initial data (Table 1), a and b are coefficients of regressions $Q=Q(t)$ according to three experiments that correspond to the humidity data.

Dependences $a(W_{RB})$ and $b(W_{RB})$ will be sought in a form of quadratic polynomials of the following form:

$$a(W_{RB}) = a_1 \cdot W_{RB}^2 + b_1 \cdot W_{RB} + c_1, \qquad (7)$$

$$b(W_{RB}) = a_2 \cdot W_{RB}^2 + b_2 \cdot W_{RB} + c_2. \qquad (8)$$

Find the coefficients a_1, b_1, c_1 by the method of least squares [13] from the system of equations:

$$\begin{cases} a_1 \sum W_{RBi}^2 + b_1 \sum W_{RBi} + n \cdot c_1 = \sum a_i, \\ a_1 \sum W_{RBi}^3 + b_1 \sum W_{RBi}^2 + c_1 \sum W_{RBi} = \sum W_{RBi} a_i, \\ a_1 \sum W_{RBi}^4 + b_1 \sum W_{RBi}^3 + c_1 \sum W_{RBi}^2 = \sum W_{RBi}^2 a_i. \end{cases} \qquad (9)$$

Substitution of the data from Table 5 gives a system of equations:

$$\begin{cases} 378.65a_1 + 33.7b_1 + 3c_1 = 1.3582, \\ 4255.441a_1 + 378.65b_1 + 33.7c_1 = 15.2313, \\ 47835.338a_1 + 4255.441b_1 + \\ +378.65c_1 = 170.8489. \end{cases} \qquad (10)$$

Based on the solution of the system of equations (10) by the Cramer method, the desired equation is obtained:

$$a(W_{RB}) = -3.4067 \cdot W_{RB}^2 +$$
$$+ 75.9333 \cdot W_{RB} - 422.5536.$$

The coefficient of correlation $R(a, W_{RB}) \approx 1$ which indicates a very close relationship between values of a and W_{RB}. Similarly, remaining dependencies are found. Thus, we have:

– for SDS 1:

$$a(W_{RB}) = -3.4067 \cdot W_{RB}^2 + 75.9333 \cdot W_{RB} - 422.5536;$$

$$b(W_{RB}) = 10.6166 \cdot W_{RB}^2 - 236.7443 \cdot W_{RB} + 1317.7511; \qquad (11)$$

– for SDS 2:

$$a(W_{RB}) = 11.065 \cdot W_{RB}^2 - 290.9027 \cdot W_{RB} + 1912.5648;$$

$$b(W_{RB}) = -53.49 \cdot W_{RB}^2 + 1402.5211 \cdot W_{RB} - 9195.4679. \qquad (12)$$

If we replace coefficients a and b in equations of the correlation-regression model (Table 5) by corresponding dependences (11), (12), we can obtain unified equations for the mode of operation of drainage structures depending on the initial humidity W_{RB}.

5. 3. Operating modes of drainage trench structures and their influence on drainage intensity

According to the obtained results of experimental observations, modes of operation of each variant of the drainage trench design were studied and one of the main properties of filler materials for drainage trenches was determined, namely, drainage intensity.

Table 6

The intensity of drainage with SDS 1 and SDS 2

Trench filler	Date	Formed flow		After the flow was broken (in drops)			Total indices	
		Drainage intensity $I_{drain.form}$, l/min	Percentage of drained water from Q_{tot}, %	The volume of the drained water Q_{broke}, l	Drainage intensity $I_{drain.broke}$, l/min	Percentage of drained water from Q_{tot}, %	Drainage intensity $I_{drain.tot.}$, l/min	Percentage of drained water from $Q_{tot.}$, %
PVC pipe, sand of 2–3 mm fraction	17.02.2020	0.3308	34.40	2	0.0111	8.00	0.0515	42.40
	19.02.2020	0.4259	46.00	2	0.0111	8.00	0.0652	54.00
	21.02.2020	0.4214	47.20	4	0.0222	16.00	0.0760	63.20
Crushed stone core	11.02.2020	0.4156	53.20				0,4156	53.20
	12.02.2020	0.3415	56.00				0.3415	56.00
	14.02.2020	0.9278	66.80				0.9278	66.80
Mean value								
PVC pipe, sand of 2–3 mm fraction	17.02.2020–21.02.2020	0.4	42.53	2.7	0.0148	10.67	0.0643	53.20
Crushed stone core	11.02.2020–14.02.2020	0.6	58.67				0.4835	58.67

The intensity of drainage of the formed flow when water flowed out the trench as a jet was defined as $I_{drain.form.}=Q_{drain.}/t_{form}$. The intensity of drainage of the broken flow when water was already flowing in drops was defined as $I_{drain.broke}=Q_{broke.}/(t_{dr.\,tot.}-t_{form.})$ where $Q_{broke.}=Q_{drain.tot}-Q_{drain}$. The total intensity of drainage was defined as $I_{drain.tot.}=Q_{drain.tot.}/t_{drain\cdot tot}$.

It should be noted that the volume of discharged water for the SDS 2 is $Q_{drain}=Q_{drain.tot}$, that is, the structure is working in a mode of formed flow and water is leaving the trench in a fast stream, thus the drainage intensity is $I_{drain.form.}=I_{drain.tot.}$ Drainage intensity for the SDS 1 should be divided into two indicators: for drainage of the formed flow $I_{drain.form.}$ and drainage of the broken flow $I_{drain.broke.}$

6. Discussion of the study results concerning the possibility of using shallow drainage structures in road construction

The studies conducted with a special installation for modeling a road structure with a transparent front wall have allowed us to elucidate the processes of forming the filtration flow in two types of drainage structures with dimensions corresponding to the design dimensions with the use of various trench-filling materials which is impossible to in real road construction projects. It is also important that the experiments were conducted for adverse critical conditions that occur during heavy or continuous rains.

Based on the equations of the correlation-regression model derived from the experimental results for $\widehat{Q}(t)$ and polynomial dependences for coefficients $a(W_{RB})$, $b(W_{RB})$, it is possible to predict the amount of water drained by the proposed drainage structures for a certain period of time depending on the initial roadbed moisture W_{RB}.

Observations of the formation of the filtration flow have allowed us to establish the fact that the water drainage process is different for each drainage structure under the same conditions. For example, the total drainage time was on average 30 min for the SDS 2 with a crushed stone core and 206 min for the SDS 1 with a PVC pipe. This is explained by the fact that the filler material in the SDS 1, that is, the coarse-grained sand of 2–3 mm fraction acts as a storage and drains water fast for the first 26 minutes and then slowly.

When comparing the intensity of drainage of the formed flow $I_{drain.form.}$, it was higher by more than 30 % in the SDS 2 than in the SDS 1. Also, there was an order of magnitude larger difference in the total mean drainage intensity $I_{drain.tot.}$ (Table 6). But on the other hand, lower drainage intensity in the SDS 1 was observed at the final stage. The amount of drained water was only 8–10 % of the total amount Q_{tot}. and the difference between the two structures in the amount of drained water was only 5.5 % of the total amount (Table 6).

As a result of laboratory studies of shallow drainage structures of two types made of different materials, it can be noted that the SDS 1 had a lower water discharge and longer drainage time than the SDS 2. Accordingly, the SD with a crushed stone core of high drainage intensity is the most suitable for use. However, the question of SDS 2 duration remains open because at this drainage intensity it can be silted up faster than SDS 1 where PVC pipe has double protection: a filler of coarse sand and GSM wrapping the pipe body. It should also be noted that the distribution of stresses and strains in the structures during the arrangement of drainage layers under which there are trenches with different fillers have a different nature. This issue was discussed in [8] and requires separate studies.

Design of optimal road structures with SD is based on three main principles: ensuring strength, frost resistance and shear resistance of pavement provided minimum reduced costs which are the sum of capital investment in road construction and the cost of road maintenance are ensured. An SD is selected for each equivalent strength variant of the road structure proceeding from the type of wetting of the RB working layer, soil, hydrological and climatic conditions, terrain, availability, and properties of local road-building materials. Such design measures should provide a small, preselected design range of soil moisture fluctuations and the accepted design modulus of elasticity and the lowest estimated cost of entire road structure under given natural conditions. Accordingly, the search for optimal design solutions should be the next step in future studies.

7. Conclusions

1. The drainage intensity of two SDS with different filler materials in the trench was studied. The experiment was carried out in accordance with real unfavorable meteorological conditions of operation of the two SDS with rainfall intensity of 5 % of supply, i_{zd5}. Results of measurement of RB soil moisture W_{RB} before moistening, the volume of drained water Q_{drain} and time of flow formation t_{form}; total volume of drained water $Q_{drain.tot.}$ and time $t_{drain.tot.}$ were obtained.

A field of correlation between the amount of filtered water and its filtration time was constructed for each SDS based on the obtained experimental data. The nature of the distribution of points on the correlation field indicates the shape and direction of the relationship between the results of experimental measurements.

2. Based on the results of experimental studies, the equation of correlation-regression models in a combination with polynomial dependences for two types of drainage structures was obtained between the following factors: initial soil moisture, time and volume of water drainage in SDS. The proposed structure of regression equations is hyperbolic which most accurately describes features of the studied drainage systems for both small and large time t.

The values of the pair correlation coefficients of 0.93–0.99 indicated a very close relationship between the studied factors (amount of water removed and time of its removal). For all correlation-regression models, the actual value of Fisher's criterion significantly exceeded its critical value which indicates statistical significance, reliability, and adequacy of the obtained regression models. Mean approximation error for all correlation-regression models was 2.72–12.35 % which has allowed us to conclude that they are highly accurate.

3. The SDS 2 with mean drainage intensity of 0.6 l/min removed more water than the SDS 1 in the same period which gives grounds to argue about its higher efficiency at 58.67 % of the total volume of water entering the structure. In contrast to the SDS 1, the SDS 2 operates in one mode of the formed flow. According to the drainage intensity, its operation is divided into short-term and long-term modes at corresponding values of 0.4 l/min and 0.0148 l/min. The SDS 1 has lower water drainage because filler of the drainage trench, coarse-grained sand of 2–3 mm fraction, absorbs

a certain amount of water and holds it. But the PVC pipe is perforated with holes corresponding to the drainage filler size, respectively, will not be silted up so quickly and will have a longer service life. The average amount of drained water was 53.20 % of the total amount. Given this, the choice of the type of transverse SD design will depend on soil, hydrological and climatic conditions, terrain, and estimated cost of the overall road structure.

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