Thermal load of the final lining of traffic tunnels

Lukas Duris¹, Josef Aldorf¹ and Jiri Geryk²

¹Technical University of Ostrava, Ludvika Podeste 1875/17, Ostrava 70833, Czech Republic
²Inset Ltd., Rudna 21, Ostrava 70030, Czech Republic

E-mail: lukas.duris@vsb.cz

Abstract. The final lining of mined tunnels using NATM is connected with the need to ensure long-term durability of the construction. The interaction between the secondary lining and surrounding rock mass is ensured by contact with the primary lining. Static load depends already on the interaction between tunnel lining and rock mass. Loading is given by geotechnical conditions, the size of the excavation, construction progress and very important is weather conditions. In this paper presents the results of long-term temperature measurements of the final lining of traffic tunnel. Measurement at selected tunnel pass over ten years. The monitoring results should be available for future design of the final lining of tunnel construction.

1. Introduction

The design of the lining of traffic tunnels has a number of requirements that the lining must fulfill over the lifetime of the tunnel. Any interruption of the traffic always has far-reaching socio-economic consequences. Many of these requirements, such as the completion of the load development and stabilization of the rock mass with the tunnel lining are fulfilled after successful completion and commissioning of the tunnel. There are some factors that in the short term are of little weight, but as their effect gradually accumulates, they can significantly affect the lifespan of the structure in the long term. Representative of these factors are periodic stress changes in tunnel linings due to temperature variations in tunnels. In countries such as the Czech Republic, with four seasons characterized by different temperatures and also by temperature fluctuations during the day, this phenomenon can not be ignored and must be included in the design when assessing the life of the tunnel lining.

Geological arrangement, direction, height and layout of the tunnel route, but also the range of projects and machinery potential of contracting companies in the Czech Republic are the reasons why in recent times the absolutely decisive majority of our mined tunnels are designed on the principles of conventional tunnelling using the “New Austrian Tunnelling Method” (NATM). The NATM system uses two types of lining to ensure stability. The primary lining is usually a layer of shotcrete with welded mesh, supplemented by bolts. This lining is temporary and secures the mined space during the construction. At this stage, the deformations usually stabilize and the stress in the massif regroups. The secondary lining is a continuous supporting structure carrying the entire applied load throughout the life of the structure. The final lining is generally composed of monolithic concrete or reinforced concrete structures, consisting in a cross section of the upper vault, the side (base) blocks and possibly bottom vault. Unfortunately, our modern tunnels so far only rarely use final lining just of plain concrete. Abroad, the use of plain concrete is commonplace.
Pouring of concrete of the individual structural elements of the lining usually uses the continuous method in sections; in the bottom vault into the formwork system, the top vault into hydraulically controlled mobile steel form. The length of working widths vary with the size of the transverse profile, the horizontal alignment and length of the form used, from about 5 m to about 15 m. Each ring of the final lining acts statically on its own.

The final lining is nowadays already designed using modern computer tools. Internal forces and deformations of the lining are calculated with numerical models using the finite element method, where the whole geological environment is simulated including the progress of the excavation and insertion stages of both the primary and the secondary lining. Static calculations are carried out mainly in areas with the most adversely loaded profiles, taking into account the number of load cases and combinations thereof, including:

- Own weight
- Geostatic load of the rock environment
- Hydrostatic groundwater pressure (in the case of closed insulation)
- Creep and shrinkage of the final lining
- The effect of temperature (cooling/warming)
- Technological load, etc.

Based on the above, it was decided to determine how in reality the existing tunnels are stressed or loaded and whether their actual behaviour is consistent with the assumptions in the static calculations. Therefore, in the context of a research project within the geotechnical monitoring, selected devices were placed in the final or temporary tunnel lining to monitor relative stress and temperature; strain vibrating string gauges. The strain gauges are today used to monitor, for example, these tunnels in the Czech Republic:

- Valík (motorway D5)
- Panenská (motorway D8)
- Libouchec (motorway D8)
- Klimkovice (motorway D47)
- Mrázovka (City Ring Road in Prague)
- Dobrovského Tunnels in Brno
- Tunnel complex Blanka (City Ring Road in Prague)
- Vítkovské (railway tunnels of the New Connection in Prague)
- Cable tunnel Vltava (Prague)
- Jablunkov (railway tunnel)

The paper presents the results of measurements on the tunnel lining in Klimkovice. The automatic measuring system was installed as the first in the Czech Republic in the Klimkovice tunnel, built in 2006, during the installation of the secondary lining. Systems for measuring temperature and stress in the final lining then also became to be more used for newly-built tunnels to gain more accurate knowledge of the behaviour of the final lining during operation of the structure. The measuring system has been in operation for over nine and a half years and still keeps collecting the necessary data from two measuring profiles. [1]

Secondary lining measurements are common. We can see examples of tunnel measurements that were presented in [5, 6].

2. Measurement system on the Klimkovice Tunnel
In 2008 the next section of the motorway D47 - Lipník nad Bečvou - Bohumín was put into operation, designated as construction 4707. On this section, less than 10 km long, is also the Klimkovice Tunnel -
one of the major civil engineering structures of the motorway. The tunnel itself is 1,080 m long and is located near the municipality of Klimkovice at a distance of about 1 km from the building of Klimkovice spa. It passes here underneath the ridge between the villages of Klimkovice and Hýlov. If the tunnel had not been built, the area would be inconsiderately and quite drastically divided by the busy motorway and its traffic. The underground route of the motorway will allow development of this territory in the future.

The tunnel is routed in two separate tunnel tubes A and B; both tunnel tubes have two lanes. Both tunnels have the same spatial parameters of the one-way two-lane tunnel T9.5 category, and same layout. The lane in the tunnel has a unilateral cross slope and width of 9.50 metres between curbs. The clearance above the ground is 4.80 m. Two-sided walkways have a width of at least 1.10 m. The tunnel has a clear width of 12.204 m. The gross cross area of the tunnel, including the technologically required overcut, is 120.17 m$^2$. Because of the routing of the motorway in the terrain configuration and geological conditions, the tunnels were mined in longer stretches of rock massif; the shorter sections next to the portals were excavated in open trenches with subsequent backfilling. The excavated sections of the single-tunnel construction have reverse umbrella waterproofing and the vault strips sit on longitudinal footings. The mined sections are double-walled construction tunnels with closed intermediate waterproofing.

The tunnel was mined using the new Austrian tunnelling method with the application of shotcrete, honoring the NATM principles, and with a horizontal articulation. In the first step, the full width of the top heading was mined with the excavation area of about 65 m$^2$ and a minimum height of 6.10 m of the vault crown. The lower profile opening was further spatially divided into three parts - the lower bench in two steps (right, left) and excavation of the invert. The primary lining supporting the excavation is shotcrete with reinforcing steel mesh, lattice girders and bolts. Construction of the lining distinguishes 5 types of protection depending on the nature of the geological environment.

The final lining of the Klimkovice tunnel is designed as reinforced concrete C30/37. The vault is reinforced with armature. The basic length of the individual section (tunnel block) is 12 m. The lining of the Klimkovice tunnel has already claimed one first - to increase the fire resistance of concrete vaults concrete filled with polypropylene fibers was used. This solution was selected because the coarser fractions of aggregate in the concrete were greywacke. Fire resistance tests confirmed the correctness of the selection of concrete type – the reinforced concrete of the secondary lining passed the tests [2].

![Figure 1. Tunnel cross-section with monitoring equipment.](image-url)
During the construction of the secondary lining, a controversy occurred regarding the thermal load of the tunnel lining. For this reason, temperature sensors were installed at different distances from the portal in two cross sections of the tunnel B for measuring temperature and lining strain. Furthermore, temperature sensors were installed to measure air temperature in the tunnel and in the rock 1.0 m behind the lining.

In each profile there are 12 such sensors. The sensors were placed in three positions (see Figure 1). At each position they were fitted to the upper and lower edge of the reinforcement in the radial and tangential direction. In each measurement profile a sensor for measuring air temperature is also mounted. The measurement system is automatic. The reading and collection of data is automatic. The intervals of reading are every four hours.

The first measured section was in the block labelled B90, approximately 55 m from the eastern portal. The record of temperature measurements is shown in Figure 1. Block B90 is the first strip from the portal on the transition between excavated and mined part of the tunnel. The second profile was located 190 metres from the entrance portal in the tunnel strip labelled B78.

3. The temperature measurement on the Klimkovice Tunnel

As mentioned, the design of the tunnel lining is always complex due to the effect of a large number of load cases and combinations thereof. Among these influences are the temperature changes, which reflect the climatic conditions outside the tunnel. This paper will evaluate a single profile that is close to the portal. This profile is influenced more by external factors, as indicated by the current measurement and the difference of readings between the two profiles is up to 8 °C (air temperature). This paper will assess the measurements over the full nine years. Overall temperature during this period is recorded in Figure 2. The recorded temperatures are those on the three levels of the tunnel vault, in the outer and inner face of the lining, and the air temperature and the temperature in the rock.

The air temperature is measured at the crown where the thermometer is just below the top of the crown. Rock temperature is also monitored at two levels, both in the top of the crown and in the side of the vault. The respective sensor is always placed in a one-metre-deep borehole. The course of the air temperature is the most interesting, as it obviously varies according to the time of day and the season. Its extremes fall to both times of the year (summer and winter). This temperature is faithfully copied by the temperature in the lining in all three positions. The seasonal trends act of course on the temperatures in the rock. Its maximum and minimal manifestations are less than the air temperature in the tunnel, but again respond to external influences. Of course the temperature in the rock shows some lag compared to the air temperatures. Maximum, minimum and average values are shown in Table 1 below. Over twenty-nine thousand entries were evaluated. The highest air temperature was measured in August 2013 (34.15 °C). Usual summer extremes amounted to thirty degrees Celsius. The lowest temperatures were achieved in February 2012, when the temperature in the tunnel fell to -15.3 °C. This was due to long-term low temperatures, which lasted for over twenty days. In winter, temperatures routinely fall below freezing. This usually happens in January and February. The average air temperature in the tunnel is about 13°C. The temperature in the rock reacts to external weather influences and the temperature varies from 17°C to 4°C throughout the year. In summer, extreme temperatures in concrete are about 20% lower than the air temperature inside. During winter extremes the difference is greater. The measurement shows that the highest or the lowest air temperatures are not identical with the temperatures in the lining at the same time.
Table 1. Measured temperature.

|        | Air | Back 1 | Face 1 | Diff. | Back 2 | Face 2 | Diff. | Back 3 | Face 3 | Diff. | Rock |
|--------|-----|--------|--------|-------|--------|--------|-------|--------|--------|-------|------|
| Maximum| 34.1| 27.4   | 24.9   | 4.6   | 27.5   | 24.9   | 6.0   | 27.0   | 24.3   | 5.7   | 17.6 |
| Minimum| -15.3| -1.4   | -2.0   | 0.0   | -1.1   | -1.9   | 0.0   | -2.0   | -2.0   | 0.0   | 4.1  |
| Average| 13.2| 13.1   | 13.2   | 0.5   | 13.1   | 13.1   | 0.7   | 12.9   | 12.9   | 0.9   | 12.0 |

Table 1 also shows the temperature differences. This means the difference between the face and the reverse side (back) of the structure. Strain gauges are placed on the reinforcement on both sides of the cross section, and therefore we are able to determine a simple linear temperature gradient across the cross section. This is very important in terms of the structural design and stress of construction due to temperature influences. The load is not determined by the highest or lowest temperature attained, but rather by the temperature gradient between the reverse and face of the structure. The maximum and minimum value is always set for the difference at the time of reading, not from the maximum and minimum values. This temperature gradient is not uniform for all three sensors positions in the vault. At the crown, the differences are minimal. 70% of the measured values are within 0.5 °C. The concrete thickness is 0.35 m here. In the heel the vault is extended to 0.7 m. At the position of sensors two and three, only 65% and 50% of the measured values respectively fall within 0.5 °C. The temperature difference from 0.5° to 1.0°C is roughly around 17%. The highest value of the difference that has been reached is 6 °C, and only rarely. This maximum was recorded for sensor position 2 (see Table 1). Minimum values are limited to zero, because the difference was determined from the absolute value of the difference between the face and the reverse. A zero value means that at that time both temperatures were the same.

The significance of the temperature gradient has already been mentioned. Another reason for monitoring the temperatures at both surfaces of the lining is the German railway directive DS 853 [4]. This directive prescribes what temperature differences must be considered in the design of the final lining of tunnels. The directive takes only the tunnel length (the distance from the portal) and the season (summer, winter) into account. It has been found that the temperature gradient is also influenced by the thickness of the lining and the distance from the portal. The prescribed temperature differences are absurdly large, and completely diverge in comparison with the measurement results.
Figure 3. Detail of temperatures during extreme summer.

To illustrate the daily temperature course, two detailed graphs for a short period (5 days) were compiled. These graphs show the extreme temperatures of the air in the tunnel in summer and winter. All three sensor positions in the vault, the air temperature and the temperature in the rock were always evaluated. Furthermore, the differences in temperature between the face and the reverse of the structure were determined.

Figure 4. Detail of temperatures during extreme winter.
Figure 3 shows the recorded detail of summer. The air temperature climbed briefly to a maximum of 34°C, but the other days were cool, which is also reflected in the course of temperatures. The difference between the air temperature and the highest temperature in the structure is 4°C. The courses of temperature at the outer edge are almost identical; the differences are greater on the reverse of the lining. The courses no longer overlap and it is possible to see the differences by the sensor position or the thickness of the lining. The temperature in the rock is constant (16°C) and the difference between the outer surface of the lining and the rock is up to 6°C. When the temperature of the air drops, the temperature in the lining reacts and the temperatures of the reverse and the face equalize. This effect is particularly evident from the difference in temperatures at the top of the tunnel vault. These results show that the structure is not heated to the air temperature in the tunnel and this temperature acts only briefly and is not able to affect the lining too much. Extreme weather will have only a minimal effect and for a very short time. The temperature gradient in the structure is affected mainly by the thickness and position of the cross section of the vault (the upper part is heated more). The temperature in the structure does not respond immediately to changes in outside temperature, and may even have a higher temperature than the ambient air. This is caused by accumulation of heat and partial heating of the back part of the rock, which has no possibility to quickly dissipate the heat from the structure, i.e. the structure is cooled from one side only.

Figure 4 is a detailed curve for winter. The winter temperatures demonstrate a significant difference from the rail directive. For extreme recorded values the air temperature was -15°C, and also for long periods (3 days). Despite this long-term cooling, no significant drop in temperatures in the tunnel lining occurs. The lowest temperatures on the face are around -2°C, which is a 13°C difference from the air temperature. The temperature in the rock gradually decreases due to the long lasting frosts. Its temperature does not drop below +4°C, which causes heating of the underside of the secondary lining. The reverse side is cooled to 0°C. Temperature differences in the wall (temperature gradient) in these winter temperatures are far lower than anticipated by the rail directive; within two degrees Celsius. This finding is of great significance in terms of stress of the structure due to climatic conditions. The combination of loads with winter temperatures in the static calculation is much more unfavourable than at summer temperatures. It is very different to consider a temperature gradient of 10°C or 2°C when calculating the load of the structure (see [3]).

The second measurement profile is located 190 m from the portal. The course of temperature practically corresponds to temperatures in the first measurement profile. The difference of the average air temperature in the tunnel between the profiles is 0.3°C. Virtually the same maximum values during the same period were achieved. The difference is in winter when the temperature difference is up to 3°C. Winter temperatures are higher deeper in the tunnel than closer to the portal. The temperatures are virtually identical in both profiles, and then the findings for block B90 apply also for the second measurement profile.

4. Conclusion

Summary of findings from measurement:

- Maximum, minimum and average values obtained in each measurement nodes, the air temperature at the ceiling and surrounding rock were determined.
- Temperature differences between the face and the reverse of the lining and the maximum, minimum and average values were determined. Based on evaluation of the frequency of temperature differences it has been found that the majority of differences is within 0.5°C with the frequency of over 70%.
- For the assessment of extremes the effects of hydration of concrete were eliminated.
- The temperature in the rock does not fall below freezing in the winter; the annual temperature difference in the rock is 13°C.
In terms of measuring temperatures in the tunnel the extreme values of these temperatures were obtained, which brought a lot of new knowledge. In particular, the lining responds to the course of the ambient temperatures, but also does not drop to the temperature of ambient air at very low temperatures. Temperature differences between the reverse and the face are less than projected by the rail directive. The temperature differences are a function of the thickness of the reinforcement, position in the vault and distance from the portal. The temperature is also affected by the temperature of the rocks.

The measurement of temperature and relative deformations in the lining of the Klimkovice Tunnel clearly demonstrated their importance and necessity. Monitoring allows tracking the effects of climatic conditions in a tunnel lining. The acquired knowledge significantly contributes to a more realistic look at these temperature effects. It even brings verification of the assumed static solutions in terms of the loading process of the lining.

Acknowledgements
The paper was prepared with the support of the Competence Center of the Technology Agency of the Czech Republic (TAČR) within the project Center for Effective and Sustainable Transport Infrastructure (CESTI), project number TE01020168.

References
[1] Šourek P, Vítek J, Aldorf J and Ďuriš L 2008 Měření deformací a teplot na definitivních tunelových ostěníh Tunel 17(4) pp 70-76
[2] Pechman J et al 2008 Klimkovický tunel uveden do provozu Tunel 3 pp 18 - 25
[3] Ďuriš L and Aldorf J 2011 Vliv ochlazení na tunelové ostění Geotechnika 14(3) pp 22-25
[4] DB Netz – Deutsche Bahn Gruppe 2002 Richtlinie 853, Eisenbahntunnel planen, bauen und instand halten
[5] Zhao X and Qiu H 2007 Application of fiber Bragg grating sensing technology to tunnel monitoring Yanshilixue Yu Gongcheng Xuebao/Chinese Journal of Rock Mechanics and Engineering 26(3) pp. 587-93
[6] Iida H, Iura T, Konishi S, Ono T, Koyama Y and Mizuhara K 2006 Internal strain measurement method of the extruded concrete lining Tunnelling and Underground Space Technology 21(3-4)