Technical Note on The Fire Protection of Tunnel Structures & Services

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Contents - Technical Notes on The Fire Protection of Tunnel Structures & Se

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Fires in tunnels are a major hazard to human life and cause costly damage to the infrastructure. The limited escape facilities and the difficulties encountered by intervention forces in gaining access, call for extensive safety arrangements which must be complementary and mutually coordinated.

Tunnels and underground transport facilities are important means of communication, not only in terms of shorter journeys, but also increasingly out of consideration for the local population and the environment, as well as the local economy and industry. Generally speaking, important underground transport links are expected to be available without any restrictions and to operate smoothly round the clock. Interruptions due to accidents, technical malfunctions or maintenance work quickly cause traffic jams and delays, and figure in transport policy statistics as economic losses.

Rising traffic densities and the growing demand for underground communication links result in a higher probability of accidents, injuries and damage. Added to this are other factors which increase the potential hazards of traffic tunnels:

- the increasing length of modern tunnels
- the transport of hazardous materials
- two-way traffic (with undivided carriage ways)
- higher fire loads due to growing traffic volumes and higher loading capacities of vehicles
- mechanical defects in motor vehicles

When considering a tunnel(s), it is usually in relation to road and rail infrastructure, however, use of the word tunnels can be slightly misleading, as the following information applies equally to pedestrian walkways, underground rail stations, underground car parks etc, in fact; to any concrete structure. Therefore although this document will refer to tunnels throughout, all details apply also to underground spaces of any description.

It is usually assumed that because a structure is constructed using concrete, that it is inherently fire resistant, and therefore requires no additional fire protection measures to be taken. Unfortunately, experience over the years has shown that this is not necessarily the case and consideration must be given to the performance and behaviour of concrete structures under fire conditions. In addition, where tunnels and underground spaces are concerned, consideration must also be given to the provision of services protection, e.g. smoke extraction systems, protection to cables and wiring servicing, emergency equipment etc.

This handbook is intended to provide some background into the behaviour of concrete under fire conditions, To show proven methods of protecting structures against fire, and of providing protection to services within tunnels and underground spaces.

European Union Tunnel Projects

For further information, readers should consider reviewing the current projects into tunnel safety being carried out under the auspices of the European Union, these are as follows.

Fire In Tunnels (FIT)

Launched in March 2001, this is a four year project which aims to establish and develop European networking and to optimise efforts on life safety in tunnels. This project is to produce a number of databases which can be accessed from outside parties, the work will involve details on design fires, fire safe design and best practice for fire response management practices etc.

The expected database titles are detailed below.

- Database 1: Projects description on fire safety in tunnels (BBRI)
- Database 2: Specialised test sites for the study of fire in tunnels (INERIS)
- Database 3: Numerical models for tunnels fires (BRE)
- Database 4: Safety equipment in tunnels (DMT)
- Database 5: Assessment reports on fire accidents in tunnels (INERIS)
- Database 6: Upgrade activities on tunnels (STUVA)
- Database 7: Short description of FIT Corresponding members

Durable & Reliable Tunnel Structures (DARTS)

This is a three year project, started March 2001 which aims to develop tools allowing designers and construction companies to achieve cost optimisation in terms of environmental conditions, technical issues, safety precautions and long service life for tunnels. This is primarily concerned with the construction of new tunnels, but will also develop procedures pertinent to existing tunnels being upgraded. The work of this group will be co-ordinated with FIT and is to include investigations on performance relative to explosions, water ingress and earthquake precipitance.

Safe Tunnels (SAFE T)

This is a three year project, initiated in 2003. Its main objective is to develop guidelines for the decision making process and to provide best practice solutions for preventing and mitigating accidents within tunnel environments. The objectives of this project include the drafting of harmonised European guidelines for tunnel safety, focusing on management and cross border issues. The contributions of national government agencies (local authorities, fire and rescue services etc.) industry and tunnel specialist organisations (Stuva, Cetu, Dmt etc) will all provide input into the draft.

Upgrading Existing Tunnels (UPTUN)

This project has a four year duration, UPTUN stands for “Cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels.”

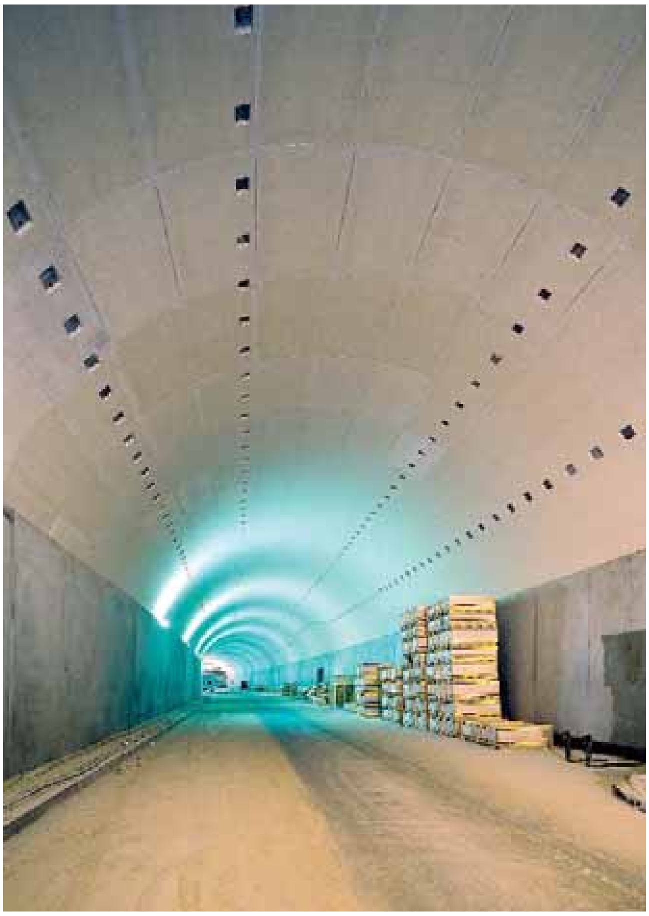
The Project goals of UPTUN are as follows:

- The development of innovative technologies for tunnel application.
- The development, demonstration and promotion of procedures for rational safety level evaluation and technology transfer.

The desired spin-off from the UPTUN project is the restoration of faith in tunnels as safe parts of the transportation systems, the levelling out of trade barriers imposed by supposedly unsafe tunnels and to provide links to existing and future (inter)national (upgrading) tunnel projects.

Safety for Improvement in Road & Rail Tunnels (SIRTAKI)

This project (whose full title is Safety for Improvement of Road and rail Tunnels using Advanced information Technologies and Knowledge Intensive decision support models) is of three years duration. It is responsible for the development and assessment of an advanced tunnel management system that specifically tackles safety issues and emergencies and the integration within the overall network management. The decision support system (DSS) is one of the main components of SIRTAKI.



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Why Protect Tunnels?

There are three reasons for providing protection against fire within tunnels, firstly, there is the matter of life safety, this is not necessarily a function of structural performance under fire, although a collapsing structure would not enable people to exit a structure in safety, but more to do with the function of services such as emergency lighting, smoke extraction systems etc.

Within Europe alone, there have occurred within road and rail tunnels at least 10 major and countless minor fire situations. These fires have resulted in a major loss of life (221 dead in four fires that occurred within a period of two years) and in all cases significant structural damage, not to mention the economic costs. As an example, detailed below are some of the tunnel fires which have occurred in past years, and the resultant death toll.

Table 1: Casualties in tunnel fires

Location	Casualty	Location	Casualty
BOSNIA	34	Hokuriku Tunnel, JAPAN	34
Mont Blanc Tunnel, FRANCE	39	Pecorile Tunnel	8
Tauern Tunnel, AUSTRIA	12	O Shimizu Tunnel, JAPAN	16
Vierzy Tunnel, FRANCE	108	Salang Tunnel, AFGHANISTAN	700
Pf nder Tunnel, AUSTRIA	3	Kings Cross, ENGLAND	31
Huguenot Tunnel	3	Isola delle Femmine, ITALY	5
Nihonzaka, JAPAN	7	Velsen Tunnel, NETHERLANDS	5
Caldecot Tunnel, USA	7	Kaprun, AUSTRIA	155
St. Gottard Tunnel, SWITZERLAND	11	Gleimalm Tunnel, AUSTRIA	5

Secondly there is the performance of the structure itself, will it remain in-situ, will it collapse, possible causing collateral damage to other structures and injuries to people passing by etc. In the Mont Blanc fire, there was severe spalling of the structural concrete. During the fire which occurred inside the St Gotthard tunnel in 2001, a 100m long section of the structure collapsed, hampering the activities of the rescue services. Although both these tunnels pass through rock and therefore localised collapse or spalling, although costly and inconvenient, did not endanger persons located away from the damaged areas, but if these tunnels had been of the immersed type, the structural damage could have resulted in flooding of the tunnels, with all its associated implications.

It should be noted that after the fire in the Channel tunnel, the only thing standing between loss of this tunnel and a situation where effective repair could be carried out was the thin grout layer between the concrete structure and the water bearing rock layer, so severe was the spalling of the concrete. A very slim margin to rely on, but which risk could easily have been alleviated had adequate passive fire protection systems been included to compliment the active systems.

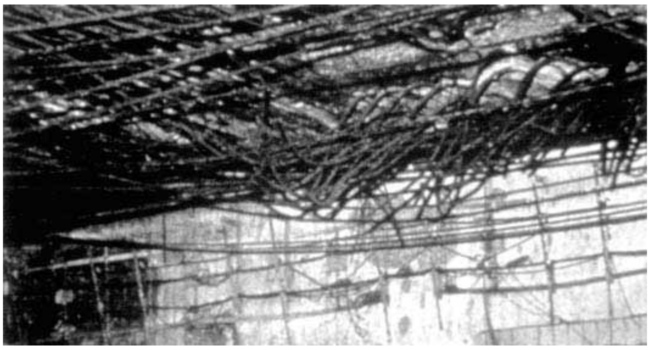
Thirdly, there is the economic damage caused as a result of the failure of a tunnel etc. This economic cost is not related solely to the repair or rebuilding of the structure; more usually it is the knock on impact of loss of business, traffic diversions etc which result in the largest costs.

An example of this is the fire inside the Channel tunnel where the economic damage was estimated to be over twice the cost of the actual tunnel repairs, the direct repairs to the tunnel cost by some estimates €87 million. The additional cost in lost business, replacement of infrastructure, materials e.g. lorries, train carriages etc together with the impact of the tunnel closure on other, unrelated businesses bring the estimated economic loss alone to some €211 million, according to some sources.

Using Mont Blanc tunnel as an example for a simple road tunnel, the differences are not so marked, with the cost of repair being estimated at some €189 million and the economic cost at some €250 million in addition. However, consider the socio-economic impacts on a wider basis rather than simply the tunnel itself. The estimates of the effects on the local Italian economy around the area of the Mont Blanc tunnel has been estimated at €2.5 Billion. Therefore in any risk analysis, the socio-economic costs need to be taken under consideration.

Figure 1: Examples of fire damage

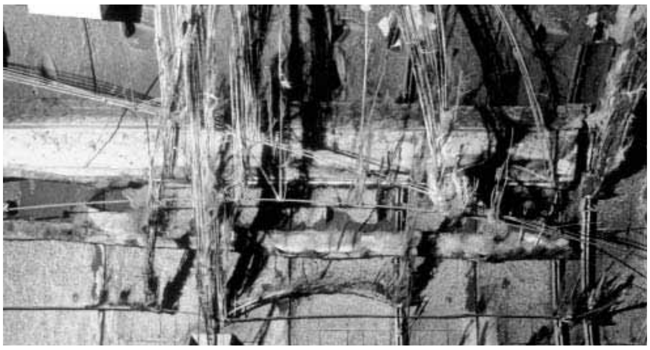
Example 1 Moorfleet Tunnel, GERMANY



Example 2 Mont Blanc Tunnel, FRANCE

Example 3 Velsen Tunnel, NETHERLANDS

Example 4 Channel Tunnel, UK



Thus in terms of fire protection within tunnel and underground systems, the following items require consideration:

- Enhancing the fire resistance of the structure
- Air supply systems
- Smoke extract duct systems
- The provision of fire and smoke resistant safe havens in long tunnels
- Active and Passive detection systems
- Fire extinguishing systems

Table 2: Fires in tunnels

Country	Tunnel	Length (m)	Type	Ventilation	Cause of fire	Duration (Hrs:Mins)	Minimum HRR	Type of goods involved
AUSTRIA	Felbertauen	5281	Mountain	Semi longitudinal*	Brakes Locked	1:30	15	Not available
AUSTRIA	Pfander	6719	Mountain	Transverse	Collision	1:00	20	Bread
AUSTRIA	Tauern	6400	Mountain	Transverse	Collision	15:00	200	Paint products
FRANCE	Frejus	12870	Alpine	Transverse	Unknown	2:00	15	Plastic materials
FRANCE	Pt. D"Italie	425	City	Natural	Engine fire	0:45	15	16t Polyester fibres
FRANCE	Mont Blanc	11600	Alpine	Semi longitudinal*	Engine fire	4:15	30	20t cotton
FRANCE	Mont Blanc	11600	Alpine	Semi longitudinal*	Engine fire	53:00	300	9t Margarine + 12t Flour
FRANCE	L"Arme	1100	City	Transverse	Collision	Unknown	20	Not available
FRANCE	Castellar	570	City	Natural	Tyre blow out	Unknown	20	Waste paper
GERMANY	Moorfleet	243	City	Natural	Overheating tyres	1:30	15	14t Polyethylene granules
ITALY	Peccorila	662	Unknown	Unknown	Collision	Unknown	Unknown	Fish
ITALY	Serra Ripol	442	Unknown	Unknown	Collision	2:30	100	Rolles of paper
ITALY	Is. D. Femm	148	Unknown	Unknown	Collision	Unknown	200	Not available
JAPAN	Kajiwara	740	City	Semi longitudinal*	Overheating gearbox	1:20	30	3600 litres of paint in 200 cans
JAPAN	Nihonzaka	2045	Unknown	Semi longitudinal*	Collision	4 Days	300	Not available
JAPAN	Sakai	459	Unknown	Natural	Collision	3:00	150	Not available
NETHERLANDS	Velser	768	Sub River	Transverse	Collision	1:15	40	Flowers and soft drinks
NORWAY	Ekeberg	1563	City	Longitudinal	Engine fire	1:57	35	Not available
NORWAY	Røldal	4657	Mountain	Longitudinal	Engine fire	Unknown	15	Not available
NORWAY	Hovden	1283	Mountain	Natural	Collision	1:30	150	400m Poly-ethylene lining
NORWAY	Hitra	5645	Sub Sea	Longitudinal	Engine fire	2:05	20	Not available
SOUTH AFRICA	Huguenot	4000	Unknown	Transverse	Overheating gearbox	0:47	15	Not available
SPAIN	Guadarram	2870	Unknown	Semi longitudinal*	Overheating gearbox	2:45	100	Tanks of pine resin
SWITZERLAND	Gumefens	343	Unknown	Unknown	Collision	2:00	50	Not available
SWITZERLAND	St. Gotthard	16918	Alpine	Transverse	Overheating tyres	2:00	30	750 bicycles in carton boxes
SWITZERLAND	St. Gotthard	16918	Alpine	Transverse	Engine fire	0:20	20	Not available
SWITZERLAND	St. Gotthard	16918	Alpine	Transverse	Engine fire	3:00	50	8 private cars
UK	Kingsway	2000	Sub River	Transverse	Engine fire	1:13	15	Not available
USA	Wallace	933	City	Unknown	Engine fire	Unknown	100	1 camper van
USA	Caldecott	1083	City	Unknown	Collision	2:40	200	Not available
USA	Holland	2567	Sub Sea	Unknown	Falling load from HGV	4:00	300	11t Carbon Bisulfate
USA	Blue Mt.	1302	Mountain	Unknown	Engine fire	Unknown	20	Fish oil
USA	Chesapeake	Not known	Sub Sea	Unknown	Tyre blow out	4:00	15	50 Gallon fuel tank

*Semi longitudinal ventilation = Combination of longitudinal and transverse ventilation

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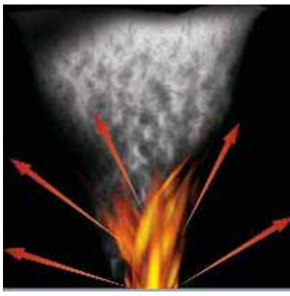
In recent years, a great deal of research has taken place internationally to ascertain the types of fire which could occur in tunnels and underground spaces. This research has taken place in both real, disused tunnels, and under laboratory conditions, as a consequence of the data obtained from these tests, a series of time/temperature curves for the various exposures have been developed as detailed below.

Whilst research in tunnel fire phenomena continues, it should be noted that the existing data shows that fires within tunnels show the severity to be much higher than would be experienced under open air conditions. By comparing heat release rate (HRR) data (which is taken by many to be a good measure of the severity of a fire) from tests carried out on different vehicle types, wooden crib fires, fuel oil tray experiments etc, and comparing the results from tests within tunnels to those with the same tests carried out in buildings, the conclusion has been arrived at that a tunnel can increase the HRR by up to four times. Further experimentation has shown that the increase will vary with the ratio of the fire width to the tunnel width in a cubic manner.

$$\frac{HRR_{In\_tunnel}}{HRR_{In\_tunnel}} = Ø = 24 \times \left[\frac{W_F}{W_T}\right]^3 + 1$$

Where _ is the degree of enhancement;
W_F is the width of the fire base;
W_T is the width of the tunnel.

It should be noted that at present, this information only appears accurate for a fire width up to approximately half the tunnel width, and to naturally ventilated tunnels. Investigations by the Swedish National Testing and Research is on-going.



The methods of ventilating a tunnel can also have a marked effect on the HRR of the burning items, and thus should be factored in to any proposals when designing the type and period of fire protection being specified.

The illustration on the left is indicative of 900~1100°C and on the bottom 1000~1400°C.

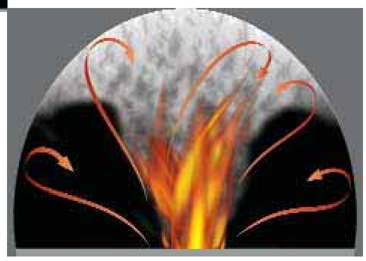
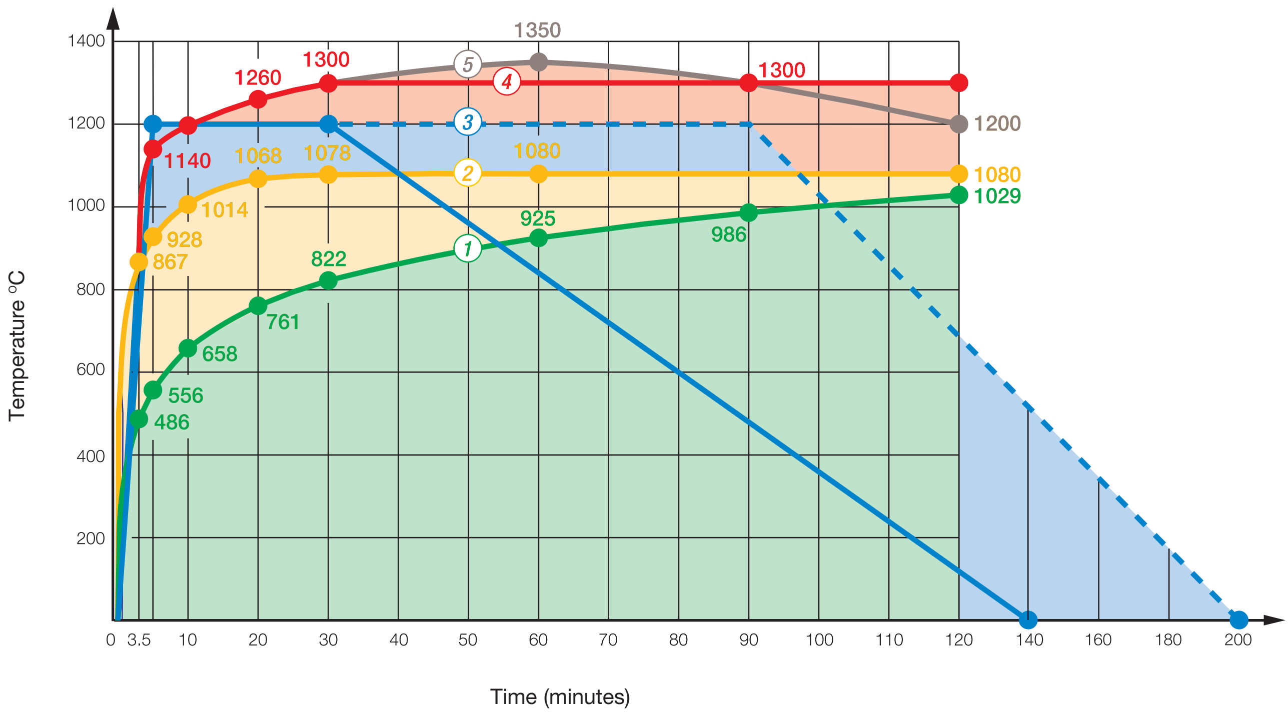


Figure 2: Time/temperature curves



1 = Cellulosic ISO Curve *2 = Hydrocarbon Curve* *3 = RABT-ZTV Curve* *4 = HCM Curve* *5 = RWS Curve*

Cellulosic ISO Curve

Standard fire tests to which specimens of constructions subject to are based on the use of the Cellulosic time/temperature curve, as defined in various national standards, e.g. ISO 834, BS 476, DIN 4102, AS 1530 etc. Although there are other types of fire test curve e.g. BS 7436, the curve as detailed below for this exposure is the lowest used in normal practice. This curve is based on the burning rate of the materials found in general building materials and contents, although in itself, this curve is based upon research dating back to the late 1940s, and it is recognised that with the use of thermoplastic and other modern materials, the Cellulosic curve could be considered to be less onerous than it should be when applied to modern building design and contents, let alone tunnel applications.

Therefore, although generally accepted for normal buildings, this curve is NOT representative of most tunnel fires.

Table 3: Cellulosic curve

Time (minutes)	Furnace temperature (°C)	Time (minutes)	Furnace temperature (°C)
0	20	90	1006
5	576	120	1049
10	678	150	1082
15	738	180	1110
20	781	210	1133
30	842	240	1153
45	902	300	1186
60	945	360	1214

Hydrocarbon Curve

Although the Cellulosic curve had been in use for many years, it soon became apparent that the burning rates for certain materials e.g. petrol gas, chemicals etc, were well in excess of the rate at which for instance timber would burn. As such there was a need for an alternative exposure for the purpose of carrying out tests on structures and materials used within the petrochemical industry, and thus the hydrocarbon curve was developed. Initially, this time/temperature curve was developed separately by various gas and oil companies, and all had slight differences, however, today, the curve as detailed in Table 2 is as per the relationship between time and temperature that is generally in use for testing.

The hydrocarbon curve is applicable where small petroleum fires might occur, i.e. car fuel tanks, petrol or oil tankers, certain chemical tankers etc. In fact, although the hydrocarbon curve is based on a standardised type fire, there are numerous types of fire associated with petrochemical fuels, some of which are detailed below.

CLOUD FIRE
A transient fire resulting from the ignition of a cloud of gas or vapour and not subject to significant flame acceleration via the effects of confinement or turbulence. It can therefore only occur after a relatively slow release of hydrocarbon and in an open, free space.

FIREBALL
The rapid turbulent combustion of fuel as an expanding, usually rising ball of flame. It is more intense than a cloud fire and can be close to an explosion.

BLEVE
A Boiling Liquid Expanding Vapour Explosion which results from the sudden failure of a vessel containing a pressurised liquid at a temperature well above its normal (atmospheric) boiling point. E.g. a LPG tanker.

POOL FIRE
A turbulent diffusion fire burning above a horizontal pool of vapourising fuel under conditions where the fuel vapour of gas has zero or little initial momentum. A burning pool fire is extremely difficult to control. It may accompany a jet fire where burning liquid is spilling from the jet stream.

RUNNING FIRE
A fire from a burning liquid which flows by gravity over surfaces.

JET or SPRAY FIRE

A turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction.

Table 4: Potential fire duration

Fire types	Potential duration
Cellulosic fire	Hours
Hydrocarbon fires	
CLOUD FIRE	Seconds
FIREBALL	Seconds
BLEVE	Seconds
POOL FIRE	Hours
RUNNING FIRE	Hours
JET or SPRAY FIRE	Hours

Hydrocarbon fires are different from Cellulosic in the manner in which the temperature increase is far more rapid, as can be seen in Table 2 above, and that after the initial 30 minutes rise, the temperature follows an almost straight horizontal line.

This curve does represent a typical fire which occurs very near a tunnel portal opening. However, within the tunnel, a much more severe fire can be expected for the same fire load.

Table 5: Hydrocarbon fire

Time (minutes)	Furnace temperature (°C)	Time (minutes)	Furnace temperature (°C)
3	887	60	1150
5	948	90	1150
10	982	120	1150
30	1110	120+	1150

The figures given in Table 5 referring to hydrocarbon fire temperatures should not be confused with those relating to the modified hydrocarbon curve which is now in use in some countries (see HCM curve, Figure 2 and Table 6). This modified hydrocarbon curve has a temperature rise similar to that of the RABT, but with a higher maximum temperature, reaching 1300°C, only slightly under that achieved using the RWS curve. This modified Hydrocarbon exposure is then partway between RWS and RABT requirements, and is much more severe than exposure to the standard curve detailed within such standards as UL 1709, BS 476: Part 20: Appendix D etc.

Table 6: Modified Hydrocarbon curve

Time (minutes)	Furnace temperature (°C)	Time (minutes)	Furnace temperature (°C)
3	1047	60	1300
5	1120	90	1300
10	1222	120	1300
30	1297	120+	1300

RWS (Rijkswaterstaat) Curve

The RWS curve was developed by the Rijkswaterstaat in Netherlands. This curve is based on the assumption that in a worst case scenario, a fuel oil or petrol tanker fire with a load of 300MW lasting up to 120 minutes could occur.

The RWS curve was based on the results of testing carried out by TNO in the Netherlands in 1979. The difference between the RWS and the Hydrocarbon curve, bearing in mind that they are both using as the fire load similar materials, is that the latter is based on the temperatures that would be expected from a fire occurring within a relatively open space, where some dissipation of the heat would occur, whereas the RWS curve is based on the sort of temperature you would find when a fire occurs in an enclosed area, such as a tunnel, where there is little or no chance of heat dissipating into the surrounding atmosphere. The RWS curve simulates the initial rapid growth of a fire using a petroleum tanker as the source, and the gradual drop in temperatures to be expected as the fuel load is burnt off.

Table 7: RWS fire

Time (minutes)	Furnace temperature (°C)	Time (minutes)	Furnace temperature (°C)
3	890	60	1350
5	1140	90	1300
10	1200	120	1200
30	1300	120+	1200

In the Netherlands the RWS curve is applied for durations of up to 120 minutes, at which time it is assumed the fire load has reduced sufficiently for fire fighting personnel to be able to gain access to the source and start in their attempts to extinguish the fire. However, in Switzerland and Austria, where tunnels through mountains tend to be far longer in length and more remote in their location, the RWS curve is also applied, but extended to 180 minutes duration. The failure criteria for specimens exposed to the RWS time/temperature curve is that the temperature of the interface between the soffit of the concrete and the protective covering should not exceed 380°C and the temperature on the reinforcement should not exceed 250°C, for concrete grades up to C30.

RABT-ZTV Curve

The RABT-ZTV curve was developed in Germany as a result of a series of test programmes such as the Eureka project. In the RABT-ZTV curve, the temperature rise is very rapid up to 1200°C within 5 minutes, faster than the Hydrocarbon curve which rises only to 1150°C after 60 minutes. The duration of the 1200°C exposure is shorter than other curves with the temperature drop off starting to occur at 30 minutes (see Table 2).

Table 8: RABT-ZTV fire

Time (minutes)	Furnace temperature (°C)	Time (minutes)	Furnace temperature (°C)
3	890	30+	Cooling down phase
5	1200		Cooling down phase
10	1200		Cooling down phase
30	1200	140	terminated

This test curve can be adapted to meet specific requirements. In testing to this exposure, the heat rise is very rapid, but is only held for a period of 30 minutes, similar to the sort of temperature rise you would expect from a simple truck fire, but with a cooling down period of 110 minutes. If required, for specific types of exposure, the heating period can be extended to 60 minutes or more, but the 110 minute cooling period would still be applied.

The inclusion of the controlled cooling period after the 30 or 60 minute period or heating is very important, as the cooling process can often lead to rapid deterioration of the concrete or any protection system.

30 minutes RABT-ZTV is the minimum requirement for road tunnels. For rail tunnels, the EBA guidelines are applicable, which asks for 60 minutes RABT-ZTV.

The fire tests carried out using the RABT-ZTV curve have slightly different failure criteria to the RWS requirements. For exposure according to the RABT-ZTV curve, the failure is regarded as the time the steel reinforcement reaches or exceeds 300°C. The requirements of other countries who strictly apply fire protection to tunnels is as follows.

Austria and Switzerland apply 180 minutes RWS.

France applies a modified Hydrocarbon curve similar to RWS but with 50°C lower maximum temperature.

Based on specific tunnel characteristics, Japan applies either 60, 90 or 120 minutes RABT-ZTV curve for all fire protected tunnels.

Ireland applies 180 minutes Hydrocarbon curve to some new tunnels.

Australia and the USA apply 240 minutes Hydrocarbon curve.

China typically applies Hydrocarbon or RABT-ZTV depending on location and tunnel type.

As can be seen from the above, Ireland would generally apply the Hydrocarbon curve in tunnel applications, but would extend the exposure period to which the structure must be protected against, this provides a trade off between a lower, less severe temperature rise, against the longer exposure period.

As can be seen from the table below detailing the typical fire loads and exposure periods, it is possible to utilise a hydrocarbon curve in place of using the RWS, provided the exposure period is extended.

Table 9: Fire load / Fire curves

Traffic type	Fire exposure period	Representative nominal fire curve
Pedestrian	0	None (negligible)
Bicycle	2 minutes	None (negligible)
Hay wagon	90~120 minutes	Hydrocarbon
Car (5~10 MW)	30~60 minutes	Cellulosic/Hydrocarbon
Container/Shuttle	120 (+) minutes	Hydrocarbon/RABT
Lorry (100 MW)	120 (+) minutes	Hydrocarbon / RABT
Tanker (300 MW)	120 minutes 240 minutes	RWS and/or Hydrocarbon
Bus	90~120 minutes	Hydrocarbon
MTR/Light rail (40 MW)	120 minutes	RWS/Hydrocarbon
Train	120 minutes 240 minutes	RWS Hydrocarbon

The temperatures detailed in Figure 3 below, are those taken from a series of fire tests carried out in disused tunnels, as part of a European research programme. The highest temperature shown of 1000°C was recorded in the area of a small lorry loaded with 3 tonnes of modern furniture. This shows that even loads which could be considered relatively safe to carry through a tunnel, can have a marked effect on the heat generated by a fire within such an enclosed space.

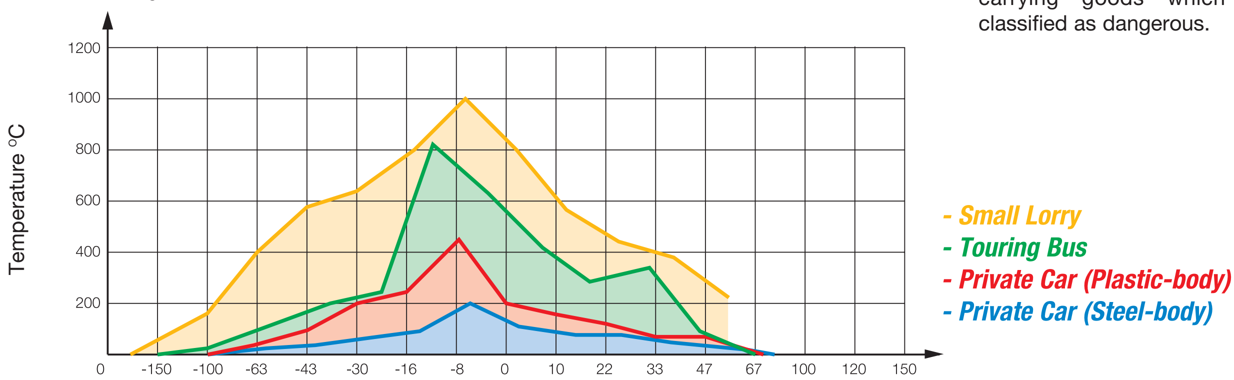
It should be noted that none of the vehicles used in the tests detailed above would in general be regarded as hazardous. It is estimated that a tanker load of petroleum spirit or liquefied gas would burn much hotter and for a greater duration than any of the above. As an example of this, take the scenario of a petrol tanker loaded with 50,000 litres of petroleum spirit, the fire load in this instance equates to some 300MW with a fire duration of at least two hours before the spirit burns off. This is based on the assumptions of the combustion energy of petrol of 2MJ and a pool area of fuel of 150m^2 (approximately a square area with sides equivalent to a standard tunnel width of 12 metres).

Tunnel fires are of a different nature when compared to the types of fire experienced in "normal" buildings; with very hot temperatures lasting much longer. The tunnel itself sometimes works like a convection oven, drawing air in to fuel the fire. The air temperature during the Channel tunnel fire reached sufficiently high enough to heat the concrete to nearly 1300°C.

As an example of the duration of real fires within tunnels, refer to Table 2 on page 5. It should also be noted that in the majority of cases, the vehicles involved in the initial fire were not carrying goods which could be classified as dangerous.

Figure 3: Temperature at ceiling level during tunnel fires

Maximum temperatures in the ceiling area of a tunnel recorded during fire tests using road vehicles as the fire load.



Over the past hundred years or so, since Portland cement was invented in 1824, and first used in an engineering solution by Isambard Brunel in 1828 in the Thames Tunnel, people have come to regard concrete as a solid and dependable product, used in every conceivable type of structure; for buildings, bridges, tunnels and sometimes even ships.

Concrete has always been thought of as behaving well in a fire. Not just because it is non combustible, but also because as part of a structure, concrete has better fire-resistant properties than, say, unprotected steel. Yet if we compare the loss of strength in both concrete and steel as temperature rises we find that the two materials differ very little in this respect.

The fire resistance of a concrete structural member is derived from the following properties:

LOW COEFFICIENT OF THERMAL CONDUCTIVITY
This term refers to the fact that the heat generated by exposure to fire is less able to penetrate structural members.

HIGH THERMAL CAPACITY
This means that the rise in temperature in the outermost surface layer of the concrete is far more rapid than in that within the depth of the concrete. As a result, the average rate of temperature rise in a concrete member is relatively low.

MASS
Because concrete has less inherent strength than steel, the cross sections of concrete structural members are always larger, given the same loadbearing capacity, than those of steel members.

COMPOSITE ACTION
Only reinforced or pre-stressed concrete can absorb tensile stresses. However, the behaviour of the reinforcement is important not only in structural members subjected to bending and tension but also in reinforced concrete members subjected to compression.

In a fire, the rate of temperature rise to the critical temperature (approximately 500°C) in reinforcement subjected to tension is comparable to that in a steel girder, assuming that the steels are of approximately the same type and the maximum tension is of roughly the same order of magnitude.

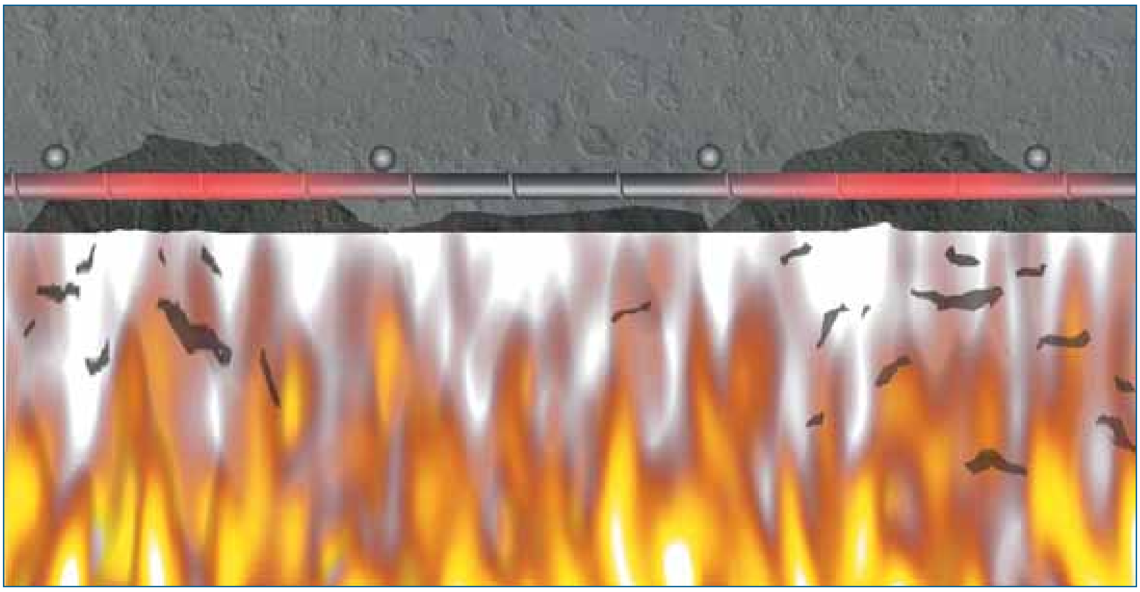
Experiments using standard fires (see Figure 3) have shown that where reinforcement lacks the protection afforded by the concrete this critical temperature of approximately 500°C is reached within 10 minutes of exposure to the sort of temperatures that would be expected under fire conditions within tunnels.

Given that a concrete member has inherently good fire resistance, the question naturally arises why, then, is it necessary in certain circumstances to protect it with fire-resistant cladding. Laboratory tests have shown that concrete structures subjected to compression generally fail when their compression strength is exceeded. In practice it will be rare for an entire structure to be subjected to compression, except perhaps where pre-stressed concrete has been used.

In the laboratory the concrete cross-section is heated by a standard fire. As a result of this the strength of the concrete falls when the critical temperature is reached. The critical temperature depends on the load. Netherlands standard NEN 6071 sets out, in 10.1.2.1, a simplified method of calculating this. There it is assumed that a cross-section is fully loadbearing at a temperature of 400°C or less. However, this 400°C is not the critical temperature: The hotter shell continues to bear some of the load while the core is not 100% loadbearing.

What is spalling? When mature dried concrete is exposed to extreme heat for long periods of time, the chemical bonds between the water molecules in the concrete break, destroying molecular bridges that bind together the various materials that make up concrete. As the water molecules are extracted from the concrete through dehydration, the concrete loses its cohesion and weakens, pushing pieces of the concrete off the tunnel walls in very thin layers resembling onion peel. This phenomenon, called spalling, can eventually work its way through the entire concrete ring lining a tunnel, layer by layer.

Figure 4: Spalling



- Free & Chemically bound water combine to cause steam pressure build-up
- Expansion Ratio of water-to-steam = 1 : 1700
- Fire temperatures in excess of 500°C
- Concrete Grade dependant
- Moisture content over 3% = Spalling almost 100% within 30 minutes of exposure.

NOTE: On recent tests carried out on tunnels in Netherlands, the average moisture content of the concrete 10 years after construction was approximately 6~7%.

Research has shown that concrete structures can suffer surface spalling as a result of high compression stresses in the heated outermost layers and by the generation of water vapour at a high pressure behind those layers. The probability of spalling increases with compression stress and the moisture content of the concrete. With a moisture content of over 3% of the mass, the probability of spalling is virtually 100%.

Rapid rates of heating, large compressive stresses or high moisture contents (over 5% by volume or 2% to 3% by mass of dense concrete) can lead to excessive spalling of concrete cover at elevated temperatures, particularly for thicknesses exceeding 40mm to 50mm. This water is not only physically present (moisture), but also chemically bound within the concrete (hydrated water).

Such spalling may impair performance by exposing the reinforcement or tendons to the fire or by reducing the cross-sectional area of concrete. Concretes made from limestone aggregates are less susceptible to spalling than concretes made from aggregates containing a higher proportion of silica, e.g. flint, quartz and granites. Concrete made from manufactured lightweight aggregates suffer a lesser degree of spalling. The use of high strength concrete has been introduced as it can reduce the necessary thickness required to obtain a certain structural performance. However, high strength concrete is particularly prone to severe spalling when exposed to fire. As the depth of the concrete has been reduced already, the effects of spalling are even more severe than normal.

Table 10: Points of consideration when comparing PROMATECT®-H or PROMATECT®-T boards to Polypropylene fibres (PPF) for fire protection of concrete structures

Item	PROMATECT®-H or PROMATECT®-T boards	PP fibres
Insulation of the rebars	Fully insulates to pre-set and pre-designed limits of maximum requirements.	No insulation at all.
Bond between steel and concrete	Maximum temperatures not exceeded at reinforcement, maintains bond.	At 300°C the bond between rebars and concrete will be significantly reduced.
Replacement of concrete after fire	Only the PROMATECT® boards must be replaced after severe fires.	All concrete, which was exposed to temperatures exceeding 380°C must be replaced. Even after small fires (T>160°C) repairs are required because the fibres have melted, and therefore can no longer fulfil their intended function.
Long term durability, chlorides	PROMATECT® boards have no adverse effect on the durability of concrete structures.	PP fibres create small channels in the concrete, due to the hydrophilic properties, enabling chlorides and sulphates to penetrate the concrete and attack the rebars.
Damaged area after fire	Relatively small damaged area.	Damaged area (T>380°C) bigger than that directly affected by fire.
Avoid spalling	PROMATECT® boards are designed to reduce temperature increase on and in the concrete structure and therefore prevent spalling occurring.	Until now all tests with PP fibres have shown spalling of the concrete specimen. PPF do not stop structural damage occurring due to high temperatures (micro cracks occur at 150°C)
Influence on the concrete properties	PROMATECT® boards have no adverse effect on the properties of concrete structures.	PPF reduces compressive strength leading to brittle failure. PPF will also cause reduced pull out strength of anchors due to melted fibres.
Influence on workability of the concrete	PROMATECT® boards have no adverse effect on the workability of concrete structures.	Workability decreases with increasing concentration of fibres. 3kg/m³ of fibres dehydrates the concrete mixture severely, making it difficult to pump or pour the concrete.
Being able to withstand all types of fires	PROMATECT® boards can withstand all types of fires, up to the most severe RWS fire.	A smouldering fire will cause dehydration of the outer layer of concrete, causing even more aggressive spalling when temperatures increase after 20~30 minutes.
Influence on the clearance of the tunnel cross section	PROMATECT® systems are relatively thin, <40 mm depending on the fire requirements.	PPF tunnels require larger cross sections, bigger TBM's, more tubing segments, bigger volumes of excavated soil etc. Sacrificial linings, containing PPF can be over 250 mm thick.
Quality control of the fire protective system	PROMATECT® boards are produced to ISO 9001 quality standards.	How controllable is a homogeneous mix made up on site? PP fibres must be evenly distributed throughout a mixture. Impossible to control or to check. Therefore performance under fire is unpredictable.

In addition to surface spalling, the in depth research that has taken place, both after real fires, and when tests have been carried out in disused tunnels (e.g. the Eureka project) show that deep cracks will appear in the concrete after the substrate has cooled down.

When spalling occurs - which can also be dangerous for the immediate environment due to the explosive nature of the spalling on some types of concrete - the reinforcement is exposed. In a ‘normal’ fire ordinary reinforced concrete is unlikely to fail completely but repair costs can be considerable. Where pre-stressed concrete has been used the detrimental effect of spalling is greater and more dangerous.

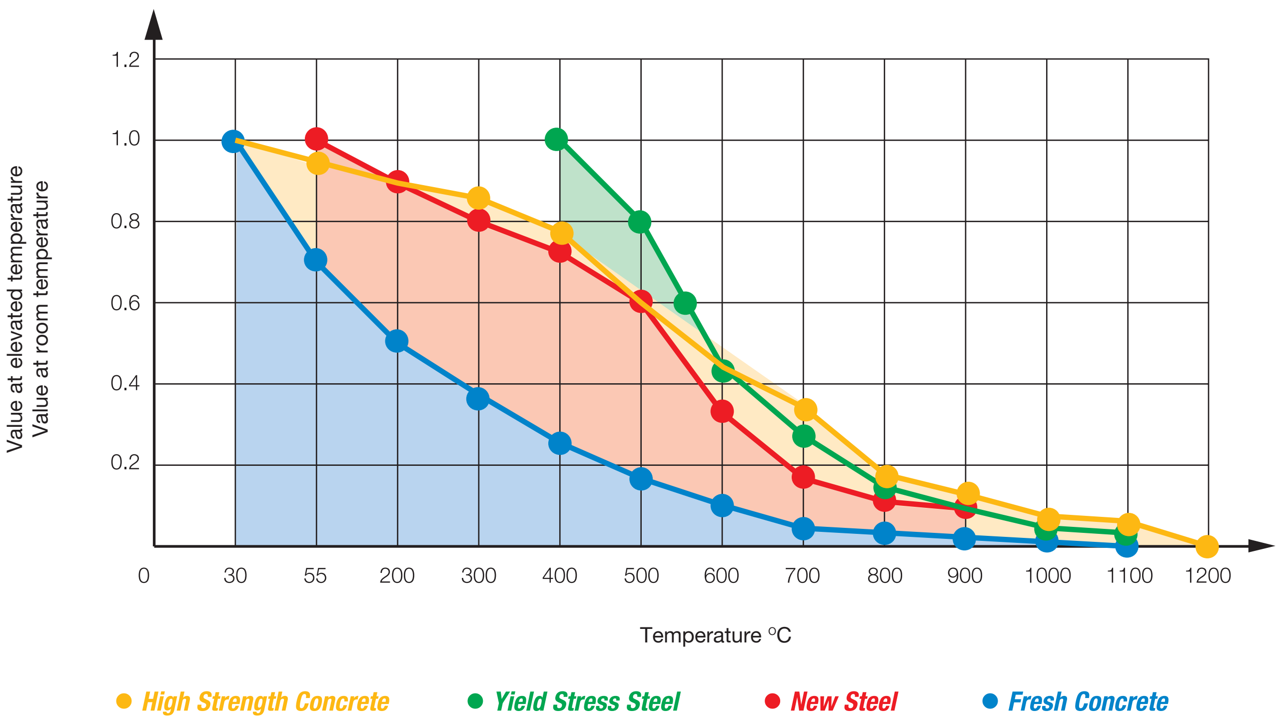
At the time of writing the latest investigations into the fire performance of concrete show that even the addition of polypropylene fibres into the concrete mix, will not always suffice to reduce this water vapour pressure, and thus can have little effect on reducing the incidence of spalling. It should also be noted that the majority of testing carried out to date on the performance of concrete with the addition of polypropylene fibres has been to the standard cellulosic curve, and not to the greater exposure requirements of tunnel fire curves. Even for these relatively low temperature rise fires, the proportion of PP fibres to concrete mixture required is such that the concrete is often very stiff and difficult to work. Care should therefore be taken to ensure claims for the performance of PP fibres are substantiated by adequate evidence.

Figure 5: Spalling in brick lined tunnel

3

Figure 6: Influence of temperature on concrete

Influence of elevated temperatures on the mechanical material properties of concrete and steel.



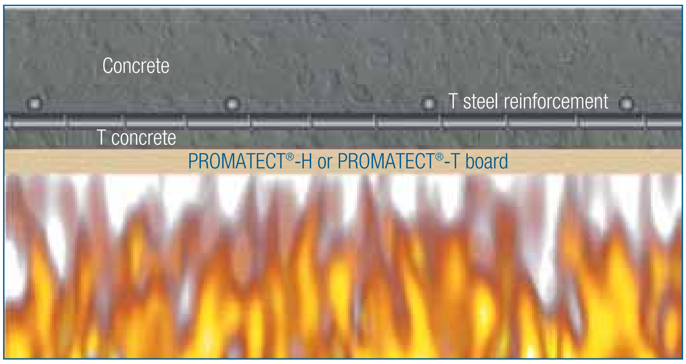
Criteria for The Fire Resistance of Concrete

As explained previously, unprotected concrete with a moisture content of over 3% of the mass will suffer surface spalling in a fire, probably after between 5 and 30 minutes. It is also possible for aggregates in the concrete (e.g. quartz) to have undesirable effects on its behaviour in a fire.

The criteria for fire resistance has been drawn up by a number of official bodies. The Dutch standard gives it as a rule of thumb that in the case of loadbearing members account should be taken only of cores whose temperature is less than 500°C (for structural steel). At the tension at which reinforcing steel is commonly used today, the steel becomes non loadbearing at 500°C. In statistically determinate structures this leads to failure. In statistically indeterminate structures redistribution of the moments is often possible, so that a higher temperature of the reinforcing steel need not necessarily lead to failure.

Figure 7: Spalling of concrete after real fire

Figure 8: Reinforcement temperatures



Based on the requirements for exposure to an RWS type fire:

- Temperature on the concrete interface should not exceed 380°C (for bored tunnels this limit is 200~250°C). No spalling is allowed.
- Temperature on the reinforcement should not exceed 250°C with a minimum of 25mm concrete cover (NOTE: For exposure to RABT, the reinforcement temperature should not exceed 300°C).

There is a high risk of failure due to the temperature of the steel in the concrete in columns with a high reinforcement level under high loads. For this reason, the (non-normative) tables give a critical steel temperature of 500°C for ordinary concrete and 400°C for tension steel.

In the Netherlands, Rijkswaterstaat lays down for tunnels a maximum permissible concrete surface temperature of 380°C.

This maximum was set not because of any perception that concrete fails at that temperature, but because it is assumed that in practice this is a temperature at which there is only a very small probability of damage to concrete.

This requirement also implies that the temperature of the underlying reinforcement remains low, so that its strength is unimpaired. In Switzerland the maximum is set even lower: there the surface of the concrete in tunnels must not exceed 250°C.

Some other relevant points are as follows:

- The design of the tunnel section has an effect on fire induced collapse.
- Rectangular tunnels are typically constructed using a grade C30 concrete.
- Failure of rectangular structures is usually due to the premature development of sagging plastic moment caused by elevated temperatures of the concrete and the reinforcement.
- Rectangular structures suffer from less spalling than circular tunnels and have limited compression loads.
- Circular tunnels constructed from segmented reinforced concrete sections typically use a C50 grade concrete.
- After completion, the reinforcement in circular tunnels is more or less obsolete, it is really only required to assist handling during installation.
- The reinforcement in circular tunnels is not required to take tension forces in sagging moment because the concrete is typically in compression.
- The higher strength concrete (C50) suffers a higher percentage and depth of spalling.
- The depth of spalling under fire conditions is an average 100% deeper on these types of circular tunnels.
- Concrete of close, small pore (e.g. C70) will suffer more substantial spalling in the event of exposure to fire.

Considerations When Applying Protective Materials

In the design of a system to protect concrete, the following questions need to be answered to determine the correct material types to be used.

- **What type of fire needs to be resisted?**
- **How long must the protected structure survive?**
- **What is the traffic load in ordinary use?**
- **Type of concrete?**
- **The maximum temperature of the fire to which the lining will be exposed, i.e. what is the likely fire load? Will dangerous goods such as petrol, liquefied gas etc be transported through the tunnel?**
- **The time taken to reach the maximum projected temperature, i.e. what type of time/temperature curve should be applied to the projected scenario?**
- **The moisture content of the concrete?**
- **The density of the concrete?**
- **The aggregates used in the concrete mix itself.**

The period of time the structure has to be able to survive without failing and the type of fire to be withstood; together determine the thickness of the protection that is required. The requisite protection material thicknesses will be found in the fire test reports provided by the manufacturer of the protection materials. These reports also give guidelines for the complete protection system, including any fixings and/or framing requirements.

Spray Materials

Although many concrete structures are protected with cementitious spray materials, particularly to the underside of soffits in car parks etc, the use of spray materials in tunnel applications has on occasion proved problematical in the past. This is partly due to the environmental conditions of tunnels, and partly due to the fact that in general the adhesion relies on a chemical bond which has been seen to fail. Resulting in some instances, that the tunnel owner has been forced into a position of needing to replace the spray with a board type material for extra durability offered by board systems. In most cases where spray is to be applied, a steel reinforcement mesh has to be applied, which can increase the installation time and the costs of the systems.

Unlike a board material, for which the thickness of the board is easily checked and therefore the protection afforded to the structure is guaranteed. The application of spray materials are susceptible to operator error, with varying thickness of application, and variations in the quality of the mix itself, both of which in turn can lead to premature failure of the protective coating, even under normal ambient conditions.

Many cementitious sprays also provide inadequate performance when subject to water ingress, such as may well be experienced in immersed tunnels. Weak adhesion caused by water filtration through the rear of the spray can be exacerbated by the suction from passing traffic, leading to the spray falling away from the substrate in some instances.

It is very difficult, where spray materials are used, to allow for periodic inspection of the concrete substrate, when spray is removed for these inspections, the requirement for specialist equipment to reapply the covering will result in delays in reapplying the fresh spray, which will, in turn, mean that for this period of time, the concrete is, in effect, unprotected.

Board Materials

Board materials can be easily checked for thickness and thus the application can be guaranteed to meet with the specifications as per the tested constructions. In addition, being mechanically fixed, suction and wind loading from passing traffic has no adverse effect on boards, with correctly installed products remaining in place without any deformation occurring.

Boards are completely unaffected by combustion by products of traffic passing through tunnels, and are also unaffected by the ingress of water. In fact in very wet tunnels, boards can act as a conduit for water, ensuring the excess runs off into the tunnel drainage systems rather than dripping onto the road surface.

Board protection systems will also act as a form of filter during exposure to fire, ensuring the chlorine gases etc given off by burning rubber and plastic used in the construction of modern vehicles, and which are extremely corrosive in nature, do not have direct access to attack the concrete and reinforcement of the tunnel linings.

Using a board product such as PROMATECT® ensures that condensation as a result of wet tunnels does not form on the exposed surface of the boards, but rather this small amount of moisture is absorbed by the PROMATECT® and then evaporated into the surrounding air. The absorption of water into PROMATECT® has no adverse effect on the performance of the board in any manner whatsoever.

Board systems in general require no maintenance at all. Where access is required to periodically inspect the concrete substrate, boards can quickly and easily be removed and reinstated, thus maintaining the fire protection layer at all times.

Bored Tunnels Using Concrete Segments

A bored tunnel refers to a construction method for tunnels which involves digging a tube-like passage through the earth. The term usually refers to tunnelling through rock, as blast tunnelling is not widely used these days. Bored tunnels are created using a full face boring machine. This is a tunnelling machine which has cutting teeth at its front. It creates the tunnel opening while passing the waste material through the rear.

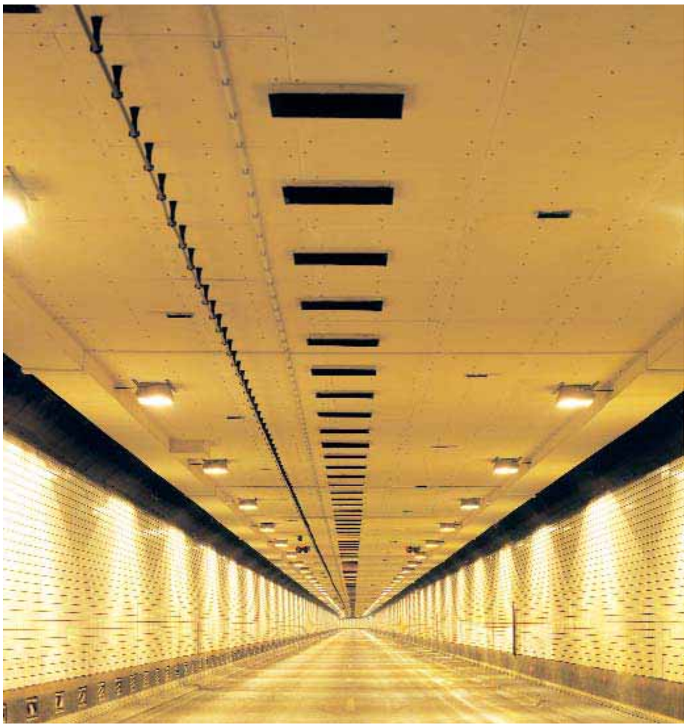
Many types of tunnel boring cut small sections which are progressively enlarged. A full face boring machine cuts the complete cross section of the tunnel at once.

The Tunnel Boring Machine (TBM) consists of a long machine with a circular cutting head that rotates against the face of the tunnel. Attached to the cutting head is a series of steel disk cutters that gouge out the rock on the face as the machine rotates and the cutting head is pushed forward by hydraulic power. TBM's provide several advantages over drilling and blasting. The tunnel can be bored to the exact size desired, with smooth walls, thus eliminating the condition called overbreak, which results when explosives tear away too much rock.

The use of TBM's also eliminates blasting accidents, noise, and earth shocks. Workers need not be concerned with fumes or noxious gases and can clear away broken rock without stopping for blasting intervals.

A TBM can advance about 76 metres (about 250 ft) a day, depending on the diameter of the tunnel and the type of rock being bored. Despite these advantages, TBM's have some drawbacks. They are very costly and the cutting head must be the same diameter as that required for the tunnel. They are useless in soft ground and mud, which may collapse as soon as the machine digs in and removes spoil.

Often the TBM is part of a long train of machines, at the rear are stored circular concrete sections, which are installed as the TBM moves along the route, thus the tunnel is simultaneously lined as it is being drilled. This was the method used for the construction of the Channel tunnel between England and France.



Immersed Tunnel

Immersed tunnel is a method of constructing each section using pre-fabricated tube sections. While the ends are sealed, it is lowered into position under the water and attached to other sections.

Another method of underwater tunnel construction uses a caisson, or watertight chamber, made of wood, concrete, or steel. The caisson acts as a shell for the building of a foundation. The choice of one of three types of caissons, the box caisson, the open caisson, or the pneumatic caisson depends on the consistency of the earth and the circumstances of construction.

Difficult conditions generally require the use of the pneumatic caisson, in which compressed air is used to force water out of the working chamber.

Another method of constructing underwater tunnels, such as the Noord tunnel in the Netherlands, have been built by fabricating short tunnel sections in a trench in or near the riverbed or seafloor. Each section, after completion, is then sealed at the ends, floated out and located in position, where it is then sunk onto the riverbed.

After sinking, the sections are then attached by oversized bolts to the previously sunk section in line. Heavy, thick concrete walls prevent the tunnel from floating once the water is pumped from the completed sections.

Cut & Cover Tunnels

A construction method which involves excavating a large trench, building a roof structure, then covering it with earth. Commonly used for subways and relatively flat locations.

The cut-and-cover method can also involve digging a trench; building the concrete floor, walls, and ceiling, or installing precast tunnel sections; and then refilling the trench over the tunnel. In built-up areas in cities, use of this method is often not possible. In soft earth or mud, a large-diameter pipe like device can be driven through the ground by jacks or compressed air. Workers remove the earth as the pipe moves forward, its edge cutting into the earth.

One method of building a form of cut and cover tunnel is detailed in Chapter 7. In the instance detailed, the diaphragm walls are constructed within a trench, the roof is then built over the earth and once the concrete has set, the spoil within the tunnel is removed. In this manner, the earth left in position between the diaphragm walls can be used to act as a base for the formwork.

Where daily use of a road or rail tunnel involves high traffic loads, the demands placed on means of attachment will be more onerous. Traffic passing through a tunnel causes high suction loads on ceilings due to the displacement of air by vehicles. This suction load depends on the type of vehicle (e.g. car, train or tram) and the headroom. The value usually taken is 100kg/m^2, or 1kN/m^2.

The weight of the cladding and the number of attachment points can be determined by means of a load simulation for traffic passing through a tunnel. The manufacturer of the pertinent cladding material should provide reports which show the exact types of fixing methods employed, and the loads from suction etc that the systems are designed and tested to take.

Attention need also be paid to the material from which the fixings are manufactured, e.g. fixings can be zinc galvanised steel, stainless steel etc; and the condition of the concrete itself.

Therefore, before any choice of fixing can be made, some of the major considerations include: The likely corrosion to which the anchors may be subject, the crack width, if any, and the compressive strength of the concrete.

Corrosion

Following extensive research, anchors made from stainless steel grade 1.4401 and 1.4571 have, in some countries, been banned from use in such chloride contaminated atmosphere. An atmosphere with extreme chemical pollution such as road tunnels have an extremely corrosive environment, caused by traffic pollution (sulphur oxide); the ingress of underground water (sodium chloride, sodium sulphate, calcium sulphate); materials and chemicals used for de-icing, and the possibility of salt laden air in coastal regions and by rivers.

Combined with the fluctuating air pressure from passing vehicles, this leads to ideal corrosive conditions and thus stainless steel fixings of these grades are unsuitable as the atmospheric pollution can possibly result in stress corrosion cracking of the fixing.

As a result of the recent research carried out, only anchors made from high alloy stainless steel should be permitted for use in tunnel applications.

With the research that has taken place over the last ten years or more, both by fixing manufacturers and independent research bodies, it has been determined that the optimum material for fixings in tunnels should consist of stainless steel of grade 1.4529. This material is resistant to all types of corrosion, surface pitting, and corrosion induced stress cracking.

Crack Width in Concrete

In accordance with many international standards (e.g. BS, DIN, Euro codes), the maximum acceptable crack width in reinforced concrete is limited to wk = 0.3mm under semi permanent loadbearing conditions. If structures are subject to exceptional loading i.e. seismic, then there is a possibility that wider cracks could occur. Recent analysis shows that the cracks in reinforced concrete structures could be as wide as 1.5mm after being subjected to earthquakes to the maximum design load.

Anchors could be situated near to, or even within cracks in the concrete, and as worst case, could even be positioned at the intersection point of two cracks. Tests have confirmed that in the event of concrete cracking, there is a high probability that at some point, these cracks would radiate into contact with the fixings. This is particularly true of expansion bolts, because there are local tensile stresses in the area surrounding the fastening due to the expansion forces of the bolts.

The type of bolt to be used should be chosen with due consideration of the possibility of the concrete cracking, and an appropriate type of fixing utilised.

Compressive Strength of Concrete

If a tunnel is constructed using high strength concrete, the nominal compressive strength of the concrete would be approximately 60N/mm^2. However, it is often the case that the compressive strength is far higher than this, at around 90~100N/mm^2.

Anchors in which the fastening is by means of torque control or displacement controlled friction locking are not suitable for use in this type of high strength concrete. Torque controlled anchors are not capable of creating the deformation in the concrete which is required for the bolt head to expand into, and thus the load would be held by friction of the bolt within the drilled aperture only. As a drilled hole tends to be smooth, the friction between the anchor and the hole is minimal and the loading that can successfully be applied is rather low.

For fixing into high strength concrete, undercut anchors should be used, as these do not rely on the compressive strength of the concrete, nor the smoothness of any drilled hole.

Table 11: Austenitical steel (Stainless steel)

Group	Material number	DIN code	AISI code	Chemical composition						
				C	Si	Mn	Cr	Ni	Mo	Sundries
A1	1.4300	X12CrNi18.8	302	0.12	1.00	2.00	18.00	9.00	NA	NA
A1	1.4305	X12CrNiS18.8	303/303F	0.15	1.00	2.00	18.00	9.00	NA	S-0,15
A1	1.4310	X12CrNi17.7	302	NA	NA	NA	NA	NA	NA	NA
A2	1.4301	X5CrNi18.9	304	0.07	1.00	2.00	18.00	10.00	NA	NA
A2	1.4303	NA	NA	0.10	1.00	2.00	17-19	11-13	NA	NA
A2	1.4306	X2CrNi18.9	304L	0.03	1.00	2.00	18.00	11.00	NA	NA
A2	1.4550	X10CrNiNb18.9	347	0.10	1.00	2.00	18.00	10.00	NA	NA
A2	1.4551	X10CrNiTi18.9	321	0.10	1.00	2.00	18.00	10.00	NA	Ti
A4	1.4401	X5CrNiMo18.1	316	0.07	1.00	2.00	17.50	12.00	2.25	NA
A4	1.4404	X2CrNiMo18.10	316L	0.03	1.00	2.00	17.50	12.00	2.25	NA
A4	1.4435	X2CrNiMo18.12	317L	0.03	1.00	2.00	17.50	13.50	2.75	NA
A4	1.4436	X5CrNiMo18.12	D319	0.07	1.00	2.00	17.50	13.00	2.75	NA
A4	1.4529	X1NiCrMoCuN25.20.6								
A4	1.4571	X10CrNiMoTi18.10	316Ti	0.10	1.00	2.00	17.50	11.50	2.25	Ti

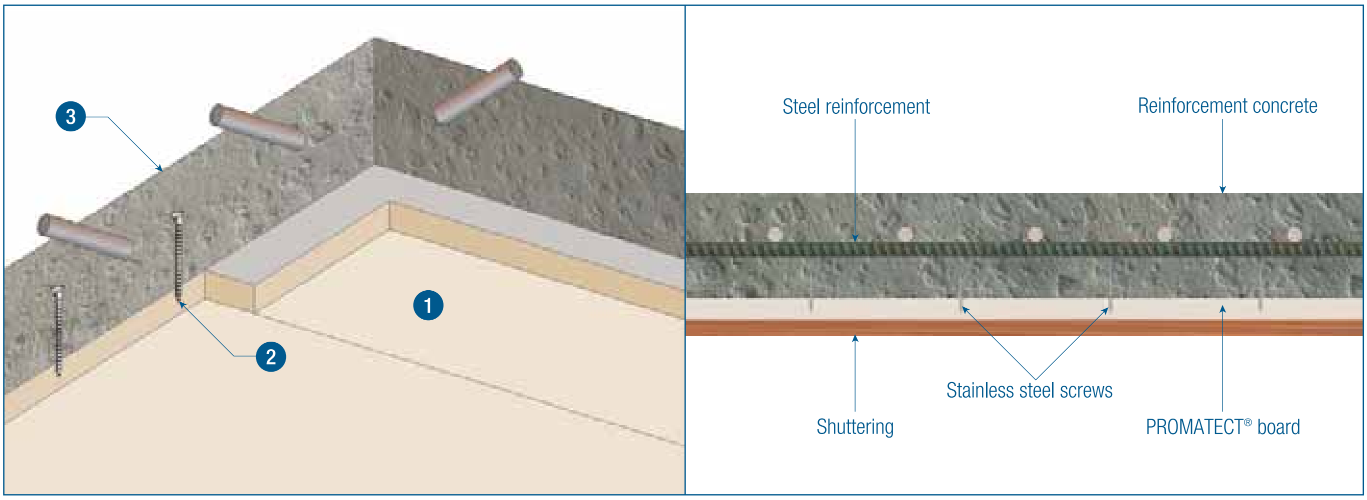
NA = Not applicable

As Lost Shuttering

In certain tunnels, it is possible to use PROMATECT®-H or PROMATECT®-T boards as a form of lost shuttering. In these instances, a bed of earth is built up to form the inner shape of the tunnel, over which is laid a bed of soft sand. This sand is rolled and compressed to form a hard stabilised layer.

1. **PROMATECT®-H or PROMATECT®-T, thickness commensurate with fire resistance requirement.**
2. **Stainless steel screws, length and quantity per square metre in accordance with the details in Table 12.**
3. **Concrete forming tunnel roof.**

Figure 9: PROMATECT®-H or PROMATECT®-T board used as lost shuttering



Substrate

The condition of the substrate is critical in that it cannot allow any movement of the PROMATECT®-H or PROMATECT®-T boards once they are in position, and therefore must be very well compacted. Onto this substrate, the PROMATECT® boards are positioned. If using this method in locations where heavy rain could be expected, drainage channels should be prepared beneath the PROMATECT® board, and the boards then lain over these channels. It should be noted that the dimensions of such drainage channels should not be so great as to remove too much support from the PROMATECT® board positioned above.

Where temporary support or columns are to be included, it may be sensible in these locations to use standard formwork, which can be removed after the concrete pour, and the PROMATECT® board in these areas reinstated using the post construction method.

As an alternative to using the earth bank method, standard shuttering supports can be employed, substituting the PROMATECT® board on top of the usual plywood.

Figure 10: Noord Tunnel, Rotterdam

Figure 10 above, shows details of the Noord tunnel, Rotterdam, Netherlands, being constructed using standard shuttering supports, with PROMATECT®-H boards in place of Plywood formwork.

Laying of PROMATECT®-H or PROMATECT®-T Board

For this type of application, the PROMATECT®-H or PROMATECT®-T boards are supplied cut to dimensions of 1200mm x 1200mm, to make for easy handling. These boards are supplied cut to very close tolerances to ensure there should be no gaps between offset boards.

The PROMATECT® boards should be laid with the smooth face down, as this will provide the fair faced finish after completion of the tunnel. Care should be taken that as the boards are laid, grit does not become trapped between the edges of adjacent boards, as this will cause a gap to be created through which cement slurry can run.

If during laying, there is any apparent running out and gaps start to appear, then boards may have to be lifted, the joints cleared out, and the PROMATECT® board realigned. However, if sufficient care is taken to ensure joints are clean, this problem should not occur.

When laying boards, care should be taken not to walk on exposed edges as damage may occur. If any damage occurs to boards, they should be placed to one side for use towards the end or walls of the tunnel where it may be necessary to cut the PROMATECT® board to suit, in which case possibly the damaged boards can be used in these areas.

Figure 11: PROMATECT®-H or PROMATECT®-T formwork as soffits at wall junction

In Figure 11 above, the PROMATECT®-H or PROMATECT®-T board is being laid onto a soft sand substrate, which would be removed after the concrete pour, as an alternative to the use of the standard shuttering support as depicted in Figure 10 previously.

Cutting PROMATECT®-H or PROMATECT®-T Board

Cutting of PROMATECT®-H or PROMATECT®-T should be undertaken using a mechanical hand saw, the ideal specification is for a portable saw with a minimum 10" (250mm) blade, with tungsten carbide teeth. The saw should run at a minimum of 2500 RPM. When cutting thick PROMATECT® board, it is recommended that a bench be set up to support the weight of the boards during cutting, to ensure good quality clean cut edges are provided.

In all instances it should be noted that although the dust from PROMATECT® board is not harmful under normal circumstances, we would recommend the use of dust extraction equipment and the wearing of face masks as standard practice. In certain countries, health and safety regulations would require the use of safety glasses to protect the eyes from particles, which recommendation Promat would endorse entirely.

A health and safety data sheet is available from the Promat Technical Department and, as with any other materials, should be read before working with the board. The board is not classified as a dangerous substance and so no special provisions are required regarding the carriage and disposal of the product to landfill. They can be placed in an on-site skip with other general building waste which should be disposed of by a registered contractor.

Joint Treatment

Although the PROMATECT®-H or PROMATECT®-T boards are produced to very close tolerances, if any gaps occur during laying of the boards, there exists a possibility of slurry leakage through these gaps. Although this would not in any way adversely affect the performance of the finished system, it could be considered unsightly, and therefore where large gaps occur (in excess of 1mm) it may be considered desirable to tape the joints prior to the application of the reinforcement, or apply mastic to the joints between boards to prevent this water leakage.

The tape to be used should have the following characteristics.

- The ability to adhere to a surface which is slightly rough in texture, and would possibly be dusty in nature.
- Should be unaffected by exposure to inclement weather.
- Should be unaffected by wet concrete.
- Should have a minimum width of 75mm.

Angles & Inclines

There are areas where the design may call for an incline of slope to the tunnel soffits, or where a step may need to be incorporated. Such details occur where ventilation shafts or recesses for axial fans form part of the design.

Situations such as these need to be addressed individually as each will differ from project to project, however, the general considerations are as follows.

- The PROMATECT®-H or PROMATECT®-T board must be supported in such a manner that no movement is possible during pouring of the concrete.
- The edges of the PROMATECT® board should be mitred to the correct angles to ensure the protective layer of board retains its full thickness in these positions.
- The joint should be sealed with tape to avoid slurry leakage through any small apertures.
- The joint should be properly supported beneath the panel, i.e. by a timber former as depicted in Figure 12.

Figure 12: Joint support at slopes and angles

Figure 12 above shows a timber batter beneath the joints between the boards, the edges of the boards have been cut to form the requisite angle, and a small steel section is affixed to the top surface of the boards to ensure the boards do not creep apart.

7

As Lost Shuttering *Continued from page 17*

Screws

Once the lower reinforcement layers have been constructed, it is necessary to insert screws into the face of the PROMATECT® boards (see Figures 15 and 16) which act as an additional mechanical key for the concrete onto the surface of the board. In tests, it has been shown that these screws are not really necessary, but they should be included as an additional safety factor.

Figure 13: Support for reinforcement

Figure 14: Reinforcement spacing from PROMATECT®-H or PROMATECT®-T boards

7

The screws are of a length as detailed in Table 12 on page 34, and are positioned at twelve screws per square metre of board surface. The screws are driven approximately 15mm to 20mm into the rear face of the board (see Figure 15), and should be minimum M4 and of the requisite grade of stainless steel alloy.

Care should be taken not to over drive the screws in order to ensure no penetration of the lower face of the PROMATECT® board occurs.

Figure 15: Detail of screws into back face of board

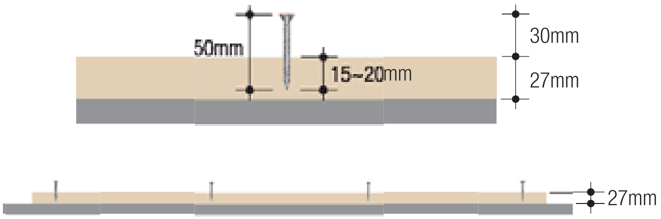
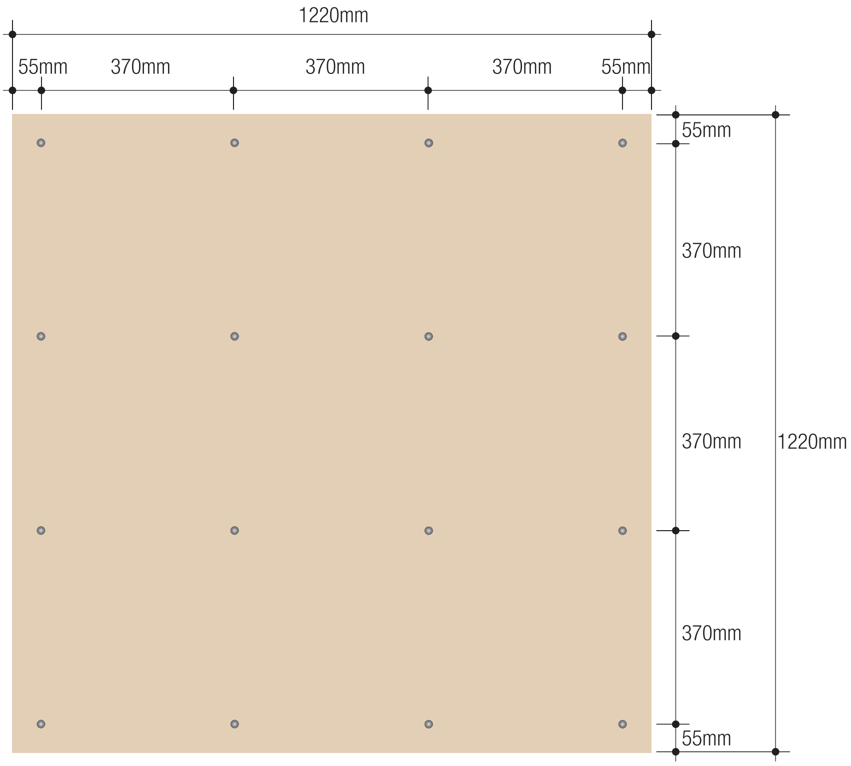


Figure 16: Schematic of screw locations



Pouring of Concrete

It must be remembered that PROMATECT®-H or PROMATECT®-T board is not as durable as standard plywood formwork and therefore consideration must be given to general site practice during the pouring of the concrete.

Before the concrete is poured, the PROMATECT® boards can be hosed down to remove the accumulated site debris, excessive force or volume of water should not be used in order to avoid disturbing the screws. Excessive water should be removed from the surface of the boards prior to the pouring of the concrete.

Pumped concrete should be directed at the reinforcement, thus dissipating the concentrated stream away from the PROMATECT® boards.

During vibration of the concrete, the machinery being used should be kept away from the surface of the PROMATECT® boards.

No special allowance has to be made for curing time when using PROMATECT®-H or PROMATECT®-T board as formwork, follow standard engineering advise for treatment of the cured slab.

Figure 17: Excavation of tunnel beneath PROMATECT®-H or PROMATECT®-T formwork

Excavation

Where the PROMATECT®-H or PROMATECT®-T has been laid upon earthwork support, excavation to the underside will be required once the slab has cured. Where the PROMATECT® boards have been supported on standard formwork, which can simply be struck once curing is complete.

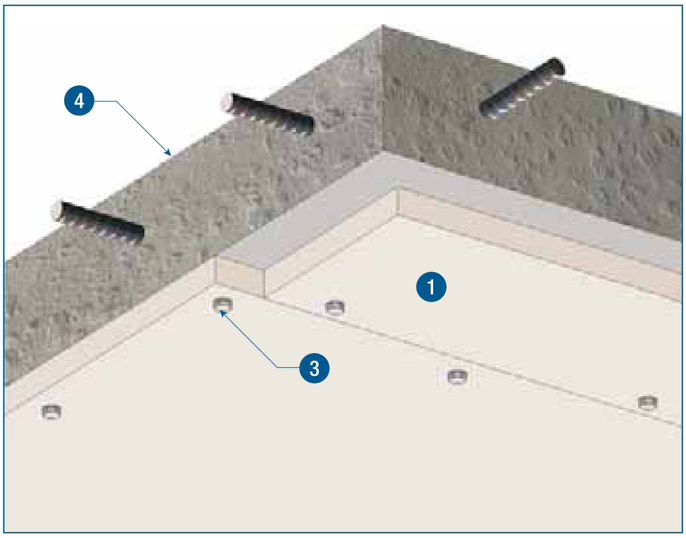
Once the slab is cured, and excavation of the supporting earthworks can proceed, care should be taken to avoid damaging the boards. Care should be taken when removing spoil from the underside of the PROMATECT® boards.

Once excavation is complete, cleaning of the underside of the PROMATECT® board and removal of any spoil clinging to the surface involves simply hosing and brushing the boards down to the desired cleanliness. Any apparent staining from concrete slurry etc should be carefully removed if required, or can be left, these marks would not adversely affect the performance of the PROMATECT® boards in any way.

Post Construction Installation

In many instances, the construction method used to build a tunnel would prohibit the installation of the PROMATECT®-H or PROMATECT®-T using the lost shuttering method. It is also the case that many older tunnels may simply require upgrading. To this end, Promat have also developed and tested systems for the protection of concrete where the fire protection boards are applied after the concrete has been poured.

Figure 18: Post installation of single layer of PROMATECT®-H or PROMATECT®-T boards



1. **PROMATECT®-H or PROMATECT®-T boards fixed to the underside of the concrete using fixings of a length and at appropriate centres in accordance with the details in Table 12 on page 34.**
2. **Where required, a second layer of PROMATECT®-H or PROMATECT®-T is applied to increase the fire resistance of the construction.**
3. **Expansion bolts or alternative fixings of a length and at appropriate centres in accordance with the details in Table 12 on page 34. Note that for single layer system, bolts used in conjunction with washers to prevent penetration of the bolt head into the board. For multiple layer system, it is possible to finish with the bolt heads flush to the surface of the board, subject to cladding thickness.**
4. **Concrete slab with minimum 25mm cover to the reinforcement. Cladding thickness concrete grade type dependent.**

Figure 19: Post installation of multiple layers of PROMATECT®-H or PROMATECT®-T boards

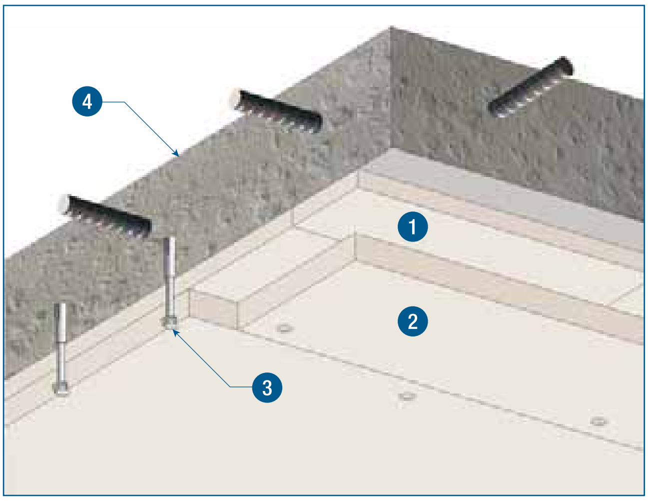


Figure 20: Post construction method in Zeeburg Tunnel, Netherlands

PROMATECT®-H or PROMATECT®-T Board for Post Cladding

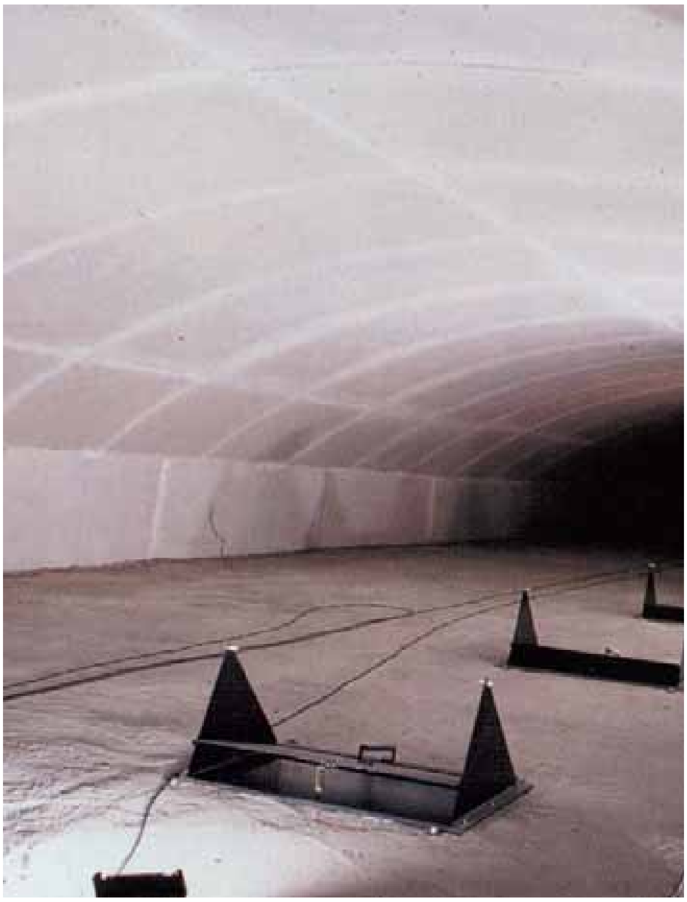
The PROMATECT®-H or PROMATECT®-T boards are available in dimensions up to 3000mm x 1200mm, In general for post cladding installation, the PROMATECTfi boards are supplied cut to dimensions of 1200mm x 1200mm, to make for easy handling on site. These boards are supplied cut to very close tolerances to ensure there should be little or no gaps between boards.

The PROMATECT® board should be installed with the fair face of the board looking down into the tunnel. The boards should be placed into position and carefully held by use of sentries whilst the holes for the bolts are being drilled and the bolts inserted. Although the PROMATECT® boards are relatively small in size, the thicker boards are of a reasonably substantial weight, e.g. 1200mm x 1200mm x 27mm PROMATECT®-H or PROMATECT®-T board weighs approximately 36kg, thus installation should be considered to be a two person operation.

PROMATECT®-H or PROMATECT®-T board can also be supplied in curved sections for application to circular tunnels. It should be noted that these boards are supplied specially manufactured to order, and the specifier should clarify whether or not the boards can match the requisite radius with the Promat Technical Department.

PROMATECT®-T boards can be curved at site, dependent on the diameter of the tunnel and the thickness of the boards, see Figure 37 on page 25. Where a thicker board is required to provide the specific fire resistance level, it is possible to install the PROMATECT®-T boards in multiple layers of thinner panels in order to make up the required thickness whilst still allowing the panels to be curved at site.

Figure 21: Application of curved PROMATECT®-H board in the Elbe Tunnel, Hamburg, Germany (See also Figure 37)



Fixings

Fixings should be of a length and diameter as detailed in table aa. When considering the type of fixings to be used, attention should be drawn to such matters as the likely atmospheric pollution, the type of concrete into which the bolts would be installed, the risk of cracking etc. In addition, the types of bolts used should be consistent with those used in the construction of specimens subject to fire testing.

It is likely that the concrete to which the PROMATECT®-H or PROMATECT®-T boards are being fixed would not be completely flat, therefore care need be taken when fixing the boards to ensure the removal of any large nibs of concrete. In addition, the bolts fixing the boards should be carefully tightened to avoid over turning, and cracking of the boards where positioned on uneven surfaces.

Bolts should be installed a minimum of 100mm from edges of the boards, and should not be located directly in the corners of the boards but should be offset to avoid cracking or breakage at the corners.

Bolts used in the installation of PROMATECT®-H or PROMATECT®-T boards should be used in conjunction with washers of a minimum of 30mm diameter, or should have their own integral washer, to prevent the heads of the bolts being driven into the surface of the boards. Note that the washers should be manufactured of the same material type as the bolts to ensure that galvanic corrosion does not occur. Note that in multiple layer systems, as depicted in Figure 20, the systems have been subject to fire test with the heads of the bolts recessed into the board to provide a flush finish. This is only possible where the second and lower board layer is a minimum of 25mm thick, and care needs be taken not to drive the bolts too far into the surface of the boards.

Care should be taken when drilling holes into the concrete to avoid the positions of the reinforcement within the concrete as far as is possible. The PROMATECT® boards should be properly supported when drilling takes place to ensure the rear face of the boards do not "blow" at the exit point of the drill bit.

Minimum requirements for anchors used to secure the PROMATECT®-H or PROMATECT®-T panels.

- M6 in diameter.
- Made of stainless steel of 316 grade.
- Of appropriate length to secure the panel thickness.
- Minimum 30mm anchor depth penetration into the concrete.
- Expansion action of the anchorage shall be within the concrete and not on the PROMATECT® panel.
- Can be supplied with a nut and washer head to facilitate removal of the PROMATECT® panels were required.
- Suitable for use in the tension zone of concrete (cracked concrete).
- Suitable for use where the bolts will be subject to positive and negative pressure fluctuation.

Post Construction Installation *Continued from page 21*

Steel Framing

Tests have been carried out on systems for both horizontal and vertical applications where the PROMATECT®-H or PROMATECT®-T boards have been fixed to a steel frame system. The type of steel used as the framing is of course dependent on the environmental conditions of the tunnel, but would generally be of 316 grade stainless steel.

The steel frame for horizontal applications would generally consist of either zed sections or top hat (omega) sections positioned at nominal 600mm centres onto the concrete soffit. The fixing of the steel frame to the concrete would be subject to the exact same considerations as for the direct fixing of PROMATECT® board, see Chapter 6 page 15.

Fixings would be at nominal 500mm centres into the concrete, subject to the fire performance requirement and substantiation by fire test reports. Please consult Promat Technical department for details pertinent to any specific installation.

It is not possible to provide a definitive statement on the types of steel framing for vertical wall systems, as these are again dependent on a number of factors i.e. the fire performance requirement of the system. Consideration must be paid, in addition to those mentioned above for horizontal applications, to the effects of wind loading and suction induced by the passage of traffic.

The framing system employed would tend to be designed on a project by project basis because the section size of the framing is determined by the effects of suction forces etc, as well as the height of the construction, and the need for protection to any services that may be located behind the walling system. Thus the dimensions and shape of the steel supporting section are determined by the section modulus required to be capable of resisting the compressive loads, bending moments and other forces which may be imposed on the wall lining.

Wall Linings & Decorative Claddings

The Promat systems for the fire protection of concrete, tunnels and underground spaces are also available as part of the decorative claddings range available from Eternit. A separate handbook entitled *GLASAL® FOR TUNNELS* is available which provides full details of the properties and installation details for decorative tunnel linings.

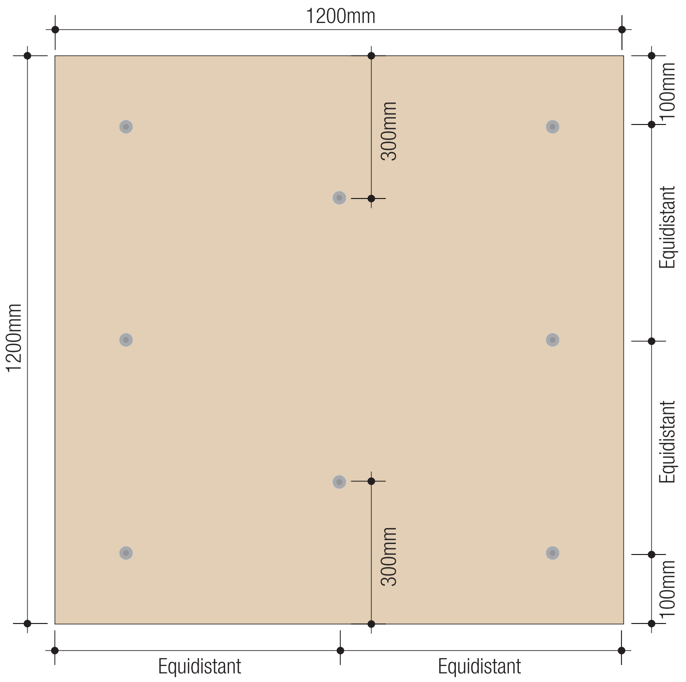
GLASAL® cladding panels are part of a wall lining system which can fulfil all a designers expectations and performance requirements. These wall lining systems offer optimum performance in terms of light reflection, low cost maintenance, the ability to withstand mechanical cleaning, and is resistant to all types of atmospheric pollution, together with a long project history of successful installations dating back decades, and installed in well over 120 tunnels worldwide.

The GLASAL® system, used in conjunction with PROMATECT®-H or PROMATECT®-T boards as a backing panel, can be used to combine the requirements of fire resistance together with the aesthetics of a decorative cladding system. Depending on the type of fire exposure expected, the combination of PROMATECT® board and GLASAL® can offer a fire performance of up to 240 minutes depending on the fire curve exposure and performance criteria.

The standard wall lining system for providing both fire resistance and decorative cladding consists of a backing board of 20mm PROMATECT® board laminated to a 5mm thickness of GLASAL® board. These panels are laminated in our manufacturing facility in Belgium, where both PROMATECT® and GLASAL® are produced, so that the end user can be assured that the quality of the lamination process is matched to the quality of the panels. The composite panel resulting from this match of products provides an extremely efficient system in terms of durability, impact resistance, fire performance etc.

For further details of the systems details pertinent to GLASAL®, please consult the separate technical manual.

Figure 22: The indication of fixing positions



Installation of PROMATECT®-H or PROMATECT®-T Boards

PREPARATION OF BOARDS

Wherever possible, PROMATECT®-H or PROMATECT®-T boards should be processed and made ready for installation prior to delivery to site. The preparation works shall be carried out in a suitably equipped workshop either at an off-site location or if the conditions permit at an on-site location. However provision for remedial work should be made available at the installation site if it becomes necessary to make dimension and edges changes.

The preparation works include the following.

Cutting of PROMATECT® panels to size according to the requirements of the ceiling plan.

Pre-drilling of holes made PROMATECT® panels ready for securing of impact anchors. The position for holes for various PROMATECT® panels are predetermined according to the anchor layout plan as shown. Figure 22 shows a typical anchor layout for the panels used in the general soffit protection. Suitably prepared templates can be used to pre-drill the anchor layout on each PROMATECT® panels.

The anchor layout is dependent upon:

- Board type
- Board thickness
- Aesthetical and dynamic load requirements.

Please consult Promat for advice or possible fixing layout schemes.

INSTALLATION OF BOARDS

With the smooth face of the PROMATECT®-H or PROMATECT®-T panels facing down, the panels are held in positions flat against the substrate using suitable clamp equipment.

Figure 23: Panel lifting hoist

Drill into concrete to the required anchor depth. Whenever required, a rebar detector should be employed to ensure avoidance of the reinforcing bars. At all times, the required panel area to anchor ratio shall be maintained.

Insert impact anchors into predrilled holes, and knock the anchor into position until the washers are in tight contact against the PROMATECT® panel surface.

Visually inspect that the anchors are tight and secure. Any dislodged anchors shall be replaced.

Care should be taken not to overdrive the anchor and damage the PROMATECT® panel.

Place the next PROMATECT® panel tightly against the installed panel and repeat the process. Repeat installation of panels outwards from the inner tunnel wall towards the outer tunnel wall.

Figure 24: Drilling of concrete

DISCREPANCIES IN SUBSTRATE LEVELS

Where discrepancies in substrate level occur such that the PROMATECT®-H or PROMATECT®-T boards cannot comfortably be laid in a flat manner to the soffit, it may be necessary to utilise spacer strips to level the soffit.

Should discrepancies in the substrate flatness tolerance occur, adjustments to the installation of the PROMATECT® panels and additional measures can be made to accommodate the following discrepancies.

<u>1) Minor discrepancies in level of substrate not exceeding 3mm</u>

In general, where minor discrepancies in substrate level occur and the PROMATECT®-H or PROMATECT®-T boards can still be comfortably sit in a flat manner, no specific remedial action is needed. Where the levelling discrepancies do not exceed 3mm, it is acceptable to observe a slight step between two PROMATECT® boards. Figures 25 and 26 below illustrates these conditions.

Figure 25: Minor discrepancies in levels, not exceeding 3mm

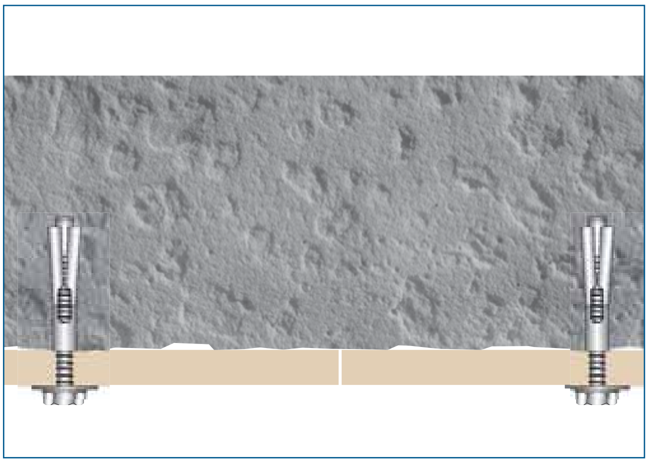
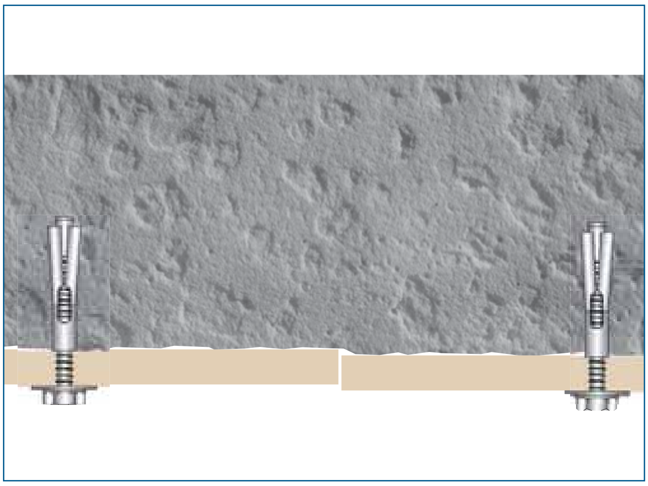


Figure 26: Minor uneven substrate



Post Construction Installation *Continued from page 23*

DISCREPANCIES IN SUBSTRATE LEVELS

2) Discrepancies in level exceeding 3mm

Where the PROMATECT®-H or PROMATECT®-T panel does not sit flat on the concrete structure due to an uneven substrate, care shall be taken not to over tighten the bolts which could result in cracked panels.

Spacers (or shim strips) made of PROMATECT®-H or PROMATECT®-T boards of appropriate thickness should be used to take up such discrepancies. Guidelines in the use of spacers are as follows.

Spacer made of 6mm, 9mm or 12mm thick PROMATECT®-H or PROMATECT®-T boards can be used where appropriate to provide the best level for the flat installation of the PROMATECT® panels.

As level discrepancies are discovered as the panel laying progresses, noted either as a reduction or an increase in level in the next consecutive panel, different measures need to be used make up for the discrepancy.

Figure 28 illustrates a reduction in level discovered when laying the panel on the right, while Figure 29 illustrates an increase in level.

Figure 27: Use of PROMATECT®-H or PROMATECT®-T spacers when level increases

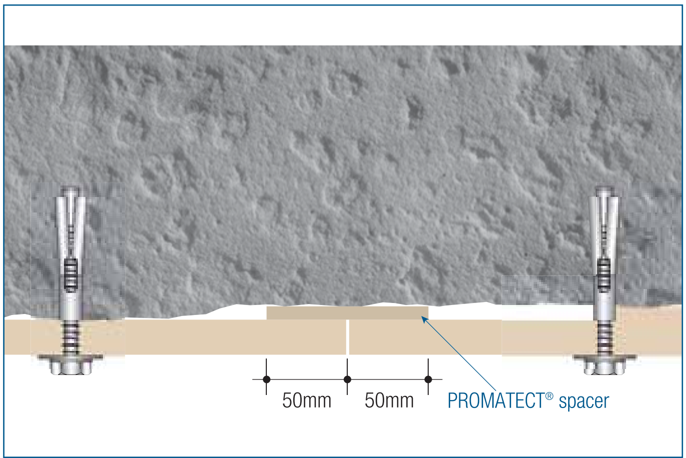
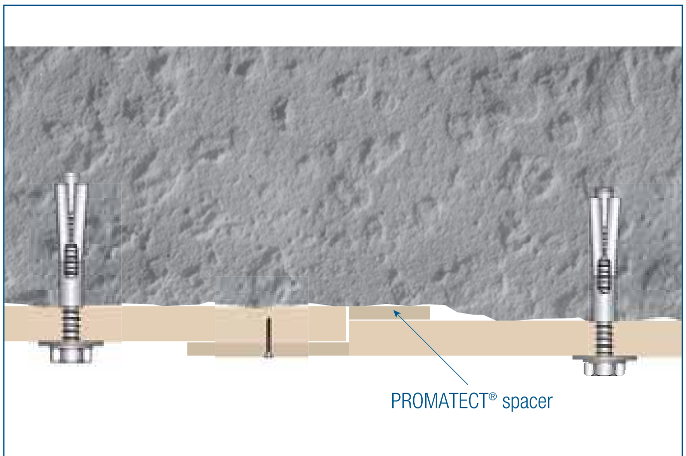
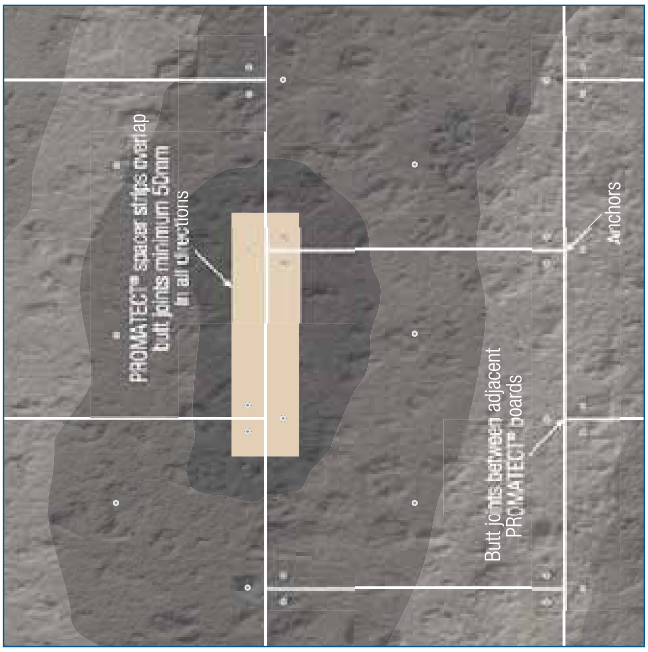


Figure 28: Use of PROMATECT®-H or PROMATECT®-T spacers where level reduces



Wherever possible butt joints of two such spacers should not coincide with butt joints of the main PROMATECT®-H or PROMATECT®-T panels. Where spacers are unavoidable at butt joints, it is good practice to have a full spacer piece overlapping a minimum of 50mm wide over the butt joint as shown in Figure 27 and 28 above.

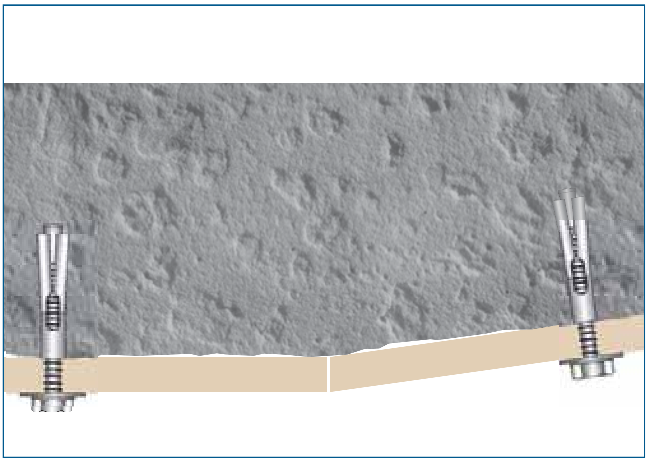
Figure 29: PROMATECT®-H or PROMATECT®-T spacer at butt joint of its panel



3) Change in angle of the substrate

Where an inclination occurs in the soffit in such a way that the use of spacers is unsuitable, a joint shall be introduced where the edges of the boards are angled such to provide a closed gap.

Figure 30: Illustrates an angled joint

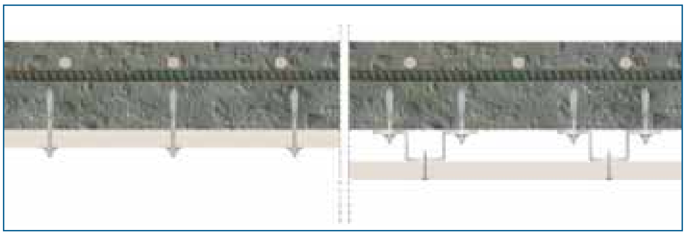


- Introduce a butt joint where the change in inclination occurs.
- On-site bevelling should be carried out to suit the angle of the inclination.

Application of Curved & Framed Sections

PROMATECT®-H or PROMATECT®-T boards do not necessarily need to be fixed directly to the concrete soffit of the tunnel, it is feasible for some fire performance requirements to use steel framing members or PROMATECT® strips. It should be noted that although the performance of galvanised steel sections is adequate under fire conditions, the aggressive environmental conditions encountered within tunnels suggests that the use of stainless steel framing members would be preferable for extended durability.

Figure 31: Section showing top hat steel framing members



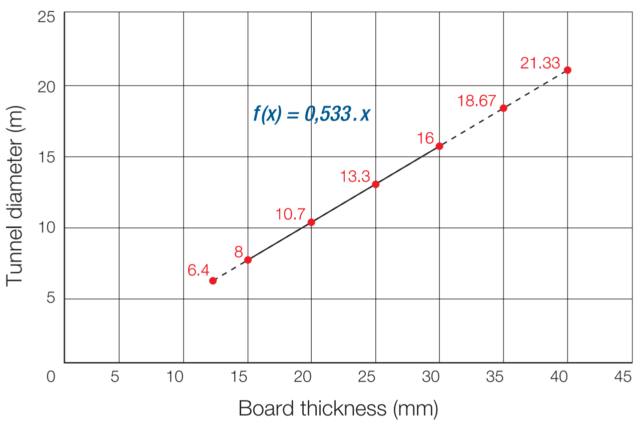
The above Figure 31 shows the PROMATECT®-H or PROMATECT®-T boards fixed either directly to the soffit or onto top hat sections. The dimensions of the steel sections and the centres of positioning are dependent on a number of factors, eg fire performance, span, thickness of the PROMATECT® board, type of concrete etc. Please consult Promat for further details.

Figure 32: Curved sections, direct to substrate

Figure 32 above shows the PROMATECT®-H or PROMATECT®-T boards fixed directly to a curved concrete section.

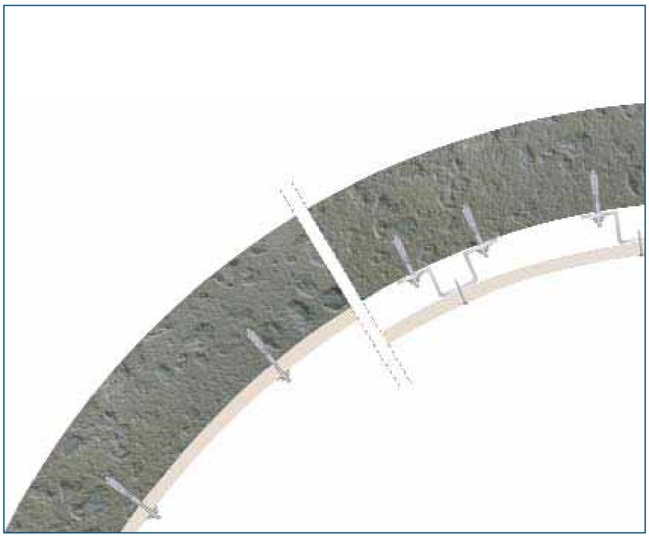
PROMATECT®-T boards can be supplied as flat sheets and can be curved on site. Care should be taken to ensure that the thickness of the PROMATECT®-T board is commensurate with the diameter of the tunnel lining. If the diameter is too tight, it may be necessary to install in a double layer of thinner boards rather than one single board thickness. See Figure 33 below.

Figure 33: Thickness PROMATECT®-T vs tunnel diameter



PROMATECT®-H or PROMATECT®-T boards can be curved on site dependent on the ratio of board thickness to diameter of the tunnel sections. Generally PROMATECT®-H or PROMATECT®-T board would be supplied from the factory pre-formed to the required radius. There are limitations on the thickness and minimum radius applicable and therefore any requirements should be discussed with Promat prior to any specification being finalised.

Figure 34: Curved section onto steel framing



The above Figure 34 shows PROMATECT®-H or PROMATECT®-T boards fixed either directly to the soffit or onto top hat sections of a curved section. The dimensions of the steel sections and the centres of positioning are dependant on a number of factors, eg fire performance, span, thickness of the PROMATECT® board, type of concrete etc. Please consult Promat for further details.

On-site installation samples of a curved tunnel.

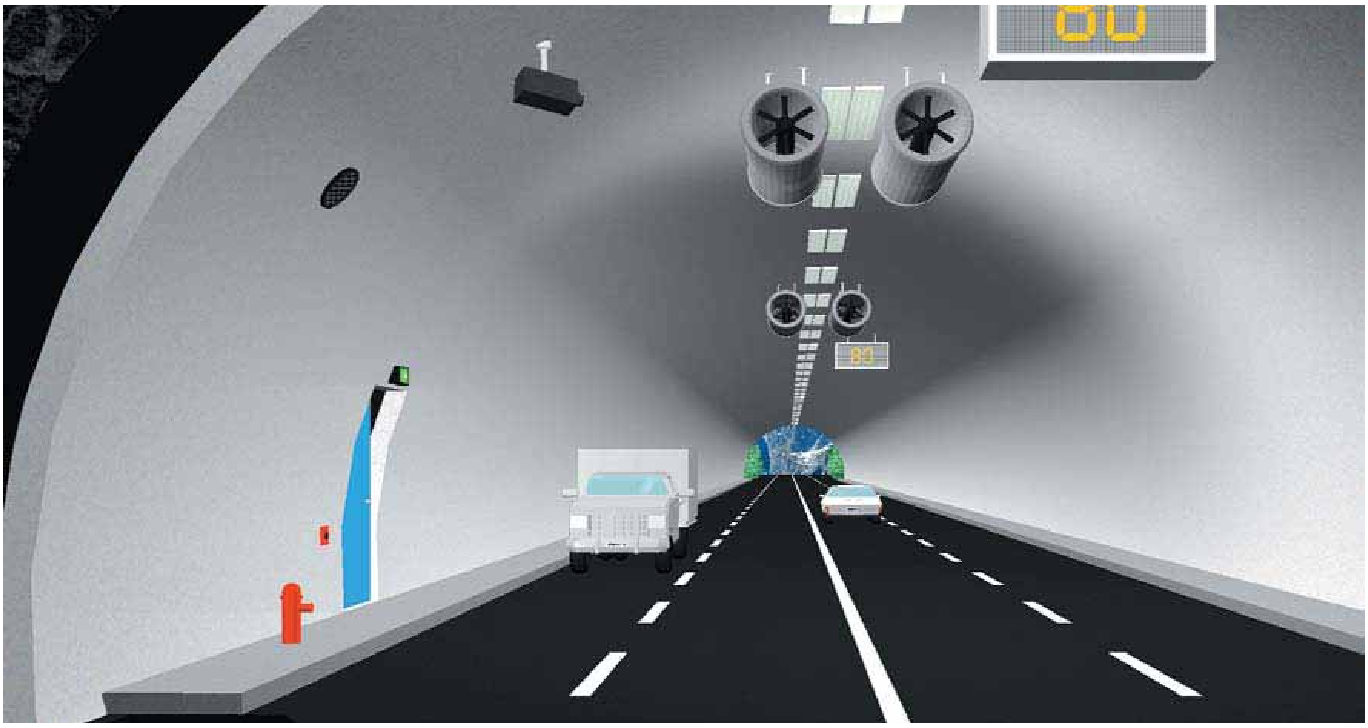
In any tunnel construction, applying a protective material to enhance the fire resistance of the structure is only part of the story. On its own, this is not going to prevent the loss of life which could occur if there is a fire within a tunnel. Additional active and passive systems need to be incorporated into the design to ensure a full set of life safety systems should be considered, these would include the following items.

- Enhancing the fire resistance of the structure
- Air supply systems
- Smoke extract duct systems
- The provision of fire and smoke resistant safe havens in long tunnels
- Active and Passive detection systems
- Fire extinguishing systems
- Fire doors and fire stopping systems

The active systems within tunnels should consist of the following items, Lighting, Signal Systems, Monitoring Cameras, Fire Alarms, Loudspeakers, Antenna Systems (for two way radio communication), Hydrants, Pump Cellars, Escape Routes and Air supply and Smoke Extracting Systems.

In this document we are concerned only with the systems pertinent to proactive fire protection, e.g. air supply and smoke extract ducts, escape and cross tunnel fire doors, provision of safe havens, and systems for the protection of cables for important services.

Figure 35: Tunnel services active systems



Air Supply & Smoke Extraction Systems

As has been shown in many case studies of the cause of deaths resulting from fire in tunnels, the majority of these are as a result of inhalation of smoke particulates.

Smoke can have a wide ranging effect on people:

1) The atmospheres may be hot; temperature near the seat of the fire may exceed 1000^{o}C. Inhalation of hot gases may cause serious burn injury to the respiratory tract.
2) Toxic and narcotic gases, such as carbon monoxide and hydrogen cyanide, will be present. At high concentrations, carbon monoxide will cause rapid death; lower concentrations may bring about a loss of co-ordination, particularly on exertion.
3) A fire atmosphere will contain a low concentration of oxygen; this in itself can bring about unconsciousness and death but normally the effects of toxic gases predominate.
4) There may be many small particles in the atmosphere that vision is restricted.
5) The effects of irritants to the upper respiratory tracts and eyes may impede escape.

Studies on the causes of deaths due to fire have indicated that carbon monoxide (CO) poisoning accounts for roughly one-half of total fatalities. The remaining half is accounted for by direct burns, explosive pressures, and various other toxic gases.

Although the analysis of blood cyanide (which would come from exposure to hydrogen cyanide) in fire victims is sometimes reported in autopsy data, blood carboxyhemoglobin saturation, resulting from exposure to CO, is often the only fact provided.

It is therefore imperative that for long tunnels, some form of smoke extraction system is included within the design. By the very nature of the gases and particulates that any system is required to remove from the location, any duct or extract system will need to be constructed in such a manner that it is itself resistant to fire.

However, it is not such a simple matter as installing ventilation or extract fans and assuming these will perform the necessary services. Significant research (some 98 tests) were carried out in the early 1990's in the Memorial tunnel in the USA which provided some significant data on the performance of ventilation systems, ranging through Natural, semi transverse, fully transverse and longitudinal ventilation systems with fire loads ranging through 10, 20, 50 and 100MW in severity. A few sprinkler/deluge systems were also tested during this programme.

More recently, a series of tests has been carried out in a the new Benelux tunnel in The Netherlands on the effects of ventilation on smoke layering and sprinklers etc.

In tunnels with longitudinal ventilation systems, the ventilation can have a marked effect on the HRR of the fire. Investigation and experimentation have shown that longitudinal ventilation within a tunnel can cause different types of fire to behave in very different ways. The HRR of fires in heavy goods vehicles in particular can be greatly enhanced, even with low rates of ventilation, whereas the HRR of a car under the exact same conditions could be greatly reduced. There is no simple method of calculating the complex relationships between ventilation speeds and increases in heat release rates.

Ventilation can also affect the spread of fire along a tunnel. For example, during the Mont Blanc disaster, fire spread from the source of the fire to cars situated some 90m away.

As can be seen from the pictures below, the effect of the ventilation results on the fire moving horizontally instead of mainly vertically, as a result of this action, vehicles positioned down stream of a fire could possibly ignite.

The effects of natural and longitudinal ventilation in tunnels has been subject to some experimentation, the effects on tunnel fires from semi or fully transverse ventilation is at present less well known.

Figure 36: Effects of air flow on car fire

Example 1 Fire with neutral air flow

Example 2
Fire with 2m/sec air flow

Air Supply & Smoke Extraction Systems *Continued from page 27*

In tunnels, there are a number of ways for providing the extract systems, in general though, these can be determined in two basic concepts, the first is the construction of a plenum within the tunnel roof space, either from concrete, or by building a soffit from PROMATECT®-H or PROMATECT®-T boards. Figure 37 a section of a bored tunnel shows just such a concept. Figure 39 shows a diagrammatic cross section of such a plenum ceiling construction.

Figure 37: Section through typical tunnel showing air plenum construction

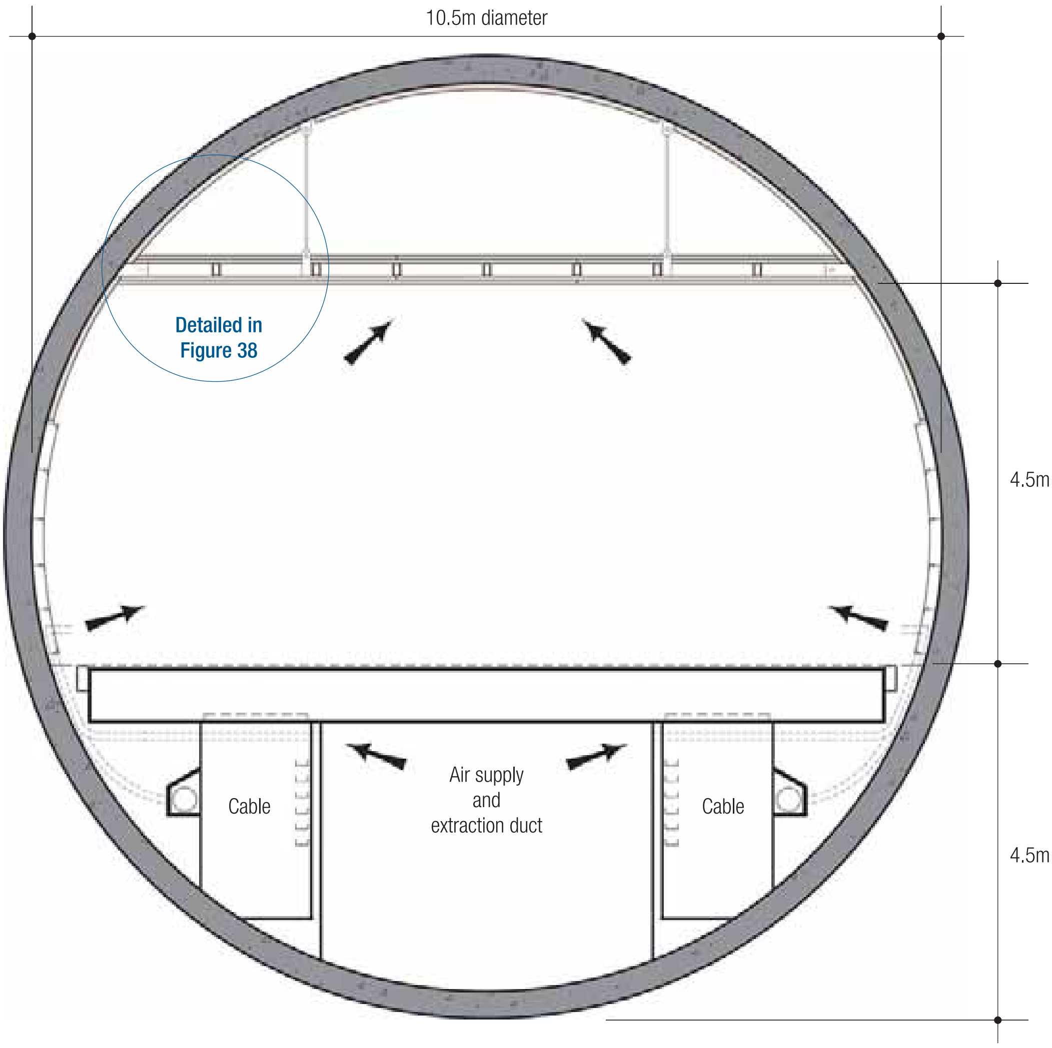
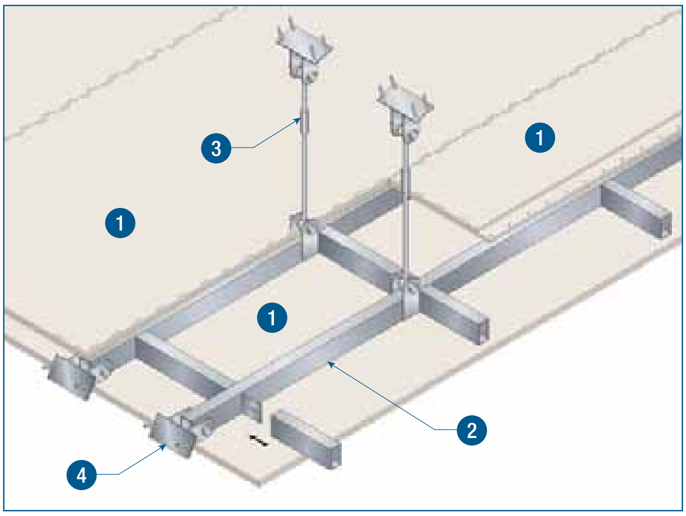


Figure 38: PROMATECT®-H or PROMATECT®-T membrane ceiling construction in tunnels



In this instance, the PROMATECT®-H or PROMATECT®-T board provides both protection to the concrete sections, and with the inclusion of a horizontal membrane constructed from the board, forms the smoke extract system.

The second method is to install a steel duct system, and then clad with a fire protective material, such as PROMATECT®-H or PROMATECT®-T board to provide the duct with a degree of fire resistance. For specially aggressive environments, where the required greater degree of strength and impact resistance is required, the product PROMATECT®-S should be considered.

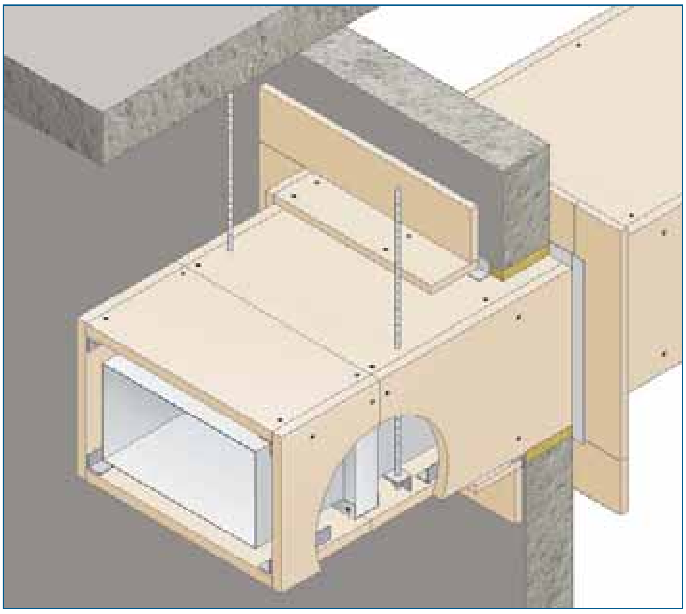
1. **PROMATECT®-H or PROMATECT®-T board**
2. **Framing system**
3. **Hanger support system where required**
4. **Connection to tunnel lining**

Please consult Promat for full specification details.

8

A typical detail for providing protection around steel ducts is depicted in Figure 39 below.

Figure 39: Cladding of steel duct using PROMATECT®-H or PROMATECT®-T boards

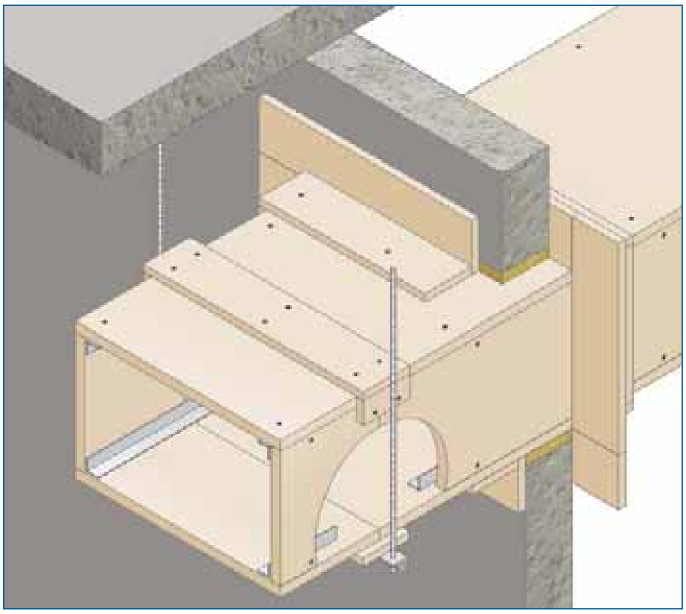


The detail depicted in Figure 39 shows a steel duct clad with PROMATECT®-H or PROMATECT®-T boards, which would be suitable for use in areas where the ducts are protected from impact and shock damage. It is also possible in all duct systems, to construct the duct from the board alone, and without the inner steel liner, however, this is dependant on the air pressure that the duct is designed to take.

The thickness of the PROMATECT® boards would be determined by a number of factors, these would include, obviously, the performance required under fire conditions, and the type of exposure curve, and the air pressure of the duct combined with the dimensions of the duct itself.

For details on the manufacture and installation of PROMATECT®-H or PROMATECT®-T duct systems, please consult the Promat Technical department.

Figure 40: PROMATECT®-H or PROMATECT®-T duct without steel liner



For use in extreme or aggressive environments, and where the ducts could be exposed to impact and require resistance to seismic shock etc, the use of PROMATECT®-S boards for the construction of ducts would be preferable.

As a brief description, PROMATECT®-S is a composite board, manufactured with a fibre reinforced cement core, with outer facings of 0.5mm perforated steel sheet mechanically bonded to each surface of the core. The outer steel sheet can be manufactured from galvanised, Grade 316 Stainless or other monal alloy steels.

PROMATECT®-S boards are available in one standard dimension of two differing thicknesses. The boards are 2500mm x 1200mm, and is available in 6mm board and 9.5mm thickness within systems tested for up to six hours fire resistance periods. This fire resistance period is of course dependant on the exposure curve followed.

PROMATECT®-S can provide the following advantages over other board products:

- Fast track construction
- Maximises floor space
- High impact resistance
- Interior/Exterior usage
- Hose stream resistant
- Maintenance free
- Can be supplied with stainless steel facings
- Lightweight but strong
- Relocatable and suitable for retro installation
- Moisture resistant
- Retro-installation
- Water resistant
- Employs dry trade installation methods

Figure 41: PROMATECT®-S self-supporting duct system

As with the PROMATECT®-H or PROMATECT®-T system, PROMATECT®-S can also be used as a cladding around steel duct systems.

For details on the manufacture and installation of PROMATECT®-S duct systems, please consult the Promat Technical Department.

Cable Protection Systems

In the event of a fire it may be vital to the safety of the tunnel occupants that certain electrical systems remain functioning until people have escaped. Such systems will therefore require to be protected from fire for a specified period of time and may include:

1) Electrically operated fire alarms
2) Emergency escape route lighting
3) Electrically operated extinguishing systems
4) Smoke extraction vent systems
5) Power supply for fire service elevators in high-rise buildings.

In addition to protection from fire outside the duct, it is normally vital that any fire within the duct is contained e.g. if cable sheathing ignites due to an electrical overload.

A suitably designed duct will:

6) Prevent the propagation of fire from one building compartment to another
7) Assist in maintaining escape routes
8) Ensure the continuing operation of other services within a common service shaft
9) Reduce damage to localised areas
10) Contain smoke and toxic fumes from burning cables.

By enclosing standard cables in the Promat Cable Duct Systems, all the above requirements can be met, providing up to four hours fire protection, dependant on the duct construction, and the fire exposure curve, whilst avoiding the use of more expensive and bulkier fire-rated cables, which generally cannot provide a performance to the more extreme exposure curves.

Design Considerations

The following points are some of the factors which should be considered when determining the correct specification to ensure the cable duct system will provide the required fire performance. Further advice can, of course, be obtained from the Promat Technical Department.

1) Required fire exposure: The specification of a cable duct system will depend on whether it is expected to resist external fire, internal fire, or both.
2) Required fire performance: Generally, the most onerous requirement is to maintain the integrity of the circuit(s) when the system is exposed to external fire. If this is not needed, the performance requirements may be reduced by the approval authority to provide only stability, integrity and insulation of the duct system and/or the wall and floor penetrations. On occasions further relaxations may be approved e.g. a reduced insulation performance can sometimes be acceptable if no combustible materials or personnel could be in contact with the duct.
3) Supporting structure: The supporting hangers and their fixings should be capable of bearing the load of the complete cable system including any applied insulation material or other services suspended from it. Chemical anchors are not generally suitable. It is usually not advisable to use unprotected hangers if the stress exceeds 6N/mm^2 and/or if hanger lengths exceed 2m. The hanger centres should not exceed the limits given for the relevant Promat system, in addition, the points raised in chapter 6 page 15, Fixings, are equally applicable for the fixings supporting services etc.
4) Penetrations through walls and floors: Care should be taken to ensure that movement of the cable system in ambient or in fire conditions does not adversely affect the performance of the wall, partition or floor or any penetration seal.
5) Other requirements: Acoustic performance, thermal insulation, water tolerance, strength and appearance can also be important considerations.

The cable protection systems can be constructed from either PROMATECT®-H, PROMATECT®-T or PROMATECT®-S in much the same manner as ventilation duct systems.

Figure 42: Cable protection system constructed from PROMATECT®-S

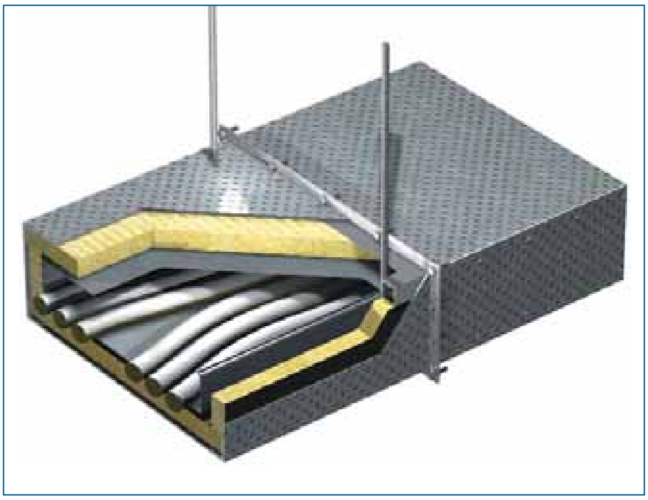


Figure 43: Cable protection system constructed from PROMATECT®-H or PROMATECT®-T

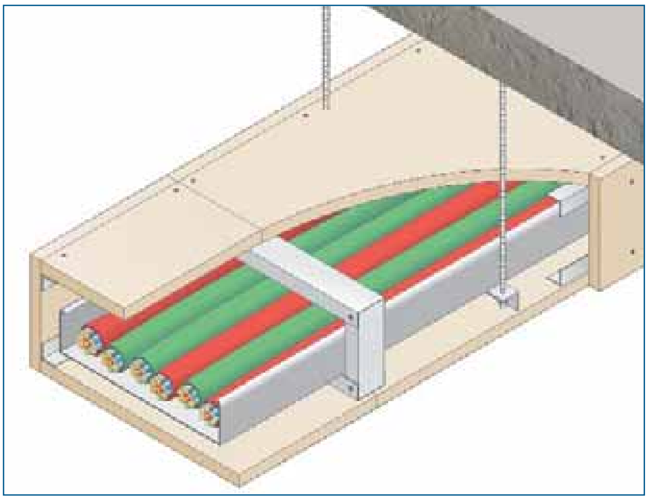
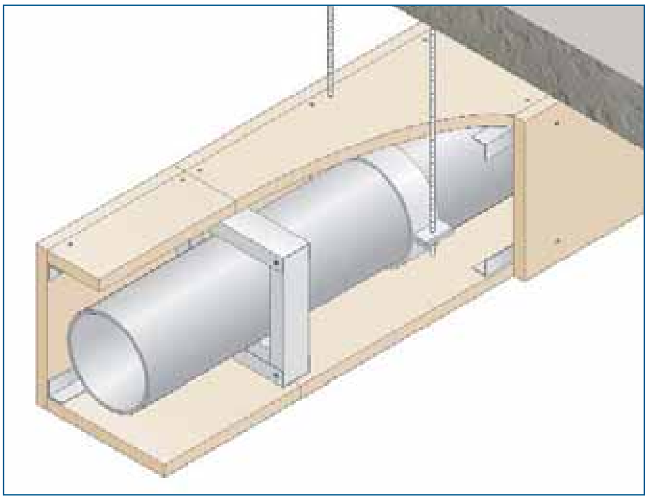


Figure 44: Using Promat boards for the protection of other services



For details on the manufacture and installation of Promat cable and services protection systems, please consult the Promat Technical Department.

Figure 45: Service tunnel with important cables protected with Promat systems

Safe Havens

In long tunnels, safe havens should form an integral part of the tunnel design. Recent fires in tunnels have shown that exposure to smoke and toxic fumes from burning vehicles is the main cause of loss of life, and deaths have occurred even at relatively short distances from the seat of the fire. The provision of safe havens therefore is imperative in long tunnels, both to provide protection for passengers from vehicles until the fire services can reach them, but also as a place which can provide respite from the heat and smoke for fire fighters.

Ideally, any safe haven should have a minimum fire resistance period to match that of the main structural protection, and should be constructed in such a manner that they are resistant to both heat (insulation) and ingress of smoke into the chamber. In recent fires, personnel who have managed to reach a safe haven have then died through exposure to the effects of heat and smoke ingress into the chamber, therefore consideration should be given to providing a separate air supply into these areas.

Promat can offer the designs and systems required to construct such safe areas for all types and durations of fire exposure. Please contact the Promat Technical department for further details.

Fire Doors

The design and construction of fire resisting doors is a complex operation involving the skills and specialised knowledge of architects, fire experts, door manufacturers and ironmongers.

The designer is the first in the line of those concerned with the provision of fire doors. It is he who ascertains the requirements of the users and decides where and in what form doors will be required. He also assembles the specialised information from the other experts into a design for the complete door, and arranges for the doors to be manufactured.

The first principle to be considered in relation to Fire Resisting Doors is that, in most respects they are merely ordinary doors with certain additional features, and throughout most of their life will be operating as such, indeed it is hoped that most fire doors never have to function in a fire situation.

Fire resisting doors, therefore, have to be opened, closed, locked, latched, bolted, cleaned and maintained like any other doors. They need to be able to resist the wear and tear of normal use and in many cases, of abuse. They need to be of robust construction and be capable of being fitted with a wide range of glazed panels and ironmongery. They frequently need to be protected from damage.

The planning of any structure involves the arranging of circulation routes, allocating rooms and spaces, with all their servicing needs. It is then necessary to locate openings and/or doors to provide access from space to space. Single or double doors must give suitably sized clear openings to permit the passage of pedestrian and vehicular traffic. Doors must be hung or pivoted to open and close to suit the requirements of the users. Doors will frequently require to be self closing and a number will be fitted with locks.

In view of the smoke emissions from vehicles, and the high toxicity of this smoke as a result of the types of materials used in modern car manufacture, it is also imperative that any door will provide a high degree of resistance to the passage of smoke, and ideally, where used as access to safe havens, should provide a high degree of thermal insulation to reduce the affects of heat on the occupants of the chambers.

Figure 46: Example of steel fire door within a tunnel

Any fire door situated within a tunnel should be capable of providing the same degree resistance to the aggressive and polluted environment as any other services.

Design Considerations

The following points are some of the factors which should be considered when determining the correct specification to ensure a doorset will provide the required fire performance. Further advice on doorsets can of course be obtained from the Promat Technical Department.

1) Relevant test standards and fire/smoke

2) Size of door leaf, generally the doorset should be no larger than the tested doorset, but larger doorsets may be considered suitable for assessment depending on the performance of the tested doorset.

3) Number of door leaves, generally testing a double leaf doorset is more onerous than a single leaf doorset.

4) Action of door leaf, the performance of a doorset can vary considerably depending on which side is exposed to the fire. It is particularly difficult to ensure double swing doorsets satisfy the test standard criteria.

5) Ironmongery, generally all ironmongery should have a melting point no less than 800ºC. The number, size and position of hinges can be critical. Care should be taken when considering alternative ironmongery to that which was tested.

6) Door strips/smoke seals, Intumescent strips, and smoke seals if required, are normally installed down the sides and along the top edge of the door leaf. Alternatively, they can be inserted into the door frame. Care should be taken that they are fitted correctly around ironmongery.

For further information, Please consult the Promat Technical department.

1. Should the vertical tunnel walls be protected as well as the soffit?

This depends on the assessment of the risk by the relevant authorities and fire consultants. In many tunnels up to 1 metre of the wall down from the tunnel soffit requires fire protection.

2. Which is the best protection method that will minimise servicing requirements after the tunnel is completed. Post cladding is easier to remove, while lost shuttering is more difficult?

Promat have over 28 years of experience in detailing and providing fire protection systems to tunnel applications. To date there has not been a requirement to totally remove PROMATECT® boards for servicing. It is true that post cladding facilitates ease in removal to allow access for inspection of concrete etc.

3. How are cracks in the concrete during fixing of protection material treated?

Cracks in the concrete pose no problem to the PROMATECT® boards. If cracks in the concrete need to be repaired, the boards can be removed, or drilled through to gain access to the concrete for grouting repairs.

4. Does the PROMATECT® protection inhibit the regular inspection and maintenance procedures of the tunnel, especially for water seepage and concrete spalling?

Water seepage is expected especially in the sub-sea tunnels such as those in the Netherlands. For example, Westerschelde tunnel has a 12m water column. Water can be absorbed by PROMATECT® boards but these are unaffected by water. Wet spots are therefore visible and hence do not inhibit inspection.

5. How about rebar carbonisation? How would a PROMATECT® lining affect the treatment of this problem in tunnels?

The concrete cover should be designed for addressing this aspect, although the PROMATECT® lining shields the concrete from direct contact of aggressive car pollution. An examination of the 9-years old PROMATECT®-H board cladding to Velser tunnel in Netherlands was conducted. The PROMATECT®-H showed negligible lost in strength and the no rebar carbonisation was visible in the concrete.

6. What is the experience of such repairs in other protected tunnels?

The worst case scenario is the PROMATECT® panel has to be removed to allow access for the concrete repair. This is quite easily achieved.

7. How will the protection material react to the chemicals in the water seepage?

PROMATECT® boards are inert and will not have any adverse reaction to chemicals in the water.

8. How will the protection material react to alternating pressure from vehicular traffic?

A test has been carried out in Germany's iBMB subjecting PROMATECT® specimens to 110,000 cycles of alternating pressures; 3 times more than normally encountered in vehicular tunnels. No displacement of the board or the fixing system occurred.

9. How do we build in maintenance and service procedure for PROMATECT® after the protected tunnel is operational?

PROMATECT® boards themselves need no maintenance, other than an occasional visual inspection for damage.

10. How does the fixing of services and lighting to a protected concrete soffit affect the fire performance of the concrete?

Drilling through the panels does not adversely affect the performance of the system, assuming of course that the installer does not go too far and drills holes everywhere. Tests have been carried out to both RWS and Hydrocarbon Curves where services have been bolted through the PROMATECT® (simulated in the tests by suspending weights from expansion bolts) and the performance of the system is consistent between these tests and the standard tests where no penetrations have been made. Of course, all services should be supported directly from the concrete and the installer should not rely on fixing any services only to the PROMATECT® boards. It should be noted however, that the diameter of bolts can have an affect on localised spalling of concrete, care therefore should be taken in the choice of fixings.

11. How do we ensure the screws or bolts remain in situ?

If the PROMATECT® is used as permanent shuttering the screws are embedded within the concrete, thus they cannot fall out, if the bolts used for fixing using the post installation method described, are not tight, the board will fall as the support is removed. Tests have been carried out to show that even without the screws, a section of board used as shuttering has a very high adhesion to the concrete and will not fall away, tests on fully soaked boards have been carried out to simulate the effects on suction and to ascertain whether the bolt heads and washers would pull through the board. These tests were carried out on 15mm, 20mm, 25mm, and 30mm and showed that very high loads are required to pull the fixings through the boards. The average pull through strength measured for a 25mm board, fully immersed in water for 72 hours prior to the test, was a pull through load of 1884N for a 6mm diameter expansion bolt, and 1271N for a 5mm diameter screw.

12. What happens if after installation there are any gaps between the PROMATECT® boards ?

This depends on the size of the gaps. Panels have been tested where gaps of 5mm were deliberately left between the panels in an attempt to simulate poor installation, no adverse affects were recorded in these tests. Promat has a repair compound available for facilitating small repairs. Thus product has been tested to 120 minutes in accordance with the requirements of RWS.

Appendix 1: Tables of Cladding Thickness

Table 12: Points of attachment for post cladding

Fire type	Cladding thickness (Based on C30 concrete)	A = Number of fixing points per m² of board B = Length of fixing		
		New construction	Post construction installation	
		Screws 5mm	Bolts M6	Bolts M8
Cellulosic	12mm	A = 12 B = 40mm	A = 4.5~5 B = 30mm	A = 4.5~5 B = 35mm
Hydrocarbon	25mm	A = 12 B = 50mm	A = 4.5~5 B = 45mm	A = 4.5~5 B = 50mm
RWS	27mm	A = 12 B = 50mm	A = 4.5~5 B = 55mm	A = 4.5~5 B = 60mm

Appendix 2: Specifications For Tunnel Structure Fire Protection

1. Physical Properties

1.1 PROMATECT®-H and PROMATECT®-T boards are autoclaved calcium silicate board with a smooth upper surface and are off-white (beige) in colour. The board is extremely versatile and ideally suited for a wide range of internal and sheltered external applications.

1.2 The standard dimension of PROMATECT®-H boards are 2500mm x 1250mm, for PROMATECT®-T boards are 2500mm x 1200mm. Both boards are available in 3000mm lengths. The board can be supplied in various thickness to suit the requisite fire performance. Non-standard sizes and thickness are also available, depending on quantity required. The PROMATECT® board supplied for tunnel applications would normally be in dimensions of 1200mm x 1200mm to enable easier handling on site. The board is also available to order in curved sections to fit circular tunnels.

1.3 All board products should be stored flat, in the dry, clear of the ground and well protected from weather and other trades. The polythene envelope should not be regarded as sufficient protection for storage in the open.

1.4 The fire resistant board material used for the protection of the tunnel concrete shall have physical properties that are at least equivalent to the specifications detailed in Table 13 or 14 and the following items 2 to 9.

1.5 PROMATECT®-H or PROMATECT®-T boards are produced to the highest standards and carry warranties of performance and manufacture. The warranties include the manufacturing process, supply tolerances and the abilities of the PROMATECT® board to provide the requisite fire performances when installed in accordance with the recommendations of Promat International N.V.

1.6 All Promat materials are manufactured under EN ISO 9002 accredited Quality Assurance procedures. Comprehensive independent testing of all Promat products and systems has been carried out by internationally approved laboratories to meet the relevant sections of many international test standards.

2. Fixing Post Construction Installation

2.1 The fire resistant board protection shall be fixed to the concrete by means of stainless steel bolts anchored into the concrete, the diameter of the bolts and the depth of penetration into the concrete should be determined and proven by exposure of the proposed system to the test detailed in the following item 4.1 (see Table 12 for details).

2.2 The number of bolts used to secure one square metre of fire resistant board shall not exceed 5 bolts.

3. Fixing New Construction

3.1 Where the boards are to be installed by means of positioning as lost shuttering, and the concrete poured to the top surface, the reinforcement bars shall be positioned prior to the application of the screws. The screws shall be of a suitable grade of stainless steel to suit environmental conditions, and shall be driven approximately 15mm to 20mm into the upper surface of the board (see Table 12 for details).

3.2 The number of screws used to secure one square metre of fire resistant board shall not be less than 8 number.

4. Fire Resistant Performance

4.1 The fire resistance of the cladding board and the applicable fixing bolts, including diameter, length of the bolt and the depth of penetration of the fixings into the concrete shall be proven by fire tests in accordance with the relevant time/temperature curve.

4.2 All materials to be tested, including the concrete itself, should be shown to have been conditioned together under the exact same controlled climatic conditions until equilibrium density and moisture content have been maintained for a period of at least 14 days to within a maximum further loss of not more than 0.1% per 24 hours.

5. Performance To Alternating Pressure Fluctuations

5.1 The board protection system including and its fixing system as employed for fire resistance shall be capable of withstanding alternating pressure fluctuations of minimum 3.0Kpa applied to a minimum repetition of 110,000 cycles.

5.2 The displacement of the board shall not exceed a maximum of 3.6mm.

6. Behaviour To Influence of Vehicular Exhaust Fumes

Samples of the proposed cladding material should be proven to be resistant to the effects of vehicle exhaust by products. Based on exposure in atmosphere over a period equating to a minimum of four years and average of 40,000 vehicles per day throughout that period. The samples should show no loss or gain of density, no loss of flexural strength and no degradation caused by carbonisation. Cross sections of the tested samples should show no penetration into the cladding material of combustion by products and should show no anomalous characteristics.

Appendix 2: Specifications For Tunnel Structure Fire Protection *Continued from page 33*

7. Behaviour To Influence of Water In In-Situ-Concrete

Where the cladding material is to be used as a form of permanent shuttering, onto which will be poured the concrete, test evidence should be provided to show that adherence of the cladding material to the concrete is unaffected by either the water from the concrete, or admixtures used in the preparation of the concrete. Tests should show a minimum tensile strength of adhesion of not less than 250 N/mm^2.

8. Mechanical Properties:

Screw Pull Out When Soaked With Water

8.1 For use in tunnels where water ingress may be considered a problem, test evidence should be provided to show that water saturated cladding materials will retain at least 60% of their strength when 100% saturated, and that when dried should regain 100% of their original strength.

8.2 The cladding products should be tested for pull through strength of the fixings. The cladding products should be proven to have a fixing pull through resistance of a minimum average of 2197N for M6 bolts and 1271N for M5 screws where the cladding product is 100% saturated by being fully immersed in water for a period of not less than 72 hours and being subject to test immediately after being removed from the water. The above parameters based on a 27mm cladding thickness. Differing limits would be applicable for other thicknesses.

9. Construction Manual

A full construction manual detailing full installation methods and including sections covering future maintenance is to be provided by the supplier of the cladding materials.The construction manual should incorporate evidence to show that all the requirements outlined within this specification have been adequately tested for and the proposed system is proven to meet the required parameters.

Table 12: PROMATECT®-H physical properties (average production values)

PROPERTIES	DESCRIPTION
Neutral designation	Calcium silicate (asbestos free)
Material class	Non combustible in accordance to DIN 4102 and BS 476: Part 4: 1970
Surface spread of flame	Class 1, in accordance to BS 476: Part 7
Building regulations classification	Class O
Bulk density	Nominal 900 kg/m^3
Thermal conductivity	0.17 W/mK at 20°C
Thermal resistance	0.143 m^2K/W (25mm boards)
Heat transition coefficient k	3.20 W/m^2K (25mm boards)
Alkalinity	Nominal pH 12
Water vapour diffusion factor	20
Moisture content	Approx. 7% (air-dried)
Water absorption capacity	Maximum 0.55 g/cm^3
Expansion when under water, 100% saturation	Maximum 0.5 mm/m
Length and width tolerance (for sheets of 1220 x 1220 x 27mm thick)	Length x width: ± 0.5mm Squareness: ± 1mm across diagonals Thickness: ± 0.5mm
Coefficient of thermal expansion (a)	-6.4×10^{-6} m/mK (20~600°C)
Surface condition of standard boards	Visible face smooth, opposite face honeycombed.
Arc resistance	Proof by tests in accordance with DIN VDE 0303, Part 5.
Biological	Will not rot nor support the growth of mould, inorganic material that will not attract pests.
Modulus of elasticity E	Longitudinal: 4200 N/mm^2 Transverse: 2900 N/mm^2
Flexural strength F	Longitudinal: 10 N/mm^2 Transverse: 5.5 N/mm^2
Tensile strength T	Longitudinal: 5 N/mm^2 Transverse: 4 N/mm^2
Compressive strength	9.3 N/mm^2 (perpendicular to surface of board)
Screw pull out resistance	Screw inserts (Type B 3815) RAMPA Screw depth of 15mm on board face: 330N

NOTE: All physical properties figures are based on standard, averaged production values. If a particular characteristic or property is of prime importance, please consult Promat for advise.

Table 13: PROMATECT®-T physical properties (average production values)

General technical data

PROPERTIES	DESCRIPTION
Neutral designation	Calcium silicate-aluminate fire protective board with outstanding performances for protection of concrete and cast iron tunnels.
Combustibility	A1 in accordance to DIN 4102 A1 in accordance to EN 13501: Part 1 (EN ISO 1182, EN ISO 1716) Non combustible in accordance to BS 476
Board format	1200mm x 2500mm
Board thickness	12, 15, 20, 25, 30, 35 and 40mm (other thicknesses available upon request)
Density (dry)	900 kg/m³ ± 10%
Thermal Conductivity	ca. 0.212 W/m°K (flux meter method: ASTM C518-75) (value at 20°C)
Alkalinity	ca. pH 10
Water damp diffusion resistance	ca. 5
Typical moisture content	< 5%
Tolerances on length and width	± 1mm
Tolerances on thickness	± 0.5mm
Surface description	Smooth upper surface, back surface slightly textured
Waste disposal	To be handled as general building waste in accordance with the local legislation.

Static technical data (Average data of the production)

Bending strength	Bending strength: Modulus of elasticity:	4.5 N/mm² 1,400 N/mm²
Compressive strength (perpendicular to the surface)	1% deformation: 10% deformation:	1.2 N/mm² 7.8 N/mm²
Screw pull-out resistance (board thickness = 25 mm, screw depth 20 mm, screwed in the surface)	Quick fix screws 5mm x 50mm Airdry: Water saturated:	 657N 372N
Bolt Pull through resistance (board thickness = 25 mm)	Bolt M8, washer diameter 30 mm:	 3,220N

Additional data

Water permeability	The standard board is not permeable according to EN 492 (DIN 492). Accidental exposure to water does not affect the characteristics of the board when dried afterwards.	
Water absorption	0.6 g/cm³	
Hydric movement (elongation is +) (shrinkage is -)	Airdry to saturated: Saturated to oven dry: Airdry to oven dry: Oven dry to saturated:	+ 0.84mm/m - 1.06mm/m - 0.47mm/m + 1.19mm/m
Coefficient of thermal expansion (105~20°C)	- 8.3 m/m°K x 10^{-6}	
Thermal shrinkage	3 hours at 950°C: 3 hours at 1250°C:	1.5% 4.0%
Melting point	> 1400°C	
Abrasion resistance (taber test, weight loss after 1000 turns)	4,600 g/m²	
Frost Thaw resistance	With a method of accelerated ageing, developed together with the STUVA, which consist of 100 cycles of 24 hours per cycle of heating, raining, freeze and thaw, the board does not degrade and remains with it s mechanical properties and performances. A slight flaking of the surface could be possible.	

NOTE: All physical properties figures are based on standard, averaged production values. If a particular characteristic or property is of prime importance, please consult Promat for advise.

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NOTE: National and International standards for testing, codes of practise etc, have not been detailed within the above list.

Appendix 4: Terminology Used In Tunnel Construction

Axis
The lengthwise course of a tunnel, especially along the centre line.

Bentonite
Clay formed from volcanic ash which can absorb large amounts of water and expands to many times its normal volume. Used to retain the sides of excavations in wet, unstable soil.

Bore
Construction method for tunnels which involves digging a tube-like passage through the earth. Usually refers to mountain tunnelling. See drill and blast.

Caisson
A pressurised, bell-shaped structure which allows construction fully under the water. Compare with cofferdam.

Cofferdam
A waterproof wall, open at the top, enclosing a construction area below the water level. Compare with caisson.

Conduit
Pipe or liner used as a passage for other pipes or wires.

Course
In tunnels, the path of a tunnel. In masonry, one horizontal row of blocks.

Consolidation
Soil stabilisation; see grouting.

Cross section
The shape of a tunnel; shapes include ovoid, horseshoe, round or square.

Cut and cover
Construction method which involves excavating a large trench, building a roof structure, then covering it with earth. Commonly used for subways and relatively flat locations.

Dewater
Removal of water during construction.

Diaphragm wall
Watertight wall formed from cast-in-place reinforced concrete. Commonly uses slurry wall construction.

Drift
A horizontal, underground passage.

Drill and blast
Construction method in which pilot holes are drilled for explosive charges. The resulting debris is carried out and the process is repeated.

Embedded wall
Retaining wall constructed using sections placed side-by-side or interlocking to form a continuous structure. Includes sheet pile, soldier pile, bored pile and diaphragm wall.

Excavation
The process of digging or the hole which results.

Full face boring machine
A tunnelling machine which has cutting teeth at its front. It creates the tunnel opening while passing the waste material through the rear. Many types of tunnel boring cut small sections which are progressively enlarged. A full face boring machine cuts the complete cross section of the tunnel at once. See tunnel boring machine (TBM).

Grade
The elevation of the ground surface. Often used to describe the angle or slope of the surface.

Gravity wall
Retaining wall relying on significant mass, dimensions or modular sections. Little or no stability is gained from the natural resistance of the supported. soil. May be large stone blocks, pre-fabricated concrete modules, or reinforced construction with spread foundations.

Grouting
Unstable rock and soil is strengthened by the injection of chemicals, cementitous grout, freezing or other methods.

Immersed caisson
A pressurised, bell-shaped structure which allows construction fully under the water.

Immersed tube
Construction method using pre-fabricated tunnel sections. While the ends are sealed, it is lowered into position under the water and attached to other sections. Also sunken tube.

Initial support
Applied or installed immediately to the interior surface after excavation to maintain the opening. Includes shotcrete, rock bolts and/or steel ribs.

Jacking
Construction of small diameter passages by forcing pipe through the soil. Also known as Pipejacking.

Lagging
Boards placed side-by-side to retain the face of an excavation. Held in place by soldier piles.

Line
A description of the location and grade of a tunnel.

Lining
Materials used to finish the inside surface of the tunnel. The initial supports and preliminary liner are placed as the tunnel is being excavated. These help stabilise the interior surface. Shotcrete may be sprayed on as a preliminary liner. Later, additional coatings may be applied or other types may be used such as prefabricated steel or concrete panels, rock bolting, steel ribs and wood lagging, or masonry. Waterproofing liners are also used.

Longitudinal
Along the length of a structure.

Micro tunnelling
Construction method for tunnels which are too small for humans to dig inside. May be performed using tethered, remote-controlled drilling machines or pipe jacking.

Muck
Debris removed during excavation.

NATM (New Austrian Tunnelling Method)
Construction method, also known as the shotcrete method. As the excavation progresses, a layer of concrete is immediately sprayed on the interior surface of the tunnel and rock bolts are driven in. This method attempts to maintain the original rock structure by avoiding settling, subsidence and deformation. Additional liners may be added or more layers of shotcrete may be applied.

Overburden
The soil and rock supported by the roof of a tunnel.

Pipe roof method
Construction method in which steel pipes are laid along the sides and roof of the tunnel course and the tunnel was then constructed inside.

Portal
The open end of a tunnel. Usually includes a wall to retain the soil around the opening. May also include service and ventilation building.

Profile
A side view of the tunnel.

Reinforced soil wall
Retaining wall using various methods of attaching strips, mesh or other reinforcements to an excavated face. Soil nails may be driven in to attach the reinforcements and added further stability.

Rock bolts
Steel bar with larger plates at its head. These are driven into the interior surface of the tunnel to stabilise and add strength to the rock. See soil nails.

Shaft
A vertical, underground passage.

Sheet pile
Pre-fabricated sections installed vertically side-by-side to form a retaining wall.

Shield
A metal frame used to maintain the opening as the tunnel boring progresses. As forward progress is made, the liner is constructed behind the shield, and the shield is jacked or moved forward.

Shotcrete
Quick-setting concrete is sprayed onto the bare rock surface immediately after excavation. It forms preliminary tunnel liner.

Slurry Wall
Construction method used in wet, unstable soil. As the trench is excavated, it is filled with bentonite slurry. This fluid mixture allows the excavation to continue while preventing the passage of groundwater or the collapse of the trench walls. The trench is later backfilled with other material, forms for poured concrete walls, or pre-fabricated wall sections.

Soil nail
Steel rod driven into the ground to stabilise soil. Used as part of a retaining wall and may be attached to reinforcing strips, mesh or other buried anchors (deadman). Also call a tieback.

Soldier pile
Steel H-shape beam driven vertically into the ground to provide supports for lagging.

Spile
Rod driven into soft ground or unstable rock to provide stabilisation. A grouted spile is one which is inserted into a pre-drilled hole, when is then back-filled with grout.

Sunken tube
Construction method using pre-fabricated tunnel sections. While the ends are sealed, it is lowered into position under the water and attached to other sections. Also immersed tube.

Tailings
In mining, waste material remaining after the valuable minerals have been extracted. Stored in piles or used as fill.

Tunnel
An underground passage for vehicles or pedestrians, especially one which is created by digging into earth. Occasionally, tunnel structures are built in an excavated area then covered over.

Tunnel Boring Machine (TBM)
A tunnelling machine which has cutting teeth at its front. It creates the tunnel opening while passing the waste material through the rear.

Vault
An enclosing structure formed by building a series of adjacent arches. A long passageway having a curved ceiling or roof.

Ventilation
Circulation of fresh area and exhaust gases.

Water table
The underground elevation below which the earth is saturated with groundwater. Groundwater includes rainwater which has seeped below the surface or is supplied by aquifers, water-saturated layer of rock.

Ref.	Year	Country	Location	Project name	Tunnel type
1	2003	Australia	Brisbane	INB3 Tunnel	Road tunnel
2	2003	Australia	Sydney	Central Business District	Service tunnel
3	2003	China	Huangzhou	XiHu Lake Tunnel	Road tunnel
4	2003	France/Italy	Frejus	Frejus Tunnel	Road tunnel
5	2003	Netherlands	Terneuzen	Westerschelde Tunnel	Road tunnel
6	2003	Sweden	Gothenburg	Gotha Tunnel	Road tunnel
7	2002	Australia	Sydney	M5 Tunnel	Road tunnel
8	2002	Austria	Vienna	Rennweg Train Station	Railway station
9	2002	Austria	Vienna	Sankt Marx Train Station	Railway station
10	2002	China	Nanjing, Jiangsu province	Xuan Wu Lake Tunnel	Road tunnel
11	2002	Denmark	Copenhagen	Copenhagen Metro Station	Metro station
12	2002	France	Toulon	Toulon Tunnel	Road tunnel
13	2002	Netherlands	Amsterdam	A5 Schiphol Airport (airplane viaduct)	Road tunnel
14	2002	Netherlands	Rotterdam	Caland Tunnel	Road tunnel
15	2002	Netherlands	Roelofarendsveen	High Speed Line Aquaduct	Railway tunnel
16	2002	Netherlands	Rotterdam	High Speed Line Oude Maas & Dordtse Kil	Railway tunnel
17	2002	Netherlands	Dordrecht	Kil Tunnel	Road tunnel
18	2002	Netherlands	Voorburg	Seitwende	Road tunnel
19	2001	Australia	Sydney	Eastern Distributor	Road tunnel
20	2001	China	Ningbo, Zhejinag province	Ningbo River Crossing Tunnel	Road tunnel
21	2001	Germany	Hamburg	Elb Tunnel Western Tube	Road tunnel
22	2001	Germany	Hamburg	Elb Tunnel 4th Tube	Road tunnel
23	2001	Japan	Tokyo	Rinkaidoro	Road tunnel
24	2001	Netherlands	Rotterdam	1e Benelux Tunnel	Road under canal
25	2001	Netherlands	Rotterdam	2de Benelux Tunnel	Road tunnel
26	2001	Netherlands	Enkhuizen	Naviduct Enkhuizen	Road under lock
27	2001	Netherlands	Oud Alblas	Sophiatunnel	Undergroud route
28	2000~2001	Germany	Hamburg	Elbtunnel Western Tube	Road tunnel
29	2000	Australia	Melbourne	Burnley Tunnel	Road tunnel
30	2000	Germany	Hamburg	Elbtunnel Central Tube	Road tunnel
31	2000	Germany	Hamburg	Elbtunnel Eastern Tube	Road tunnel
32	2000	Netherlands	Leidschendam	Aquaduct onder de Vliet	Tramway route
33	1999	Germany	Hamburg	Krohnstieg Tunnel	Road tunnel
34	1999	Germany	Freiburg	Schützenallee Tunnel	Road tunnel
35	1999	Japan	Tokyo	Dainikouro	Road tunnel
36	1999	Netherlands	Rotterdam	2e Benelux Tunnel	Road under canal
37	1999	Netherlands	Rotterdam	Botlek Tunnel	Road under canal
38	1999	Netherlands	Amsterdam	Ij-Tunnel	Road under canal
39	1999	Netherlands	Leidschendam	Seitwende Tunnel	Road tunnel
40	1999	Netherlands	Zeeland	Westerschelde Tunnel	Road under canal

Continued on opposite page. See page 43~45 for some of the photos per ref.

Ref.	Year	Country	Location	Project name	Tunnel type
41	1998	Australia	Perth, Western Australia	City Northern Bypass Tunnel	Road tunnel
42	1998	Switzerland	Grellingen	Eggflue-Tunnel	Road tunnel
43	1997	China	Hong Kong	Hong Kong Airport Tunnel	Road tunnel
44	1997	Germany	Bad Godesberg	Urban Tunnel (below the B9)	Road tunnel
45	1997	Netherlands	Alphen/Rhine	Aquaduct Alphen	Road tunnel
46	1997	Netherlands	Delft	Aquaduct Delft	Tramway route
47	1997	Netherlands	Amsterdam	Schiphol (kaagbaan)	Road under runway
48	1997	Netherlands	Schiphol	Schiphol Tunnel	Road tunnel
49	1996	Netherlands	Akrum	Aquaduct Akrum	Road tunnel
50	1995	Singapore	Singapore City	Suntec City Convention Center	Underground parking facility
51	1994	Belgium	Brussel	Belliard Tunnel	Road tunnel
52	1994	Germany	Hamburg	Elbtunnel	Road tunnel
53	1994	UK	London	Leicester Square	Electricity sub-station
54	1994	Italy	No record	Mont-Blanc-Tunnel	Road tunnel
55	1994	Malaysia	Kuala Lumpur	Shah Alam Sports Complex	Road tunnel
56	1994	Netherlands	Barendrecht	Heineoord Tunnel	Road under canal
57	1994	Netherlands	Velsen	Wijker Tunnel	Road under canal
58	1993	China	Hong Kong	Times Square Shopping Complex	Underground parking facility
59	1993	UK	Wadham	Power transmission tunnel	Service tunnel
60	1993	Malaysia	Kuala Lumpur	Denmark House	Underground parking facility
61	1993	Malaysia	Kuala Lumpur	Shah Alam Sports Complex	Underground parking facility
62	1993	Malaysia	Kuala Lumpur	Sogo Department Store	Underground parking facility
63	1993	Netherlands	Schiphol	Schiphol Tunnel 2	Road under runway
64	1993	Netherlands	Ijmuiden	Wijker Tunnel	Road under canal
65	1993	Singapore	Singapore City	Ngee Ann City Shopping	Undergroud parking facility
66	1992~1998	China	Hong Kong	Hong Kong MTR	Underground stations
67	1992	China	Hong Kong	Route 5	Road tunnel
68	1992	Germany	Frankfurt/Main	No record	Underground route
69	1992	Germany	Munich	Munich Airport Tunnel	Suburban railway
70	1992	UK	London	Bow Road Station	Underground station
71	1992	UK	London	Eurostar Waterloo	Int. rail terminal
72	1992	Malaysia	Kuala Lumpur	Swiss Garden Hotel	Undergrond parking facility
73	1992	Netherlands	Grouw	Aquaduct Grouw	Road tunnel
74	1992	Netherlands	Schiphol	Schiphol Tunnel 1	Road under railway
75	1991	Belgium	Antwerp	Bevrijdings Tunnel	Road tunnel

Continued on page 42. See page 43~45 for some of the photos per ref.

Ref.	Year	Country	Location	Project name	Tunnel type
76	1991	Germany	Rendsburg	No record	Road tunnel
77	1991	Netherlands	Zeeland	Vlake Tunnel	Road under canal
78	1990	Belgium	Antwerp	Beveren Tunnel	Road tunnel
79	1990	Belgium	Zelzate	Hoge Weg Tunnel	Road tunnel
80	1990	Belgium	Antwerp	Liefkenshoek Tunnel	Road tunnel
81	1990	Belgium	Antwerp	Tijsmans Tunnel	Road tunnel
82	1990	China	Hong Kong	Pacific Place	Road under canal
83	1990	UK	London	St. Pauls Thames Link	Underground station
84	1990	Netherlands	Barendrecht	Heineoord Tunnel	Road under canal
85	1990	Netherlands	Velsen	Velser Tunnel	Road under canal
86	1990	Switzerland	Zürich	Not available	Suburban railway
87	1989~1992	Singapore	Singapore	MRTC	Underground stations
88	1989	Australia	Sydney	Sydney Harbour Tunnel	Road tunnel
89	1989	Belgium	Bruxelles	Leopold II Tunnel	Road tunnel
90	1989	China	Hong Kong	Second Cross Harbour tunnel	Road tunnel
91	1989	China	Hong Kong	Eastern Harbour Crossing	Road tunnel and suburban railway
92	1989	Germany	Not available	Ems Tunnel	Road tunnel
93	1989	Germany	Düsseldorf	Underground	Underground route
94	1989	Netherlands	Schiphol	Schiphol Tunnel	Road tunnel
95	1989	Netherlands	Schiphol	Schiphol Tunnel	Road under runway
96	1989	Netherlands	Hendrik Ido Ambacht	Tunnel onder de Noord	Road tunnel
97	1989	Netherlands	Amsterdam	Zeeburger Tunnel	Road tunnel
98	1989	USA	Boston	Harbour Tunnel CANA	Road tunnel
99	1988	Belgium	Antwerp	Kennedy Tunnel	Road tunnel
100	1988	UK	Medway	Power transmission tunnel	Service tunnel
101	1987	China	Hong Kong	First Cross Harbour Tunnel	Road tunnel
102	1987	Netherlands	Schiphol	Schiphol Tunnel	Road under runway
103	1987	Switzerland	Genf	Suburban railway	Suburban railway
104	1986	Belgium	Antwerp	Jan de Voslei Tunnel	Road tunnel
105	1986	Netherlands	Schiphol	Schiphol Tunnel	Road under runway
106	1985	Belgium	Bruxelles	Rogier Tunnel	Road tunnel
107	1982	Belgium	Brugge	Tunnel 't Zand	Road tunnel
108	1981	Belgium	Antwerp	Craeybeckx	Road tunnel
109	1980	Germany	Berlin	Schlangenberger	Road tunnel
110	1980	Switzerland	No record	Gotthard Tunnel	Road tunnel
111	1975	Germany	Hamburg	Elb Tunnel	Road tunnel
112	1963	UK	Dartford	Dartford Tunnel	Road tunnel

See page 43~45 for some of the photos per ref.

Ref.2 Central Business District service tunnel, Sydney, Australia

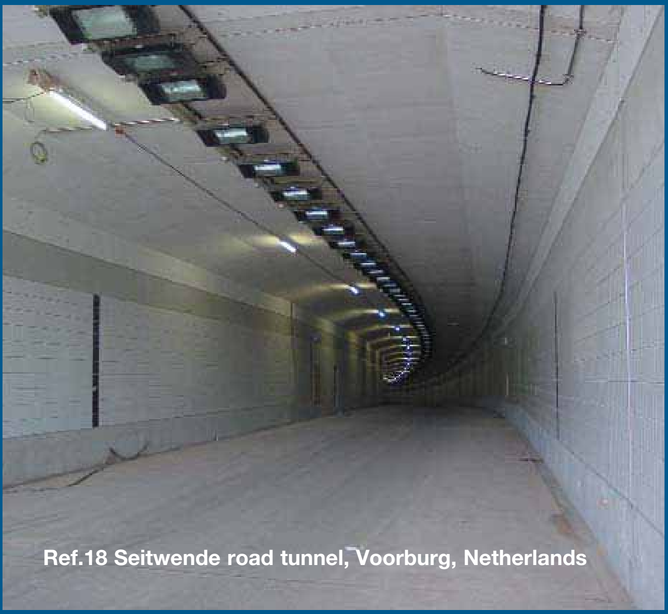
Ref.12 Toulon road tunnel, France

Ref.5 Westerschelde road tunnel, Terneuzen, Netherlands

Ref.16 High Speed Line Oude Maas & Dordtse Kil railway tunnel, Rotterdam, Netherlands

Ref.8 Rennweg train station, Vienna, Austria

Ref.17 Kil road tunnel, Dordrecht, Netherlands



Ref.18 Seitwende road tunnel, Voorburg, Netherlands

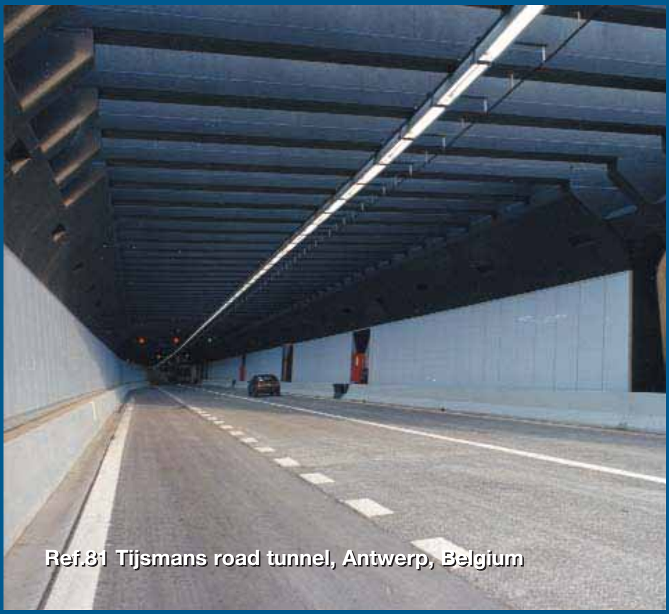
Ref.41 City Northen Bypass road tunnel, Perth, Australia

Ref.21 Elb Tunnel Western Tube, Hamburg, Germany

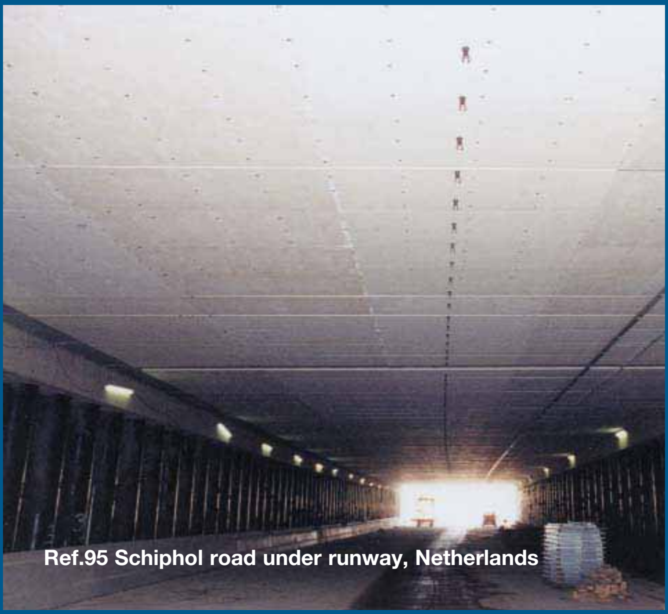
Ref.49 Aquaduct Akrum road tunnel, Netherlands

Ref.22 Elb Tunnel 4th Tube, Hamburg, Germany

Ref.66 Hong Kong MTR underground stations



Ref.81 Tijsmans road tunnel, Antwerp, Belgium



Ref.95 Schiphol road under runway, Netherlands

Ref.88 Sydney Harbour road tunnel, Australia

Ref.96 Tunnel onder de Noord,
Hendrik Ido Ambacht, Netherlands

Ref.98 Harbour Tunnel CANA, Boston, USA

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