

CAST-IN-PLACE LINING OF TUNNELS EXCAVATED BY TBM

P. Vítek

HOCHTIEF CZ, Prague, Czech Republic

Š. Pešková

CTU, Prague, Czech Republic

ABSTRACT:

Tunnel excavation using TBM includes segmental lining. Lining production and assembly systems are developed and implemented. In addition to the advantages, segmented lining also has certain disadvantages, which are mainly a large number of joints in the lining and production requiring large areas and traffic demands. To simplify the production of lining, a cast-in-place lining system has been designed and verified, which eliminates the main disadvantages.

The lining is made of concrete reinforced with dispersed steel reinforcement, which is transported to the tunnel face in a mixer mounted on the MSV (multi-service vehicle) chassis. The section of the machine where the lining is installed is equipped with a steel form. The space between the form and the rock will be filled with concrete. Subsequently, during the excavation of the next section, the pressure rollers expose the concrete mixture to considerable pressure, which compacts it. Subsequently, the concrete solidifies and hardens, still with the support of the form. After it has achieved sufficient strength for the lining to resist rock pressure, the form is moved towards the face to be used for concreting the next ring. The process is repeated in cycles in this way.

The research was devoted exclusively to the material and technology of the production of the lining itself, not to the design of machine components. The use of the technology is expected mainly in cohesive rocks. The crucial processes were experimentally verified on samples of sufficient size.

1. USING TECHNOLOGY IN THE PAST

The cast-in-place lining technology was used, among others, in Prague during the construction of the I.A. metro line in the Malostranská – Můstek section. The section also includes an underpass on the Vltava River. The Soviet TŠČB tunnelling machine was used for the excavation, which with its parameters and performance did not even come close to the current TBM. Despite a few problems, including a high failure rate, the resulting tunnel lining made of plain cast-in-place concrete shows reliability and low seepage. Let us remind you that the construction industry in the 1970s was generally not very focused on diligence and reliability, as it is now, and yet we can evaluate the time-tested result positively.

2. SEGMENT LINING

Let us briefly recall the typical production and installation of segmented lining. Segments are usually produced in a factory that is equipped with a mixing centre for concrete production. The concrete is transported to forms, where it is deposited and then compacted. This is followed by solidification and hardening, which is sometimes accelerated by warming. When the concrete reaches the required handling strength, the segment is removed from the form, properly treated and then transported to the depot. The production usually does not achieve the capacity corresponding to the need for tunnelling machines, so it is started in advance of excavation. This is associated with the need for a large area for the storage of manufactured segments. The segments are equipped with a gasket around the entire perimeter, which is either glued to the finished segment or inserted into the form before concreting. The usual length of the ring is 1.5 to 2 m, with the ring usually composed of 6 to 8 segments, including the keystone. The parameters depend mainly on the diameter of the tunnel.

Depending on the distance of the segment production plant from the access to the tunnel, the appropriate mode of transport is selected. At the construction site at the tunnel portal, the segments are transferred to a special vehicle (MSV), which is adapted for driving in the tunnel on the assembled lining. At the end of the machine hinge (TBM), the segments are put onto the feeder and transported to the erector, which puts the segments in the prescribed positions. The length of the ring is slightly variable around the circumference. An appropriate sequence of successive rotations of the rings ensures the approximation of directional and elevation arcs. The pressure of the TBM machine during excavation is secured against the assembled lining.

The axial force from the pressure of the machine rollers is a significant load aspect for the segments, which determines the material and dimension of the segment. The action of this load is completely different from the effect of rock pressure. Each segment is subjected to machine pressure only once, during excavation, and the additional loads applied over the lifetime are different. On some construction sites, e.g. during the excavation of the V.A1. metro (but also, elsewhere abroad), it was in this condition that the segments were damaged by cracks in full thickness, which disrupted the watertightness of the lining.

Another problem is the sealing of the joints between the segments. Tightness is conditioned by the precise assembly of the ring. If the individual segments do not adhere to each other or are displaced from each other from the plane, the contact area of the seal is reduced, and there is a risk of water seepage through the joints. This problem manifested itself to a greater extent in the railway tunnel near Ejpvovice. Normally, segments are made of reinforced concrete or fibre-reinforced concrete. Fiber-reinforced concrete is a more ductile material. If we compare fibre-reinforced concrete and reinforced concrete of the same strength loaded with tension, the dispersed reinforcement of fibre-reinforced concrete prevents the localization of cracks, which is why a larger number of small cracks will form. This is a more favourable condition for the watertightness of the lining.

The space between the lining and the felling is filled with grout. The grouting compounds are different. In the Czech Republic, liquid grouting has been used so far, where the main components are water (approx. 700 l/m³), cement, bentonite and gelling additive. The grouting quickly turns into a gel after filling the space and is resistant to groundwater flooding. However, the resulting mass has very little strength and dries up and loses volume in a dry environment.

3. CAST-IN-PLACE LINING

The basic idea of a lining is not new, as mentioned in the introduction. The research team set itself the goal of developing a new technology that will meet the performance parameters of conventional TBM. The material for the lining is assumed to be concrete with dispersed steel reinforcement.

3.1 PRODUCTION AND TRANSPORT OF CONCRETE

Concrete production is assumed in a mixing centre located directly on the construction site near the portal. High-quality mixed concrete is a basic prerequisite for the reliability of the lining, so it is planned to dose the fibres (dispersed reinforcement) directly into the mixer, in the form of fibres separated from each other by the distributor. The process of adding fibres takes time, which increases the actual mixing time. Indirect dosing of fibres together with aggregate is not recommended, as there is a great risk of the formation of clusters of fibres, the so-called hedgehogs. The dimensions of the mixer must therefore correspond to the need for concrete to be able to supply the TBM sufficiently. Regarding reliability, having two independent mixing centres within one concrete plant is assumed.

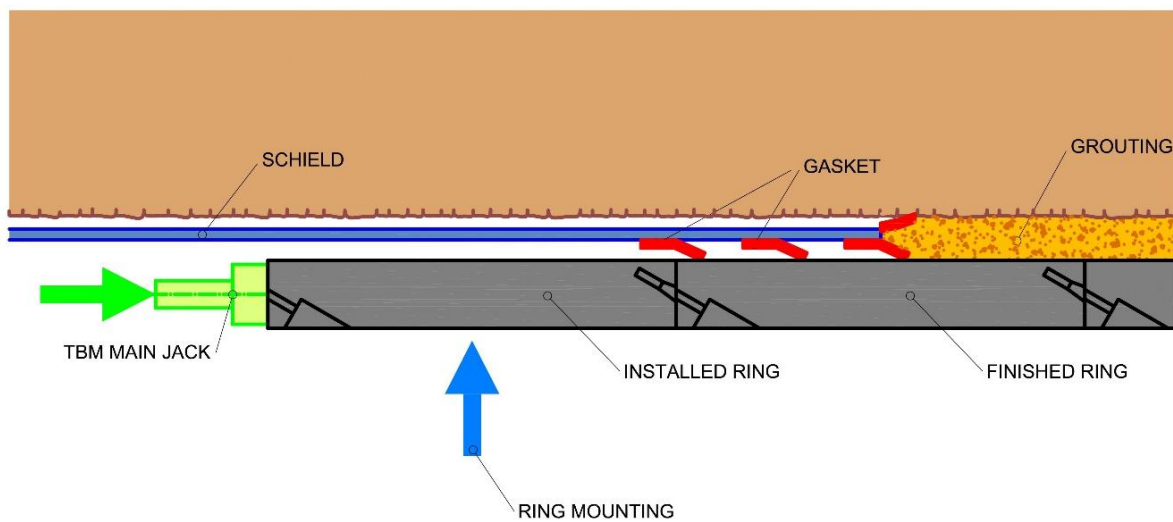
The concrete mixture is gradually filled into a mixer mounted on the MSV tunnel vehicle (which is normally used to load segments). The speed of the vehicle in the tunnel is expected to be 15 km/h, which means that the net time for transport through the 5 km long tunnel is 20 minutes. If we add to this the time of mixing the mixture and the time needed to fill the space, we get the necessary processing time over 1-2 hours. This is a feasible parameter.

In connection with the construction of lining, apart from concrete, it is no longer necessary to transport any material to the machine. Unused concrete left in the mixer is separated, whereby aggregate and fibres can be reused.

3.2 DIFFERENCES IN TECHNOLOGY COMPARED TO STANDARD TBM

While in the standard TBM the segmental lining is mounted directly into the shield envelope, in the cast-in-place lining a telescope is inserted into the back of the envelope (Fig. 1). It is a steel cylinder inserted into an envelope and controlled by separate hydraulics. During excavation, it remains in place and thus ensures the stope. If there is pressurized groundwater in the environment, a waterproofing membrane is stretched over the inner wall of the telescope. The primary purpose of the membrane is to prevent the concrete mixture from being flooded by groundwater. Of course, the membrane will remain around the lining, and it can be counted on as a secondary cause of the tightness of the lining or resistance to the influence of stray currents. However, the lining is designed to be waterproof, as it cannot be guaranteed that the membrane will not be damaged.

SEGMENTAL LINING



CAST IN SITU LINING

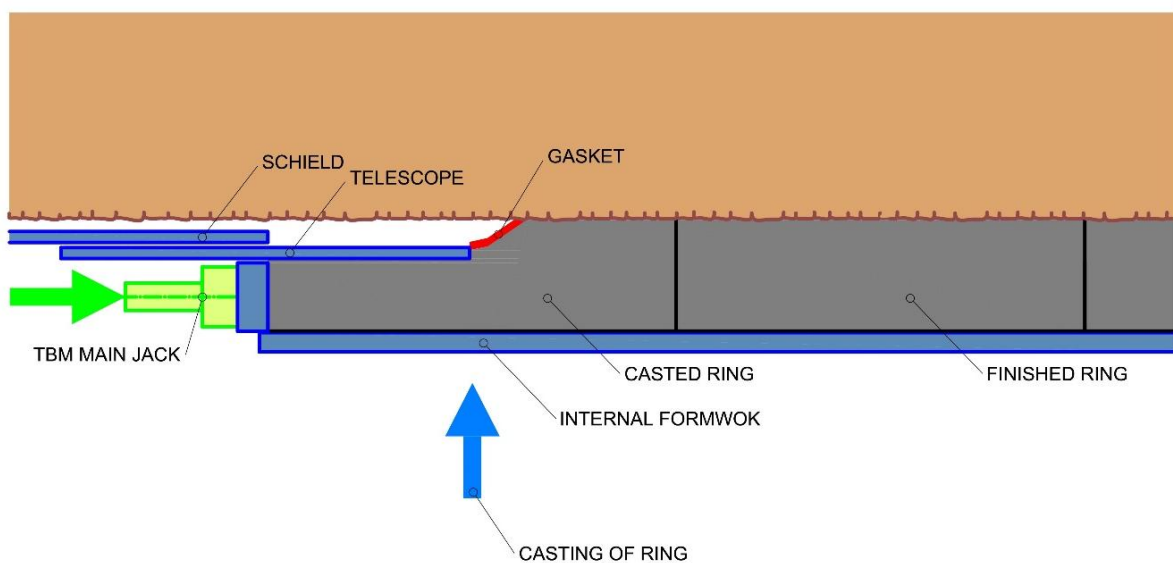


Figure 1: Comparison of segmental and cast-in-place lining

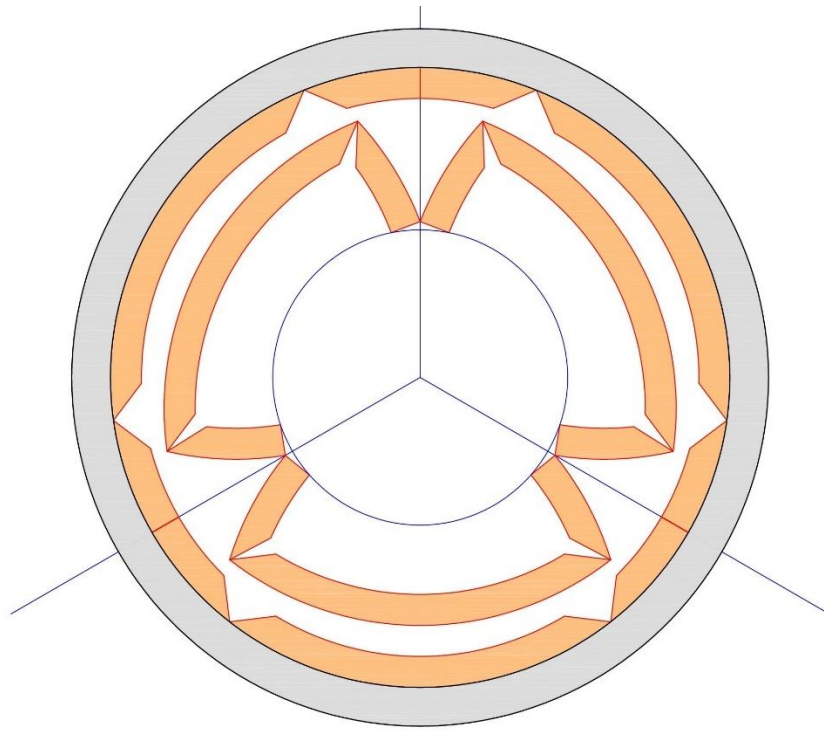


Figure 2: Unfolded and collapsed form for a cast-in-place ring lining

The boring section of the TBM is connected to the back-up by a so-called bridge. In the case of cast-in-place lining technology, the bridge is used for the transport of formwork of lining (Fig. 2). A circular form is composed of sections that can be collapsed into a smaller diameter that is stretched through the unfolded formwork. Individual forms have a cutting length of the TBM, i.e. 1.5 to 2 m as standard. A manipulator moves on the bridge, which is similar to an erector. The manipulator packs the last part of the form and moves it towards the face into the area where the lining is built, i.e. at the level of the telescope. There, the form of the supports is unfolded. The form of the cylinder shape is slightly conical, i.e. the bases of the cylinder described are not parallel, similar to the segmental ring. The rotation of the form ensures the approximation of directional and elevation arcs; the rotation is performed by the manipulator as the last phase of the form placement. The form is connected to the previous section.

The push rollers of the machine are finished with a cover that blocks the space between the form and the telescope. The cover is modified so that an insulating sheet can be inserted into it, which prevents any water penetration through the working joint between the individual rings.

In addition to the above, the machine is not equipped with elements for handling segments and the entire technology of grouting behind the lining is also eliminated.

3.3 CONCRETING THE RING

Concrete is pumped into the designated space defined on the outside by a telescope, on the inside by a steel form, at the front by a front and at the back by a connecting ring in such a way that it completely fills the space in question. Next, the pressure corresponding to the pressure of groundwater is derived in the mixture. In our conditions, a maximum of 50 m of water column is assumed, i.e. 5 bars = 500 kPa. Then, while maintaining pressure, the telescope is gradually retracted. The replenished mixture therefore fills the space outside the telescope. During this activity, the sealing membrane is stretched and pushed to the stope or filled with overbreak. The movement of the telescope is so slow that the mixture pump can supply the mixture, and the required pressure does not drop. This is done until the entire space is filled.

The thickness of the lining between the form and the telescope is guaranteed to be minimal. If the loose rock rests against the telescope, it is not expected to penetrate the first layer. The thickness of the lining will be increased in most ranges by the distance between the face of the telescope and the stope. Occasionally, the thickness of the lining may increase by the size of the overbreak.

After inserting the telescope and filling the space, the space is completely filled with high-quality concrete lining material. This is followed by the start of driving. The face is loaded with the normal force from the push rollers of the machine. This force is considerable and usually corresponds to a face pressure of 5 MPa on concrete. At this pressure, the concrete is pushed into the rock, and the mixture is compacted very effectively. The mixture must be pumpable, so a certain amount of excess water is assumed. During compression, water is forced out of the mixture. The compression itself strengthens the concrete structure and the apparent strength of the concrete in the order of tenths of MPa (e.g. 0.3 MPa).

The newly created ring is loaded by the pressure of the machine in the concrete mix phase. This eliminates the risk of cracks due to machine pressure. The mixture will begin to harden and is expected to reach strength for possible stripping in 16 hours.

Alternatively, the possibility of using the waste heat of the machine to heat the concrete of the ring is envisaged. As standard, TBMs are equipped with water cooling, where cold water is supplied through a tunnel used to cool machine technologies, and hot water is taken away from the machine. This water can be introduced into heat exchangers located on the forms, thus transferring part of the heat to the concrete mixture to speed up the solidification process.

3.4 DEVELOPMENT IN TIME

Let us assume a tunnel diameter of 6 m, a minimum lining thickness of 30 cm, and a ring length of 1.5 m. Work cycle of tunnelling – tunnelling itself 30 min, moving the form + installation of the membrane 30 min. Pumping the mixture also 30 minutes. The whole cycle is therefore 1.5 hours.

With a real thickness of lining of 40 cm and overbreak, the volume of concrete will be about 12 m³. The production of concrete requires 6 cycles in a 2 m³ mixer. Prolonged mixing, including fibre dosing, can be done in 10 minutes. The production of concrete for one ring requires about 1 hour, which is less than the expected excavation cycle of 1.5 hours. So, it can be done with one mixing centre, but two are still needed for reasons of reliability and possible repairs.

Tunnelling at a speed of 1.5 m in 1.5 hours reaches a performance of 24 m/day. That means, in the necessary time of concrete hardening of 16 hours, 16 m of tunnel are dug. Therefore, 16 m of forms (11 forms) are sufficient. With regard to deviations, we assume 13 forms and a formwork length of 19.5 m. This corresponds to a normal bridge length of around 20 m for TBMs. So, the machine does not need to be fundamentally modified in terms of this parameter.

4. EXPERIMENTAL ACTIVITIES

The technology is based on assumptions that were appropriate to being verified experimentally. The design of the experiment and the size of the sample were based on the nature of the tested variables. Although more tests have been carried out, in this paper we focus on the most important ones.

4.1 STRENGTH INCREASE TEST

It is assumed that concrete of the same strength class as is commonly used to produce segments – C 50/60 – will be used. The strength at the time when it is possible to dismantle the form was set at 15 MPa. Such lining should resist rock pressures and the effects of pressurized water. It was assumed that the strength will be reached in 16 hours. In the table of strength increases, the specified requirement is met.

Table 1: Increase in concrete strength over time

Hours	Days	Compressive strength (MPa)
16		17.2
18		17.3
24	1	24.1
	2	35.2
	3	44.8
	7	55.7

If there is a requirement for higher lining strength, it is possible, for example, to increase the number of forms and thus extend the hardening time of concrete in the form-supported state. Hardening can also be accelerated by warming the concrete with TBM waste heat.

4.2 SEPARATION MEMBRANE RESISTANCE TEST

The primary goal of the separation membrane is to prevent the concrete from being flooded by groundwater. Particularly problematic is the situation where groundwater flows through cracks in the rock and can significantly degrade concrete. Secondly, it ensures the cleanliness of the space for casting the concrete and in the long term contributes to the watertightness of the lining and to the elimination of the influence of stray currents.

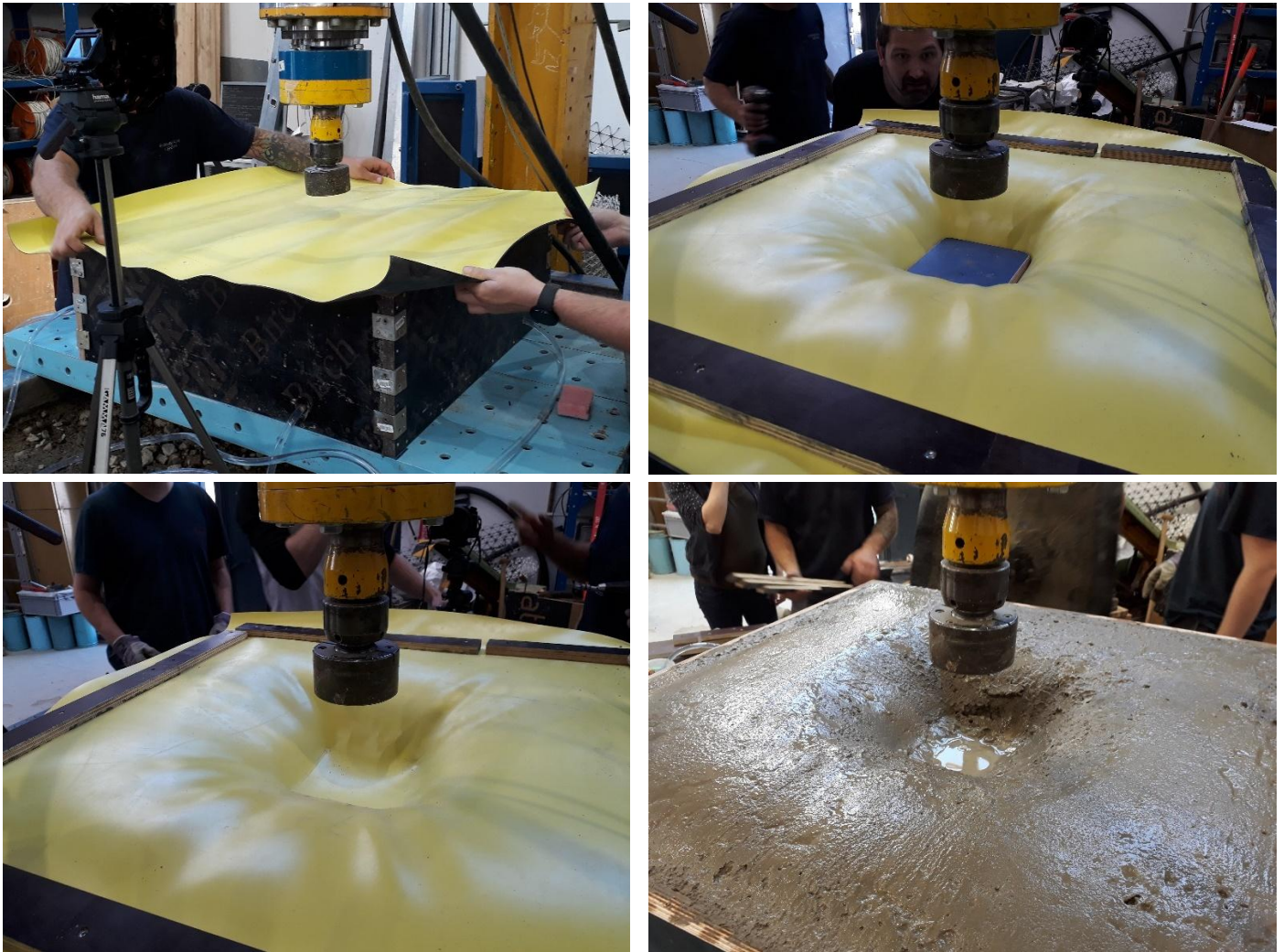


Figure 3: Separation Membrane Resistance Test Procedure

When identifying the risks, there was a concern about what would happen in the event of the release of a sharp-edged rock fragment that would penetrate the fresh concrete of the lining. During tunnelling, the area is protected by a shield envelope and a telescope. Any fragment can penetrate the lining when the telescope is retracted, i.e. when the space is filled with concrete. Therefore, there will be no free fall, but penetration into concrete laid under a pressure of about 500 kPa. The membrane was tested to see under what circumstances it would break.

The experiment consisted of a block of fresh concrete in formwork without compaction, covered with membrane, into which a square with a side of 10 cm made of plywood was pressed (Fig. 3). The pushing of the plate was measured under a load gradually increasing to 10 kN and at the same time the condition of the membrane was visually monitored. On a 25 cm high slab shaped sample, 125 mm was gradually pushed in, i.e. to half the thickness of the element. The separation membrane was not damaged. Let us

note that this is primarily a membrane test; a force of 10 kN (1 t) on an area of 0.01 m² corresponds to a pressure of 1 MPa, which is a very unfavourable value corresponding to an overburden of 40 m height, which should not occur in reality, which is why even a push of 125 mm is significantly above the actual values.

4.3 PRESSURE COMPACTION TEST OF CONCRETE MIXTURE

It is obvious that the pressure created on the concrete compacts the mixture and also pushes out excess water. Enough water is required for the processability and pumpability of the mixture. Separation of the excess water in the cast concrete is therefore not a disadvantage. At the same time, it was interesting to verify the effect of the machine's pressure on concrete in other previously made rings.

Here it is worth mentioning that opinions on repeated compaction vary greatly – from increasing the resulting strength to decreasing the strength. This is probably due to the test conditions and the method of compaction. Therefore, it was appropriate to verify how the secondary compression would manifest itself on the previous ring.



Figure 4: Arrangement of the Concrete Mixture Compression Test

The experiment was arranged in such a way that the concrete mixture was placed in a cylindrical vessel and was subjected to a compressive force acting on the mixture to create a pressure of 5 MPa. After an hour, a second container was placed on the container with the compressed mixture, filled with the mixture and loaded with the same pressure. Uniform pressure on the mixture was implemented through a concrete cylinder to create a uniform load simulating the face of the ring form (Fig. 4).

While the 28-day strength of the reference unloaded samples showed an average value of 71 MPa, samples loaded in one cycle achieved an average strength of 88 MPa and samples loaded with two cycles showed an average strength of 83 MPa. It follows that compression compaction compared to normal vibration on the reference samples leads to a significant increase in strength, while the second load cycle slightly reduced the strength, but remains significantly higher than that on the reference sample.

During the loading of the samples, water was forced out, especially during the first loading cycle. Each sample consists of a cylinder with a diameter of 150 mm and a height of 300 mm. The amount of water released is about 250 ml/sample, which is about 5% of the volume.

4.4 LINING RING TEST

The most important experiment was the verification of the entire process of lining production on a large sample on a scale of 1:3. Since it was not feasible to carry out the experiment in the conditions of the lining, a massive concrete outer form was created to simulate a rock massif. The internal steel form was also replaced by a massive concrete element for economic reasons. Space for lining was created between the forms. On one side, the two forms were firmly connected by a concrete slab simulating the previous ring, on the other side, a sliding face was installed, on which a total of 10 presses were used.

The test was carried out in accordance with a realistic assumption. C 50/60 concrete with dispersed steel reinforcement made of 0.8 mm profile fibres and a length of 60 mm was brought to the site. Transport from the concrete plant took about an hour, which corresponds to the transport time to the tunnel in real life. The concrete was pumped into the space between the forms by a pump with a pressure of up to 500 kPa. Next, the concrete was loaded over the front. The forces in the presses and the push of the front were measured. The presses were connected to two circuits, so that unsymmetrical load assemblies were also created, simulating the need for uneven pressure to change the motion vector of the TBM. The conditions of the experiment were set to correspond as closely as possible to reality.

The experiment proved the expected process of water displacement, already at the time of pressurization of the mixture by the pump to 500 kPa. This was followed by a gradually increasing full load of all presses around the perimeter up to the required pressure value of 4.5 MPa, which simulates the pressure of the TBM on the lining. This corresponded to pushing the front by 23 mm at the bottom of the ring and 30 mm at the top.

Subsequently, the load was reduced, and the load diagram was modified so that only a third of the load was about 1.5 MPa in the upper cylinders and the full pressure was 4.5 MPa in the lower cylinders. This corresponded to pushing the front about 25 mm around the entire circumference.

After the load reduction, the deformations stabilized at 18 mm (top) to 22 mm (bottom).

The test was carried out twice with very similar results. In the first sample, the form cover was uninstalled after about 1 hour from the start of loading. The concrete was already very solid, and it was very difficult to remove it from the space. It was necessary to use a jackhammer and wash the remains with pressurized water. This proves that there is no risk of disturbing the concrete of the ring when the front is removed.



Figure 5: Inserting a face into a prepared rock and form model



Figure 6: Assembled and instrumented sample

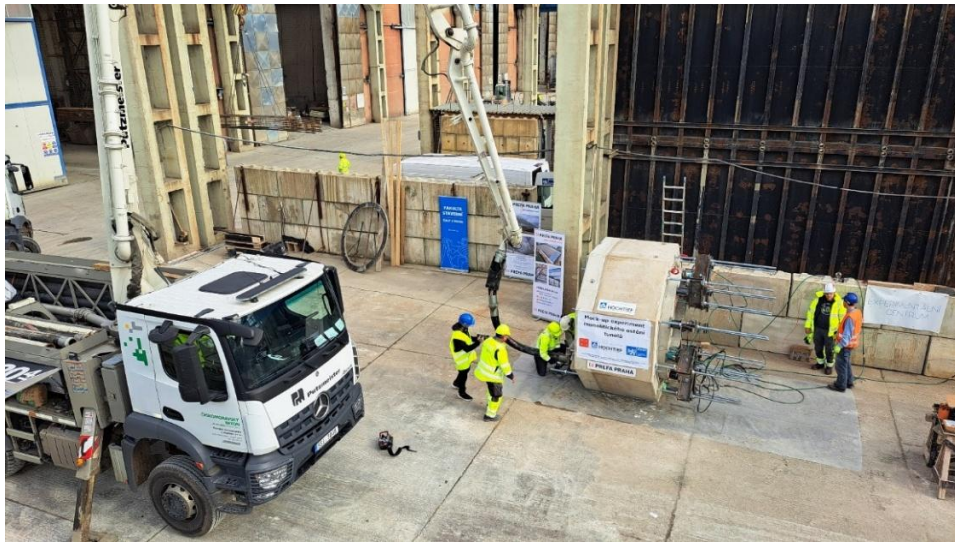


Figure 7: Pumping concrete into the ring space at a pressure of up to 500 kPa

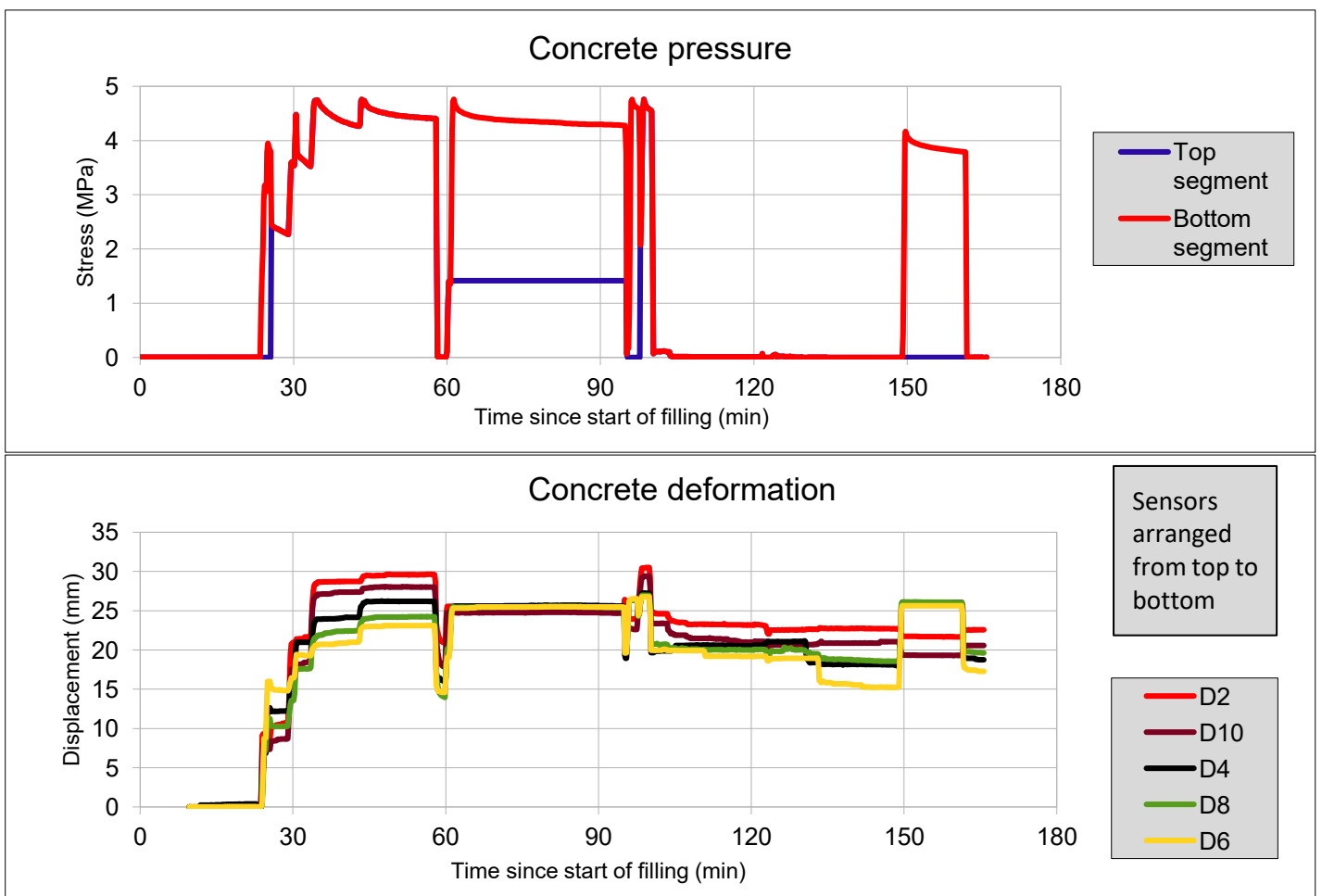


Figure 8: Development of forehead pushing over time. Time 25-28 min gradual increase to full pressure 4.5MPa, 60-95 min lower half pressure 4.5MPa, upper half pressure 1.5 MPa, 102-150 min complete relief.

5. CONCLUSION

As part of the research project, the technology for the production of cast-in-place lining was successfully verified. This technology is not universal; it is not suitable especially for unstable environments where bentonite TBMs are used. On the contrary, it is suitable for cohesive soils and soft and hard rocks.

The main advantages of the cast-in-place method include:

- Elimination of segment production, warehouse space and segment transport.
- Absence of the entire grouting technology behind the back of the lining.
- Limitation of the number of joints in the lining, creation of a continuous uniform ring, with only transverse working joints between the rings, which can be sealed with common elements.
- Reduction of lining thickness in the sense that the space for grouting behind the segments becomes part of the lining. It is assumed that the total thickness of the cast-in-place lining will be greater than the thickness of the segment but less than the thickness of the segments along with grouting.
- The risk of crack damage to the lining by the pressure of the machine's drive presses is eliminated. Instead of finished segments, the concrete mixture is stressed, and the compression force is used for the compaction process.
- Any overbreaks are properly filled with high-quality material injected under high pressure.

These advantages lead to an increase in the final quality of the work, and also to better cost-effectiveness. Last but not least, they also have a beneficial effect on the environment.

6. RESEARCH TEAM

Dr. Ing. Petr Víték – principal researcher

Ing. Šárka Pešková, PhD. – co-researcher

Ing. Libor Mařík – member of the research team

Prof. Ing. Vít Šmilauer, Ph.D. – member of the research team

Ing. Pavel Růžička Ph.D. – member of the research team

doc. Ing. Jan Valentin Ph.D. – member of the research team

Ing. Marcel Jogl, Ph.D. – member of the research team

Ing. Martin Válek Ph.D. – member of the research team

Ing. Michal Mára Ph.D. – member of the research team

Ing. Rostislav Šulc Ph.D. – member of the research team

prof. Ing. Bc. Radoslav Sovják Ph.D., LL.M. – member of the research team

Prof. Ing. Miroslav Petrtýl, DrSc. – member of the research team

prof. Ing. Petr Konvalinka CSc., FEng. – member of the research team

Ing. Robert Coufal, Ph.D. – member of the research team

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Dr. Ing. Petr Víték

HOCHTIEF CZ, Plzeňská 16/3217, 150 00 Prague 5, Czech Republic

Petr.Vitek@hochtief.cz

Ing. Šárka Pešková, Ph.D.

CTU, Faculty of Civil Engineering, Thákurova 7/2077, 166 29 Prague 6, Czech Republic

Sarka.Peskova@fsv.cvut.cz