Strength indices of sand reinforced by foamed bitumen

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Abstract. The purpose of the article is to determine the dependence of the parameters, the strength of sand reinforced by foamed bitumen on the content of organic binder. Tests were carried out by uniaxial compression using a measuring and computing complex. As a result, the ultimate compressive strength and the parameters of shear resistance are determined. To determine the angle of internal friction by uniaxial compression, a new technique is proposed, based on measuring the angle of inclination of the shear area to the main axes. According to the experimental work, mathematical models of the dependence of strength indicators from the content of organic binder in the Irtysh sand have been developed.

1. Introduction

The problem of rural regions of Russia is the outflow of the population to cities and large regional centers. This circumstance must be taken into account when building roads. Building norms and rules that force in Russia regulate the rules for calculating capital, lightweight and transitional pavements, but do not consider the design of pavements of the lowest type. Nevertheless, in the road network of the Russian Federation, the length of unpaved roads is 29.4%, and in some regions it can reach 50% or more. In the Omsk Region, 42% of the roads of the road network are not hard surfaced. Therefore, the actual tasks of the construction industry are: the use of local materials, and on roads with low traffic intensity, the development of albums of typical designs of pavements. Assessing the prospects of using local materials for roads in the Omsk Region, we note that the region does not have rocks and uses crushed stone materials supplied from the Ural region of Russia or from the Republic of Kazakhstan. Local materials include dispersed soils (loams, clays and sandy loams), sands mined by the hydraulic fill from the Irtysh River and ash and slag materials stored in ash dumps of thermal power plants in Omsk. Ash and slag materials and fly ash are used in construction quite widely [1, 2]. In road construction, the construction of a subgrade in an embankment requires the implementation of a large amount of earthwork. Therefore, an actual task of the road construction is study the mechanical properties of fly ash of wet catch. Experimental studies [3–5] show that the parameters of shear resistance and the deformability parameters of fly ash are comparable with similar characteristics of dispersed soils. Therefore, fly ash can be used in the construction of embankments of the subgrade, but their use in the construction of pavements is limited.

Soils have a relatively low bearing capacity [6–10] and shear resistance [11], small deformation modulus [12, 13]. With increasing moisture of cohesive soils, the strength and deformability parameters decrease. Therefore, dirt roads accumulate deformations and numerous defects, the
elimination of which requires repair work. In the dry season, dirt roads are dusty, which requires periodic dust removal.

Of course, the solution to this problem can be the pavement of the lower type, in the designs of which there is one or two structural layers. In such pavements use local soils reinforced with binders (bitumen, bitumen emulsion, cement, lime, active fly ash and other industrial wastes) [14–19] and skeletal additives (crushed stone, gravel, industrial wastes). At present, a preliminary national standard of the Russian Federation (PNST 371-2019) has been developed that regulates the rules for the construction and calculation of pavements of the lowest type. The construction of the pavement is shown in figure 1.

![Figure 1. The pavements of the lowest type](image)

The calculation of the pavement of the lowest type is carried out according to the criterion of elastoplastic deformation, in which on the surface of the pavement provide the required total deformation modulus with the corresponding to reliability the coefficient of strength \(k_{str} (k_{str} \geq 1)\). In addition, the design is checked for resistance to rutting. The rut depth is calculated by the sum of the two components. The first component is the residual deformation accumulated by the pavement and the subgrade, and the second is surface wear out. This calculation is different from the methods of calculation the pavement of the other types. Therefore, during the period of the preliminary standard, it is necessary to obtain and accumulate experimental data about parameters of the mechanical properties of materials.

The purpose of our article is the experimental determination the parameters of strength and deformability of sand mined in the Omsk region and reinforced with foamed bitumen.

2. Materials and Methods

For the preparation of samples used sand, the grain composition of which is presented in table 1.
Table 1. Grain size composition of sand.

| Total residues on a sieve with holes, mm \% by mass | 5 | 2.5 | 1.25 | 0.63 | 0.315 | 0.16 | 0.071 | Bottom |
|---------------------------------------------------|---|-----|------|------|-------|------|-------|--------|
| -                                                 | 0.27 | 1.93 | 12.17 | 45.71 | 82.87 | 87.34 | 100    |

The modulus of sand size is determined by the traditional formula

$$M = \frac{A_{2.5} + A_{1.25} + A_{0.63} + A_{0.315} + A_{0.16}}{100},$$

where $A_{2.5}$, $A_{1.25}$, $A_{0.63}$, $A_{0.315}$ and $A_{0.16}$ – full residues on sieves with holes 2.5, 1.25, 0.63, 0.315 and 0.16 mm.

For the manufacture of samples from sand, reinforced with foamed bitumen, laboratory work was carried out to determine the maximum density and optimal moisture. Laboratory work was carried out using method of standard compaction with moisture determination by drying to constant weight. When processing the test results, in addition to the maximum density and optimal moisture, their values are calculated, determined by the standard and modified methods of R. Proctor. The calculated values of these parameters correspond to the characteristics determined by US standards ASTM D 698-12, ASTM D 1557-12 and ASTM D2216-10. The values of the characteristics are given in table 2.

Table 2. Maximum density and optimum moisture.

| Characteristic | Value of characteristic by standards |
|----------------|--------------------------------------|
|                | GOST 22733-2002 | ASTM D 698-12 | ASTM D 1557-12 |
| $\rho_{d,\text{max}}, \text{g/cm}^3$ | 1.74 | 1.74 | 1.77 |
| $W_{\text{opt}}, \%$ | 9.61 | 9.61 | 8.36 |

Viscous bitumen of the BND 100/130 grade of the Omsk Oil Refinery was used as a binder. Bitumen used to reinforce each sand sample was dosed by weighing and stored in polyethylene until foamed and mixed with sand.

The sand was moistened to the moisture necessary to obtain the optimum liquid phase content. The optimal content of the liquid phase is understood as the total content of water and foamed bitumen, at which the maximum density is reached during the molding of samples. Laboratory work to determine the optimal content of the liquid phase was carried out in accordance with the requirements of Wirtgen standards. For this, a sand sample weighing 2.1 kg was prepared, which was subsequently divided into 7 samples weighing 300 g. Into each sample was injected the different amount of water 0.5; 1; 1.5; 2; 2.5; 3.0 and 3.5 %. Then the sand and water were mixed until homogeneous and the same amount of bitumen was added, 6% by weight of sand, i.e. 18 g. After that, the sand was mixed with bitumen, preparing a homogeneous mixture. Next, the samples were molded and standard density tests were performed. According to the results of such tests, it was found that the optimal content of the liquid phase is 8.5%, including 6% of bitumen and 2.5% of water. Subsequently, when selecting the compositions of the sand reinforced with foamed bitumen, the amount of added water at a different dosage of bitumen was determined by the optimal content of the liquid phase.

Each of the doses of bitumen was heated to a temperature of 140 - 150 °C, which corresponds to the requirements of regulatory documents of the Russian Federation and Wirtgen standards. Foaming of bitumen was carried out by introducing water into hot bitumen. The flow rate of water required for foaming bitumen, taken in the amount of 3% by weight of bitumen.

Table 3 shows the consumption of materials used for the preparation of sand reinforced with bitumen and water for foaming bitumen.
Table 3. Consumption of materials for the preparation of sand reinforced with foamed bitumen.

| Amount of sand, g | Water consumption for sand moistening | Bitumen consumption | Water consumption for foaming bitumen |
|------------------|---------------------------------------|---------------------|---------------------------------------|
|                  | % by weight of sand g | g                  | % by weight of sand g | % by weight of bitumen g |
| 2500             | 5.5 | 137.5 | 3 | 75 | 3 | 2.25 |
| 2500             | 4.5 | 112.5 | 4 | 100 | 3 | 3 |
| 2500             | 3.5 | 87.5 | 5 | 125 | 3 | 3.75 |
| 2500             | 2.5 | 62.5 | 6 | 150 | 3 | 4.5 |
| 2500             | 1.5 | 37.5 | 7 | 175 | 3 | 5.25 |
| 2500             | 0.5 | 12.5 | 8 | 200 | 3 | 6 |

After the introduction of water, a portion of sand weighing 2.5 kg was fed to the bitumen foam, which was mixed with sand using a mixer. In the process of sample molding, the temperature of the initial, heated viscous bitumen, and prepared reinforced soil was controlled. The temperature of the sand treated with foamed bitumen was controlled as it cooled to a temperature of 20 - 30 °C, which is the most common when compaction of stabilized soils using cold recycling technology in place. To control the temperature of cooling sand, which stabilized by foamed bitumen, a bimetallic thermometer was used.

The samples were molded in accordance with the requirements of GOST 30491-2012. The stages of sample production are shown in figure 2.

![Figure 2](image-url)

Figure 2. Sample production: a—form filling; b—molding; c—height measurement; d—finished sample.

For manufacture the samples, a mold with a diameter of 50.5 mm was used, into which, when molding the first sample of each composition, the mixture was fill in an amount of 220–240 g see figure 2a. The mold, pressing the mixture was set to the lower plate of press and monitored so as bottom liner protrude from the forms at 1.5-2.0 cm see figure 2b. Next, the mixture was densified by pressure. The pressure increases to a value of 30 MPa, which was held for 3 minutes. After molding the sample, its height was measured, which should be equal to 50.5 ± 1 mm see figure 2c. If the height of the sample did not correspond to this interval, then the mass of the sample was corrected. The adjusted weight of the sample was used for the manufacture of all other samples. In this case, the form with the bottom insert inserted was filled with the specified amount of the mixture. After completion of compaction,
the samples were pressed out of the mold using a mechanical ejector. The extracted sample was inspected for absence of defects and to assess the evenness of the surface of the bases see figure 2d.

Groups of samples were prepared for testing, which were tested for compliance with the requirements of the state standard. According to these requirements, when testing samples, the ultimate compressive strength are determined at a temperature of 20 °C and 50 °C (R_20 and R_50), the ultimate compressive strength of samples in a water-saturated state at a temperature of 20 °C R_w20, swelling on volume and frost resistance coefficient. In the table 4 shows the requirements for physical and mechanical properties of reinforced soils.

| Name of indicator                      | The value of the indicator for soils reinforced | Liquid, foamed or emulsified organic binder | Also with the addition of a mineral binder |
|---------------------------------------|------------------------------------------------|-------------------------------------------|------------------------------------------|
| Ultimate compressive strength at temperature, MPa t=20 °C | Not less than 1.2                           | Not less than 1.5                          |                                          |
| Ultimate compressive strength of the sample in a water-saturated state at t=20 °C, MPa | Not less than 0.5                           |                                          |                                          |
| Frost resistance coefficient          | Not less than 0.8                           | Not less than 0.8                          | Not less than 0.85                      |
| Swelling on volume, %                 | Not less than 4.0                           | Not less than 4.0                          | Not less than 0.8                        |

Table 4. Requirements for physical and mechanical properties of reinforced soils.

To determine the swelling, groups of samples with different foamed bitumen contents were prepared. In each group, three samples were prepared with the same bitumen content. Testing of the samples was carried out according to the standard method with determining the swelling of each sample with the calculation of the average value according to the results of testing three samples. The swelling of the sample was calculated by the formula:

$$A = \frac{(m_1 - m_2) \cdot (m_3 - m_2)}{m_1 - m_2}$$

(2)

where m_1 and m_2 - mass of sample before water saturation, weighted in air and in water, g; m_3 and m_4 - mass of water-saturated sample in air and in water, g.

Groups of samples were prepared for strength tests. Each group consisted of 9 samples with the same content of foamed bitumen. From each group, 3 samples were tested at a temperature of 20 °C, the other 3 samples were tested at a temperature of 50 °C, and the remaining 3 samples were saturated with water and tested at a temperature of 20 °C. For such tests, samples suitable for testing were selected from prepared samples, which were marked and placed on a metal tray for storage in air in room conditions see figure 3a. The samples were thermostated in a climatic chamber. For this, three samples were taken from each group of samples and thermostatically controlled at a given temperature. In figure 3b shows thermostating of samples to a temperature of 20 °C. Samples of the required temperature were tested using a measuring and computing complex. Strength was determined as the average value according to the test results of three samples.
Figure 3. Strength tests: a - samples reinforced with 8% of bitumen prepared for the determination of \( R_{20} \), \( R_{50} \) and \( R_{w20} \); b - thermostating in a climatic chamber; c - uniaxial compression test.

The strength of the sample was determined by the formulas:

\[
R_{20} = \frac{N_{20}}{F}; \quad R_{50} = \frac{N_{50}}{F}; \quad R_{w20} = \frac{N_{w20}}{F},
\]

where \( N_{20} \), \( N_{50} \) and \( N_{w20} \) – breaking loads for samples with a temperature of 20 °C and 50 °C, as well as a water-saturated sample with a temperature of 20 °C; \( F \) – cross section area of the sample before testing.

For frost resistance tests, three samples were prepared with the same content of foamed bitumen. These samples were subjected to freeze and thaw cycles. The number of cycles correspond the requirements of Russian standards. After that, thawed samples at a temperature of 20 °C were tested by compression to determine their strength \( R_{FR20} \). Strength calculation was performed according to the first dependency formula (3). The coefficient of frost resistance was determined by the formula:

\[
K_{FR} = \frac{R_{FR20}}{R_{w20}},
\]
where \( R_{m,FR20} \) and \( R_{m,w20} \) – average values of corresponding strengths.

The determination of cohesion and the angle of internal friction required the development of a special technique based on the determination of the angles of inclination the sliding pad (\( \alpha_{\text{shear}} \) and \( \alpha_{\text{shear}} \)) to the main axes. For this, a video was taken during the deformation of the sample. During the video recording, the location of the crack developing along the shear pad relative to the vertical and horizontal axes of the sample was recorded. Further, using the trigonometric relations of right-angled triangles (the length of the crack - hypotenuse, and the axes - cathetus), the angles of inclination of the crack to the main axes were determined. Since the crack develops along the shear pad these angles are the angles of inclination of the shear pad to the main axes.

To calculate the angle of internal friction, we used traditional dependencies that connect the angles of inclination of the shear pad to the main axes [20–22]. Table 5 shows the calculation scheme for determining the angles of inclination of the shear pad to the main axes and the formulas for calculating these angles through the angle of internal friction.

**Table 5. Calculation of the angle of inclination of the shear pads to the main axes and the angle of internal friction.**

| Calculating scheme | Calculated parameter | Formulas |
|--------------------|----------------------|----------|
| \( \alpha_{\text{shear}1} = \frac{\pi}{4} + \frac{\varphi}{2} \) | The angles of inclination of the shear pads to the main axes | \( \alpha_{\text{shear}1} = 45^\circ + \frac{\varphi}{2} \) |
| \( \alpha_{\text{shear}3} = \frac{\pi}{4} - \frac{\varphi}{2} \) | Inverse relationship for calculating the angle of internal friction through the angles of inclination of the shear pad to the main axes | \( \varphi = 2 \cdot \alpha_{\text{shear}1} - \frac{\pi}{2} \) |
| \( \alpha_{\text{shear}3} = 45^\circ - \frac{\varphi}{2} \) | | \( \varphi = \frac{\pi}{2} - 2 \cdot \alpha_{\text{shear}3} \) |

To calculate the cohesion \( c \) we used the traditional dependence connecting the ultimate compressive strength \( R_c \), with the parameters of the Mohr – Coulomb criterion. This dependence has the form:

\[
R_c = \frac{2 \cdot c \cdot \cos \varphi}{1 - \sin \varphi}. \tag{5}
\]

From equation (5) we can express the cohesion which is determined by the formula:

\[
c = \frac{R_c \cdot (1 - \sin \varphi)}{2 \cdot \cos \varphi}. \tag{6}
\]

Having completed all the tests and applying formulas (3), table 5 and (6), all the necessary parameters of the strength of sand reinforced with foamed bitumen can be calculated. In figure 4a shows the dependence of the ultimate compressive strength of soil reinforced with foamed bitumen under various test conditions on the binder content. In figure 4b, an illustration is given of the development of a crack in a sample under uniaxial compression. For visibility, the crack trajectory is painted black. Figure 4c and figure 4d show the dependences of the angle of internal friction from the content of
foamed bitumen.

Data analysis of figure 4 allows us to state that the reinforcing of very fine sand with foamed bitumen can significantly increase any strength parameter and shear resistance parameters.

Figure 4. Dependence of ultimate strength and shear resistance parameters from the content of foamed bitumen in a very fine sand: a – ultimate compressive strength; b – illustration of crack development in a sample under uniaxial compression; c – angle of internal friction; d – cohesion.

Table 6 shows empirical formulas for determining ultimate compressive strengths.

**Table 6.** Empirical formulas for determining the ultimate compressive strengths (MPa) from foamed bitumen content (%).

| Function name   | Formula for determining the ultimate strengths, MPa                                                                 |
|-----------------|---------------------------------------------------------------------------------------------------------------------|
| Linear          | $R_{20}=0.0674 \cdot D + 1.1091; \ R^2=0.95$                                                                       |
|                 | $R_{50}=0.064 \cdot D + 0.428; \ R^2=0.96$                                                                         |
|                 | $R_{w20}=0.0543 \cdot D + 0.7048; \ R^2=0.95$                                                                     |
| Exponential     | $R_{20}=1.1427 \cdot \exp(0.0464 \cdot D); \ R^2=0.94$                                                          |
|                 | $R_{50}=0.4828 \cdot \exp(0.0852 \cdot D); \ R^2=0.93$                                                          |
|                 | $R_{w20}=0.7364 \cdot \exp(0.0554 \cdot D); \ R^2=0.93$                                                         |
|                 | $R_{20}=0.986 \cdot D^{0.2439}; \ R^2=0.98$                                                                     |
| Power-law       | $R_{50}=0.3677 \cdot D^{0.4486}; \ R^2=0.99$                                                                     |
|                 | $R_{w20}=0.6174 \cdot D^{0.2911}; \ R^2=0.98$                                                                   |
| Logarithmic     | $R_{20}=0.3527 \cdot \ln(D)+0.8974; \ R^2=0.99$                                                                 |
|                 | $R_{50}=0.3339 \cdot \ln(D)+0.2284; \ R^2=0.99$                                                                |
|                 | $R_{w20}=0.2839 \cdot \ln(D)+0.5344; \ R^2=0.99$                                                               |
3. Conclusion

The work performed showed that the rational content of foamed bitumen in very fine sand is 3–6%. With an increase in the content of foamed bitumen in excess of 6%, the strength parameters increase, but the intensity of their increase is not significant. Therefore, when designing pavements, the content of foamed bitumen expedient taken within 3–6%.

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