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MONITORING OF THE TEMPERATURE REGIME AND THERMO-TECHNICAL PROPERTIES OF RAILWAY SUBGRADE MATERIALS

Summary. The modernisation of the Slovak Railways infrastructure has become a challenge to re-evaluate the dimensioning of the railway subgrade design for non-traffic loading, particularly in terms of the application of new materials into its construction and gradually changing climatic conditions. The first part of the paper shows the results of the long-term monitoring of the temperature regime of the railway subgrade on the railway track structure in the test stand (the position of the zero isotherm, the behaviour of the temperatures in the design layers and in their interfaces, the temperature of the air). The second part presents the results of the experimental determination of the thermo-technical properties of the built up materials into the railway subgrade of the trial stand structure (the thermal conductivity modulus, specific thermal capacity). The conclusion deals with the preliminary results derived from the comparison of the findings from both experimental measurements.

Keywords. railway, climatic conditions, frost index, depth of frost, thermal conduction modulus.

MONITOROWANIE PARAMETRÓW TEMPERATUROWYCH I WŁASNOŚCI TERMOTECHNICZNYCH MATERIAŁÓW PODTORZA KOLEJOWEGO

Streszczenie. Modernizacja Kolei Słowackich napotkała na szereg wyzwań związanych ze zmianą podejścia do gradacji i wymiarowania podtorza w warunkach braku obciążenia oraz w szczególności z zastosowaniem nowych materiałów konstrukcyjnych, zwłaszcza w kontekście stopniowo zmieniających się warunków klimatycznych. W pierwszej części artykułu przedstawiono wyniki długoterminowego monitorowania parametrów temperaturowych podtorza na stanowisku testowym toru kolejowego (pozycja izotermy zerowej, kształtowanie się temperatur w warstwach projektowych i w powierzchniach styku, temperatura powietrza). W drugiej części przedstawiono wyniki doświadczalne badań

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własności termotechnicznych materiałów konstrukcyjnych podtorza na stanowisku testowym (moduł przewodnictwa cieplnego, termiczna pojemność właściwa). W końcowej części artykułu przedstawiono wstępne porównanie wyników obu badań doświadczalnych.

Słowa kluczowe. transport kolejowy, warunki klimatyczne, głębokość zamarzania, modułu termicznego przewodzenia..

1. INTRODUCTION

Real loading of a track in operational conditions is variable. In general, the railway track construction is loaded not only with transport but also with non-transport loading. Moving railway cars or trains of wagons load the railway track construction – rail grate, railway (gravel) bed and its subgrade with complex force effects of static, quasi-static and dynamic character, which together form so-called ***transport loading***. Opposite to these direct force effects by railway cars, the railway track structure is exposed to further effects, mainly weather and climatic conditions (water, frost, solar radiance and wind), so-called ***non-transport loading.***

It is not possible to omit the influence of weather and climatic factors (the influence of non-transport loading) on the railway track. It influences quality of the track during the whole year. Particularly the influence of frost on the railway subgrade structure is one of the main factors of non-transport loading which remarkably affects its quality in connection with unfavourable water regime. The contaminated railway bed and the soil of subgrade surface made of frost-susceptible soils or dangerously frost susceptible soils have a significant impact on volume changes of the railway subrade which results in the whole railway track structure damages. Consequently, the protection of the railway subgrade against frost effects has become very essential. From this aspect it is eligible to design a structural layout and dimensions of various structural parts of subgrade to achieve minimum freezing of subgrade surface in the case of adverse winter conditions (high rain and snowfall and strong frosts) so that the frost-susceptible subgrade surfaces are best protected against frost effects.

There have been experienced radical changes in climatic conditions influencing the reached frost and snowfall values in winter period that significantly differ from the values reached at the initial monitoring at the meteorological stations in Europe. Within increasing demands on quality of roadway considering the increasing speeds as well as new materials, which were applied to the railway subgrade structure in recent years, it is more than eligible to verify not only the current methodologies of subgrade dimensioning on the adverse frost influence, but also a coefficient of thermal conductivity of materials that are built into the subgrade structure and which substantially affect its temperature regime.

This paper analyses the results of more years of the experimental monitoring of the thermal regimen of railway subgrade structure in experimental stand during the winter period. Additionally, the selected values of the coefficients of thermal conductivity obtained by experimental measurements with accordance to the currently applicable regulatory documents are presented here.

2. CLIMATIC CONDITIONS AND THERMAL REGIME OF RAILWAY SUBGRADE [1]

Climatic conditions play a very important role in searching for reasons and effects of railway substructure damages. Therefore, it is inevitable to quantify them by those characteristics on the basis of which their influence on the thermal regime of the railway subgrade and the depth of its freezing can be expressed.

From this point of view the main climatic characteristics are:

- air pressure,
- air humidity and amount of rain fall,
- air temperature,
- snow cover

The result of the difference in **air pressure** is wind as a horizontal movement of air caused by the pressure gradient force. Except from global air movement, local movement of air plays a very important role. It is caused mainly by articulation of landscape. Air, which gets cooler at night in higher locations flows into valleys that cause remarkable differences in microclimate.

Humidity is a result of water evaporation into the air. By steam condensation evaporated water returns to the Earth's surface in form of rainfall and snowfall. Rainfall is given by amount and intensity.

Air temperature is one of the most important characteristics of climatic conditions of a particular area. It changes during the day (higher temperatures in the daytime, lower in the night), but mainly during a year (higher temperatures in summer, lower in winter). The course of air temperatures is expressed by the following characteristics:

a) *average day air temperature* $\boldsymbol{T_s}$

$$T_s = \frac{T_7 + T_{14} + 2T_{21}}{4} \qquad (^{o}C) \qquad (1)$$

where $\boldsymbol{T_7}$, $\boldsymbol{T_{14}}$ a $\boldsymbol{T_{21}}$ are temperatures measured at 7.00 a.m., 2.00 p.m. and 9.00 p.m. of Greenwich meantime 2 m above ground,

b) *maximum air temperature* $\boldsymbol{T_{max}}$ *and minimum air temperature* $\boldsymbol{T_{min}}$ in a day's or year's cycle,

c) *average year air temperature* $\boldsymbol{T_m}$ expressed with the following equation

$$T_m = \frac{\sum_{i=1}^{365} T_s}{365} \qquad (°C) \qquad (2)$$

d) *number of frost days* – days during which minimum air temperature equal to or lower than -0,1^{o}C occurs,

e) *number of ice days* – days during which maximum air temperature equal to or lower than -0,1^{o}C occurs (all-day frost),

f) *frost period* – period with continuous frost or ice days,

g) *frost index* $\boldsymbol{I_m}$ (°C day) – maximum negative value of the sum of the average day temperatures in the winter period.

From the above mentioned characteristics the **frost index** $\boldsymbol{I_m}$ is the most common characteristic which is used when considering the thermal regime and the assessment of the railway subgrade from the point of view of its protection against frost. The frost index is not a constant value, but rather changeable. It depends directly on air temperature, which is influenced by several factors. It is possible to mathematically express the influence of individual factors on the size of the index to only a certain extent. The more precise determination of the frost index is possible only by the *direct measuring of temperatures* at particular meteorological stations.

Thermal regime of the railway subgrade is defined as a course of thermal changes of individual structural layers and soil in the sleeper which are caused by solar radiance, thermal radiance and air temperature changes in the day or during a year. Freezing depth of the railway subgrade h_{pr} is a very important characteristic in this sense.

Freezing depth of the railway subgrade is defined as a distance of zero isotherm (0°C) from the surface of railway bed. The following factors influence the thermal resistance of the railway subgrade:

- temperatures in the winter period characterised most commonly by the frost index I_m,
- thermal-insulation features of the railway subgrade structure layers,
- condition of subgrade surface soil (humidity w, bulk density ρ, granulometric composition, etc.),
- thickness of snow cover on the railway track.

The frost index Im is given by summing up the medium day air temperatures Ts in the winter period according to the equation (3)

$$I_m = \sum_{t_z}^{t_k} T_s \qquad (^{o}\text{C.day}) \qquad (3)$$

In this way a line of sums in °C.day is received. In the case that the temperature value on the surface of the rail construction (surface of the rail bedding) is used instead of the value T_s , the frost index on the surface I_{mp} is received.

3. CHARACTERISTICS OF EXPERIMENTAL MONITORING OF FREEZING THEPTH OF RAILWAY SUBGRADE

Direct experimental measurement is one of relatively reliable but also rather time-consuming methods of monitoring the freezing depth of the railway subgrade h_{pr}. In the case of experimental monitoring of the freezing depth it is possible to use the following methods:

- modelling in laboratory conditions,
- measuring on experimental track sections.

The freezing depth of the railway subgrade in experimental measurements is determined by *the level of water freezing in soil* or *zero isotherm position.* The level of water freezing is usually found out by built-in frost meters and the position of zero isotherm is determined from continuous temperature measurements in the railway subgrade structure by built-in thermometers.

In 2003 a so-called exterior experimental stand was built at the Department of Railway Engineering and Track Management (DRETM) to monitor the deformation resistance (bearing capacity) of the railway substructure structure and the thermal regime of the most commonly applied railway subgrade construction on modernized Slovak Railways tracks for a long time according to the regulation [2] sleeper subgrade of type No. 3. Above all, the aim of the experimental monitoring is to receive relevant data for technically correct and economical design of the railway subgrade structure from the point of view of its required thermal resistance.

3.1. Description of the outer experimental stand of DRETM

The railway track structure in the so-called exterior experimental stand of DRETM is created from the following structural layers (*Fig.1*):

- *ballast bedding with thickness* 500 mm, fraction 31.5/ 63 mm,
- *subbalast layer* 450 mm from broken stone, fraction 0/32 mm,
- *bracing geocomposite MACRIT GTV 50/50 B* laid on subgrade surface,
- *subgrade surface built in bilateral transversal gradient 5 %* from sandy clay *(F4 = CS)*.

In the structural layers of the experimental stand 11 resistance thermometers built in vertically (see their placement on the *fig.1.*), which scan temperature in the given surroundings. Thermometers output is recorded automatically to the measuring base ***MS 4***, from which it is possible to remove the measured data to a computer with program ***Comet***.

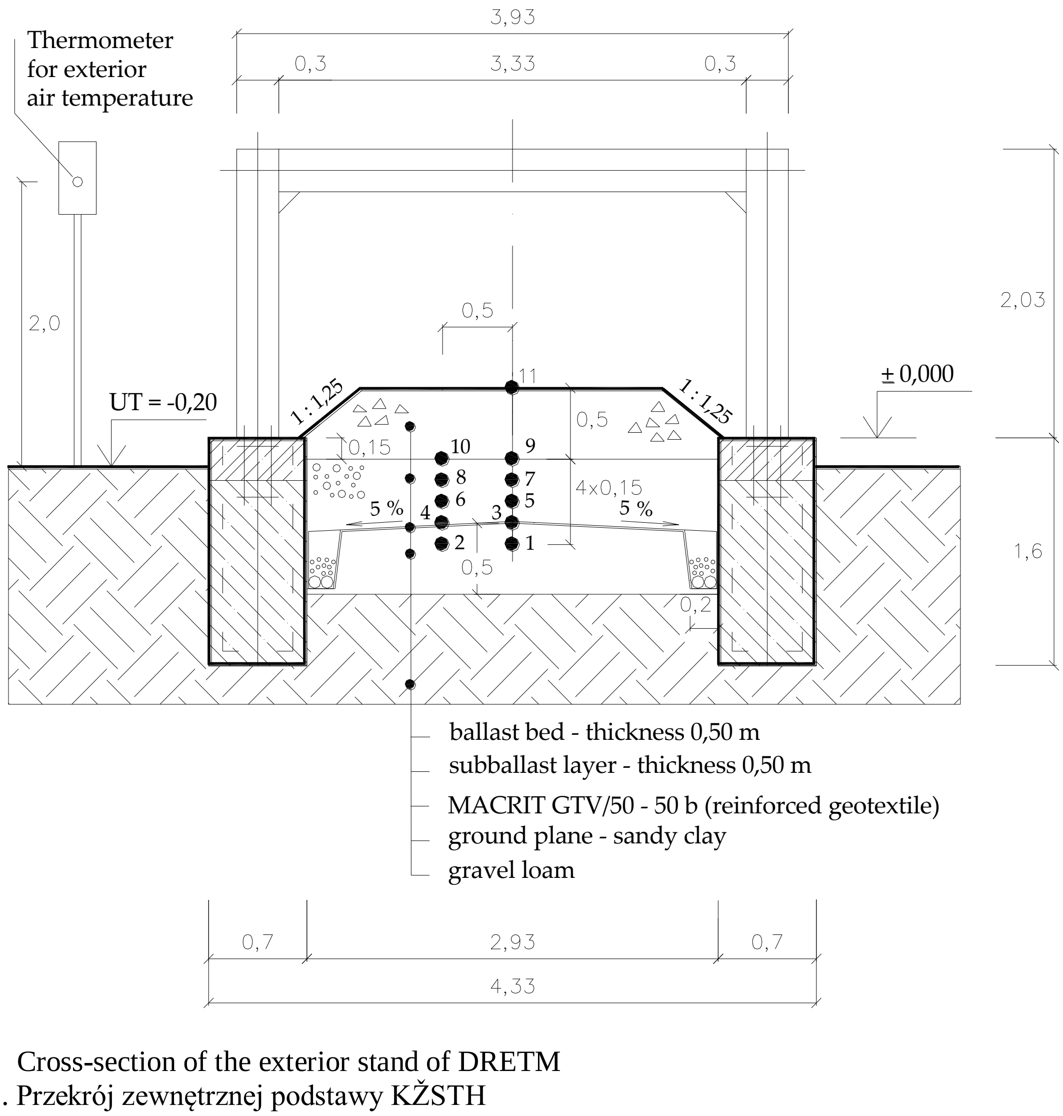


Fig. 1. Cross-section of the exterior stand of DRETM
Rys. 1. Przekrój zewnętrznej podstawy KŽSTH

3.2. Monitored characteristics

Temperatures in the whole profile of the built experimental stand structure were monitored during experimental measurements. Measurements realized in the experimental stand are presented in this paper are from the period from 2003 to 2012.

The next monitored characteristic during a given period was air temperature measured 2, 0 m above rail bedding surface. According to the relation (1) not only medium daily air temperatures were expressed from measured temperatures T_s, but also frost indices I_m were enumerated according to the relation (3).

3.3. Evaluation of experimental measurements

The winter period 2005/2006 was the coldest winter in the period 2003 till 2012. During this period it was monitored as the maximum medium daily temperature $T_{s,\ max,\ 05/06}$ = 5.7°C and minimum medium daily temperature $T_{s,min,05/06}$ = -16.7°C.

During this winter period the rail bed surface was almost permanently covered by snow, thickness of which was monitored and maintained with a template on the value approximately 100 – 120 mm. The frost index was determined from measured air temperatures $I_{m,05/06}$ = 387.56°C.day.

Course of medium whole day air temperatures T_s and frost index I_m is obvious from Fig. 2.

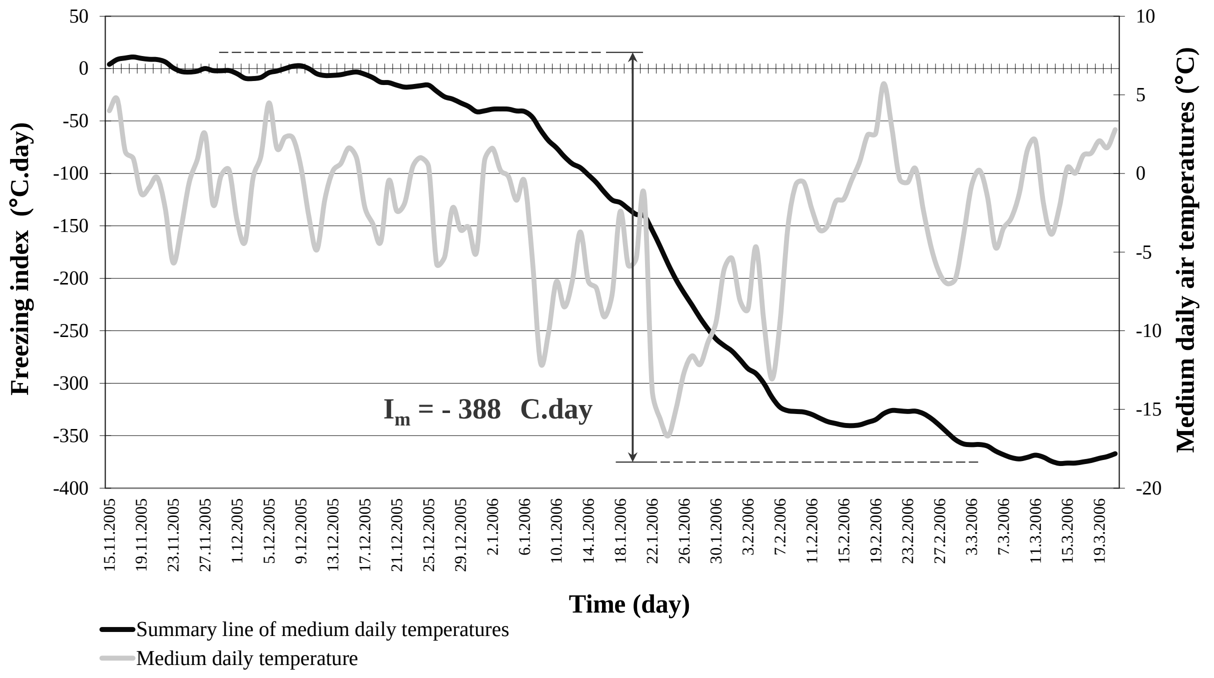


Fig. 2. Course of medium daily air temperatures T_s and frost index I_m in winter period 2005/2006 [4]
Rys. 2. Krzywa średniej dziennej temperatury powietrza T_s i wartości I_m w zimie 2005/2006 [4]

The course of minimum daily air temperatures in individual depths of experimental stand structure during monitored winter periods is obvious from Fig. 3. The maximum value of freezing depth of railway subgrade was $h_{pr,max}$ = 0,84 m and it was reached 10.2.2006 for the frost index I_m = 333,64°C.day. The highest value of h_{pr} during the monitored period

2003/2012 was noticed in winter 2011/2012 and reached the value ~ 0,98 m for I_m ~ 250°C.day.

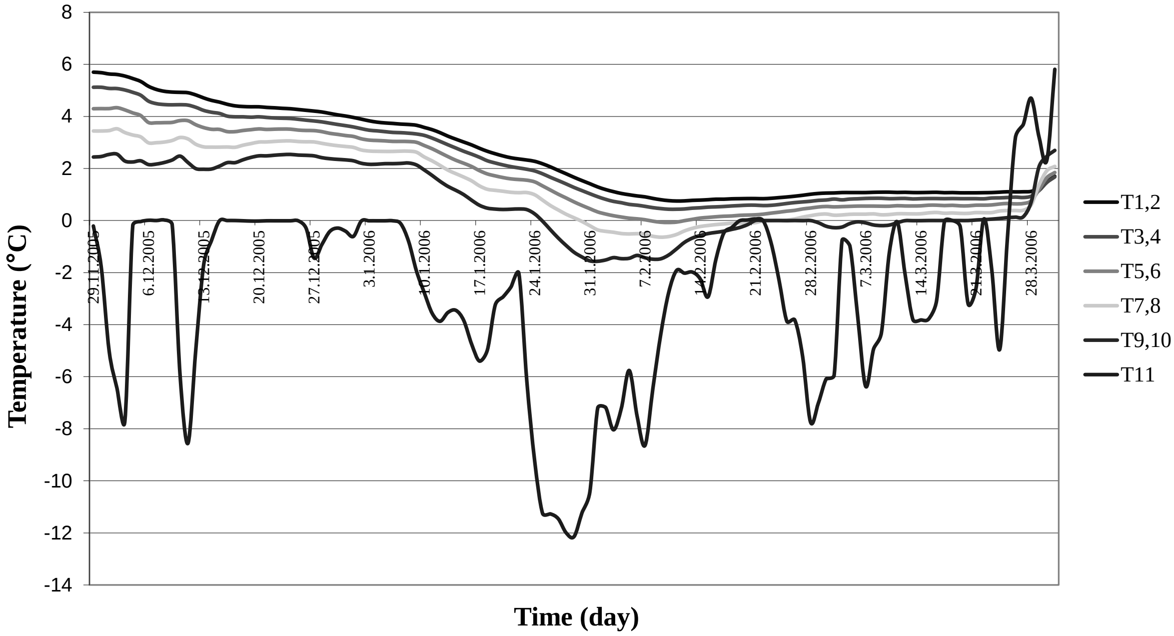


Fig. 3. Course of minimum daily air temperatures in the experimental stand structure in winter periods 2005/2006 [4]

Rys. 3. Wykres minimalnej temperatury powietrza przy eksperymentalnych podkładach w zimie 2005/2006 [4]

Winter 2005 - 2006 has set the reference interdependence between freezing depth h_{pr} and freezing index I_m of the structure (Fig. 4) [4].

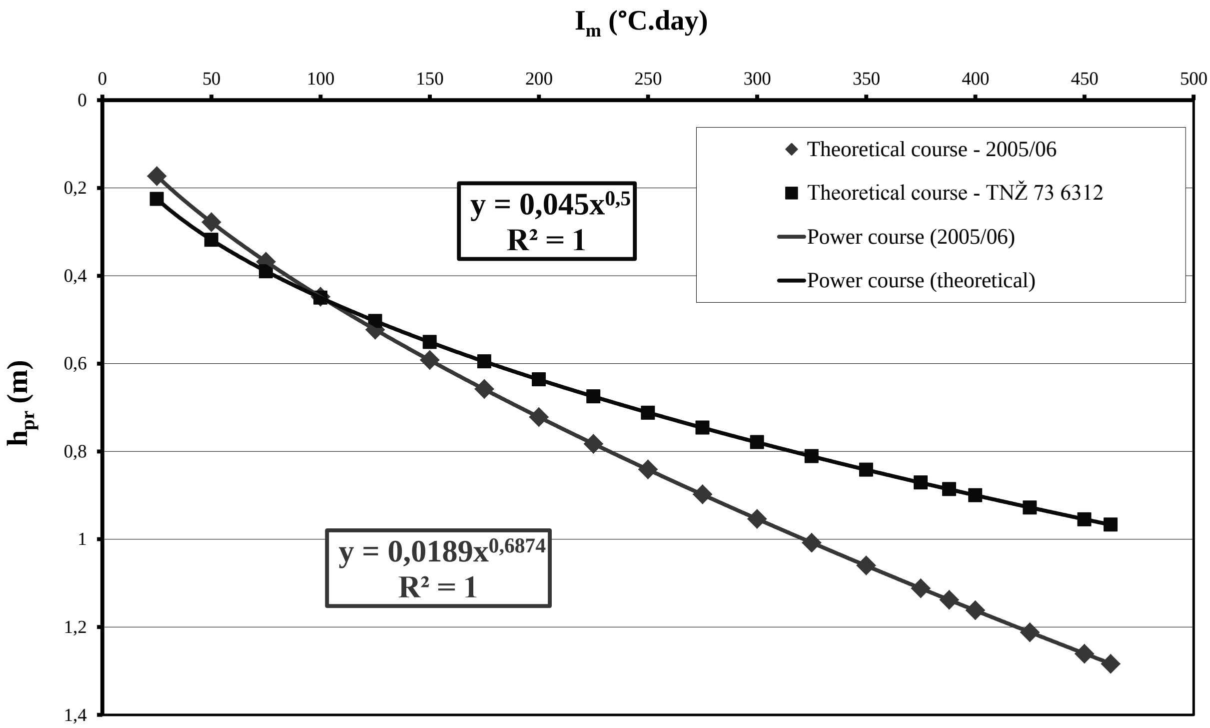


Fig. 4. Diagram of dependence of freezing depth of freezing index value

Rys. 4. Schemat zależności głębokości zamarzania h_{pr} od wartości I_m

4. CHARACTERISTICS OF EXPERIMENTAL DETERMINATION OF THERMO – TECHNOLOGICAL PROPERTIES OF RAILWAY SUBGRADE MATERIALS

Methods of measurement are based on the standard *STN 72 1105 Determination of the coefficient of thermal conductivity by the method of non-stationary flow.* The principle on which the procedure is based is fully observed, but from the point of view of differences of the investigated materials, it was necessary to modify this process and also to design new measuring equipment. Measurements which are made under this legal document are a suitable maximum for the fraction 0/16 mm, the new procedure allows the examine materials of much bigger fraction 0/63 mm, including the oversize fraction (up to 125 mm).

In principle, it is an indirect determination of the coefficient of thermal conductivity of examined material by the method of no stationary thermal flow and specific thermal capacity. The physical principle of the method is based on one-way propagation of heat conduction in homogeneous materials characterized by the Fourier differential equation [4]:

$$q(x,t) = -\lambda \cdot \frac{\delta T(x,t)}{\delta x} \tag{4}$$

where:
q(t,x) – heat - flow density at the point *x* and time *t*, (W.m^{-2}),
λ – coefficient of thermal conductivity, (W.m^{-1}.K^{-1}),
T(x,t) – temperature at the point *x* and time *t*, (K).

The heat flow changes in the environment by equation:

$$\frac{\delta q(x,t)}{\delta x} = -q \cdot c \cdot \frac{\delta T(x,t)}{\delta t} \tag{5}$$

where:
ρ – specific weight, (kg.m^{-3}),
c – specific heat capacity, (J.kg^{-1}.K^{-1}).

The coefficient of thermal conductivity that can be derived from equations (4) and (5):

$$\lambda = 0{,}249 \cdot \frac{h^2}{\Delta t_c} \cdot \rho \cdot c \tag{6}$$

where *h* is sample thickness (m).

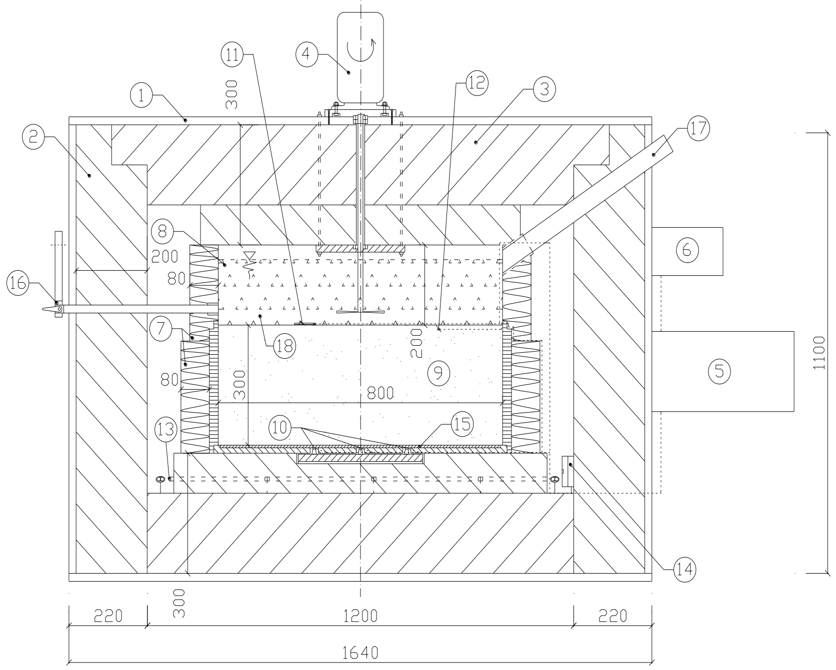
The time interval Δt is determined between *10* and *50%* decrease of temperatures of lower surface of the test sample, since in that range is the stable course of temperature drops.

Temporal change of surface temperature of the sample is determined in a special test equipment ZPK 1 (Fig. 5) and specific heat capacity c in the calorimeter KPK 1 (Fig. 6). These facilities were to determine the coefficient of thermal conductivity developed at the Department of Civil Engineering and Track Management of the Faculty of Civil Engineering, University of Žilina and it is the only one of its kind in Slovakia.

4.1. Measuring equipment [4]

Measurement of temporal changes of the sample surface temperature Δ*t*

Measuring equipment for determining the time interval Δ*t* is shown in *Fig. 4.1* consists of a temperature insulated "climatic equipment/chamber" (internal temperature of the environment shall take only positive values) with a lid in which is stored a test sample (9), refrigeration medium (8), heaters (radiating element and heating wires (13)). In this area, the thermo resistance sensors are installed below the sample (10) and are in close contact with the transfer (contact) plate of aluminium alloy (15). One thermometer is placed on the upper surface of the sample (12) and the other is placed directly in the refrigeration medium (11) for the indication of the required temperature. The sample in a circular container and the container with the refrigeration medium is insulated with a special thermal insulation *Izoflex* (7). In addition to these elements, it is still equipped with a stirrer device (4) necessary to maintain the required temperature of the refrigeration medium (18) in a stainless container. The container is equipped with a filler pipe for pouring a mixture of drift ice and water (17) and with the drain valve with the pipe to control the level of the refrigeration medium of the organic glass (16). The registration and the control centre *MS 4* (5) are located outside the climatic chamber. The climatic chamber allows the recording of data in the required intervals and also regulates the temperature in the climatic chamber. The temperature regulation is possible due to a thermometer which detects the inside air temperature (14) and the already mentioned heating equipment connected with the control centre *MS 4*. The assembly further includes a electricity source (6) to supply power to the control centre and thermometers. Under the radiating element is used as the insulation the aluminium foil.



***1** climatic equipment/chamber, **2** thermal insulation of climatic equipment/chamber (polystyrene), **3** thermal insulation of the cover of climatic equipment/chamber (polystyrene), **4** electric stirrer, **5** registration and control centre MS 4, **6** source of electricity, **7** thermal insulation of the box for the refrigeration medium and the sample box, **8** box for refrigeration medium, **9** test sample, **10** thermometers Pt 1000 used to indicate the temperature of the bottom surface of the sample (the transfer of temperature is secured by the contact solder), **11** immersion thermometer Pt 100 which monitors the temperature of refrigeration medium, **12** thermometer Pt 1000 used to indicate the temperature of the upper surface of the sample, **13** heating wires, **14** thermometer for detecting the current air temperature, **15** transfer (contact) plate of aluminium alloy, **16** drainage with the drain valve and with the possibility to control the level of the refrigeration medium, **17** filler pipe, **18** refrigeration medium*

Fig. 5. Equipment for time interval Δt measurement – *ZPK 1*

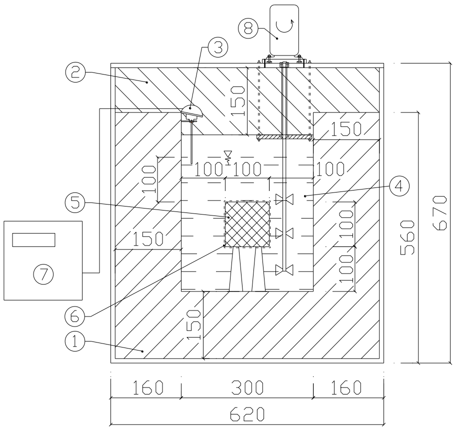
Rys. 5. Schemat sprzętu pomiarowego – *ZPK 1*

The above test is desirable, particularly those devices:

- dryer,
- compacting equipment,
- laboratory scales,
- sieving screens.

Measurement of specific heat capacity *c* using the calorimeter

Measurement of specific heat capacity could be realized by the calorimeter (Fig. 6). This equipment is creative from waterproof thermally insulated box with cover. The thermometer connected to the control centre *MS 4* monitors the temperature of water. The sample is isolated from the water with a polyethylene foil. As in the previous case, for this measure it is necessary to use the stirrer to get the objective value of the water temperature so that it could be recorded.



1 *thermal insulated box,* ***2*** *thermal insulated cover,* ***3*** *thermometer Pt 100,* ***4*** *water heated to 40 °C,* ***5*** *tested sample,* ***6*** *polyethylene sheet,* ***7*** *registration centre MS 4,* ***8*** *electric stirrer*

Fig. 6. Calorimeter – *KPK 1*

Rys. 6. Kalorymetr – *KPK 1*

4.2. Evaluation of measurements [4]

The specific heat capacity in the dry state measured in the calorimeter is calculated from the equation:

$$c_0 = \frac{m_v \cdot c_v + K}{m} \cdot \frac{T_p - T_k}{T_k - T} \qquad (\text{J. kg}^{-1}.\text{K}^{-1}) \qquad (7)$$

where:

m_v – weight of water, (kg),

c_v – specific thermal capacity of water, (J.kg^{-1}.K^{-1}),

K – thermal capacity of calorimeter, (J.K^{-1}),

m – weight of the measured sample, (kg),

T_p – initial temperature of water, (°C),

T_k – final temperature of the system, (°C),

T – sample temperature, (°C).

The Fig. 7 shows the method of graphic assessment of the thermal capacity measurement.

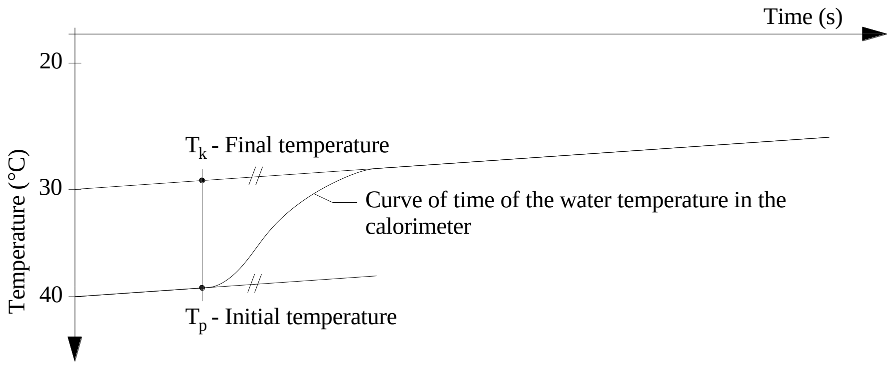


Fig. 7. Graph of the water temperature curve in the calorimeter and the method of determination of the required temperature values
Rys. 7. Wykres krzywej temperatury wody w kalorymetrze i metoda określenia wymaganych wartości temperatury

Coefficient of thermal conductivity λ of the stamps is calculated from the equation:

$$\lambda = \frac{0{,}249 \cdot h^2 \cdot \rho \cdot c}{\Delta t} \qquad (\mathrm{W.m^{-1}.K^{-1}}) \qquad (8)$$

where:
h – sample thickness, (m),
ρ – specific weight of the sample, (kg.m^{-3}),
c – specific thermal capacity of the sample, (J.kg^{-1}.K^{-1}),
Δt – the time interval measured in the test equipment, (s).

Calculated coefficient of thermal conductivity is determined from the equation:

$$\lambda = \bar{\lambda} + 2\sigma \qquad (\mathrm{W.m^{-1}.K^{-1}}) \qquad (9)$$

where:
$\bar{\lambda}$ – arithmetic average of the measured values,
σ – standard deviation.

The measured thermo-technical values of the materials built into the railway subgrade structure of the so called outside experimental stand are resulted in the Tab. 1.

Table 1

The measured thermo-technical characteristics of railway subgrade structure materials

Material (experimental stand)	***w*** **(%)**	**ρ_v (kg.m^{-3})**	**ρ (kg.m^{-3})**	**λ (W.m^{-1}.K^{-1})**	***c*** **(J.kg^{-1}.K^{-1})**
Track bed	1.17	1702	2691	0.621	1119
Subbalast layer (0/32 mm)	3.80	1956	2728	1.035	1295
The soil of subgrade surface (sand clay)	17.50	2081	2582	1.504	1585

5. PRELIMINARY RESULTS FROM THE EXPERIMENTAL MEASUREMENTS

The evaluation of the measurement temperatures in the structure of the experimental stand revealed that in the coldest winter season 2005/2006 the zero isotherm penetrated to the bottom of the subbalast layer. It is assumed that the zero isotherm would penetrate closer to the subgrade surface, respectively to the subgrade surface, as it is documented by the *Fig. 3.*, but the existence of snow cover which has heat-insulating properties, caused the reduction of the frost effects on the railway subgrade design in that case. This assumption is supported by the fact that much lower effect of freezing index to shift the zero isotherm up to subgrade surface occurred last winter. Since the ballast track material was not affected by the real impact of rail traffic and so wasn't polluted and re-compacted, it is supposed that the layer of the ballast might achieve higher thermal resistance than in the real operated railway track. The high proportion of air gaps and the absence of the fine size fraction as well as a higher moisture content of railway bed, make the structural layer of relatively high thermal resistance, respectively the layer with a low coefficient of thermal conductivity λ, which retards the penetration of zero isotherm to the larger depths of the subgrade design of the experimental stand. This presumption was confirmed by measuring the coefficient of the thermal conductivity of the track bed material, where its value reached less than a third of the design value for the track ballast, according [2].

To assess the railway subgrade construction carefully, in terms of its thermal resistance to frost influence, it is suggested to place the rail bed from the operating track into the experimental stand for the following period, to compact it to presupposed bulk density and to imbed a previous rail grate. It is also advised to build a new experimental stand, in which all the design subgrade layers will be situated above ground level that would allow the impact of the effects of the cold from the sides, too. These measures should provide not only the conditions similar to a real railway track, but also the overview of the temperature regime of the subgrade of the track sections route in the embankment and a larger set of relevant values of the reached depth of freezing of the tested railway subgrade.

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Bibliography

1. Ižvolt L.: Železničný spodok – namáhanie, diagnostika, navrhovanie a realizácia konštrukčných vrstiev železničného spodku. Vedecká monografia, EDIS – vydavateľstvo ŽU, 2008, str. 324, ISBN 978-80-8070-802-3.
2. TNŽ 736312 „Navrhovanie konštrukčných vrstiev podvalového podložia“. GR ŽSR. Účinnosť od 01.09.2005.
3. Ižvolt, L., Kupčuliak, P.: K problematike navrhovania konštrukcie podvalového podlo-žia na nepriaznivé účinky mrazu. 6. Fórum koľajovej dopravy, 16.-17.3.2010 Bratislava, str. 117 – 128, ISBN 978-80-88973-59-1.
4. Kupčuliak, P. Návrh a posúdenie konštrukcie podvalového podložia z aspektu zaťaženia klimatickými faktormi. ŽU Žilina, 2011, Doktorandská dizertačná práca. SvF, ŽU v Žiline, 09/2011.