Design, construction and conditions of the application of unreinforced concrete final lining in conventionally driven tunnels

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Abstract. The way to an economic design in the final lining in conventionally driven tunnels lies in structural analysing based on the actually encountered geotechnical conditions. Regarding reinforced concrete structures, many standards and regulations applicable to designing and building structures and taking them over by the client before their commissioning and before the end of the warranty period respectively exist in the Czech Republic. If the local conditions allow it, it is possible to design the final lining as an unreinforced concrete structure. In such a case it is necessary to take the differences into consideration in the structural design and in the possibilities of the lining behaviour and to set criteria for taking over the lining allowing for its use. Setting too stringent criteria for cracking can lead to an increase in the contract price, either because of the necessity for reinforcing the lining or because of the fact that the contractor reduces the risk by incorporating the assumed cost of repairs into the total cost. The paper describes basic differences in the approach to reinforced concrete and unreinforced concrete linings, the possibilities of limiting formation of cracks by means of the concrete mix design, by selection of the technological procedure of the work and the method of curing after stripping. The text contains a comparison of criteria for assessing the surface of an unreinforced concrete lining with criteria in foreign regulations.

1. Introduction
The use of unreinforced concrete final lining is currently usually associated with conventionally driven tunnels, where the primary lining is formed by shotcrete and the final lining is cast-in-place. The NATM prevails in the Czech Republic in the area of conventionally excavated tunnels. All tunnels in the modern tunnelling history, with the exception of the Březno tunnel driven using the Mechanical Pre-cutting Method, were driven using the NATM principles. The NATM application was made possible only after the revolution in 1989, which opened borders and gave the green light to technologies which had not been used until then. Designers gradually gained access to high performance computer technology and program equipment, construction companies access to mechanical equipment and building materials and both groups jointly gained the possibility to draw on foreign experience.

In the context of the NATM it is often mentioned that it is a tunnelling method allowing operative responding to the actually encountered geotechnical conditions and expending only such financial means that are necessary for adhering to the quality requirements and requirements for construction work safety. To make it possible, it is necessary to create space not only for the above-mentioned
modern technological equipment and for obtaining the knowledge and experience necessary, but also
to create the technical and legal framework which would allow both parties to the contract to carry out changes during the construction legally and operatively. The excavation of a tunnel and the method of stabilising the excavation is what we mostly understand under the term “optimisation of a technical solution with respect to geotechnical conditions”. Not less important role in terms of laboriousness, minimisation of risks during works execution and the final amount of investment costs is played by the technical solution of the final lining. Even in this case is it possible to speak about the NATM as an observational method. It is possible to create a mathematical model approximating realistic conditions on the basis of the results of geotechnical measurements conducted during the underground excavation, condition surveys of the faces of individual excavation advance rounds and responsible determination of geotechnical parameters of the ground mass, thus obtaining the inner forces required for the design of the amount of reinforcement or for the application of an unreinforced concrete lining.

2. Differences in designing reinforced concrete and unreinforced concrete linings

2.1. Two approaches to the function of primary and final linings

No unambiguous opinion exists among the technical public on the load-carrying function of the primary and final (secondary) linings. Supporters of the basic load-carrying function of the primary lining stand on one side. They assign it, in cooperation with the ground ring stabilised with anchors, the capability of transmitting ground pressure throughout the tunnel design life. In such a case, the final lining fulfils only the facing and aesthetic role because it is loaded only by its own weight and effects of volumetric changes. Only in the cases of pressure insulated tunnels they have to resist hydrostatic pressure as well. The Pisárky tunnel in the Czech Republic was constructed under these assumptions. High-durability fibreglass anchors were used for reinforcing the ground ring. Supporters of the theory of total degradation of the primary lining stand on the other side. In their opinion, the primary lining loses its load-carrying function earlier than the assumed life period ends and all loads have to be carried by the final lining. A fundamental issue of durability of the primary lining is the effect of aggressive environment not only on the individual components of the primary lining (shotcrete, supporting frames and welded mesh), but also on the elements reinforcing the ground ring in the excavation surroundings. In the Czech Republic the latter approach is usually applied to designing the final lining and the final lining fully takes the loading from the primary lining that is considered to be temporary. An answer regarding the degree of degradation of the primary lining after tens of years can be obtained from a research conducted currently in Austria, where the second tubes of tunnels, which were opened to traffic over 30 years ago, are driven in order to improve operation safety. It is possible to collect samples of the primary lining during the building of cross passages or repairs of linings of existing tunnel tubes and analyse them. Recent results have proved that the speed of degradation of the primary lining shotcrete is far from the assumptions and both the concrete and steel keep fulfilling their load-carrying function [10]. An answer regarding the durability of shotcrete linings can, in addition, be found on numerous Scandinavian tunnels, where cast-in-place secondary lining is virtually unused. The required lining quality remains even after many years despite direct exposure to effects of the environment from the side of both the ground mass and the road space. In the text below we will deal with unreinforced concrete final lining as the only load-carrying element providing stability to a tunnel throughout its life (100 years).

2.2. Principle of designing reinforced concrete linings

When a lining is being designed and criteria for the unreinforced concrete lining are being determined, it is necessary to take into account the differences in the static action of an eccentrically compressed reinforced concrete or an unreinforced concrete structure. In case of the reinforced concrete lining, cracks start and develop at adequate exploitation of tensile reinforcement in adjacent concrete because the tensile strength of concrete is exceeded already at a small strain of tensile fibres in the section. For that reason, an assumption is introduced that concrete in tension is excluded and tensile stresses in the section are transmitted solely by reinforcing bars. However, a linear material model is sufficient for
the calculation of inner forces for which the lining is being designed; it means that the stiffness values of lining sections are not affected by the formation of cracks and the full (initial, unreduced) values enter the calculation. The resultant position of the normal force can be under these conditions even outside the section boundaries.

2.3. Principle of designing unreinforced concrete lining
A different situation is in the case of an unreinforced concrete lining. If the unreinforced concrete lining is modelled using a linear material model, the unavoidable result of the design is an uneconomically great thickness of the lining. In such a case the insufficiently sophisticated calculation model where the lining is designed according to the tensile strength of concrete is blamed for the unsatisfactory result. Tensile strength is smaller by an order of magnitude than compressive strength. However, the compressive strength is in reality crucial for the bearing capacity. For that reason it is necessary to proceed to calculation with a non-linear model of the lining, where the cracks and potential plastification of the sections are taken into account. The problem can be solved, for example, using the FEM with planar elements or even using a simpler beam-based model of the lining.

In the models where total exclusion of tension is assumed in the area of the crack, the resultant of normal stresses always lies inside the section and the bearing capacity exclusively depends on the compression strength of concrete. It leads to a thinner lining, thus also to a more economic design.

In the method of calculation of unreinforced concrete lining outlined above, the results are arrived at by means of an iteration process. The state of stress and deformations in the section is calculated under predefined assumptions. For example, on a beam-based model of a structure with a non-linear model of the lining, a linear distribution of stress is assumed in the compression zone of the section; during additional loading, the design compression strength of concrete is first reached in the outermost fibres and, subsequently, the phase of gradual plastification of the material starts. It ends by reaching the ultimate limit state of the section. The assumption of planar section deformation is adopted for the development of deformations.

In the text above it is possible to find some differences in the approach to the structural design of a reinforced or unreinforced concrete lining. However, some differences must be applied even in the phase of evaluation of success of the lining the design. The assessment of cracks in the lining is an important issue related to this statement.

2.4. Difference in the approach to the width of cracks in reinforced and unreinforced concrete linings
One of the criteria for assessment of function and building quality of the lining is the width of cracks and their number in a certain area of the tunnel profile (e.g. the top of arch, a tunnel sidewall). Here it is necessary to note that the formation of a crack caused by direct (static) loading does not have to be considered as a defect or failure. Rather the contrary, the origination of cracks is a usual phenomenon arising from the principles and adopted assumptions regarding the static action of a reinforced concrete or only unreinforced concrete structure. Nevertheless, there are some aspects which must be monitored in this respect and they are different for both of the lining types.

In case of reinforced concrete linings, the crack width is limited and the values which are not to be exceeded can be found in respective standards and regulations. The main purpose of limiting the crack width is in this case to protect the steel reinforcement and to prevent its corrosion. Limit values are recommended for various types of the environment in which the lining may be located and for those kinds of substances which can threaten the reinforcement. When these prescribed values are fulfilled and the concrete cover is sufficient, it is possible to expect that the penetration of harmful matters into the area of the reinforcement will be prevented and neither the load-carrying function nor the durability of the structure, which is planned for 100 years in the case of tunnel structures, will be disturbed. Another criterion for limiting the width of cracks is the potential unfavourable influence on the structure appearance.

Another situation occurs in the case of an unreinforced concrete lining. The requirement for the undisturbed load-carrying function of the section remains the same, but this function is ensured by the concrete itself as the only structural element. The transition of forces by means of steel reinforcement
ceases to exist in this case and the criteria relating to cracks and determined for reinforced concrete lose their significance. The main requirement for the function of an unreinforced concrete lining is the safe transition of forces in the concrete section, which has to be ensured mainly by the sufficient depth of the compression zone corresponding to particular stress conditions in the section. The resulting crack width therefore can be different and greater under various stress states in comparison with a reinforced concrete section. Just as with reinforced concrete, this width may be limited by requirements for the structure appearance.

In general, the possibility of designing the tunnel lining as an unreinforced structure depends on several factors. Above all, it is a reliable assessment of the geological conditions. The possibility of applying unreinforced concrete linings only in favourable geological and geotechnical conditions is accepted even in foreign regulations. It is assumed that reinforced concrete is used in the cases of geological faults with an impact on the magnitude and different intensity of loads acting around the tunnel circumference. Another factor important for a successful design is the geometry of the tunnel excavation cross-section and the shape of the lining. It is especially in the case of unreinforced concrete that the success of the design is very sensitive to this parameter. But it is obvious that only seldom is it possible to adapt the shape of the lining purely to the needs of statics. The convergence of the iteration process and the final position of the normal force inside the section are achieved in the calculation of a lining which is statically satisfactory. If the equilibrium is not achieved in the calculation (in the case of reinforced concrete it is possible to solve it by additional reinforcement), the only way of remedy available is changing the shape of the lining, designing a greater section thickness or a change from unreinforced to reinforced concrete lining.

It is particularly important in the case of unclosed tunnel profiles to thoroughly determine the boundary conditions to describe the contact of the vault and footings. In such a case, we consider it to be correct if the tunnel profile is analysed comprehensively, i.e. jointly with the lining vault and the footing.

3. Principles of designing concrete mix formula for unreinforced concrete lining

From the aspect of material, the formation of cracks in unreinforced concrete is predestined first of all by the low tensile strength of the material. It is a property which can be changed only with difficulty without the use of steel reinforcement. The means for limiting the formation of cracks caused by volumetric changes during the initial hours after casting of concrete is a correct design of the concrete mix formula with low hydration heat and slow strength gain. The reduction of the hydration heat magnitude can be achieved by adhering to several rules. Reducing the hydration heat is positively affected by the low content of cement ranging from ca 250 to 280 kg/m$^3$ and by the use of suitable cement with low content of C3A, the use of fly ash as a concrete improving admixture (ca 50–80 kg/m$^3$) and the design of such a mixture which reaches the maximum temperature difference up to 15K during laboratory tests on insulated cubes. The initial temperature of the mixture should be moderately low (13 – 18 °C) and it is recommended that the fresh concrete temperature should not be higher than 25 °C. It is quite common abroad that a combination of several different cement types is used to achieve optimum values of the mixture being designed for unreinforced concrete linings. In addition, it is necessary to choose low water content within the interval of ca 170 – 190kg/m$^3$ to increase the proportion of fine particles – cement, cinder, fine aggregate < 0.125 mm to the volume > 370 kg/m$^3$, to limit the amount of silt particles, to provide 4/8 mm fraction aggregates in the recommended amount of ca 3-5 %, to maintain the w/c ratio at 0.63 as the maximum and to use aggregates with a low coefficient of thermal conductivity as much as possible. The use of aggregate fraction D = 32 mm is recommended in the case of an unreinforced concrete lining.

Even the low concrete strength at formwork stripping is important as far as the formation of cracks is concerned. With respect to the fact that the final lining concrete is usually cast after the stabilisation of the primary lining deformations and the final lining is not loaded by ground pressure, it is not necessary from the static point of view for the structure to exhibit the required terminal strength value already after 28 days. It is possible to expect that the value of loading assumed by the calculation will
act on the lining later, after the complete degradation of the primary lining, if ever. It is advantageous for the mixture design if it is possible to use a “slow” concrete formula with low hydration heat and the terminal compressive strength is reached after 56 or even 90 days.

4. Assessing the quality of the surface of unreinforced concrete lining and contractual criteria

4.1. Causes of the formation of cracks and their influence on the function of linings

An unreinforced concrete tunnel lining is still rather a rarity than a generally established practice in the Czech Republic. An often discussed issue is the number, orientation, depth and width of cracks in a lining. We can divide the cracks into several types, assign significance to these types and, with a certain degree of simplification, even the cause of their origin. The first cause of their formation lies in volumetric changes of concrete - shrinkage, temperature changes during concrete casting due to hydration heat and, during the tunnel life, due to the temperature changes corresponding to the seasons. Another cause of the formation of cracks lies in the static loads acting on the structure.

Cracks due to volumetric changes of concrete are either vertical cracks usually on the tunnel sides, which can in some cases run across the whole lining vault, or directionless “cobwebby” cracks in the whole area of the structure. An example of a vertical shrinkage crack is presented in Figure 1.

Cracks due to static loading are usually oriented in the direction of the tunnel axis (horizontal). They are usually created in the vault crown; they can appear even on the tunnel sides, depending on the loading intensity and proportion between the vertical and lateral pressure. In reality, the two causes of the formation of cracks cannot be strictly distinguished one from the other. The size of a crack due to a static action is affected by the state of stress in the lining due to concrete shrinkage and vice versa.

The approach to assessing cracks from the point of view of the lining functionality is also double. First of all, it is necessary to distinguish the crack direction. Vertical cracks do not fundamentally influence the static action of the lining. It is possible to imagine their function as splitting of the lining into shorter blocks, the static function of which does not change in the transverse direction. The main criterion in this case is aesthetic. It is a matter of an agreement between the contractor and the client about the client’s idea of the lining surface appearance. On the contrary, cracks due to static loading may directly affect the static function of the lining. When they start, an imperfect hinge develops in the lining, the statical schema of the structure changes as well as the distribution of inner forces, mainly bending moments. With the normal force almost unchanged, the compression zone of the lining section is reduced. In such a case it is necessary to assess the structure and determine the allowable width and depth of the crack on the basis of a structural analysis. Apart from assessing the compression zone of the section it is necessary to assess also the danger of secondary cracks formation in the lining perpendicularly to the direction of radial cracks, which may cause falling of the parts thus damaged from the lining. It is dangerous first of all with respect to the operation safety. This phenomenon is described in Reference [9].
4.2. Assessing the quality of unreinforced concrete linings in the Czech Republic

Whilst in Austria and Germany the problems of assessing cracks are known and contained in directives and regulations, no regulation defining the relationship between the client and the contractor during the final acceptance at the end of the warranty period existed in the Czech Republic until the end of 2015. In a better case, the allowable parameters of the lining surface were defined in tender documents, whilst, in a worse case, the rules were set later, in the course of the construction. In such a case, the contractor takes the risk of an undefined scope of potential rehabilitation work. In case of a responsible attitude, the contractor evaluates this risk and incorporates it in the bid for execution of the works, thus the investment cost is unnecessarily increased.

In case of railway tunnels this situation still exists, in case of road and motorway tunnels it changed after the issuance of a review of Technical Specifications of the Ministry of Transportation No. 18 – Concrete Structures and Bridges in January 2016. The regulation allows use of unreinforced concrete as a structural material and contains not only criteria for the allowable formation of cracks, but also requirements for the quality of the unreinforced concrete lining surface. Cavities (bubbles) with closed surface and maximum diameter of 25mm or maximum area of 5cm² and maximum depth of 10mm are permissible on the surface of an unreinforced concrete lining. An example of these cavities is presented in Figure 2.

![Figure 2. Surface cavities in the lower part of the lining (photo courtesy of Libor Mařík).](image)

Cavities in the lining surface have to be treated if one of their dimensions (diameter, area, depth) exceeds the respective limit. The repair of concrete surface in the repair design, for example by grinding, if possible, is better and more durable than a thin layer of a repair material. Such a layer may cause a far greater damage if it breaks away from the substrate and falls on a passing vehicle than an imperfect surface of the lining. It applies first of all to the area at the tunnel vault crown above the roadway. Breaking of concrete at the edges of construction or expansion joints and/or in the vicinity of cracks is assessed from the point of view of its location in the lining. If a crack of unknown depth is located at a distance of 200mm or smaller from a construction or expansion joint or another closest crack, it is necessary to assume that a part of the lining concrete can break off. If the crack and the construction or expansion joint and/or more cracks form a continuous closed shape delimiting the possibility of breaking away or loosening a part of concrete (see Figure 3), the crack width (including a non-structural crack) will be monitored during regular inspections at least once a year, unless the width exceeds 0.2mm.
Figure 3. Loosened part of the lining at the joint between concrete casting blocks (photo courtesy of Viktor Petrás).

At the width ranging from 0.2 to 0.8 mm the crack will be monitored during extraordinary inspections 1x in 3 months and, at the width over 0.8 mm, it is necessary to design and implement measures (for example a repair of the particular section of the lining). Spalls and loosened parts of concrete, first of all those loosened from the edges of construction or expansion joints and/or cracks, are considered to be a defect preventing safe operation and have to be repaired before opening to traffic.

In the case of unreinforced concrete lining the maximum depth of structural cracks is defined by the requirement for the minimum compression zone depth of the concrete section. It has to be determined on the basis of a structural analysis for the particular case. The depth of non-structural cracks in a reinforced concrete lining is not limited and can run throughout the lining thickness. Cracks in linings of all of the above-mentioned types must not pass across anchors to concrete serving, for example, to fix tunnel equipment. In the case of the unreinforced concrete lining it is necessary to fill cracks when their full load-carrying capacity and usability of the structure are not proved and/or when their dimensions exceed the permitted values presented in Table 1.

Table 1. Maximum permitted values for cracks in unreinforced concrete linings [1].

| Maximum permitted values of monitored parameters of defects of unreinforced concrete linings | Unit | Criterion at final acceptance | Criterion at the end of warranty period | Criterion at the end of design life |
|---|---|---|---|---|
| Structural cracks | | | | |
| Width of cracks (horizontal) | [mm] | 0.5 | 1 | 1.5 |
| Depth of cracks | [mm] | To be determined by structural analysis | | |
| Vertical displacement (perpendicularly to tunnel axis) | [mm] | 1 | 2 | | |
| Horizontal displacement (perpendicularly to tunnel axis) | [mm] | 1 | 2 | 3 |
| Number of cracks (horizontal) in a 12m long section | [pcs] | 3 | 4 | 5 |
| Non-structural cracks | | | | |
| Width of cracks (horizontal) | [mm] | 2 | 3 | 3 |
| Depth of cracks | [mm] | Up to the full lining depth | | |
| Number of cracks in a 12m long section (vertical, running across the whole vault) | [pcs] | 2 | 2 | 2 |

4.3. Examples of criteria from foreign practice
In the Czech Republic, the unreinforced concrete lining is at the moment found in the Pisárky tunnel in Brno, the Libouheč tunnel on the D8 motorway linking Prague and Dresden, both tubes of the Vitkov railway tunnels in Prague and the Olbramovice, Tomice I and Sudoměřice tunnels on the fourth
railway corridor leading from Prague to Linz. The formation of cracks is being monitored in these tunnels without significantly negative experience. However, long-term monitoring is not available yet.

The relative lack of experience with the use of unreinforced concrete linings in the Czech Republic in comparison with the Alpine countries, where economically designed tunnels are necessary for securing the transport infrastructure, probably leads to the determination of more detailed criteria for assessing the cracks in linings. Above all, it is defining the number of cracks per concrete casting block, but also detailed defining the time to which the crack width is related. An advantage is a transparent relationship between the client and the contractor in potential claim enforcing procedures. In foreign regulations the criteria are set in a substantially simpler way because of the fact that experience shows that use of an unreinforced concrete lining is not a risk from the point of view of the tunnel operation or even securing its stability.

The Austrian regulation [3] does not consider cracks due to volumetric changes or mechanical effects up to the width of 1mm to be defects. When the width is greater, the cracks have to be assessed in terms of durability of the lining, tightness and static function. First of all, this regulation defines possible defects of reinforced concrete and unreinforced concrete lining including photodocumentation. It, in addition, prescribes the way of their treatment.

According to a German regulation DB853 [7] it is necessary to treat unbranched radial cracks wider than 2mm, longitudinal cracks in the sidewalls or in the vault crown wider than 1.5mm and crescent cracks in the vicinity of construction joints and anchoring elements wider than 0.5mm by injecting grout into them. In comparison with this regulation the criterion for the permissible width of crack of 0.5mm contained in the regulation [1] for horizontal structural cracks at the moment of the final acceptance by the client appears to be very strict. It may be limiting when the decision about use of reinforced or unreinforced concrete is being made, thus negatively affecting the cost of the works. It would be more appropriate to set the same criterion as that for the end of the warranty period or, as in the case of assessing the crack depth, to require a static assessment. The reason is the possibility of formation of secondary cracks, which is described in Reference [8]. Another reason is the fact that when a crack does not start immediately after stripping, it is usually caused by the action of ground pressure on the structure.

5. Measures restricting surface defects and formation of cracks in unreinforced concrete lining

In the case of a reinforced concrete lining it is possible to a certain degree to control the width and depth of a crack by a suitable design of reinforcement. In the case of unreinforced concrete lining it is impossible to prevent from the formation of cracks in economically designed cross-sections. From the aspect of the static function and usability of the structure it is even unnecessary, unless the crack parameters exceed the statically or contractually defined limits. Nevertheless, the formation of cracks can be limited during the concrete casting process by designing a suitable formula, adhering to construction principles, a suitable concrete casting procedure and curing of the concrete lining after stripping.

Measures designed to limit the formation of cracks in an order without considering the weight of importance:

1. Maintaining the geometry of the primary lining surface smooth and unbroken as much as possible (without tothing, edges);
2. Using intermediate waterproofing or a separation membrane between the primary and final linings;
3. Reducing the time lag between the casting of concrete for footings/invert and the lining upper vault to a technologically possible minimum (best between 2 and 3 days, acceptable up to 7 days);
4. Using concrete mixture with low hydration heat;
5. Using concrete mixture with slow gain of strength in the initial period after casting the concrete;
6. Stripping the lining block when the concrete strength is low (1.5 MPa to maximum 3 MPa), with the stripping time of ca 12 hours;
7. Curing of concrete after stripping with focus on restricting drying and moderating the thermal shock (temperature conditioned travelling scaffolding);
8. The use of tunnel form travellers with good thermal conductivity skin (steel);
9. Low initial temperature of concrete mixture ranging from 13 °C to 18 °C, under controlled conditions max 25 °C can be acceptable;
10. Recommended length of a concrete casting block up to 12.5 m.

5.1. Permissible deviations from the theoretical thickness of lining
An unreinforced concrete lining is usually used in tunnel sections located in ground mass allowing excavation with longer advance rounds or the application of a primary lining without support frames. As a result, technologically conditioned overbreaks and larger deviations from the designed excavation geometry occur. The overbreaks within allowable tolerances are backfilled with cast-in-place concrete of the final lining. When unreinforced concrete is used, it is necessary to avoid too rapid changing of the thickness and creating toothing in the primary and final linings, which could introduce undesirable components of the tangential stress into the lining. When intermediate waterproofing is used, the conditions for its installation mostly meet also the requirements for the smoothness of the inner surface of the primary lining. Another limiting criterion securing fluent changing of the final lining thickness is the permissible deviation from the design thickness. It is, for example, according to the Austrian directive on the final lining, 100% of the theoretical thickness. With respect to the fact that the theoretical thickness of an unreinforced concrete lining usually ranges from 200mm to 300mm, the maximum real thickness of the final lining is up to 600mm. All irregularities failing to meet the two criteria are filled with shotcrete prior to the installation of the waterproofing membrane and casting of the final lining concrete. This way it is guaranteed that the real thickness of the final lining will not vary sharply and the variable loading by hydration heat in the concrete casting phase and shortly after stripping will not be a cause of excessive formation of cracks.

5.2. Measures on formwork
From the point of view of operation safety it is important to maintain integrity of the structure in the area of joints between concrete casting blocks. They are carried out either as butt construction joints or as expansion joints containing an elastic strip. An important role is played also in this case by the flatness of the surface of the concrete casting block front end, which should be ideally smooth. In general, all construction joints between the blocks must be perfectly cleaned up. The creation of a crack having the shape of a flat parabola in the vault crown (see Figure 4) is a frequent defect.

Figure 4. Crescent crack at the vault crown (photo courtesy of Libor Mařík).
It is caused by rough handling of the tunnel form traveller, where a part of the skin leans against the freshly stripped block cast in the previous step. In combination with the unfilled top of the vault, this procedure leads to damaging the top of the vault. A measure for preventing this phenomenon is careful handling of the tunnel form traveller and installation of a soft strip on the contact steel sheet at the end of the form traveller to reduce the local load acting on the traveller.

For achieving the required appearance of the lining surface it is necessary to pay attention to preparation of the formwork surface. The formwork structure must be designed to be sufficiently stiff and watertight. All external vibrators installed on the formwork must be fixed in a way ensuring that the vibration is transmitted first of all to the concrete casting area. It is desirable that the quality of processing all joints in the formwork skin is high. The most suitable surface material for the formwork skin is steel. Prior to the casting of concrete, the formwork must be cleaned up and treated with a suitable separation spray, which ensures that the external surface of concrete does not adhere to the form and smooth stripping is possible. A separation spray must be applied uniformly in thin layers on the whole surface and must be chosen with respect to the necessity of preventing physical or chemical damage to the concrete surface. An important role is played by the compatibility of the separation spray with subsequently applied curing sprays or coloured and protective coats applied to the already finished secondary lining.

5.3. Measures regarding transport of concrete mixture and casting concrete
The overall quality of the lining is influenced by the production, transport and placement of concrete behind formwork. If possible, the temperature of fresh concrete should range from 13 °C to 18°C. Fresh concrete for casting the upper vault with the temperature lower than +10 °C and higher than +25 °C is not considered to be suitable for unreinforced concrete linings. It is therefore necessary to respond flexibly to seasonal fluctuations of temperatures and humidity conditions. Protection against external climatic effects must be ensured during the transport of a fresh concrete mixture. In addition, it is necessary to choose suitable concrete workability time taking into consideration the distance of the batching plant from the construction site and to place concrete on site in time. A rule generally applicable to pouring concrete mixture behind formwork is that the maximum concrete casting rate should be 2 m/h and the horizontal spacing of concrete casting gates should not be greater than 3 m. It is necessary to take care of continual supply of concrete mixture to the construction site so that undesired construction joints are not formed.

5.4. Measures regarding technological procedure and stripping
The formation of both vertical and horizontal cracks can be limited by a suitable technological procedure of casting the concrete. Vertical shrinkage cracks running from the foundation approximately up to the centre of the upper vault can be best limited by a short time lag between casting of the concrete footings and the upper vault. This can be achieved by a suitably selected procedure of the work in the streamlined system of the construction of the final lining. A general recommendation is reducing the time lag between casting the concrete footings and casting the tunnel vault so that it does not exceed 48 hours. This way, an approximately identical shrinkage is achieved in both parts of the structure. The horizontal cracks which mostly appear on a part or the whole length of the concrete block shortly after stripping are not caused by ground pressure. The final lining concrete is attached to the primary lining usually under the condition of stabilisation of deformations and when a predefined very low rate of the deformation increase is achieved. The most important cause of the origination of the horizontal cracks is delayed stripping, when the concrete strength is already too high. According to the Austrian directive [2] it is recommended that unreinforced concrete tunnel linings are stripped when the concrete compression strength reaches 1.5 to 3MPa as a maximum, during ca 12 hours after casting the concrete. Strength values at stripping higher than 3MPa are indicated in the directive as a case with increased risk of the formation of cracks. It is guaranteed by stripping the structure in the moment when the compressive strength is still low that the “young”
concrete of the block being stripped will induce sufficiently high compressive stresses in the lining through its own weight, which will contribute to timely closing of originating cracks.

5.5. Measures regarding curing after stripping

It is necessary to duly cure each concrete structure after stripping and secure the required climatic conditions during the concrete casting work with respect to the resultant quality of the surface. The airflow velocity in the tunnel should be reduced to 1 m/s as a maximum and the humidity of air should not drop under 90%. The formation of cracks can be significantly limited by eliminating the thermal shock after stripping the formwork.

Temperature conditioned travelling scaffolds are successfully used apart from the standard measures, such as closing the portals, reducing airflow velocity or applying spray against drying. It is another traveller in the overall final lining production flow. It is deployed just behind the travelling form. Its length ranges from two up to three lengths of the concrete casting block, which means that in a model example with casting 5 blocks in 7 days ca 34 hours are allotted to one cycle and each block is protected after stripping for 68 up to 102 hours. During this time a significant part of hydration heat fades away, thus the risk of the cracks formation due to rapid cooling is minimised.

The structure of the temperature conditioned travelling scaffold differs depending on the possibility of curing. The simplest scaffolds consist only of a steel structure covered with a thermally insulating membrane, which maintains natural temperature and humidity in the gap between the just stripped concrete and the scaffold structure.

The concrete curing travelling scaffold standing in front of the Považský Chlmec motorway tunnel on the D3 motorway near Žilina, Slovakia (see Figure 5) is presented as an example. It is a lightweight steel structure covered with a thermally insulating membrane. Inflatable rims serving to seal the space between the inner surface of the lining and the cover of the traveller are presented in Figure 6. The length of the curing scaffold is 25 m, which corresponds to the length of two concrete casting blocks.

Figure 5. Steel structure of the temperature conditioned travelling scaffold (photo courtesy of Vladimír Prajzler).

Figure 6. Inflatable rims and thermally insulating cover of the temperature conditioned travelling scaffold (photo courtesy of Vladimír Prajzler).

More complex temperature conditioned travelling scaffolds have water and air brought to the system and create a cold mist by means of spraying jets. In this way sufficient moisture of the concrete surface is secured. The most complex temperature conditioned travelling scaffolds are fully controlled and they allow regulating the humidity and temperature in the gap between the temperature conditioned travelling scaffold and the concrete surface or, as the case may be, to actively cure the concrete structure with steam. The temperature conditioned travelling scaffold structure is in the case of these scaffold types in addition insulated, for example by a polystyrene layer. All parameters of curing can be set and regulated as needed, depending on the changing external conditions.
Nevertheless, in any case the maximum temperature at the surface of the curing concrete structure should not exceed 45°C.

6. Conclusion
Unreinforced concrete has its irreplaceable position as a material for final linings of conventionally driven tunnels. In suitable geotechnical conditions it represents a way to reduce investment costs with the required quality maintained. In addition, minimisation of the risk of damaging the intermediate waterproofing layer, which the placing of reinforcement undoubtedly is, and the complete exclusion of problems with concrete carbonation, can be considered as a bonus. Whilst the formation of cracks and surface irregularities plays no important role in terms of maintenance and the static function, it is necessary to pay special attention to filling of the top of the vault and possibly to creation of cracks in the vicinity of construction or expansion joints between concrete casting blocks, which could pose a threat to the operation safety.

As in the beginnings of using the NATM when it was necessary to start thinking „outside the box“ and to cope with the idea of the self-supporting capacity of rock mass and begin to perceive ground as a building material, it is necessary to respect properties of unreinforced concrete, first of all, the low tensile strength and the formation of cracks associated with it. A different approach in thinking must be applied in all stages, from the lining design through the construction up to the takeover by the client. The designer must take into account the non-linear behaviour of the structure as a whole and assess the existence of cracks in terms of the lining function; the contractor must adapt the concrete mixture design, the technological procedure for building and curing; the client must define realistically possible quality requirements. Only through synergy of all of the above-mentioned components an economic design of the structure can be reached and the NATM principle can be confirmed as an observational method capable of responding to the actually encountered conditions not only in the field of securing the excavation stability, but also in the solution of final lining.

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