ABSTRACT:

This work presents the project "TUNNEL FOR SAFE TRAFFIC" which is a result of two patent solutions. In this project, the safety elements in the tunnel include multifunctional prefabricated secondary lining "Tribo-Beton", 3K ventilation "Ekovent", fire extinguishing by water spray, video-surveillance and fire-alarm.

After primary tunnel lining is placed, the elements forming a self-supporting arch are installed by using a special symmetrical scaffold. This scaffold enables the handling and placement of precast elements, which also serve as a self-supporting formwork for filling fresh concrete into the space between the elements and the primary tunnel lining. After having installed the 200 m secondary lining, the installation of 3-K ventilation elements can start.

These precast elements will play a multiple role in tunnel construction and performance. Their special composite structure makes them fire and water-resistant. Their prefabricated nature keeps construction costs at an acceptable level; in addition, better quality of concrete is achieved in controllable factory conditions. The “SKEMOT-3” scaffold specifically intended for such construction enables continuous traffic even during the reconstruction of the tunnel, but, of course, with reasonable speed and traffic flow restrictions.

1 INTRODUCTION

Catastrophes caused by fires in several road tunnels in Europe in a very short period of time have radically changed the attitude towards fire protection systems. The effects of fires in tunnels highlighted two main problems: damage to the conventional secondary tunnel lining and the breakdown of the ventilation system supplying fresh air to the captured people. The spalling of the concrete in secondary tunnel lining prevented rescue teams and firemen from approaching the fire and people captured in the tunnel, [1-5]. Concrete changes its mechanical properties under high temperatures. According to the PIARC document (Chapter VII. 4.3.) [6] the concrete lining cracks and spalls already at the temperature of 200°C blocking, to a large extent, the firemen’s intervention on the pavement. The firemen, being equipped for a short stay at temperatures from 400 to 450°C (in a tunnel such temperatures can produce a radiation level of about 5 kW/m², which is the maximum tolerable value for firemen), are directly endangered by the spalling of concrete lining. Furthermore, usual fire extinguishing with water gushes stimulates the spalling of the concrete lining due to a sudden cooling of the concrete mass (temperature shock). After those experiences it can be concluded that secondary tunnel lining should be fire resistant, especially in the case of one-tube tunnels without alternative approaches for firemen. Secondary tunnel lining can be designed and performed as monolithic construction or a construction consisting of precast elements. Precast elements for tunnel lining have been in use for many years. There are many tunnels built with segmental linings, like the Channel Tunnel, Elbtunnel Hamburg, Germany, LRTS Izmir.
Turkey, Plave-Doblar, Slovenia and other tunnels. In all these cases no fastenings are required between elements, and the dimensions of a member may be chosen to provide an “aspect ratio” sturdy enough to survive accidental damage during the processes of handling and erection. Fireproofing has always been applied separately after the secondary lining has been installed [7 – 9].

The project has been developed in co-operation of two Croatian companies: "Tribo-Beton" and "Ekovent" which in turn co-operate with the Faculty of Civil Engineering and other scientific institutions and companies.

The proposed solution for secondary tunnel lining involves construction of precast fire-resistant elements consisting of four layers, i.e. a double fire-resistant layer, a layer of structural concrete and a waterproof layer. These precast elements would play a multiple role in tunnel construction and performance. Its special composite structure makes them fire resistant even at high temperatures, thus ensuring structural stability during a fire in a tunnel. They would also serve as a self-supporting formwork for the filling of fresh concrete into the space between the precast elements used for secondary tunnel lining and the primary tunnel lining. In addition, they would provide enough space for fire protected ventilation pipes intended to supply the security chambers (passenger shelters) with fresh air.

3K ventilation

The lowered ceiling is installed at the height of 4.5 m along the tunnel, and the space above is divided by two longitudinal bulkheads into three channels. At each end of the side channels there are special exhaust fans, and reversible ones are in the centre. All of them are designed for continuous operation at a temperature of 300°C, and they operate regardless of smoke, water droplets or dust. In every channel, at intervals of 50-100 m in the lowered ceiling there are big fire-resistant electrically driven louvres.

3K ventilation in normal operation

The fans in the side channels operate constantly at minimal capacity of ca. 30%, and all the louvres are open in percentage according to the program determined in trial operation after the start-up, thus providing constant flow of fresh air through the traffic opening of the tunnel towards the tunnel centre, whereas polluted air gets sucked out of the tunnel through the louvres of the side channels. The central channel serves for the supply of fresh air to the position where sensors detect excessive pollution. By supplying fresh air to the point of pollution only the necessary airing of the polluted section of the tunnel is performed, rather than of the whole tunnel. In this way, in case of local pollution the side fans need not be turned on to maximum power. In order to maintain tunnel ventilation at the required level with minimum necessary corrections of ventilation power, all the fans have their operation regulated by frequency controllers.

Operation of 3K ventilation in case of fire

All the louvres in all the three channels, except those in immediate vicinity on each side of the fire, close down hermetically. All fans switch to maximum capacity operation for exhaust of gases and smoke from the tunnel. The louvres in the vicinity of the fire are completely open and they provide momentarily complete exhaust of the smoke mixed with fresh air flowing from the head of the tunnel towards the point of fire, thus preventing smoke from spreading against the airflow coming in from the head of the tunnel towards the point of fire. In this way the louvres on each side of the fire represent the "air gates" so that there is no longitudinal
flow of air between the open louvres, nor is there any supply of fresh air to the point of fire. This allows efficient extinguishing of fire by means of water fog from the stationary plant. Moreover, due to the sub-pressure created and the consumption of oxygen from the air caused by burning, the fire itself gets reduced, and the firemen can access the very spot of the fire, and start the fire-fighting operations immediately using any method planned for the given tunnel.

What is important is for the operator to have continuous video-surveillance of the traffic in the tunnel so as to be able to locate the exact place of accident without any delay.

It has to be noted that the exhaust of polluted air is completely controlled behind the fan, and the polluted gases can be cleaned by means of efficient filters fitted in the 3K ventilation system, thus preventing further environmental pollution. This also provides conditions which allow even the heavy-duty freight vehicles to pass through the tunnel without restrictions, excluding of course those that have to be specially controlled.

To summarise, 3K ventilation can achieve the following:

− prevent smoke and fire from spreading outside the controlled area between two louvres,
− provide efficient operation of a stable fire-fighting system by means of water fog, since there is no longitudinal airflow and no supply of new air to the place of fire,
− provide fast and safe evacuation of people and vehicles from the tunnel, as well as undisturbed arrival of firemen and rescuers to the very location of the fire with flow of fresh air from behind,
− provide flexible operation of the fan and louvres regulation system,
− that the fans are located outside the tunnel accessible above the head of the tunnel in a closed engine-room next to the power transformer stations,
− the equipment can be maintained without having to stop the traffic flow through the tunnel,
− there is no danger of either the lowered ceiling or the concrete lining from caving in.

2 PREFABRICATION OF ARCHED TUNNEL ELEMENTS

Arched tunnel elements made of reinforced concrete are precast in moulds bent to match the horizontal curve of a tunnel centre line. The moulds are closed and opened by horizontal translation of vertical mould walls.

The precast arched tunnel elements made of reinforced concrete consist of four layers, i.e. four different materials which are bonded, during fabrication, into a single body. The first layer of the arched precast member is a fireproof cement-silica plate of 15 mm in thickness; on it another layer of fireproof material, i.e. a special micro - concrete of 40 mm is placed; and then the third layer of structural concrete is cast. After concrete is hardened and set in the warehouse of a concrete plant, a forth layer, i.e. a waterproof layer, is spread (Figure 1).

The sides of elements are provided with rubber sheets - profiled to suit the concrete shape - which serve as matching and waterproof elements (Figure 1). The rubber sheets are protected against fire by using permanently elastic filling and fireproof seal resistant to temperatures up to 1350°C.

Structural concrete for precast elements used for the secondary tunnel lining meets very strict requirements with regard to water-cement ratio, concrete strength and protection of reinforcement from corrosion, i.e. requirements for durability of a reinforced concrete member. In order to meet these requirements, a new generation of superplasticizers was used. In this way an increased plasticizing effect of a fresh concrete mixture was provided, which

The multi-layer precast elements consisting of various combinations of materials were tested for fire resistance in order to obtain the optimum combination. This combination consisted of a double fireproof layer involving a fireproof plate with 1.5 cm thickness and a special micro-concrete of 4 cm thickness. The elements were tested according to the Rijkswaterstaat tunnel curve, [8, 12]. The above-mentioned combination of materials in the precast multi-layer member has satisfied the requirements of the Rijkswaterstaat test, [13].

3 CONSTRUCTION OF PRECAST TUNNEL ELEMENTS

Elements are placed under the crown of a tunnel by using a self-propelled scaffold to pull them over in a transversal direction. The scaffold has a symmetrical shape, which enables the handling, launching and installation of the elements on the left and the right side of the tunnel, depending on site conditions.

The scaffold consists of a central part - with an opening allowing site vehicles traffic - and lateral parts. The lateral parts are used for handling and constructing bottom elements of the lining, and for handling the crown elements of the lining and their launching to the top part of the scaffold. The top, rounded portion, is provided with rollers which receive and transport the crown member in the longitudinal and transversal directions.

Building procedure is presented in Figure 2 (A-D), where the whole cycle including handling, construction and jointing of the precast elements and construction formatting of the arch of the secondary tunnel lining can be seen.

Figure 2. Mounting procedure of secondary tunnel lining in the tunnel.

On the side of the rear part of the self-propelled circular scaffold, a stationary pump is provided to pump concrete into the space between the tunnel calotte and the precast elements of the secondary tunnel lining. The pump is installed in such a way as to be directly fed with concrete from a mixer truck, and to pump concrete through a platform “l’affut”, into the space between the precast arch and the tunnel calotte. Concrete is placed on the left side and then on the right side, in succession, from the arch foot and the tunnel calotte (Figure 3). The concrete used for filling may be concrete with or without reinforcement, as may be provided by the design of the tunnel construction.

Before concrete is placed, ventilation pipes are laid. After the space between prefabricated lining and the tunnel calotte is filled with concrete, and before the construction of the next arch is started, further ventilation pipes are connected to those already covered with concrete and fastened, if necessary, to the tunnel calotte. After the installation of the ventilation pipes is completed, the construction of the following arch is carried out (Figure 3). In case of fire in the tunnel, pipes installed in this way are protected by the lining, which allows them to provide uninterrupted delivery of both fresh air and compressed air required by firemen.

After the erected arch is stressed with longitudinal force of about 150 kN, and the arch is supported by adjustable bolt foundation as well as stressed with the already built arch, the scaffold is lowered to a transport beam and pulled over into a new position for the construction of the next arch. In this position, first a platform “l’affut” is installed, and then concrete carrying pipe is connected to the stationary concrete pump. After all preparations are completed, the concreting of the arch supports and the space between the previous arch and the tunnel calotte is commenced. In this way huge saving of time will be done, because the
scaffold and tools used for the arch construction can also be used to provide effective and
controllable placement of concrete between the tunnel calotte and the constructed arch.
Working processes are automated and run by remote control of all the stages of handling a
precast member, its bringing into the centre line of the circular self-propelling scaffold and
putting it in the final position. Unfitting of the scaffold and its relocation to a new working
position is also ensured by remote control, i.e. laser guidance allowing high degree of
accuracy measured in millimetres.

4 ADVANTAGES PROVIDED BY PREFABRICATED LINING ELEMENTS
APPLIED IN CONSTRUCTION OF ROAD TUNNELS

The construction of secondary lining of the road tunnel presented in this paper provides the
following technical and technological advantages:

• The constructed precast multi-layer concrete elements are connected so as to form an arch
  and no other finish for a tunnel surface is required; in addition, it also fills the role of a fire
  protection element.
• The waterproof layer on the outside surface in conjunction with the rubber seals at the
  side surfaces of the elements make them waterproof.
• The stage of tunnel construction that involves the waterproofing of shotcrete is eliminated.
• Formwork used for construction of the monolithic lining of a tunnel is no longer required.
• The already installed precast reinforced concrete elements serve as forms for concrete
  filling.
• Built-in ventilation pipes supply safety chambers with sufficient quantities of fresh air
during a tunnel fire.
• Fastenings used during construction to handle and erect plates are also used to fix
  ventilation, tunnel lightning and other signals and signs in the tunnel.
• If slight modifications to the self-propelled scaffold are made, it can also be used as a
  working scaffold in regular maintenance of road tunnels and in possible tunnel
  rehabilitation allowing the tunnel to remain for traffic.
• Fire resistant plates on the inner surface of prefabricated linings are bonded during
  fabrication in a factory, thus providing the best adhesion of these plates with the layer of
  micro-concrete.
• In the space between primary lining and the precast lining a number of ventilation pipes
  can be built-in around the tunnel periphery to supply safety chambers (passenger shelters)
  with air in the event of a tunnel fire. The location of these pipes described in this paper is
  found to be the best solution compared to the existing solutions involving pipe laying
  under the pavement structure or their installation under the tunnel crown with
  subsequently placed fire resistant coating.

5 CONCLUSION

The prefabricated self-supporting arched elements, consisting of reinforced concrete, fire
resistant and waterproof layers, in order to be used in tunnel construction as a secondary
lining, are found to be a technically and economically viable solution.
The combination with 3K ventilation, whose elements are manufactured in the quality of
secondary fire-fighting prefabricated lining, and fire extinguishing by means of water fog
with high-quality video-surveillance have made the vision of the project "TUNNEL FOR
SAFE TRAFFIC" come true.
6 LITERATURE

[6] PIARC: Fire and Smoke Control in Road Tunnels, Chapter VII.4.3.,1999;