Characteristics of highway subgrade frost penetration in regions of the Kazakhstan

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ABSTRACT

In 2010 temperature and moisture sensors were made and installed into the pavement and subgrade of the "Astana-Burabay" highway (North region of the Kazakhstan). In 2013 similar sensors were used for the "Atyrau-Aktobe" (West region) and "Almaty-Bishkek" (South region) highways. In the present paper the study results of subgrade frost penetration of the above stated highways are given. For each highway a subgrade frost penetration starting and finishing times are determined; frost penetration and thawing graphs are constructed; frost penetration and thawing rate values are determined; dependence of the amount of unfrozen water from the value of negative temperature and initial moisture is established.

Keywords: subgrade soil, frost penetration, unfrozen water, moisture

1 INTRODUCTION

It is known that strength and deformation properties of subgrade soil have a strong influence on strength and durability of highway pavement. In countries with climatic conditions that have a seasonal character, is necessary to take into account the variability of strength and deformation properties of soils.

The climate of Kazakhstan is sharply continental. The southern and western parts of the country are characterized by hot summer, and northern and eastern parts differ in cold winter. In winter in all territory of the country frost penetration in soil basis of engineering structures takes place. Depth of frost penetration in highways in the south is 120-150 cm, and in the north reaches 260-280 cm. In the north of the country a highway subgrade within 160-180 days is in a frozen state, and in the south – within 90-100 days. Therefore it is relevant to study frost penetration characteristics of highway subgrade in regions of the country.

2 EXPERIMENTAL SECTIONS OF HIGHWAYS

In the present paper frost penetration characteristics in subgrade of the "Astana-Burabay" (km 76+030), "Almaty-Bishkek" (km 58+895), and "Atyrau-Aktobe" (km 598+050) highways are investigated. Experimental section of the "Astana-Burabay" highway is in the northern part of Kazakhstan, experimental section of the "Almaty-Bishkek" highway is located in the south and experimental section of the "Atyrau-Aktobe" highway is in the west of the country.

Pavement structure of the "Astana-Burabay" highway consist of the following layers: stone mastic asphalt (6 cm), coarse-grained asphalt (9 cm), black crushed stone (12 cm), crushed stone and sand mix + cement of 7% (18 cm), crushed stone and sand mix (15 cm), sand (20 cm). Subgrade soil – heavy sandy clay loam.

Pavement structure of the "Almaty-Bishkek" highway consist of the following layers: fine-grained asphalt (5 cm), coarse-grained asphalt (10 cm), old fine-grained asphalt (6.5 cm), old cold asphalt (15 cm), sand and gravel mix (60 cm). Subgrade soil – heavy sandy clay loam.

Pavement structure of the "Atyrau-Aktobe" highway consist of the following layers: stone mastic asphalt (5 cm), coarse-grained asphalt (10 cm), coarse-grained high-porous asphalt (13 cm), sand and gravel mix (40 cm). Subgrade soil – dusty sand.

Measurement of temperature and moisture in points of pavement and subgrade was carried out by means of special sensors (Teltayev 2013).

3 UNFROZEN WATER

3.1 Temperature and moisture
To establish the amount of unfrozen water in subgrade soil of highway and regularities of its variation, these measurements of temperature and moisture in a subgrade of the "Astana-Burabay" highway, during the consecutive winter periods (2010-2011, 2011-2012, 2012-2013 and 2013-2014) were used. As an example, in Table 1 values of negative temperatures and unfrozen water are given in different depths of subgrade in different time points of the winter period of 2010-2011. Analysis of the available data showed that with decrease of temperature moisture content decreases, i.e. part of initial moisture transforms to ice; the minimum temperature in a subgrade takes place on its surface in the coldest months (January and February) and is equal to -11...-12°C.

3.2 Unfrozen water content
Using the data in Tables 1 and 2, graphs of relations between unfrozen water and negative temperature were created. Such graphs for the winter period of 2010-2011 are shown in Figure 1. From these graphs it is visible that with reduction of negative temperature at all specified depths the content of unfrozen moisture decreases. Points in the figure are related to depths of 80 and 150 cm lay on one curve, but points related to depths of 80 and 150 cm are strongly differ from them.

3.3 Initial moisture
In Figure 2 graphs of distribution of initial (prewinter) moisture in points of subgrade which are at different depths from the surface of pavement are shown. As can be seen, distribution of moisture on depth is complex. But a qualitative picture of distribution of initial moisture is in all considered years is identical. The lowest moisture is at a depth of 150 cm, the highest moisture is on the surface of subgrade and at a depth of 220 cm. Now becomes clear differences of unfrozen water content at depths of 80 and 150 cm from other depths in Figure 1. At a depth of 150 cm initial moisture is the lowest, therefore unfrozen water content at this depth is the lowest. And at the depth of 80 cm initial moisture has the largest value, therefore unfrozen water content at that depth is the greatest. Thus the more the initial moisture the more the unfrozen water content.

Table 1. Temperature and unfrozen water in points of subgrade (2010-2011)

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth, cm</th>
<th>80 cm</th>
<th>115 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T, °C</td>
<td>W_{uf}, %</td>
</tr>
<tr>
<td>12-13.12.2010</td>
<td></td>
<td>-0.9</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Table 2. Temperature and unfrozen water in points of subgrade (2010-2011)

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth, cm</th>
<th>150 cm</th>
<th>185 cm</th>
<th>220 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T, °C</td>
<td>W_{uf}, %</td>
<td>T, °C</td>
</tr>
<tr>
<td>12-13.12.2010</td>
<td></td>
<td>-5.9</td>
<td>11.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>09-10.01.2011</td>
<td></td>
<td>-11.0</td>
<td>8.7</td>
<td>-7.0</td>
</tr>
<tr>
<td>22-23.01.2011</td>
<td></td>
<td>-11.0</td>
<td>8.8</td>
<td>-8.1</td>
</tr>
<tr>
<td>26-27.01.2011</td>
<td></td>
<td>-11.0</td>
<td>8.5</td>
<td>-8.6</td>
</tr>
<tr>
<td>15-16.02.2011</td>
<td></td>
<td>-6.4</td>
<td>10.4</td>
<td>-5.5</td>
</tr>
<tr>
<td>25-26.02.2011</td>
<td></td>
<td>-11.6</td>
<td>8.5</td>
<td>-9.0</td>
</tr>
<tr>
<td>13-14.03.2011</td>
<td></td>
<td>-6.0</td>
<td>10.5</td>
<td>-5.9</td>
</tr>
<tr>
<td>30-31.03.2011</td>
<td></td>
<td>-2.1</td>
<td>13.4</td>
<td>-2.7</td>
</tr>
<tr>
<td>14-15.04.2011</td>
<td></td>
<td>-1.1</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>26-27.04.2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-15.05.2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4 Correlation dependences

With seven different values of initial moisture \((W_0 = 9,0; 11,8; 13,1; 15,5; 17,1; 18,9; 22,3\%)\) graphs of dependence of unfrozen water content from absolute value of negative temperature were constructed as shown in Figure 3. It was found that these dependencies are approximated with high reliability by a logarithmic function:

\[
W_{uf} = a + b \cdot \ln|\theta|,
\]  

where \(W_{uf}\) - unfrozen water content, \%; 
\(|\theta|\) - absolute value of negative temperature, °C; 
a, b - regression coefficients.

Values of \(R^2\) and correlation coefficients \(a\) and \(b\) at different initial moisture are given in Table 3. It is seen that values of coefficients \(a\) and \(b\) varies depending on initial moisture. Corresponding graphs are shown in Figures 4 and 5. The coefficient \(a\) is numerically equal to unfrozen water content in the soil subgrade at a temperature of \(-1\ °C\). As expected, this coefficient increases with increase of initial moisture, and it varies on the linear law. The coefficient \(b\) characterizes a variation rate of unfrozen water content with temperature variation. Specifically, it shows how much decreases an unfrozen water content at change of low temperature on \(2,72\ °C\) in negative temperatures range. It is seen that the value of this ratio decreases with increase of initial moisture content in the linear law. Thus, specified dependences have an appearance:

\[
a = -1,299 + 0,765 \cdot W_0, \quad (2)
\]

\[
b = -0,316 - 0,60 \cdot W_0, \quad (3)
\]

where \(W_0\) – initial moisture, %.

We will note that the obtained correlation dependences have high values of \(R^2\) equal to 0,97 and 0,83 respectively.

Substituting expressions (2) and (3) in equation (1), we obtain a single expression describing dependence of unfrozen water content from the absolute value of negative temperature and initial moisture:

\[
W_{uf} = -1,299 + 0,765 \cdot W_0 - 0,316 \cdot \ln|\theta| - 0,60 \cdot W_0 \cdot \ln|\theta| \quad (4)
\]
Table 3. Values of $R^2$ and correlation coefficients $a$ and $b$

<table>
<thead>
<tr>
<th>Initial moisture $W_0$, %</th>
<th>Coefficients</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>9,0</td>
<td>5,470</td>
<td>-0,80</td>
</tr>
<tr>
<td>11,8</td>
<td>6,865</td>
<td>-1,10</td>
</tr>
<tr>
<td>13,1</td>
<td>9,039</td>
<td>-1,13</td>
</tr>
<tr>
<td>15,5</td>
<td>11,660</td>
<td>-1,06</td>
</tr>
<tr>
<td>17,1</td>
<td>12,050</td>
<td>-1,45</td>
</tr>
<tr>
<td>18,9</td>
<td>12,870</td>
<td>-1,61</td>
</tr>
<tr>
<td>22,3</td>
<td>15,380</td>
<td>-1,55</td>
</tr>
</tbody>
</table>

Thus, the increase in initial moisture by 1% increases of unfrozen water content to 0.77% and the decrease of temperature by 2.72 °C reduces of unfrozen water content to 0.32%.

At application of expressions (1) and (4) it is necessary to remember that logarithmic function with an argument equal to 0, is not defined. At the same time it is known that freezing of water in clay soils happens at temperatures below 0°C. For example, in work (Li et al. 2013) temperature of freezing of dusty loam is accepted equal to - 0.02°C, and in monographs...
(Tsytovich 1973 and Maslov 1982) for loams it is specified equal to -0,1…-0,9°C and -1,0°C respectively.

4 FROST PENETRATION DEPTH

One of the important integral indicators of highways in winter period that characterize deformability of subgrade soil and materials of pavement layers is a depth of frost penetration (Zolotar et al. 1971). This indicator is taken into account in design of pavement structures in Kazakhstan (CN RK 2007).

In Figures 6 and 7 graphs of frost penetration and thawing of the "Astana-Burabay", "Almaty-Bishkek" and "Atyrau-Aktobe" highways are shown. Figure 6 contains data on frost penetration and thawing of the "Astana-Burabay" highway, obtained during consecutive four winter periods from 2010 to 2014. It should be noted that the data obtained in different years are close enough. It was found that approximately on 10 November steady frost penetration of pavement is started, subgrade frost penetration starts on December 5.

Maximum depth of frost penetration was 245 cm. Subgrade during the 176 days is in a frozen state. The period of frost penetration of subgrade can be divided into two sub-periods: the first with a constant rate of frost penetration (2,8 cm/day) and the second with a constant depth of frost penetration (245 cm); the length of the first sub-period is 85 days, and the second sub-period - 91 day. Thawing of pavement starts on 21 March and finishes on 30 May, i.e., the thawing duration of pavement and subgrade is 69 days and the average thawing rate is 3,6 cm/day.

Figure 7 shows that although the "Atyrau-Aktobe" highway is located in the western part of the country, and the "Almaty-Bishkek" highway in the southern part, graphs of frost penetration and thawing are very close. Frost penetration of pavement starts on 10th December, and its thawing cycle starts on 1st March. Frost penetration duration of subgrade on the "Almaty-Bishkek" highway is 93 days, and on the "Atyrau-Aktobe" highway is 63 days. The maximum frost penetration depth of both roads is 147 cm.

CONCLUSIONS

In whole territory of Kazakhstan in winter highway subgrade freezes. It was experimentally established that on the southern and western regions depth of frost penetration reaches 147 cm, and in the north reaches 245 cm. Frost penetration duration on the southern, western and northern regions amounted to 93, 63 and 176 days, respectively.

According to the results of experimental studies a reliable correlation dependence of unfrozen water amount in the highway subgrade from initial moisture and absolute value of negative temperature have been established.

REFERENCES


