TECHNICAL OPTIONS FOR FIREPROOF TUNNEL LININGS – LIMITS, ADVANTAGES AND DISADVANTAGES OF THE VARIOUS SOLUTIONS

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Abstract - Comprehensive research work is running to improve the knowledge about the application of concrete for tunnel lining, its basic performance, its long term behaviour and in particular also its fire proofness for example when used for the lining of road tunnels. Some of these items are selected and explained to more details below. So, the latest state of the art of concrete and its application in Europe's tunnels is described, and some statistics concerning the European and world-wide development of traffic and tunnelling are given. Complementary thoughts about fireproof claddings in traffic tunnels round off the range of today's possibilities of a hardened fire safety concept.

Keywords - tunnel, tunnel lining, fireproof claddings, fire resistant concrete

IMPORTANCE AND WORLD-WIDE DEVELOPMENT OF TRAFFIC AND TUNNELLING

Tunnelling and transport tunnel construction in particular has gained increasing importance both in Europe and internationally during the past 10 to 15 years. This development seems bound to continue over the years ahead. The reason is provided by the results of a recently completed study by the Viennese Academy of Sciences. It carried out an extensive survey on behalf of the Austrian Automobile and Touring Club on how **tourist and goods traffic** has developed in Europe. It reveals that private motoring in Europe will rise by around 20 % by the year 2010 compared with 1997, and by as much as about 40 % by 2030 [1].

Forecasts by more than 100 internationally recognised scientists, who estimate that good traffic in Europe will rise by about 60 % during the next 30 years, follow a similar pattern. This means that Europe's highways will come ever closer to reaching their capacity in the near future thus introducing more stop than go for traffic than ever (Fig. 1).

Fig.1: Traffic jam on a highway in Germany

Other surveys are no less pessimistic. The OECD (Organisation for Economic Co-operation and Development) for instance, reckons that by the year 2020, there will be a roughly 50 % rise in the number of vehicles on Europe's roads compared with today.

There is a further aspect that gives rise to an increasing need for underground transportation facilities. It derives from the **growth in the world's population and ever increasing urbanisation**. In 1995, roughly 45 % of the world's population lived in cities. By 2015, this proportion will have risen to some 55 %. The following scenario is provided by considering the developing nations alone: In 1995, around 39 % of the population there lived in cities. However, by 2015, the figure will probably have grown to no less than 50 %. As far as the industrialised countries are concerned, as much as 75 % of the population lived in cities in 1995. This figure is due to rise to around 80 % by 2015. All in all, it can be assumed that on a world-wide scale at present, the urban population is growing by some 60 million inhabitants annually.

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Further predictions indicate that by the year 2015, around 10 % of the urban population will be living in so-called mega cities with more than 15 million inhabitants. 26 mega cities of this kind are anticipated, distributed all over the globe, with no less than 18 of them located in Asia (Fig. 2). The use of underground space will be required to a high degree to make sure that such mega cities and expansive urban regions in general are capable of functioning so that the quality of life is assured. This applies to transport tunnels as well as to supply and disposal facilities and the storage of goods.

Fig. 2: Shanghai, Metropole in China

In view of such developments, it is imperative that new logistics concepts, new ways to secure mobility and also new supplementary measures to improve the infrastructure are found. One solution is certainly to be found in exploiting the chances afforded by tunnelling pertaining to the overall securing of mobility, speeding up transportation processes and essentially for protecting the environment and countryside as well. As a consequence, the latest statistical data give rise to the **expectation of substantial tunnelling activities** on a world-wide scale over the next 10 to 15 years (Fig. 3). The following figures relate to transport tunnel construction for Europe alone:

• approx. 450 km in Germany [2]

• approx. 260 km in Austria

• approx. 300 km on the Iberian Peninsula (Spain and Portugal)

• approx. 150 km in France

• approx. 200 km in Italy and

• approx. 500 km in Scandinavia.

In summing up, the European tunnelling market can expect a total construction volume of around 2,100 km in the years to come. Immense efforts designed to improve the infrastructure are being planned in other parts of the world as well. Statistics relating to the Asian market indicate a volume of around 2,350 km for future transport tunnel projects. Roughly 650 km of transport tunnels is scheduled for construction in South America within the next 10 to 15 years and at least the same magnitude on the North American continent. Australia and northern and southern Africa are also planning tunnelling projects, but to a considerably less degree.

Fig. 3: Tunnelling in Nuremberg, Germany

The current and future **major tunnel projects** undoubtedly represent particular challenges. In this connection, the Gotthard Base Tunnel (Fig. 4), the Lötschberg Base Tunnel, the Brenner Base Tunnel and the tunnel between Lyon and Turin should be mentioned here, some of which are already being built or are very far advanced in terms of the design and decision-making process. Further projects of this size have already been envisaged in various regions of the world. These include passing under the Straits of Gibraltar between Morocco and Spain or under the Tartar Strait between Russia and the Russian peninsula of Sachalin with a further link to Japan or under the Bering Strait between Russia and Alaska (USA). All these projects represent driven lengths of between 30 and 60 km or even more. They call for special consideration relating to the driving technology, their subsequent operation and thus in turn, the safety concept.

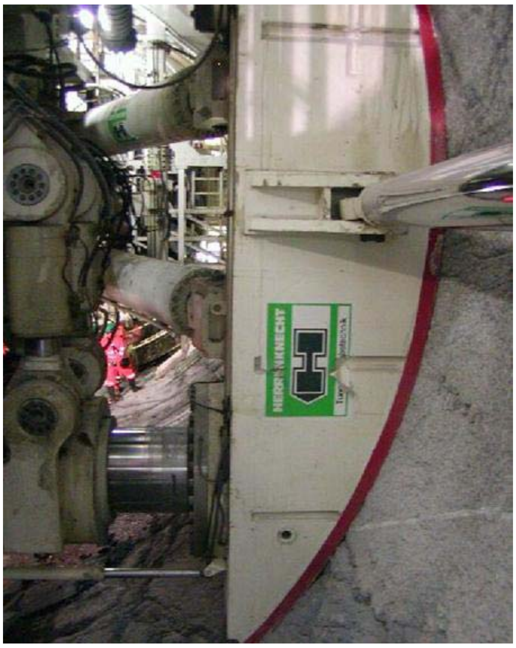

Fig. 4: Tunnel excavation for the Gotthard Base Tunnel, Switzerland, section Bodio-Faido, using a TBM

TO DATE FIREPROOF CLADDINGS

Apart from improving the technology of the vehicles (road, railway, metro) in general and of the heavy goods trucks in particular, a higher standard of structural fire protection is imperative. This does not simply apply to choosing the right construction materials, building sections designed to confine the fire or the creation of the shortest possible escape ways but also of course, to every measure that is able to sustain the bearing capacity. Thus it is essential to make sure that the tunnel structure does not fail or fail prematurely even when a major conflagration breaks out, e.g. when a lorry and its load completely go up in flames. This would have disastrous effects on escape and rescue; however, in many cases it would also affect the tunnel's environment, above all in inner urban, densely populated areas.

An important element of preventive structural fire protection is thus to be seen in all these measures, which exclude to the greatest possible degree any substantial negative effects on the bearing capacity especially that of the tunnel roof vault or the tunnel ceiling during and after a fire. There are various technical possibilities that can be applied here. The ZTV-ING, part 5, section 2, § 9.3.2 [3] for instance, propose the setting up of an additional reinforcement on the part of the structural element affected by the fire so that concrete splintering resulting from the heat is effectively restricted and to ensure that the main reinforcement is protected against being heated up in excess of 300° C. Temperatures above this limit value that affect the reinforcement lead to a permanent reduction in the bearing capacity, to lasting major deformations and ultimately to the structure collapsing.

Alternatively, fire protection lining on a mineral basis in the form of plates or casts is installed on the endangered structural parts [4 to 6]. However, such systems have the disadvantage that the bearing tunnel structure can no longer be scrutinised behind the fireproof plates and casts when inspections are undertaken and is practically inaccessible. Against this background, a perforated steel sheeting system was developed during the late 1990s, which is provided with an insulating layer former at both sides with a total thickness of 1.5 to 2 mm [7].

It goes without saying that it would be ideal to be able to apply a concrete for new structures that does not require any kind of fire protection measures. Such a solution would do away with the need for additional fire protection reinforcement as well as any kind of fireproof plates or casts. Both references [8 and 9] deal with such a system. This development is commented on and assessed in the following.

FIREPROOF CONCRETE AND ITS ADVANTAGES FOR THE TUNNEL CONSTRUCTION

The starting-point for developing a special, high-bearing capacity fireproof concrete can be attributed to plans for building an underwater tunnel, which was to be constructed using the shield driving method. The segments required for this project provide a single shell tunnel support and call for a concrete quality, whose strength is essentially higher than concrete of strength class C 55/67. Such high-strength concretes are far more prone to splintering in the event of a fire than concrete qualities C 20/25 or C 30/37 that are generally applied in civil engineering. Structural parts made of concretes in these last-mentioned quality classes are distinguished by a greater pore volume, more open structural surfaces and altogether by greater viscosity compared with higher-strength concrete qualities. Reinforced steel segments, however, call for the application of more effective concrete mixes for static reasons as well as with respect to the manufacture of the segments. Of late, the tendency has been to subsequently provide the structure with a fire protection lining on account of the greater risk of splintering possessed by such concretes. This applies particularly to single shell reinforced concrete segmental supports for transport tunnels. Examples are provided here by the 4th Elbe Tunnel Tube roadway and the Weser Tunnel to the north of Bremen as well as – as appears likely – the rail tunnels on the Dutch Betuwe Line, which is currently being built.

Fig. 5: Crossing the river Thames by the high speed railway line between the Euro Tunnel and London applying a segmental lining made of fireproof concrete

The application of a structural concrete that is not prone to splintering in tunnelling generally offers numerous, in some cases substantial advantages, especially in conjunction with a segmental structure, which possesses many joints (Fig. 5). Against this background comprehensive and systematic test series were conducted to define an appropriate concrete mixture (Figs. 6 and 7). These resulted in an admixture of polypropylene fibres in a volume of 2 to 3 kg/m³ concrete beside an optimised selection of aggregates [8]. The fire proof concrete is linked with different advantages concerning the structural execution. This will be looked at more closely in the following from various viewpoints.

Fig. 6: Fire test with recently developed fire proof concrete at the TU Braunschweig, Germany under a fire load of 1200 °C over more than 90 minutes

Fig. 7: Nearly no spalling effects after the test according to Fig. 6

The construction costs and the construction time play a considerable role when a tunnel is being built. The application of fireproof concrete with an optimised mix (concrete matrix, nature and grain diameter of the aggregates used, nature and amount of the added plastic fibres) means that there is no need for an additional fire protection reinforcement or for fireproof plates or casts. This signifies that what is generally a considerable outlay for material can be avoided as well as the related additional working phase that is mostly associated with high costs quite apart from being time consuming. Further cost savings result from the reduced excavated cross-section. In this connection, it can be reckoned that the excavated diameter can be reduced by some 8 to 10 cm when there is no need for a fire protection reinforcement especially in the case of fireproof plates and casts. The excavated volume is thus diminished by roughly 1.5 to 2.0 % in accordance with the tunnel diameter. This of course, exerts an effect on the energy requirements for the extraction and transporting operations as well as with regard to dumping costs. It must be said, however, that fireproof concrete is somewhat more expensive than the segment concrete that is generally used. The added costs depend on the fire loads and the fibres, aggregates and reinforcements that are applied. The figure ranges from 5 to 10 % [9].

A number of problems arise in conjunction with the multiple joint system of a segmental support in the case of plate-like fire protection linings. The plates have to be divided in accordance with the joint pattern of the segments. This applies especially to the conicity of the segmental rings for spatial curves along the tunnel route. The plates have also to be attached in keeping with the joint pattern in the segment support, furthermore, however, they must also be geared to the reinforcement layer. In other words, special dowel gauges have to be used for drilling the dowel holes. This problem does not arise, of course, when segment concrete is used, which possesses sufficient technical properties of its own with respect to fire protection.

In addition, there are added costs in conjunction with the production and transportation of arched fireproof plates. This extra expenditure is inevitable for shield-driven tunnels as fireproof plates, which normally are produced in an even form, would inevitably break if they were to be fitted to the vaulted wall.

A very important additional aspect for the construction phase can be seen in the fact that when fireproof concrete is used, each segmental ring must be provided with adequate fire protection immediately following assembly. The considerable effects of the machine fire during the construction of the rail tunnel below the Great Belt in Denmark would not have occurred, namely causing splintering up to 27 cm deep given 40 cm thick segments, if such resistant segment concrete had existed at the time.

Fireproof concrete also offers remarkable advantages as far as the tunnel equipment is concerned. The attachment of fans, traffic signs, traffic lights, monitoring and measuring units to check the tunnel atmosphere as well as cable bridges and the likes can simply be undertaken far more easily as it can be carried out directly on the structural concrete. In the case of conventional plate and cast linings, the protective system is interrupted at such points or bays have to be correspondingly created in advance. Nor are any problems to be anticipated in the event of fire for special fireproof concrete that does not have to be additionally protected for heavy-duty dowels e.g. used for assembling jet fans. Such dowels must in any case extend to a level that is located far beneath the bearing reinforcement. Given a total damage depth of locally only 2 to 3 cm the maximum in fireproof concrete with an optimised mix [9], no risk is involved regarding concrete splintering caused by fire, which could result in dowel failure.

FIREPROOF CONCRETE AND ITS ADVANTAGES CONCERNING LIFE CYCLE, OPERATION AND MAINTENANCE

The long-term behaviour of the tunnel support represents a further important aspect in terms of the overall economy. As far as this issue is concerned, the usual service life of 100 years that is accepted in tunnelling can be assumed given a fireproof concrete with an optimised mix. The situation is different though when it comes to fire protection lining consisting of plates or casts. At present, the general conviction is that they have to be renewed some two to three times during the cited service life. This signifies that such systems have an endurance life of 25 up to a maximum of 35 years given the present state-of-the-art. There are also frequent problems relating to the endurance life with regard to attaching the plates. These can result through the constant change in conjunction with suction and pressure load as well as the resultant oscillations. This applies especially in conjunction with more constricted traffic zones given a relatively high degree of obstruction during the passage of a heavy goods truck.

Such long-term problems can also be the outcome of corrosion, which can occur in road traffic zones on account of water and thawing salt spray.

Operational and maintenance requirements also represent an important criterion when fire protection measures have to be appraised. In this connection, the fireproof concrete indubitably again affords considerable advantages. This is easily recognisable in connection with the regular tunnel cleaning stints that are required. There is no need to worry that the surface of the fireproof concrete will be harmed by rotating water brushes, high-pressure water jets, the application of detergents or the general use of water. In contrast, fire protection systems consisting of plates or casts do tend to cause problems in many cases, above all in the long term. As leaks can be present in the tunnel support, some plate and cast systems furthermore also entail problems in conjunction with increasing water inflow. This on the one hand leads to an increased weight of the plates with possible negative results for the plate attachment or in the case of a cast, to a part loss in the rear-side adhesive bond with the possibility that is dissolves altogether and on the other to a loss in the heat insulating effect in the event of fire. Such problems can generally be excluded as far as fireproof concrete is concerned. It is scarcely affected mechanically when struck by vehicles providing there collision is not severe. The same cannot be said about cast and plate systems, which can sustain considerable local damage even in the event of a slight collision (e.g. if the loading gauge is exceeded).

Inspections and general tests are prescribed for the monitoring and maintenance of a tunnel at given intervals of time in corresponding regulations. Plate and cast systems (with the exception of the perforated sheeting system described in [7]) represent a major problem in this respect. The bearing structure cannot be inspected visually without removing part of these linings. Crack formations or their time-related changes, leaks in certain joint sections or general areal moist patches in the tunnel support can thus neither be located nor observed in the course of time when such fireproof systems are utilised. Such damage can, on the other hand, be identified immediately when fireproof concrete is applied and can also be repaired at any time without any problem without any additional need for assembly on account of its accessibility. With respect to the tunnel lighting and the associated electric energy requirement, fireproof concrete affords further advantages that are worth mentioning. There is no need to add paint to brighten it up.

CLOSURE

The tragic fire accidents during the last years led to strong discussions in professional circles all over Europe and all over the world as well [10]. The national governments and the European Commission started to update the existing regulations or to propose first drafts of directives respectively for improving the safety conditions in road, rail and metro tunnels. This development can only extremely be appreciated. It is complemented by intensive research activities both on national and international level. These efforts are for example aiming at the introduction of newly or further developed fireproof materials for the tunnel lining. With regard to planning new traffic tunnels or upgrading already existing ones, it appears vital to collect all the Europe- and world-wide available knowledge and experience, to co-ordinate it and to use it in a way of integrative and holistic safety concepts. Only following this way, the discomfort and fears in the public concerning the use of tunnels can be overcome. In this direction no effort should be missed against the background that tunnels form a part of our traffic infrastructure, which cannot be disclaimed and contributes significantly to ensure the politically high-profiled mobility in our modern societies.

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