Universal design concept of mitigation measures to tunnel structures in the case of fire

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ABSTRACT

Fire resistance of tunnel structures is an important issue.

Over the last 15 years there have been a number of serious underground fires in road tunnels.

These fires have caused extensive loss of life and severe collateral loss to the infrastructure, aside from the tragic loss of life, the long-term financial effects to the local infrastructure, the loss of public confidence in the safe use of tunnels.

This paper describes the mitigation measures for the protection of the structural elements to allow users to safely evacuate, to allow rescue personnel to enter the scene and effectively perform their required duties and to limit damage to the tunnel.

Following aspects are focusing in this text,

1 Historical major tunnel fire, 2 Research for mitigation measures, 3 Time–Temperature curve for mitigation measures, 4 Basic concept of the acceptable critical temperature for concrete and steel materials,

5 Mitigation measures, and 6 Conclusion

KEYWORDS: Tunnel fire, mitigation measures, concrete.

INTRODUCTION

In the recent years, several serious tunnel incidents were occurred in the world.

In the case of tunnel fire, the major cause for injury person and fatalities were inhaled the smoke and fume under the high temperature environment, in addition, damaged tunnel structure and collapsed tunnel ceiling were fell down on the carriageway, which are also big problems for tunnel safety and rescue management. The mitigation measures consists following aspects,

- Analysis of deterioration mechanism of composite materials with concrete materials and reinforcement.
- Access way to incident site from open section.
- Study of temperature control in traffic space in the case of fire.
- To improve more efficient mitigation measures.
- Delay of refurbishment work after the incident and reconstruction costs and period to reopen to traffic are also significant social damage for public transport.

1 Historical major tunnel fire

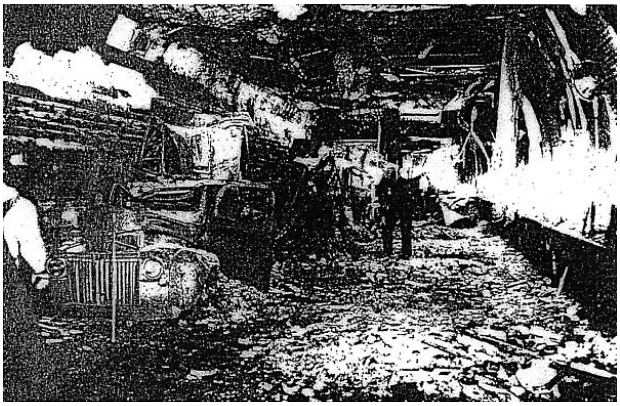
There are more than hundreds vehicle fire were occurred in the world since 1945.

Major tunnel fires are shown in following pictures.

All of these fired tunnel were serious damaged to the tunnel structure itself and facilities.

1.1 Holland tunnel fire (1949 USA National Board of underwriters 13/5 1949)

The Holland tunnel fire occurred at May 13th 1949. The hazardous goods loading trucks passing at Holland tunnel under the Hudson River. Enormous damage was occurred in south tube (bound for Manhattan N, Y). Sixty six persons were injured but nobody was killed and nearly $600,000 worth of damage to the structure at that time. As a result, the Port Authority of N,Y and N,J adopted a strict series of rules on the transportation of hazardous materials. This picture presents the collapsed exhaust air duct of reinforced concrete at ceiling by high temperature in fire.



1.2 Nihonzaka tunnel fire (1979 Japan, photo by Dr T, Konda)

Nihonzaka Tunnel fire was continued for seven days in 1979. The fir**e** consumed 127 lorries, including two tanker trucks with trailers, and 46 cars. 7people were killed by fire.

This picture presents totally collapsed tunnel inside and wrecked vehicles.

1.3 Channel tunnel fire (18/Nov 1996, 21/Aug 2006, 11/Sep 2008, UK-Fr. Photo by Trans Link Ltd, Geo front Research Institute 1998-1999).

On 18 November 1996, a fire broke out on a heavy goods vehicle shuttle wagon on boarding the rolling stocs in the tunnel, but nobody was killed by fire. Cause of fire was not a Eurotunnel equipment or rolling stock problem; it may have been due to arson of a heavy goods vehicle. It is estimated that the heart of the fire reached over than1,000°C. Internal tunnel lining concrete was severely damaged at several hundred meters.

This picture presents the Peeling off of concrete segment and wrecked the rolling stock with burnt out vehicles (Euro Star Cargo) in Channel Tunnel at first fire of 18/sep, 1996.

1.4 Mont Blanc Tunnel Fire (1999, France- Italy, photo by News, BBC, CO, UK)

On 24 March 1999, 39 people died. The bottom part of Belgian heavy truck was caught of fire by mechanical trouble. This truck caught fire in the tunnel at Italian side (near the boarder of France and Italy) and was carrying the flour and margarine. (these roading goods are not dangerous materials on the point of view of International reles of transportation through tunnels). 50 passengers were by the fire, most of drivers rolled up their windows and waited for rescue. The fire burned for 56 hours and temperatures reached over than 1,000 °C. As a results, 27 people died in their vehicles. And 10 person were died to trying to escape on foot, 12 person were survived. This picture presents just after the fire extinguished of Mont Blanc tunnel. Tunnel lining is peeled off the concrete lining. Maximum temperature reached to approximately 1,300°C.

1.5 Tauern Tunnel Fire (1999 Austria、Kleine Zeitung, May 30,1999)

On May 29, 1999 a fire took place in Tauern Road Tunnel in which twelve people were killed and fifty injured. Caused by a collision involving up to 60 individual vehicles, the incident occurred at 5 o'clock in the morning when a truck collided with a column of stationary vehicles waiting at a traffic signal which vehicles loaded the certain amount of flammable fiquids (paint in the can).

As far as investigators could determine, eight people were killed by the force of the collision of the truck.

This picture presents the collapsed concrete ceiling for fresh and exhaust duct. The concrete chips were big obstacles for rescue management.

1.6 Gotthard Tunnel fire (1999 Switzerland)

On Friday, October 24, 2001, a collision of two trucks created a fire in the tunnel, killing eleven and injuring many more, the smoke and gases produced by the fires being the main cause of death. Thus, tunnel fire is extremely serious due to an inability for gases and heat to disperse and limited performaces of smoke control system. As a results, 11 persons were died in the fire, 8 other person had to be injured (smoke intoxication).The victims died because of CO asphyxiation. The tunnel was closed for two months after the accident for repair and cleaning up.

This picture presents the collapsed concrete ceiling for fresh and exhaust duct by fire near the fire source.

1.7 Viamala Tunnel fire (2006, Sep Swiss Auto bahn 13, photo by Swiss info))

This picture presents the totally destroyed vehicles and 9 persons were killed by fire but not serious structural damage. This tunnel was not equipped the sufficient smoke control system due to the short length in bi-directional traffic tunnel.

In many cases

(1) Time to collapse of tunnel structures (concrete pieces, mechanical - electrical equipments) will be several hours delayed, after evacuation of tunnel

users at instance. Less possibility to injury by tunnel collapsed materials. Collapsed materials felled on carriage way, such as, Concrete pieces of air ducts, Mechanical and electrical equipments.

(2)These materials will be very serious obstacles for the accessibility of rescue and emergency vehicles, at second stage (after arrival of emergency and rescue service) and also delay to the recovering construction works.

2 Fire test for mitigation measures

Several kind of full scale fire tests were executed in the mean time of tunnel fire and research program on regular basis.

The main purposes of full scale test program are as follows

- Forecast of maximum heat release rate and smoke generation rate in combine within each vehicle type and loading materials.
- To grasp the temperature conditions (maximum degree ,temperature distribution to structure) in tunnel space and heat transmittance to tunnel structure in combine with cross sectional tunnel shape and ventilation condition with air supply (oxygen consumption conditions).
- Prediction of spreading area for flammable liquids dispersion on the carriage way in the case of fire, which must be controlled (appropriate drainage design must be necessary).

Figure2.1 Small fire test (photo by 9 EU countries, Up TUN)

Fig 2.2 Full scale heavy goods vehicle (40t) fire test (photo by EUREKA, Repparfjord tunnel, Norway)

3 Estimated maximum temperatures by vehicle fire (Report of World Road Association, here after: **PIARC**, Fire and Smoke Control in Road Tunnels, 1999, C5).

Following maximum temperatures at the tunnel wall or ceiling could be developed based on several research results for the following vehicles types:

- Passenger car 400°C
- Bus/small lorry 700°C
- Heavy Goods Vehicle (HGV) with normal combustible goods, 1000° C
- Petrol Tanker (general case) 1,200° C
- Petrol Tanker (extreme case) 1,400° C

4 Acceptable critical temperature for concrete and steel materials

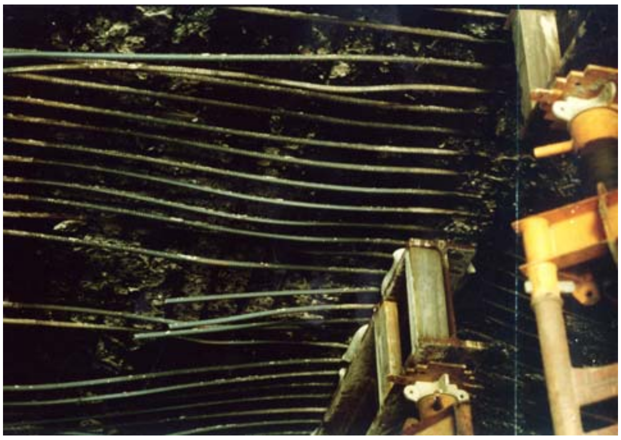


Figure 4.1 Serious damage of concrete slab by fire

(photo by RWS, Netherlands)

4.1 Concrete

The compressive strength of concrete will be deteriorated by the rapid growth of thermal environment. The reduction of strength of concrete can be normally expressed in temperature variation and Young's modulus rate from the ambient air condition up to 800°C－1.000°C. Generally, the concrete strength could not be expected up to 600°C (C.T: Critical Temperature) for the structural members. However, in the case of tunnel fire which are based on the figure 4.2, the material strength will be reduced around 350°C－400°C due to the rapid temperature increment.

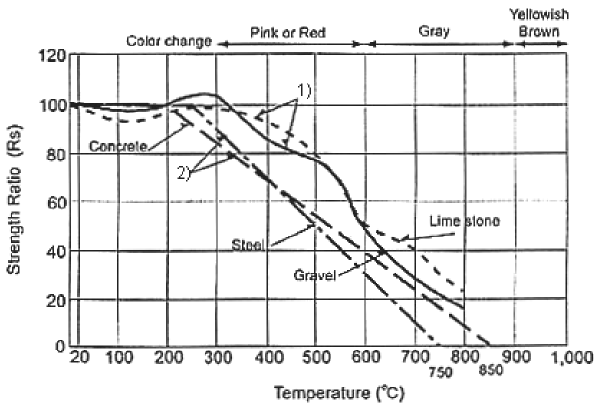


Figure 4.2 Deterioration rate of compressive strength of concrete and steel reinforcement after temperature increment

4.2 Thermal penetration to RC concrete

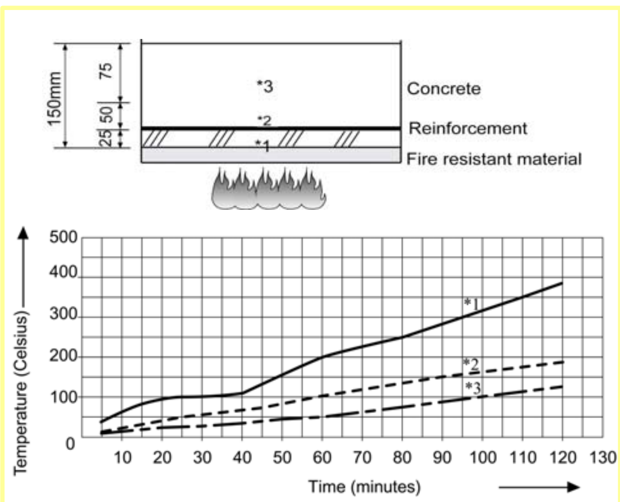


Figure 4.3 Temperature distribution curve by time at Concrete Surface and inside [3]

5 Type and system of fire resistant materials

As far as the fundamental concept of fire resistant policies are concerned, considering the temperature rise up to 1400°C within short period by vehicle fire, it is common to allow for temperatures as high as the permissible temperature of fire resistant performances are up to 250 - 300°C, in case of concrete and reinforcements. On the other hand, “when concrete is heated slowly during in considerable length of time. There after, cooling it slowly, said that the deterioration rate of strength in concrete due to heating is small”[4].

Recently, a new technological innovation has been introduced[5]. (Stainless) steel studs are inserted into concrete structure at regular intervals on the surface for the (stainless) Steel punching sheet , there by controlling the loss of concrete strength through delaying the heat dissipation into concrete surface. This method can be applicable for retro fitting with appropriate costs without special tools and technologies. It is expected that there would be less (only little) strength drop to the concrete in case of road tunnel fire. Figure 5.1 presents the punching steel insulation in the case of fire.

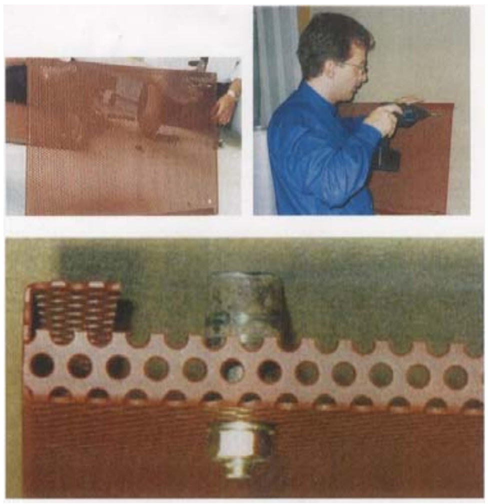


Figure 5.1 Holed steel insulator for fire[5]

5.1 Spraying

Fundamental performance of the spray type is as follows:

<A. Major characteristics>

- Even in case of complicated cross-sections, construction is simple.
- At narrow locations like pipe sleeves, construction is very appropriate.
- Renovations are simple at places where concrete is damaged.

<B. Basic performance>

Inorganic spray system can be applied easily to complicated shape of structure with narrow locations, and also renovation work is very simple for damaged part of concrete structure Improved adhesion performances of concrete surface varies due to the surface condition to be necessary. Finished surface is not flat, if in the case of surface cleaning to be necessary, it may be trouble some. If in the case of organic materials are contained, it may produce the toxic fumes and smoke.

The finished sprayed surface is appeared some roughness, so that, finished surface has some of sound absorbent performance. However, which will be stained by smoke and soot. The side wall cladding will be necessary for the better reflection of lighting system and maintenance for cleaning.

Figure 5.2 Mitigation measures by sprayed fire protection [6)]

5.2 Board (Panel type)

Materials are manufactured in the plant according to standard dimensions, on concrete form, which are generally fixed by two methods of placement with simultaneous concreting, and fixation into the completed structure with anchor bolts. These panel types are especially used in submerged tunnels of the Netherlands. As far as these panels are concerned, the following characteristics and advantages are commonly seen.

Figure 5.3 Fire protection panel are fixed on the concrete surface (photo by RWS, Netherlands)

Finished surface is smoother than spray system. And also has some sound absorbent performance due to material density. Additionally, level of blemish by smoke and soot is better than spray finished surface. Figure5.4 presents the panel installation on the curved surface. This method seems to be more costly than flat surface.

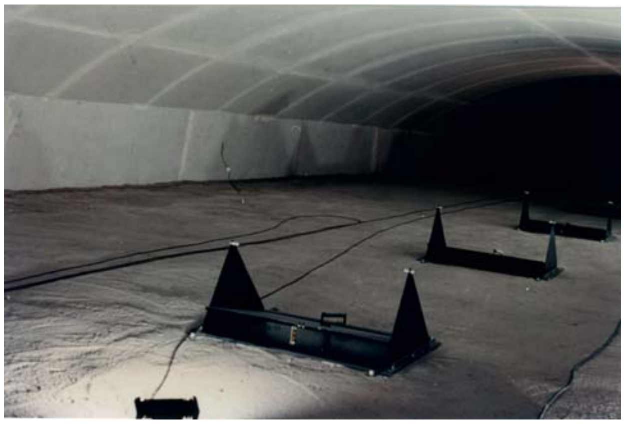


Figure 5.4 Fire protection panel are fixed on the circular ceiling (photo by 4th Elbe Tunnel, Germany)

Generally, panel system is applied on the flat surface in rectangular cross section (submerged tunnels in the Netherlands) in many cases. Typical panel dimensions are 1200mm x 300mm, thickness 25-27mm. As fire resistance materials, these are mainly fixed on the ceiling with the vacuum pressure 100 kg/m by traffic piston action.

5.3 Development of Fire Resistant Concrete

With the objective of protecting the tunnel structure from high temperatures in case of fires, fire resistant concrete has been developed, having upgraded the quality of concrete. In one such method, it has been attempted to increase the fire resistance of concrete by mixing chemical compounds to those existing in concrete. It is expected to meet new innovations of these fire resistant concrete types, thereby minimizing the cost of new tunnels to be constructed. Figure 5.5 presents the heated in red colored specimen and Figure 5.6 presents the comparison figure of PP(polypropylene) fiber specimen performance and normal concrete specimen. This PP fiber concrete is installed at ceiling part for several tunnels in Austrian road tunnels. If P.P fiber is mixed in concrete (contamination approx 3kg/m3), the fire resistance performance was significantly improved up to 1200°C. However, in the case of temperature rise is higher condition by Heavy goods vehicle fire, resistance performance and durability of repetition fire will not be adequate, therefore, further investigation of fire resistance performance of chemical fiber concrete to be necessary.

Figure 5.5 High temperature heated chemical fiber concrete specimen [7)]

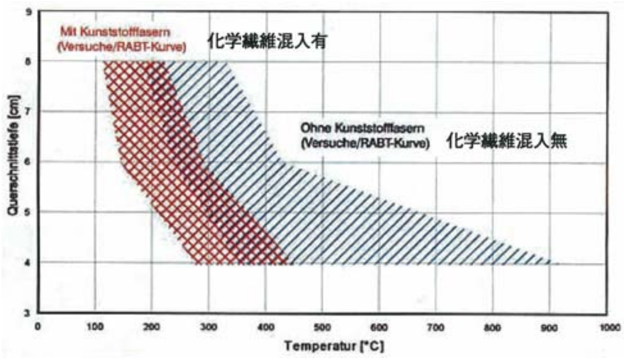


Fig 5.6 Temperature penetration to normal concrete in comparing with chemical fiber mixed concrete [7)]

6 Summary and Recommendations by ITA (International Tunnelling and underground space Association):

Guidelines for Structural Fire Resistance for Road Tunnels May 2004

Recommendations for design of the structure should consider the time-temperature curve with regard to the possible events within the tunnel. Hence the early stages of the fire development, it will require a consideration of escape and the time conceived for evacuation. There should be no collapse during this period that can affect the zones where there may be users or rescuers.

Spalling of the structure will occur in the early stages of a fire but no incidents have been reported by several tunnel operators and fire fighters in the case of fire, where it has had major consequences for firemen, although it may indicate a rapid deterioration of the structural strength. The main concern at the time of fire service intervention would be the collapse of items, such as jet fans, signs or lights from the tunnel ceiling or walls. This question of fire resistance has been addressed in the PIARC 1999 report [2.1], which states:

"In all cases, the minimum requirement is that heavy equipment should not fall down when evacuating users or rescue personnel are in the tunnel. This means no heavy item must fall under exposure to temperatures of 400-450°C during the time

necessary to fighting to fire (in a tunnel, such temperatures can produce a radiation level of about5 kW/m2, which is the maximum tolerable value for fire fighters)”

Figure6.1 Time – Temperature curve for fire resistance design to tunnel structure

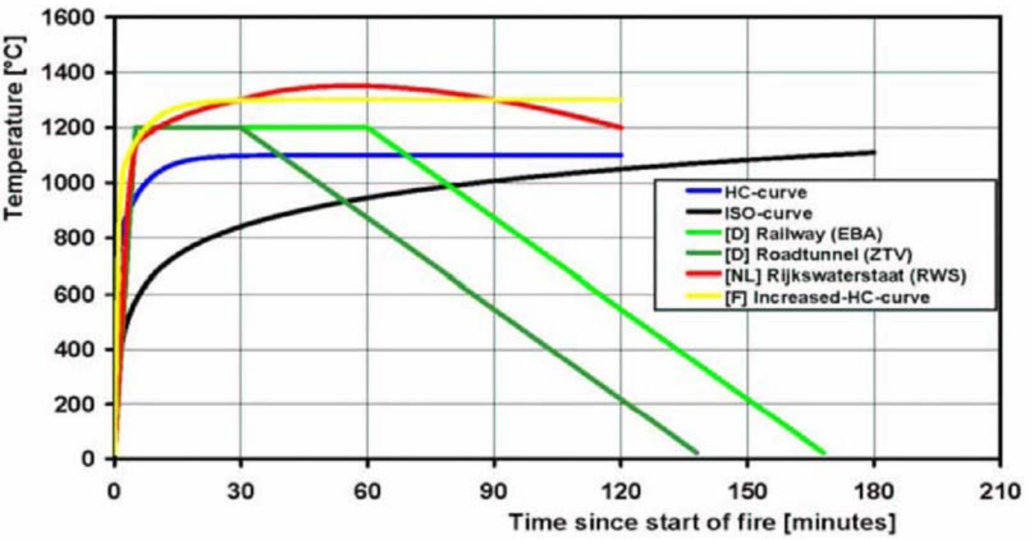


Table6.1 Adoptable time temperature curve with traffic type and tunnel structure

Traffic Type	Main Structure				Secondary Structures[4]			
	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts [5]	Emer-gency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/ Vans	ISO 60 min	ISO 60 min	[2]	[2]	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/ Tankers	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/HC_{inc} 120 min[1]	RWS/HC_{inc} 120 min[1]	ISO 120 min	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

With regarding to table 6.1, following additional issues to be correspond with number in each column.

1 180 min maybe required for very heavy traffic of trucks carrying combustible goods

2 Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

− ISO 60 min in most cases

− No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection) under building or large influence on road network

3 Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

− RWS/HCinc 120 min if strong protection is required because of property (e.g. tunnel under building)

− ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property.

− No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g light cover for noise protection)

4 Other secondary structures should be defined on a project basis

5 In case of transverse ventilation

6 Shelters should be connected to the open air

7 A longer time may be used if there is a very heavy traffic of trucks carrying combustible goods and the evacuation from the shelters is not possible within 120 min.

Additional remarks,

1. Concrete: Structural elements wall, ceilings, partition walls, cast-in-place concrete etc:
2. Protect the concrete surface for a maximum heat rise at surface of 380°C.Pre cast concrete elements: including high strength concrete segments, pre cast concrete slabs etc: Protect for a maximum heat rise at surface of 200-250°C.Concrete Ceilings shall be suitably protected from collapse for a minimum of two hours with a maximum temperature rise at the surface of 380°C.
3. Clay brick masonry and dimension (ash) stone are not considered critical and do not necessary protection.
4. Segmental Steel liners shall be protected at the surface for a maximum temperature rise of 550°C.
5. Segmental Cast Iron liners shall be protected at the surface for a maximum
6. temperature rise of 550°C.
7. Leaded Joints in segmental liners shall be protected for a maximum heart rise of 200°C.
8. Ceramic fired tile finishes of tunnels shall be protected from explosive spalling to a maximum temperature rise of 200°C (Note, the use of ceramic fired tile finishes in new tunnels should be avoided).
9. Steel structural elements and ceiling hanger rods shall be protected for a maximum temperature rise of 550°C.
10. Cast Iron structural elements and ceiling hanger rods shall be protected for a maximum temperature rise of 550°C.

"More sophisticated assessment methods could be used to develop more economical solutions taking into account other factors influencing:

- *Temperature Gradients*
- *Heating Rates*
- *Structural Load levels"*

11. Stainless steel structural elements and ceiling hanger rods shall be protected for a maximum temperature rise of 800°C.
12. Anchorages must be designed for a minimum factor of safety of 3.5 for fixity of anchor. Fixity is described as the bond/ attachment to the substrate
13. Epoxy resin anchors shall be protected for a temperature heat rise at a depth of 6 cm from the surface of 200°C (Note: France prohibits the use of epoxy anchors in environments that may be above 300°C).
14. All epoxy anchors shall be designed with the bond zone not less than 6 cm from the surface of the concrete or material that the anchor is being installed within.
15. Lead shield anchors or anchors with lead components are not permitted for structural or emergency equipment supports, (i.e. dampers, fans, etc.).
16. Brass, zinc or other low melting point anchors are not permitted for structural or emergency equipment supports, (i.e. dampers, fans, etc.)
17. All fireproofing materials shall not be degraded in regard to bond to the substrate or in fire resistance rating from the presence of water.
18. All materials incorporated in tunnel structures or within tunnels shall be non-toxic and non-flammable.
19. All emergency equipment to be installed shall conform to PIARC Guidelines and local codes, ordinances and regulations

21 Emergency access/escape areas shall be designed not to exceed a maximum temperature of 40°C in areaways as per PIARC Guidelines and local codes, regulations and ordinances.

7 Conclusion

Over the last 15 years there have been a number of serious underground fires in road tunnels.
These fires have caused extensive loss of life and severe collateral loss to the infrastructure, aside from the tragic loss of life, the long-term financial effects to the local infrastructure.
In addition, the loss of public confidence in the safe use of tunnels have been necessitated the development of mitigation measures to structures. Which is significantly important to allow to users for safely evacuate, to allow rescue personnel to enter the scene and effectively perform their required, which is duties to limit damage to the tunnel. Improved specifications for tunnel fire resistance to be required in order to mitigate the consequences of a serious fire, which could result in structural failure or complete collapse.

ITA guideline is now involved to several local guide lines in world wide countries which are concerning to the new and retrofitting traffic tunnel projects for the purpose of mitigate the both of structural and economic damage by consequences of fire.

The assessment methods are constantly being developed to demonstrate the ability of materials, such as insulation materials, surface coatings to prevent concrete spalling and deterioration of steel and other elements from sudden temperature rise under fire exposure conditions.

Yoshikazu OTA of Japanese delegate contributed to arrangement of this guideline during in 1999-2004 as a part of responsible author in the Working Group in ITA and other International, domestic research groups with regarding to this issues.

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