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FINAL LINING BEHAVIOUR IN EXTREMELY LOW TEMPERATURES

CHOVÁNÍ DEFINITIVNÍHO OSTĚNÍ PŘI EXTRÉMNĚ NÍZKÝCH TEPLOTÁCH

Abstract

Design of a tunnel lining is complex task. The tunnel lining structure works in close interaction with the surrounding rock mass. The value of the load depends on geotechnical circumstances, primary lining, shape and size of opening, construction technology and as well on the temperature distribution in a lining that is determined by climatic conditions. The article deals with the temperatures in the tunnel lining that are brought about by air temperature changes in tunnel space and a constant temperature inside the rock mass. This problem is solved making use of temperature records in tunnel, on the inner and outer surface of the tunnel lining and in rock mass measured at a motorway Tunnel Klimkovice. These records are analyzed and submit to FE model of the tunnel lining so that the lining temperature state is converted for a lining stress state.

Keywords

Secondary lining, temperature, monitoring, tunnel lining.

Abstrakt

Návrh definitivního ostění ražených tunelů je složitý úkol. Statická činnost definitivního tunelového ostění je podmíněna interakcí s okolním horninovým masivem. Hodnota jeho zatížení je závislá na geotechnických podmínkách, primárním ostění, tvaru a velikosti výrubu, způsobu výstavby a také na vývoji a rozložení teplot v ostění, které jsou ovlivňovány klimatickými podmínkami. Článek se zabývá stavem napjatosti v definitivním tunelovém ostění, které je indukováno kolísáním teplot ovzduší na vnitřním líci ostění tunelu a konstantní teplotou uvnitř horninového masivu. Problém je řešen s využitím záznamů teplot ovzduší, teplotních stavů na vnitřním a vnějším líci tunelového ostění a uvnitř horninového masivu, které byly naměřeny na dálničním tunelu Klimkovice. Naměřené teploty jsou analyzovány a uplatněny v MKP modelu tunelového ostění, kterým jsou teplotní stav a jeho změny transponovány na hodnoty napětí.

Klíčová slova

Definitivní ostění, teploty, monitoring.

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1 INTRODUCTION

Projecting the secondary lining of mined tunnels is a complex task. Static behavior depends on the interaction of tunnel lining with rock massif. Loading is dependent on the stiffness of the lining, size of the excavation, geotechnical conditions, the construction process and the climatic conditions. Regarding the traffic importance of tunnels, it is not possible to accept any exclusion or limitation of the traffic. The lining scheme must be safe and economical. It needs to meet the highest standards of performance over the entire life of the structure. Experience with long-term function and the actual loading, however, are in the world different. In the Czech Republic there is not much experience yet. To monitor the behavior of the lining, various measurements and monitoring are performed.

The subject of this paper is to present the results, especially in the lining temperature measurement. Interesting results were obtained in winter seasons when extremely low temperatures were measured in the long term. These measurements make for the design of new structures.

Modern tunnel structures are now supported mainly by the modern method of the excavation using the New Austrian Tunneling Method. To ensure the excavated space there are usually used two tunnel linings. The primary lining is used for excavation support during the excavation. Secondary lining provides us with safe use of the building over its life time. Design and assessment of the tunnel lining is a complex process including a range of input conditions. We are not always able to define precisely these inputs. To determine the size of the load of the secondary lining it is necessary to know the loads of rocks, hydrostatic load and deformation behavior of concrete during its solidification. The lining is also influenced by the local climatic conditions. It is also necessary to include the effect of different temperatures on the lining. For the correct determination of the size of the thermal load, we need to know the temperatures in the cross section of reinforcement. Measurements of finished buildings are used for an even more accurate determination of these temperatures. Results of these measurements can provide more precise temperature distribution in the cross section and the behavior of the structure, depending on the climate. Specification of this behavior should lead to savings of materials in the design of new structures [2]. Monitoring of tunnel lining and monitoring temperatures are devoted in other papers [5, 6, 7, 8, 9].

2 THE EVALUATION OF MEASUREMENT RESULTS

Designing an accurate lining is a very complex process. There are a large number of factors, load cases and combinations influencing the structure. One of the external factors is the temperature change that responds to external climatic conditions. To monitor the behavior of the lining in response to these changes, measuring sensors are placed in the newly constructed tunnels allowing us to track all the changes. One of these tunnels is an operating tunnel Klimkovice. The building is located on the route D47 near the town Klimkovice. The place for the tunnel construction was chosen to protect the city and the neighbouring Spa. The tunnel with its 1080 meters is composed of two separate tunnels which are connected by five joints. During the construction of the secondary lining, temperature sensors of the rock massif were installed there. Subsequently, the secondary tunnel lining embedded vibration sensors of deformation and temperature. The sensors were fitted in two tunnel strips – measuring profiles. Each profile was used for 12 pieces of these sensors placed in three positions. At each position they were fitted to the top and bottom reinforcement in a radial and tangential direction. More about sensors in [1,3,4]. Each profile measurement is equipped with sensors to measure the air temperature. The measurement system is operated automatically with ongoing automatic meter reading and measurement data collection. There are four-hour reading intervals.

This paper evaluates the lowest measured temperatures so far, for the entire period of operation of the tunnel (since 2008). Due to the relatively short period of operation (four years), the results cannot be regarded as valid and definitively confirmed. Watching each period shows a certain trend, particularly the effect of external temperatures on the lining. Winter period, when the temperatures drop below zero has the biggest influence on the tunnel lining and shrinkage of the lining. In previous years, the winters were mild. Temperatures did not drop below zero too significantly. The only exception was the period 1/2010 when the temperatures dropped lower −10 °C. These low temperatures lasted only briefly. Better results were obtained in winter 2/2012 when sustained low temperatures were recorded. Frosts under −10 ° C inside the tunnel lasted over a longer period of time. According to data from the outdoor sensors, temperature reached to −20 °C. Such low temperatures persisted up to 20 days. This situation can be considered extreme. In addition to evaluating the internal temperatures in the tunnel, there were also measurements available from the tunnel operation and management. These measurements monitor the temperature on the portals, temperature inside the tunnel as well as the air speed. The monitoring focuses on just two selected sections which are 55 meters and 140 meters away from the portal. Extremely low temperatures were recorded during 2/2012. A similar process applies to the distant profile. The lowest temperature measured was −15.3 ° C. The average temperature over the period of twenty days was −9 °C.

Values of the measured temperatures in the reference section are listed in Table 1. All the values are given in degrees Celsius. Max is the maximum value of the measured value, min is the minimum value. Average indicates the average temperature or average temperature difference. A trend that the previous measurement suggested has been confirmed. The lining is not cooled to an ambient air temperature and there is an apparent time delay. In particular, differences between the underside and face temperatures are very small. On average, these differences are around 0.5 °C. The differences are twice as high in the lower part of the vault above ground, which was confirmed by the results of previous measurements [1, 2].

Tab. 1: Extreme temperature of the block B90

B 90	Air	Back1	Face1	Diff.1	Back2	Face2	Diff.2	Back3	Face3	Diff.3	Rock
Max	0,48	1,71	1,27	1,31	1,74	1,33	1,56	2,50	1,31	2,00	8,06
Min	−15,30	−1,35	−2,01	0,01	−1,14	−1,93	0,00	−0,41	−1,73	0,00	4,35
Average	−8,96	−0,50	−0,91	0,44	−0,32	−0,92	0,62	0,32	−0,73	1,06	5,99

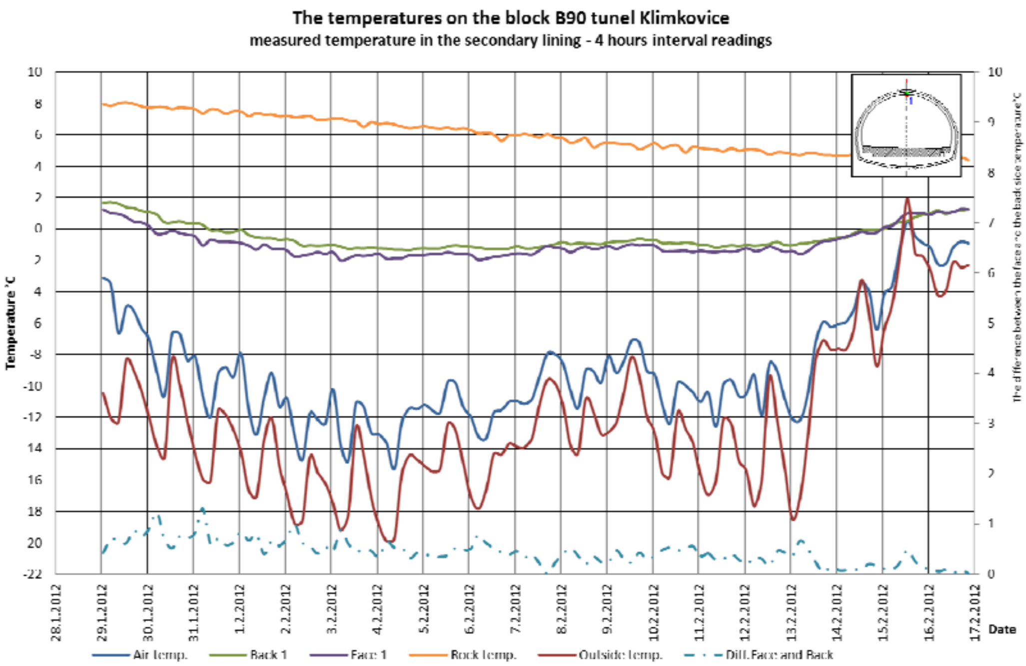

Fig. 1: Detail of the temperatures progression at the crown of the vault, block B90

Figure 1 shows a detail of the period observed, including the recorded temperature on the portal (outside temperature). The profile distance is about 55 m from the portal. Outside air temperatures are up to five degrees lower than the inside ones. The biggest difference is in the morning, afternoon temperatures then equalize. The courses of the two temperatures correspond to each other. It is clear that the climate in the tunnel is affected by the outside temperature. The internal temperature reaches its minimum with a slight delay of about four hours. The lowest temperature in the tunnel was measured usually around nine o'clock in the morning. The temperature in the lining always responds very slowly and with delay. Gradual cooling causes an increase of the difference between the face and the back side and during the warming the differences are minimal. The biggest measured difference was 2 °C (see Table 1). Daily differences of air temperature can be up to 8 °C. The final lining reacts to these differences very slightly. An ambient mass temperature (measured at a depth of 1m) responds also to changes in outside temperature. The rock response is delayed up to 10 days. At average temperatures, the temperature of the massif is very close to the temperature of the secondary lining.

Along with the integrated temperature measurement sensor is already reading strains on the final lining. The strain gauges are located in both directions in the longitudinal and tangential. Record this measurement is shown in Figure No. 2. Waveforms are compared in the lining temperature and strain at the crown of the tunnel. Records on the back side are larger than on the face, both in longitudinal and tangential direction. On the face side are significantly less strains in the transverse (tangential) direction than in the longitudinal direction. The responses to short-term temperature changes are negligible. When evaluating all three measurement nodes that strains are the largest in middle part of the vault.

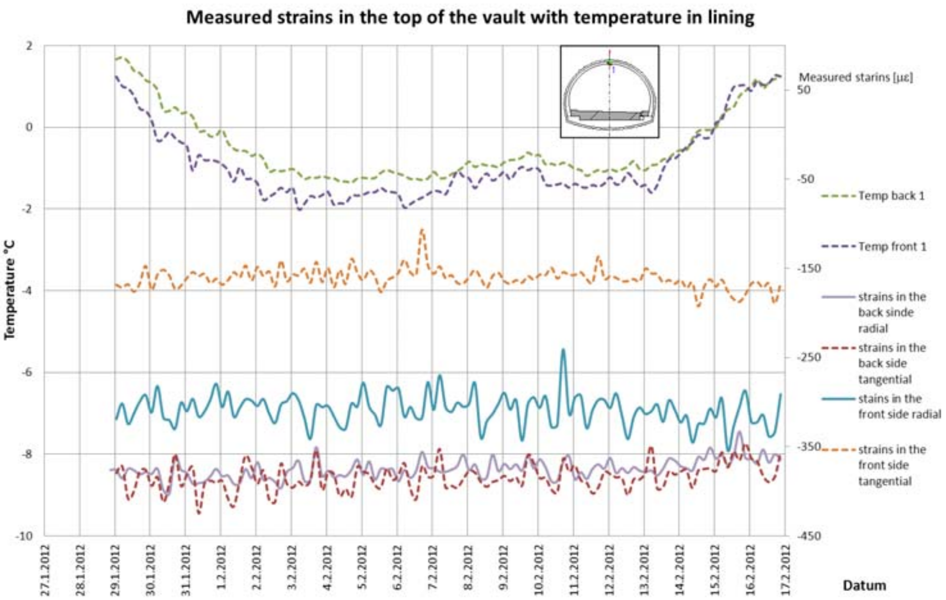

Fig. 2: Measered strains in the top of the vault with temperature

In the second profile there are greater differences in the results. This profile is further from the portal. The minimum measured air temperature was −12 °C. In the second profile, the temperature is one degree higher than the average. Specific values of the measured temperatures in the reference section are listed in the Table 2. All the values are stated in degrees Celsius. Max is the maximum value of the measured value, min is the minimum value and average indicates the average temperature or average temperature difference. Temperature curve is indicated on the figure 3.

Tab. 2: Extreme temperature of the block B79

B 79	Air	Back1	Face1	Diff.1	Back2	Face2	Diff.2	Back3	Face3	Diff.3	Rock
Max	0,34	4,16	3,88	1,32	4,04	3,47	1,23	5,14	3,34	1,98	8,37
Min	−11,98	0,98	0,52	0,03	0,87	0,39	0,00	1,92	0,67	0,06	5,10
Average	−7,19	1,85	1,44	0,44	1,76	1,28	0,51	2,76	1,55	1,21	6,77

The detailed figure 3 for the top tunnel vault shows that there are bigger differences compared to the temperatures at the portal. Differences may be up to 8 °C. The differences between face and back side are again very small. When the temperature is decreasing these differences are larger. Gradually also temperatures in the lining moderate and the differences between the back side and face are just within 1 °C. This is the fundamental difference between the German Railway Standard which considers a constant difference between back and face 10 °C. Anticipated −15 °C in the lining inside of the tunnel in accordance with the standard was never reached. Despite the lower temperatures that were measured, the differences between back and face are very small and it is confirmed by the measurement results.

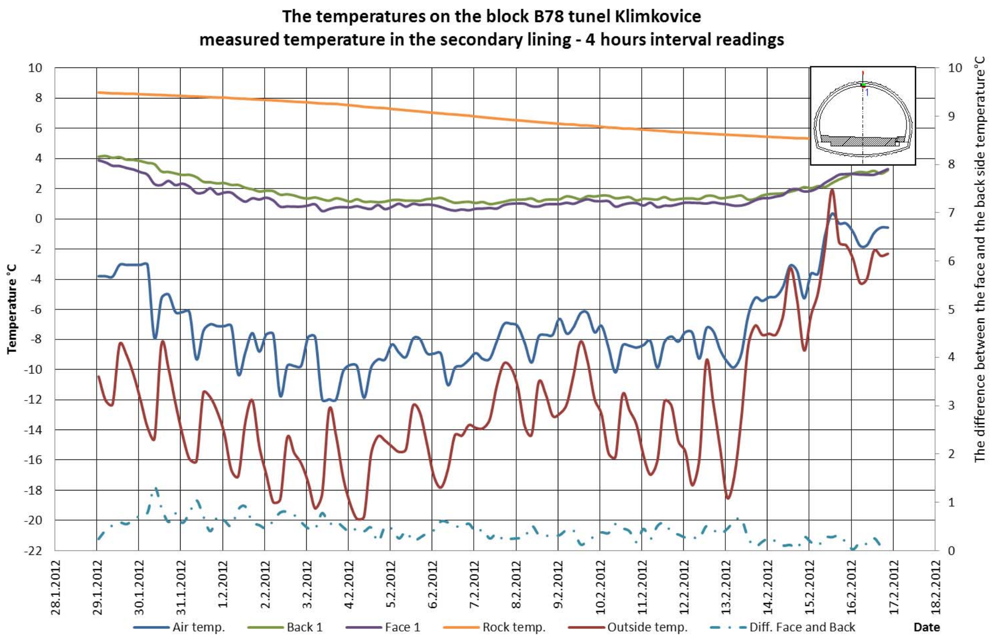

Fig. 3: Detail of temperatures progression at the crown of the vault, block B78

From the temperatures progression, it is evident that the temperature inside of the tunnel affects the final lining. The face of the lining was never cooled down to an ambient temperature. The air temperature is measured at the top of the tunnel that is the hottest point. The sensor is just a few centimeters from the lining, and yet there are differences of both temperatures around 10 °C. The largest share of this behavior has probably the ambient massif temperature. This applies, however, only when cooling down. The lining does not cool rapidly with the decreasing rate of the air temperature. In contrast, when it is warming the air temperature may be higher than the temperature of the lining.

3 COMPARISON OF THE MEASURED RESULTS WITH THE STANDARD

When calculating the effect of these temperatures a 2D software system CESAR – LCPC was used. Modeling was performed by using the finite element method (FEM). An axially symmetric model of the tunnel lining Klimkovice was created. The geometry of the model included also an invert and a carriage way. The thickness of the tunnel vault changed. The crown of the vault was 36 cm; the vault width was 60 cm. Secondary lining was precisely divided into several parts. Two states were modeled. The first condition was a thermal load prescribed under the Standard DS 853, the second state, according to the measurement results. The temperature values were entered as for the back and face lining.

The reference temperature was chosen as either the usual temperature +15 °C or 0 °C. For the measured values were taken into the account the previous long-term temperatures in the rock +7 °C. The system does not make possible to enter the variable temperatures over time. In fact, the temperatures in the tunnel constantly change within 24 hours. For the loads there were used constant values and calculation was done in 24 steps within an interval of 3600 s. During this time the temperatures in the section set up according to the specified boundary values. The results are in Figure No. 4. For the measured values the maximum temperature of the load face of the lining set to −2 °C and the back of the lining to 0 °C. The outside air temperature was not considered there. For comparison was used data from deutsche standard DS 853 [10]. Load temperature was considered on the face −15 °C and −5 °C on the back side. Temperature changes in the lining are determined by calculating of the finite elements. The material properties are characterized by the coefficient of thermal conductivity and volumetric heat capacity. Effect of the initial reference temperature on the overall course of temperatures in the lining is rather essential. At high temperature, the reference is not completely linear process. This effect is also noticeable at the measured temperatures. In fact, the temperatures fluctuate during the day and night. Therefore, linear progression does not reflect reality. The resulting temperature distribution was loaded into the model allowing calculation of stress and deformation. When calculating the stresses the temperature coefficient of expansion material ($\alpha = 5.10^{-6}$ 1/°C) is taken into consideration. These results can evaluate the stress and strain curves in the vault. The results will also evaluate the internal forces in the vault.

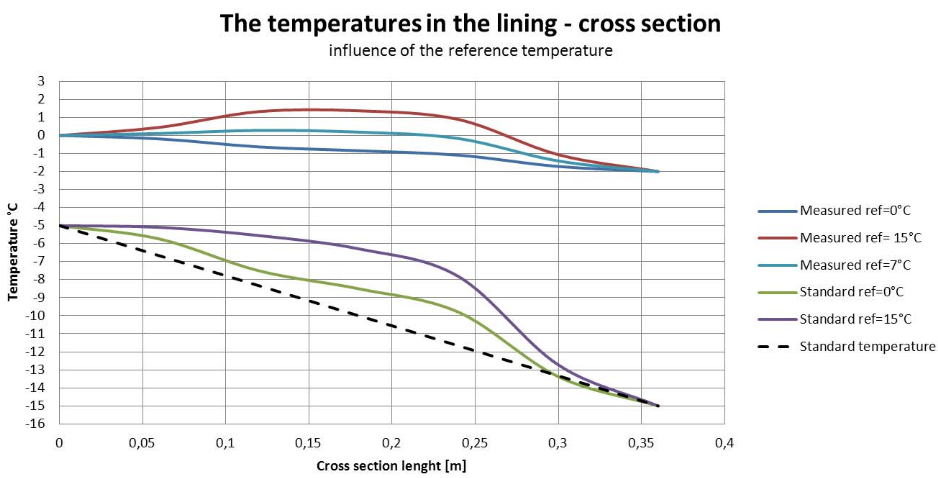

Fig. 4: The temperatures in the lining – cross section

The size of the bending moments (Fig. 5) revealed different loads. There is a visible difference between the measured values and the standards. Considering the measured values, the bending moments are reduced up to 80%.The effect of different reference temperature has not been significantly demonstrated. Courses of the axial forces in the lining are stated in Figure No. 6.

When calculating axial forces the impact of the reference temperature was again reflected to. Unlike the bending moments, during axial forces larger differences can be seen. The results apply to the combination of loads. The load is the temperature and the weight of the vault. All the results of the axial forces are mostly positive. This means that the cross-section is drawn. Larger differences between the face and the back side lead to more stress. When referring to the measured temperatures it applies that the higher reference temperature the greater the load.

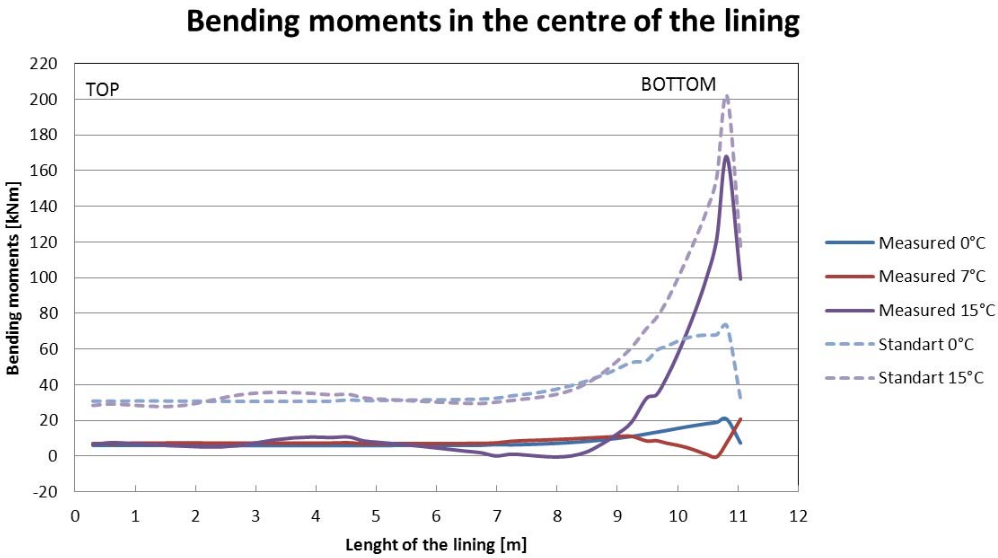

Fig. 5: Bending moments in the center of the lining

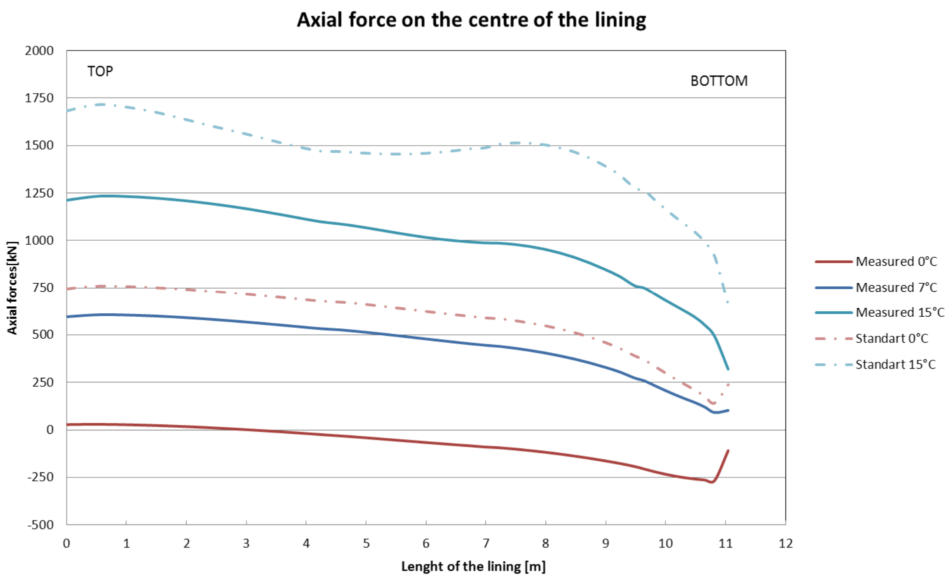

Fig. 6: Axial force on the center of the lining

4 CONCLUSION

Measured temperatures and relative deformations in the tunnel lining in Klimkovice clearly demonstrated their importance and necessity. Monitoring allows us to track the effects of climatic conditions in the tunnel lining. The knowledge gained contributes significantly to a more realistic view of these temperature effects. It brings us the verification of the assumption of static solutions in terms of course of load lining. In terms of measurements of temperatures in the tunnel, extremely low cooling values were obtained. The cooling lasted quite a long time and has brought several findings. In particular, that the lining reacts to the temperatures, but even at very low temperatures, does not reach the temperature of ambient air. Differences of the temperature between the backside and face are still limited to 2 °C.

The results of calculations on a mathematical model showing differences in the actual values of load measurement and the values are given in the DS 853. Internal forces induced by changes in temperature – cooling are small and that the resultant tensile stress section lining. Temperature changes over the cross section of lining are influenced by the initial (reference) temperature, which affects the results of internal forces.

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