practical passive fire protection in TBM driven road tunnels

ensuring the water seal of precast linings in the event of a large tunnel fire

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ABSTRACT

Fires in tunnels are known for their violent nature, their effects pose a major threat to the tunnel and its users. Protection of the tunnel users against the effects of a fire can be achieved by providing sufficient ventilation combined with prevention of collapse of the tunnel within a period of time. However, tunnel structures are important assets to road networks and represent a high economic value. For this reason, it is beneficial to prevent structural failure to occur at all in a worst case scenario.

Many countries around the world incorporate the Rijkswaterstaat fire curve (RWS curve) as a worst case heat loading scheme on the lining. The RWS curve is the result of research on large hydrocarbon pool fires in tunnels (e.g. due to an accident with a $50m^3$ gasoline truck). Recent research has identified the temperatures of the RWS curve to be valid for more realistic fires (e.g. with heavy goods vehicles) as well.

The RWS curve is used to engineer fire protection on concrete linings. Concrete is susceptible to thermal spalling. Hence, to prevent fire induced structural failure of the tunnel, passive fire protection should be used. The current practice uses fire protective shotcrete, or boards to cover the lining. Recent developments in concrete technology have shown that concrete itself can be made heat resistant by suppression of the spalling mechanism.

The technology of making concrete heat resistant is an interesting option for tunnel boring machines (TBM) driven tunnels. In the current practice, fire protective shotcrete and boards are used to cover the lining, decreasing the internal diameter of the tunnel.Heat resistant concrete segments can be used, but lead to the direct exposure of the rubber gaskets to the tunnel fire.

Tunnel linings build by TBM'suse precast concrete segments, to keep the lining watertight rubber sealing gaskets are used between the segments. The circular shape of the tunnel needs circumferential soil pressure to remain stable. Therefore, watertightness is needed not only to sustain tunnel functionality, but also to prevent soil erosion.

It has been found that a fire according to the RWS curve on open segment joints, increases the temperatures at the gasket area to 100°C or even 290°C for common segment designs. The temperature of 100°C is also reached in case the gasket area is shielded from direct exposure to the flames.

It has also been found that failure of water seal will certainly occur at temperatures of 100°C maintained for 24hours and gaskets do not disintegrate at temperatures of 200°C. It is found to be likely that temperatures of 100°C for shorter periods of time will also lead to failure of the water seal. However, a rubber plug will remain present between the segments.

To prevent repair works on the water seal, three methods are distinguished that may prevent the water seal from failing: protection of the gasket by closing the segment joint, alteration of the gasket, and using the tailvoid injection layer at the extrados of the lining as a secondary water seal.

It is certain that the water seal will fail in a situation with heat resisting segments, and it is likely that the water seal will fail in the current practice of fire protection. The closing of the segment joint will lead to failure of the water seal, alteration of the gasket will probably lead to high maintenance costs, and it is not feasible yet to control the quality of the tailvoid injection to form a water sealing layer.

The suggested preventive measures therefore have no or little effect on the failure of the water seal, lead to increased maintenance costs, or cannot be constructed yet. Preventive measures require an investment in the entire tunnel, corrective measure require an investment in the part of the tunnel that is affected by the fire and only in case fire occurs. For this reason, corrective measures on the water seal are more appealing.

LIST OF ABBREVIATIONS

C=C	Double valence bond between two carbon atoms
CFD	Computational Fluid Dynamics
CTRL	Channel Tunnel Rail Link (Rail tunnel between London (United Kingdom) and The Channel Tunnel (United Kingdom and France))
EPDM	Ethylene Propylene Diene Monomer (elastomer part of EPDM rubber)
FKM	Fluor Carbon Monomer (elastomer part of Fluor carbon rubber)
HGV	Heavy Goods Vehicles
HRR	Heat release rate
HSC	High Strength Concrete
PP-fibre	Poly-propylene fibre
RWS	Rijkswaterstaat (Dutch ministry of public transportation)
SFRC	Steel Fibre Reinforced Concrete
T-joint	Location where 3 segments meet each other: one flat surface and two corners
TBM	Tunnel Boring Machine

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

This chapter is an introduction of this thesis. Its aim is to familiarize the reader with the topic and to provide background information concerning the reasons of this research. First the research goals and questions are presented. Secondly, the strategy to meet the goals and answer the research questions will be elaborated. To conclude, the framework of the thesis will be presented.

1.1   BACKGROUND OF THE RESEARCH

Delta areas, like the one found in The Netherlands, are often characterised by unstable, erodible soils with high water tables. These conditions are unfavourable for tunnel construction as failure of the soil retaining structure will inevitably lead to failure of the tunnel. Most transport tunnels in these areas therefore use durable concrete linings for soil retaining purposes.

Tunnel Boring Machine (TBM) driven tunnels have a precast segmental lining. Leakage of water, soil or liquid grout can therefore occur at the segment joints. This impairs the functionality and/or the structural integrity of the tunnel. To provide a seal, rubber gaskets are used at the joints of the segments.
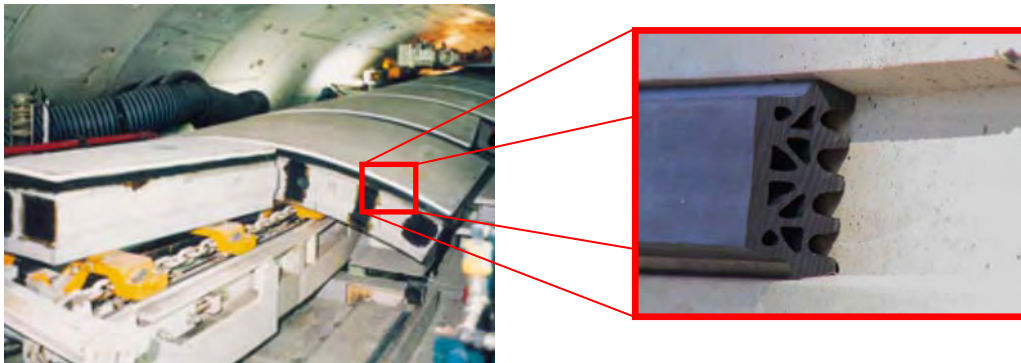
FIGURE 1: TUNNEL SEGMENTS AND AN EXAMPLE OF A GASKET IN A GROOVE [33]

The past decades have seen several fire disasters in tunnels. Well known examples are: the fire in the Channel Tunnel (1996&2008, France/Great Britain), the fire in the Gotthart Tunnel (1997, Switzerland) and the fire in the Mont Blanc Tunnel (1999, France/Italy). Fire poses a severe hazard to the structural integrity of a tunnel as conventional concrete structures do not perform well at high temperatures. The risk of failure of concrete structures exposed to intense heat loading can effectively be reduced by passive preventive measures.

Commonly used measures shield the concrete from the heat source by the use of an additional heat resistant layer, but these measures come at a cost. Additional linings have proven to be difficult to install and can only be installed in a post-TBM construction phase. The additional lining inside the tunnel requires a lot of construction materials, reduces the

internal diameter of the tunnel, and increases building time compared to a tunnel without protection.

Promising innovation efforts in the field of passive fire protection of concrete structures are based on making concrete heat resistant. At the time of this writing, several tunnels have been constructed using the principle of heat resisting concrete. The tunnels constructed for the Channel Tunnel Rail link (TBM, United Kingdom)[39], the Liefkenshoek rail tunnel (TBM, Antwerp, Belgium)[10], and the DoDo tunnel (cast in-situ road tunnel, near Utrecht, The Netherlands) [6] are examples of this.

1.2   RESEARCH QUESTIONS

By omitting the heat shielding measures in TBM driven tunnels, sealing gaskets are directly exposed to the heat of a tunnel fire. Therefore uncertainty arises about sealing performance of the gasket. The aim this research is to contribute to the goal:

"to use heat resistant segments in TBM driven tunnels, without fire protective covering and without endangering structural integrity"

At the time of this writing research is and has already been performed on heat resistant segments and structural integrity of the segments. However, literature overview and expert consultation did not lead to an unambiguous statement that gasket performance is not affected by heat from the tunnel fire. For this reason, this thesis focuses on the question if omitting fire protective covering leads to performance issues of the water seal and if so, could additional measures solve these issues? Several research questions have therefore been formulated. The main research question is:

"In case of the use of heat resisting precast linings for TBM driven tunnels, how can the water seal be guaranteed and how do the solutions compare to the current practice?"

Several sub-questions have been derived from the main question. The sub-questions are:

1) **_What is the current practice of passive fire protection in TBM driven tunnels and how do the innovative heat resistant segments change the existing system?_**
2) **_How does a fire in the tunnel affect the conditions at the location of the sealing gasket in case innovative fire protection is used?_**
3) **_What are the functions of the sealing gasket, how does it fulfil its functions and how is the performance affected by the conditions caused by the tunnel fire?_**
4) **_What measures can be taken to ensure the water sealing function of the lining?_**
5) **_How do the measures compare to the current practice?_**

1.3   RESEARCH METHODOLOGY

To answer the main research question, actually means answering the sub-questions. In some cases conclusions on a sub-question depend on the conclusion of another sub-question. To answer the research questions, four main topics were identified as isolated research areas:

- Fire and fire protection in TBM driven tunnels
- Sealing gaskets and the gasket issue
- Solutions to the gasket issue
- Comparison of the solutions to each other and the current practice

To investigate the different topics in the correct order a research scheme has been made (figure 2). All research is based on literature, expert consultation and experiments.
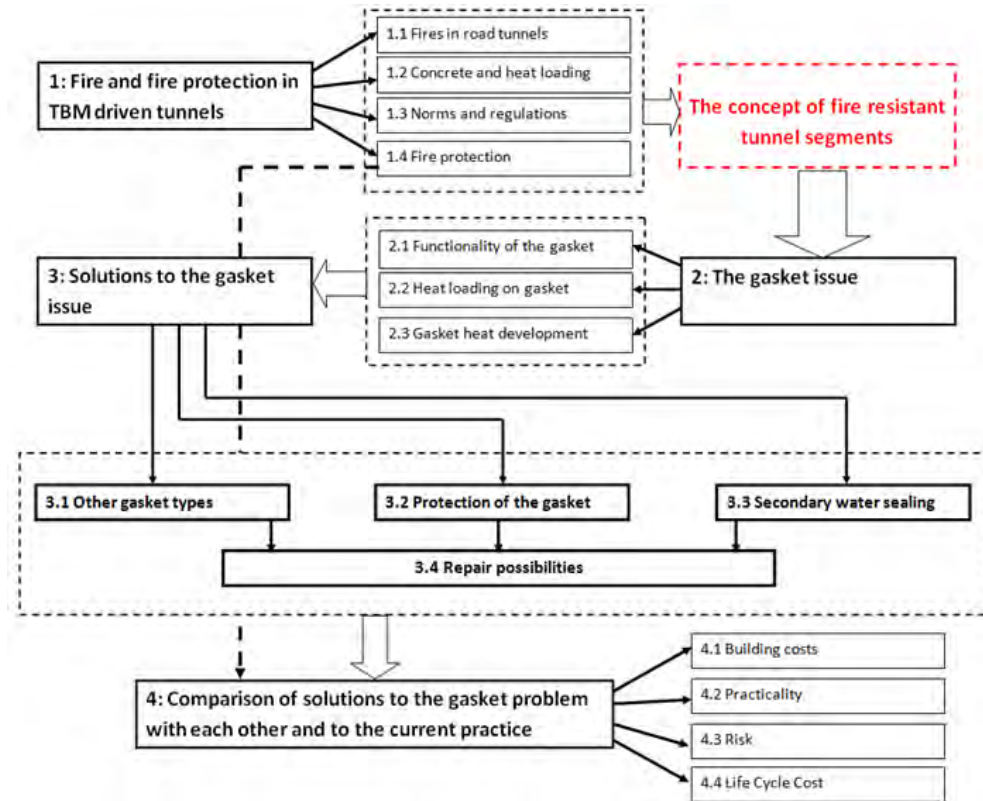
FIGURE 2: RESEARCH SCHEME

Assumptions on the availability of information about the gasket issue were made at the start of the research, which led to an initial strong focus on the solutions to the gasket issue. The assumptions have proven to be false, more research was needed to assess the gasket issue. As the topics were designed to be researched subsequently, the focus of the thesis shifted to the gasket issue.

1.3   OUTLINE OF THE THESIS

This thesis consists of 6 chapters. Chapter 1 and chapter 6 represent the introduction and the conclusion, the other chapters discuss the research topics. The research topics are divided into four chapters: research topic 1 is discussed in chapter two, research topic 2 is discussed in chapters three and four. Research topic 3 and 4 are discussed in chapter five.

First, chapter two will discuss the structure of a TBM driven tunnel and its susceptibility to heat induced failure. Fire, normative design fires, legislation and measures to prevent heat induced failure of the tunnel are discussed as well. Chapter two will conclude by providing insights in the differences between the common practice of passive fire protection and the solution of heat resistant segments.

Secondly, chapter three will discuss heat transfer science to provide a knowledge base on the heat transfer processes in the segment joint. Calculations based on findings in chapter two are provided and a fire experiment is discussed. The chapter concludes with a description of the thermal conditions at the gasket.

Furthermore, chapter four will discuss gaskets, groove design and rubber technology. An experiment was performed on the performance of gaskets subjected to high temperatures. This experiment is discussed as well. The chapter concludes with a description of the effects of a tunnel fire on the water seal.

Finally, chapter five discusses the effect of the gasket issue on the structural integrity of the tunnel. Means to prevent gasket failure and to execute repair works are presented and compared to each other and the current practice.

CHAPTER 2

FIRE AND PASSIVE FIRE PROTECTION IN TBM DRIVEN ROAD TUNNELS

This chapter aims to answer the first research question: "What is the current practice of passive fire protection in TBM driven tunnels and how do the innovative heat resistant segments change the existing system?" by providing insight into road tunnel fires and fire protection in TBM driven tunnels. The reason the lining of TBM driven tunnels needs to be protected from fire is discussed in section 2.1. Section 2.2 discusses the normative fire that occurs in road tunnels. Then section 2.3 discusses passive fire protection guidelines, and conventional and innovative methods of passive fire protection. Finally, conclusions on the first research question are discussed in section 2.4.

2.1 THE EFFECT OF HEAT LOADING ON PRECAST CONCRETE LININGS IN TBM DRIVEN TUNNELS

To assess the effect heat loading has on segmented tunnel linings, the structure of the tunnel as well as the structure of its segments needs to be known. This section therefore discusses the structure of TBM driven tunnels. The building blocks of the tunnel: precast concrete segments, are discussed in 2.1.2. The chemical and physical effects of heat loading on concrete will be elaborated in 2.1.3. The behaviour of heat loaded segmental lining is discussed in 2.1.4.

2.1.1 THE STRUCTURE OF TBM DRIVEN TUNNELS
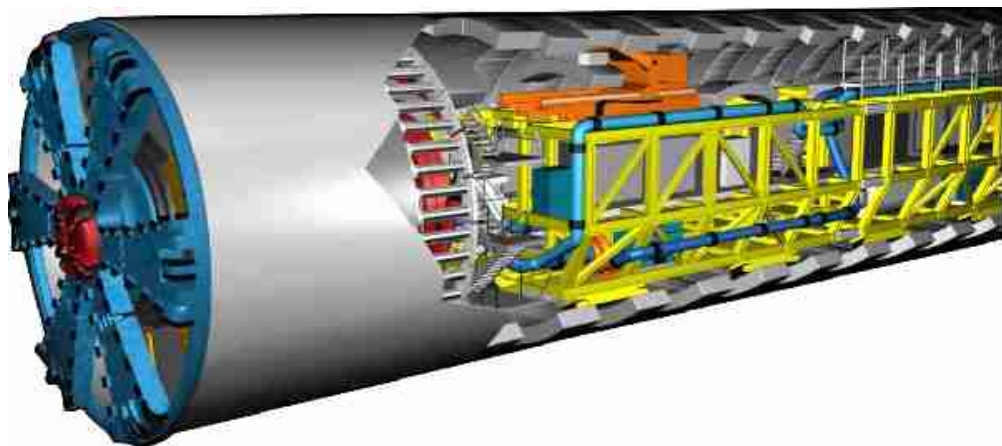
FIGURE 3: TUNNEL BORING MACHINE [9]

The TBM method for tunnelling is a mechanised way of tunnel construction. The method has a big influence on the structural design of the tunnel. Basically, a TBM is a moving assembly factory that excavates soil at its front and leaves a tunnel at its back. The whole process takes place in an area that is shielded from surrounding soil. Due to the advantages of hoop forces in structures, most TBM driven tunnels have a circular cross-section. The

circular lining is constructed with the use of precast concrete segments. The shielded part of the TBM is a small part of the tunnelling machine. The shield is followed by gantries that support the production process. Precast segments are supplied to the TBM through the tunnel and handled by the gantries.

Inside the shield precast segments are connected to each other and the last build ring. Ring joints and longitudinal joints are formed in the process. The longitudinal joints determine the layout of the segments. If the longitudinal joints are continuous the segment layout is called regular, if they are interrupted at each segment the layout is called masonry. In masonry layouts two corners and one flat surface meet, four corners meat in regular layouts [5].

The tunnel is constructed inside the TBM, and will therefore not be able to completely fill the gap the TBM has created. As the structural stability of the lining is based on hoop forces, it is important that the lining is supported at its complete circumference. For this reason and to avoid settlements, the tail gap left by the machine is filled by a mortar (geometry can be found in figure 4).
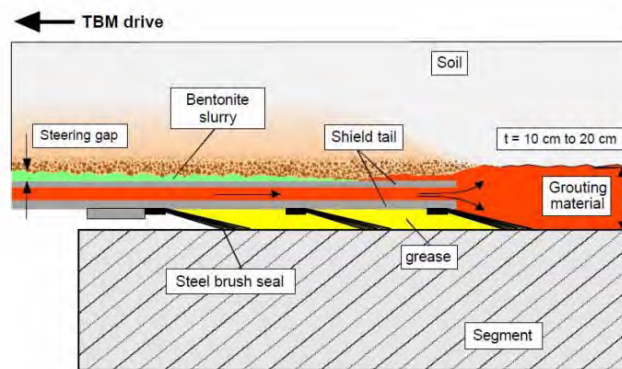
FIGURE 4: TAILVOID INJECTION [3]

As the lining is stable due to the circumferential support of soil, failure to support part of the circumference leads to a redistribution of stresses in the lining. Soil erosion leads to voids on the extrados of the lining. Finite element studies [29] have shown that void size, earth pressure coefficient and location of the void are important factors in the redistribution of the stresses. The effect of voids at the tunnels horizontal axis were found to be most critical. Soil erosion therefore must be avoided to ensure stability of the lining.

To keep the tunnel watertight and prevent soil erosion, rubber gaskets are used between the concrete segments. Gaskets are the only water sealing measure between the segments and play a large role in segment joint design.

2.1.2   SEGMENT PRODUCTION AND DESIGN

Segment design

Three different loading phases can be distinguished for the segments: transport, installation and exploitation. The forces acting on the segments are different for each phase. A rule of thumb for designing precast TBM tunnel linings is that segmental thickness should be around $1/20$th of the tunnel diameter. Concrete alone cannot resist the stresses that transportation and TBM advancement introduce, and must therefore be reinforced in

some way. Stresses during the exploitation phase do not require reinforcement in the segments due to the positive effects of soil loading on the circular shape. The way forces are introduced to, and transferred by segments determine a great deal of the reinforcement in the segment. Segment joints are unreinforced parts of the segment that cope with large stresses. Joint design therefore is an important part of segment design, and is mostly determined by the gasket system and the pressure pads.

Gaskets are located at the extrados of the joint, this part of the segment is difficult to reinforce in a conventional way. But gasket compression induces a force into the segment that may cause cracking of a corner of the segment, leading to a leak joint. Depending on gasket type and groove depth, a minimum distance from the edge of the segment should be observed.

The same holds for the use of pressure pads and load transfer material. Pressure pads and load transfer materials are used in segment joints to introduce compressive stresses (e.g. from TBM thrust forces) at strategic locations in the segments. They essentially prevent the cracking susceptible regions of the segment joints from contacting each other. A conceptual cross section of pressure pads and gasket grooves in a segment joint is presented in figure 5. Pressure pads and load transfer materials are considered to be the same in this thesis.
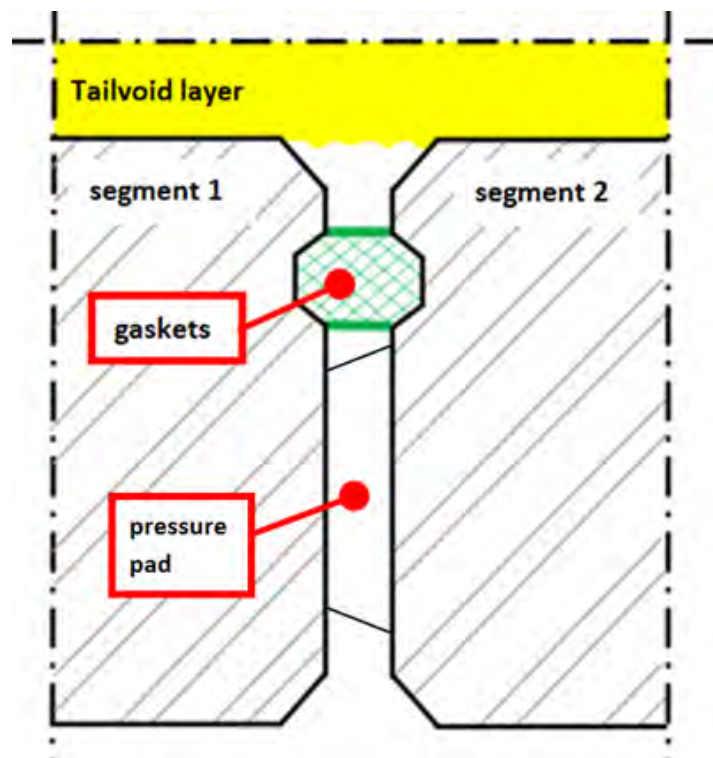
FIGURE 5: REPRESENTATION OF A CONCEPTUAL SEGMENT JOINT CROSS SECTION

Stresses in the tunnel are transferred by the segment joints. Ring joints and longitudinal joints have different loading schemes. The TBM advances by introducing very high stresses at the ring joints of the lining. These stresses are parallel to the tunnel axis but due to lining deformation behind the TBM, eccentric to the axis of the segments [5]. Every modular technique of construction has risks with respect to geometrical compatibility of the components. Installation tolerances and segment production inaccuracies (commonly 1-5mm [25]) lead to the risk of high local stresses in the segments and therefore concrete spalling. To introduce the stresses at strategic locations, pressure pads can be used. They

create a predictable path of compressive forces in the segment layout of a tunnel (which makes it possible to perform reinforcement calculations), and eases installation tolerances (which makes it easier to maintain production speeds). Pressure pads also create a gap between the segments. In some projects interconnection of the rings may be necessary, dowel and socket, or tongue and groove systems can be used in those cases.
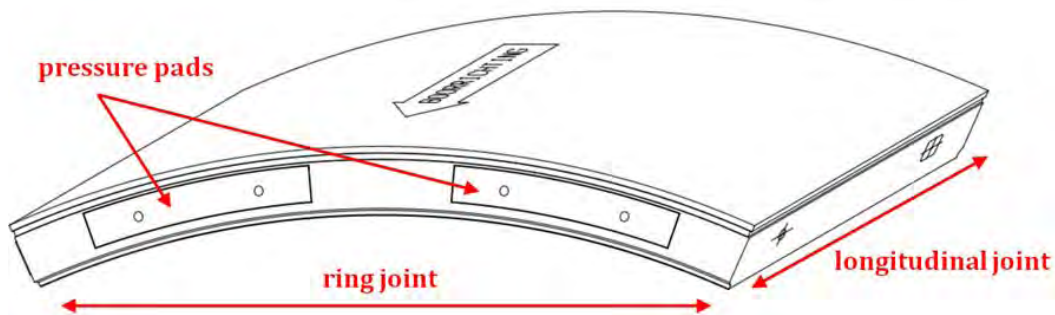
FIGURE 6: EXAMPLE OF A SEGMENT WITH PRESSURE PADS IN THE RING JOINT AND A FLAT SURFACE AT THE LONGITUDINAL JOINT [19]

The longitudinal joints are loaded in a different way than ring joints. Reinforcement needed for the construction stage of the tunnel does not play a big role in the exploitation stage: soil loading is dominant and leads to tangential normal forces. These forces are transferred by longitudinal joints and generally lead to much lower stresses than the ring joint stresses introduced by the TBM. Flat joints can therefore be used but splitting reinforcement may be necessary.

Segment production

The number of identical segments used in a TBM driven tunnel is substantial. Segment production can therefore be economised by industrialization and optimization techniques. TBM tunnelling projects commonly use factories or have even build temporary factories to produce the segments.

Due to the large forces during ring erection and the subsequent loading by TBM advancement and tailvoid injection, deviation from geometrical tolerances can lead to high local stresses and cracking of concrete. Minimizing deviations from the design is therefore essential to the construction process. This leads to demands on mould types and minimum concrete strength at the time of demoulding.

In a common factory setup, the casting moulds are part of a conveyer system. In the conveyer system the moulds undergo several processes before casting. After demoulding the freshly cast concrete segments, the casting moulds return to the conveyer system to start the process over again. The concrete segments are stored to cure further.

Due to the strict geometrical tolerances and the amount of production cycles, casting moulds are often made of steel. This makes the moulds relatively expensive. Fast re-use of the moulds is therefore important in obtaining an economic production process. Production cycle times can be reduced significantly by using a concrete with fast curing properties.

Also, most tunnels are being constructed below the water table and have a design lifetime of over 50 years. This leads to strict durability requirements which are generally met by reducing permeability, pore volume and pore sizes of the concrete. High strength concrete (HSC) is a dense concrete that shows fast initial strength development and relatively low permeability. HSC thereby allows for the option of fast reuse of the production moulds and provides the means for a durable construction. The extra strength HSC provides with respect to conventional concrete is not needed for the forces acting on the tunnel structure. But the fast curing properties, together with its durability and the fact that there is a lot of experience using this type of concrete, leads to HSC being the material of choice for production of precast tunnel segments.

2.1.3 CONCRETE AND HEAT LOADING

Compared to other building materials concrete possesses very good heat resistance and thermal insulation properties. Unfortunately it does degrade under extreme heat loading and is susceptible to thermally induced spalling.

Thermal spalling

Spalling is the deterioration of a concrete structure by breaking or shooting off of pieces of concrete. Spalling can be caused by several phenomena, but is always the result of high local stresses. Heat loading on a concrete structure induces thermal spalling by splitting of aggregates, and loss of cohesion due to thermal stresses and high pore pressures. By observation two types of thermal spalling can be distinguished: sloughing off and explosive spalling. Sloughing off describes pieces of concrete falling out of a structural element, explosive spalling is a violent burst-out of pieces of concrete.
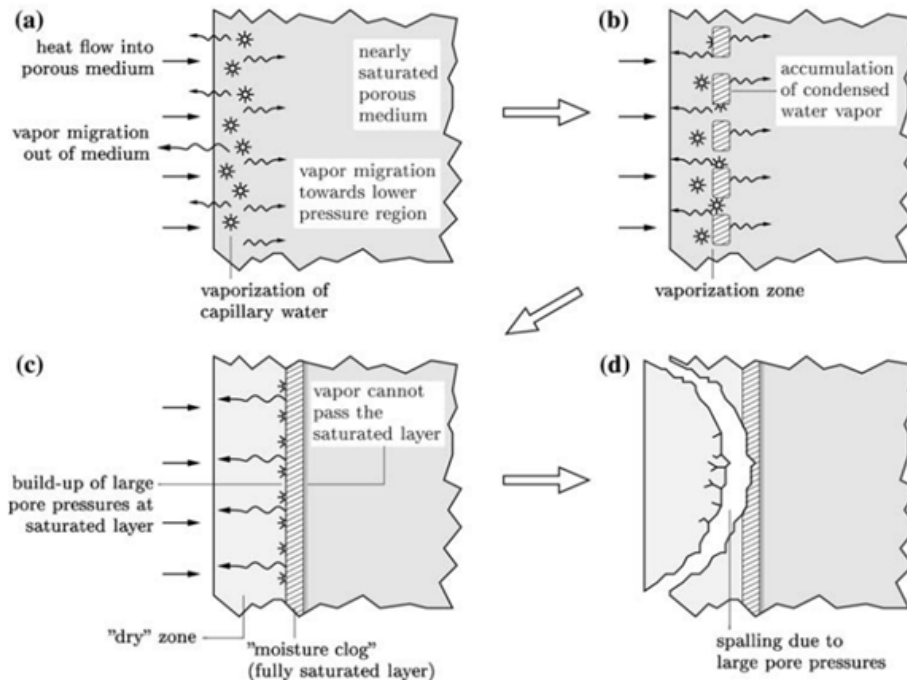
FIGURE 7: PORE-PRESSURE SPALLING [44]

Explosive spalling is considered to be the most dangerous form of spalling as it can quickly deteriorate a structure. High pore-pressures and thermal-stresses are the driving factors to explosive spalling. Pore-pressure spalling is induced by the vaporization of the free and

bounded water inside concrete at temperatures of 100°C or higher (depending on the pressure). Due to the relatively low permeability of concrete the steam cannot dissipate easily. This results in the steam migrating towards the concrete surface, but also towards the core of the structure. Because the core of the concrete is colder than the heated surface, steam that migrates to the colder region cools down and condenses. This leads to an accumulation of water and creates a saturated layer. The viscosity of liquid water is much higher than the viscosity of steam, so it takes more pressure for liquid water to migrate through the concrete. This causes the steam to be virtually blocked from travelling further. But the production of steam continues, creating higher pore pressures and tensile stresses in the concrete. At some point tensile loading will become too severe and a piece of concrete will burst off, accompanied by a popping sound. The process of pore-pressure spalling is schematised in figure 7. Water content and permeability of the concrete at the time of heat loading are important parameters to the susceptibility of concrete to pore-pressure spalling.

A physical body cannot be heated uniformly by heat loading from the outside, hence a fire will lead to temperature gradients in the cross section. The low thermal conductivity of concrete increases the severity of temperature gradients. As concrete shows expansion when heated, temperature gradients will lead to a zone that shows compressive stresses. The compressive stress zone introduces tensile stresses in the colder region of the cross section and perpendicular to the heated surface. The tensile stresses perpendicular to the heated surface can cause cracks parallel to the heated surface and pieces of concrete to spall. This entire process is called thermal-stress spalling. A graphical representation of the process can be found in figure 8.
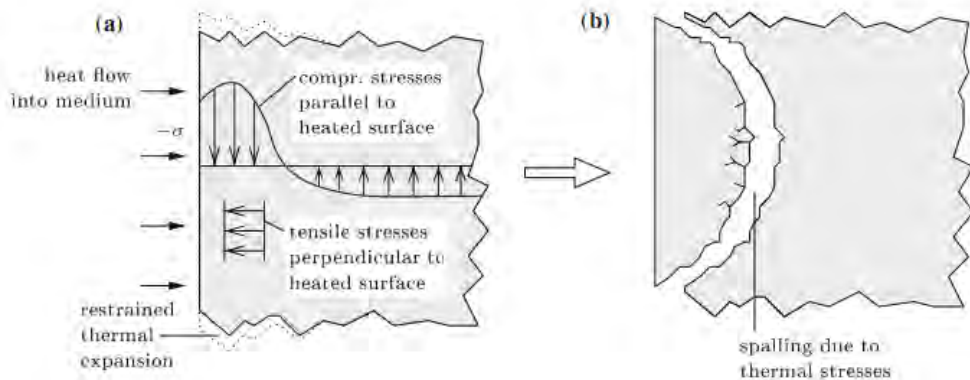
FIGURE 8: THERMAL-STRESS SPALLING [44]

Spalling leads to the exposure of a new surface of concrete. As it was previously shielded from heat, the newly exposed surface will have a lower temperature than the surroundings. If spalling occurs due to temperature gradients, the process will repeat itself and will continue to deteriorate the structure (progressive spalling).

Concrete degradation due to heat loading

If concrete does not spall under heat loading, it will thermally degrade. Concrete can be described as a porous material built up by a mix of cement stone, aggregates and often steel. The thermal conductivity of concrete is very low (about 43 times less conductive than steel), concrete can therefore act as a thermal barrier if it does not disintegrate.

During heating several reactions take place in concrete, the components of concrete react differently to certain temperatures. Most changes are irreversible upon cooling. The various processes concrete endures during heat loading are summarised in figure 9a.

The pores of concrete may contain liquid water. This water is able to flow freely (free capillary water) or is enclosed by the cement stone. Cement stone is hydrated cement that contains chemically and physically bounded water. The free capillary water is the first component of the concrete that is affected by a temperature increase. Water in concrete vaporizes at temperatures varying from 100°C to 140°C (pressure dependent). Vapour and liquid water can migrate through the porous structure of concrete, but is hindered by the low permeability. Pressure can therefore build up in the pores of the concrete [16]. Vaporisation of water consumes a lot of thermal energy, this leads to a cooling effect if the vapour can escape. Up to temperatures of 250°C physically bounded water vaporizes as well, the structure of the cement stone will not be affected by the loss of the physically bounded water. The dissipation of the free and physically bounded water often leads to an increase of compressive strength of the concrete at temperatures ranging from 100°C to 250°C. The reason for this is pore pressure reduction. Cement or aggregate types do not play a significant role in the processes occurring at these temperatures [40].

At a temperature of about 400°C the calcium hydroxide in the cement stone starts to dehydrate, thereby decomposing the structure of the cement stone. The cement stone reacts by contracting [22]. The severity of this process depends on the cement type used in the concrete [40]. This process continues until a temperature of about 1200°C is reached. At that temperature all water in the concrete has vanished. All these processes lead to a significant strength decrease of the concrete.

A wide range of aggregates can be used in concrete. Natural materials found in large quantities in the vicinity of the concrete factory are often used. The most commonly used aggregates are: siliceous, granite/basalt, and limestone aggregates.

Aggregates play a large role in the response of concrete to heat loading. According to Khoury [22] cement stone shows contraction, but most aggregates show expansion as the temperature increases (figure 9b). Due to the fact that aggregates are embedded in the cement stone, the differential expansion can lead to cracking of the concrete.

Siliceous aggregates show a large difference in expansion coefficient from cement stone. Siliceous aggregates generally are quartz based. Quartz shows distinctive expansive behaviour at temperatures around 575°C. It is called the α to β expansive inversion and leads to instant volumetric increases of about 2%, inducing sudden cracks. Concretes based on siliceous aggregates therefore are unstable for higher temperatures.

Basalt, granite and limestone aggregates show relatively modest thermal expansion behaviour. Concretes based on these aggregates perform well under heat loading and are called thermally stable. Basalt and granite do not decompose at the temperatures of tunnel fires, limestone aggregates do. The main component of limestone aggregates is calcium carbonate. Calcium carbonate will decompose into calcium oxide and carbon dioxide at about 800°C.
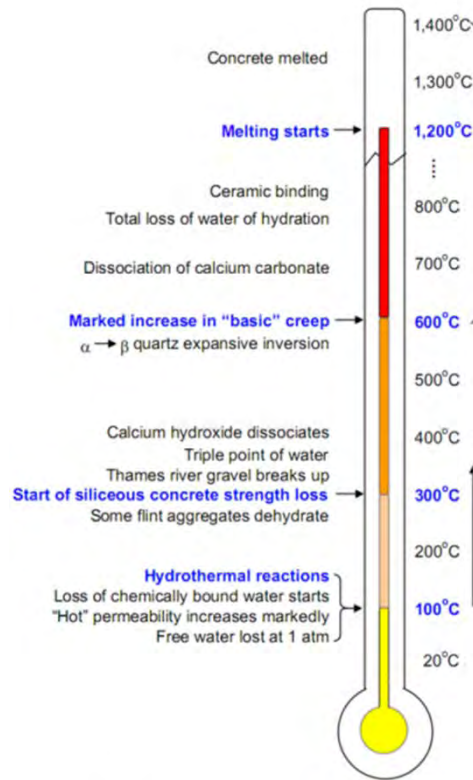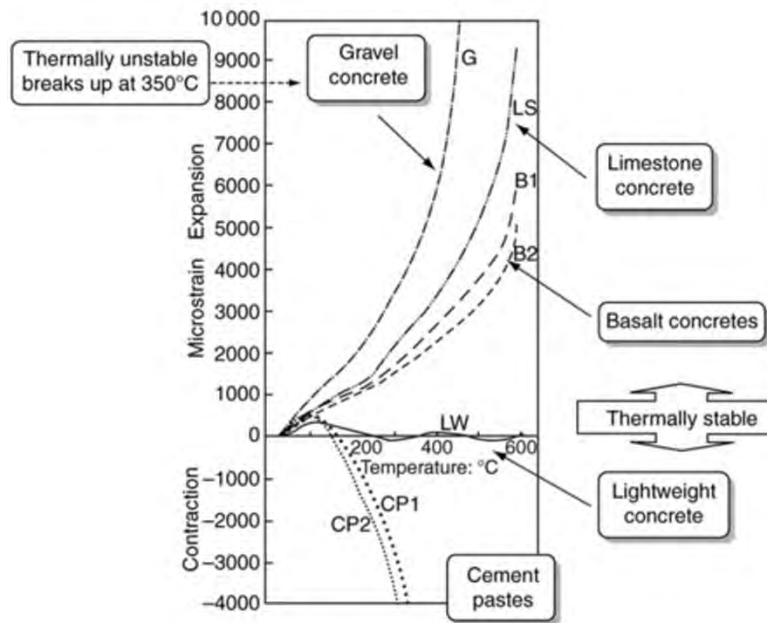
FIGURE 9: A) CHEMICAL PROCESSES IN CONCRETE AT HIGH TEMPERATURES [21], B) THERMAL EXPANSION OF AGGREGATES AND CEMENT PASTES [22]

At temperatures above 1200°C ceramic processes will take place. The dehydrated cement is able to react with the aggregates and the weakened concrete will show an increase in

strength. A similar process occurs in pottery firing. Dependent on the cement type, concrete will start to melt if the temperature increases further.

All components of concrete are affected by a large increase in temperature. These processes eventually lead to a severe loss of strength, which is slightly compensated by ceramic binding before the concrete melts. Extensive testing by Khoury has shown that (given a relatively wide margin of error) concrete strength generally is nearly unaffected up to a temperature of 200°C to 250°C, but starts to decrease at higher temperatures (figure 10). The behaviour of reinforcement steel shows a similar path. The strength of reinforcement steel is constant up to a level of 250°C and decreases linearly to 0% at 850°C [14].
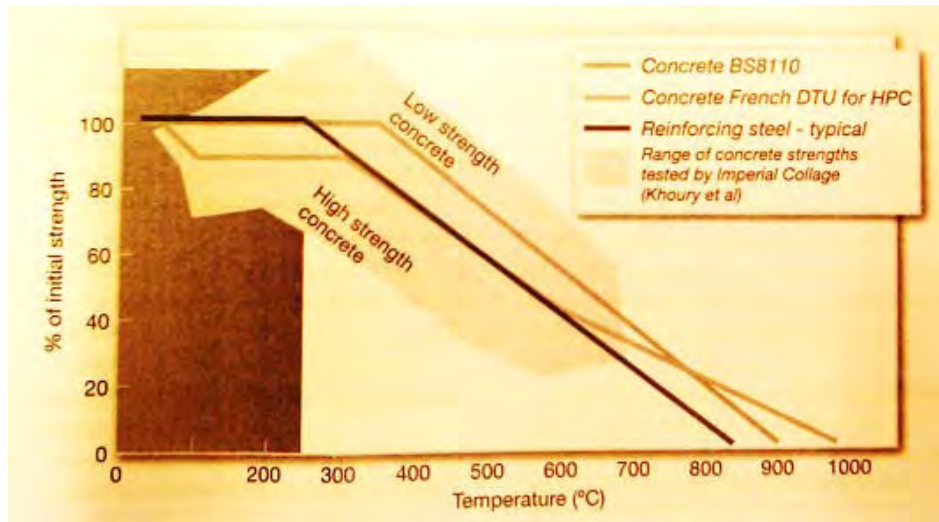
FIGURE 10: CONCRETE STRENGTH AS A FUNCTION OF TEMPERATURE [42]

2.1.4 HEAT LOADING ON TBM-DRIVEN TUNNELS WITH HSC PRECAST SEGMENTS

HSC has advantages during segment production, but unfortunately has proven to be susceptible to thermal spalling. The reason for this can be found in the durability performance of HSC. Pore sizes and pore volumes of HSC are limited compared to conventional concrete. Pore pressures can therefore build up very quickly, as there is little room for the vapour to expand into, and a saturated layer takes less water to form. The structure of TBM driven tunnels with HSC segmental lining thereby creates a worst case scenario with respect to thermal spalling. The lining is subjected to, and possesses:

- High temperatures and fast initial increase of temperature
- Compressive forces parallel to the heated surface
- HSC with a high water content

Road tunnel fires are well known for reaching very high temperatures very quickly, leading to large temperature gradients in the concrete. The ring shape of the tunnel causes the lining to be loaded by a tangential normal force, hence compressive forces exist parallel to the heated surface. The TBM method for tunnelling in soft soils also leads to requirements with respect to minimum soil cover; in most cases leading to high water pressures at the tunnel lining. This will in time result in water ingress and will increase the water content of

the concrete. A schematization of the compressive forces and high temperature gradients in the cross section of the segment can be found in figure 11.

If spalling does not occur, the heat of the fire will affect the concrete and its reinforcement. However, the low thermal conductivity of the concrete will lead to a slow pace of heating, hence little degradation of the cross section.

An important aspect of heating segments from the intrados is the curved shape of the segments, it induces additional deformation. Thermal expansion at the intrados of the segment forces the curved shaped segment to straighten out. Due to this effect, longitudinal joint faces can rotate and cause the gaskets to lose contact pressure [32]. This effect while significant, is neglected in this thesis as the focus is on the functionality of the gaskets after thermal loading.
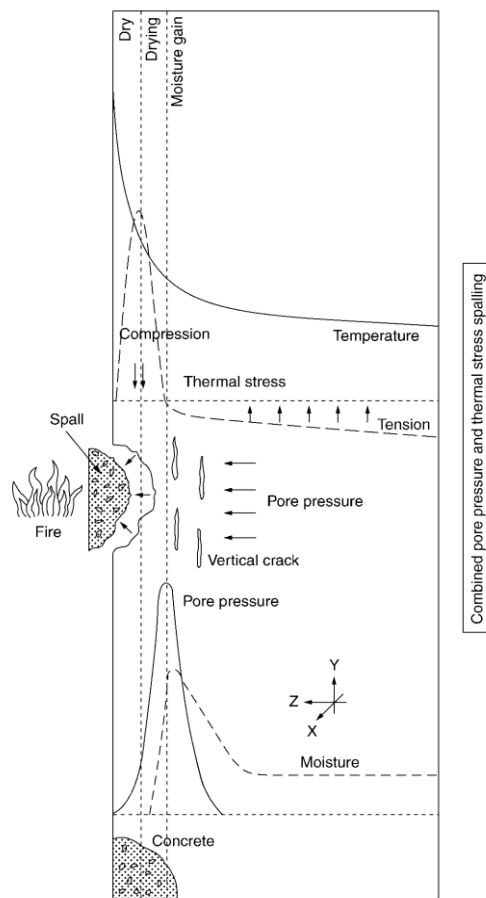
FIGURE 11: COMBINED PORE PRESSURE AND THERMAL STRESS SPALLING MECHANISM [23]

2.2 ROAD TUNNEL FIRES

Fire is the driving force for protective measures in tunnels, it is also the driving force to uncertainty about the water seal of the precast tunnel lining. This section discusses fire and fire in tunnels. 2.2.1 will discuss the phenomenon of fire and what kind of circumstances influence the severity of a fire. Then, tunnel fires will be discussed in 2.2.2. The last section: 2.2.3, will discuss design fires for road tunnels.

2.2.1 FIRE

The definition of fire is: the rapid oxidation of a material in the chemical process of combustion, releasing heat, light and various reaction products [11]. For fire to exist three components have to be in place, which are:

- oxidizing agent
- fuel
- heat

During a fire, heat triggers a chemical reaction between the fuel and the oxidizing agent. This means an activation temperature needs to be reached. Three different activation temperatures can be distinguished:

- flash point
- fire point
- auto-ignition temperature

First, the flash point is defined as the lowest temperature at which fuel can vaporize to form a combustible mixture in air. If ignited at the flash point, the vapour will burn momentarily and will extinguish if the ignition source is removed. Secondly, the fire point is a slightly higher temperature at which vapour catches a fire that is sustained when the ignition source is removed. If a combustible material is heated up to the auto-ignition temperature, the material does not need an ignition source to combust.

Chemical processes can be divided into two types: exothermic and endothermic. An endothermic process consumes energy, the end product thereby has a higher energy level than the original material. By this definition endothermic processes will not produce large fires, as they will extinguish themselves by absorbing heat energy in their end products. Exothermic processes are processes that produce energy in the form of heat and, or light. The end product of an exothermic process has a lower energy level than the original material.

The components needed for fire are presented schematically in figure 12. Most literature considers a fire triangle but in order to sustain a fire without an external ignition source, the fire needs to produce and maintain a chain reaction (i.e. a self-perpetuating exothermic chemical process needs to be in place). When discussing tunnel fires a fire tetrahedron is therefore more appropriate.
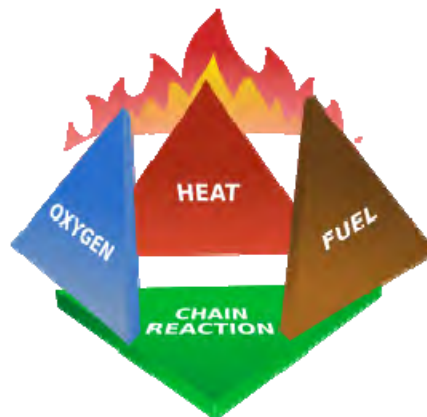
FIGURE 12: THE FIRE TETRAHEDRON [11]

As seen in figure 12, fires are dependent on four components. The severity of the fire will differ as the mix of components differs. Depending on the combination of the components, fires will eventually develop to a steady burning rate. Burning rate is important to the severity of a fire. It determines fire temperatures and duration. In order to be able to describe the severity of a fire quantitatively, a component of interest can be isolated out of the fire tetrahedron.

Temperature is considered to be the most influential effect of fire with respect to the structural integrity of tunnels. Temperature is the result of heat loading on a physical body. Heat is scientifically described as energy, fuel can therefore be described as an energy container. The amount of potential energy in the container is quantified by the calorific value Joule, the rate of energy release by combustion can be measured in Watt. The term used for the release of energy by combustion is Heat Release Rate (HRR). The HRR value affects fire severity and duration. Based on duration and severity two types of fires can be distinguished:

- fuel bed controlled (fuel bed control in figure 13)
- ventilation controlled (vent. control in figure 13)
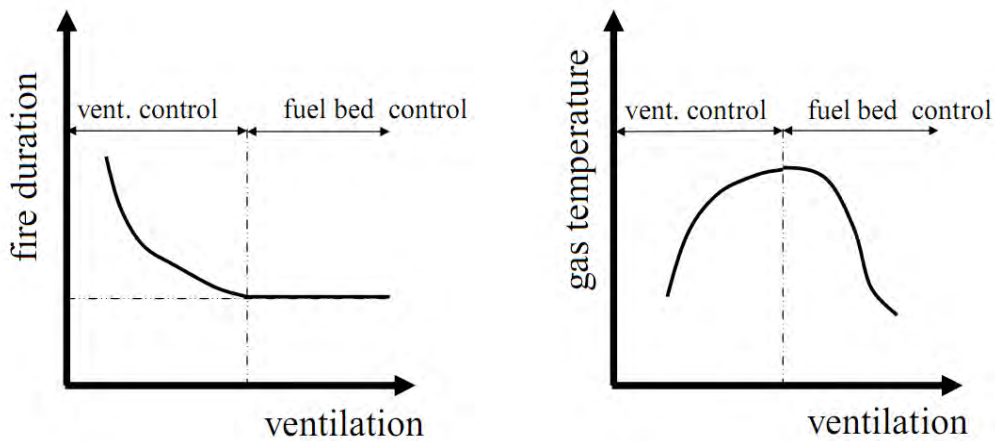
FIGURE 13: VENTILATION AND FUEL BED CONTROLLED FIRE [7]

Fuel bed controlled fires occur in case of a free fire and sufficient oxygen supply. Fire development is therefore fully dependent on the burning rate of the fuel, which in turn is dependent on fuel type, phase and availability. Temperatures produced by the fire will drop if the ventilation capacity increases.

Ventilation controlled fires are underdeveloped fires. The supply of oxygen is insufficient to support complete combustion of the fuel. The burning rate is lower compared with fuel bed fires due to the sub-optimal conditions, the duration of the fire therefore increases. If the ventilation capacity decreases further, burning rate decreases further as well. The HRR will therefore be lower and heat production will drop, leading to lower gas temperatures. Ventilation controlled fires are dangerous due to the fact that gases at their auto-ignition point may be present. As soon as ventilation capacity increases, these gases will combust or explode.

Every fire has a start and an end; in between several scenarios can take place. Fires in road tunnels generally fit the scenario presented in figure 14. An incipient, growth, fully developed and decay phase can be distinguished.
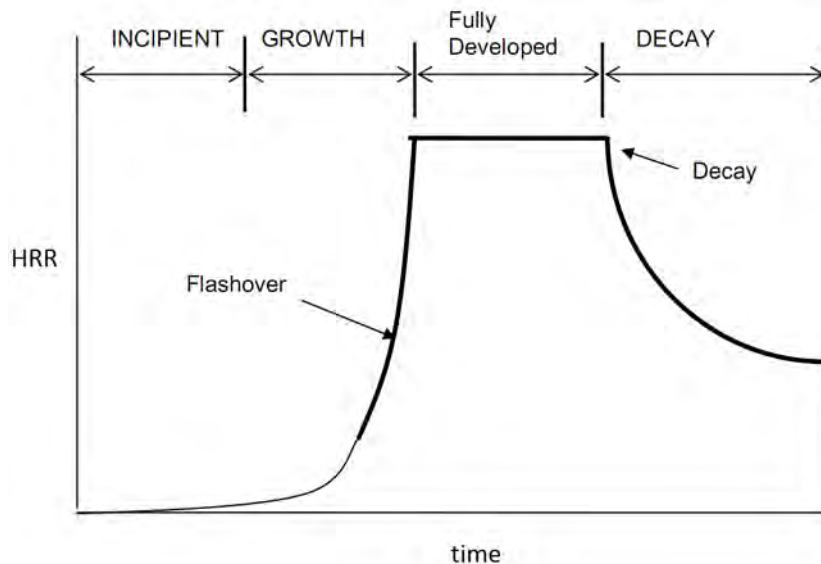
FIGURE 14: SCHEMATIC REPRESENTATION OF A FIRE SCENARIO [15]

Incipient and growth phase

In order to start a fire, ignition needs to take place. A survey performed by the European Thematic Network: Fire In Tunnels (ETN-FIT) on the causes of several major road tunnel fires, concluded that the vast majority of the fires is due to vehicle defects (e.g. overheated engines and brakes) and rear end collisions (a percentage of 62 and 34 respectively)[15]. At the start of a fire the energy output is still small due to the little amount of burning fuel, but as soon as more fuel becomes involved the fire starts growing increasingly faster. The speed of growing is dependent of fuel type (e.g. the vehicle, petrol or goods carried by a lorry) and fuel availability (e.g. a pool of petrol or petrol leaking from a ruptured tank).

During the growth phase radiation levels increase and hot smoke accumulates in the tunnel. This heats up other potential fuel sources which will eventually reach their flash point and start to combust. At some point all fuel sources in the vicinity of the fire suddenly become involved in the fire, this is called the flash over. The flashover is an important part of the growth phase, it is a turning point in the course of a fire. If a flashover occurs, the fully developed stage of a fire is reached almost instantly.

Fully developed and decay phase

The peak HRR is reached and maintained in the fully developed phase. All available fuel sources are involved in the fire and are burning at the fastest rate the fire tetrahedron permits. Fuel type and ventilation capacity are very important parameters for fully developed fires in tunnels. According the Dutch ministry of public works, the definition of a tunnel is: a long, enclosed, rectangular or circular construction used to accommodate a railroad or a road [36]. This definition indicates that tunnels are enclosed spaces, hence ventilation capacity is limited. Most fires in tunnels are fuel controlled, but very large fires (HRR in excess of 200MW) generally do become ventilation controlled [20].

At the end of the fully developed phase some fuel sources become depleted while others continue to burn. This leads to a decrease of the HRR until all fuel is depleted and the fire is extinguished. This phase is called the decay phase.

Gas flow and ventilation

The most important function of tunnel ventilation during a fire is to increase the safety level of the tunnel users. The fire produces large quantities of smoke that is hazardous to people. To provide a safety to people the smoke should be kept away from people escaping the tunnel, and from the people working for the emergency service.

Several types of tunnel ventilation exist (appendix E). The optimal type of ventilation system depends on the length and the usage of the tunnel. Natural ventilation may suffice for short tunnels, but longer tunnels need additional measures like mechanical ventilation.
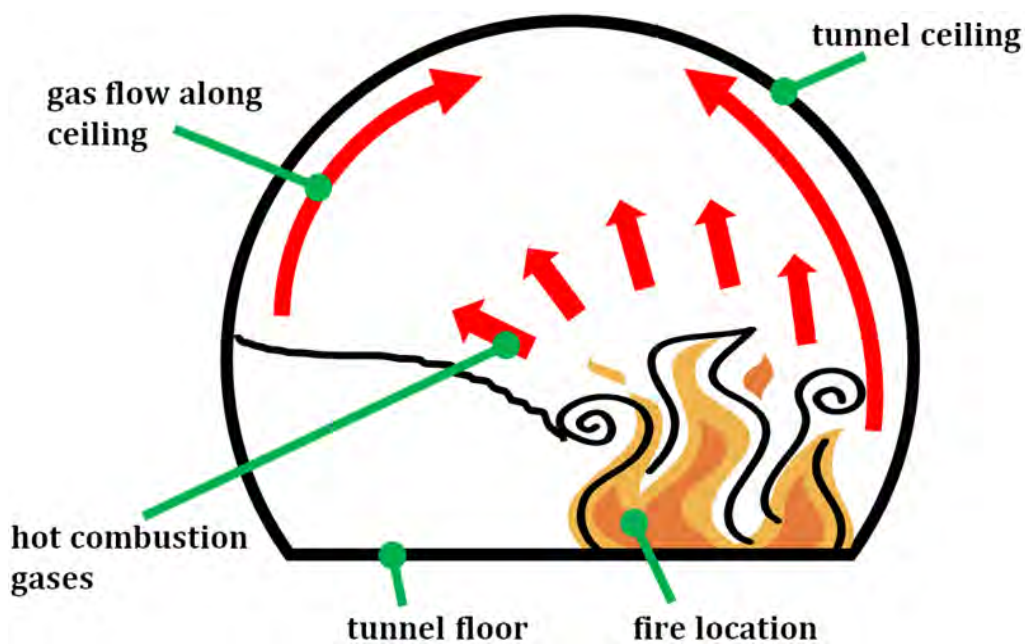
FIGURE 15: GAS FLOW ALONG TUNNEL CEILING

The fire creates hot combustion gases, which will flow towards the ceiling by buoyancy forces (figure 15). At the ceiling, the hot gases will flow towards the exits of the tunnel. At the same time, cold air flows towards the fire. The difference in density leads to stratification of the combustion gases as long as the gases are hot enough. In case of longitudinal ventilation combustion gases are blown to one exit of the tunnel, but the process ofbacklayering can occur which is unfavourable to the safety level of tunnel users. A graphical representation of the stratification of combustion gases in a longitudinal ventilated tunnel can be found in figure 16.

Due to the enclosing structure of a tunnel, thermal energy generated by a fire cannot easily dissipate. This results in an accumulation of heat, hence high temperatures in the vicinity of the fire. To prevent hot gas mixes that auto-ignite in other places in the tunnel, vaporised fuel needs to be fully combusted by the fire. Therefore a sufficiently large ventilation capacity is needed.

As the hot combustion gases flow towards the exits of the tunnel they encounter unheated lining. The hot gases transfer heat to the colder lining and therefore are effectively cooled by the construction. The cooling effect of the construction leads to lower gas temperatures at greater distance from the fire.
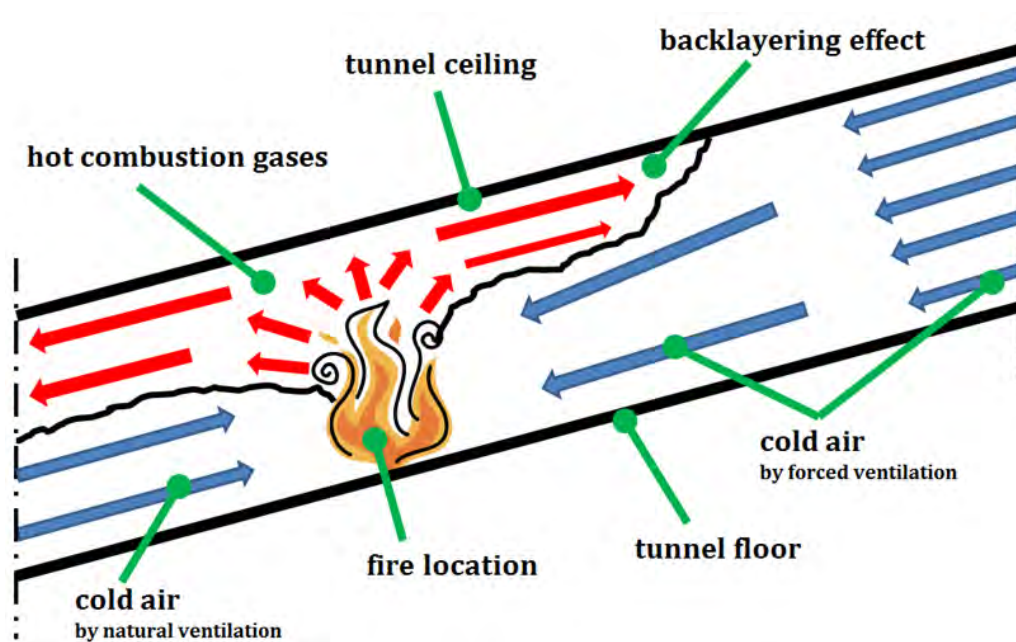
FIGURE 16: GAS FLOW ALONG TUNNEL AXIS IN A LONGITUDINAL VENTILATED TUNNEL

2.2.3 DESIGN FIRES FOR ROAD TUNNELS

To be able to effectively design structural components of tunnels, heat loading on construction parts should be defined. It is possible to predict the spatial temperature development of a tunnel fire by the use of computational fluid dynamics (CFD) models. Fire location, ventilation capacity, fuel availability, duration of the fire, the cooling effect of the construction and the weather outside the tunnel play a role in the temperature development. Therefore, an infinite amount of fire scenarios can be distinguished, hence an infinite amount of computer models can be performed. CFD models require a lot of computational power, predicting spatial temperature development by the aid of CFD modelling therefore should be limited to normative fire scenarios.

Fire safety engineering practice for buildings, uses fire compartments to assess the size and duration of a fire. A compartment contains a certain amount and type of fuel and is ventilated in some way. Fire in a compartment will produce heat and increases the temperature. The development of a fire is represented as a relation between HRR (or temperature), to time. A distinction can be made between pre-flashover and fully developed fires. Graphically presented time-temperature relations are called fire curves. The temperature described by the curve holds for the compartment as a whole, every surface exposed to the fire in the compartment is considered to be affected by the temperature. However, this is generally untrue for road tunnel fires due to the fact that tunnels are long stretched structures and the likelihood of combustion of all vehicles inside the tunnel at the same time, is negligible. So, therefore fire curves for tunnels are based on the type of vehicle(s) burning, and the temperatures that are produced in the vicinity of the fire. Since the vehicles are mobile, the fire can occur at any place in the tunnel. The fire curve can therefore hold for every part of the tunnel.

An important note has to be taken about fire curves. Fire curves only represent heat loading on a structural component, they do not contain information about gas flow, speeds and direction.

Design curves for pre-flashover fires

As can be seen in figure 14, the incipient and growth phase prior to flashover is the pre-flashover phase of a fire. Pre-flashover fires are not of interest to assess the structural integrity of the compartment, but are of importance in life safety analysis. Starting fires may not produce large amounts of heat, but they do produce smoke that can cause visibility problems, thereby hindering the exits, or even kill people. An important characteristic of pre-flashover fires is the growth rate. It described the time it takes for a localised fire to develop into a fully involved (fully developed) fire. The development of the HRR in the pre-flashover phase can often be described by an exponential or power-law. A commonly used relationship between time and HRR is the "t^2 fire" (appendix F).

Design curves for fully developed fires

As described earlier, the structural integrity of a tunnel is threatened by high temperatures and high temperature gradients. So, temperature development from fully developed fires is of importance to structural tunnel design. Due to the fact that multiple types of fully developed fire scenarios can be distinguished, several time-temperature curves have been developed. The most commonly used fire curves are:

- ISO-834 curve
- HC/HCM curve
- RABT/ZTV curve
- RWS curve

The "ISO-834 curve" is also called the "cellulosic curve". It is based on the burning rate of materials commonly found in buildings. The temperature development is represented by the purple line in figure 17.

The HC-curve (Hydro Carbon) was developed by the petrochemical industry due to the fact that petrol, gas and other chemicals have a faster burning rate and higher heat production than materials used for the "ISO-384 curve". The HC curve can be used for small petroleum fires in relatively open spaces. The maximum temperature of the fire is 1100 degrees Celsius. French guidelines on hydrocarbon fires in enclosed spaces have led to a modification of the HC curve into the HCM (Hydro Carbon Modified) curve. The HCM curve is an aggravated version of the HC curve and can be used to mimic the temperature development of larger petroleum fires and petroleum fires in enclosed spaces. The maximum temperature reached by the HCM curve is 1300 degrees Celsius. Both the HC- and the HCM curve show a very large temperature gradient in the first few minutes of the fire. Temperature development of the HC and the HCM curves are represented by the light-green and dark-green lines in figure 17 respectively.

The RABT-ZTV curves are the result of a series of test programmes. They were developed in Germany and is described by a set of points in the time-temperature space, that are linearly connected. The RABT-ZTV curve reaches temperatures of 1200 degrees Celsius and shows a large temperature gradient in the first five minutes of the fire. It is the only design fire that incorporates a cooling phase. The curves for the RABT-ZTV car and train are represented by the light-blue and dark-blue line respectively in figure 17.

The RWS curve is developed by the Dutch Ministry of Transport and is used across the globe to mimic the temperature development of a worst case scenario pool fire in tunnels. At the time of this writing it is the most severe fire loading scheme for tunnels. Like the RABT-ZTV curve, the RWS curve is described by a set of points in the time-temperature space. The RWS curve reaches a maximum temperature of 1350°C and shows a large temperature gradient in the first five minutes. Its duration is based on a fire with a 50m^3 petrol tanker burning at an average HRR of 200MW, the amount of fuel in the tanker can sustain such a fire for 118 minutes [36].

Large petrol fires therefore are not the only fires that can be described by the RWS curve. Fires involving lorries with wooden pallets follow a similar time-temperature path, the duration however, is shorter [27]. This has been confirmed by full scale fire tests on wooden pallets in the Runehamar tunnel in Norway [34]. The temperatures of the RWS fire curve therefore can be considered as realistic and not as worst case scenario.

The RWS curve is graphically represented by the red line in figure 17. To describe larger fires with a longer duration, the standard RWS curve is sometimes prolonged to 180 minutes at 1200°C (the RWS 180 curve).
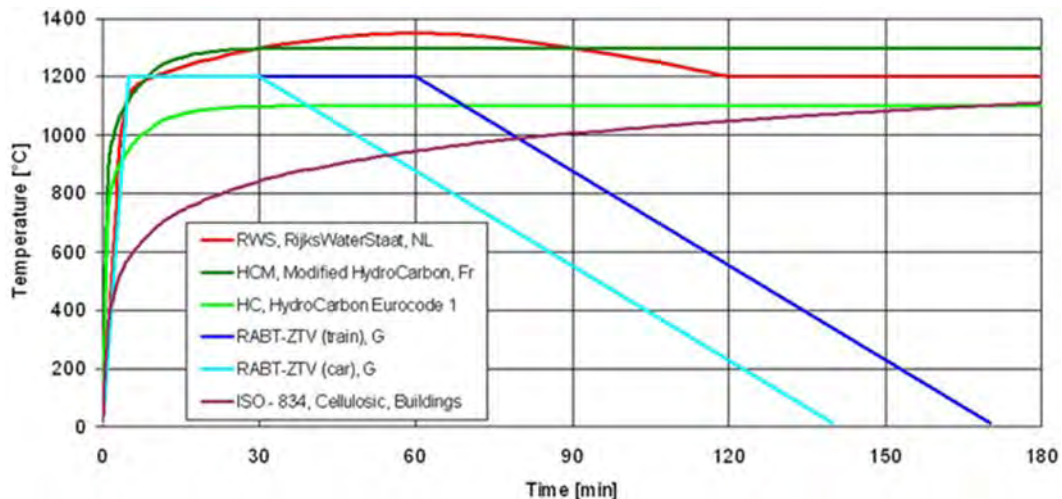
FIGURE 17: FIRE CURVES [34]

2.3 PASSIVE FIRE PROTECTION IN TBM DRIVEN TUNNELS

This section will discuss passive fire protection methods and regulations on passive fire protection in TBM driven tunnels. The thermal spalling susceptibility of tunnel linings in TBM driven tunnels often leads to the choice to protect the tunnel. Fire protection in tunnels can be achieved in many ways, in which a distinction is made between passive and active fire protection. Active fire protection is protection that needs to be enabledin case of fire (e.g. sprinklers) and is not discussed in this thesis. Passive fire protection is fire protection that does not require action to function after being installed. As fire protection is a costly part of the tunnel, the risk attitude of the tunnel owner is important to the type and amount of fire protection. 2.3.1 will discuss guidelines of potential tunnel owners. Conventional passive fire protection is discussed in 2.3.2. The innovative method of protecting tunnels from heat loading will be discussed in 2.3.3. The differences between the methods of passive fire protection will be discussed in 2.3.4.

2.3.1 LEGISLATION AND GUIDELINES ON PASSIVE FIRE PROTECTION IN ROAD TUNNELS

The catastrophic tunnel fires that took place in Europe at the end of the 20th century marked the start of several research programs in order to support new European guidelines on tunnel safety. At the time of this writing European guidelines on road tunnels is in place: directive 2004/54/EG. Implementation of the guidelines in national legislation is obligatory to all EU member states. The purpose of the EU-directive is to provide a minimum level of safety in tunnels on the complete trans-European road network; member states are free to implement higher standards. Prevention of events leading to fire, mitigation of events that have occurred and rescue options are discussed in the guidelines. In case an event does lead to a fire, safety of tunnel users and emergency services needs to be provided for a safe escape. This means the tunnel must be intact and safe, long enough for users to escape. The European guidelines focus on safety of tunnel users and rescue workers, economic considerations are the responsibility of the member states.

Tunnels are high value assets to road networks. A fallout of such an asset can lead to high economic costs. In table 1 an overview is given on the estimated direct economic costs of the fallout of three well known tunnels.

Tunnel	Lost Revenue		Repair costs		Total
	[Mio. €]	[% of total]	[Mio. €]	[% of total]	[Mio. €]
EuroTunnel	204	81	49	19	253
Mont Blanc (Estimated)	203	52	189	48	392
Tauern Tunnel	20	70	8.5	30	28.5

TABLE 1: DIRECT ECONOMIC LOSSES OF SEVERAL TUNNEL FIRES [42]

From a risk oriented view, the possible economic losses can justify costly implementation of passive fire protection. Several member states of the EU have enhanced the guidelines on passive fire safety measures because of economical motives. The sole purpose of passive fire protection is to prevent the tunnel from collapsing for a certain amount of time. The general perception is that passive fire safety measures are an insurance to the high or unbearable costs of failure of a tunnel. In table 2, fire design requirements of several EU nations are presented.

Country	Design fire	Duration [minutes]	Remarks
The Netherlands	RWS	120 or 180	No loss of watertightness, no collapse of part of the tunnel allowed. Damage should be repairable.
France	HCM ISO-834	HCM: 120 ISO: 240	Resistance levels are based on four resistance levels in order to fit the needs of each structural part separately. Separation is also made between tunnels with clearance levels below and above 3.50m and surrounding soil/rock. In worst case scenario two types of design fires should be checked.
Germany	RABT-ZTV	140	No damages threatening the load-bearing capacity of the tunnel structure. No resting deformations diminishing the usability of the tunnel construction. Almost retaining the water tightness.
Spain	-	-	Requirements are specific for each individual tunnel project. Specific requirements are under development.

TABLE 2: WORST CASE FIRE DESIGN REQUIREMENTS OF DIFFERENT COUNTRIES [15]

As can be seen in table 2, The Netherlands (represented by the Dutch ministry of public transportation: Rijkswaterstaat), requires their tunnels to withstand the severe RWS design fire. Economical motives are the reason for the requirements of remaining water tightness and preventing the collapse of part of the structure. The geology in the Netherlands will cause a partial collapse of a tunnel to lead to total collapse, or very difficult and costly repair works.

Rijkswaterstaat makes a distinction in type of structure. Tunnels with a rectangular shaped cross sections are vulnerable to thermal degradation of reinforcement at the heated face part, and crack formation at the cold part of the tunnel. Guidelines for tunnels with rectangular cross sections introduced by Rijkswaterstaat prescribe maximum temperatures at the heated concrete face and the reinforcement [36, 37]. These guidelines will always lead to a design with passive heat protective covering.

In tunnels with a circular cross section, reinforcement is not considered to be an essential part of the construction. Failure of the structure occurs in case of excessive spalling and extensive thermal degradation of the lining. Rijkswaterstaat acknowledges this fact and has introduced descriptive as well as prescriptive guidelines for passive fire protection of the lining of TBM driven tunnels. The guidelines are the following [36, 37]:

- The tunnel is subjected to the RWS fire curve for 120 minutes (in some cases 180 may be applied)
- The design lifetime of irreplaceable essential parts of the tunnel is 100 years [37]
- Damage resulting from the fire may not result in problems with respect to structural integrity
- Concrete affected by temperatures higher than 380°C may not be included in strength calculations
- The whole ceiling of the tunnel has to be protected (from pavement to pavement)
- Damage resulting from the fire has to be repairable
- Concrete that has reached temperatures of 400°C and higher has to be replaced
- Preferably keep temperatures at rubber seals below 80°C

2.3.2 CONVENTIONAL PASSIVE FIRE PROTECTION

Two types of conventional passive fire protection exist for TBM driven tunnels: protective mortar and boards. Both systems perform well with respect to shielding the structure, but the systems are inherently different. In this section the systems are described, a comparison of the properties of the systems can be found in 2.3.4.

Mortar

Protective mortar acts as a thermal barrier, it is applied at the lining after the TBM construction phase has finished. The reason for this is that the TBM is supplied with construction materials through the tunnel and application of mortar partly blocks the tunnel. Several methods of mortar application exist: spraying, cast in situ and precast in segments. To reach high production speeds robots can be used to apply the mortar in the form of fire protective shotcrete, it is therefore often used in TBM driven tunnels (figure 18). Cast in situ and mortar precast in segments are not often used [8].

The sprayed mortar systems need to be durable enough to resist physical and chemical attacks during the lifetime of the tunnel. Early mortars types were relatively weak

vermiculite based systems. These systems need mechanical bonding with the tunnel lining (e.g. stainless steel meshes) and may fail to meet durability requirements. Modern sprayed mortars are based on light weight concrete and exhibit improved fire protection and durability.

FIGURE 18: CONVENTIONAL PASSIVE FIRE PROTECTION: FIRE PROTECTIVE SHOTCRETE (LEFT, [41]) BOARDS (RIGHT, [34])

Boards

Like protective mortars, protective boards act as thermal barriers. The boards need to be attached to a framework or can be used as lost formwork. Mass fabricated boards are flat, making them suitable to tunnels with rectangular cross section but unsuitable to tunnels with a circular cross section. The boards can be produced in a curved profile, but fabrication will be project specific. An advantage of using boards over sprayed mortar is the surface finish. The surface of the boards can be altered in the factory, leading to the possibility to cost effectively alter the board to any requirements to the finish.

Using boards as lost formwork in precast tunnel segments can lead to problems with respect to installation of the segments. The erector in a TBM often uses vacuum to pick up the segment, the board needs to be able to transfer the force and to provide the vacuum [35].

During construction of the rings the segments are bolted together, the lost formwork should provide openings for the bolts to enter the segments. Later, these openings have to be covered to prevent heat leaks in the segment.

Designs using protective boards that are installed after the TBM construction phase, encounter problems due to segment installation tolerances. The surface of the lining of a TBM driven tunnel cannot be regarded as flat, offsets between the segments will occur. Therefore a frame needs to be attached to the lining before boards can be installed (figure 18).

2.3.3 HEAT RESISTANT CONCRETE SEGMENTS

The solution of heat resistant concrete segments does not use an additional thermal barrier. The segments themselves should therefore be thermally stable enough to endure a fire. Two factors should be addressed to obtain a thermally stable concrete segment:

spalling should be suppressed and the depth of concrete degradation should be limited to a safe value.

Spalling suppression

As HSC segments are very susceptible to thermal spalling, driving factors of spalling should be suppressed. Tangential normal forces in the lining unfortunately cannot be decreased, they will theoretically increase as the concrete at the heated surface starts degrading. Thermal stresses and pore pressure however, can be reduced effectively to avoid spalling.

FIGURE 19: FIRE TESTED CONCRETE SLABS WITHOUT (LEFT) AND WITH (RIGHT) PP-FIBRES [39]

Pore pressure builds up due to the fact that steam cannot dissipate easily enough. To prevent spalling induced by pore pressure, the permeability and/or pore volume of the concrete needs to increase at the time of heating. This objective can be met by the use of polypropylene fibres (pp-fibres). Polypropylene melts and shrinks at temperatures of 160°C and decomposes at temperatures of around 300°C. Several tests [39] have shown that pp-fibres significantly reduce the risk of spalling (figure 19) (table 3). It is also shown that monofilament fibres (single fibres) perform better than fibrillated fibres (fibre clusters). It is believed that the formation of reservoirs and/or the formation of continuous channels are responsible for this effect, but research on this topic is still ongoing. The tests have also shown that the amount and type of fibre have a great impact on spalling suppressing performance.

The type of aggregates used in the concrete mix is of great importance to prevent thermal stresses. A thermally well balanced concrete mixture will prevent thermal stresses to occur. Lightweight concrete, granite and limestone aggregates are known for their low thermal expansion. Aggregate size is another important parameter. Smaller grains lead to smaller absolute differential expansion, hence smaller local thermal stresses.

Aggregate	Steel fibres	Monofilament fibres	Fibrillated fibres	Observations during tests
Granite	x	x	x	Spalling visible after 30 minutes
Granite	YES	x	x	Spalling visible after 20 minutes
Granite	YES	YES	X	No evidence of spalling
Granite	YES	x	YES	Minor spalling visible
Granite	x	YES	x	No evidence of spalling
Limestone	x	x	x	Spalling visible after 20 minutes
Limestone	YES	x	x	Spalling visible after 20 minutes
Limestone	YES	YES	x	No evidence of spalling
Limestone	YES	x	YES	Minor spalling visible
Limestone	x	YES	x	No evidence of spalling
Lightweight	x	x	x	Extensive violent spalling
Lightweight	YES	x	x	Extensive violent spalling
Lightweight	YES	YES	x	No evidence of spalling
Lightweight	YES	x	YES	Extensive spalling
Lightweight	x	YES	x	No evidence of spalling

TABLE 3: TEST DATA CTRL TUNNEL FIRE TESTS [39]

Concrete degradation

The philosophy of heat resisting segments is to use the lining itself as a thermal barrier to the part of the segment that is load bearing. The typical reduction of segmental thickness by a RWS tunnel fire amounts to about 100mm [36]. A brief calculation was performed on stresses in the segments in the exploitation phase, before and after a fire (according to Blom's method [5]). The results of the calculation can be found in table 4.

The results lead to the conclusion that the safety factor of the construction does decrease when the segment thickness decreases. But the safety factor does not drop below 1.9, so the structure can still be regarded as safe. Hence it can be concluded that the structural stability of the lining can be regarded as properly insulated from the heat of the tunnel fire.

Diameter tunnel [m]	Distance tunnel axis - surface [m]	Has fire occurred? [-]	Moment [kNm/m]	Normal force [kN/m]	Tensile stresses in cross section? [-]	Stress in pressure pad [N/mm2]	Safety factor pressure pad [-]	Change of safety factor [%]
8	20	No	54	1070	No	8	4.1	
8	20	Yes	49	1070	No	16	1.9	-47
10	25	No	105	1670	No	8.4	3.4	
10	25	Yes	100	1670	No	12.5	2.1	-61
12	30	No	181	2404	No	9	2.8	
12	30	Yes	177	2404	No	12	1.9	-68

TABLE 4: FORCES IN SEGMENTS: CHANGE OF SAFETY FACTOR DUE TO FIRE

2.3.4 COMPARISON OF THE PASSIVE FIRE PROTECTION SYSTEMS

All passive fire protection systems aim to protect the structural stability of the tunnel, but differences between the systems exist. A brief comparison of the passive fire protection systems can be found in table 5.

The method of heat resisting segments only protects the lining from thermal spalling. The other methods protect the whole structure (figure 20). This leads to the fact that structural repair works after a fire in a tunnel with heat resistant segments are focused on the lining, whereas structural repair works for the other methods are focused on restoring the protective cover.

Property	Fire protective shotcrete	Boards	Heat resistant segments
Fire protective properties			
Protection against thermal spalling	Yes	Yes	Yes
Protection against thermal degradation	Yes	Yes	No
Protection against thermally induced deformation	Yes	Yes	No
Gaskets directly exposed?	Yes	Yes	No
Installation			
Experience with system	Common practice	Common practice	Innovation
Application time frame	Weeks	Months	None
Project phase of application	Post-TBM	Post-TBM	TBM
Application costs	100%	150-200%	0%
Cover thickness	30-50mm	Boards:20-35mm Frame: 40mm	0mm
Repair works			
Post fire repair works on segment	No	No	Yes
Post fire repair works on cover	Yes	Yes	No
Collision vulnerability of fire protection	Limited vulnerability	Very vulnerable	Not vulnerable
Post collision repair works	Comprehensive	Easy	-
Visual tunnel deformation inspection?	Yes	No	Yes

TABLE 5: COMPARISON OF PASSIVE FIRE PROTECTION SYSTEMS

The absence of a cover in tunnels with heat resistant segments leads to a decreased vulnerability of the fire protection, to collision. Also, tunnel deformation can be inspected visually. Maintenance therefore is cheaper for these tunnels.

Application costs, in money and time, are lower for fire protection in the form of heat resistant segments. However, risks are higher as the technology is still at the innovation stage.

2.4   CONCLUSIONS ON RESEARCH QUESTION 1

"What is the current practice of passive fire protection in TBM driven tunnels and how do the innovative heat resistant segments change the existing system?"

Tunnel design needs to be adjusted to the specific requirements of the TBM method of tunnel construction. This causes the tunnel to be build up in precast segments, with pressure pads in between and the lining to be thicker and more reinforced then actually necessary during the exploitation phase. The water seal of the precast lining is ensured by the use of rubber gaskets that bridge the gaps between the segments. The type of seal depends on gaps dimensions and differ for each tunnelling project.

Failure of a road tunnel can lead to large economic losses and troublesome, expensive and time consuming repair works. Passive fire protection is a good measure to prevent those losses by ensuring the load bearing structure. TBM driven tunnels in soft soils are a relatively new phenomena, therefore most countries use descriptive design guidelines that are based on preventing collapse of the structure.

Two types of fires can be distinguished: fuel bed controlled and ventilation controlled. Fuel bed controlled fires are supplied with enough oxygen to reach the fuels theoretical HRR. The HRR of ventilation controlled fires is limited due to insufficient oxygen supply.

The RWS-curve is the most severe design scenario for tunnel fires in the world today, which is acknowledged and used in several countries. The RWS-curve has proven to be accurate to describe the time-temperature behaviour of large tunnel fires like heavy goods vehicles (HGV) and gasoline pool fires. These and larger fires in tunnels generally are ventilation controlled; higher HRR's are therefore less likely to occur. The RWS design fire will be used for the assessment of the performance of the gasket. Fire curves represent time-temperature behaviour and unfortunately do not contain information about gas speeds and directions inside the tunnel.

The structure of TBM driven road tunnels is very susceptible to thermal spalling. The conventional implementation of passive fire protection is based on prevention of high temperatures at the concrete surface by covering the complete surface of the lining.

Due to the fact that TBM tunnel linings are thicker than necessary in the exploitation phase, casting segments in thermally well balanced, pp-fibre enhanced concrete is a promising way to make costly conventional passive fire protection superfluous. The innovative solution does have its drawbacks. It does not provide cover for the segment joints, hence rubber gaskets are left directly exposed to the tunnel fire. The lining also may be more troublesome to repair, as part of the lining loses its quality in a tunnel fire.

The difference between the current practice and the method of heat resistant segments is presented in figure 20.
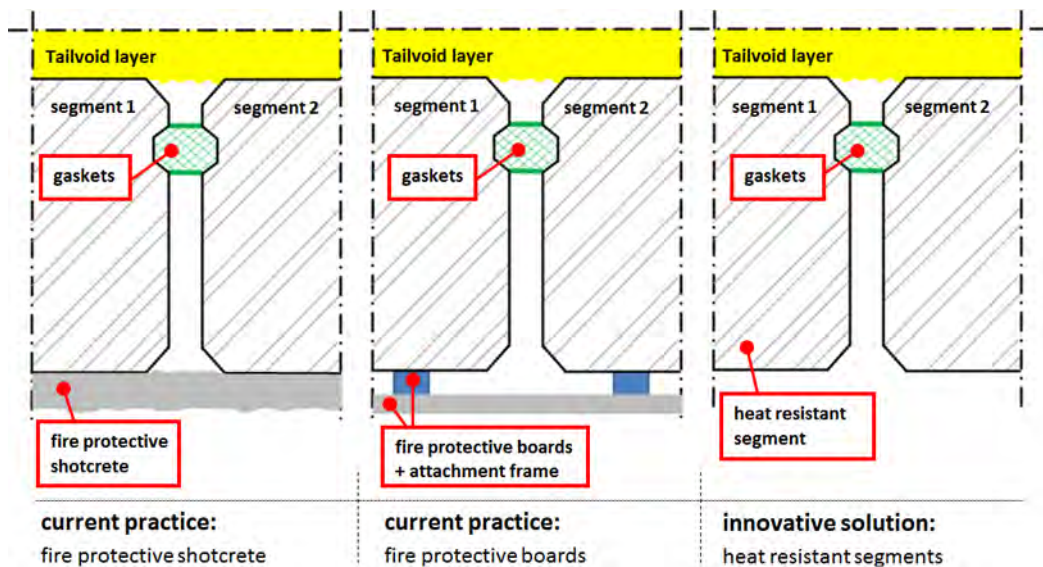

FIGURE 20: PASSIVE FIRE PROTECTION: CURRENT PRACTICE VS. INNOVATIVE SOLUTION

CHAPTER 3

FIRE AND THE THERMAL CONDITIONS IN A SEGMENT JOINT

This chapter aims to answer the second research question: "How does a fire affect the conditions at the location of the sealing gasket in case innovative fire protection is used?" by providing knowledge about heat transfer mechanisms. Heat transfer science is used to assess the temperature development at the gasket. An experiment is conducted to validate the assessment, gain more knowledge and measure unknown or non-estimable factors. The results and conclusions of the experiment are discussed in this chapter. Conclusions on the second research question are provided as well.

3.1   FUNDAMENTALS OF HEAT TRANSFER

Heat transfer is thermal energy in transit due to a spatial temperature difference. Whenever there exists a temperature difference in a medium or between media, heat transfer must occur [12]. The concept of heat and temperature is further discussed in the following section. The fundamentals of heat transfer are also discussed. There are three modes of heat transfer distinguished: conduction, convection and thermal radiation.

3.1.1   TEMPERATURE AND HEAT TRANSFER

Temperature is a macroscopic thermodynamic state of a substance. It represents the mean kinetic energy of individual molecules and atoms (not to be mistaken for kinetic energy of a body in motion). The kinetic energy of molecules and atoms is also referred to as thermal energy and is part of the internal energy of a substance. Next to thermal energy, internal energy of a substance is also defined by molecular potential energy (due to the forces that act between the atoms of a molecule, and between molecules), and other kinds of molecular energy [11].

Every substance contains internal energy, but a substance cannot contain heat as heat is the energy that flows between two objects due to a temperature gradient. It is measurable in Joules; the same unit used for work, kinetic energy and potential energy. Heat affects the internal energy of a substance, which will thereby encounter a change in temperature.

Laws of thermodynamics

Thermodynamics plays a large role in heat transfer science, as the science describes energy conversion relations between heat, work and other forms of energy. Several base laws have been formulated, the laws that are of interest to this thesis are stated below.

The zeroth law of thermodynamics states that if two systems are individually in thermal equilibrium with a third system, they are also in thermal equilibrium with each other [11]. In other words: if two objects individually share the same temperature with a third object, they also share the temperature with each other. This is independent of size or density of the individual objects, as temperature describes the mean kinetic energy of the atoms and molecules and not the total amount of energy in the object.

The first law of thermodynamics is also known as the law of conservation of energy. It states that energy can neither be created nor destroyed, it can merely be transformed. Heat and work generally are the variables related to the first law of thermodynamics. If they are added to or subtracted from a system, the internal energy of that system changes [11].

The second law of thermodynamics states that heat flows spontaneously from a substance at a higher temperature to a substance at a lower temperature and does not flow spontaneously in the reverse direction [11]. This is due to the fact that particles at higher energy levels transfer some of their energy to particles at a lower energy levels by collision. If the temperatures of two bodies are equal there will be no net heat transfer between the substances.

Temperature development due to heat transfer

Heat transfer problems can be schematised by using the interfaces between materials and/or phases of materials. Heat transfer between the phases or materials can occur by three modes: conduction, convection and radiation. Radiation and convective heat transfer take place in fluids (e.g. liquids or gases). In case the fluid is stationary, conduction can take place as well. Conduction is the only heat transfer mode in non-transparent solids. In (semi)transparent solids, conduction and radiation can take place. Heat transfer by each of the modes is cumulative as is shown in the following equation:

$$q''_{total} = q''_{rad} + q''_{cond} + q''_{conv}$$

q''_{total}	=	total heat flux per unit area perpendicular to the direction of transfer [W/m^2]
q''_{rad}	=	radiative heat flux per unit area perpendicular to the direction of transfer [W/m^2]
q''_{cond}	=	conductive heat flux per unit area perpendicular to the direction of transfer [W/m^2]
q''_{conv}	=	convective heat flux per unit area perpendicular to the direction of transfer [W/m^2]

Heat transfer alters the temperature of a system, the amount of heat needed to increase the temperature by a certain degree is of great importance to thermal science and engineering. The material property specific heat capacity (or specific heat) formulates this by stating that the specific heat capacity is the amount of energy needed to increase the temperature of 1kg of substance by 1°K. Due to the first law of thermodynamics, two types of specific heat exist; specific heat at constant volume (c_v) and specific heat at constant pressure (c_p). Specific heat at constant pressure can be used for most situations.

Determination of temperature development due to heat transfer can be a very extensive and complex process. For this reason boundary conditions can be imposed to a system. The boundaries of systems either are under heat loading, or are simplified by stating it is an isothermal or adiabatic surface. The isothermal surface can be described as a surface of constant temperature. The body can lose or gain heat at this surface, but the temperature of the surface does not change. The adiabatic surface is a surface that acts as a perfect insulator, heat is neither lost nor gained at this surface.

3.1.2   CONDUCTIVE HEAT TRANSFER

When a temperature gradient exists in a stationary medium, which may be a solid or a fluid, the term conduction is used to refer to the heat transfer that occurs across the medium [12]. Conduction takes place at atomic and molecular level and can be viewed as the transfer of kinetic energy between particles due to interaction between those particles.

Fourrier's law

In order to be able to quantify a conductive heat transfer process, rate equations can be used. The rate equation used for conductive heat transfer problems is known as Fourrier's law. It calculates the transferred amount of energy as a function of time.

$$q''_x = -k\frac{dT}{dx}$$

q''_x = heat flux in x-direction: heat transfer rate per unit area perpendicular to the direction of transfer [W/m²]

k = thermal conductivity, material property [W/m*K]

dT/dx = temperature gradient in x-direction [K/m]

The symbol "k" represents the thermo physical transport property of matter: "thermal conductivity". Thermal conductivity describes the ability of a material to conduct heat, its reciprocal is known as thermal resistivity.

The heat diffusion equation

Fourrier's law can only be used if the temperature gradient is known, this is often not the case. In most heat transfer problems the boundary conditions are known, but the subject of interest is the temperature distribution inside the medium as a function of the heat loading and time.

In order to perform calculations on temperature development inside a body, the thermodynamic material properties: density (ρ, kg/m³) and specific heat (under constant volume: c_v, under constant pressure: c_p, J/kg*K) are introduced. The product of the density and the specific heat is called the volumetric heat capacity (J/m³*K), it describes the ability of a material to store energy. The ratio of the thermal conductivity to the volumetric heat capacity is called the thermal diffusity (α, m²/s) and is an important parameter in assessing the ability of a material to respond to changes in its thermal environment.

$$\alpha = \frac{k}{\rho c}$$

α = thermal diffusity [m²/s]

k = thermal conductivity, material property [W/m*K]

ρ = density [kg/m³]

c = specific heat, material property [J/kg*K]

Temperature gradients inside a body due to imposed boundary conditions can be computed using the heat diffusion equation (or heat equation). The equation is based on the energy conservation requirement (first law of thermodynamics) and uses the thermal diffusity parameter. It can be described in words by the following statement:

"At any point in the medium, the net rate of energy transfer by conduction into a unit volume plus the volumetric rate of thermal energy generation must be equal to the rate of change of thermal energy stored within the volume" [12]

The heat diffusion equation is mathematically defined as:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

α	=	thermal diffusity [m²/s]
k	=	thermal conductivity [W/m*K]
q'	=	rate of energy produced per unit volume of the body inside the body [W/m³]
T	=	temperature [K]
t	=	time [s]
x,y,z	=	dimensions in a Cartesian coordinate system [-]

3.1.3 RADIATIVE HEAT TRANSFER

Heat transfer by thermal radiation occurs between two solid surfaces or gases. The concept of thermal radiation is that the temperature of a body causes the energetic state of the atoms to be excited. As a result energy is released due to oscillations or transitions of the electrons within the matter. The released energy leads to the emission of electromagnetic waves at a wide range of wavelengths. These waves do not require matter to propagate and can be absorbed by another atom which in turn will encounter a change in its energetic state. The absorption and emission of thermal radiation by a body is governed by the properties of the material. There are two material types which can be distinguished: grey-body and black-body emitters. Black-body emitters are perfect emitters/receivers, grey-body emitters are imperfect emitters/receivers and lose a portion of the emitted energy at emission and/or reception.

The Stefan-Boltzmann law

Due to higher temperatures energetic states of atoms increase, the energy released by electromagnetic radiation will therefore also be higher. Wavelengths in the range of 0,1 to 100μm (infrared, visible light and part of the ultraviolet spectrum) are termed thermal radiation as radiation at those wavelengths is caused by and affects the thermal state of matter.
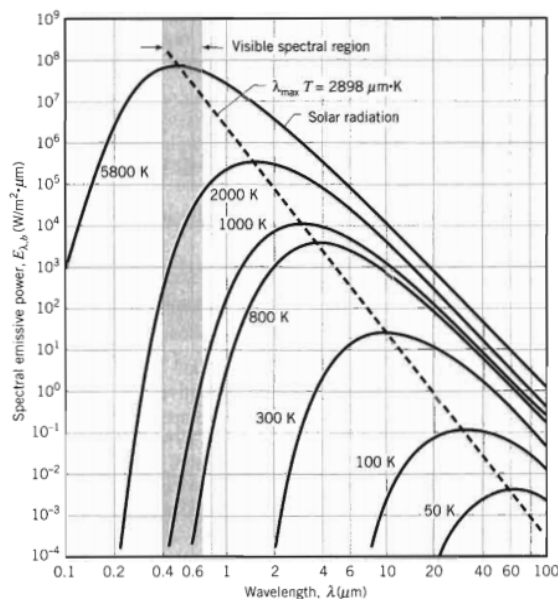

FIGURE 21: SPECTRAL BLACKBODY EMISSIVE POWER [12]

The distribution of emitted wavelengths of a black-body emitter is temperature dependent. As the objects temperature increases, the maximum spectral emissive power increases and displaces to shorter wavelengths. The shifting behaviour is described by Planck 's law of radiation (figure 21), the wavelength of maximum emissive power can be determined by Wien's displacement law (dotted line in figure 21).

When assessing heat transfer by thermal radiation between two bodies, the total emissive power of all wavelengths in the thermal radiation zone is of importance. The total emissive power can be found by integrating the area underneath the graph. Stefan and Boltzmann found a relation between the total emissive power and the thermodynamic temperature of a body:

"The total energy radiated per unit surface area of a black body in unit time is directly proportional to the fourth power of the black body's thermodynamic temperature T." [12]

In case of a grey body, a fraction of the radiative flux of a black body is emitted. This portion is denoted by the emissivity (ε) and is dependent on wavelength (λ). The law of Stefan-Boltzmann can therefore be written as:

$$E = \varepsilon(\lambda)\sigma T^4$$

E   =   radiant flux: amount of energy radiated per unit surface area in unit time [W/m^2]
$\varepsilon(\lambda)$ =   emissivity: fraction of the radiant flux of a black body [-]
σ =   Stefan-Boltzmann constant $5.67040040*10^{-8}$ [W/m^2/K^4]
T   =   Thermodynamic temperature [K]

The amount of energy effectively transmitted to a body will be determined by the amount that will be reflected, absorbed and transmitted by the receptive body (figure 22).
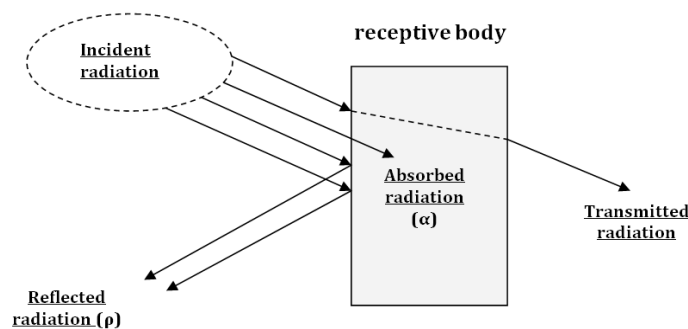

FIGURE 22: RADIATION ABSORPTION, REFLECTION AND TRANSMISSION [12]

A body will therefore have 3 types of properties when the reception of thermal radiation is concerned: spectral absorptivity (α), spectral reflectivity (ρ) and spectral transmissivity (τ). All elements are dependent of the radiated wavelength (λ), and their sum must equal one. Kirchhoff's law of thermal radiation states that the spectral absorption factor is equal to the emissivity factor found in the Stefan-Boltzmann law. In case of a perfect black body the emissivity factor is one, hence the absorption factor equals one. The reflectivity and transmissivity therefore do not play a role in heat exchange between black-bodies.

The view factor

Emission of radiation from the surface of a black-body takes place in all possible directions (a black-body is a so-called diffuse emitter), incidence of radiation on a surface can take place from all possible directions as well. Both directional properties of radiation, as well as

shape and size of emitting and receiving surfaces, have an effect on radiation intensity. Radiation intensity is defined as:

"The rate at which radiant energy is emitted in the (ϑ,φ) direction, per unit area of the emitting surface normal to this direction, and per unit solid angle about this direction" [12]
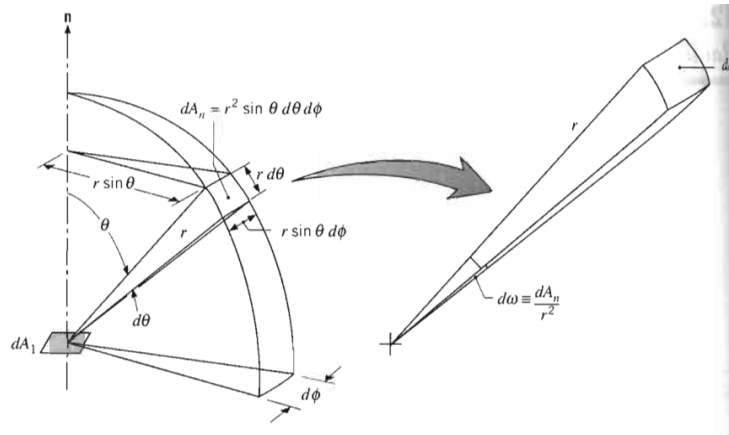

FIGURE 23: DECREASE OF RADIATION INTENSITY DUE TO INCREASE OF DISTANCE [12]

The surface of a black-body radiates into a half-sphere, this causes radiation intensity to decrease with distance. As the surface of a sphere increases as function of an increasing radius, the emissive power of the radiation source must be divided over a larger surface (figure 23).
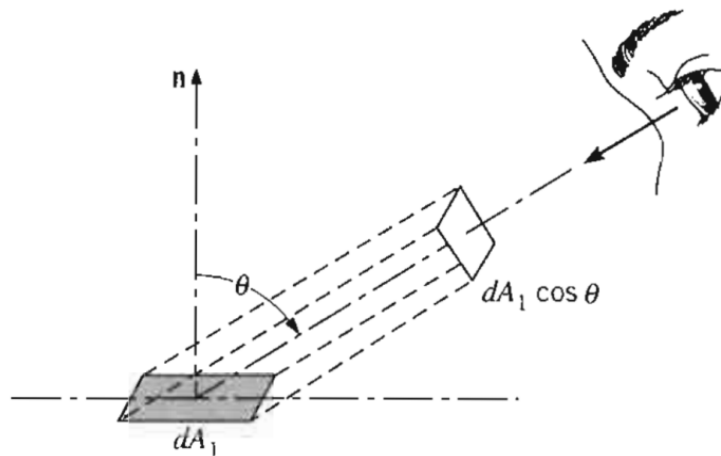
FIGURE 24: PROJECTION OF RADIATION TO A SURFACE NON-NORMAL TO THE RADIATION DIRECTION [12]

The angle of incidence of the radiation to the receiving surface is also of importance to the intensity. Radiation intensities at receiving surfaces normal to the direction of radiation will be higher than radiation intensities at receiving surfaces that are not normal to the radiation direction. This is due to the fact that surfaces not normal to the radiation direction "see" a smaller portion of the surface of the radiation source (figure 24).

Shape and size of, and distance between the emitting and receiving surfaces also play a big role in radiative heat transfer. Their relation, together with the angle of incidence, governs the way both surfaces "see" each other. In a stationary situation this is constant and is called the view factor:

"The view factor F_{ij} is defined as the fraction of the radiation leaving surface i that is intercepted by surface j" [12]

The view factor is used to determine the amount of incident radiation (or radiation intensity) on a surface, originating from another surface. The relation is:

$$q_{1 \to 2} = A_1 \times F_{1 \to 2} \times \varepsilon_1 \sigma T_1^4$$

or in intensity:

$$q''_{1 \to 2} = F_{1 \to 2} \times \varepsilon_1 \sigma T_1^4$$

$q_{1 \to 2}$	=	radiant flux of surface 1 to surface 2 [W]
$q''_{1 \to 2}$	=	radiant intensity of surface 1 to surface 2 [W/m²]
ε_1	=	emissivity of surface 1 [-]
$F_{1 \to 2}$	=	view factor surface 1 to surface 2 [-]
σ	=	Stefan-Boltzmann constant $5.67040040*10^{-8}$ [W/m²/K⁴]
T_1	=	Thermodynamic temperature of surface 1 [K]

The view factor is calculated by considering all properties of radiative heat transfer. This leads to complex relations. However, view factor relations have been established for several standard situations.

3.1.4   CONVECTIVE HEAT TRANSFER

This section will now discuss convective heat transfer. Convective heat transfer is heat transfer by the bulk movement of a fluid (advection), or by random motion of fluid molecules (diffusion). Unlike conduction and radiation, convective heat transfer is caused by movement of mass and can only occur in fluids (i.e. liquids or gases). Convective heat transfer is considered to be the most effective mode of heat transfer in fluids.

There are two types of convective heat transfer can be distinguished: natural convection and forced convection. Natural convection (also called free convection) is buoyancy driven flow. Due to temperature variations in the fluid, density differences (hence buoyancy differences) will lead to bulk movement of the fluid. Heat transfer by forced convection is heat transfer due to forced fluid movement over an object. Both natural and forced convection can occur in a(n) (semi-)enclosed system, or at a free surface. Convection in enclosures is called internal convection, convection at a free surface is called external convection.

The rate equation for convective heat transfer is also known as Newton's law of cooling. It states that the heat flux is proportional to the difference between the temperatures of the surface and the fluid. The rate equation is:

$$q'' = h(T_s - T_\infty)$$

q''	=	convection intensity: heat transfer rate per unit area perpendicular to direction of transfer [W/m²]
h	=	convection heat transfer coefficient [W/m²*K]
T_s	=	temperature of surface [K]
T_∞	=	temperature of fluid [K]

Several factors can be identified that influence the convection heat transfer coefficient [12]. These factors are combined in the dimensionless Nusselt number (Nu, -). The heat transfer coefficient is dependent on the Nusselt number by the following relation:

$$Nu = \frac{h \times L}{k_f}$$

Nu   =   Nusselt number [-]
h   =   convection heat transfer coefficient [W/m²*K]
L   =   geometrical factor: characteristic length [m]
k_f =   thermal conductivity of the fluid [W/m*K]

The factors influencing the Nusselt number are different for natural and forced convection. Natural convection is dependent on the Grashof number (Gr) and the Prandtl number (Pr), forced convection is dependent on Reynolds number (Re) and Prandtl's number. The general equation of the Nusselt number for natural convection is:

$$Nu = C_1 \times Gr^{C_2} \times Pr^{C_3}$$

Nu   =   Nusselt number [-]
$C_{1,2,3}$ =   arbitrary constants [-]
Gr   =   Grashof number [-]
Pr   =   Prandtl number [-]

The general equation of the Nusselt number for forced convection is:

$$Nu = C_4 \times Re^{C_5} \times Pr^{C_6}$$

Nu   =   Nusselt number [-]
$C_{4,5,6}$ =   arbitrary constants [-]
Re   =   Reynolds number [-]
Pr   =   Prandtl number [-]

Reynolds number can be described as the ratio of inertia to viscous forces in the fluid, and determines the existence of laminar of turbulent flow. It is dependent on the kinematic viscosity and velocity of the fluid, and on geometrical properties. The Grashof number fulfils the same role as Reynolds number, but for natural convection. It can be described as the ratio of buoyancy to viscous forces and is dependent on the coefficient of thermal expansion and kinematic viscosity of the fluid, temperature differences, the gravitational constant and on geometrical properties. Prandtl's number can be described as the ratio of momentum to thermal diffusity. It is a measure to present the relative effectiveness of momentum and energy transport by diffusion. [12]

Due to the vast amount of variables and their temperature and/or geometry dependence, the heat transfer coefficient often is determined experimentally. The equations for the Nusselt number however, do provide the means to identify and describe the main processes in convection.

3.2   HEAT TRANSFER PROCESSES IN THE SEGMENT JOINTS

Heat transfer science provides the means to distinguish the modes of heat intrusion in the segment joints. This section elaborates on the geometry of segment joints, heat transfer modes and other processes that occur in the segment joints. Calculations on temperature development are also provided on basis of conduction and radiation.

3.2.1   SEGMENT JOINT GEOMETRY

Segment joint design in TBM driven tunnels determines opening sizes that lead to gasket exposure. Segments generally make contact over the full width of the longitudinal joints,

but leave relatively large openings in the ring joints. Heat transfer to gaskets in longitudinal joints therefore is considered to be normative.

The gaps in the ring joints can be schematised as box shaped and therefore have three dimensions: depth, length and width. In this thesis width of the gap is defined as the distance between two segments. The definition of length and depth of the gaps can be found in figure 25.
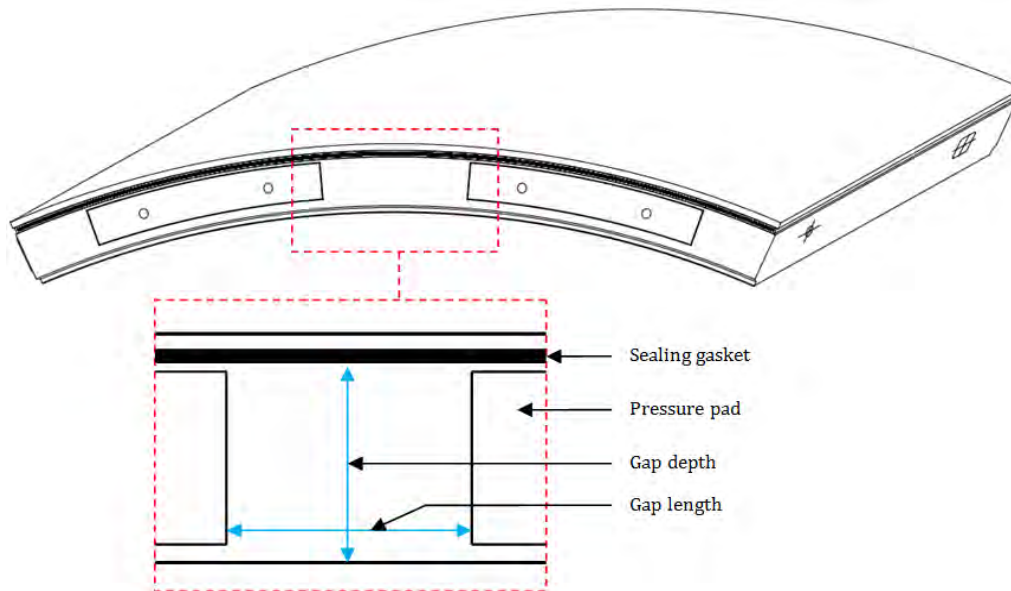

FIGURE 25: GAP DIMENSIONS [19]

The dimensions of the gaps differ for each tunnelling project, as each project has different optimizations in segment design and tunnel alignment. However, design limitations lead to a certain range in dimensions exists. Gap lengths used in the Hubertus tunnel (The Hague, The Netherlands) amount to 325mm. This gap length is regarded as common in this thesis.

The depth location of the gasket is also a result of joint design. Due to the fact that it is difficult to reinforce corners of the segment, tensile forces near the corners must be avoided. For this reason a minimum distance of the introduction of a force to the edge of the segment must be maintained. This distance is in the range of 5cm. [19, 25]. The depth of the gap therefore is the segmental thickness minus 5cm and the size of the gasket.

The width of the gap is dependent on the height of the pressure pads and the ring erection quality, which is determined by joint design, tunnel alignment and experience of the ring erection crew. Typical pressure pad heights (hence theoretical gap openings) are 6mm [25], but the quality of the ring can either lead to opening or closure of the gap. An open gap is normative for flame intrusion.

3.2.2   PROCESSES IN THE SEGMENT JOINT

Flame intrusion and convection

Tunnel fires produce very high temperature gases that quickly rise to the ceiling of the tunnel. Ventilation will displace the gases along the tunnel alignment, away from the fire location. These two processes cause a turbulent system of gas flow to occur along the tunnel wall.

Turbulence is not represented by the design fire curves as it is a highly unpredictable variable. It can however be said that in the vicinity of the tunnel fire bulk gas movement is more or less parallel to the ring joints, and further along the tunnel alignment perpendicular to the ring joints. Two types of flame intrusion will therefore occur at the ring joints.
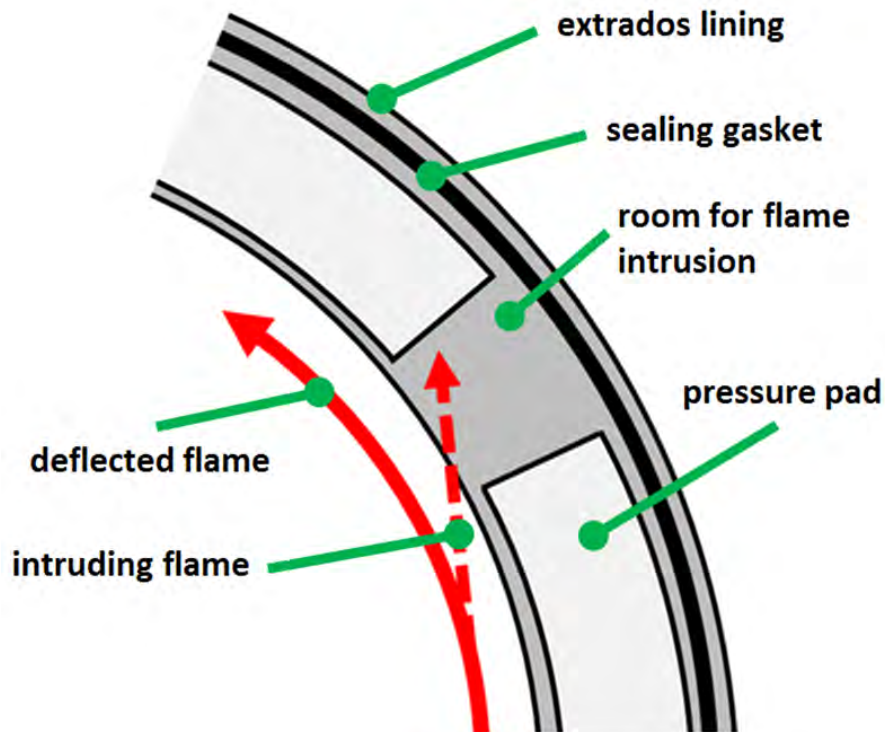

FIGURE 26: FLAME INTRUSION AND DEFLECTION

Gas flow perpendicular to the ring joints will influence the conditions inside the gap, but is probably deflected over the joint. Gas flow parallel to the ring joints will most likely show a deeper flame intrusion due to the fact that the flame is less obstructed and therefore can easier follow its original path. The shape of the tunnel increases the flame intrusion due to the fact that buoyancy forces cause the flame direction to be directed upward, but the curved ceiling causes the gas to be deflected. This leads to a gas flow that is partly directed into the segment joints (figure 27).

Flame intrusion is reduced by friction of the walls of the gap, steam production and pressure build up inside the gap. The flames heat up the walls of the gap, but the walls represent a lot of mass with a relatively high volumetric heat capacity. The size of the gap also limits energy supply, the temperature of the walls will therefore increase slowly. Flame intrusion is limited due to friction with the walls of the gap. As the gap becomes narrower and/or deeper, wall effects become more effective in protecting the gasket area. If the gap becomes narrower, thermal energy supply decreases as well due to a smaller area of heat loading.

If the gap is deep enough, flame intrusion does not reach the gasket area directly. Conduction through the remaining air layer is negligible, as air is a very good isolator, but the intruding flame may cause the air between the flame and the gasket to move and heat up the gasket (figure 27).
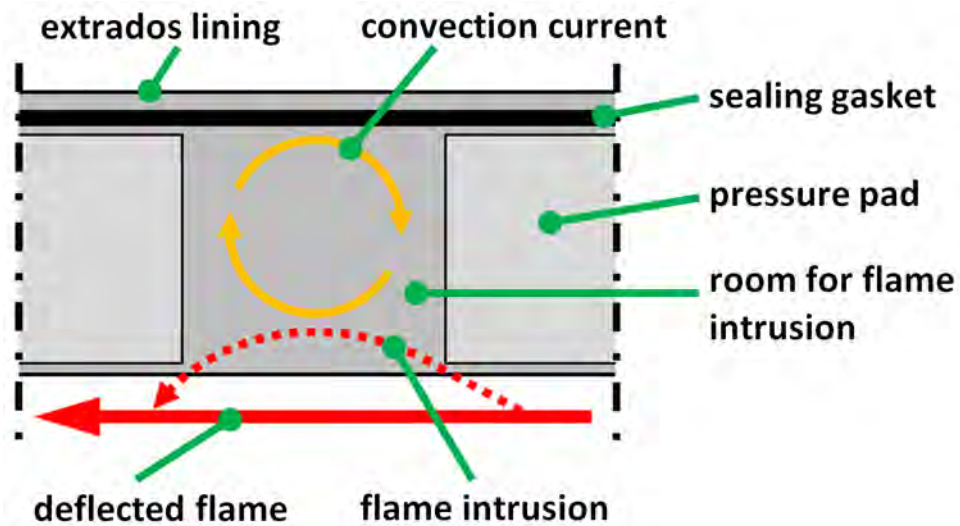
FIGURE 27: FLAME INTRUSION INDUCED CONVECTION

Conduction through concrete and steam production

Due to its low thermal conductivity and its high volumetric heat capacity, concrete has a very low thermal diffusity. It can therefore act as a thermal insulator, but it also means that a volume of concrete at a high temperature loses heat slowly to its environment. During a fire concrete shields the gasket area from heat, but part of the segment is heated up significantly. The absorbed energy is released slowly after the fire has been put out and causes heat to migrate further into the segment, even though the conditions at the surface of the concrete changed from heat loading to cooling.

As concrete contains liquid water, steam will form in case concrete reaches temperatures above 100°C. The phase change of water to steam consumes a lot of energy due to the work performed on volume expansion. This essentially means that the specific heat of concrete will temporary increase at 100°C.

Volume expansion causes pore pressures to increase and forces steam to migrate through the concrete. The use of PP-fibres in the concrete will enhance the permeability in regions of the segment that have a sufficiently elevated temperature. The dominant steam migration will therefore be in the direction of the fire, but also into the segment joints. The high steam pressure also causes water to be expelled at cooler parts of the concrete. Steam and hot water migrating outside of the segment essentially means that the amount of energy stored in the segment decreases due to loss of mass.

Radiation

The effectiveness of radiative heat transfer increases by the fourth power of temperature. A RWS design fire produces very high flame temperatures, hence an effective radiative heat transfer is to be expected. In liquids and solids radiation is emitted and absorbed by the first µm of matter from the emitting or exposed surface. Radiation levels from gases however, might be lower due to larger spacing between the molecules (figure 28).
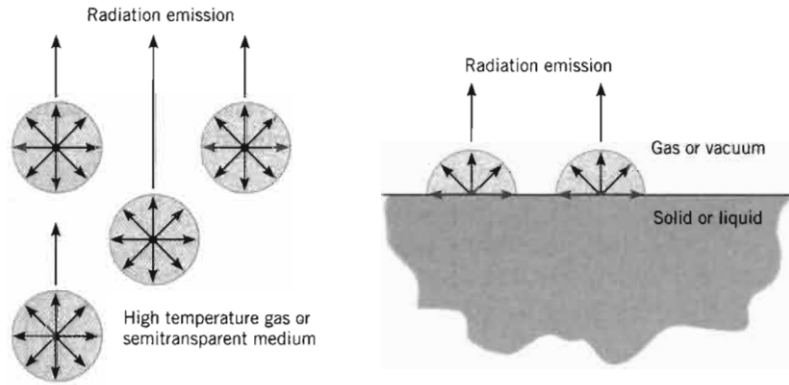
FIGURE 28: RADIATION EMISSION FROM A GAS OR SEMITRANSPARENT MEDIUM AND A SOLID OR LIQUID [12]

Tunnel fires generally produce sooth-rich gases. Research on fires that produce sooth-rich gases has shown that, if the gas layer is dense and thick enough, radiation levels are comparable to radiation originating from a solid or liquid. They have also shown that the emissivity (ε) of sooth-rich gases nearly equals one. Sooth-rich gases can therefore be regarded as a blackbody emitter [12]. With respect to radiation properties, the gases can therefore be regarded as a solid. Most construction materials can be regarded as blackbody emitters as well.

The dimension of the gaps between the segments affects the radiation incident on the gasket. The view factor relation of the situation in the segment joint can be found in figure 29. The view factor is based on the average incident intensity at the receiving surface, radiation levels will differ between the centre and the edges of the receiving surface.
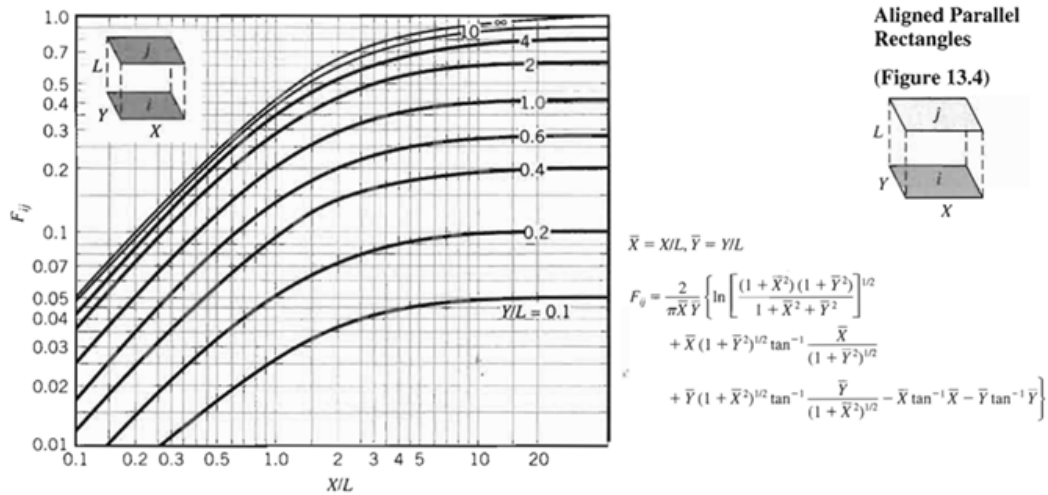

Aligned Parallel Rectangles

(Figure 13.4)

$\bar{X} = X/L, \bar{Y} = Y/L$

$$F_{ij} = \frac{2}{\pi \bar{X} \bar{Y}} \left\{ \ln \left[\frac{(1 + \bar{X}^2)(1 + \bar{Y}^2)}{1 + \bar{X}^2 + \bar{Y}^2} \right]^{1/2} \right.$$
$$+ \bar{X}(1 + \bar{Y}^2)^{1/2} \tan^{-1} \frac{\bar{X}}{(1 + \bar{Y}^2)^{1/2}}$$
$$\left. + \bar{Y}(1 + \bar{X}^2)^{1/2} \tan^{-1} \frac{\bar{Y}}{(1 + \bar{X}^2)^{1/2}} - \bar{X} \tan^{-1} \bar{X} - \bar{Y} \tan^{-1} \bar{Y} \right\}$$

FIGURE 29: VIEW FACTOR FOR RADIATION IN SEGMENT JOINTS [12]

3.2.3 COMPUTER SIMULATIONS

Simulations on temperature development at the gasket area have been made for two scenarios: conduction and retardation effects through concrete, and radiation through the gap. Flame intrusion depths have been omitted due to insufficient knowledge about turbulence circumstances inside the tunnel. Calculations on convection currents inside the gap have been omitted as a result of insufficient knowledge about the flame intrusion, but

their contribution to temperature development at the gasket area has been estimated as negligible due to the small width of the gap. The simulations have been made with the aid of a computer program: PC Tempflow [43].

Conduction through concrete and retardation effects

The parameters for simulating conduction through concrete are based on recommendations found in NEN-EN 1992-1-2:2005 (paragraph 3.3.2 Specific heat and 3.3.3 Thermal conduction coefficient). Specific heat is temperature dependent and ranges from 900J/kg*K to 1100J/kg*K, with the exception of a peak at 100-200°C. The peak represents steam production and is dependent on moisture content (figure 30).
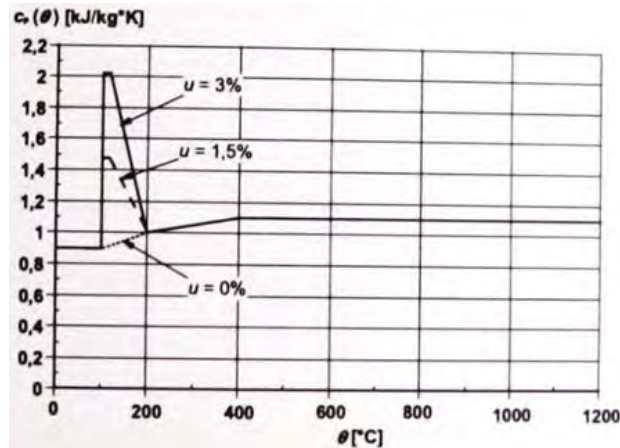

FIGURE 30: GRAPHICAL REPRESENTATION OF THE VALUE OF SPECIFIC HEAT OF CONCRETE [14] (C_P IS SPECIFIC HEAT, Θ IS TEMPERATURE)

Temperature development at several depths has been assessed by a 1-dimensional simulation in PC Tempflow (figure 31, figure 32, figure 33). For the calculations, concrete density is estimated at 2400kg/m³, heat loading is according to the RWS design fire curve.
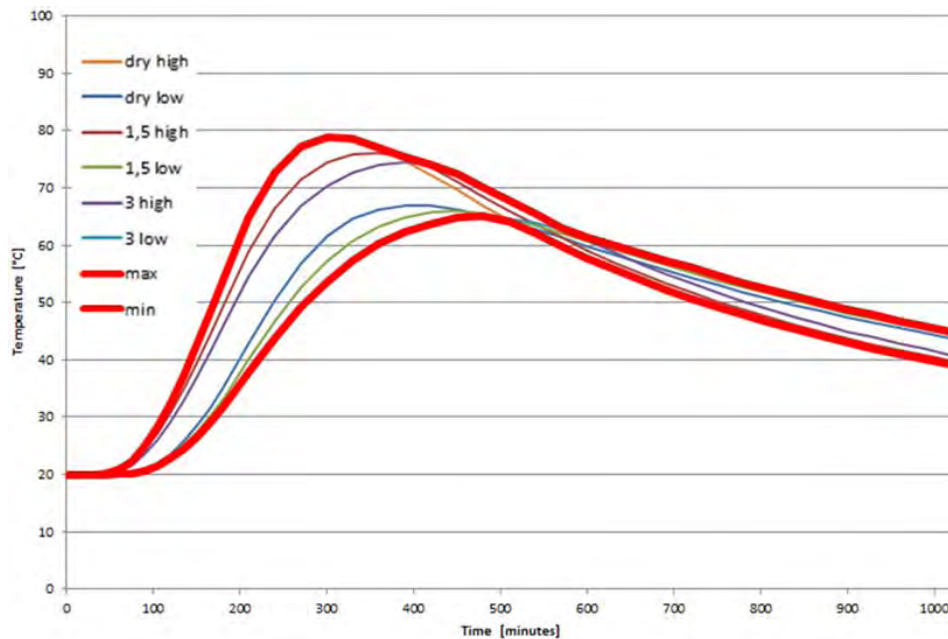

FIGURE 31: TEMPERATURE DEVELOPMENT IN CONCRETE DUE TO CONDUCTION AT 250MM DEPTH FOR VARIOUS MOISTURE CONTENTS AND CONDUCTIVITIES
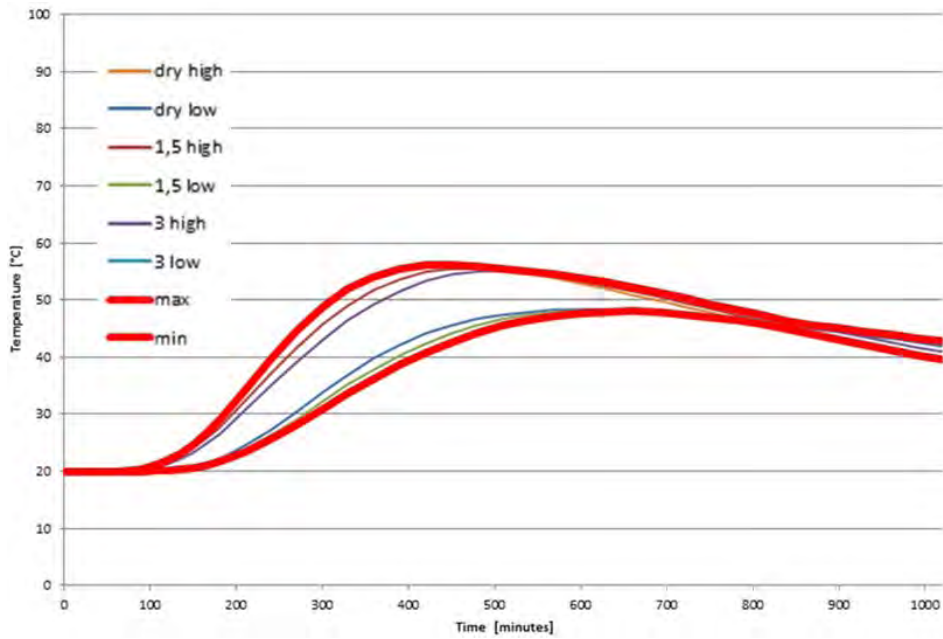
FIGURE 32: TEMPERATURE DEVELOPMENT IN CONCRETE DUE TO CONDUCTION AT 325MM DEPTH FOR VARIOUS MOISTURE CONTENTS AND CONDUCTIVITIES
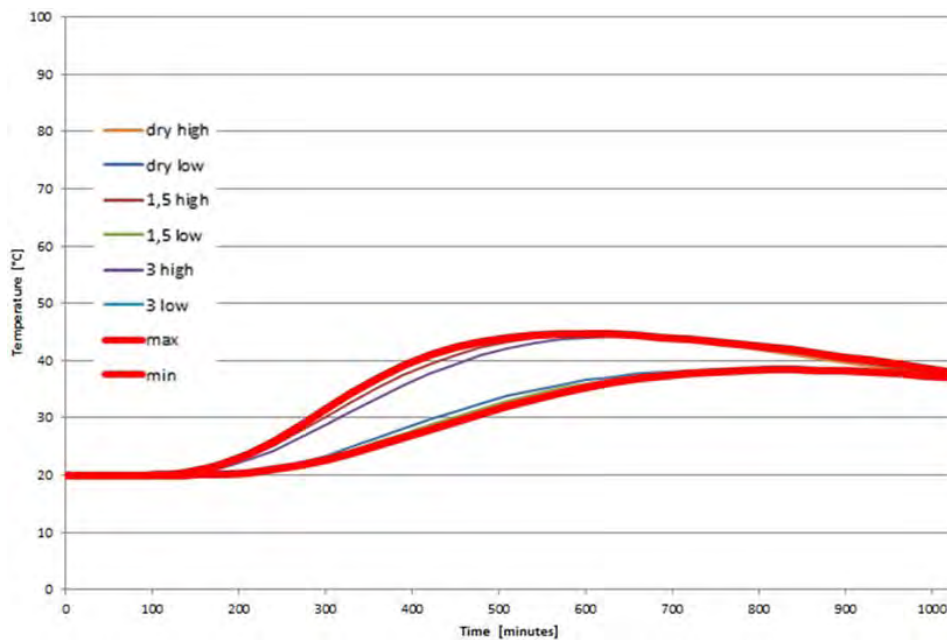
FIGURE 33: TEMPERATURE DEVELOPMENT IN CONCRETE DUE TO CONDUCTION AT 400MM DEPTH FOR VARIOUS MOISTURE CONTENTS AND CONDUCTIVITIES

As can be seen from the graphs, temperatures at the depth of the gaskets do not increase (dramatically) during the fire but a retardation effect is noticeable. The retardation phase is therefore expected to be more important to gasket performance when just conduction through concrete is considered.

Radiation

Radiation incident on the gasket, originating from a flame that intrudes the segment joint, increases the temperature at the gasket. As discussed earlier, flame intrusion is not specified in codes but can be assessed by fire tests or predicted by aerodynamics

calculations if the normative flame speeds and directions in the tunnel are known. However, temperature development at the surface of the gasket due to radiation emitted by the intruding flame, can be assessed for flame-gasket distances at various gap dimensions.

PC Tempflow was used for performing 1-dimensional simulations (appendix C). Due to the introduction of steam in the gap by the surrounding concrete, the assumption was made that the air temperature inside the gap was maintained at a temperature of 100°C. The theoretical radiation intensity – time relation of the RWS design fire is simplified to be used in PC Tempflow. Radiative heat transfer calculations are based on the simplified radiation intensity – time relation, a blackbody emitter and reciever, and view factors. The view factors of the different gap dimensions are calculated using the formula presented in figure 29. A graphical presentation of the relation between view factor, flame-gasket distance, and gap width is presented in figure 34 (gap length is 200mm).
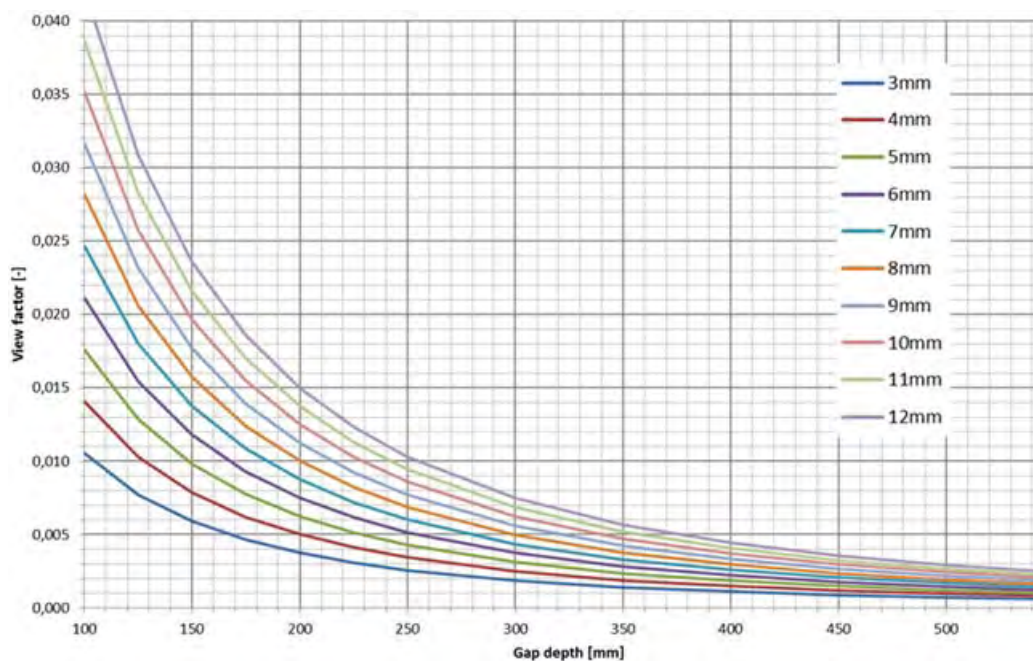
FIGURE 34: VIEW FACTOR VS. GAP DEPTH (GAP LENGTH = 200MM)

The radiation intensities combined with an air temperature of 100°C lead to a temperature increase at the surface of the gasket. The temperature development has been estimated by considering a rubber plate (thickness 5cm, density: 2400kg/m³, specific heat: 1250J/kg*K, thermal conductivity: 0,3) and wet sand behind it. A graphical presentation of the relation between view factor and temperature as a function of time can be found in figure 35.

FIGURE 35: TIME VS. TEMPERATURE FOR MULTIPLE VIEW FACTORS

As can be seen in figure 35, temperature increase is more significant for radiative heat loading through the gap than conductive heat loading through the concrete.

3.3   FIRE EXPERIMENT

Flame intrusion in the gaps is undocumented in the codes. Radiative heat transfer calculations have shown that temperature development is dependent on gap depth, hence on flame intrusion. Flame intrusion also affects convective heat transfer inside the gap.
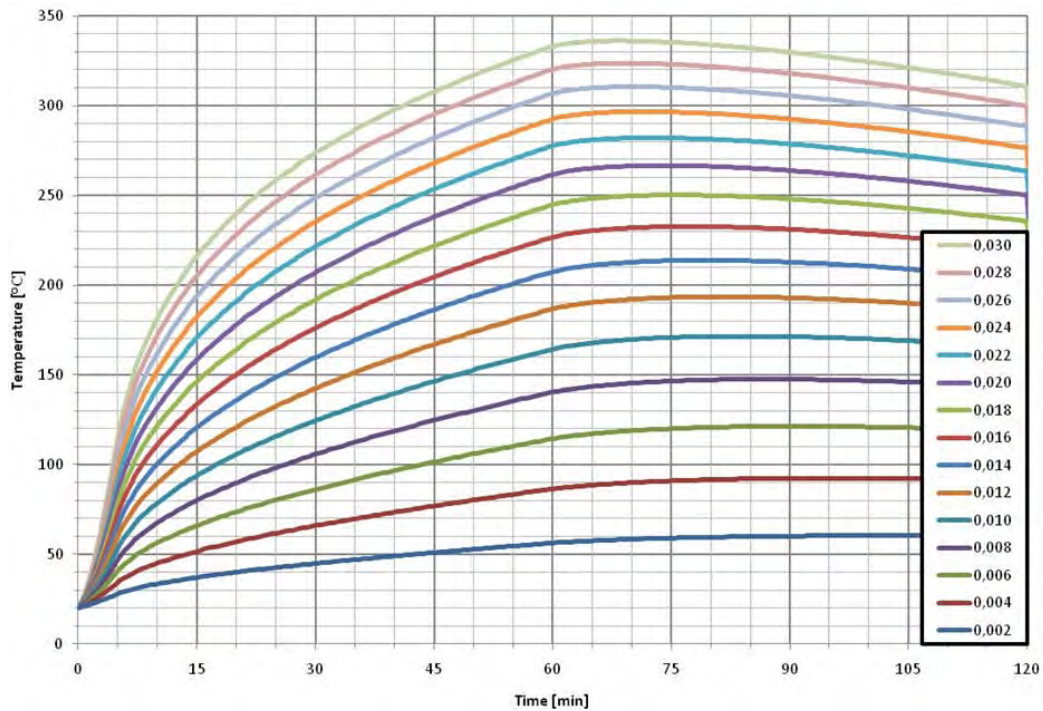
To find proper values for the temperature development at the gasket area, flame intrusion should be simulated. A physical model of the problem has been build and temperature development at the gasket has been recorded for a gap width of 11mm at several gap depths. The test was performed at Efectis b.v. (Rijswijk, The Netherlands). This section describes the setup, results and conclusions of the experiment. The full report on the experiment can be found in appendix A.

3.3.1   TEST SETUP

A small oven (l∗w∗h=1,2∗1,2∗1,2m) that is equipped with three 1MW burners (all facing the same direction) and one exhaust (opposite to the burners) has been used to conduct the experiment. The oven is capable to impose the time-temperatures relation of the RWS design fire at the sample. Two concrete blocks (l∗w∗h=1,5∗0,75∗0,55m) are placed on top of the oven and next to each other, separated by a spacing of 11mm (figure 36, figure 37). The blocks were made of PP-fibre enriched, steel fibre reinforced concrete. The moisture content was 5% at the time of heating.
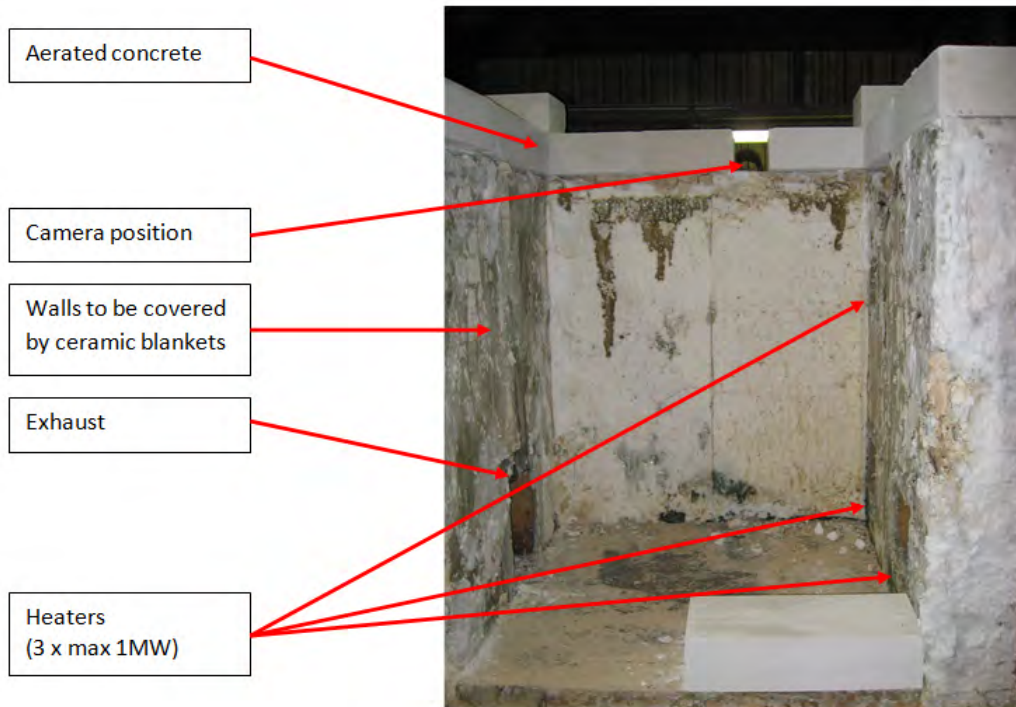
FIGURE 36: INTERIOR OF OVEN WITHOUT THE DOOR AND SAMPLE INSTALLED
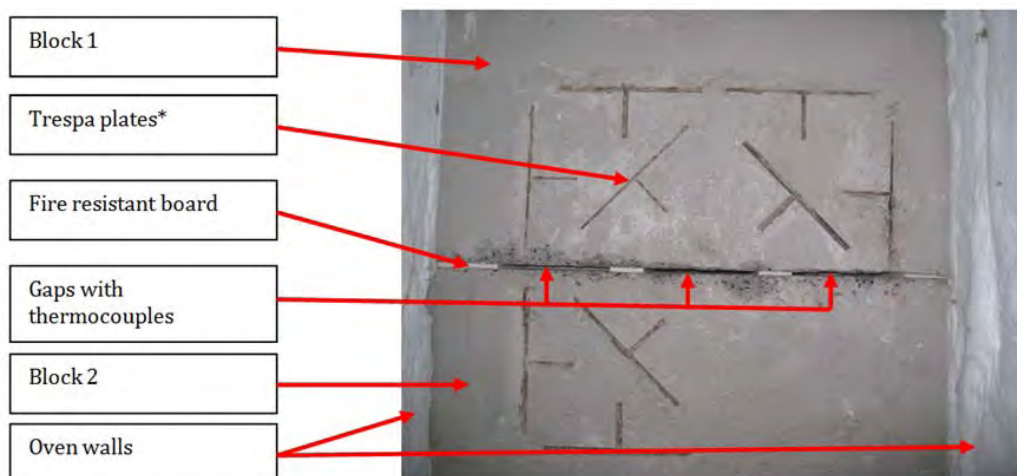
* The trespa plates were part of an initial test configuration. It has proven to be impossible to remove them from the concrete blocks. Due to time and budget constraints, the plates were left in the blocks.

FIGURE 37: HEATED FACE OF THE SAMPLE INSTALLED ON TOP OF THE OVEN

To simulate gaps, a fire resistant board with pre-cut areas (figure 38) was placed between, and glued to, the blocks. Thereby creating 11mm wide gaps at various depths (250, 325 and 400mm). The pre-cut areas were equipped with thermocouples (3 per gap) to record the temperature development at the theoretical location of the gasket.
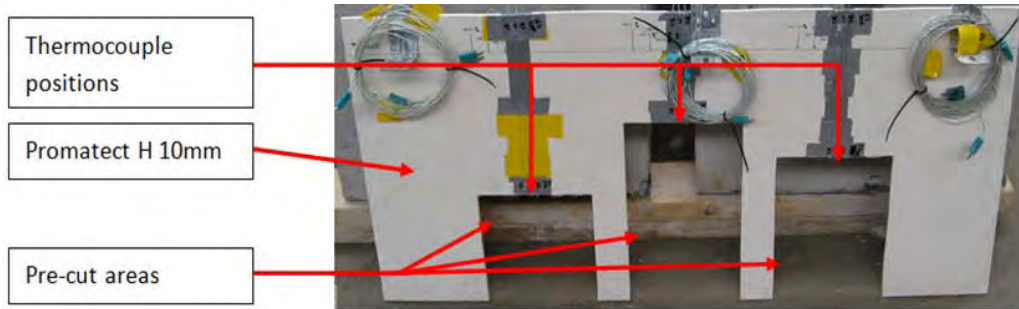
FIGURE 38: FIRE RESISTANT BOARD WITH PRE-CUT AREAS AND THERMOCOUPLES

Recordings were also made inside the oven: air pressure and temperature sensors were installed as well as a video camera.

3.3.2   TEST RESULTS AND OBSERVATIONS

Observations during the fire tests

Seepage of water could be observed from the sides of the blocks during heating. The water expelled from the concrete eventually evaporated and left white traces on the concrete. The traces are believed to be calcium deposits. The block that was supported at two sides expelled water sooner and in greater quantities then the block that was supported at three sides.Also, during test 1 steam exhaust was noticed to originate from between the blocks at the location of the 250mm gap.

Measurements in gaps: test 1

During test 1 higher temperatures were recorded in the 325mm gap than the 250mm gap (figure 40). The reason for this is that the turbulence regime inside the oven was unfavourable for the 325mm gap and favourable for the 250mm gap. The turbulence regime was adapted for test 2 by placing blocks of aerated concrete in the oven (figure 39).
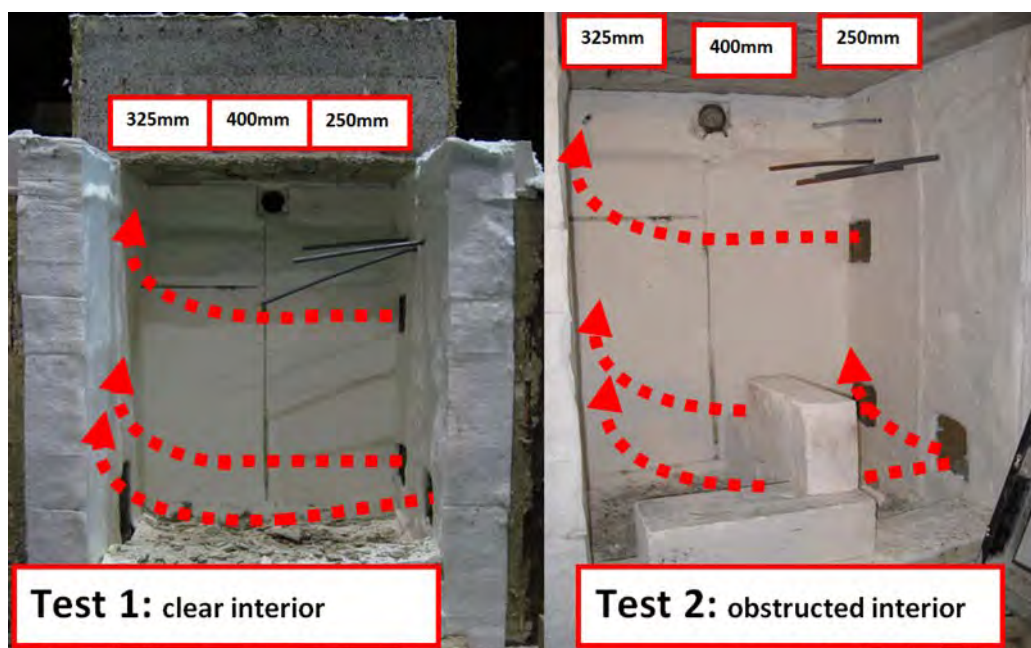
FIGURE 39: ALTERED INTERIOR OF OVEN

As can be seen in figure 38 the temperature in the 325mm gap stagnates at about 290°C. The temperatures in the 250mm and the 400mm gap increase up to 180°C and 130°C respectively and then show a drop. The heaters are stopped after 120 minutes, the temperature in the 325mm gap drops instantly to 100°C, the temperature in the 250mm gap remains about 100°C. The temperature in the 400mm gap however, soars to about 200°C but instantly drops to 100°C when the camera is removed from the oven.
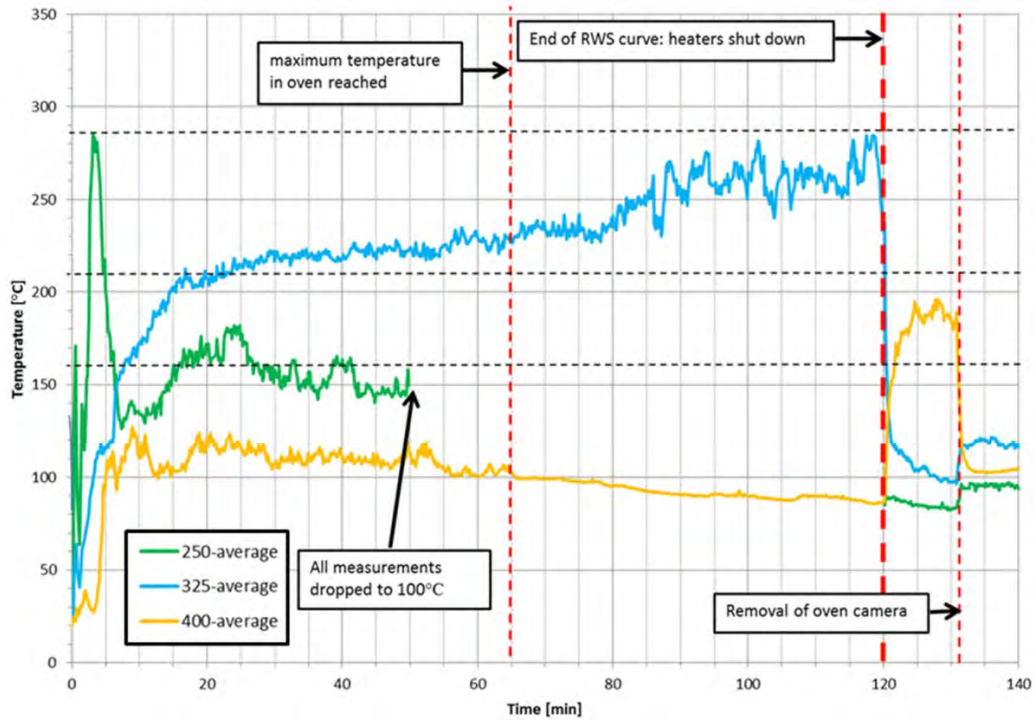
FIGURE 40: TEST 1: AVERAGE TEMPERATURES AT THE LOCATION OF THE GASKET

Measurements in gaps: test 2

Test 2 shows different results. The turbulence regime in the oven was adapted due to the high temperatures measured in the 325mm gap. The temperatures measured in the various gaps shows more consistency with the gap depths (figure 41).
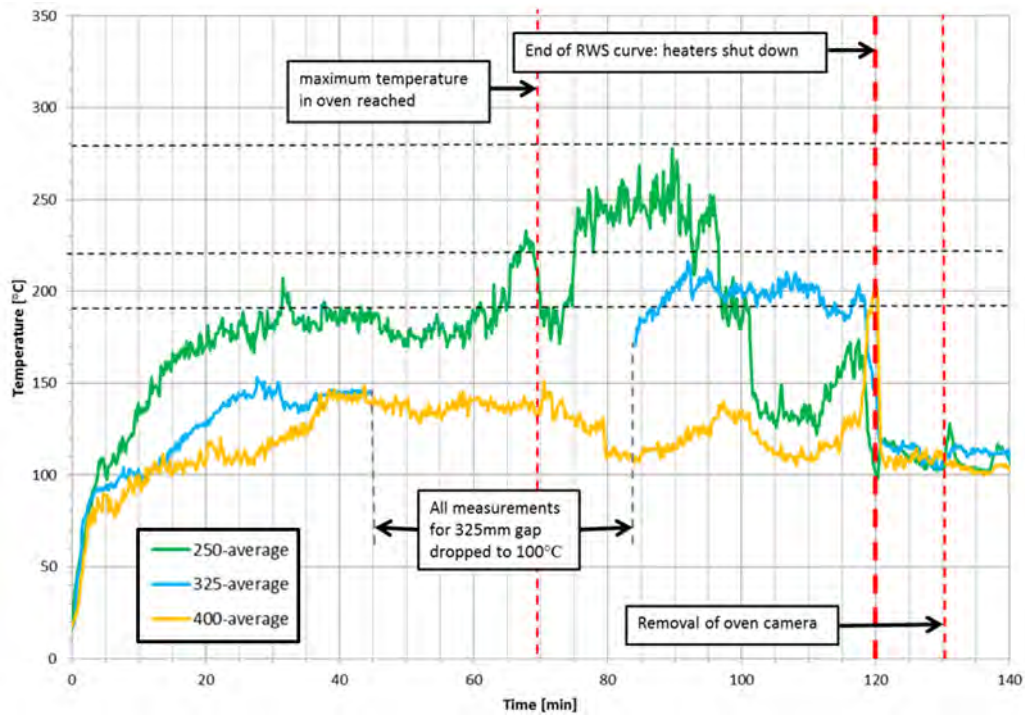
FIGURE 41: TEST 2: AVERAGE TEMPERATURES AT THE LOCATION OF THE GASKET

The temperatures in the 250mm and 325mm gaps stagnated at 280°C and 220°C respectively. Temperatures in the 325mm gap suddenly dropped to 100°C, but later suddenly soared to 180°C as well. The temperatures in the 400mm gap stagnated at 150°C, but showed a sudden increase to 190°C just before the end of the heating period. Temperatures in all gaps dropped to about 100°C as soon as the heaters were turned off.

Measurements in gaps: cooling period of both tests

Both tests exhibited a multi-day cooling period after the heaters were shut down. Temperature measurements on the first sample were stopped after one day due to preparations for the second test. Temperature measurements on the second sample were continued for about 3,5 days after the fire test started.

With the exception of the 400mm gap in test 1, temperatures in all gaps of both tests dropped to about 100°C after the heaters were shut down. The temperatures in the gaps dropped about 40°C, 20°C and 10°C during the first, second and third day of cooling respectively. At the time of cooling the average ambient temperature was 18°C. A graphical representation of the cooling period can be found in figure 42.

FIGURE 42: RECORDED TEMPERATURES AT THE GASKET LOCATION AFTER THE RWS CURVE

Visual inspection of the gaps

After the samples had been dismantled from the oven, the concrete surfaces that were facing the gaps were inspected visually (figure 43, figure 44).

One of the reasons to conduct the fire test is to obtain an impression of the effect of flame intrusion in the segment joint. A distinct difference was observed in the colour of healthy concrete and concrete that has reached high temperatures. It is possible to derive the temperature the concrete reached to its discoloration, but this was not investigated. Based on the distinct difference in colour, flame intrusion is approximated.
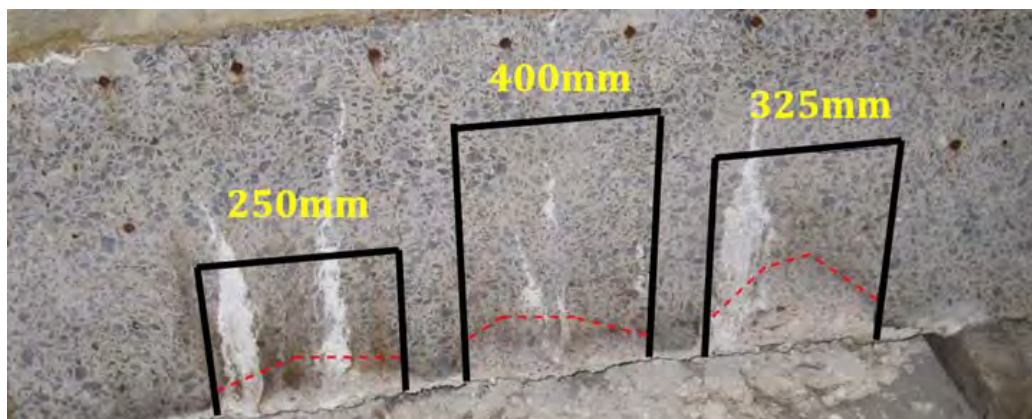
FIGURE 43: FLAME INTRUSION PATHS IN THE GAPS OF SAMPLE 1

FIGURE 44: FLAME INTRUSION PATHS IN THE GAPS OF SAMPLE 2

The flame in test 1 seems to intrude the 250mm and 400mm gaps in a similar path. The intrusion in the 325mm gap however, is approximated to be much deeper. The differences in intrusion in test 2 are smaller than in test 1. Measurements performed on the approximate flame intrusion are presented in table 6.

gap	distance flame-gasket [mm]
Test 1	
250mm	166-218
325mm	162-258
400mm	302-353
Test 2	
250mm	132-208
325mm	200-280
400mm	282-357

TABLE 6: APPROXIMATED DISTANCES BETWEEN INTRUDING FLAME AND GASKET LOCATION

Discoloration of concrete is not the only aspect that was noticeable at the concrete surface. White traces, of what appears to be calcium deposits, were found in most gaps (figure 43 and figure 44). At the origin of the traces cracks were found in the concrete. The cracks often spanned from the origin of the leak to the surface of the block that was subjected to tensile loading. The traces on the surfaces of the concrete that were facing the gaps are presented in table 7 and in table 8.

gap	number of traces [-]	severity [-- (minor) to ++ (severe)]
250mm - side 1	2	1:++, 2:++
250mm - side 2	1	++
325mm - side 1	1	++
325mm - side 2	2	1:++, 2:-
400mm - side 1	1	--
400mm - side 2	0	no trace found

TABLE 7: SEVERITY OF CALCIUM TRACES AT CONCRETE SURFACES IN THE GAPS TEST 1

gap	number of traces [-]	severity [-- (minor) to ++ (severe)]
250mm - side 1	2	1:0, 2: --
250mm - side 2	0	no trace found
325mm - side 1	2	1:+, 2:+
325mm - side 2	2	1:0, 2:+
400mm - side 1	0	no trace found
400mm - side 2	2	1:-, 2:-

TABLE 8: SEVERITY OF CALCIUM TRACES AT CONCRETE SURFACES IN THE GAPS TEST 2

3.3.3 CONCLUSIONS ON THE EXPERIMENT

Fire conditions outside the gap significantly influence temperatures at the location of the gasket, temperatures between 100°C and 290°C are recorded during the test. The recorded temperatures are larger than calculated for the respective gasket depths. This can be explained by the intrusion of flames in the gap.

Flames will intrude gaps between the unprotected segments, the severity of the intrusion depends on the speed and direction of flames. Flame intrusion for the first test reached up to 180mm, a change in oven configuration for the second test led to intrusions of 120mm. The relation between the flame speeds and directions in the test to a normative real situation is unknown.

If the intrusion of flames is taken into consideration predictions on temperature development in the gaps are more accurate (albeit that the recordings show larger fluctuations than their theoretical counterparts). This indicates that radiation is a very important heat transfer mode in narrow gaps. Temperature recordings for the individual gaps are plotted together with the predictions for various view factors (hence gap depths) in appendix D. The differences are also analysed in the appendix.

An important aspect of temperature development in the gaps is steam production. The recordings in the gaps showed sudden steep drops and rises of temperature to and from 100°C. This indicates the sudden presence and disappearance of large quantities of steam. A visual inspection at the concrete faces of the gap indicated that water has been leaking from the concrete at isolated places. The origin of most leaks were cracks in the concrete block.

Severe leaks may account for the sudden steep drops in temperature, but temperature recordings also showed slower or even stagnated temperature increase in the gap when temperatures in the oven were still rising. After a period of time stagnation ended and increase continued, but at that time the temperature in the oven was decreasing. This behaviour may be explained by steam exhaust from the pores of the concrete. Steam exhaust effectively cools down the environment in the gap, but also dries out the concrete. At some point steam production decreases and temperatures in the gap can increase again.

After the fire conditions were taken away from the samples, temperatures in the gaps instantly dropped to 100°C. The temperature decreased to 60°C after the first day of cooling and took two more days to reach a temperature of about 30°C. This means that temperatures remain at higher levels for a long period of time after the fire has been put out.

The test did not entirely mimic the real situation. The lining in the real situation has a curved surface, whereas the test used a flat surface. This may influence flame intrusion. Another difference between the test and the real situation is the connection between the gaps. Most joint designs leave room between the pressure pad and the gasket, creating canals between the gaps. Gaps therefore are connected with each other in most cases, the gaps were isolated in the test.

3.4 CONCLUSIONS ON RESEARCH QUESTION 2

"How does a fire affect the conditions at the location of the sealing gasket in case innovative fire protection is used?"

Temperature is affected by heat, heat is energy in transfer from a higher temperature medium to a lower temperature medium. Heat transfer science distinguishes three modes of heat transfer: radiation, conduction and convection.

Gaps in segment joints of innovatively protected linings are filled with air, leaving part of the gasket directly exposed to the conditions of a fire. Conduction through air is negligible, hence radiation and/or convection are the heat transfer mode in the gap. All dominant processes that take place in the gap are presented in (figure 45). The processes that take place in conventionally protected linings are presented there as well.

The thermal diffusity of concrete is very low, concrete therefore shields the gasket area from temperature increase during the fire. A tunnel fire however introduces large amounts of energy into the concrete. Temperatures at the gasket will therefore increase as the result of a retardation effect. The innovative protection solution is affected most severely by this process, as the surface of the segment is not shielded. However, the temperature rise at the location of the gasket (calculated for 250, 325 and 400mm depth) is negligible as the temperature will reach values in the order of 40-80°C. Most conventional fire protective covers are engineered to a maximum temperature of 380°C at the cover-segment interface.

Water undergoes a phase change from liquid to gas at a temperature of 100°C; steam is formed. The temperature of steam at atmospheric pressure cannot exceed 100°C. Temperatures higher than 100°C in the segment lead to the exhaust of 100°C steam into the gap. Steam exhaust into the gap can therefore be expected in all fire protection solutions. Temperature, water content and permeability of concrete are important factors to the level and duration of steam exhaust.

Gas speeds and directions are not specified in codes, it is therefore impossible to use codes to predict flame intrusion in the gaps for a RWS design fire. Forced convection as a result of flame intrusion therefore also is impossible to be estimated. Free convection can be considered negligible due to wall effects of the narrow gap and steam exhaust.

Radiation induced temperature development in the gaps can be calculated for flame-gasket distances using view factor relations. Due to steam exhaust, the calculations require an air temperature of 100°C to be imposed at the interface of air-gasket to attain accurate results. Temperature development is dependent on gap dimensions.

Fire experiments on samples with a gap width of 11mm have shown flame intrusions of 120-170mm. The turbulence regime in the oven has shown to be an important factor for flame intrusion. It is unknown if the turbulence in the oven is comparable to the conditions in a tunnel during a fire. The exhaust of steam by the concrete caused temperatures in all

gaps to rise to at least 100°C, but creates a cooling effect for temperatures in excess of 100°C. Temperatures recorded during the experiment reached values between 100°C and 290°C.

When gap dimensions are corrected for flame intrusion, radiation calculations show comparable temperatures to the measurements of the experiment. Radiation thereby can be identified as the dominant mode of heat transfer in the gap. Experiment recordings however did not fully follow the predicted time-temperature paths. At some stages of the experiment recorded temperatures were consistently lower than predicted. The reason for this can be found in water migration and steam production in the gap. At the end of most fire tests temperatures rose to their predicted value.

The retardation effect in the concrete leads to a long cooling sequence. Temperatures at the gasket drop to 100°C once the fire has stopped, cooling to 60°C takes one day at an ambient temperature of 18°C.

An important note to the fire experiment and the calculations is that they do not take interconnectivity of gaps into account. The real situation however has a small channel between the pressure pad and the gasket, that connects the gaps. It is unknown what the effects of this interconnectivity are.
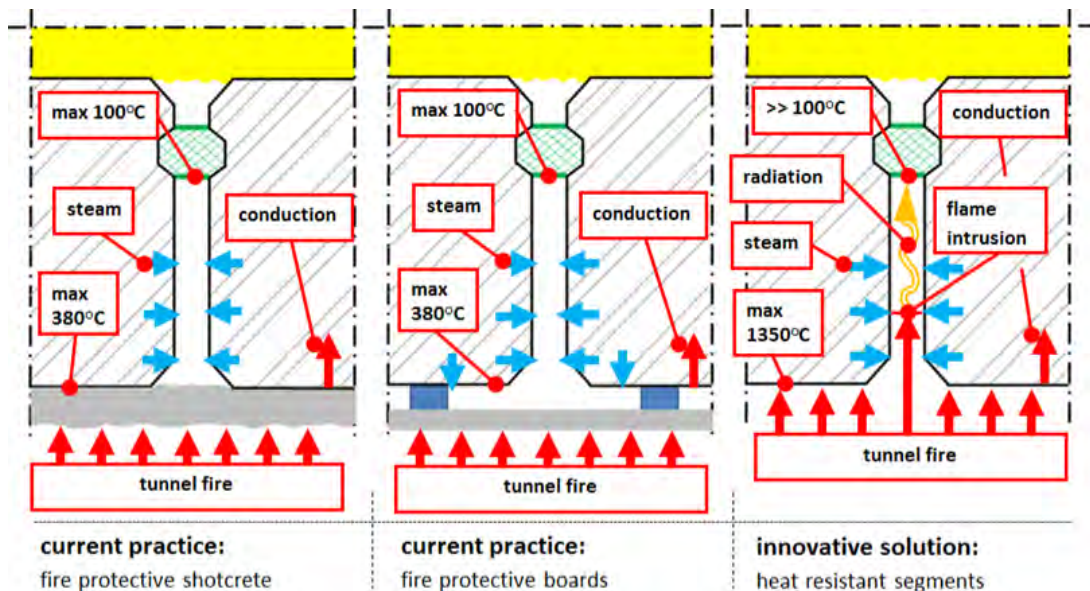

FIGURE 45: PROCESSES IN THE SEGMENT JOINT

CHAPTER 4

GASKET SYSTEMS AND HIGH TEMPERATURES

The aim of this chapter is to answer the third research question: "What are the functions of the sealing gasket, how does it fulfil its functions and how is the performance affected by the conditions caused by the tunnel fire?" by providing insights into the design of gasket systems, rubber and the effect of stresses on rubber. To gain knowledge about the behaviour of the gasket system under compression at high temperatures an experiment has been performed as well. The set up and results of that experiment will be discussed in section 4.3. Section 4.2 will discuss the design of gasket systems and section 4.1 will elaborate on rubber compounding, elasticity and relaxation. The conclusions on the third research question will be presented in the final section, 4.4.

4.1   RUBBER

Rubber is a versatile product that is used in numerous applications. A rubber type that is commonly used for sealing profiles of tunnel segments is the synthetic rubber Ethylene Propylene Diene Monomer (EPDM). The following section discusses the properties of synthetic rubbers, especially EPDM, compounding, and also the concept of elasticity and stress relaxation.

4.1.1   RUBBER COMPOUNDING

Synthetic rubber is a compound of several materials. The ingredients that can be used in a compound can be divided into the following categories:

- Elastomers
- Vulcanization system components
- Filler systems
- Stabilizer systems
- Other ingredients

Elastomers

Elastomers are the main ingredient of a rubber; they provide rubber its elastic properties. Elastomers exhibit the unique properties of being able to stretch and retract rapidly, have high strength and modulus when they are stretched, and are able to fully recover upon stress relieve [4].

Elastomers are a type of polymers; long chainlike molecules that typically consist of thousands of monomers, connected to each other by covalent bonds. Therefore, monomers are also called repeat units. An important aspect of elastomers is that the bonds between the repeat units is single valence and noncolinear. This means that one electron pair is used for the atomic connection and the connection of repeat units does not form a straight line, but is oriented differently in space (figure 46). Another aspect of elastomers is that rotation around the bond axis must be possible as a result of thermal agitation [28].
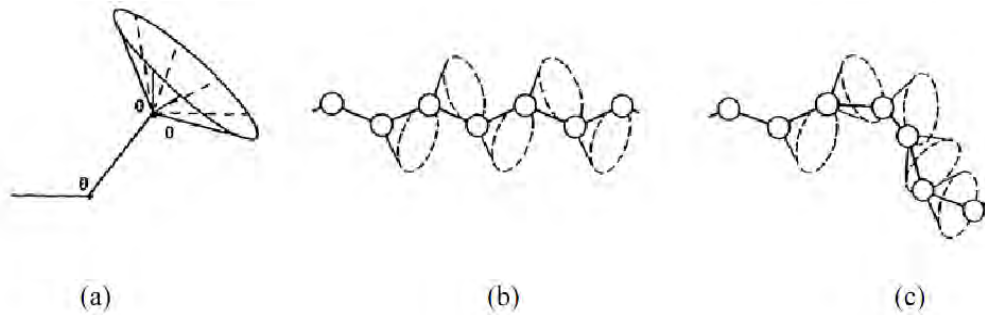
FIGURE 46: ANGLES BETWEEN BONDS IN A POLYMER [2]

When multiple polymer chains (of sufficient length) are combined, a solid can be formed as a result of chain entanglement and inter-chain Van der Waals forces. The strength of these solids is limited and highly influenced by temperature. The links created by entanglements and Van der Waals forces are weaker than covalent bonds. If the temperature in the solid would rise high enough, the solid will melt due to increased chain motion that causes easier slipping. Therefore these types of solids are called thermoplastics. Thermoplastics also show severe stress relaxation, as the weak links give room for the chains to slip under stress. This property makes thermoplastics unsuitable as a gasket material, but some thermoplastics can be altered by a vulcanization process to perform better.

Vulcanization

Stress relaxation and temperature dependence of thermoplastics is the result of weak bonds between the chains. If inter-chain bonds could become stronger, stress and temperature resistance will increase. Vulcanization is the process of locally fusing the chains together, thereby forming a network of chains (figure 47). The links created by vulcanization are called crosslinks and are formed by covalent bonds.
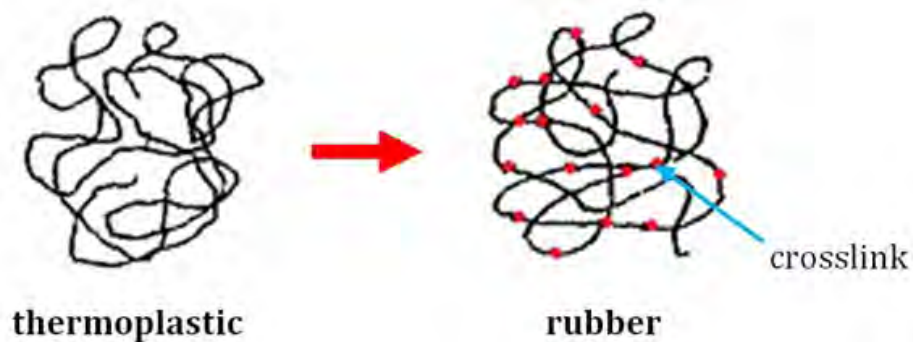
FIGURE 47: VULCANIZATION [17]

Vulcanization is known as a process involving sulphur, pressure and heat (often 140-160°C but other temperatures are also possible, the process is time and temperature dependent), but it can take place in several ways. Covalent bonds can also be created by the addition of other curing agents: oxidizing agents, generators of free radicals, or phenolic resins.

Vulcanization by just sulphur and heat takes place by breaking C=C double bonds in the chains and connecting them with sulphur, each crosslink takes about 40-55 atoms. Peroxide curing agents are often used in case the backbone does not contain C=C double bonds. The process of vulcanizing with sulphur is very slow, but accelerator agents can be used to speed up and economize the process. Most accelerators, however, additionally need activators to become active [26].

Vulcanization transforms a weak thermoplastic solid into a solid with increased tensile strength and modulus. At the same time it preserves extensibility and increases toughness of the rubber [4]. The difference in stress-strain performance of vulcanised and unvulcanised rubber is presented in figure 48.

FIGURE 48: STRESS-STRAIN PERFORMANCE OF VULCANIZED AND UNVULCANIZED (NATURAL) RUBBER [4]

EPDM is a rubber with a fully saturated backbone (no C=C double bonds present in the backbone), but the chains can be chemically altered to contain side branches that do have C=C double bonds. EPDM can therefore be vulcanized b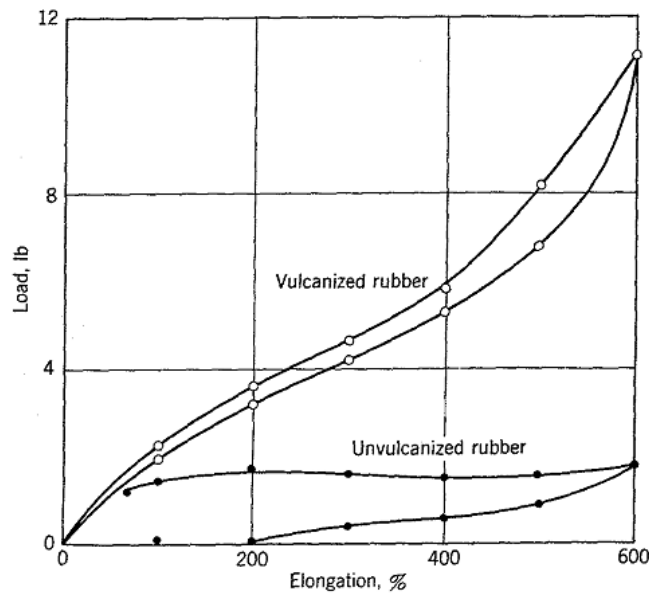y sulphur, but the process is rather slow and a large amount of accelerators are needed. Peroxide is more suitable as a curing system for EPDM. Peroxide cured EPDM rubbers exhibit increased heat resistance compared to sulphur vulcanized EPDM rubbers. Sulphur vulcanized EPDM rubbers, however, are superior with respect to ultimate and dynamic strength properties [26]. The fully saturated backbone is the reason EPDM performs well in durability.

Fillers

Fillers can be used to alter the properties of rubber. They can be divided into two categories: inert fillers and reinforcing fillers. Inert fillers are mostly used to make the rubber mixture easier to handle prior to vulcanization. Reinforcing fillers are used to enhance tensile strength, stiffness, abrasion resistance, tear resistance or combinations of them.

It is unknown how reinforcing fillers work, but it appears that the filler ads a network of many relatively weak fix points between chain and filler to the network of crosslinks. The network of crosslinks restrains large movement of the chains, but movement between the crosslinks is free. The network of fillers restrains the movement of the free chain between the crosslinks. The fillers thereby stiffen the solid and improve its toughness [4].

A commonly used reinforcing filler is carbon black. Most carbon black fillers used in rubber are made by burning gas or oil. Filler effectiveness increases as the carbon black particle diameter decreases. This is due to the fact that the relative surface area of the particle

increases, hence filler-rubber interface increases. The usable particle diameters for carbon black range from 200 to 500 Ångström [4].

Stabilizers and other ingredients

Elastomers with C=C double bonds in their backbone are vulnerable to oxygen, ozone and thermal degradation. Rubber degradation causes chain scission, or a decrease of crosslink length. The decrease of crosslink length leads to an increase in hardness and stiffness of the rubber, but fatigue resistance decreases. Chain scission is the breaking of polymer chains. It decreases the abrasion resistance and causes the rubber to soften. EPDM is vulnerable to the decrease of crosslink length.

Polymer type and vulcanization system are important factors that influence rubber degradation, but stabilizing additives can be used as well. Stabilizers can be used to reduce the effect of rubber degradation [28].

Other ingredients in rubber are often used to improve pre-vulcanization handling performance. Examples of the other ingredients are processing oils and plasticizers [28].

4.1.2   ELASTICITY AND RELAXATION

When rubber is deformed from its neutral state (i.e. at room temperature and atmospheric pressure), a reaction force develops as a function of strain. Gaskets make use of this property to provide sealing force. However, rubber shows viscoelastic behaviour; if strain is maintained on the rubber for a period in time, reaction force will decrease until an equilibrium is reached. The reason for this can be found in changes in chain segments between the crosslinks of the vulcanized polymer.

Elastic behaviour

Although vulcanization fixates the polymer chains into a structure by crosslinking the chains at several locations, the chain segments between the crosslinks still have freedom of movement. If the rubber is in a neutral position, the chains are in an equilibrium conformation (3-dimensional arrangement of the chains). If strain is applied on the rubber, this conformation is distorted by work energy: chains stretch or compress, and move closer to, or away from each other. The distortion of chains requires energy as the chains were previously in an equilibrium state.

The stiffness of the rubber is affected by temperature, polymer type, and also by the crosslink density. Temperature plays an important role in the stiffness of amorphous polymers, as four temperature dependent phases can be distinguished:

- Glassy state
- Leather like state
- Rubberlike state
- Liquid state

The amorphous polymer behaves brittle in the glassy state and exhibits leather like behaviour in the transfer phase from the glassy to the rubber like state. The temperature at which the polymer changes from the glassy to the rubber like state is called the glass transition temperature (T_g) (the exact definition is slightly different but is not discussed in this thesis). If the temperature rises high enough, the amorphous polymer will start to melt (T_m).

Cross-linked polymers do not have a T_m, as this would require covalent bonds being broken. If the crosslink bonds are being broken, other covalent bonds in the polymer will be broken as well. Hence, vulcanized rubber does not melt but disintegrates at high temperatures.

As the degree of crosslinking increases, the stiffness increases as well. The reason of this fact is that the length of the segments between the crosslinks, thereby the freedom of movement of the chain, decreases as well. An increased degree of crosslinking also increases T_g.
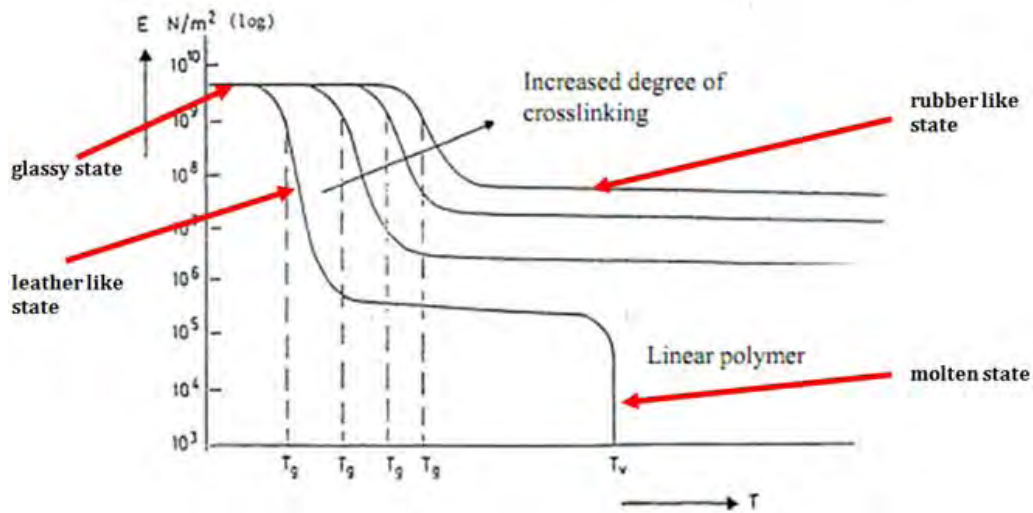
FIGURE 49: E-MODULUS OF RUBBER AS A FUNCTION OF TEMPERATURE AND DEGREE OF CROSSLINKING [17]

Relaxation

Rubber can be seen as a viscoelastic material; distortion of the polymer chain conformation will initially lead to high reaction forces, but the forces will eventually decrease as the chains find a new equilibrium state. The distorted chains find a new equilibrium by chain segment motion and rotation about chemical bonds (figure 50) [4].
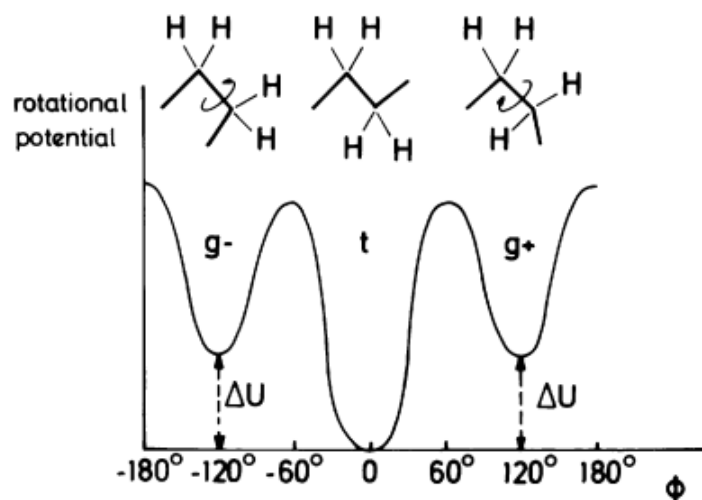
FIGURE 50: EXAMPLE OF ROTATIONAL POTENTIAL ENERGY [30]

As can be seen in figure 50, repeat unit polarity can prevent the repeat units of the chain from rotating freely with each other about their bond. Rotation of one link will cause a chain reaction in the rotation of other links. Initially this process is very fast, but as time passes and the chains relax more, the process slows down. Higher temperatures influence this process as they increase rotational energy.

Macroscopically this process can be modelled by a Maxwell element (figure 51). The Maxwell element consists of a spring and a dashpot. The dashpot represents the viscous part of the viscoelastic behaviour and introduces a retarded reaction to the reaction force resulting from the imposed strain. At t=0 the spring will be at maximum strain. But as time passes, deformation of the dashpot takes strain away from the spring which in turn will show a decrease in reaction force.

stress – strain relation:

$$\frac{d\gamma}{dt} = \frac{1}{\eta} s + \frac{1}{G} \frac{ds}{dt}$$

remaining stress in
fixed strain situation:

$$s = s_0 e^{-(G/\eta)t} = s_0 e^{-1/\tau}$$

$\gamma = strain$ $t = time$
$\eta = viscosity$ $G = modulus\ of\ elasticity$
$s = stress$
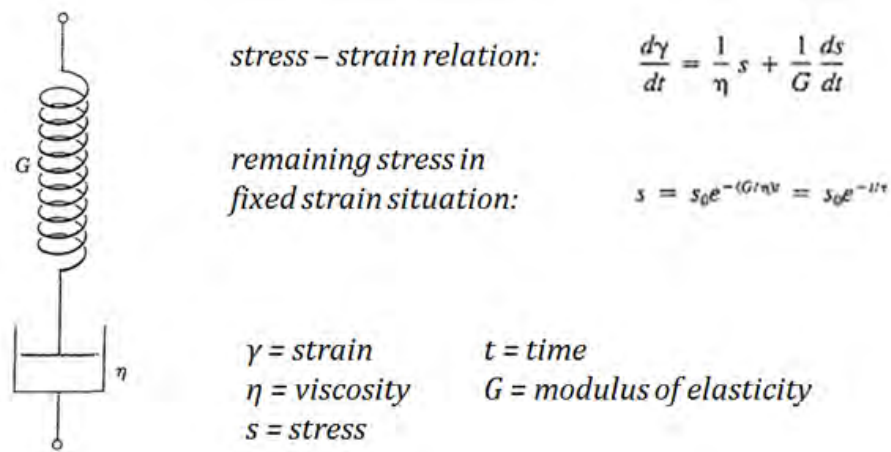
FIGURE 51: VISCOELASTIC BEHAVIOUR: MAXWELL ELEMENT [4]

The motion of atoms and molecules is determined by their temperature. As relaxation depends on chain motion and rotation about chemical bonds, high temperatures increase the rate of relaxation. The viscosity part of the equation therefore is temperature dependent.

4.2 THE GASKET SYSTEM

Several aspects need to be known about the gasket system to understand the influence of elevated temperatures on its performance. Therefore, system functions and the components that support the system functions are discussed in this section. The components of the gasket system are; the gasket and the gasket groove in the segment. The interaction between the two components is important to optimisation of the system.

4.2.1 INSTALLATION AND FUNCTIONS OF THE GASKET SYSTEM

Installation procedure

The segments of a TBM driven tunnel are installed using an erector. The erector can only exert a limited amount of force to install the segments. The higher the force needed to install the segments, the higher the capacity of the machine needs to become.

Segments can be installed at a certain accuracy, misalignment of gaskets is therefore to be expected. The installation inaccuracies also lead to the fact that the gaskets need to

function in a range of compressions and offsets. As stated in 3.2.1, the accuracy of placement is mostly determined by the kind of (temporary) connection between the segments and workmanship of the erector crew.

The installed gasket system

The function of the gasket system is to keep the tunnel dry by providing a water seal between the segments. TBM driven tunnels are constructed at large depths. If the ground water levels are high, the water pressures at the gaskets will be high as well. Failure of the gasket system will lead to water ingress into the tunnel and may lead to erosion of soil at the location of the leak.

During the lifetime of a tunnel small geometrical deviations in the lining will occur, compression of the gaskets will therefore deviate as well. The water seal must be guaranteed for the expected installation inaccuracies in a range of compression.

The project specific information about minimum and maximum compression, and minimum and maximum offset can be combined to form a usability diagram (figure 52).
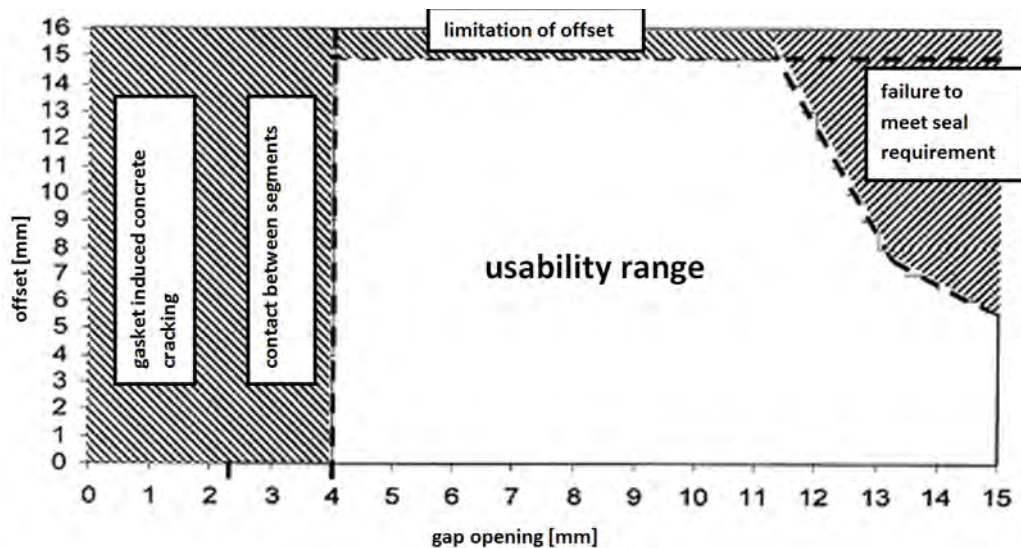
FIGURE 52: USABILITY DIAGRAM GASKET SYSTEM HUBERTUS TUNNEL [19]

TBM driven road tunnels are very costly infrastructure assets, hence most TBM driven tunnels have a design lifetime of 100 years or more. The requirements on durability of essential structural components of the tunnel therefore must meet the design lifetime.

4.2.2 GASKETS

Gaskets for TBM driven tunnels come in different shapes and sizes. The shape, size and type of rubber to be used for the gasket system is project specific and based on expected erection tolerances. Gaskets are produced using the extrusion technique; rubber is mixed, heated and pushed through a mould to form a profile (figure 53). At that time the rubber is not vulcanized, but does maintain its shape. Then, the profile is introduced to a conveyer system, where it is heated further to complete the vulcanization process (temperatures vary, a common temperature range is 140-160°C). The vulcanized profile is cut into pieces and is put together again to form frames. Finally, the individual pieces are jointly

vulcanized in the corners of the frame. To provide a tight fit with the groove, the frames are slightly smaller than the segment it is placed in.

FIGURE 53: EXTRUSION MACHINE AND MOULDS [38]

Compression characteristics

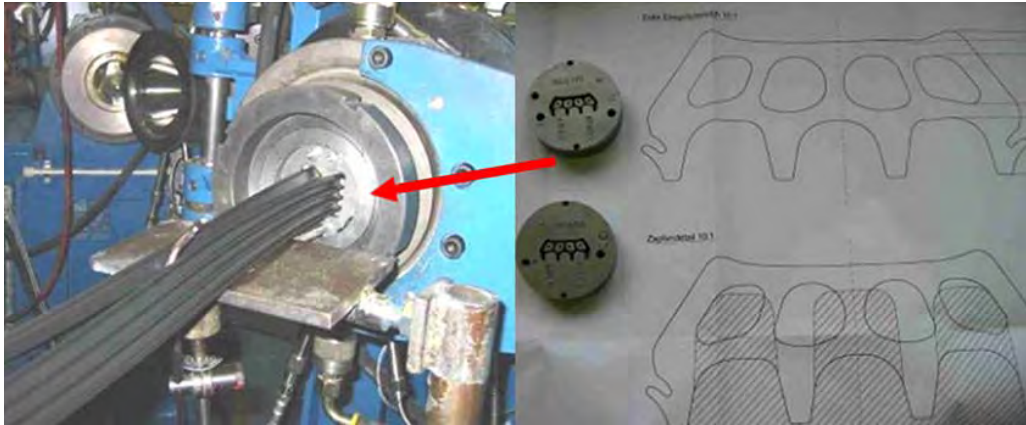Water seal of the system is reached by compression of the gasket. Each gasket design has its own compression characteristics, which in turn are affected by groove geometry and method of testing. Compression characteristics are very important to groove design and erector capacity. If the gasket is too weak, the sealing system will fail by insufficient reaction force. If the gasket is too stiff, the sealing system will fail due to concrete spalling. A stiff gasket also leads to the need of an increased erector capacity.

Compression characteristics are determined by a strain controlled compression of two gaskets facing each other directly, or with an offset, or a single gasket. The gaskets need to be installed in the project specific groove to provide a proper compression characteristic [38]. The method that exerts the highest force on the segment groove is normative.
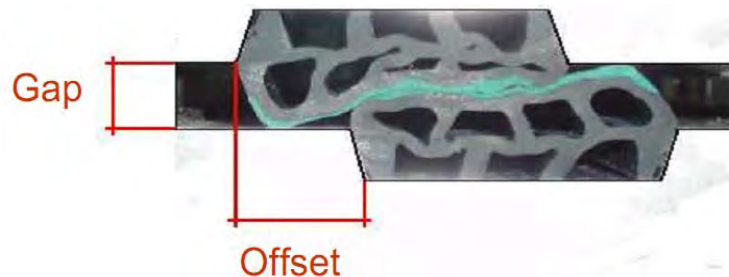
FIGURE 54: OFFSET OF INSTALLED GASKETS [18]

Water seal

As a result of designed installation tolerances, gaskets need to be tested with an offset to ensure the water seal in all possible situations. The situation that is considered to be normative to failure of the water seal is a situation where corners meet and an offset between the gaskets is present (figure 54).

A water tightness test often used in Europe replicates a T-joint and tests the gaskets at different gaps and offsets (figure 55). The pressure is increased by 1 bar at a time and kept at 1 bar for 5 minutes. Pressure is increased if the system does not fail. If the system does fail, the combination is recorded as a failure point. All failure points combined produce the

watertightness-gap diagram, which can be used to create the usability diagram of a gasket type in a project (figure 56).
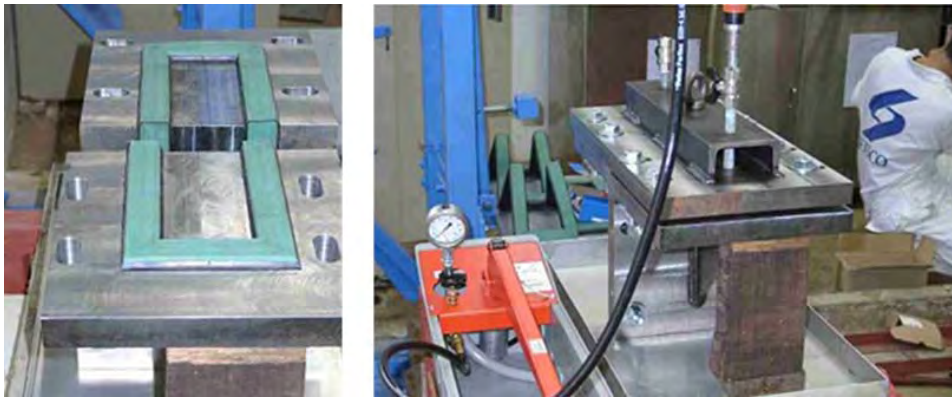
FIGURE 55: WATERTIGHTNESS TEST RIG [38]

FIGURE 56: WATERTIGHTNESS-GAP DIAGRAM [18]

Endurance

The gasket system needs to function for at least the design lifetime of the tunnel. Part of the gaskets initial reaction force is lost in time due to relaxation and often is linearly related to log-time. Relaxation is mainly influenced by the geometry of the gasket [38]. A graphical representation of short and long term relaxation can be found in figure 57.

FIGURE 57: EXAMPLES OF SHORT (LEFT [18]) AND LONG (RIGHT [19] TERM GASKET RELAXATION

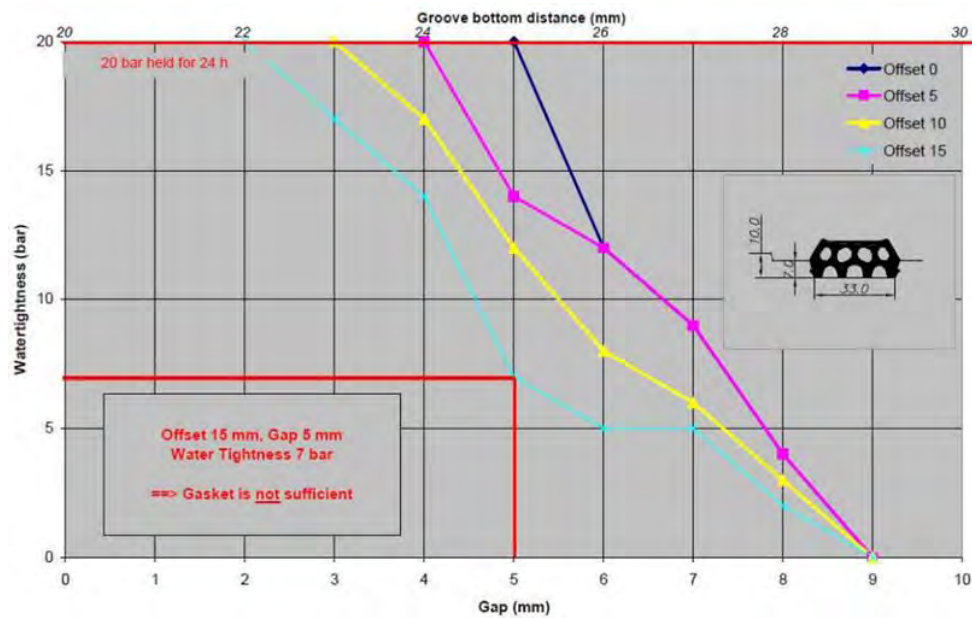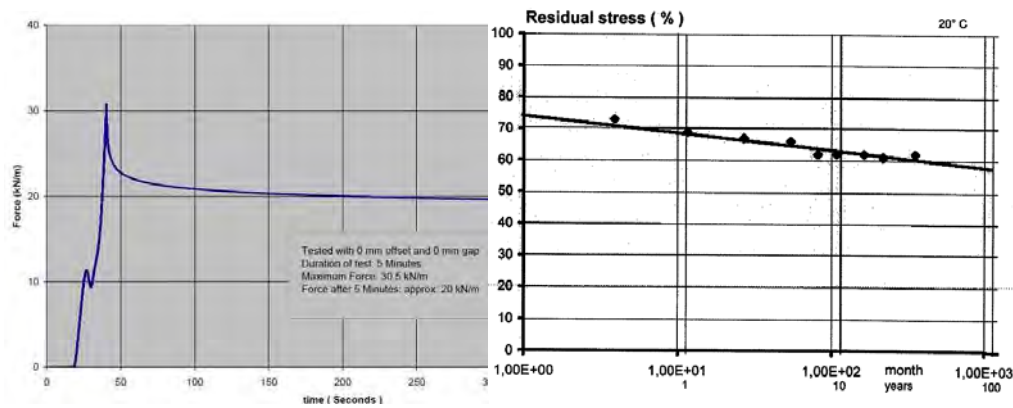Rubber quality is another important aspect of the gaskets. The rubber compound EPDM has proven to be technically and economically favourable for use in compressive sealing gaskets. It is chemically stable enough to withstand deterioration and reaction with other materials: e.g. concrete, grease or various compositions of groundwater [38]. EPDM also shows excellent resistance to weathering and heat aging [31].

4.2.3 GROOVE DESIGN

Groove geometry depends on the gasket that is used; depth and angle of the flanks must be in line with gasket geometry. The angle of the flank of the groove must be greater than 90°C with its base to allow for proper demoulding of the segment.

Groove dimensions

Gasket systems are often placed on the extrados of the lining. Compression of the gaskets will lead to a reaction force of the concrete. The reaction force is directed at the base of the groove, but will also be distributed to the flanks of the groove leading to shear forces in the concrete. Corners of segments are often not reinforced due to requirements on minimum concrete cover. To avoid large stresses and thereby possible spalling of the corner of the segment the rule of thumb for groove depth is:

"The net profile area (rubber area of the cross section of the gasket) should be a couple of percentages smaller than the groove cross section" [38]

When applied correctly gaskets will have enough room to compress, hence cracking of the segment edges should be minimized in case the segments make full contact. Practical experiences however, have shown that cracking can still occur even if the rule of thumb is met [38]. An explanation for this is that even though the theoretical gasket compression is not 100%, pressure on the flanks does lead to failure of the concrete.

Forces on groove flanks

No standard widely accepted calculation method is in place at the time of this writing, but some general assumptions can be made. If it is assumed that the compressed gasket behaves like an incompressible fluid as the groove gets filled with rubber, the force exerted on the gasket leads to a hydrostatic pressure in the groove (figure 58).
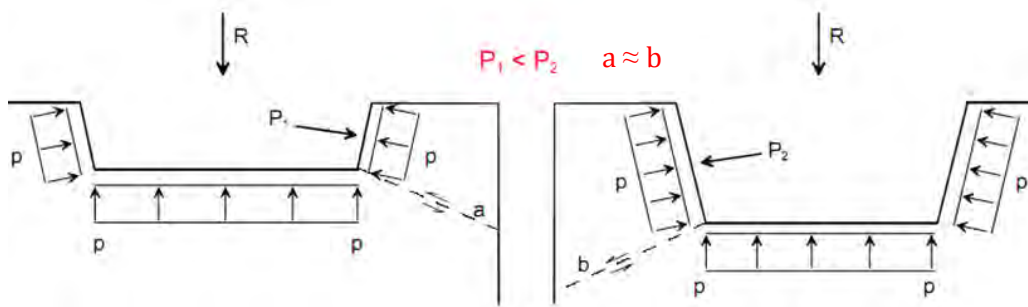
R   =   gasket force [kN/m]
p   =   hydrostatic pressure [kN/m²]
P_1 =   force on flank of groove 1 [kN/m]
P_2 =   force on flank of groove 2 [kN/m]
a   =   shear path groove 1
b   =   shear path groove 2

FIGURE 58: THEORETICAL DISTRIBUTION OF GASKET FORCE ON GROOVE BOTTOM AND FLANKS [38]

The hydrostatic pressure leads to forces perpendicular to the bottom and flanks of the groove. The groove depth and the force on the flanks are directly related; as the groove deepens, the resulting force on the flanks will increase. The path of shear failure however does not increase (significantly) as groove depth increases. Hence resisting forces of the concrete to the force exerted on the flank of the groove do not change. Deeper grooves are therefore more susceptible to gasket compression induced spalling.

4.2.4   INFLUENCE OF SEGMENT JOINT DESIGN ON THE GASKET SYSTEM

Most efforts in joint design are focused on transmitting stresses between segments. Several design philosophies can be used to design segment joints, but all philosophies need to cope with high stresses in unreinforced, spalling susceptible regions (e.g. corners and grooves).

Influence of pressure pad design

Joint designs with pressure pads up until the gasket groove (or flat joints) have a high risk of cracking of the segment edges. To avoid excessive loads in spalling susceptible regions, pressure pads can be placed at some distance from those regions. With respect to the gasket groove, two types of joint designs can be distinguished: a pressure pad up until the gasket groove (or flat joint) and a pressure pad that stops before the gasket groove (figure 59) [18].

Although the difference between the joint designs seems minimal, it severely affects the performance of the gasket. As gasket performance is greatly influenced by lateral support, an extra groove on the intrados of the segment will decrease performance of the gasket. The size of the gap created by the extra groove is an important parameter in performance decrease of the gasket. The performance decrease can be countered by using a stiffer gasket. However, this leads to higher reaction forces in the groove and hence, higher lateral forces [18].

Some joint designs use pressure pads to transfer stresses between segments. The pads may reach up to the groove providing lateral support for the gasket (situation 2 of figure 59), but gaskets are unsupported between the pads (situation 1 in figure 59).
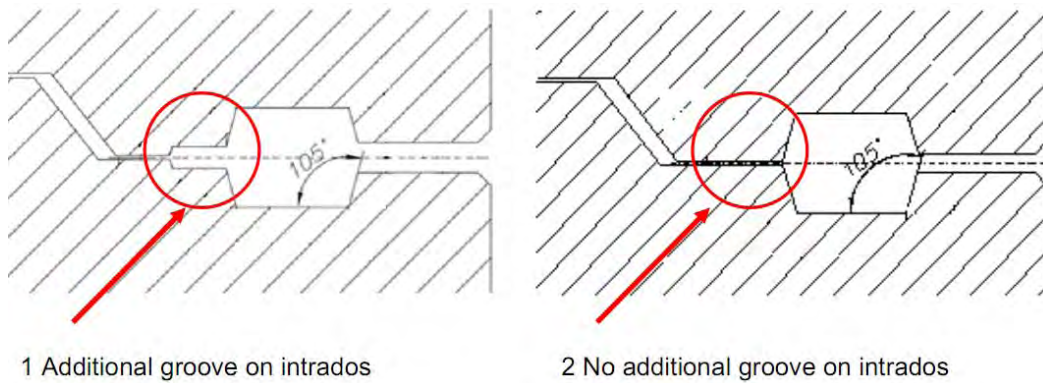
1 Additional groove on intrados   2 No additional groove on intrados

FIGURE 59: JOINT TYPES [18]

Segment linking method

Another aspect of joint design that influences the gasket system is the segment linking method. To be able to install the segments one by one during the erection process, they are bolted together and to the last build ring. The accuracy of placement, hence the accuracy of alignment of the gaskets, is influenced by the type of linking system used. Standard systems lead to gasket offsets in the range of 15mm, balljoint systems are able to reduce the offset to 5mm. Reduction of offset leads to the possibility of using smaller width, weaker gaskets [18]. Hence, the distance between groove and the extrados surface of the segment can decrease.

4.3   GASKET EXPERIMENT

To complement findings in this thesis an experiment was performed on the "Groene hart tunnel" gasket. This gasket has been used in the Hubertus tunnel (The Hague), and the Groene hart tunnel (between Leiderdorp and Hazerswoude), both in the Netherlands. The aim of the experiment was to obtain knowledge about the effects temperatures measured in the fire experiment have (described in chapter 3), on a gasket system that is in a compressive state. This section discusses the test setup, results and observations, and conclusions on the experiment. The full report on the experiment can be found in appendix B.

4.3.1   EXPERIMENT SETUP

The experiment

The aim of the experiment is to gain insight into the effects of high temperatures on compressed gaskets (the Hubertus tunnel design was used to find representative values for compression levels and gasket depth). The experiment therefore tests sealing performance indicators before and after heating. Sealing performance is influenced by the compression force on the gaskets, for this reason compression tests are performed on the gaskets at each state the samples encounter during the experiment. The states of the samples are:

- Virgin
- Relaxed by compression
- Relaxed by high temperatures and compression

The virgin state of the samples means that the samples have not been subjected to high temperatures or compression, it is comparable to the state of gaskets that have not been installed in the segment grooves. Relaxed samples have been in compression of 12mm [19] for 24 hours, their state can be compared to the state of gaskets that have been installed in the tunnel for one day. After compression relaxation the samples are heated according to 3 different schemes:

- 200°C for 2 hours (sample 1)
- 200°C for 2 hours + 100°C for 22 hours (sample 2)
- 100°C for 24 hours (sample 3)

The first scheme is based on two hours of fire loading on an unprotected segment joint. Gaskets in the Hubertus tunnel are installed at a depth of 325mm, at that depth temperatures will rise up to 220°C (according to the second fire test). The recordings in the 325mm gap of the second fire test are averaged to 200°C, as the oven was not suitable to follow a time-temperature path.

The second loading scheme subjects the gasket to 200°C as well, but incorporates a theoretical cooling phase of 22 hours at which a temperature of 100°C is maintained. This is a conservative loading scheme as temperatures in the real situation will have dropped to 60°C one day after the fire. But in the experiment, gaskets are directly cooled down to room temperature after 24hours while it takes two more days in the real situation.

The third scheme is based on a protected situation in which the heat does not penetrate the joint directly, but creates steam exhaust from the concrete of the segments. As the concrete heats up, steam is produced inside the concrete. The steam is expelled into the segment joint, leading to temperatures of 100°C at the gasket location, the cooling phase is incorporated in this test as well. The heat loading scheme represents an unprotected lining but without flame intrusion and radiative heat transfer.

Tests

Sample height is measured at each sample state and combined with the force-displacement diagram recorded by the compression test. The compression tests are performed on a servo controlled pressure apparatus at a displacement rate of 4mm/min.
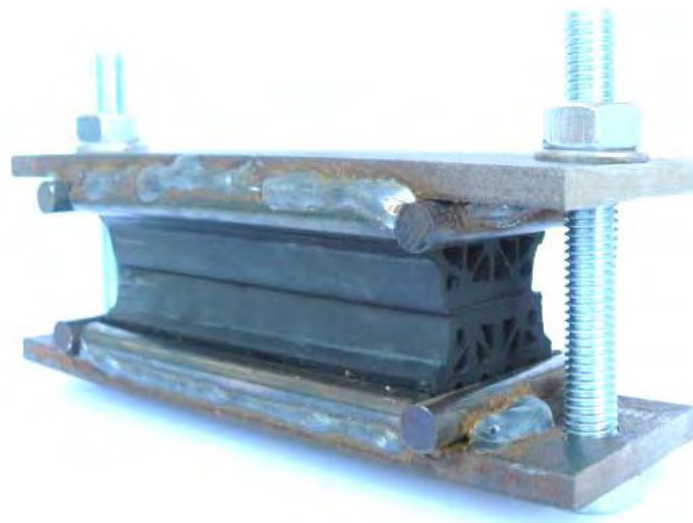

FIGURE 60: MOULDS AND GASKETS USED FOR THE TEST

During heating the samples are kept under fixed strain (12mm compression with respect to the virgin state), resembling the conditions in a segment joint. Compression performance is determined by groove geometry. To determine compression characteristics and to keep a fixed compression during heating and relaxation, moulds are used for the samples (figure 60). The moulds have small geometrical deviations, the moulds therefore are assigned to the samples.

To relate the results of the compression tests to possible changes in material properties, the material property shore A hardness was recorded by a Shoremeter for the virgin sample and the heated sample.

4.3.2   RESULTS AND OBSERVATIONS

Observations

When compressing the virgin and relaxed gaskets, three phases of compression could visually be distinguished: a fully intact gasket, collapse of the internal structure of the gasket and filling of the remaining air gaps.

The rubber did not disintegrate or catch fire during heating, but a rubbery smell was noticed. The gaskets that have been heated still exhibited rubbery behaviour, but did not recover from the imposed deformation during heating (figure 61). It was fixed in a state in which the internal structure of the gasket is collapsed. Closer inspection led to the conclusion that the internal structure was sticking together. The heated gaskets also exhibited the behaviour of sticking to each other and the moulds. Separation of the gaskets required moderate to high manual force.
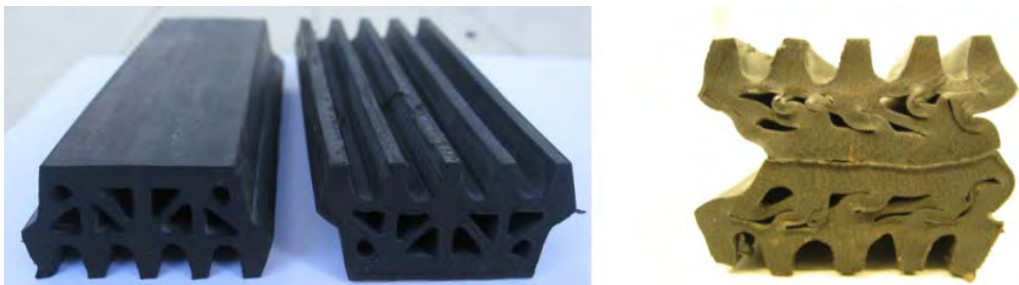
FIGURE 61: VIRGIN (LEFT) AND HEATED WHILE COMPRESSED SAMPLES (RIGHT)

Compression measurements

The compression characteristics of all samples show similar behaviour for their virgin and compression relaxed states (due to mould inaccuracies, the results cannot be interchanged for the different samples). Weak behaviour can be noticed between 6 and 12 mm compression, this behaviour coincides with the observation of collapse of the internal structure of the gaskets. The heated states of the samples do not show resemblance to the original behaviour, but both sample 1 and 2 maintain the compression force at the compression level they were heated in. Sample 3 shows weaker than original behaviour at that level of compression.

The compression characteristics for sample 1, 2 and 3 can be found in figure 62, figure 63 and figure 64 respectively. The green line represents the compression characteristics of the virgin state, the purple line of the relaxed state and the red line represents the heated and

cooled state. Compression forces decreased for the relaxed gaskets, but the gaskets still showed similar compression behaviour with respect to their virgin state.

FIGURE 62: FORCE-DISPLACEMENT DIAGRAM SAMPLE 1

FIGURE 63: FORCE-DISPLACEMENT DIAGRAM SAMPLE 2
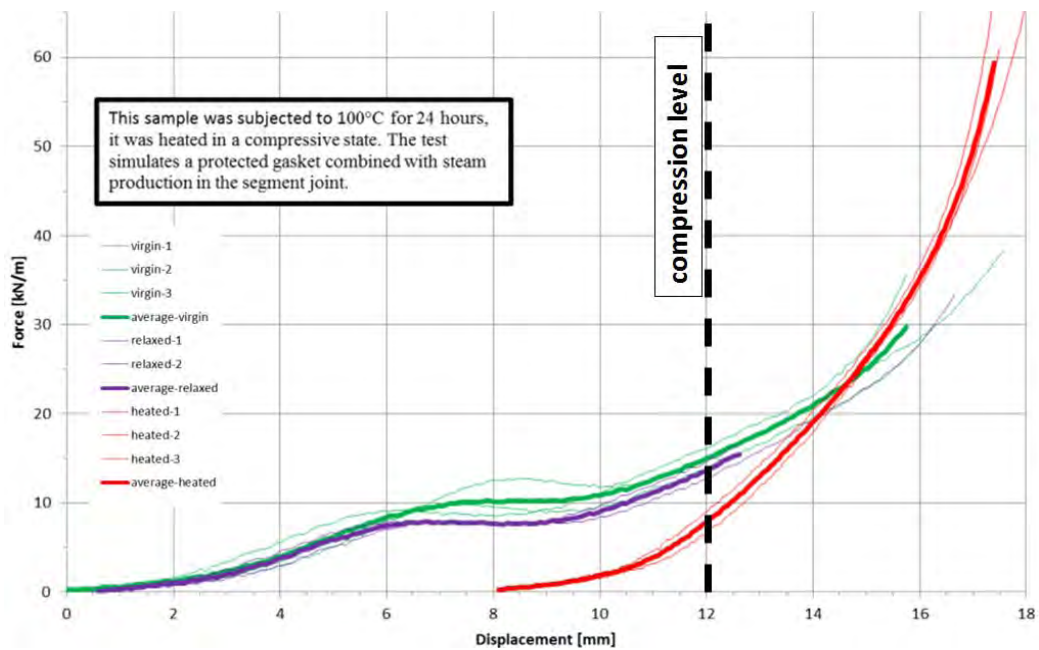
FIGURE 64: FORCE-DISPLACEMENT DIAGRAM SAMPLE 3

Hardness measurements

Shore A hardness measurements were very difficult to perform and may not represent the actual values. The reason for this is that flatness, thickness and size requirements on the test surface need to be met. To perform a test that leads to results that are comparable with each other, the same locations of the cross-section of the gasket were tested.

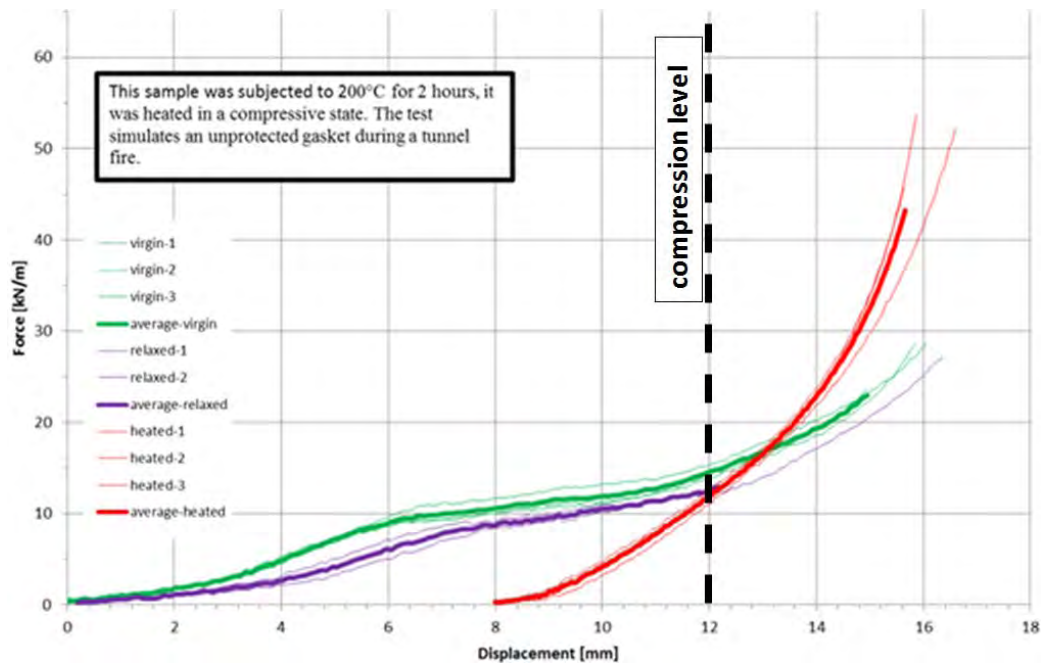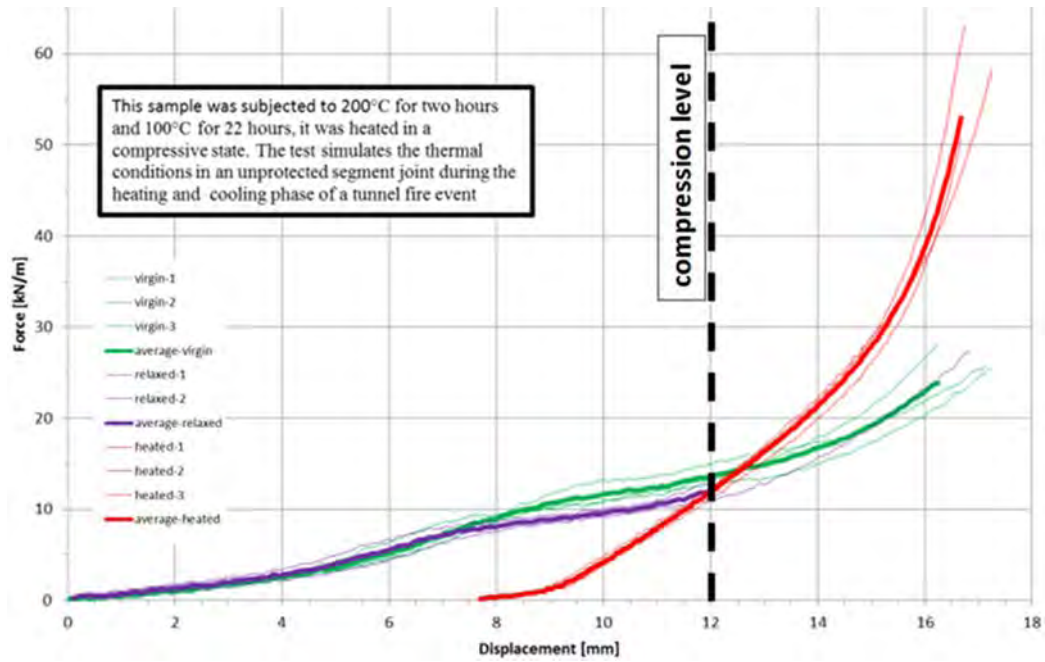The shore A hardness did not increase drastically from the virgin material (Shore A = 64). The sample that was subjected to 200°C for 2 hours did not change. The Shore A hardness of the sample that was heated at 200°C for 2 hours and at 100°C for 22 hours, increased to 66. The hardness of the sample that was heated at 100°C for 24 hours increased to 68.

4.3.3   CONCLUSIONS ON THE EXPERIMENT

The results of the experiment show that temporary high temperatures in the whole gasket system decreases the compression range of the gasket type that was tested. This leads to the fact that deviations in the gap width of segment joints cause enlarged compression force effects with respect to the original situation. If compression force is considered to be an indicating factor for water sealing capacity of the system, slight opening of the gaps will lead to failure of the gasket system.

The decreased compression range is the result of the sticking together of the collapsed internal structure of the gasket. This behaviour is not uncommon for peroxide cured EPDM rubbers [24].

Although the compression characteristics of the gasket are severely affected by temperatures of 100°C and higher, the gasket does not disintegrate and remains intact. The gaskets themselves are also sticking together, hence a solid block of rubber is created that is stuck between the segments. Leakage will probably occur directly as a result of the fire and will certainly occur if relaxation of the rubber continues or if tunnel deformation occurs. The risk for soil erosion however, is negligible due to plugging effect of the block of rubber.

"What are the functions of the sealing gasket, how does it fulfil its functions and how is the performance affected by the conditions caused by the tunnel fire?"

Tunnels must be waterproof for most applications to minimize maintenance and ensure operating safety. Leaks may lead to erosion of soil around the tunnel, thereby creating an unsupported part of the ring and increasing the moments in the lining. Gaskets are very important to the structure of TBM driven tunnels.

Gasket systems provide water sealing by compression of the gaskets. Accuracy of segment installation, gap width and groove geometry influence water sealing capacity and compression characteristics. Segment joint and coupling design, and the workmanship of the erector crew therefore are important factors in gasket system performance.

Gaskets are produced using the rubber extrusion method. To ensure a long lifetime, gaskets are commonly made of peroxide cured EPDM rubber; a rubber with excellent heat aging and stress relaxation performance. The rate of stress relaxation is temperature dependent.

The experiment on heated gaskets has shown that a commonly used gasket type will attain a permanent deformation when it is heated in a compressive state up to temperatures of 100°C and higher for a longer period in time. The permanent deformation is not the result of relaxation processes, but of parts of the internal structure sticking together. Compression characteristics of the gasket will be affected as it is fixed in a state in which the internal structure of the gasket has collapsed. The test also showed that the material of the gasket remains intact (although it behaves stiffer), and that the gaskets themselves also stick together.

As a result of the sticking behaviour, the effect of thermally induced stress relaxation could not be measured. The sticking behaviour of the gaskets is the result of an incomplete vulcanization process at the surfaces of the rubber. Peroxide cured EPDM rubbers tend to show this behaviour, sulphur cured EPDM rubbers do not [24].

The experiment does not fully resemble the situation occurring at gaskets in tunnels. Gaskets in tunnels are surrounded by concrete, water and air. Only a small portion of the gasket surface is subjected to high temperatures. This leads to temperature gradients in the gasket, of which the severity is unknown. Temperature gradients cause part of the gasket possibly to be unaffected while other parts show permanent deformation. High temperatures remain at the gasket for several hours, it can therefore be assumed that a large portion of the gasket is affected by the fire in the tunnel. The water seal of the gasket system therefore cannot be guaranteed. The risk of erosion however is negligible due to the rubber plug that remains between the segment grooves.

Even if the tunnel does not show leakage at the time of repair works, the accelerated aging by high temperatures and the high probability of tunnel deformations leads to the result that the water seal cannot be guaranteed for the rest of the design lifetime.
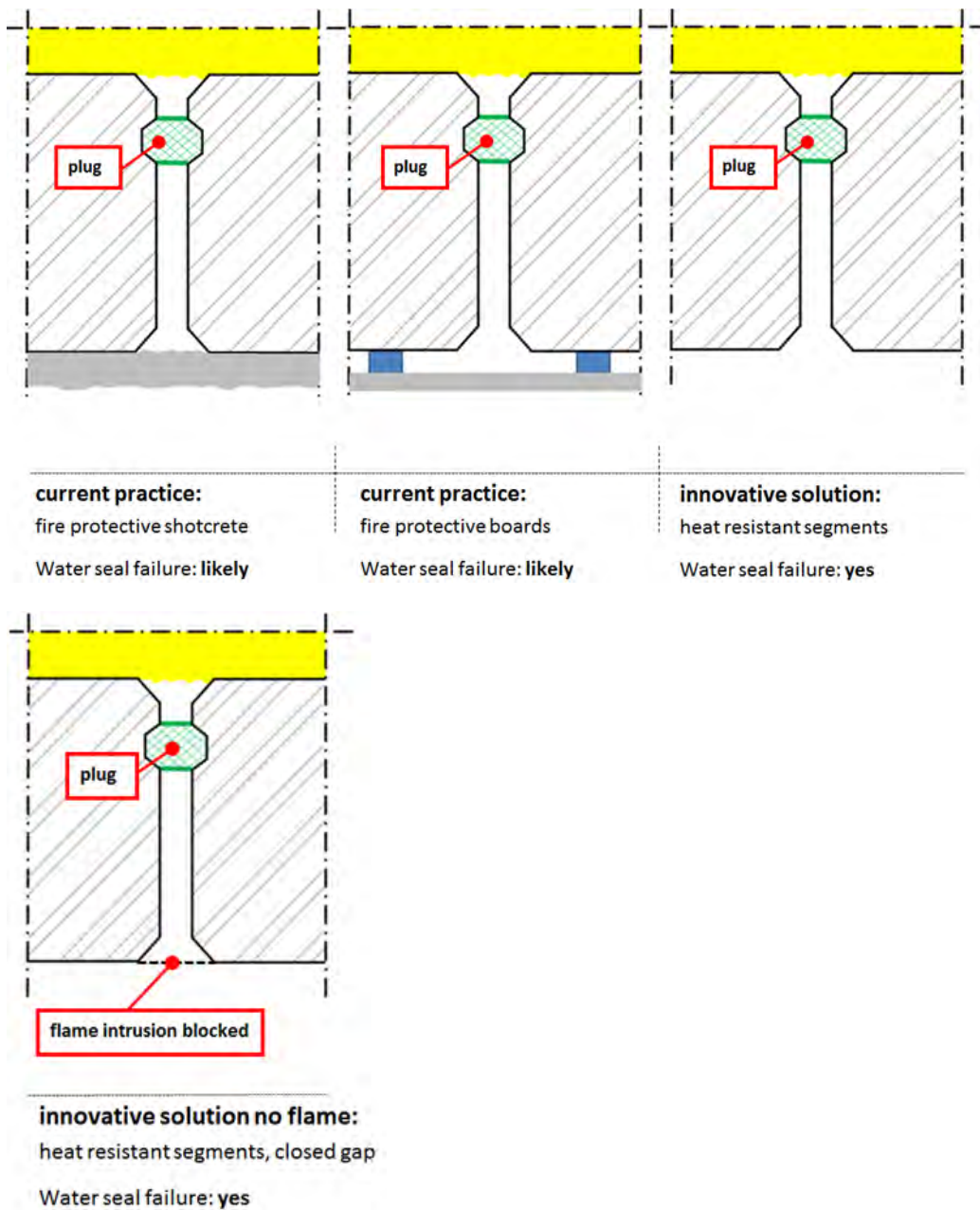
FIGURE 65: WATER SEAL PERFORMANCE OF CONFIGURATIONS

The results of the experiment indicate that water seal is not guaranteed for gasket systems that have been heated at 100°C for 24hours, or at 200°C for 2hours. This means that the water seal of gaskets systems in innovatively protected linings cannot be guaranteed, even if the system is shielded from radiation. As the failure of the gasket system occurs at 100°C, it is very likely that conventionally protected linings face the same problem. More research should be performed on this topic, as it is unknown how long the 100°C temperatures will remain at the gasket areas in conventionally protected linings. Nor is it known what the effects of shorter durations of 100°C temperatures are.

CHAPTER 5:

MEASURES TO ENSURE THE WATER SEAL

The objective of this chapter is to answer the fourth: "What measures can be taken to ensure the water sealing function of the lining?" and the fifth research question: "How do the measures compare to the current practice?". The fourth research question will be discussed in section 5.1. An assessment is made of the effectiveness of different measures that can be taken to ensure the water seal. Section 5.2 will discuss and compare the characteristics of the measures and answers the fifth research question. Finally, section 5.3 will elaborate on the conclusions on the fourth and fifth research question.

5.1   MEASURES TO ENSURE THE WATER SEAL

This section aims to answer the fourth research question. As the conclusions in chapter 4 show that soil erosion is hindered by the gasket (hence risk of lining instability due to soil erosion becomes negligible), the measures to ensure the water sealing function can be divided into two categories: preventive and corrective. Both types of measures are discussed in this section.

5.1.1   PREVENTIVE MEASURES

Preventive measures need to be installed before the tunnel is in operation. The aim of preventive measures is to prevent failure of the water seal in any case. These measures can be divided into three categories: protection, alteration of the gasket and a secondary water seal. The current practice also is a preventive measure.

Current practice: fire protective cover
Both the shotcrete and board fire protective covers, are applied in a post-TBM construction phase. As it is a cover, the internal diameter of the tunnel decreases, this results in the need to increase the tunnel diameter to maintain the profile of free space of the road. Numerous tunnel linings have been protected by the fire protective shotcrete, and board covering method (figure 66). Developments in the shotcrete cover have led to a robotic application process that can be managed relatively well and has consistent quality production. To fire proof a large tunnel with fire protective shotcrete however, still takes several weeks. Installation of fire protective boards is a comprehensive process as well.

Both the board method as the shotcrete method prevent flames from intruding the segment joint. Heat transfer by radiation from an intruding flame is therefore excluded. But the fire protective covers are designed to prevent the concrete surface from reaching temperatures higher than 380°C. Hence 100°C steam will be expelled into the segment joint by the concrete surrounding it.
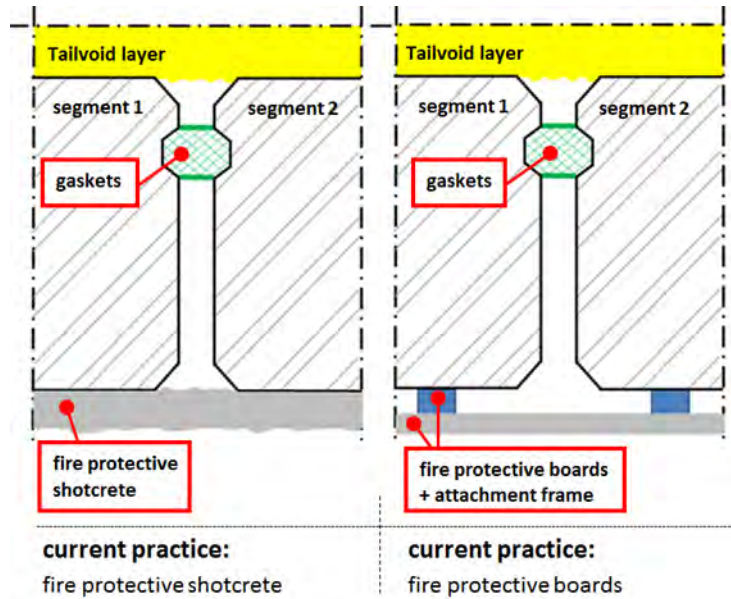
FIGURE 66: CONVENTIONAL FIRE PROTECTION

Protection of the gasket

A way to copy the effects of the current practice of fire protection to the innovative solution, is to protect the gasket from the direct heat of the fire. This can be achieved by shielding or closing the segment joint. By doing this, flames will not intrude the gap and radiative heat transfer to the gasket is blocked. Segment joint design leaves a possibility to block flames by introducing a heat resistant seal at the intrados of the segment (figure 67).
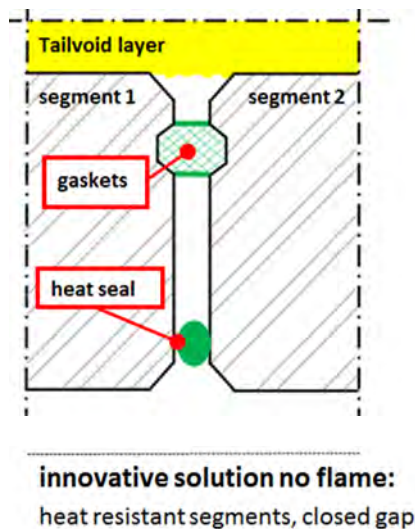
FIGURE 67: PROTECTED GASKET

The most efficient place to install the protective seal is on the intrados of, and directly next to the pressure pad. At this location, gap width deviations are small and the surrounding concrete will lead to a cooling effect. Some gaps should be left in the seal to allow for steam dissipation.

Two methods can be used to install the seal: pre-, and post-TBM. The post-TBM method requires the seal to be installed with the segments in place. Installation can be done by either injecting a thermosetting resin or by pressing a compressive heat resistant profile

between the segments. The seal of the pre-TBM method can be installed the same way as the water sealing gaskets. It also needs to be compressive and thermosetting, and the reaction force should be limited to avoid concrete spalling.

The material of the seal needs to be compressible to be able to function in a range of compressions. A large compression set is not a problem, as long as the material provides sufficient reaction force to stay in place. High reaction forces however should be avoided, as it may induce spalling. More research should be performed on suitable materials.

Just like installing sealing gaskets, installation of the heat sealing profile can take place when the segments are stored. The labour involved will be comparable to the labour needed to install the sealing gaskets. The heat sealing profile also risks being rolled up when the segments are installed. Friction between the heat seals must therefore be minimized to ensure protection. Once installed, it is difficult to check for flaws. It is however important that steam can still escape the segment joint. Small flaws in the heat seal are therefore acceptable.

Alteration of the gasket

Rubber is a very versatile product, compounds and properties can be adjusted to the specific needs of the application. However, performance increase in one property will lead to a performance decrease of another property. An example of this is the difference between EPDM and Fluor Carbon rubber (FKM), both rubbers can be used for sealing. FKM has excellent properties with respect to heat and flame resistance, but also has insufficient relaxation behaviour to be used in TBM driven tunnels (100 year performance requirement). Whereas EPDM has excellent relaxation properties but performs only moderately with respect to heat and flame resistance. Furthermore, FKM is 20 times more expensive than EPDM [13]. As relaxation performance and cost-efficiency are important aspect of gaskets in TBM driven tunnels, EPDM seems the most suitable rubber.

The decrease in gasket performance is the result of parts of the internal structure sticking together, the peroxide curing method is the reason for the sticking behaviour [24]. To counter this problem, a slower, more expensive sulphur curing system can be used instead (figure 68). Unfortunately, relaxation performance and heat resistance of the rubber decrease by using this system. More research should be performed on suitable compounds.

Alternative gaskets can be installed the same way as conventional gaskets. The gaskets may be weaker or more brittle, but the process essentially is the same.
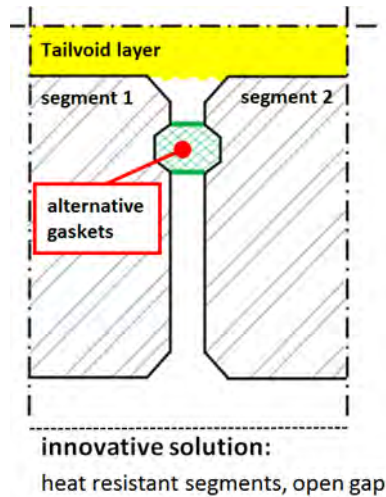
FIGURE 68: ALTERATION OF THE GASKET

Secondary water seal

Another way to prevent the water seal from failing, is to install a redundant water seal. TBM driven tunnels have a tailvoid layer between the soil and the extrados of the lining (figure 69). In the current practice the tailvoid injection layer only fulfils a lining supporting function, it is not designed as a water seal for the tunnel. If the injection process can be controlled and a minimum layer thickness can be maintained, it should be possible to alter the material properties of the mortar to provide a water sealing layer. This layer will function in addition to the gasket system (figure 70).

FIGURE 69: LAYER OF TAILVOID MORTAR (GROUT) [3]

To create a water sealing layer, the permeability of the tailvoid layer should be sufficiently low. The tailvoid layer should be able to cope with multiple bars of pressure difference (project specific), and should be flexible enough to avoid cracks induced by tunnel deformation.

Installation of the secondary water seal does not require additional materials, it essentially is a choice for a low permeability tailvoid injection material. An important factor in creating a secondary water seal with tailvoid injection, is the dispersion of the material. Mortar is injected into the tailvoid at several locations, it is important that all segment joints are covered, a minimum layer thickness is maintained, and the composition of the material is

constant. At the time of this writing injection technology has not advanced far enough to ensure these factors, nor have the methods to check injection layer thickness and consistency.
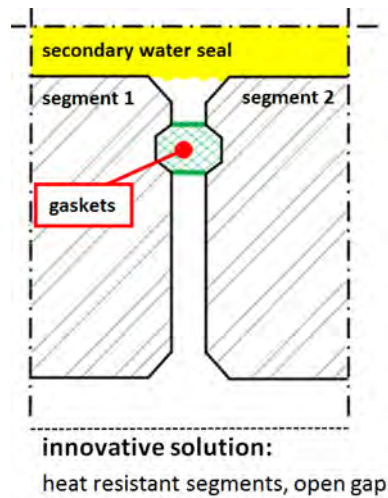
FIGURE 70: SECONDARY WATER SEAL

5.1.2 CORRECTIVE MEASURES

The corrective measures solution does not change the design of a lining with heat resistant segments (figure 71). The solution anticipates on failure of the water seal in case of fire. A large tunnel fire is a radical event to the exploitation of a tunnel. Repair works will always be necessary and repair work intensity will increase if tunnels are constructed without a fire protective cover. TBM driven tunnels constructed with heat resistant segments may show leakage and a considerable part of the lining will be affected by the fire. Soil erosion however, will not occur or is very limited. The structural integrity of the tunnel will therefore not be endangered by the failure of the gasket system. Corrective measures on sealing the lining can therefore be taken.

After a fire has occurred, the degraded concrete needs to be removed. To prevent deterioration of the load bearing structure of the tunnel during a second fire, the remaining lining should be covered by some sort of fire protection. Shotcrete can be altered to become heat resistant the same way as conventional concrete; by adding pp-fibres to the mix and creating a thermally well balanced mix.

Before the shotcrete can be applied, the water seal should be mitigated. Leak locations can relatively easily be determined as it are the segment joints. To avoid water pressure build up behind the shotcrete layer, the segment joints should either be sealed or drained before the shotcrete is applied. This will be a difficult task for severe leaks. More research should be performed on this topic.

FIGURE 71: SITUATION BEFORE CORRECTIVE MEASURES

5.2   COMPARISON OF THE MEASURES

The previous section discussed the measures that can be taken to ensure the water sealing function of the lining. This section aims to answer the fifth and final research question by comparing the measures to the current practice (fire protective shotcrete or boards). Comparison is based on three events: installation of the measure, effectiveness during a fire, and repair works after the fire. As installation of the preven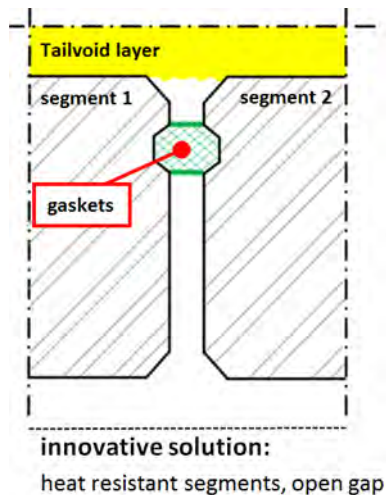tive measures is already discussed in 5.1.1, this section discusses the effectiveness of the preventive measures, and repair works and corrective measures. The section concludes with a side by side comparison of the measures.

5.2.1   EFFECTIVENESS OF PREVENTIVE MEASURES

The efforts that are put into installing the preventive measures should be effective in the event of a fire. Based on the knowledge about the reaction of the rubber gasket to different temperatures (chapter 3 and 4), effects of the measures on the water seal are estimated.

Current practice
Covering the segments and their joints by a layer of fire protective shotcrete or boards leads to a slower temperature increase at the concrete-fire protective cover interface. When fire protective covers are designed according to the Dutch RWS guidelines, temperatures do reach 380°C at the interface. This means that a portion of the concrete segment reaches temperatures above 100°C, and hence steam will be produced and exhausted into the segment joint. Temperatures at the gasket will therefore increase to 100°C, albeit for a shorter period in time than for the protected gasket measure. It is unknown for how long the temperatures will remain around and above 100°C, nor what the effects will be. But it seems likely that the water seal will fail for this preventive measure. More research should be performed on this topic.

Protected gasket
Although the gasket is protected from the direct heat of the tunnel fire, the face of the concrete is not. Temperatures in the concrete therefore rise quickly (compared to the covered situation) and steam production will start earlier than for the covered situation.

After the fire has stopped, the temperatures remain high. The cooling period is comparable to the cooling period of unprotected gaskets. The heat tests on compressed gaskets (appendix B) have shown that gasket functionality is severely impaired by these type of conditions. Although temperature gradients exist in the gasket that may lead to part of the gasket being unaffected, the water seal cannot be guaranteed by this measure.

Altered gasket

The altered gasket measure causes the gasket system to be directly exposed to the heat of the tunnel fire. The sulphur vulcanized EPDM rubber does not exhibit sticking behaviour, hence the inner structure will not be fixated in the way it has collapsed. The gasket will therefore maintain its compression force, decreasing the probability of direct leakage. Sulphur cured EPDM rubbers however, exhibit more and faster relaxation than their peroxide cured counterparts. They also show a decreased resistance to thermal loading. Long term performance therefore cannot be guaranteed (and is even questionable for gaskets that are not exposed to thermal loading) and delayed leakage is to be expected.

Secondary water seal

At the time of this writing, cement rich tailvoid injections are used near TBM start/exit shafts and cross links to limit the flow of water to those areas. At the time of this writing tailvoid mortars are not yet designed to form a secondary water seal. If injection technology advances and can guarantee the dispersion and layer thickness of the tailvoid injection, the water seal of the lining will not be affected by the fire unless the thermally induced deformation becomes too large and creates cracks in the injection layer. But at the time of this writing the solution is not yet feasible.

5.2.2   REPAIR WORKS AND CORRECTIVE MEASURES

The situation of an unprotected heat resisting lining leads to the problem that a considerable part of the concrete segment degrades due to fire. After the fire has stopped and the tunnel is cleared from debris, the repair works start. First, the degraded concrete needs to be removed from the lining. Then, in some cases the water seal must be restored or replaced. After that, the healthy lining should be covered with a fire protective cover or heat resistant concrete. The extend of work of the corrective measures varies with the severity of the leak and the area that is affected by the fire.

Leak severity

Leak severity is of great importance to the feasibility of the repair works; severe leaks lead to a difficult and unsafe work environment and more troublesome seal restoration works. Leak severity is mostly determined by the pressure head and the permeability of the soil and tailvoid injection layer. It can be approximated by calculations.

The calculations performed on leak severity represent leakage without the plugging effect of the deformed gasket. The effect of the plug is negligible for low discharges, but will have an effect on high discharges. The large pressure difference between the extrados and the intrados of the gasket causes the gasket to be pushed towards the intrados of the gasket groove, sealing the gap between gasket and concrete and limiting flow of water.

It is assumed that erosion will not take place, water entering the gap can flow freely (is not hindered by the gasket), and the pressure head at the boundary of the tailvoid injection layer with the soil is constant. Based on these assumptions a simple assessment of the leak

severity can be made for a stationary situation. The pressure distribution, a result of a spatial difference in pressure heads, can be approximated using the finite differences method. Microsoft excel was used to approximate the pressure distribution in a 2-dimensional stationary situation as a result of various pressure heads [1]. The tailvoid layer thickness was set to 100mm, the width of the gap was 10mm. The distance between the joints was set to be 1m, the error margin for the computations was set to 0,005m pressure head. The results were used to compute the corresponding discharge of a meter segment joint for different values of permeability. The results are presented in figure 72.
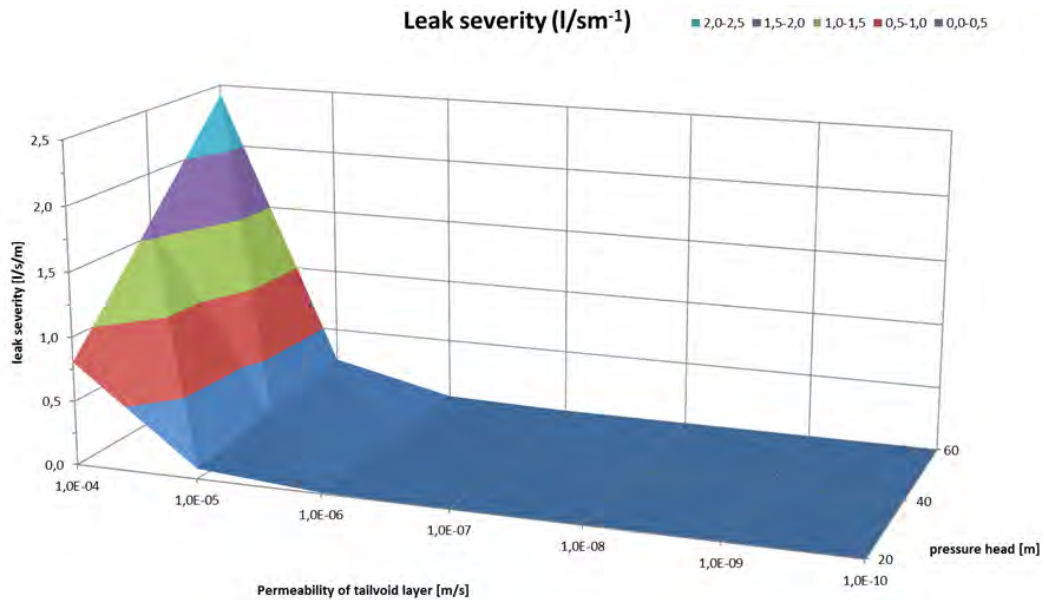
FIGURE 72: LEAK SEVERITY AS A FUNCTION OF PRESSURE HEAD AND PERMEABILITY

As can be seen in figure 72, leak severity is negligible for a permeability at and below 1×10^{-5}. It however increases significantly at higher permeability values. In table 9 the permeability of several soil types and construction materials is presented. Fast draining mortars are designed to have a high permeability, leaks will be more severe for those types of mortars than for cement-rich and two-component mortars.

permeability	materials			soils		
10^{-2}	fast draining grouts (estimated)					
10^{-3}				sand		
10^{-4}	cementious grouts (estimated)					
10^{-5}						
10^{-6}			cast concrete			silt
10^{-7}	2-component grouts (estimated, no cracks)					
10^{-8}				clay		
10^{-9}						
10^{-10}						

TABLE 9: PERMEABILITY OF CONSTRUCTION MATERIALS AND SOILS

Type of water seal failure

Two types of seal failure can be distinguished: direct failure and delayed failure. The gasket is designed to ensure sealing performance for a long period in time, usually 100 years. During that time seal performance will decrease linearly with log time. Thermal agitation

accelerates the aging process and may lead to failure to provide a water seal for the design lifetime. Joints with gasket systems that are thermally severely agitated should be provided with an additional seal system to prevent failure to meet the design lifetime. Gaskets that failed during or directly after the fire will leak. These leaks should be mitigated before restoring the lining, more research is required on this topic.

5.2.3 COMPARISON OF THE MEASURES

The measures and the current practice differ from each other at certain areas. The information given in the previous subsections is combined in table 10. A comparison is made on basis of installation of the measure, effectiveness during a fire and repair works on the lining.

	Current practice	Protected gasket	Altered gasket	Secondary seal	Corrective measures
Installation of measure					
Experience with system	excellent	good	excellent	none	-
Project phase of application	post-TBM	pre-TBM	pre-TBM	TBM	-
Application time frame	weeks	pre: more preparation post:	no additional time	no additional time	-
Installation costs	high	low	little deviation	unknown	none
Increased diameter TBM?	yes	no	no	no	no
Maintenance costs	moderate	low	high	low	low
Quality control	good	good	good	low	-
Effect of fire on gasket					
Temperature during fire	100°C	100°C	>>100°C: gap dimension dependent	>>100°C: gap dimension dependent	>>100°C: gap dimension dependent
Length of cooling period (cooling to 60°C)	<<1 day	1 day	1 day	1 day	1 day
Direct leakage	likely	yes	no	no	yes
Delayed leakage	likely	yes	yes	no	yes
Repair works on lining					
Removal of degraded concrete	no	yes	yes	yes	yes
Hindrance by leakage	likely	yes	no	no	yes
Installation of preventive additional seal required?	likely	yes	yes	no	yes
Extent of repair works	fire size and leak severity dependent, less than unprotected situation	fire size and leak severity dependent	fire size dependent	fire size dependent	fire size and leak severity dependent
Repair risks	moderate	high	moderate	Low	high

TABLE 10: COMPARISON OF MEASURES

5.3 CONCLUSIONS

This chapter discussed research questions 4 and 5. Therefore, two conclusions are presented in this section.

Conclusion on research question 4

"What measures can be taken to ensure the water sealing function of the lining?"

The goal of research question 4 is to isolate types of measures that can be taken to ensure the water seal of the lining after a large fire has occurred. The fact that the risk of soil erosion is negligible, broadens the scope of ensuring the water sealing function of the lining from just preventive measures to preventive and corrective measures.

Three types of preventive measures are distinguished: protecting the gasket from the fire by closing the segment joint with a heat seal, altering the gasket material to prevent sticking behaviour, and using the tailvoid injection layer as secondary water seal. The current practice of fire protection also is a preventive measure.

The corrective measure option takes into account that water flow is hindered by the plugging effect of the deformed gasket. As degraded concrete needs to be removed (and replaced), restoring the water seal can be part of the repair works.
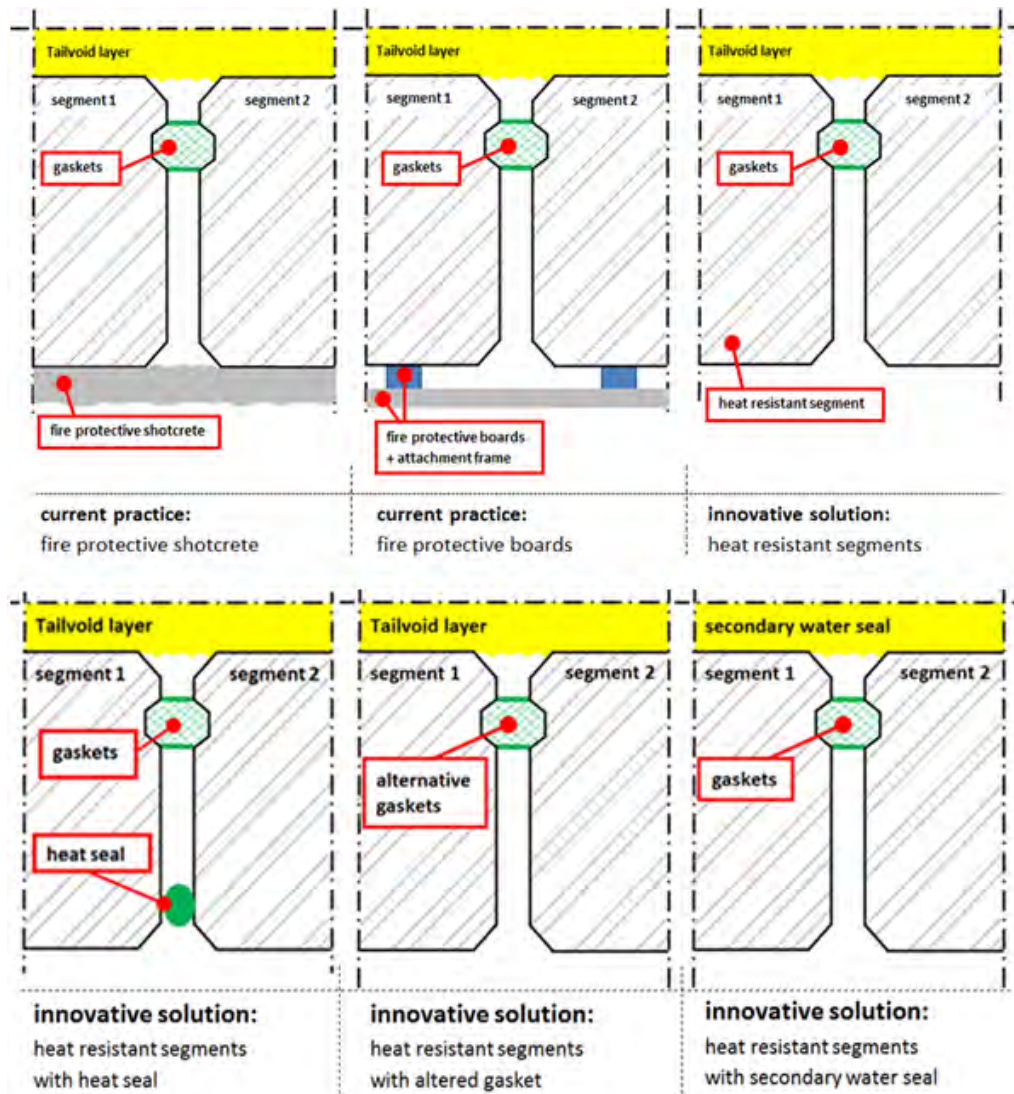

FIGURE 73: SOLUTIONS TO PREVENT WATER SEAL FAILURE

Conclusion on research question 5

"How do the measures compare to the current practice?"

The goal of research question 5 was to compare the different measures to the current practice of tunnel building and fire protection.

The current practice of fire protection leads to temperatures of 100°C at the gasket in case of fire. It is however unknown how long the temperatures remain high and what effect they have on gasket functionality. As the segments are protected, repair works on the lining will be minimal, it is likely thata water leak needs to be mitigated.

Closing the gap with a heat seal is an ineffective measure to protect the gasket. The concrete of the segment heats up quickly and starts to exhaust steam into the segment joint. Temperatures at the gasket therefore reach 100°C and are maintained for several hours. These conditions lead to permanent deformation of the gaskets. Hence leakage and mitigating measures on the water seal should be expected with this measure.

Altering the gasket material to prevent sticking behaviour of EPDM rubber leads to other curing systems than peroxide. Sulphur cured EPDM rubbers do not exhibit sticking behaviour and will therefore not fail in the same way as peroxide cured EPDM gaskets. Unfortunately, by changing the curing system from peroxide to sulphur, performance on heat and relaxation resistance decrease. The water seal may therefore be guaranteed at the time of fire, but will most probably fail in a later stage by accelerated aging and relaxation. A preventive secondary water seal should therefore be installed with the repair works on the lining.

The measure of an additional water seal in the form the tailvoid injection layer can be installed the same way the tailvoid is injected in the current practice. If it is possible to ensure layer thickness and consistency at the time of the fire, failure of the gasket will not pose a problem. To use the tailvoid injection layer solution requires more research on injection techniques, mortars, deformation behaviour of the tunnel and tailvoid injection quality control.

The suggested preventive measures cannot fully guarantee the water seal, or technology is not advanced enough to be implemented. The corrective measure option can be used if the tunnel remains stable after failure of the water seal. The high temperatures at the gasket lead to the forming of a rubber plug. The water pressure forces the rubber plug onto the flanks of the gasket groove, thereby preventing soil from entering the tunnel and limiting water discharge. The tunnel therefore does not lose structural integrity as a result of soil erosion. To restore the functionality of the tunnel, the leak should be mitigated before restoring the lining.

As it is likely that the water seal will fail in all preventive measures (except for the secondary water seal) as well as in the current practice of fire protection, the difference between the measures lies in the extensiveness of repair works. Repair works on the current practice, the protected gasket solution and the corrective measure solution are comparable: the water seal must be restored under circumstances of (severe) leakage before the lining can be restored. The altered gasket solution will most probably lead to delayed failure of the water seal, hence preventive sealing measures need to be taken during repair works. Repair works on the tunnel in case of the secondary water seal measure would not require any work on the water seal, but the solution is not feasible yet.

Repair works on the lining of the innovative solution need to be performed in all cases. It is questionable if the investment of a preventive measure installed in the entire tunnel will be comparable to the additional costs of leakage hinder during the repair works.

CHAPTER 6:

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents answers to the main research question: "In case of the use of heat resisting precast linings for TBM driven tunnels, how can the water seal be guaranteed and how do the solutions compare to the current practice?" by summarizing the conclusions on the sub research questions (also discussed in previous chapters). This chapter also provides recommendations on further research. Section 6.1 will present the conclusions on the sub research questions, section 6.2 will discuss the conclusion on the main research question and provides recommendations for further research on the topic.

6.1   CONCLUSIONS ON THE SUB RESEARCH QUESTIONS

The sub questions need to be answered to answer the main research question. This section presents the conclusions on the sub research questions.

6.1.1   RESEARCH QUESTION 1

"What is the current practice of passive fire protection in TBM driven tunnels and how do the innovative heat resistant segments change the existing system?"

The current practice of passive fire protection shields the structure from heat. The fire protection can be sprayed (fire protective shotcrete) or bolted (fire protective boards) onto the lining, thereby covering the entire structure. As concrete starts to degrade severely at temperatures above 380°C and spalls if temperature gradients are too high, the passive fire protection should reduce temperature development at the concrete surface. Temperature depends on the severity of the fire. The RWS design fire has proven to be normative for tunnel fires, countries around the world use the RWS design fire in combination with temperature requirements at the concrete face.

Segment thickness requirements in TBM driven tunnels are the result of the construction method, the tunnel does not require the thickness to be stable in the exploitation phase. For this reason part of the lining may safely degrade in case of fire. Heat resistant concrete focuses on suppressing thermally induced spalling, but does degrade under high temperatures. Linings with heat resistant segments therefore do not require additional fire protective covering: the heat resistant segments are directly exposed to the tunnel fire. Therefore sealing gaskets are also exposed due to the gaps that remain between the segments. The difference between the current practice and the innovative solution of heat resisting segments can be found in figure 74.
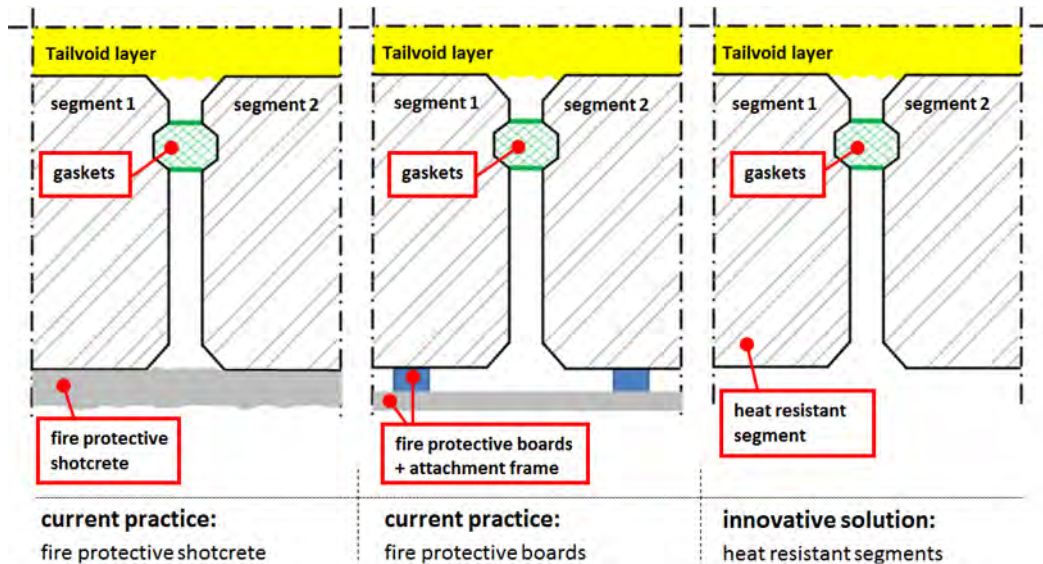
FIGURE 74: DIFFERENCE BETWEEN CURRENT PRACTICE AND HEAT RESISTING SEGMENTS

6.1.2   RESEARCH QUESTION 2

"How does a fire affect the conditions at the location of the sealing gasket in case innovative fire protection is used?"

Fire in a tunnel attracts cold air at road level and exhausts hot combustion gases at the ceiling of the tunnel. In a large fire (e.g. a RWS design fire), the temperature of the gases at the ceiling can reach values up to 1350°C. The gas flow is turbulent and intrudes segment joints. Fire experiments on gaps between concrete blocks have led to approximations of flame intrusions up to 170mm.

Gaskets are installed at a certain depth in the segment joints. Segment thicknesses used for TBM driven road tunnels lead to the fact that flames intruding the joint do not directly reach the gaskets. The main heat transfer mode from the flame to the gaskets is radiation. Convection is negligible as the concrete faces of the joint exhaust steam.

Radiative heat transfer is based on viewfactor relations, which in turn depends on sizes of, and distance between the receiving and emitting surface. Temperature development at the gasket therefore is dependent on flame intrusion, and joint dimensions. Due to the steam emission at the concrete faces of the joint temperatures will always reach 100°C if the concrete is hot enough. Fire experiments have shown that exposed gaskets can reach temperatures up to 200-290°C for common gap dimensions.

The current practice shields the lining from direct heat of the tunnel fire, but temperatures at the segment surface will still reach values of 380°C. For this reason concrete will produce steam and expel it into the segment joint. Temperatures at the gasket will therefore reach values of 100°C.

The dominant processes in the segment joint are presented in figure 75, for both the current practice as the innovative solution.
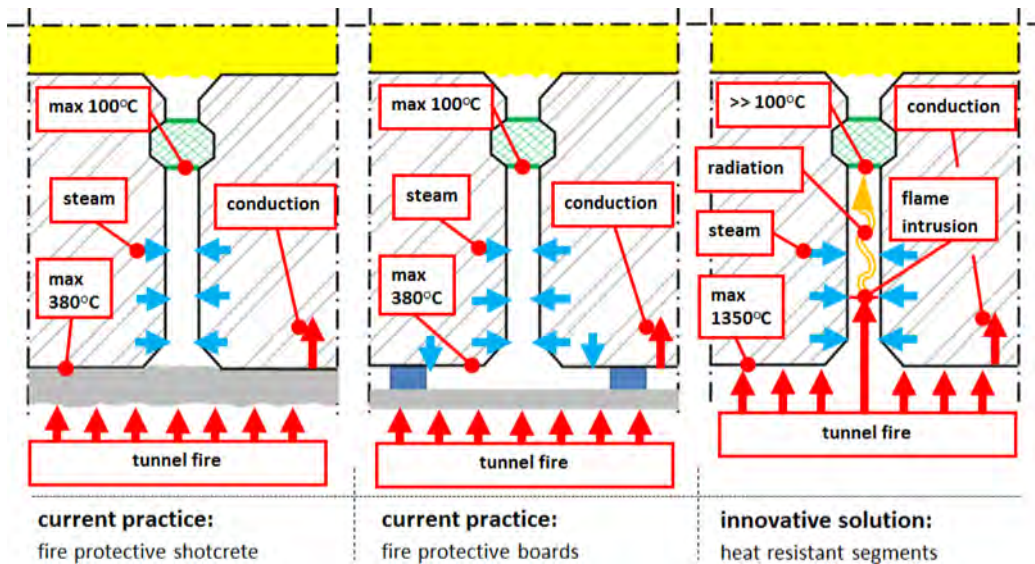
FIGURE 75: DOMINANT PROCESSES IN THE SEGMENT JOINT

6.1.3 RESEARCH QUESTION 3

"What are the functions of the sealing gasket, how does it fulfil its functions and how is the performance affected by the conditions caused by the tunnel fire?"

Sealing gaskets are installed between the segments to prevent water and soil leaking through the joints. The gaskets need to function in a range of compressions and offsets and may not introduce high stresses into the segments. The design lifetime of the gaskets must meet the design lifetime of the tunnel as they are a critical component of the structure.

Gaskets are commonly made of extruded, peroxide cured EPDM rubber. This type of rubber exhibits excellent behaviour with respect to thermal aging and relaxation, but tends to become sticky at its surfaces when heated.

The internal structure of a gasket needs to be collapsed to provide a sufficient compression force for the water seal, the internal structure of gaskets therefore is in a collapsed state when the tunnel fire occurs. As the gaskets heat up, the stickiness of the surfaces of the rubber is activated. This stickiness connects the internal structure at the locations where contact is made. As the gaskets cool down in the compressed state, they are fixated in the deformed state. The high temperatures also make the gaskets stick together.

The fixated state of the gasket decreases its ability to seal the joints if the segments move with respect of each other. The compression force can decrease as well. For this reason, the water sealing function of the gasket system cannot be guaranteed if the gaskets are exposed to temperatures of 100°C for a longer period in time. Due to the sticking behaviour of the rubber, thermally induced relaxation could not be assessed.

The rubber however does not degrade and remains intact, both for 100°C as for 200°C. Due to the pressure difference on the extra-, and intrados of the gasket system, the gasket system is forced to the intrados flank of the gasket grooves. This creates a seal that may not be watertight, but will make the risk of soil erosion negligible. The performance of the water seal is assessed for multiple situations (figure 76).
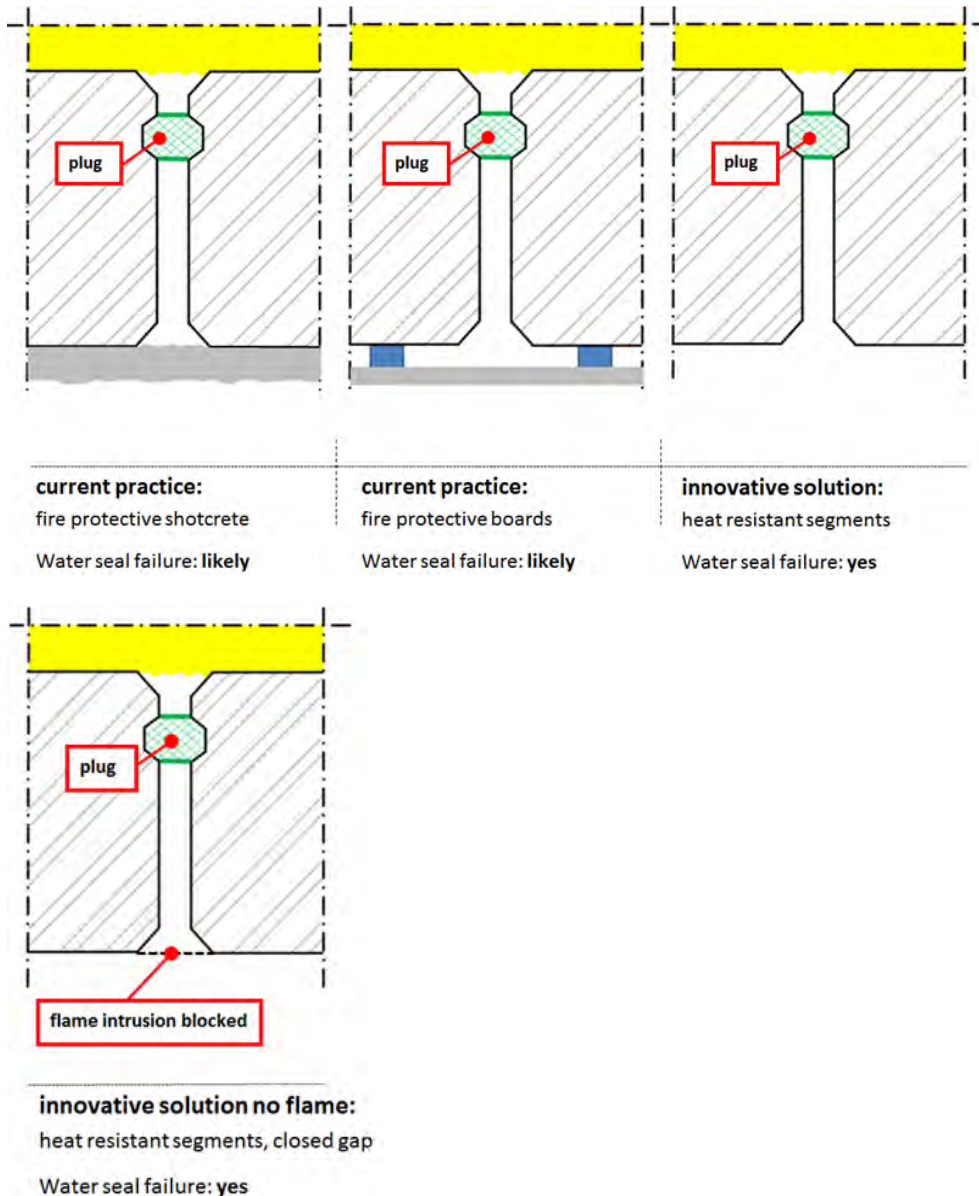
FIGURE 76: EFFECT OF HIGH TEMPERATURES AT DIFFERENT SITUATIONS

6.1.4   RESEARCH QUESTION 4

"What measures can be taken to ensure the water sealing function of the lining?"

As the risk of soil erosion is negligible, measures to ensure the water sealing function of the lining can be divided into two categories: preventive and corrective measures. Preventive measures aim to prevent the seal from failing, corrective measures aim to restore the water seal after failure has occurred.

Three types of preventive measures can be distinguished: protecting the gasket by shielding the segment joint from fire, altering the gasket material to prevent sticking behaviour, and using the tailvoid injection layer as a secondary water seal. These measures need to be taken at the construction stage of the tunnel. The current practice of shielding the entire structure from heat can be seen as a preventive measure as well (figure 77).

FIGURE 77: SOLUTIONS TO PREVENT WATER SEAL FAILURE

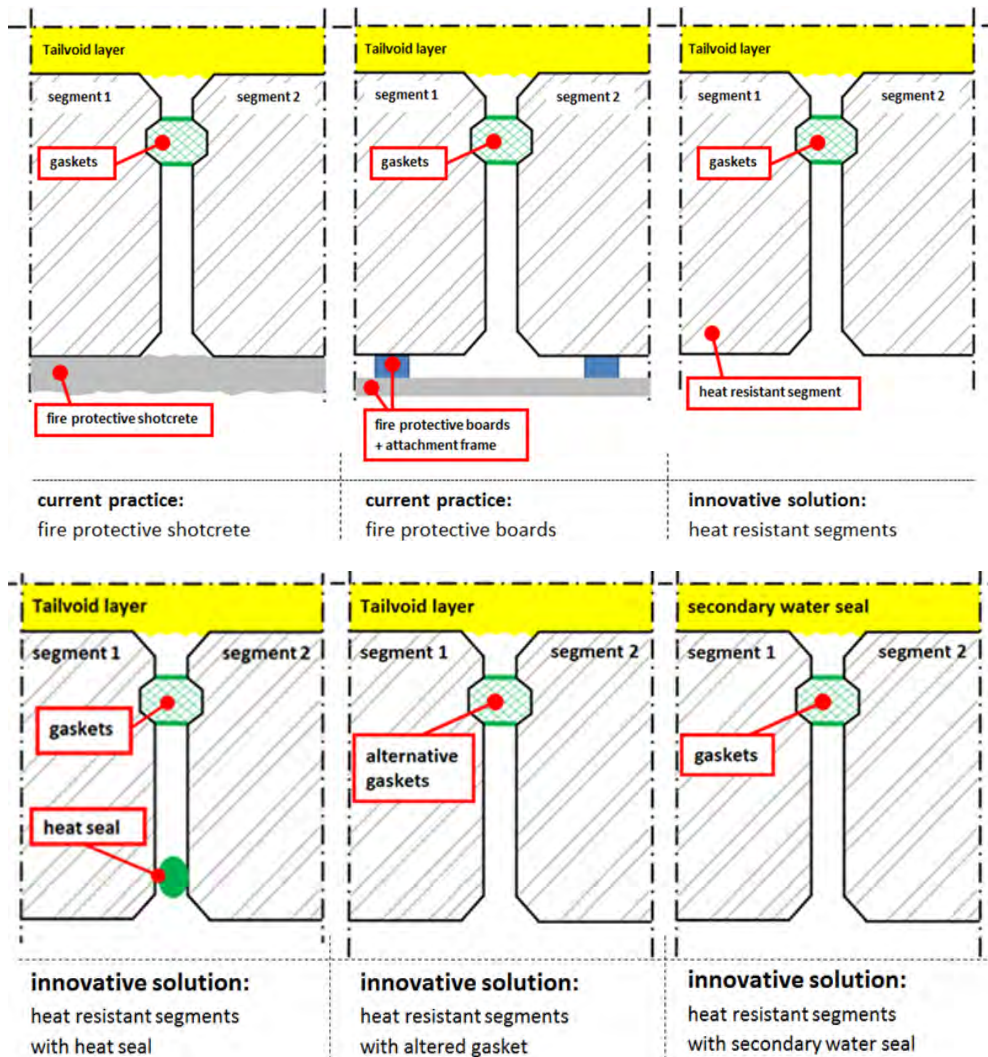As the tunnel may leak but soil erosion will not take place, the tunnel will remain stable. For this reason corrective measures are a viable option. The concrete of the tunnel lining is degraded to some extent. The degraded concrete needs to be removed and replaced to provide a new fire protective cover to the healthy part of the lining. In this process the water seal can be restored as well.

6.1.5   RESEARCH QUESTION 5

"How do the measures compare to the current practice?"

Comparisons can be made by three different stages: installation, effects during a fire and extensiveness of the repair works.

The current practice is an expensive and time consuming method to install, it will also increase the minimum tunnel diameter and thereby increase costs even further. But the lining will not degrade due to the fire and gaskets are shielded from direct contact with flames. Due to steam production of the segments, temperatures at the gasket will rise to 100°C. It is however, unknown for what period of time. Failure of the gasket system therefore seems likely, but cannot be proven. Repair works on the lining however are minimal and likely to be hindered by leakage.

The gaskets can be shielded from flames by installing a heat seal in the segment joints. Shielding the gasket from intruding flames by closing the segment joint seems like an effective measure as it resembles the current practice. But the unprotected concrete segments heat up more quickly than is the case in the current practice, hence steam production is started earlier and 100°C temperatures are maintained longer. Peroxide cured, extruded EPDM rubber gaskets show sticking behaviour at that type of time-temperature relations. Leakage is therefore to be expected directly, hindering repair works.

Alteration of the gasket to avoid sticking behaviour is possible by changing the peroxide curing system to a sulphur curing system. This however comes at a costs of material properties. Peroxide cured EPDM rubbers show excellent relaxation and heat resistance performance (this is the reason it is used in gaskets that need to perform for periods of 100 years). By changing the curing system to sulphur, heat resistance and relaxation performance decreases significantly. It is questionable if the sulphur cured EPDM rubber is able to function for 100 years, let alone after the event of heat loading. Direct failure therefore is less probable, but indirect failure due to accelerated aging and relaxation is to be expected. This type of gaskets will probably lead to high maintenance costs

Using the tailvoid injection layer as a secondary water seal is a promising, but (at the time of this writing) risky preventive measure. The layer should consist of a low permeable grout (maximum permeability $1x10^{-6}$ m/s), should be free of cracks, sufficiently dispersed to fill 100% of the tailvoid, and should have a minimum layer thickness. Tailvoid injection technology has not yet advanced far enough to ensure quality. If the factors could be ensured, failure of the gasket system will not lead to failure of the water seal and repair works would not be hindered by leakage.

The option of using corrective measures instead of preventive measures essentially means deliberately incorporating restoration of the water seal into the repair works. The post-fire repair works need to be performed in any case, if the leaks are mild this will not be a problem. If the leaks are severe, repair works are hindered and may require more time and resources, but are still feasible.

The difference between the measures lies in the type of failure; direct or delayed. Repair works on the protected gasket solution and the corrective measure solution are comparable: the water seal must be restored under circumstances of (severe) leakage before the lining can be restored. It is likely that the current practice will lead to a comparable situation. The altered gasket solution will most probably lead to a fire induced delayed failure of the water seal, hence preventive sealing measures need to be taken during repair works. Furthermore, failure of the water seal may also occur due to aging without elevated temperatures, leading to high maintenance costs. Repair works on the tunnel in case of the secondary water seal measure would not require any work on the water seal.

6.2   CONCLUSION ON THE MAIN RESEARCH QUESTION

This section presents the conclusion on the main research question and provides recommendations for further research.

6.2.1   CONCLUSION ON THE MAIN RESEARCH QUESTION

"In case of the use of heat resisting precast lining for TBM driven tunnels, how can the water seal be guaranteed and how do the solutions compare to the current practice?"

The main research question actually is a combination of sub research question 4 and 5. The conclusion of sub research question 4 provided four different types of measures to counter the problem. Research question 5 concludes that a large tunnel fire directly leads to leakage in the situation of application of protective or corrective measures, to delayed failure in case an alternative gasket material is used (failure may also occur without heat loading, leading to high maintenance costs), and that using the tailvoid injection layer as a reliable secondary water seal is technically not feasible yet.

The effects of a fire on the gasket in case of conventional fire protective covering on the tunnel lining are untested. The current practice of protecting the lining from high temperatures still leads to a large increase in temperature in the concrete (RWS guidelines: maximum 380°C at the surface of the segment). Therefore, the concrete will exhaust steam into the segment joint and temperatures at the gasket will amount to 100°C. It is, however, unknown how long those temperatures will remain at the gasket. An assessment of the performance of the gasket therefore cannot be made, but the assumption can be made that the water seal will fail as the gasket does come into contact with high temperatures.

In rationalised risk oriented approaches to the type of problem discussed in this thesis, preventive measures should only be taken in case their effects will lead to either a lower probability of failure, or lower consequences of failure itself. The implementation costs of the measure should also be lower than the product of the decrease of consequences with the probability of the event occurring.

The conventional approach of expensive implementation of fire protective covering is feasible from a risk point of view, as the structural integrity of tunnels built with conventional segments is severely endangered by high temperatures; without fire protective covering the tunnel will be lost in the event of a large fire, representing very high costs.

The implementation of heat resistant segments reduces the effects of a tunnel fire significantly: collapse of the lining will not occur due to heat loading. The effects a fire has in such a tunnel are: degradation of part of the lining and failure of the water seal (directly or delayed) without risk of soil erosion, in the influence zone of the fire. Therefore, the actual effects of a tunnel fire amount to removing and restoring the degraded part of the lining, combined with the restoration of the water seal (in case leaks occur).

The lining must be restored in all preventive and corrective measure situations. Therefore, the costs of implementation of preventive measures must be less than the product of the probability of failure with the costs of restoring the water seal (economic costs must be taken into consideration as well).

As the preventive measures have, or are likely to have no effect (protective solution, current practice), will most probablylead to maintenance issues in the entire tunnel (alternative gasket material), or are technically not yet feasible (impervious tailvoid injection layer), corrective measures are the most rational choice of ensuring the water seal of the lining. This conclusion is empowered by the fact that part of the tunnel will be influenced by the fire, hence corrective measures should be performed on part of the tunnel, and preventive measures have to be performed on the entire tunnel.

To provide a better future assessment of the problem, recommendations for further research have been made. The recommendations are presented according to the original research scheme of this thesis.

Fire and fire protection in tunnels

A lot of research has already been performed on fires in tunnels, resulting in time-temperature relations and design fires for building codes. However, temperature development at the gasket also depends on the turbulence inside the tunnel. More research should therefore be performed on the speed and direction of flames at the surface of the lining. This research should be performed for smaller fires (scenario's with just cars) and large fires like the RWS design fire.

The effect of tunnel fires on unprotected linings should be further researched. Although spalling can be suppressed, part of the lining will degrade and thermal stresses may cause deformation of the structure. This thesis bases the assumption of lining stability after a fire on a straightforward tunnel stability calculation. The amount and effect of lining degradation should be researched as well.

The gasket issue

The gasket issue is twofold: temperature development at the gasket and effect of the temperatures at the gasket.

Although the conclusions state that the water seal is likely to fail in the current practice, this has not been proven. More research should be performed on time-temperature relations at the gasket area in case the segment joint is covered by fire protective mortar or boards.

The most important aspect of temperature development at exposed gaskets has proven to be flame intrusion into the segment joint. Due to the lack of information on normative flame speeds and directions in the tunnel, flame intrusion could not be approximated. More research on flame intrusion should be performed based on earlier recommended research on flame direction and speed in tunnel fires. This research should also be performed on T-joints and flame directions perpendicular to the joints.

If the flame intrusion is known, the theoretical model of temperature development used in this thesis has proven to be reasonably accurate for the 11mm gaps (appendix D). The 11mm gap however is a relatively large gap for most segment joints. More research should be performed on other gap dimensions and configurations. The relation between heat transfer modes may shift as wall effects become more or less important.

Another important issue is the effect of a less severe fire scenario on the temperature development in the gap. The RWS design fire is based on a worst case scenario of which the probability of occurrence may be lower than for a smaller fire. Repair works on the water seal of the lining may be acceptable in case of a worst case scenario, but may be unacceptable to a more often occurring smaller fire. For this reason, more research should be performed on the scale and complexity of the repair works.

The theoretical and physical models that have been used to assess the temperature development at the gasket area assumed the gaps in the segment joints to be isolated from each other. In the real situation this often is not the case. In non-flat segment joints, small canals exist between the gaps due to the distance between the pressure pad and the gasket.

More research should be performed on the effects of these canals on the temperature development at the gaskets.

The effects of high temperatures on the gasket have not been modelled theoretically, but have been determined experimentally. The experiment was performed by heating the whole gasket system, whereas the gasket system is only partially heated in the real situation. Moreover the experiment was performed on one type of gasket that exhibited sticking behaviour. More research should be performed on other rubber compounds and gaskets, and the effect of partial heat loading on the gaskets. In case sticking behaviour does not occur, relaxation behaviour should be researched as well. The type of heat loading in the experiment was hot air, but in the real situation heat loading will occur by steam and radiation. Future experiments should use those types of heat loading.

Peroxide cured EPDM compounds exhibit sticking behaviour, it is unknown at what time-temperature relation this behaviour occurs. Peroxide cured EPDM rubbers are cost effective to manufacture and perform very well in heat resistance and stress relaxation. For this reason it is recommended to perform research on the time-temperature relations of sticking behaviour.

As sealing performance of the gaskets depends on reaction force, the conclusions on changes in sealing performance are based on loss of reaction force in the gasket. Actual decrease of sealing performance should be measured by a water seal test. To assess leak severity it is therefore recommended to perform more research on the actual water seal by water seal tests.

Solutions to the gasket issue
The tailvoid injection solution could be a very promising solution to prevent failure of the water seal. Even if the solution does not provide 100% seal, it may decrease the flow of water through the gaps significantly and may thereby simplify repair works. It is however unknown how to ensure sufficient dispersion of the injection to fill the tailvoid and if the layer remains intact during the lifetime of the tunnel. More research should be performed on these topics to be able to use the solution in practice.

Rubber is a material that can be altered to fit the needs of its purpose. Stress and temperature relaxation, and sticking behaviour are important parameters in the seal performance of the gaskets. The conclusion of the thesis is based on using a sulphur instead of peroxide cured EPDM rubber, but there may be methods to suppress the sticking behaviour of peroxide cured EPDM rubbers. For this reason more research should be performed on optimization of the rubber compound or the gasket itself.

Restoring the water seal of the lining means dealing with potential high flows, but certainly with high water pressures. More research should be performed on possibilities of restoring the water seal. Amount of work to be performed, and restoration of different types of leaks should be the topics of the research.

Comparison of solutions
The solutions are compared on basis of costs of implementation and effectiveness to reduce risk. To perform a proper risk analysis, the consequences and probability of occurrence of an event need to be known. At the time of this writing statistics on tunnel fires are limited, but the recently introduced EU legislation on tunnel safety in the trans-European road network aims to obtain statistics on road tunnel fires. These statistics may be useful to research on probability of occurrence of several tunnel fire scenario's.

To provide a proper comparison on the rationality of preventive measures, the investment costs of all preventive measures must be researched. More research should also be performed on the costs (time and money), of the repair works for the individual solutions. It is therefore important to know the type of work to be done and the size of the area that is affected by the fire. Although this is event and tunnel specific, an indication of the affected area is necessary to assess the consequences of the tunnel fire. The assessment should also be made for the current practice, as it is likely that repair works will go beyond repairing the fire protective cover.

REFERENCES

	Akhter, M.G., Ahmad, Z., Khan, K.A.	Excel based finite differences modeling of ground water flow Journal of Himalayan Earth Sciences Vol. 39, p49-53	2006
1			
2	Askeland, D.R.	The science and engineering of materials p 521	1990
3	Bezuijen, A.	Deltares Academy, March 2009, Shield tunnelling in soft soils, notes session E1	2009
4	Billmeyer, F.W. Jr.	Textbook of Polymer Science, third edition John Wiley & Sons, Inc. ISBN: 0-471-03196-8	1984
5	Blom, C.B.M.	Lecture notes CT3150 TU Delft: Concrete linings for shield driven tunnels	2006
6	Bossche, B.P. van den	Brandwerendbeton Cement Vol. 2008, issue 4, p42-46	2008
7	Breunese, A.	Lecture notes CT5131 - Fire safety design: Lecture 2B	2009
8	Clement, F.	Fire protection options for concrete tunnel linings Proceedings: Fourth international symposium on Tunnel safety and security Frankfurt am Main, Germany, March 17-19	2010
9	Combinatie Middelpaar Westerschelde v.o.f.	Website combinatie Middelpaar Westerschelde v.o.f. http://www.kmw.nl/index.php?t=p&ID=2	2010
10	Consortium Locorail	KiVINiria: Department TTOW Excursion to Liefkenshoek rail tunnel	2009
11	Cutnell, J.D., Johnson, K.W.	Physics, fifth edition Southern Illinois University at Carbondale John Wiley & Sons, Inc. ISBN: 0-471-39219-7	2001
12	DeWitt, Bergman, Lavine	Fundamentals of heat and mass transfer, sixth edition ISBN: 0-470-05554-5	2007
13	Elastomer Research Testing b.v.	http://www.ertbv.com	2010
14	Eurocode commission	NEN-EN 1992-1-2:2005	2005
15	European Thematic Network: Fire in Tunnels	ETN-FIT: Technical report part 1: Design fire scenarios	2007
16	Fletcher, E.A. et al.	Behaviour of concrete structures in fire Thermal science Vol. 11, Issue 2, p37-52	2007
17	Fraaij, A.L.A.	Lecture notes TU Delft: Plastics	2007
18	Gruber, Th.	International practices and technology in sealing precast tunnel linings ITA-AITES - World Tunnel Congress and 36th general assembly 14-20 Mai 2010, Vancouver, Canada	2010
19	Hubertus Tunnel Combinatie (HTC)	Design documents	2005
20	Ingason, H.	Design fires in tunnels Second international symposium Lausanne	2006

21	Khoury, G.A.	Effect of fire on concrete and concrete structures Progress in structural engineering and materials Vol. 2, Issue 4, p429-447	2000
22	Khoury, G.A.	Concrete spalling assessment methodologies and polypropylene fibre toxicity analysis in tunnel fires Structural concrete Vol. 9, Issue 1	2008
23	Khoury, G.A.	Polypropylene fibres in heated concrete part 2: pressure relief mechanisms and modelling criteria Magazine of concrete research Vol. 60, Issue 3, p189-204	2008
24	Kranenburg, J. van	Elastomer Research Testing b.v. http://www.ertbv.com	2010
25	Kronemeijer, J.	Talks with mr.Kronemeijer (concrete technology)	2009-2010
26	Litvinov, V.M., Prajna, P.	Spectroscopy of Rubbers and Rubbery materials, first edition Rapra Technology Limited ISBN: 1-85957-280-4	2002
27	Lönnermark, A., Ingason, H.	Gas temperature and radiation Large scale fire tests in the Runehamar tunnel	-
28	Mark, J.E., Erman, B., Eirich, F.R.	Science and technology of rubber, third edition Elsevier Academic press ISBN: 0-12-464786-3	2005
29	Meguid, M.A., Dang, H.K.	The effect of erosion voids on existing tunnel linings Tunnelling and Underground Space Technology Vol. 24, p278-286	2009
30	Multiple authors	Advances in Polymer science 152: Viscoelasticity, Atomistic models, Statistical Chemistry Springer-Verlag ISBN: 3-540-66735-0	2000
31	Multiple authors	Encyclopedia of Physical Science and Technology, 3rd edition, part: polymers Elsevier Science Ltd. ISBN: 978-0-12-227410-7	2001
32	Olffen, B.T.F. van	The behaviour of bored concrete tunnel linings under fire conditions M.Sc. Thesis Delft University of Technology	2004
33	PDT profiles	PDT profiles website http://www.pdt-profiles.com/pages/tunnelbau/tunnelbau_en.html	2010
34	Promatb.v.	Website Promatb.v. www.promat-tunnel.com	2010
35	Quaak, M.P.	Talks about construction experiences Botlekspoortunnel	2010
36	Rijkswaterstaat (Dutch ministry of public transportation)	VRC-Documents: Veiligheids richtlijnen deel C	2009
37	Rijkswaterstaat (Dutch ministry of public transportation)	ROBK: Richtlijnen voor het ontwerpen van betonnen Kunstwerken versie 6.1 Aanvullingen voor ondegrondse weginfrastructuur: wijzigingen tunnels	2009

38	Schurch, M.	Small But Important - Gaskets for Tunnel Segments ITA-AITES - International Symposium on Underground Excavation and Tunnelling 2-4 February 2006, Bangkok, Thailand	2006
39	Shuttleworth, P.	Fire protection of concrete tunnel linings Technical paper; written communication based on Rail Link Engineering tests for Channel Tunnel Rail Link U.K.	2002
40	Unknown author	Beton en hoge temperaturen Betoniek 1/19, Oktober	1971
41	Unknown author	Brand Betoniek Band 14, uitgave 16	2008
42	Verani, C., Ferrari, A.	Fire protection for new and existing underground structures Tunnel Vol. 7, p37-44	2009
43	Wolsink, G.M.	PC Templow 4.51	-
44	Zeiml, M., Lackner, R., Mang, H.A.	Experimental insight into spalling behaviour of concrete tunnel linings under fire loading ActaGeotechnica Vol. 3, p295-308	2008

APPENDICES

APPENDIX A: REPORT FIRE TEST

fire testing narrow gaps in concrete constructions

test to simulate temperature development between heat resistant concrete segments of a TBM driven tunnel in the event of a RWS design fire

Daan de Clippelaar

12-01-2011

This test is performed to complement findings in the MSc thesis of Daan de Clippelaar (2011, Delft University of Technology, Delft, The Netherlands). The subject of the thesis is: the functionality of the rubber gaskets used in TBM driven tunnels, in case of a RWS type design fire and the absence of a fire protective coating.

Index

1) Introduction

This report is about a test on the heat development in a gap between two concrete plates in case a fire exists near the plates. The interest in the heat development finds its origin in the TBM (Tunnel Boring Machine) method for tunnel construction. TBM driven tunnels are constructed in a modular way. Prefabricated concrete segments are connected inside the TBM, leaving narrow gaps in the construction. In order to keep the construction water sealed, the tunnel segments are equipped with compressive rubber sealing gaskets.

Concrete used for TBM driven tunnel segments is susceptible to thermal spalling. Hence it is customary to provide an additional heat protective lining to the construction. Placement of the additional lining however, is time and money consuming. Large cost and time savings can be achieved by omitting post-TBM phase constructed fire proofing measures.

Most developments in the field of unprotected segmental tunnel lining are concrete-technology based and focused on suppressing a phenomenon called explosive spalling. Reports on experimental fire tests show increasingly positive results in the use of pp-fibres in combination with thermally well balanced concrete mixtures. Various projects with this type of concrete have already been carried out. Among them are the DODO landtunnel for the A2 in the Netherlands, and the Channel Tunnel Rail Link in the United Kingdom.

The MSc thesis research carried out by Daan de Clippelaar is about the consequences of using fire resisting concrete for TBM driven tunnels. As the new concrete segments do not require additional fire protective covering, rubber sealing gaskets will be exposed through the construction gaps. Emphasis is therefore made on the water sealing capacity of the gaskets. Hence heat development at the location of the gaskets is of great importance.

The concrete mixture is believed to be of influence to the heat development at the location of the gasket. In order to provide a realistic scenario, Jos Kronemeijer has carried out research to create a concrete mixture that could be applied to land-, and TBM driven tunnels. Developments in tunnel segments lead to the use of steel fibre reinforced concrete (SFRC). The concrete used for the test is therefore SFRC enriched with pp-fibres.

The primary goal of this test is to gain insight in the temperature development during a large fire. The design fire used for the test is the RWS-curve with a duration of 120 minutes. Fire tests on several gap sizes will therefore be carried out. Chapter 2 will discuss the test set up, Chapter 3 will discuss the concrete mixture and type. The results of the tests will be discussed in chapter 4.

2) Test set up

Concrete used for TBM driven tunnel segments is susceptible to thermal spalling. Hence it is customary to provide the construction with an additional heat protective lining. Placement of the additional lining however, is time and money consuming. Hence large cost and time savings can be achieved by omitting post-TBM phase constructed fire proofing measures.

Case to be modelled

The purpose of the test is to complement findings in the MSc thesis of Daan de Clippelaar. The thesis focuses on TBM driven road tunnels without fire protective covering. Literature research for the thesis has shown that a RWS fire scenario is the governing fire scenario for road tunnels.

TBM driven tunnels come in different sizes. The thickness of tunnel segments is directly related to the tunnel diameter (segment thickness is about 1/22 of tunnel diameter). In most tunnel projects the sealing gaskets are placed towards the soil side of the segment joints. Gasket depth can be related to segmental thickness, and hence to tunnel diameter (table 1). In order to obtain a useable range of data, various gasket depths need to be tested.

Gasket depth [mm]	Fictive segment thickness [mm]	Fictive tunnel diameter [m]	Fictive type of tunnel [-]
250	325	7,2	metro/train single track
325	400	10	2-lane road tunnel
400	500	11	large 2-lane road tunnel

table 1: gasket depth vs. segment thickness and tunnel diameter

The gaps between segments are introduced by pressure pads. In order to introduce stresses at strategic places in the segments, wooden packers or concrete pressure pads are used between the segments. The design gap widths typically range from 4-6mm, but due to construction works the size of the gap may deviate by several millimetres. In order to test a worst case scenario, a gap width of 11mm needs to be tested.

Considering a masonry layout of tunnel segments, two types of segment interfaces can be distinguished: T-interfaces and parallel interfaces. The distance between two pressure pads defines the gap length. In most tunnel designs the pressure pads in the longitudinal joints span the entire length of the segment with the exception of the ends of the segments. At about 5cm. from the edge of the segment, the pressure pad ends. The distance between the pressure pads in the ring joints varies from 20-30cm., the T-interface between 3 segments is always located at the centre of two pressure pads in the ring-joint.

Several design fires have been developed to simulate tunnel fires. Literature studies performed for the MSc thesis of Daan de Clippelaar has shown that the RWS design fire is accepted widely to be the most representative design fire for a worst case scenario. Two types of RWS design fires are known at the time of this writing: RWS-120 and RWS-180, the numerical suffix represents the duration of the design fire in minutes. A graphical representation of the design fires can be found in figure 1. As the purpose of the test is to determine if extreme fire loading leads to a significant

increase in temperature at the base of narrow gaps, it is unnecessary to prolong the test after 120 minutes.
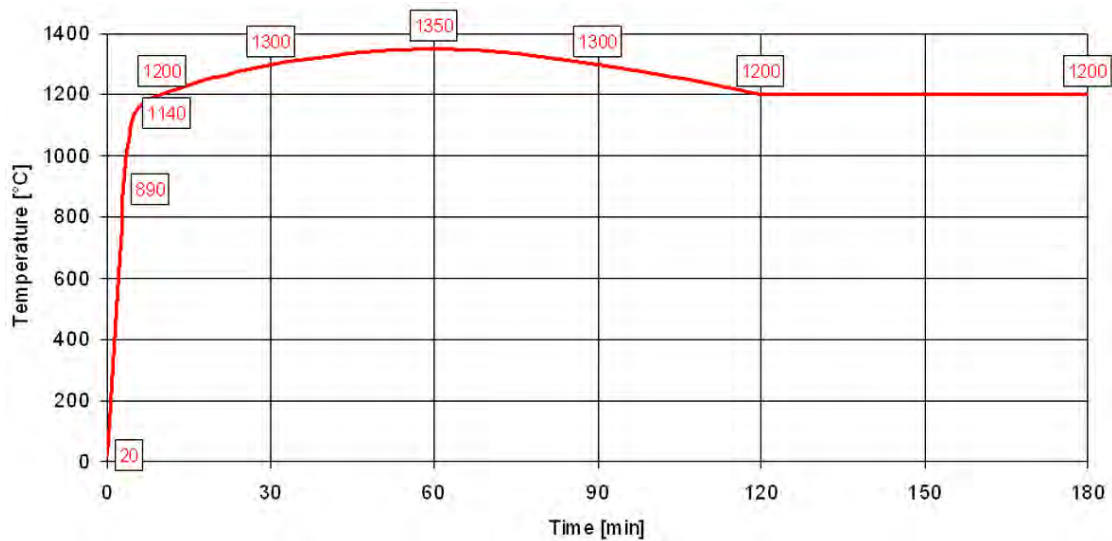

figure 1: RWS design fire curve (source: www.promat-tunnel.com)

To model the case properly, a few requirements have to be met:

- The gaps need to be embedded in concrete
- The concrete may not spall significantly
- Multiple gasket depths need to be tested

Test set up

The fire test has been executed at Efectis Nederland BV. Due to unexpected problems in the sample preparation, time and budget constraints, it was chosen to test the gaps at the parallel interfaces.

Sample setup

Two heat resistant concrete blocks were placed next to each other. The concrete blocks originally formed one block, but were cut in half due to problems arising from the original test setup*. The blocks face each other at the sawed face (the formwork side did not meet the geometrical tolerances).

A fire resistant board fitted with thermocouples in pre-cut areas (figure 2) is placed between the concrete blocks. The fire resistant board Promatect H with a thickness of 10mm was chosen for the test. The pre-cut areas in the board model the gaps discussed earlier. The concrete blocks are pulled together using tension rods (figure 3). After installation, the part of the sample exposed to the heat of the oven has 3 gaps of different depths (figure 4). Each gap has a width of 200mm.
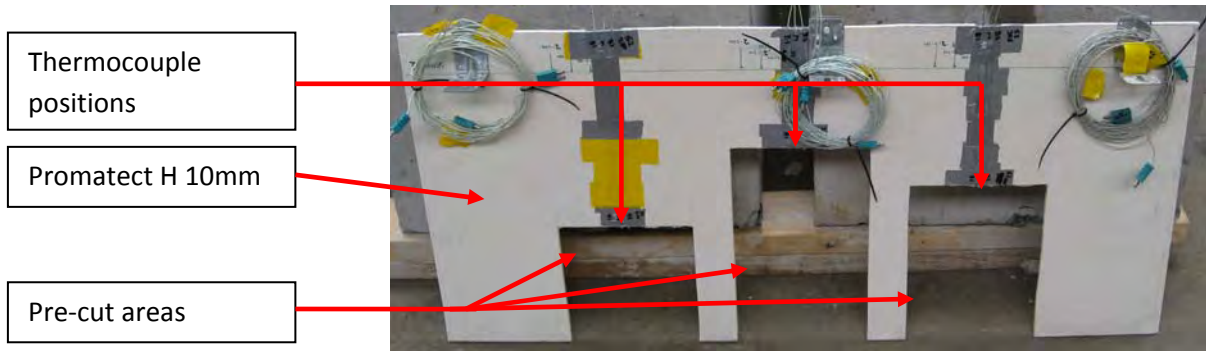
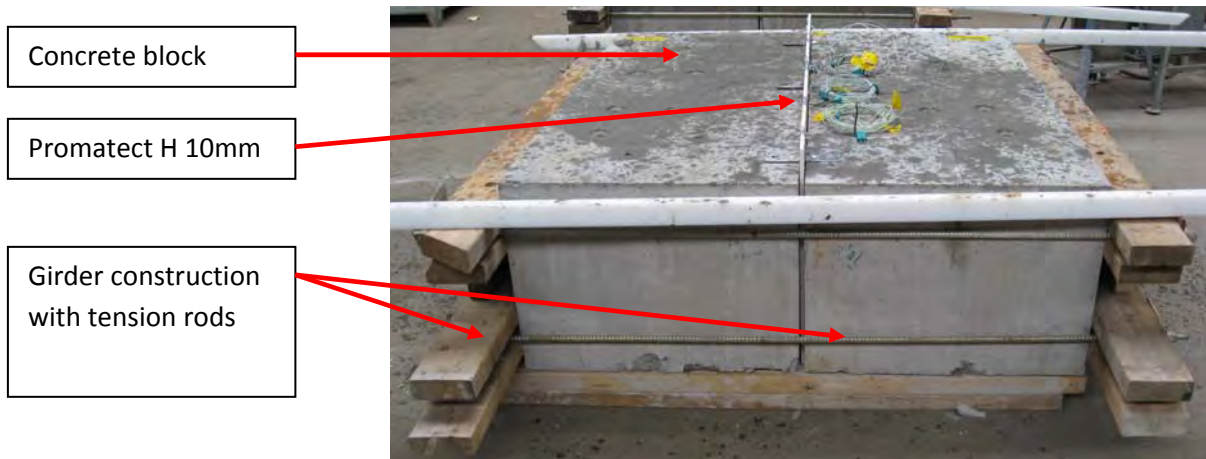**figure 2: prefabricated fire resistant board, equipped with thermocouples**

Thermocouple positions

Promatect H 10mm

Pre-cut areas

figure 3: Sample fitted with the fire resistant board

Concrete block

Promatect H 10mm

Girder construction with tension rods
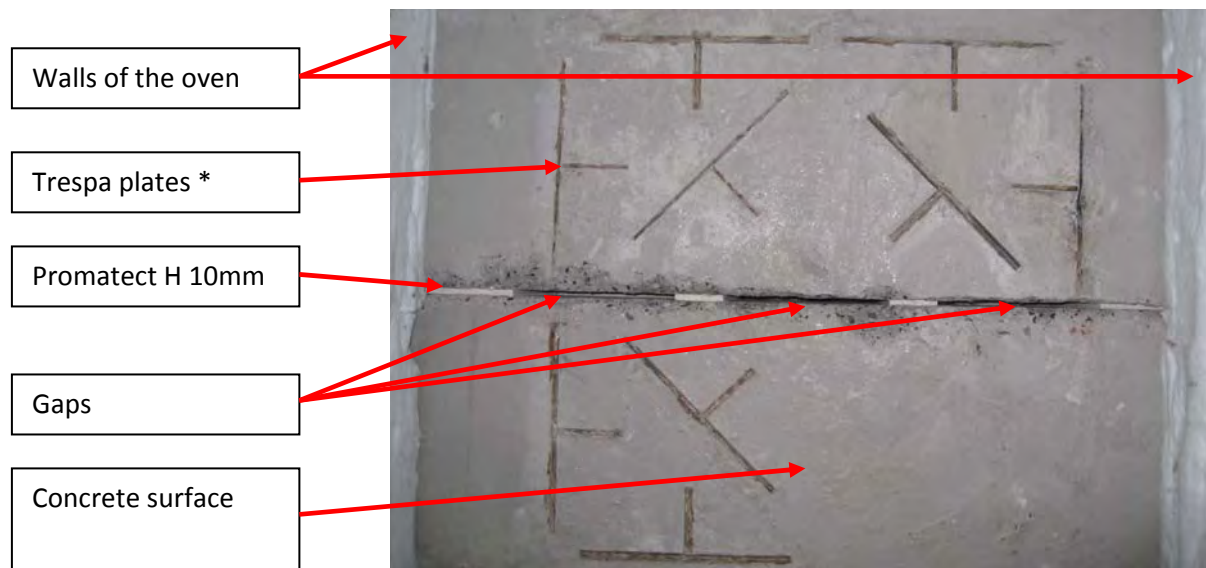
figure 4: Exposed part of the sample (sample placed on top of the oven)

Walls of the oven

Trespa plates *

Promatect H 10mm

Gaps

Concrete surface

At the first test, the fire resistant board was placed directly on the concrete. During the test a gas leak was observed that may influence test results. Hence the fire resistant plate was glued to the concrete for the second test.

Oven setup

The oven has a dimension of 1,2x1,2x1,5 (w*l*h) meters. Samples with dimensions up to 1,5x1,5x0,75m. (length x width x height) can be placed on top of the oven. The oven is equipped by an exhaust in the wall opposite to the wall of the three 1MW heaters. The walls are protected by a thermal barrier (ceramic blankets and aerated concrete), one of the walls functions as a door. The door can function as a load bearing part of the oven, in that case it cannot be opened with the sample still on top.

Gases inside the oven during a simulated RWS design fire can show a pressure difference up to 0,1 bar with respect to the atmospheric pressures. In order to prevent hot gases from exiting the oven underneath the test sample, a proper seal between the sample and the oven should be created. Aerated concrete and ceramic blankets are used for that purpose.

As can be seen in figure 5, the heaters all face one direction. This leads to a specific direction in gas flow and turbulence in the oven, and hence to differential conditions at the sample surface. At the first test it was assumed that this would not play a big role. Measurements of the first test however (chapter 4), have shown results that can only be explained by the effect of turbulence. The interior of the oven was therefore adapted for the second test. A more homogeneous turbulence regime was created by the installation of aerated concrete blocks at specific locations (figure 6).
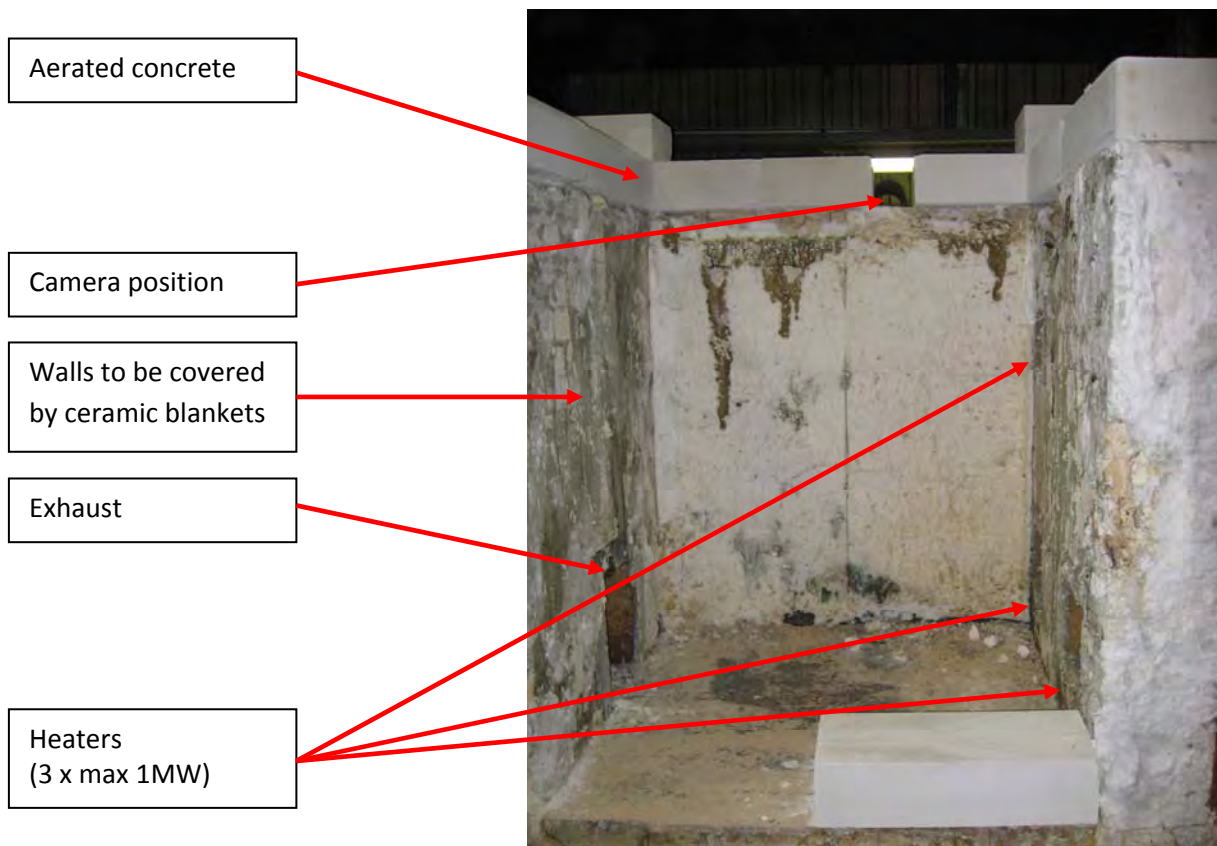

Aerated concrete

Camera position

Walls to be covered
by ceramic blankets

Exhaust

Heaters
(3 x max 1MW)

figure 5: Interior of the oven

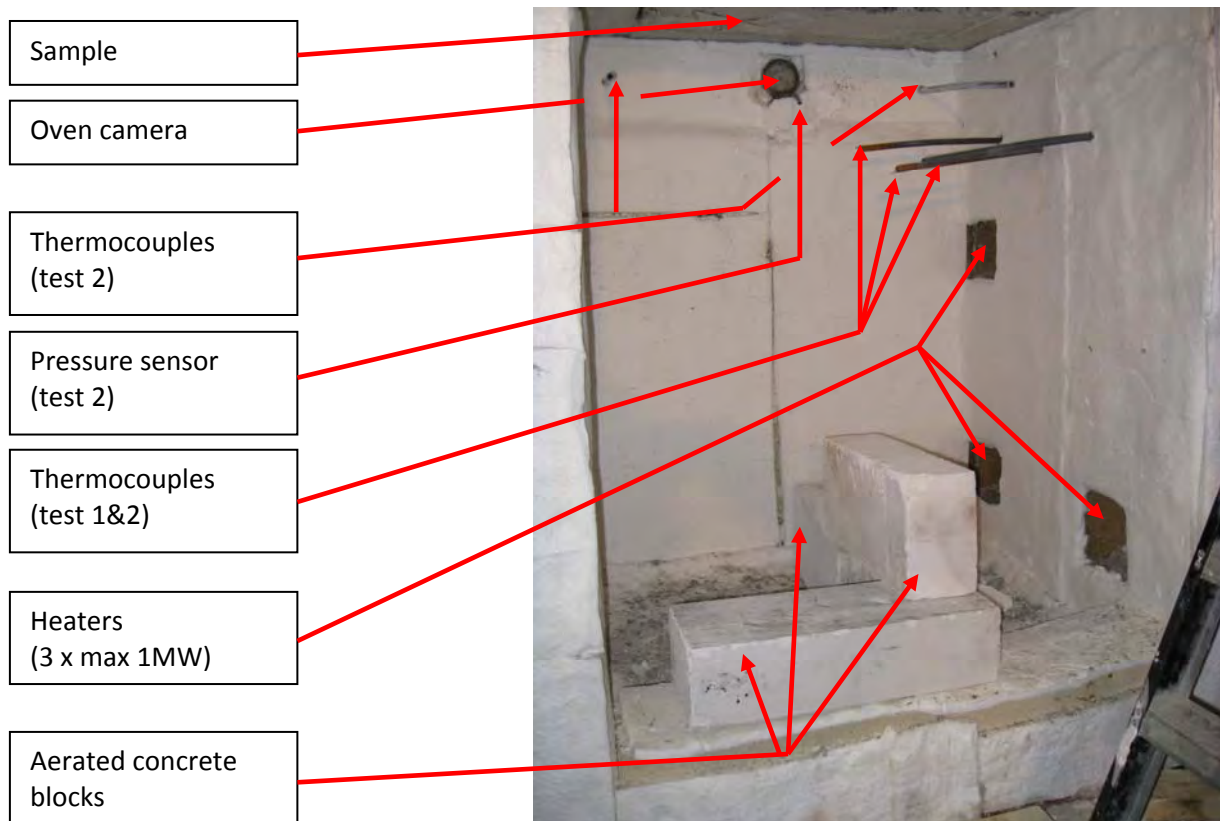| Sample |
| Oven camera |
| Thermocouples (test 2) |
| Pressure sensor (test 2) |
| Thermocouples (test 1&2) |
| Heaters (3 x max 1MW) |
| Aerated concrete blocks |

figure 6: Interior of the oven of test 2 (oven walls are covered by ceramic blanket)

The test

Five different phases of the test can be distinguished:

- Sample installation
- "Washing"
- RWS 120-curve
- Cooling down: removal of camera
- Cooling down: removal of door

The sample must be installed in a careful way as the sensor arrangement is provided by a fragile fire resistant Promatect H board (mechanical properties are comparable to plasterboard used in housing construction). The mass of the concrete blocks is about 15kN each and can easily destroy the board. Another reason for careful installation is to provide sufficient sealing capacity between the oven, the door, and the sample. The gases in the oven reach temperatures that can exceed 1350°C, gases escaping from the oven may lead to unsafe situations. The heaters of the oven need to burn at full capacity in order to simulate a RWS type design fire. Any heat leak may lead to failure to reach the time-temperature relation imposed by the RWS design fire.

As the oven is used on a regular basis, it may still contain heat from an earlier session. Typically the temperatures are in the range of 50°C. Before the design fire is started, the oven will be "washed" in order to prevent an explosive air-gas mixture in the oven. During this phase the temperature in the oven drops slightly.

When the gas-air mixture in the oven is at a safe ratio, heaters start to burn at full capacity. The temperature gradients to be reached in the first couple of minutes are very large. The oven originally is used to test isolation materials: during those tests the heat is contained in the oven and the RWS design fire is easily reproduced by the oven. Compared to fire resistant boards, concrete is a bad isolator. Hence more energy is lost through the exposed concrete surface, thereby reducing the probability of meeting the RWS design fire requirements. Meeting the requirements is further complicated by concrete spalling and heat leaks in the oven.

The heaters are stopped after 120 minutes, the oven will start to cool down. In order to assess the spalling behaviour of the concrete, an oven camera was installed. The camera is directed at the fire exposed surface of the concrete block. Due to the high temperatures in the oven, the camera needs to be cooled. The camera is the first part of the oven to be removed after the fire test. This creates a heat leak with a diameter of about 20cm and influences the temperature in the oven significantly.

The oven will need to cool down to about 400°C before the door can safely be removed. In order to assess the retarded heat transfer through the concrete, the sample is kept in place and the measurements are continued.

Due to the fact that the door of the oven needs to be removable, the long sides of the gaps are aligned with the gas flow. The test thereby simulates the situation of hot gases rising along the ring joints of a tunnel.

Instrumentation

The variable of interest in the tests is the heat development in the gaps. The heat development can be measured with the aid of thermocouples (figure 7).
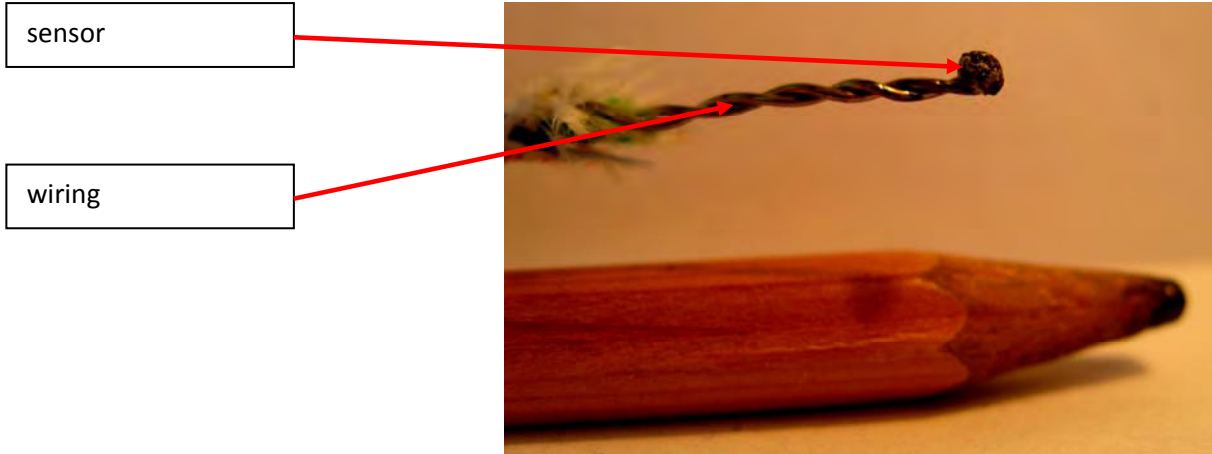

sensor

wiring

figure 7: Thermocouple

For both tests, each gap was equipped with a set of 3 thermocouples. The thermocouples have been placed at the centre (labelled M), and approximately 1 cm from the centre on both sides (labelled B1 and B2) (figure 8).
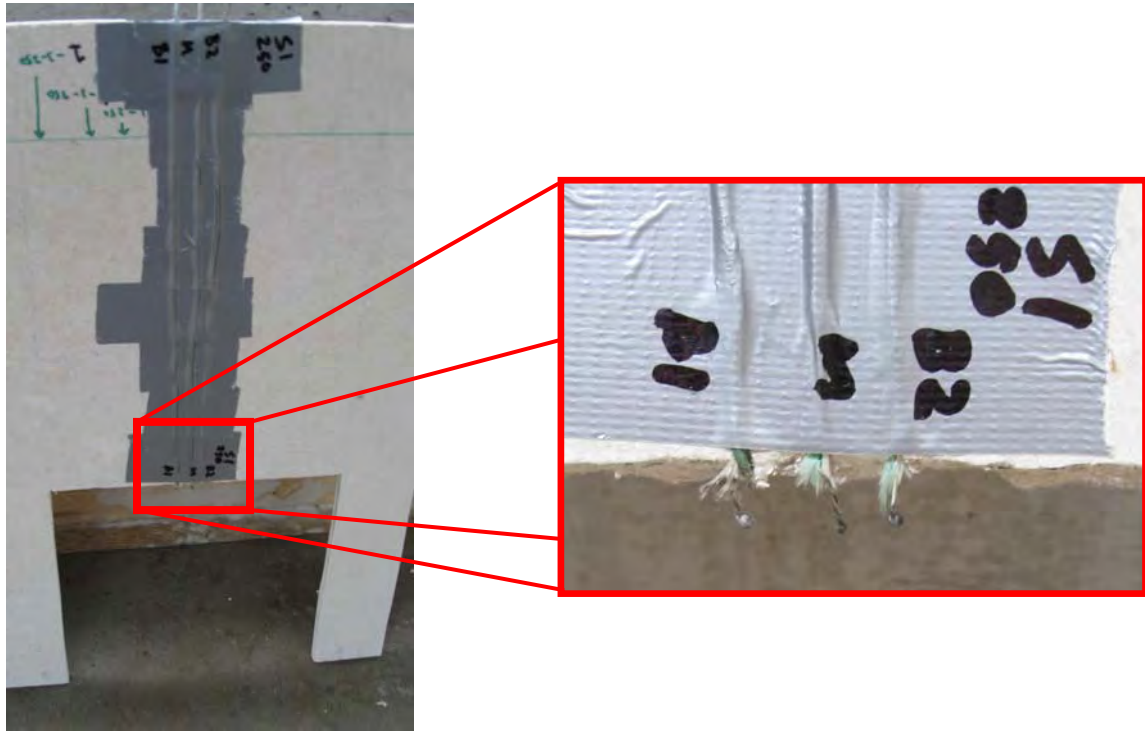
figure 8: Example thermocouple positions in gap

In order to be able to explain the measurements in the gaps, the temperatures in the oven need to be monitored simultaneously. The oven wall provides room for 3 independently moveable rods. Thermocouples are placed at the tip of these rods, they are labelled as TOV1, TOV2, and TOV3. The distance between the sample and the thermocouples is approximately 30cm. The approximate location of the standard thermocouples can be found in figure 9 (yellow coloured lines).
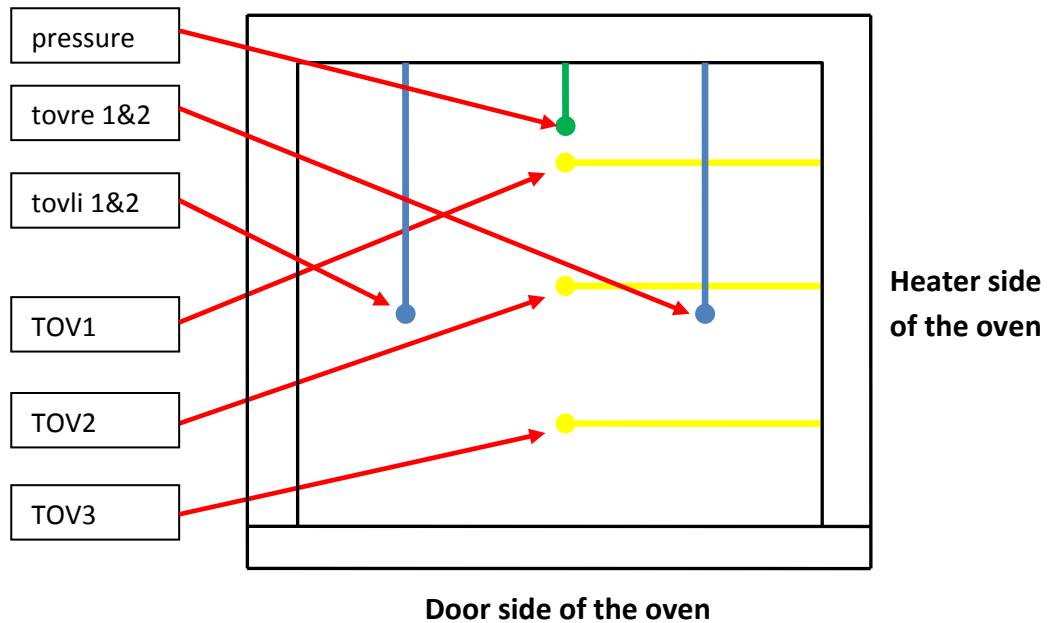

figure 9: Thermocouple positions in the oven

Measurements from test 1 led to the hypothesis that the temperatures in the oven are not as uniformly distributed as presumed. The reason for the differential temperatures may be found in the

blowing direction of the heaters. Due to the location of the standard thermocouples with respect to the heaters in the oven, this temperature difference cannot be measured. For the second test, 4 additional thermocouples have been installed at 2 different places. The extra thermocouples are coloured blue in figure 9, their distance from the sample is about 10cm.

Another non-standard measurement for tests performed with the oven, is a gas-pressure measurement. During test 1 vapour leaks trough the concrete gaps were observed. The assumption was made that a large pressure in the oven lead to leaks between the concrete and the fire resistant board. If that is the case, measurements in the gap may be conservative. Hence a pressure sensor was installed for the second test (represented by the green line in figure 9).

3) The concrete sample

The blocks used for this test originally were prepared for another fire test. The original test incorporated T-joints that were supposed to be formed by removing T-shaped trespa formwork from the concrete. This process failed, hence the trespa plates were left in the concrete. The original block (1,5*1,5m) was cut into two halves.

Concrete blocks

The blocks were made of a steel fibre reinforced, pp-fibre enriched concrete with limestone aggregates.

In order to determine the water content of the concrete at the time of testing, a sample (approximate dimensions: 7x7x7cm) was taken from the corner of one of the blocks. As the blocks were casted and treated at the same time and in the same way, it can be said that the sample is representative for both tests. Due to the size of the sample and the low permeability of the concrete, deviations from the real water content caused by absorption or evaporation at the edges of the block are assumed to be minimal.

After sampling, the block was weighed and placed inside an oven with a maintained temperature of 105°C. At day 2 and day 3 of drying, the black was weighed again. The moisture content seemed to stabilize at a level slightly higher than 5% (table 2).

Mass wet [gr]	Mass day 2 [gr]	Mass day 3 [gr]
1231	1170	1169
Water content [weight %]	**5,2**	**5,3**

table 2: Moisture content test samples

Time scheme

Date	item
10-02-2010	Casting concrete
23-04-2010	Demoulding
07-05-2010	Splitting samples
17-05-2010	Sampling in order to determine actual water content of concrete
20-05-2010	Installation of sample 1
	Fire test 1
21-05-2010	End of measurements cooling phase test 1
	Removal of remains of sample 1
	Installation of sample 2
	Fire test 2
25-05-2010	End of measurements cooling phase test 2
	Removal of remains of sample 2

table 3: timeframe fire tests

4) Test results

Measurements in gaps: test 1

During test 1 higher temperatures were recorded in the 325mm gap than the 250mm gap (figure 10). The reason for this is that the turbulence regime inside the oven was unfavourable for the 325mm gap and favourable for the 250mm gap. The turbulence regime was adapted for test 2.
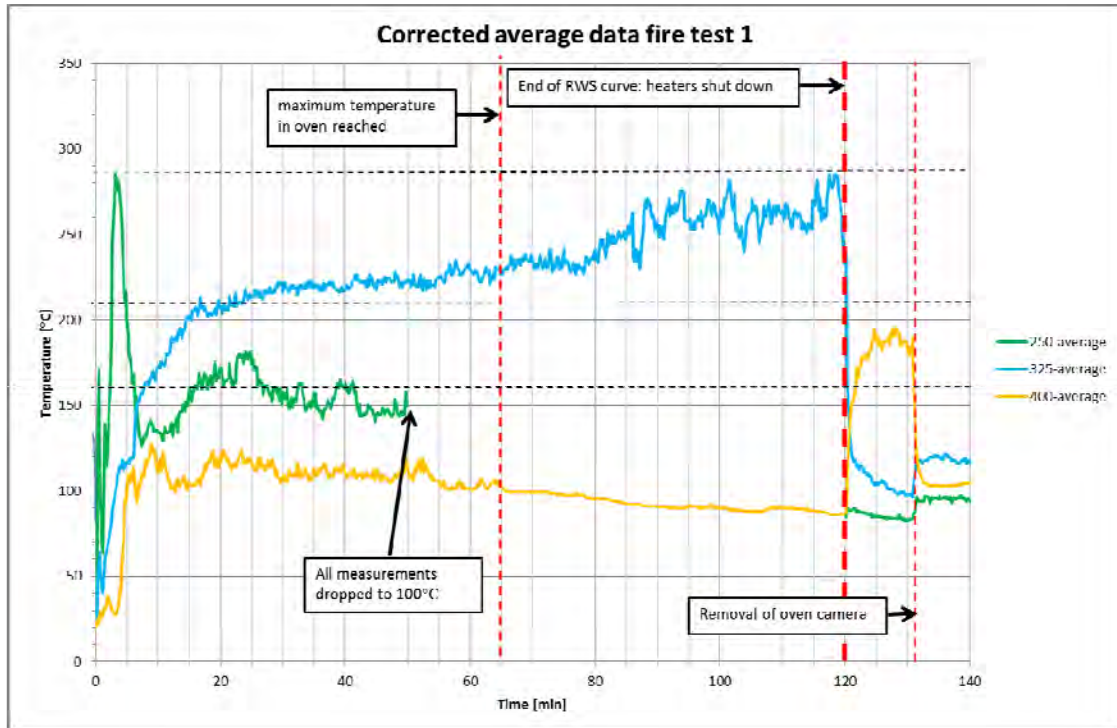

figure 10: Test 1: average temperatures in gaps

As can be seen in **Fout! Verwijzingsbron niet gevonden.** the temperature in the 325mm gap stagnates at about 290°C. The temperatures in the 250mm and the 400mm gap increase up to 180°C and 130°C respectively and then show a drop. The heaters are stopped after 120 minutes, the temperature in the 325mm gap drops instantly to 100°C, the temperature in the 250mm gap remains about 100°C. The temperature in the 400mm gap however, soars to about 200°C but instantly drops to 100°C when the camera is removed from the oven.

Measurements in gaps: test 2

Test 2 shows different results. The turbulence regime in the oven was adapted due to the high temperatures measured in the 325mm gap. The temperatures measured in the various gaps shows more consistency with the gap depths (figure 11

figure 11).

The temperatures in the 250mm and 325mm gaps stagnated at 280°C and 220°C respectively. Temperatures in the 325mm gap suddenly dropped to 100°C, but later suddenly soared to 180°C as well. The temperatures in the 400mm gap stagnated at 150°C, but showed a sudden increase to 190°C just before the end of the heating period. Temperatures in all gaps dropped to about 100°C as soon as the heaters were turned off.
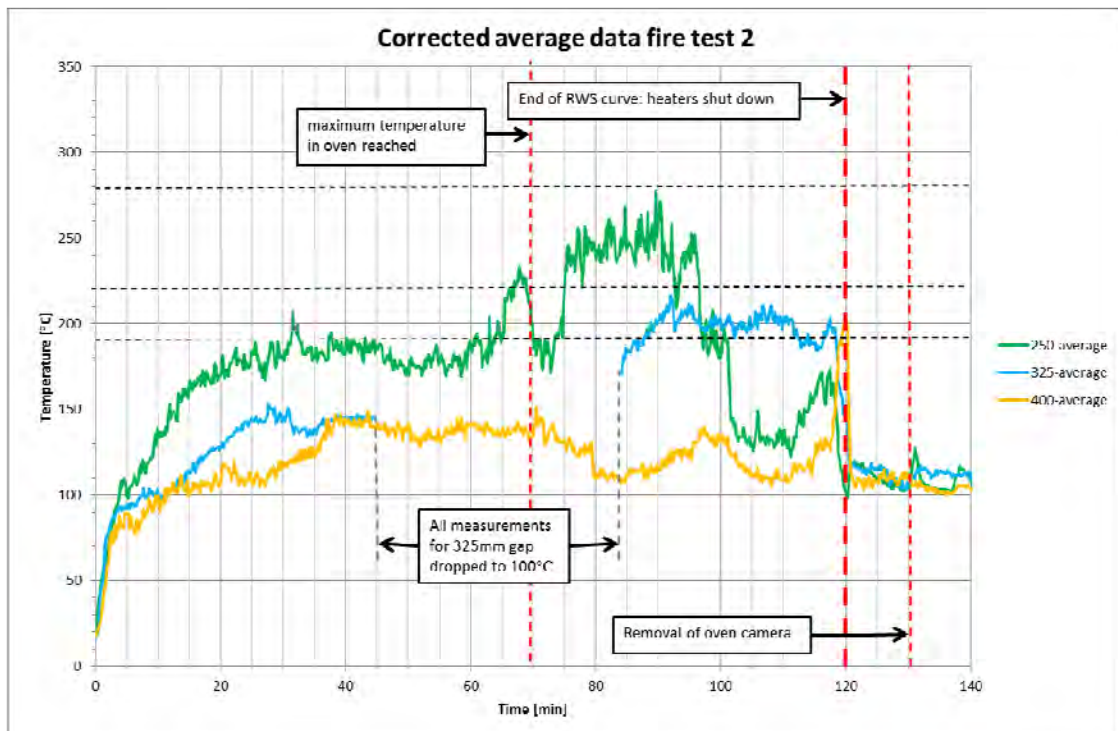
figure 11: Test 2: average temperatures in gaps

Measurements in gaps: cooling period of both tests

Both tests exhibited a multi-day cooling period after the heaters were shut down. Temperature measurements on the first sample were stopped after one day due to preparations for the second test. Temperature measurements on the second sample were continued for about 3,5 days after the fire test started.

With the exception of the 400mm gap in test 1, temperatures in all gaps of both tests dropped to about 100°C after the heaters were shut down. The temperatures in the gaps dropped about 40°C, 20°C and 10°C during the first, second and third day of cooling respectively. At the time of cooling the average ambient temperature was 18°C. A graphical representation of the cooling period can be found in figure 12.
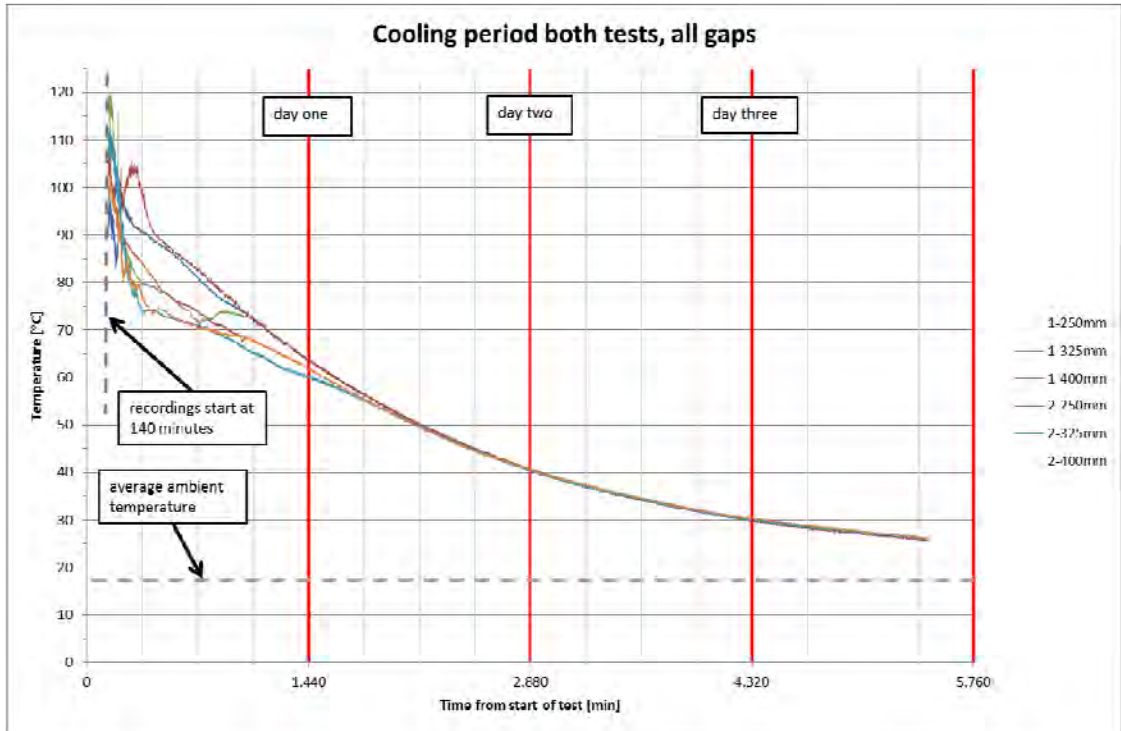
figure 12: cooling period of the gaps

Flame intrusion

After the samples had been dismantled from the oven, the concrete surfaces that were facing the gaps could be inspected visually (figure 13, figure 14). A distinct difference can be observed in the colour of healthy concrete and concrete that has reached high temperatures. Based on this difference, flame intrusion is approximated.
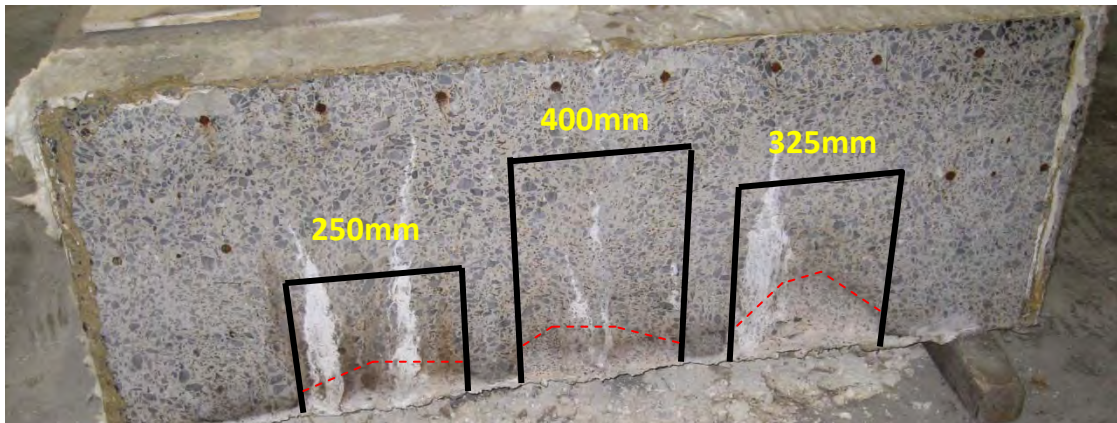

figure 13: Flame intrusion paths in the gaps of sample 1

figure 14: Flame intrusion paths in the gaps of sample 2

The flame in test 1 seems to intrude the 250mm and 400mm gaps in a similar path. The intrusion in the 325mm gap however, is approximated to be much deeper. The differences in intrusion in test 2 are smaller than in test 1. Measurements performed on the approximate flame intrusion are presented in table 4.

Gap	minimum intrusion [mm]	average intrusion [mm]	maximum intrusion [mm]	gasket-flame distance [mm]
Test 1				
250mm - side 1	42	63	84	166-218
250mm - side 2	55	68	76	
325mm - side 1	74	112	132	162-258
325mm - side 2	67	142	163	
400mm - side 1	47	74	93	302-353
400mm - side 2	76	85	98	
Test 2				
250mm - side 1	50	86	111	132-208
250mm - side 2	42	87	118	
325mm - side 1	45	94	119	200-280
325mm - side 2	46	89	125	
400mm - side 1	48	90	128	282-357
400mm - side 2	43	89	118	

table 4: Reduced gap depths due to flame intrusion

Cracks and leaks

The concrete blocks of test 1 and 2 exhibited cracks through which water was leaking. During both tests temperatures at several sensors suddenly dropped to 100°C

Gap	number of leaks [-]	apparent severity [-- (minor) to ++ (severe)]
Test 1		
250mm - side 1	2	1:++, 2:++
250mm - side 2	1	++
325mm - side 1	1	++
325mm - side 2	2	1:++, 2:-
400mm - side 1	1	--
400mm - side 2	0	no trace found
Test 2		
250mm - side 1	2	1:0, 2: --
250mm - side 2	0	no trace found
325mm - side 1	2	1:+, 2:+
325mm - side 2	2	1:0, 2:+
400mm - side 1	0	no trace found
400mm - side 2	2	1:-, 2:-

table 5: Leaks in blocks at surface facing the gaps

Observations during fire test

During the tests some observations could be made from outside of the oven. The observations were made visually and acoustically.

Test 1

Visual:

Small burning particles could be noticed in the exhaust: this was most likely burning trespa.

After some time (+/- 15minutes) water leakage could be noticed from the concrete block that was supported on two sides. Leakage of water from the block that was supported on three sides started after about 30minutes (figure 15). The water from the leaks evaporated and left white traces, presumably calcium deposits.

At the start of the test exhaust of steam or smoke could be noticed from the location of the 250mm gap. This exhaust stopped after a couple of minutes.

Acoustic:

During the test some popping sounds from the inside of the oven were noticed. Popping sounds indicate spalling of concrete. The concrete surface was investigated after the fire test and a cooling period of 90 minutes. The concrete surface was damaged but, little of the concrete surface had spalled. One day later, the severely damaged concrete has fallen from the surface.

Test 2

The second test was nearly similar to the first test; the popping sounds were briefly more violent and no gas leaks could be observed.

figure 15: leakage at outside of segment

Evaluation of measurements

Test 1

The measurements in the 250mm gap initially reached values of 290°C, but later dropped to an average value of 160°C. Later, the temperature dropped to 100°C, indicating an excessive amount of steam. The initial rise of temperature can be related to the gas leak that was observed in the first couple of minute at the 250mm gap. The initial measurements therefore are not reliable. The flame intrusion levels were about 80mm.

The temperatures in the 325mm gap reached higher average values than in the 250mm gap (about 240°C), the reason for this is that the flame intruded the gap more severely than in the 250mm gap. Flame-gasket levels were approximated at 160mm.
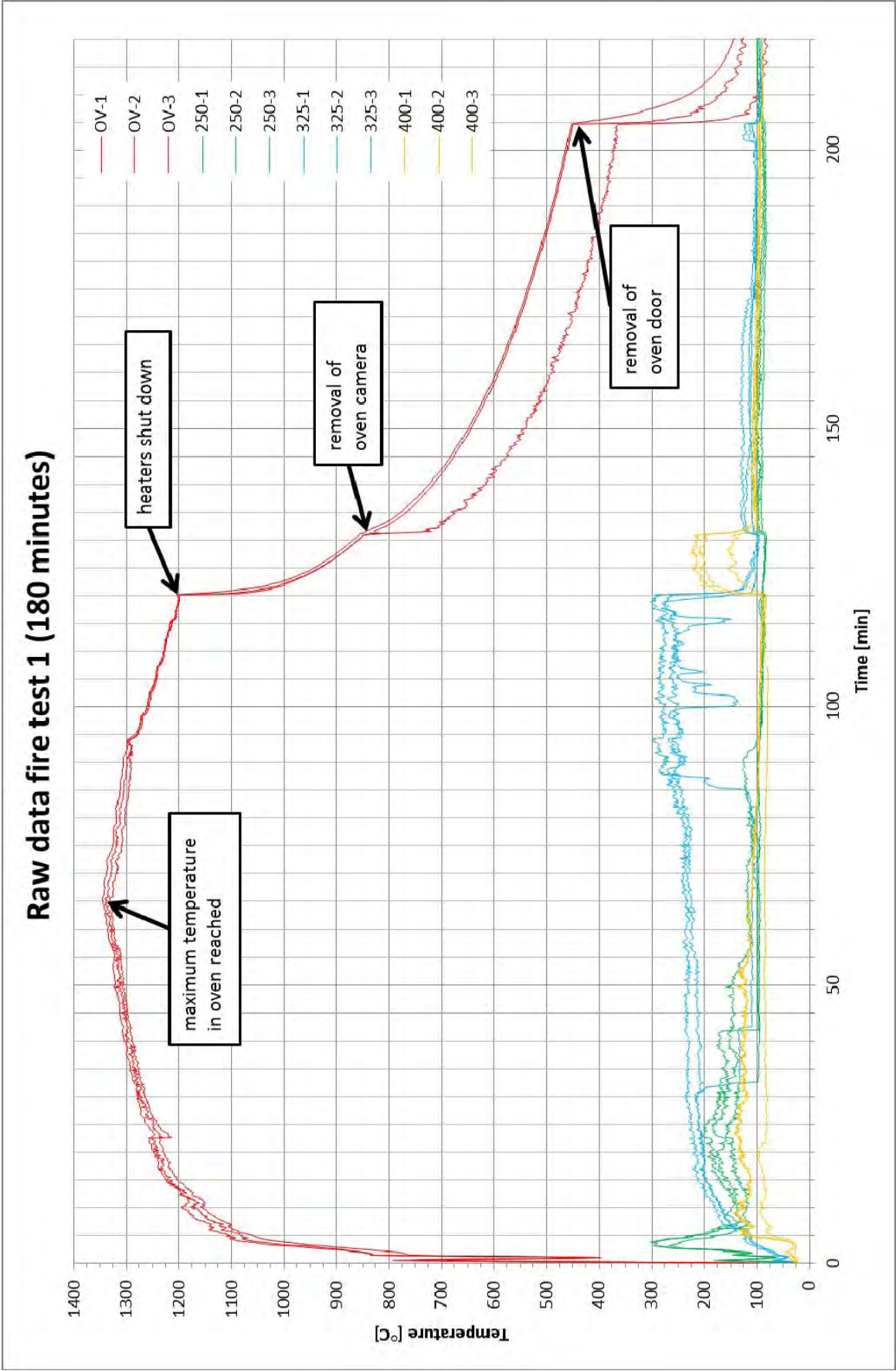
The temperatures in the 400mm gap stagnated at 100°C, indicating the presence of steam. Once the oven was stopped, temperatures rose to 200°C, it is unknown what phenomena caused this sudden temperature increase.
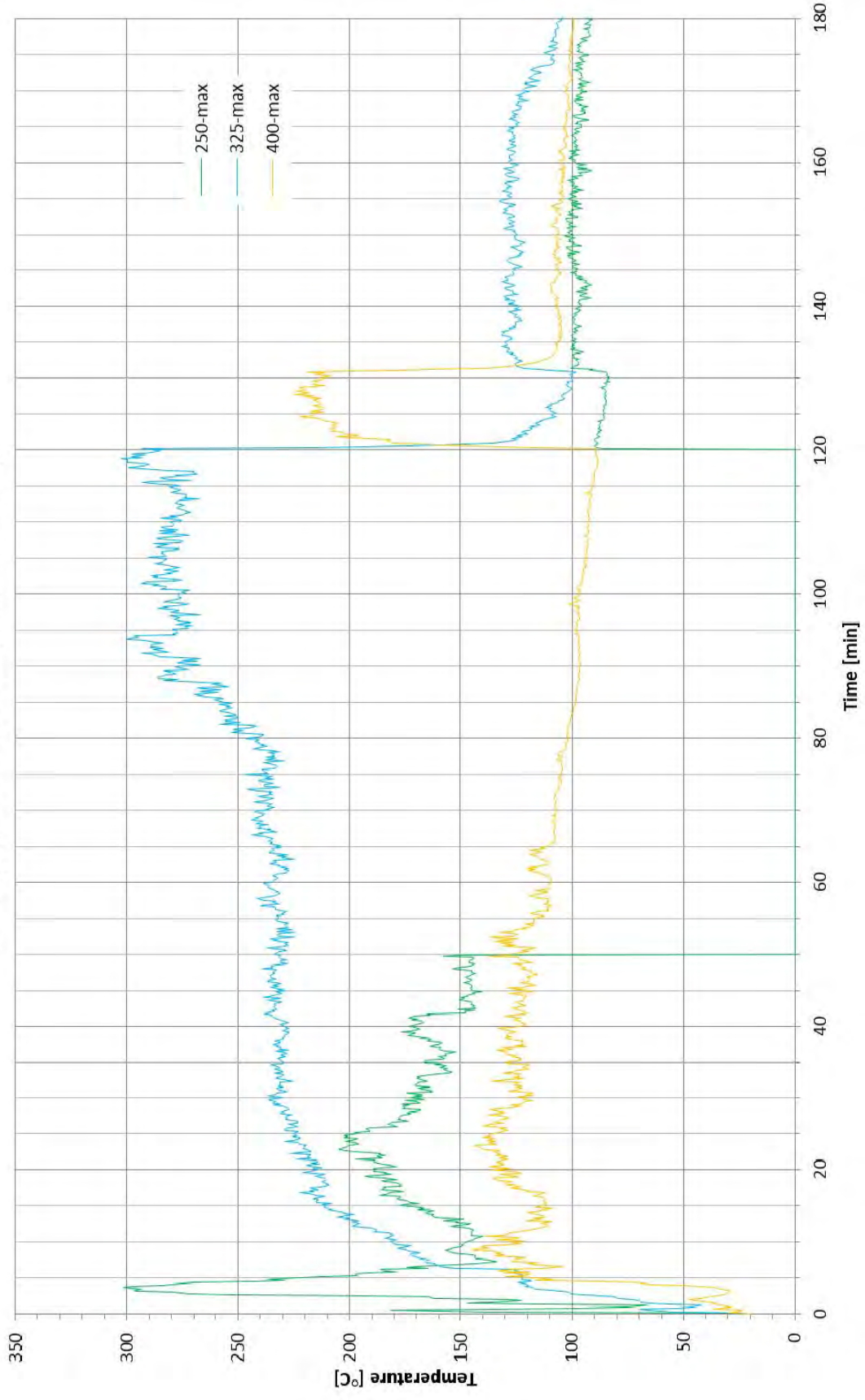
Test 2

The measurements of the second test showed more consistency with the gap configurations. The reason for this is the changed internal configuration of the oven, that led to a more evenly distributed fire loading. The temperatures reached their highest values in the 250mm gap, and the

lowest values in the 400mm gap. The 250mm gap reached temperatures of about 280°C, The 325mm gap stagnated at 200°C, and the 400mm gap stagnated at 150°C. The temperatures in the 325mm gap also dropped to 100°C during the test, indicating the presence of large amounts of steam.
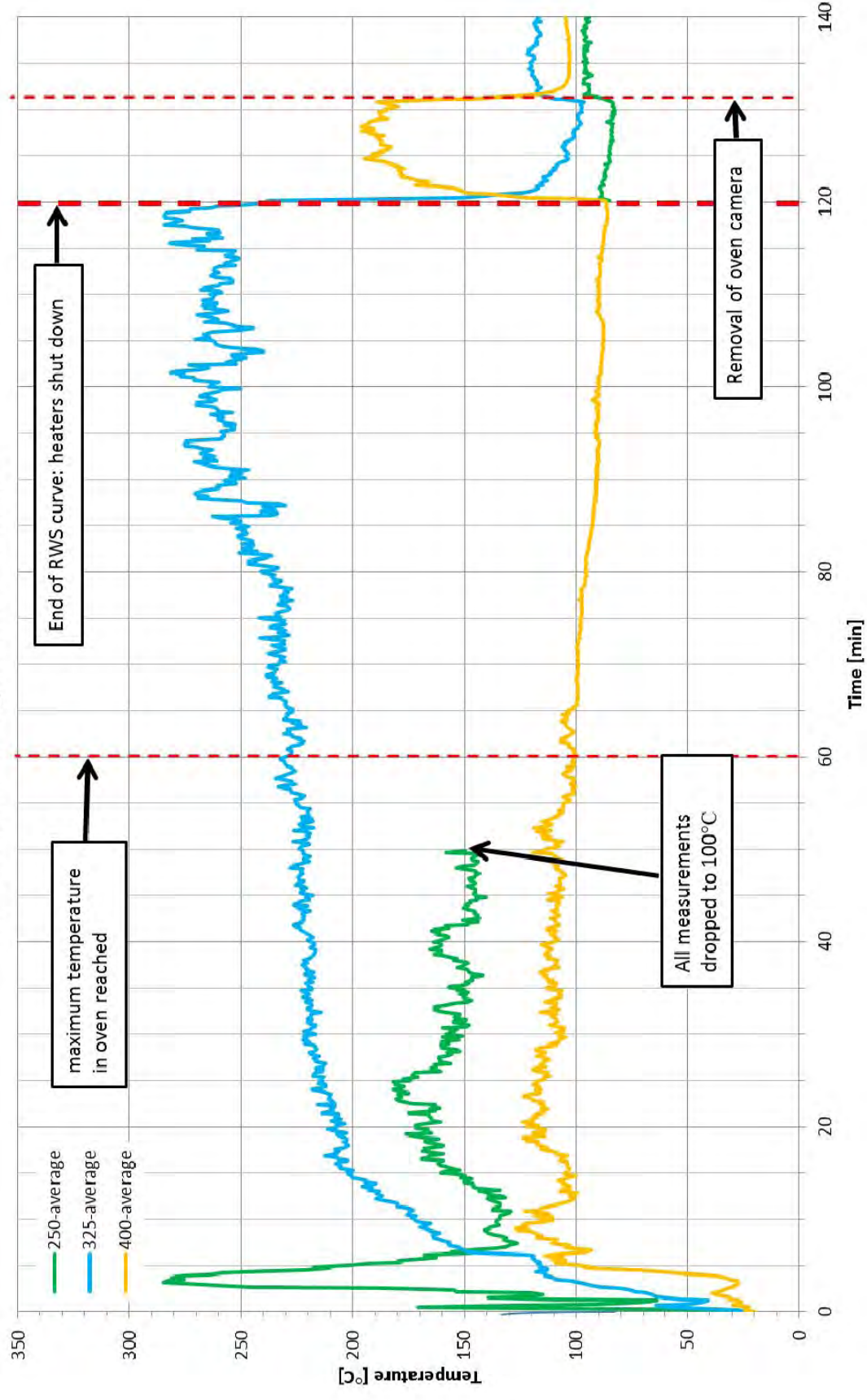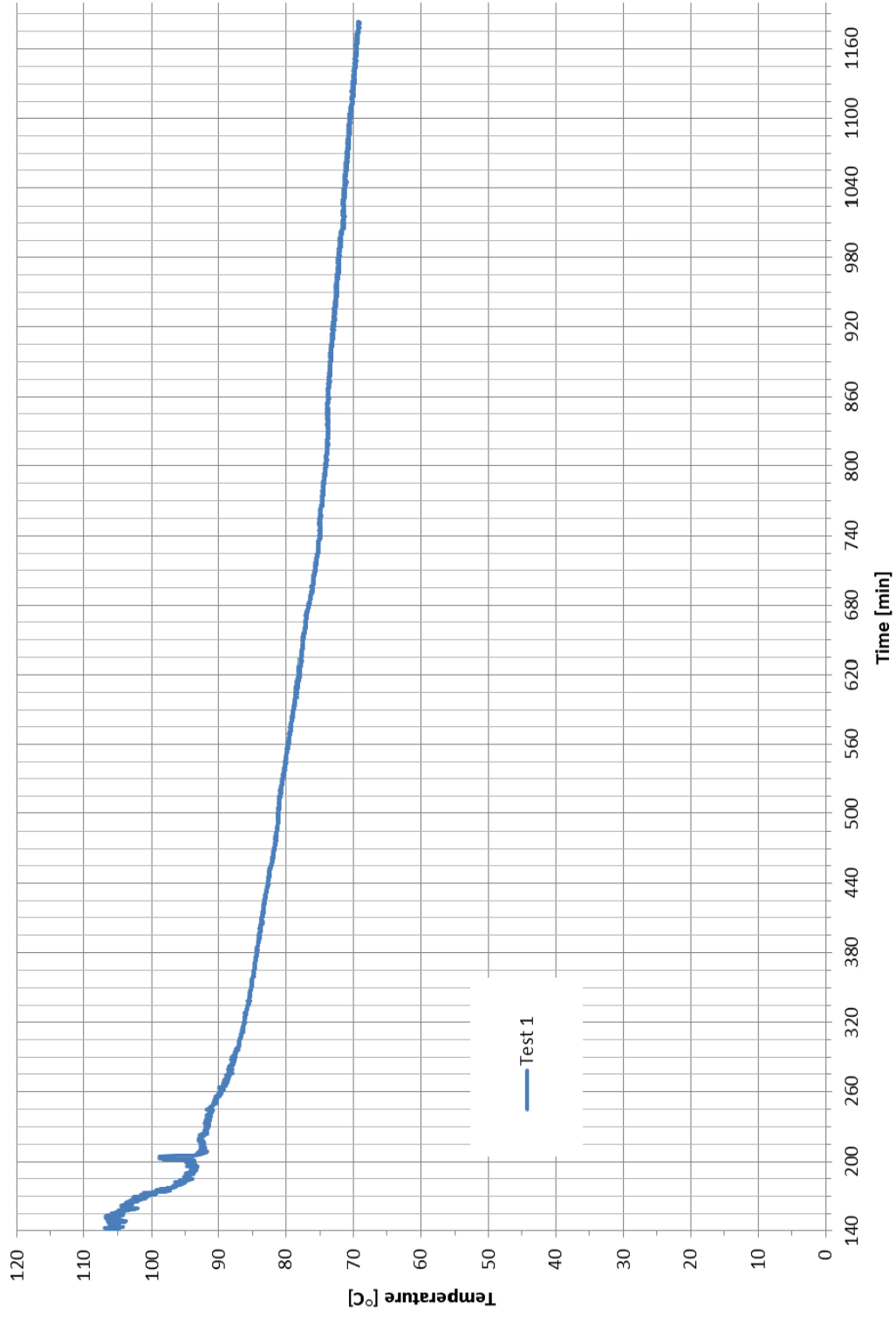
Appendix A: Data test 1
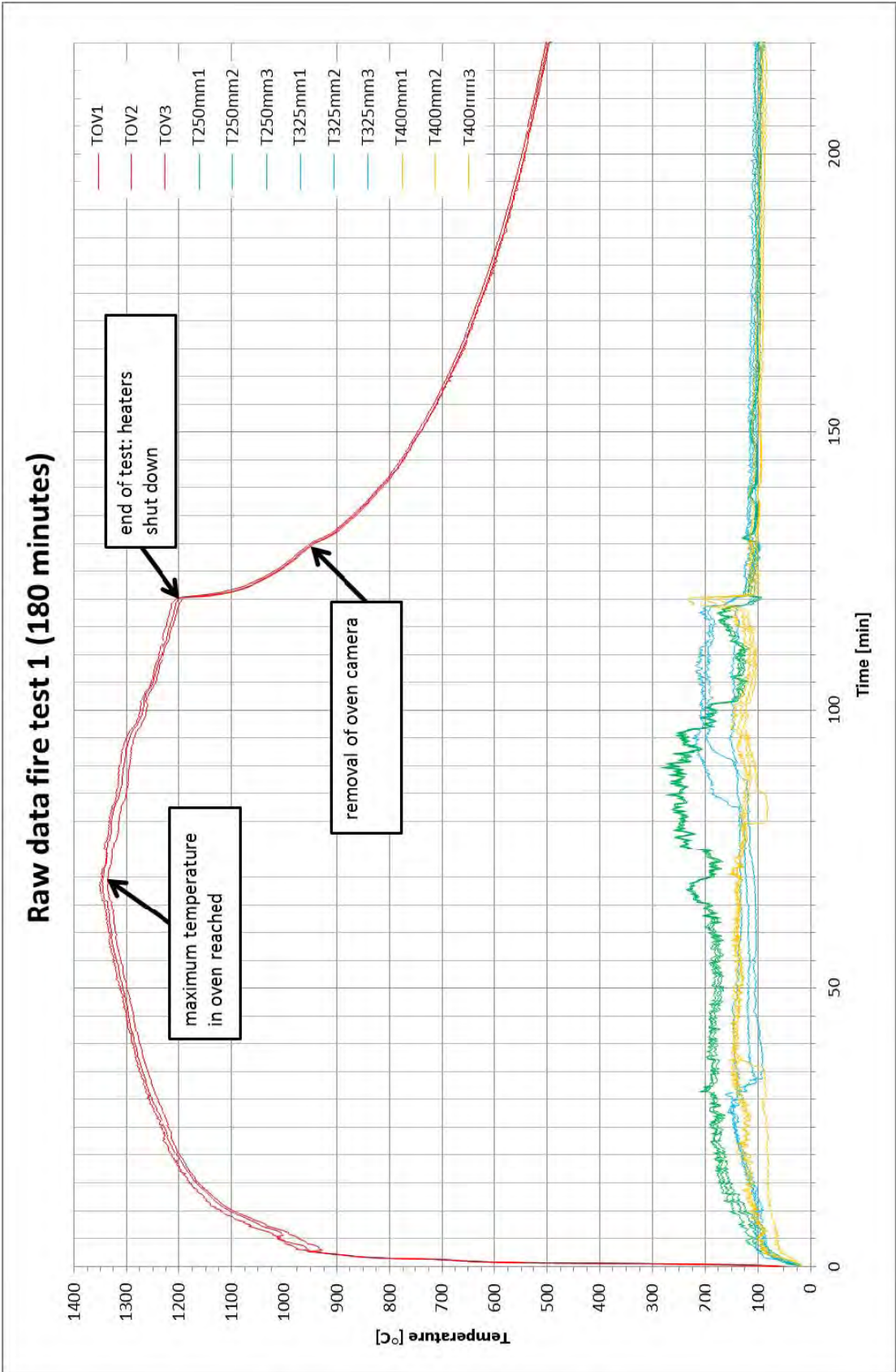
Max gaps fire test 1 (180 minutes)

Corrected average data fire test 1

Legend:
- 250-average (green)
- 325-average (blue)
- 400-average (yellow)

Annotations:
- End of RWS curve: heaters shut down
- maximum temperature in oven reached
- Removal of oven camera
- All measurements dropped to 100°C

Axes:
- X-axis: Time [min] (0 to 140)
- Y-axis: Temperature [°C] (0 to 350)

Cooling period

Temperature [°C]

Time [min]

Test 1

Appendix B: Data test 2

Raw data fire test 1 (180 minutes)

Max gaps fire test 1 (180 minutes)

Corrected average data fire test 2

Legend:
- 250-average
- 325-average
- 400-average

End of RWS curve: heaters shut down

maximum temperature in oven reached

All measurements for 325mm gap dropped to 100°C

Removal of oven camera

Temperature [°C]

Time [min]

Appendix C: Pictures of samples before and after fire test

Sample 1 before test:

Sample 1 directly after test:
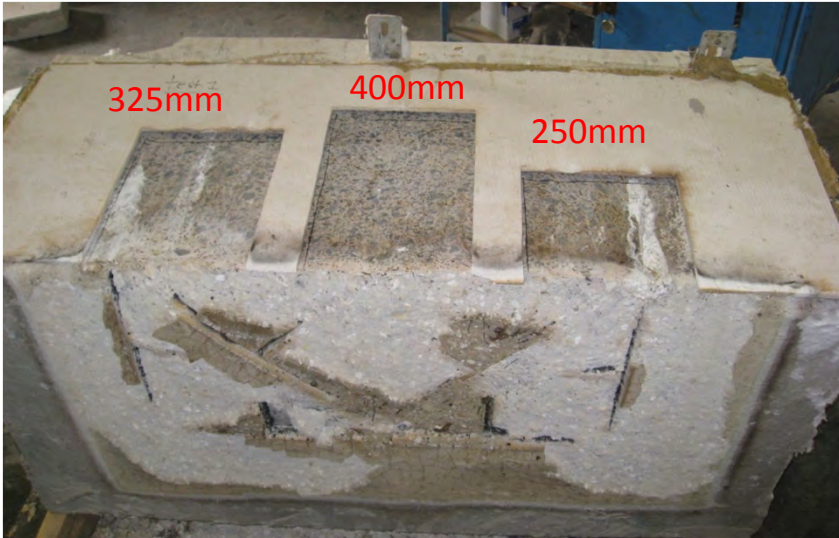
Sample 1 after one day:

Sample 2 before test:
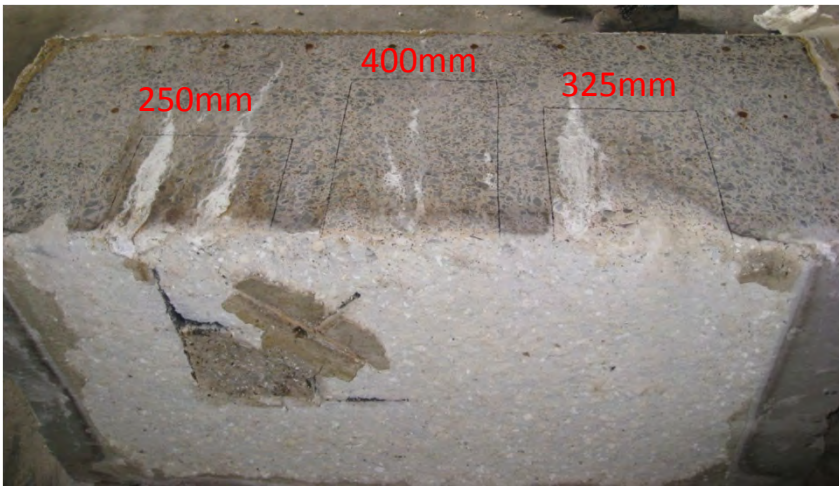
Sample 2 directly after test:
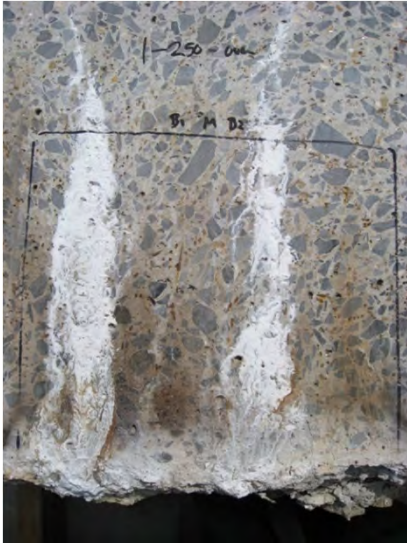

Sample 2 after one day:

Gaps sample 1

Oven side

325mm 400mm 250mm

Door side

250mm 400mm 325mm

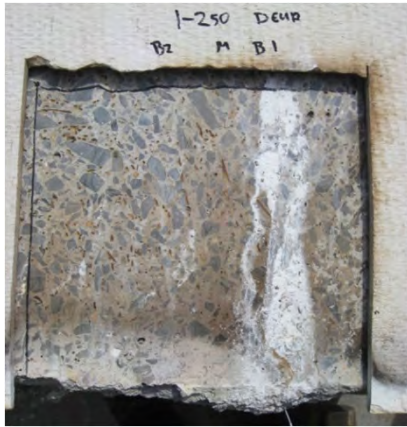Test 1

250mm door side

B1 side

B2 side

Test 1

250mm oven side

B2 side: no picture   B1 side

Test 1

325mm door side

B1 side

B2 side: no picture

Test 1

325mm oven side

B2 side

B1 side

Test 1

400mm door side

B1 side: no picture   B2 side: no picture

Test 1

400mm oven side

B1 side: no picture   B2 side: no picture

Test 1

Gaps sample 2

325mm 400mm 250mm

Oven side

250mm 400mm 325mm

Door side

Test 2

250mm door side

B1 side

B2 side

Test 2

250mm oven side

B2 side

B1 side

Test 2

325mm door side
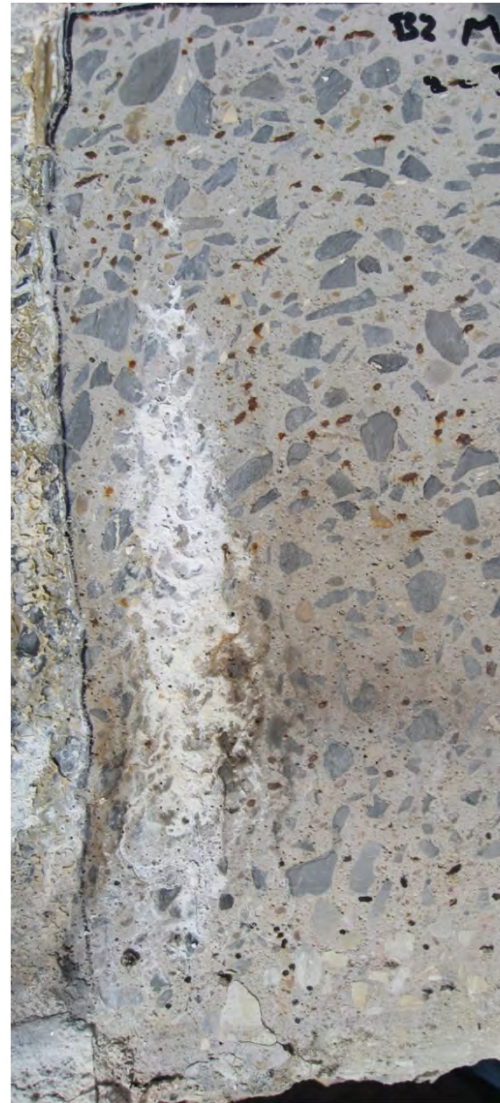
B1 side

B2 side

Test 2

325mm oven side

B2 side

B1 side

Test 2

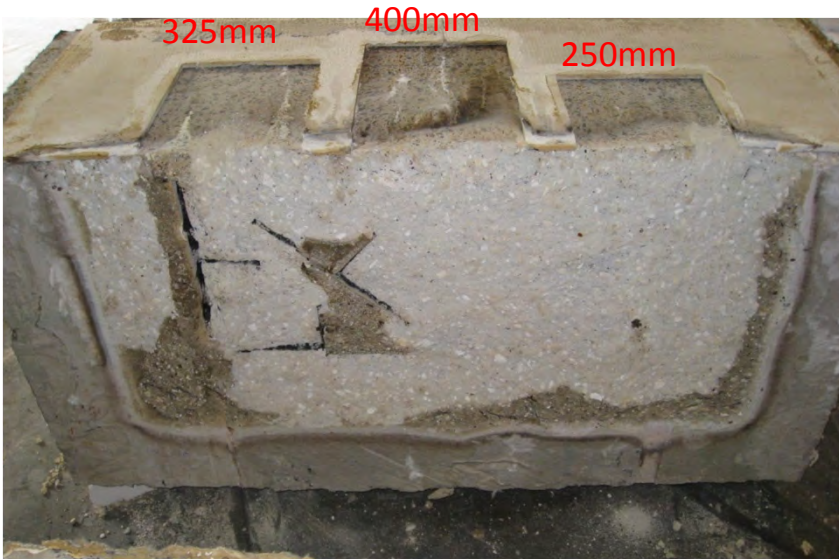400mm door side

B1 side: no picture

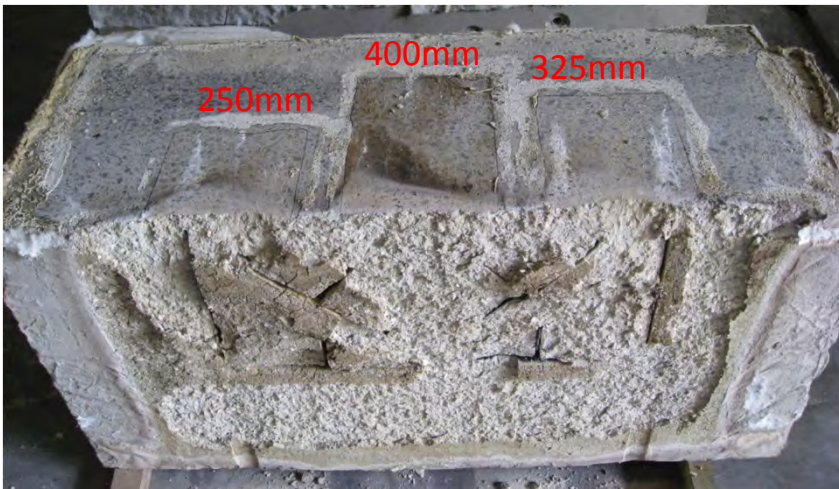B2 side: no picture

Test 2

400mm oven side

B1 side

B2 side

Test 2

APPENDIX B: REPORT GASKET TEST

performance of rubber gaskets subjected to stress and heat loading

the impact of a tunnel fire on the compression performance of rubber sealing gaskets used in segment joints of TBM driven tunnels

Daan de Clippelaar
12-01-2010

Index

1) INTRODUCTION

This report is about an experiment on sealing gaskets used in TBM driven tunnels. The purpose of the experiment is to complement the MSc thesis of Daan de Clippelaar, which focuses on TBM driven road tunnels without fire protective covering.

A TBM driven tunnel uses rubber gaskets to water seal its precast lining. Sealing functionality is accomplished by compression of the gasket. Rubber shows accelerated aging at elevated stress and temperatures. Higher temperatures therefore may lead to failure to meet the design requirements.

Experiments performed by Daan de Clippelaar [1] led to the conclusion that thermal conditions in segment joints are affected by fire loading at the surface of the segments. This is also the case if the joints are shielded from the flames. The temperatures in the segment joint are significantly lower than in the fire itself, but they do reach values that may be problematic to the functionality of the gasket. Also, high temperatures remain in the segment joint for several hours after the fire has stopped.

The experiment described in this report assesses the performance of gaskets that are subjected to temperatures found in the fire experiment. Both the exposed and protected situation are tested. The exposed situation is tested twice: once including and once excluding a segment cooling period of 22 hours.

Chapter 2 describes the overall experiment and the tests to be performed. Chapter 3 presents the results and observations. Chapter 4 discusses the results and presents conclusions.

2) EXPERIMENT SET UP

The experiment

The sealing performance of gaskets depends on compression, therefore the experiment focuses on the compressibility of the rubber gasket. Gasket compression characteristics will be recorded in the virgin state, after one day of stress relaxation and after heating in a compressive state. The material property "Shore A hardness" will be recorded of the virgin material and the heated material. The schedule of testing can be found in appendix A.

Two situations are tested: a protected and an unprotected segment joint, both include a cooling period. To evaluate the effect of temperatures in an unprotected segment joint during a fire, a third situation is tested as well: an unprotected segment joint without a cooling period. Three types of heating schemes are therefore needed for the test:

- Direct heat loading from the tunnel fire (2 hours)
- Direct heat loading from the tunnel fire (2 hours) + cooling phase (22 hours)
- Indirect heat loading (2 hours) + cooling phase (22 hours)

Temperatures during indirect heat loading and the cooling phase amount to 100°C and are independent of gasket location (in a segment joint with a single gasket configuration and common segment thicknesses). Temperatures resulting from direct heat loading are gasket location and gap width dependent. Results of a fire test [1] on gaps between concrete plates have shown that temperatures at the gasket location in a common configuration of a 11mm wide and 325mm deep gap, can reach values up to 200°C. This situation will be simulated in this experiment in the scheme: direct heat loading from the tunnel fire.

Gasket moulds

Compression characteristics of gaskets depend on the fitting they are placed in. Hence steel moulds are used to assess gasket performance. The gaskets are installed in the moulds the same way they would be in the groove of TBM tunnel segments. To create and maintain a fixed compression in the gaskets, the moulds were coupled by bolts (figure 1).
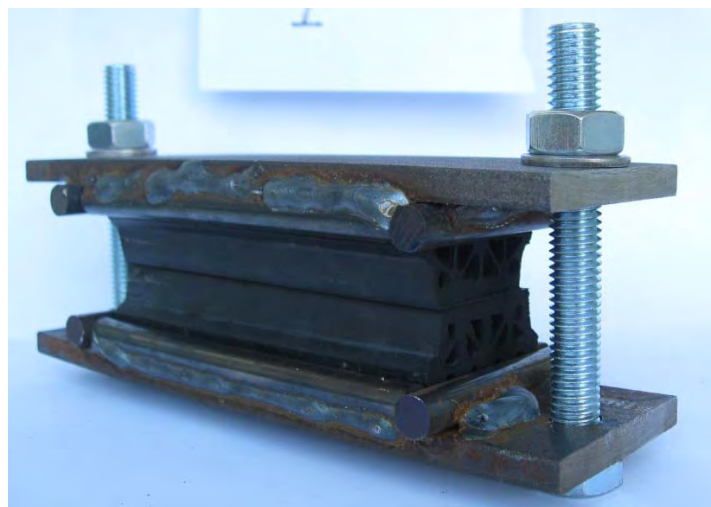

figure 1: Sealing gaskets installed in moulds

Gaskets

The gasket that is used for the experiment is called the "Groene hart tunnel" gasket (figure 2), it is manufactured by PDT-profiles (Germany). The gasket is made of an EPDM based rubber and has been used in several TBM projects (examples are the Hubertus tunnel, The Hague, The Netherlands and the Green Heart Tunnel, Leiderdorp, The Netherlands).

Limitations in testing facilities led to a sample length of 10cm. Typical compression tests performed by the producer of the gaskets are based on samples with a length of 20cm. Compression characteristics deviations from product specification are the result of imperfect moulds (gasket performance is strongly related to lateral support of the gasket) and increased boundary effects. This experiment, however, focuses on the change in performance of the gasket; qualitative testing is the first aim. Performance will be measured for the virgin sample as well as the relaxed and heated sample. Each sample has its own mould.

During stress relaxation, heating and cooling the gasketsystem is compressed 12mm with respect to the virgin state. The amount of compression is based on the Hubertus design [2]. To induce stress relaxation, compression is maintained for 24 hours.
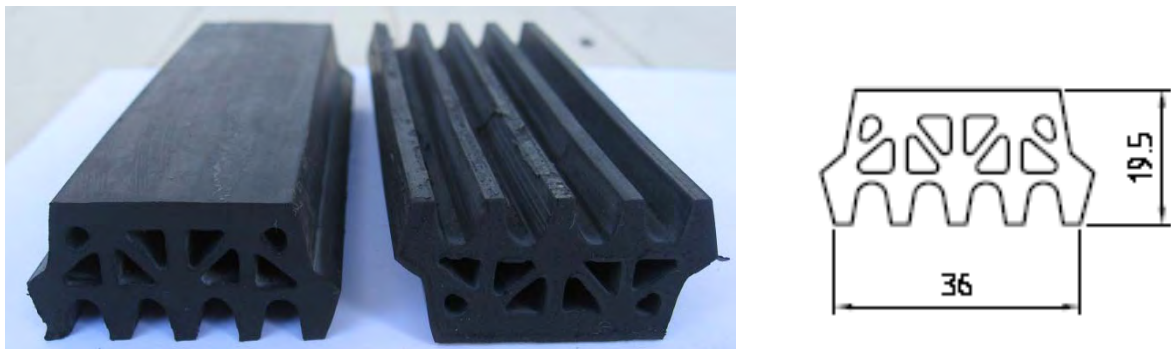
figure 2: Sealing gaskets

Sample height measurements

Sample heights measurements are performed on two gaskets stacked on top of each other without the moulds. Three different locations of the gasket are measured at each phase of the experiment: on the virgin material, after stress relaxation and after heating. Height measurements are performed with a vernier caliper.

Force-Displacement test

Force-displacement tests are performed for each sample and at all phases; virgin (3x), relaxed (2x) and heated (3x). The segment moulds are used for the compression test. A servo controlled pressure apparatus is used to compress the gaskets with a strain rate of 4 mm/minute, force is recorded as a function of displacement.

Shoremeter test

Shore A is a measure of hardness used in the rubber industry. Hardness is measured by the indentation of a ball or peg into a flat piece of rubber at a certain force. Shore A measurements have been taken on the virgin sample and all heated samples, on both gaskets of each sample. The shore meter used in this experiment can be found in figure 3. The accuracy of the

Shoremeter is +/- 5 Shore A, but is also influenced by sample size and the experience of the tester.

figure 3: Shore meter

Heating

Two ovens are used for the test and are running simultaneously. One oven is kept at a temperature of 200°C, the other oven is kept at a temperature of 100°C. All samples are heated according to a different scheme, but all have 12mm compression with respect to the virgin state. Sample one is subjected to the conditions resulting from direct heat of a tunnel fire, for two hours. Sample two is subjected to the conditions resulting from direct heat of the tunnel fire, for two hours, and to 100°C during the cooling period of 22 hours. Sample two represents the full cycle of thermal loading on an unprotected gasket. Sample three represents the protected situation and is subjected to 100°C for 24 hours.

After heating the samples are left to cool down. Compression is released when room temperature is reached.

3) RESULTS AND OBSERVATIONS

Observations

All moulds had slightly different shapes, leading to the requirement that the moulds are not interchangeable for the samples. All samples were identical in size and shape.

The gaskets were compressed multiple times, the internal structure showed a preferred deformation path: the top part shows collapse of the internal structure, the legs of the gasket stay intact.

During heating a rubbery smell was noticed (at 100°C as well as 200°C). No visual changes (e.g. vapour, flames or exhaust of liquid) were noticed.

All samples showed permanent deformation after cooling and removal of the moulds. The internal structure of all samples was severely deformed and looked like it was "frozen" in the position it was heated (figure 4).

figure 4: Permanent deformation of the gasket after heating

The material of the heated gaskets can still be described as rubber. It still exhibits elastic behaviour, but the material is a stiffer than the virgin material.

All samples exhibited the behaviour of sticking to each other and to their moulds, after being heated and cooled. Removing the samples from the moulds required moderate manual force and left the gaskets intact. A very thin, "permanent marker stripe" like residue was left on the mould. Separation of the gaskets by splitting required moderate manual force as well, the gaskets could be separated intact. After dissection of the samples, closer inspection revealed that parts of the collapsed internal structure were sticking to each other as well (figure 5).
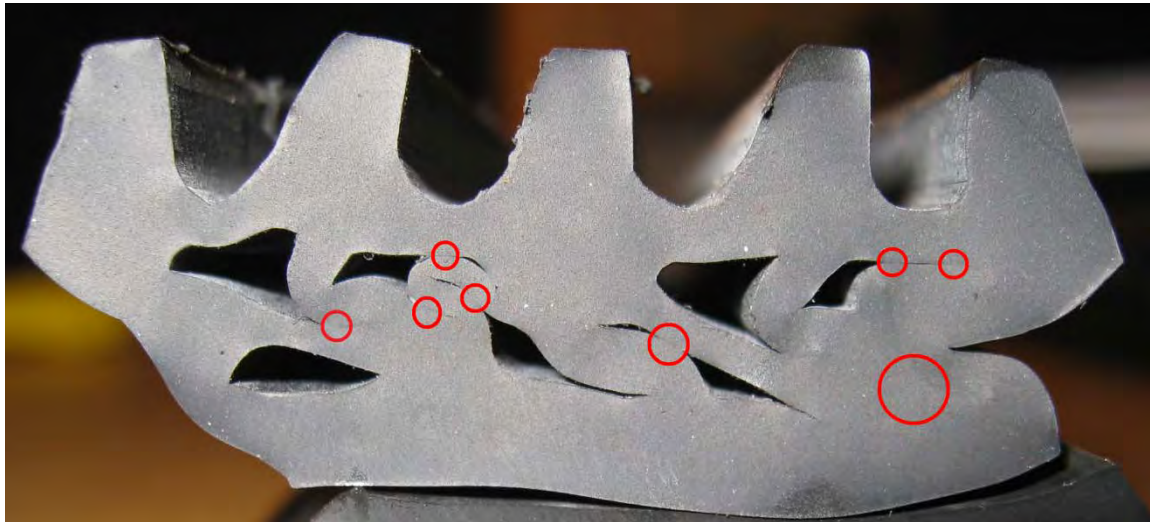
figure 5: Fused parts of the collapsed internal structure (indicated by red circles)

Results height measurements

The results of the height measurements can be found in table 1. The samples showed a permanent deformation of 0,1-0,2mm after stress relaxation. The permanent deformation after heating and cooling amounts to 7,6-8,1 mm. As combined gasket height is decreased by about 8mm, recovery from the 12mm compression is about 4mm.

Material	Sample 1 (direct heat: 2hrs 200°C)	Sample 2 (direct heat+cooling: 2hrs 200°C+22hrs 100°C)	Sample 3 (protected+cooling: 24hrs 100°C)
Virgin	39,0mm	39,0mm	39,0mm
Relaxed	38,8mm	38,9mm	38,8mm
Permanent deformation	0,2mm	0,1mm	0,2mm
Heated	31,0mm	31,4mm	30,9mm
Permanent deformation	8,0mm	7,6mm	8,1mm

table 1: results height measurements

Results pressure tests

The data gathered during the pressure tests have been used to create force-displacement diagrams, they can be found in appendix 2. All stress relaxed samples show decreased force resistance performance compared to their performance at virgin loading. The force-displacement characteristics of the intact gasket (virgin and stress relaxed) shows distinct features:

- Stress increase up to about 6mm compression
- From 6 to +/- 10mm very little stress increase
- +/- 10mm onwards increasing stress increase

The force-displacement relation of the heated samples does not resemble their original behaviour, it can roughly be described by a power law function.

The samples that were heated to 200°C maintained the stress level at 12mm compression (compared to the virgin state) that was found in the relaxed state at 12mm. The sample that was heated to 100°C showed a stress reduction at the same compression of about 45%.

Results Shoremeter measurements

The results of the Shoremeter tests can be found in figure 3. It can be seen that the sample that was heated at 200°C for two hours did not show a change in Shore A hardness, but the other samples did.

Sample	measurement 1 [Shore A hardness]	measurement 2 [Shore A hardness]	measurement 3 [Shore A hardness]	average [Shore A hardness]
virgin	64	63	64	64
Sample 1 side 1	62	64	63	64
Sample 1 side 2	63	66	65	
Sample 2 side 1	65	69	66	66
Sample 2 side 2	63	64	67	
Sample 3 side 1	68	68	69	68
Sample 3 side 2	72	68	64	

table 2: results measurements Shore A

Important notes to the shore meter measurements: To measure Shore A hardness correctly, the apparatus must be used on a flat, sufficiently large and thick surface. The deformed gaskets did not provide for those surfaces. Shoremeters are also very sensitive to way of handling.Hence, measurements were performed by one single person on the largest flat surfaces of the cross-section of the gasket.

4) CONCLUSION AND DISCUSSION

Conclusion

The 12mm compressed rubber gaskets heated up to temperatures of 100°C and 200°C show severe permanent deformation after cooling. The internal structure of the gasket remains collapsed, a permanent deformation is attained; the combined gasket height is decreased by about 8mm. As combined gasket height is decreased by about 8mm, recovery from the 12mm compression is about 4mm. Some compressive characteristics therefore remain in the gasket system.

The gaskets subjected to 200°C did not show a decrease in compression force at 12mm compression (compared to the virgin state). The sample that was additionally heated at 100°C did not show a noticeable difference in behaviour of the gasket compared to the gasket that was not subjected to an additional heating period.

The gasket subjected just to 100°C showed Compression behaviour at the first stage of compression however, was softer than the gaskets heated at 200°. The reaction force of the heated gasket at 12mm compression (compared to the virgin state) thereby decreased 45% with respect to the unheated, relaxed gasket. The reason for this discrepancy with the other samples is unknown.

The properties of the rubber will change due to heating, but the heated rubber still behaves like rubber, hardness will increase only slightly. This means that the gasket will still be in place and will not disintegrate or become porous due to temperatures caused by a tunnel fire. The fact that rubber hardness did not increase significantly, it can be said that gasket performance was mostly influenced by the fusing of parts of the collapsed internal structure.

The functionality range of the gaskets is severely decreased by compressed heating. If the gaskets would be heated in the same way when installed in a tunnel, the long term water seal cannot be guaranteed and leaking is most likely. If no large displacements occur, leaking may be marginal. The fact that the rubber has not disintegrated and the gaskets are fused together means that the remaining rubber can still function as a plug.

Discussion

The test does not fully represent the situation occurring in a TBM driven tunnel. The gasket is heated from all sides in experiment, in real tunnel just from one side and partly. Temperature gradients will therefore exist in the gasket, leading to differences in how the gaskets are affected by the high temperatures. Therefore, part of the gasket may still function even though the other part is permanently deformed.

The 200°C tests are based on heat transfer by radiation, but the heat transfer mode in the oven is convection.Higher temperatures lead to higher UV radiation levels. Rubber degradation is activated by UV radiation. However, this only occurs at the surface of rubber. Further degradation of the rubber is induced by the affected surface, but is a much slower process.

The shape of the moulds is imperfect compared to the shape of gasket grooves in concrete segments. This may lead to different failure patterns of the internal structure of the gasket. These failure patterns may prevent contact between parts of the internal structure, and hence no fusing between those parts. If fusing between parts of the internal structure does not occur, permanent deformation is less severe. It is however unlikely that this is the case. Gaskets have a

height of 19.5mm. In the most favourable situation 12mm compression of the gasket system will lead to 6mm compression of each gasket. As the legs of the gasket are well supported, this means that the top part of the gasket will collapse first. In order to reach 6mm compression, the internal structure of the top part must collapse severely and contact between parts of the internal structure is unavoidable.

Recommendation

All tests showed the behaviour of fusing between (parts of) the gaskets. This is a clear result, but it is beneficial to the designer of sealing gaskets / segment joints to know what the limits of the behaviour are. At what temperature does the fusing stop and at what temperatures does the rubber disintegrate. The time dependency of these processes also is of importance. It is therefore to recommend to perform more tests at different temperatures and durations.

The gasket type tested in this experiment is one of many products. It is to recommend to perform more tests on different gasket types and different rubber compounds.

The experiment can be altered to mimic the situation in a tunnel by replacing the steel mould by insulating boards. The sample can be isolated at all sides but the one to be exposed to heat. The effect of the temperature gradients can effectively be simulated by this procedure.

Another improvement of the test is to create better grooves. This way, the performance of all samples can be compared. To provide sufficient statistical data more iterations of the tests should be performed as well.

An addition to the experiment is recommended as well. The experiment only tests the compression performance of the gasket. Water seal performance is related to compression performance, but as proven by this experiment, heating the gasket alters the system. The test may be adapted by adding a water seal test.
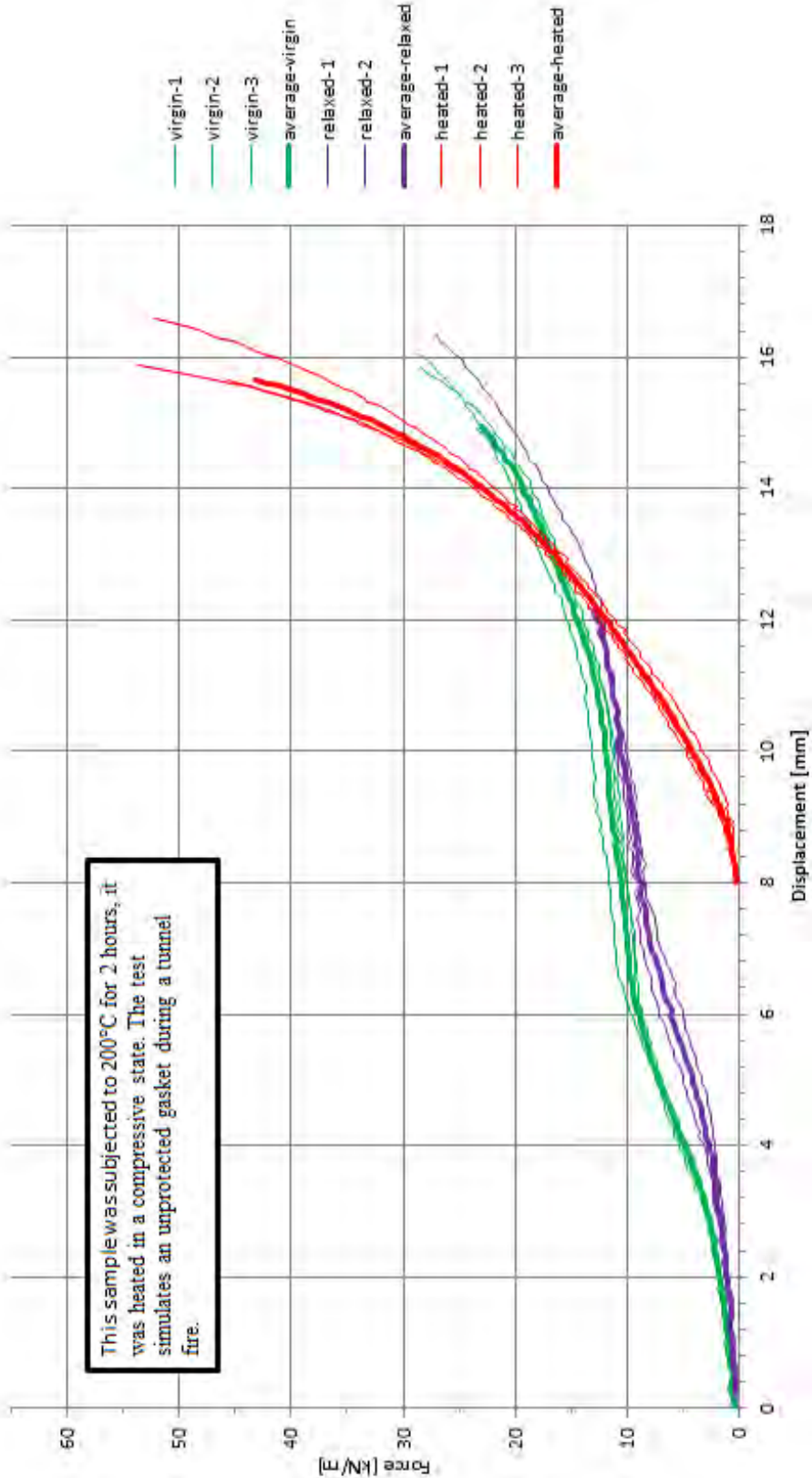
REFERENCES

1: Test report fire test
Appendix of MSc. Thesis Daan de Clippelaar (2011)
MSc. Thesis: Practical Passive fire protection – ensuring the waterseal of precast tunnel linings
Daan de Clippelaar
2: Berekeningsnota Afdichtingsprofiel tunnellining (2005)
Hubertus Tunnel Combinatie

APPENDIX A: EXPERIMENT SCHEDULE

Step	Time	Sample 1 (direct heat)	Sample 2 (direct heat+cooling)	Sample 3 (protected+cooling)
1	Day 1	Measurement of sample height		
2		Force-Displacement test		
3		Compression of gaskets by fixed displacement: 12mm		
4	Day 2	Gasket stress removal		
5		Measurement of sample height		
6		Force-Displacement test		
7		Compression of gaskets by fixed displacement: 12mm		
8		Oven: 200°C (2 hours)	Oven: 200°C (2 hours)	Oven: 100°C (24 hours)
9		Removal from oven: cooling phase	Oven: 100°C (22 hours)	
10	Day 3	Gasket stress removal	Removal from oven: cooling phase	Removal from oven: cooling phase
11	Day 4	-	Gasket stress removal	
12		Measurement of sample height		
13		Force-Displacement test		
14	Day 5	Shoremeter tests, a piece of virgin material is incorporated in this test as well		

APPENDIX B: DATA PRESSURE TESTS

Force-Displacement diagram - Sample 1

This sample was subjected to 200°C for 2 hours, it was heated in a compressive state. The test simulates an unprotected gasket during a tunnel fire.

Legend: virgin-1, virgin-2, virgin-3, average-virgin, relaxed-1, relaxed-2, average-relaxed, heated-1, heated-2, heated-3, average-heated

Force-Displacement diagram - Sample 2

This sample was subjected to 200°C for two hours and 100°C for 22 hours, it was heated in a compressive state. The test simulates the thermal conditions in an unprotected segment joint during the heating and cooling phase of a tunnel fire event

Legend:
- virgin-1
- virgin-2
- virgin-3
- average-virgin
- relaxed-1
- relaxed-2
- average-relaxed
- heated-1
- heated-2
- heated-3
- average-heated

Force [kN/m]

Displacement [mm]

13

Force-Displacement diagram - Sample 3

This sample was subjected to 100°C for 24 hours, it was heated in a compressive state. The test simulates a protected gasket combined with steam production in the segment joint.

Legend: virgin-1, virgin-2, virgin-3, average-virgin, relaxed-1, relaxed-2, average-relaxed, heated-1, heated-2, heated-3, average-heated

Axes: Force [kN/m] vs Displacement [mm]

14

APPENDIX C: PICTURES

Virgin material:
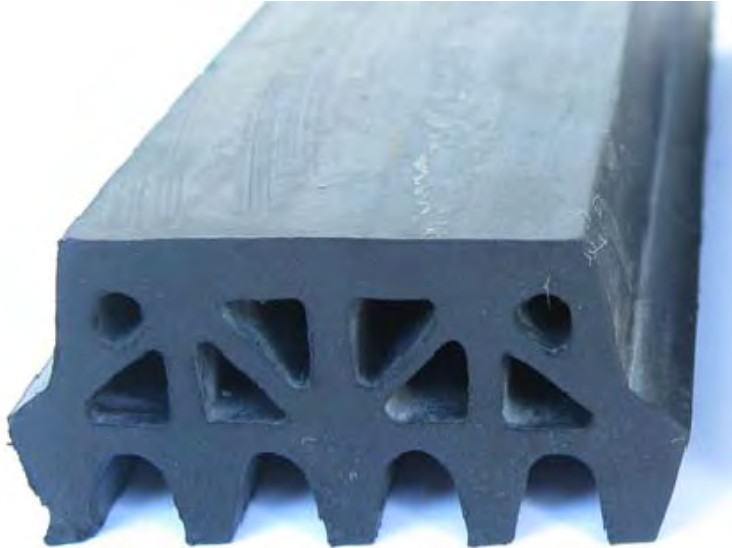
Sample 1 after heating:

Sample 2 after heating:

Sample 3 after heating:

APPENDIX C: GASKET TEMPERATURE CALCULATION

Temperature development due to radiation

PC Tempflow 4.51

PC Tempflow was used to perform calculations on temperature development at the gasket. The simulation application can be used to perform 1-dimensional transient temperature development calculations.

Input data

The program requires input data on material properties and heat loading scheme. The material properties to be used are:

-     Specific mass
-     Specific heat
-     Heat conduction coefficient

Specific heat can be configured to be temperature dependent.

The program also requiresdimensional properties of the layer: layer thickness.

The heat loading scheme can be set to a time-temperature relation, radiation-temperature relation, or a combination of both.

Modelling the temperature development at the gasket

A combined temperature and radiation heat loading scheme is used to model the temperature development. As steam will be expelled into the segment joint, the surrounding air temperature can be set to 100°C. Radiation levels depend on time (as radiation levels depend on the RWS curve) and viewfactor (gap dimensions and flame intrusion).

The heat loading scheme is subjected to a layer with a thickness of 50mm, that has the material properties of rubber:

-     Specific heat: 1,5kJ/kg°C
-     Specific mass: 2400kg/m^3
-     Heat conduction coefficient: 0,3

Behind the rubber layer, a wet soil layer with a thickness of 250mm is modelled.

-     Specific heat: 1kJ/kg°C
-     Specific mass: 2400kg/m^3
-     Heat conduction coefficient: 0,2

Temperature development is recorded at the surface that is subjected to the heat loading.

Settings PCTempflow (version: 4.51)
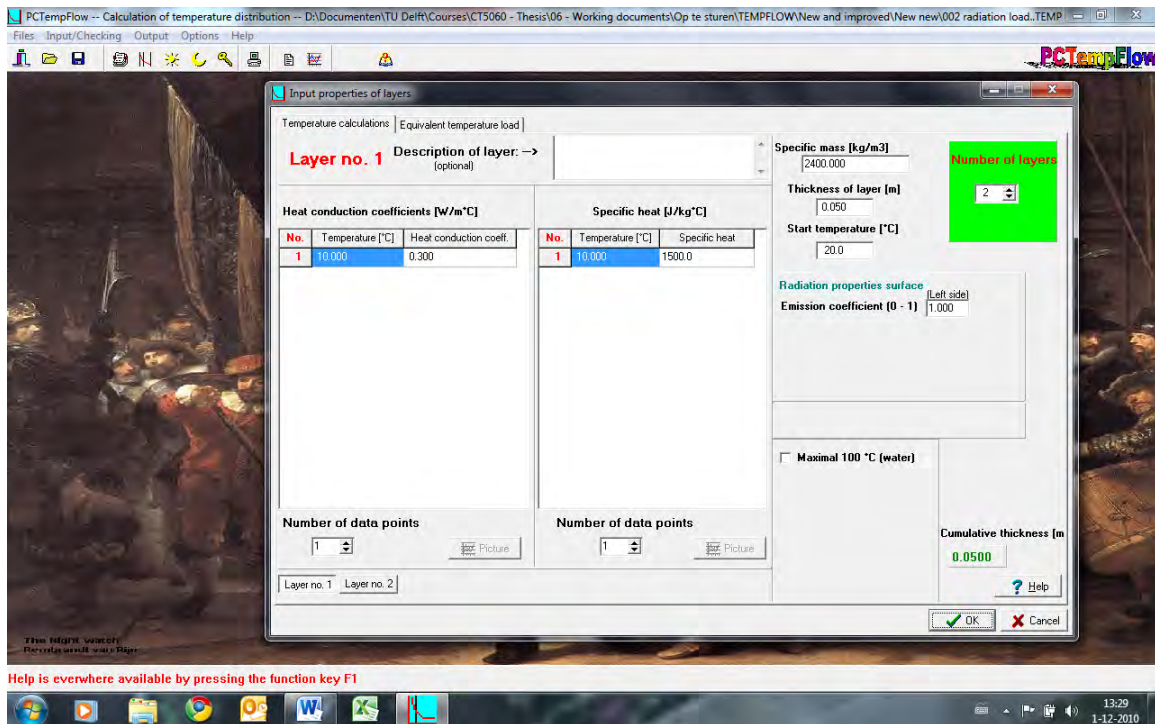

figure1: PCTempflow
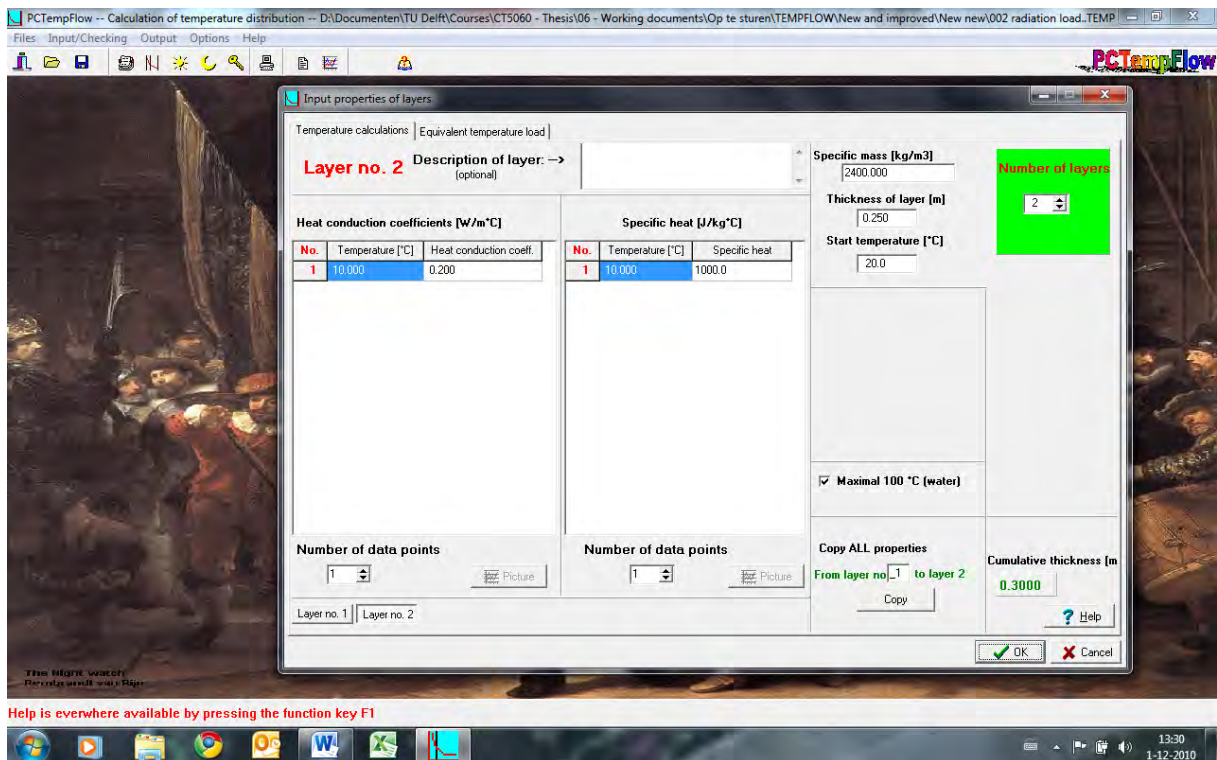

figure 2: Settings layer 1 (rubber)

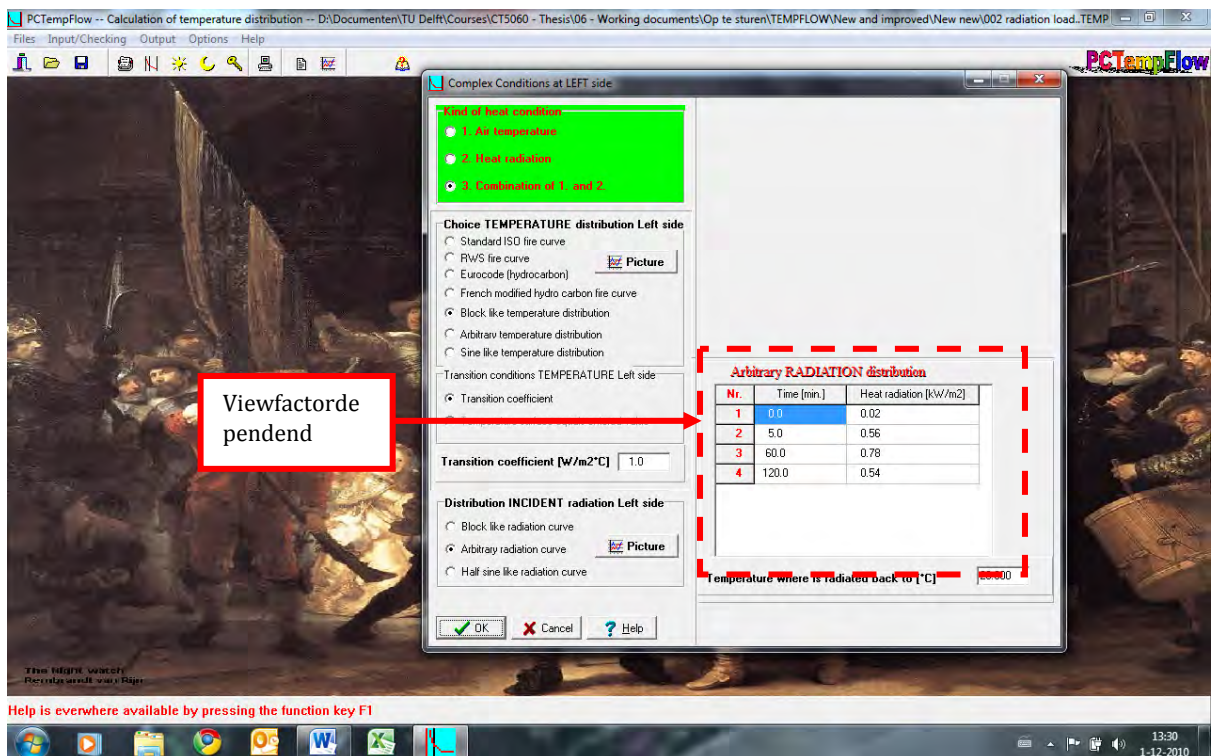figure 3: Settings layer 2 (wet soil)

figure 4: heat loading

PCTempflow only allows input of 4 radiation intensities as a function of time. The radiation intensity curve of the RWS design fire therefore has been adjusted:
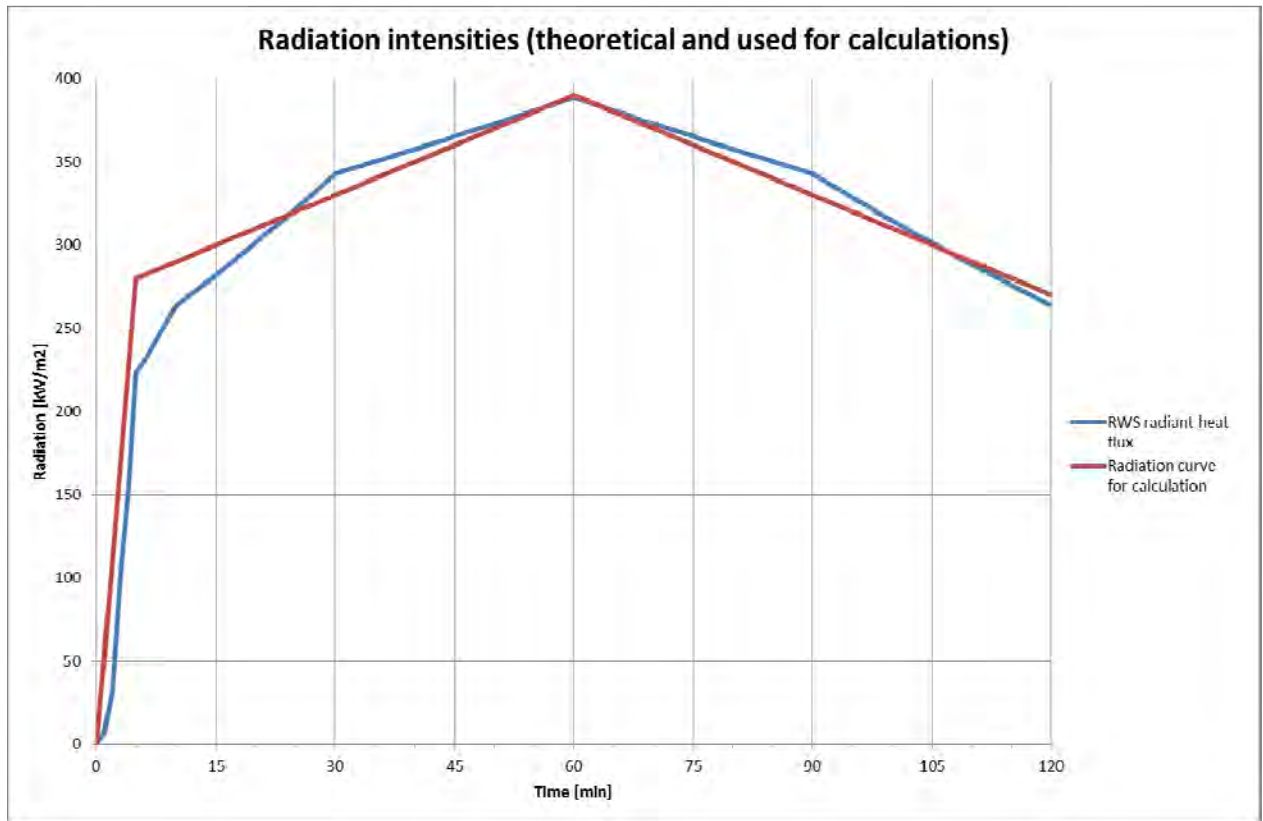
The radiation intensities (view factor= 1)are:

Time [min]	Radiation intensity [kW/m²]
0	0,02
5	280
60	390
120	270

table 1: maximum radiation intensities for calculations (view factor=1)

Temperature development is calculated for several view factors. The input values for radiation at each view factor:

View factor	Radiation [kW/m²] 0 minutes	Radiation [kW/m²] 5 minutes	Radiation [kW/m²] 60 minutes	Radiation [kW/m²] 120 minutes
0.002	0.02	0.56	0.78	0.54
0.004	0.02	1.12	1.56	1.08
0.006	0.02	1.68	2.34	1.62
0.008	0.02	2.24	3.12	2.16
0.010	0.02	2.80	3.90	2.70
0.012	0.02	3.36	4.68	3.24
0.014	0.02	3.92	5.46	3.78
0.016	0.02	4.48	6.24	4.32
0.018	0.02	5.04	7.02	4.86
0.020	0.02	5.60	7.80	5.40
0.022	0.02	6.16	8.58	5.94
0.024	0.02	6.72	9.36	6.48
0.026	0.02	7.28	10.14	7.02
0.028	0.02	7.84	10.92	7.56
0.030	0.02	8.40	11.70	8.10

table2: input valuesradiationintensities

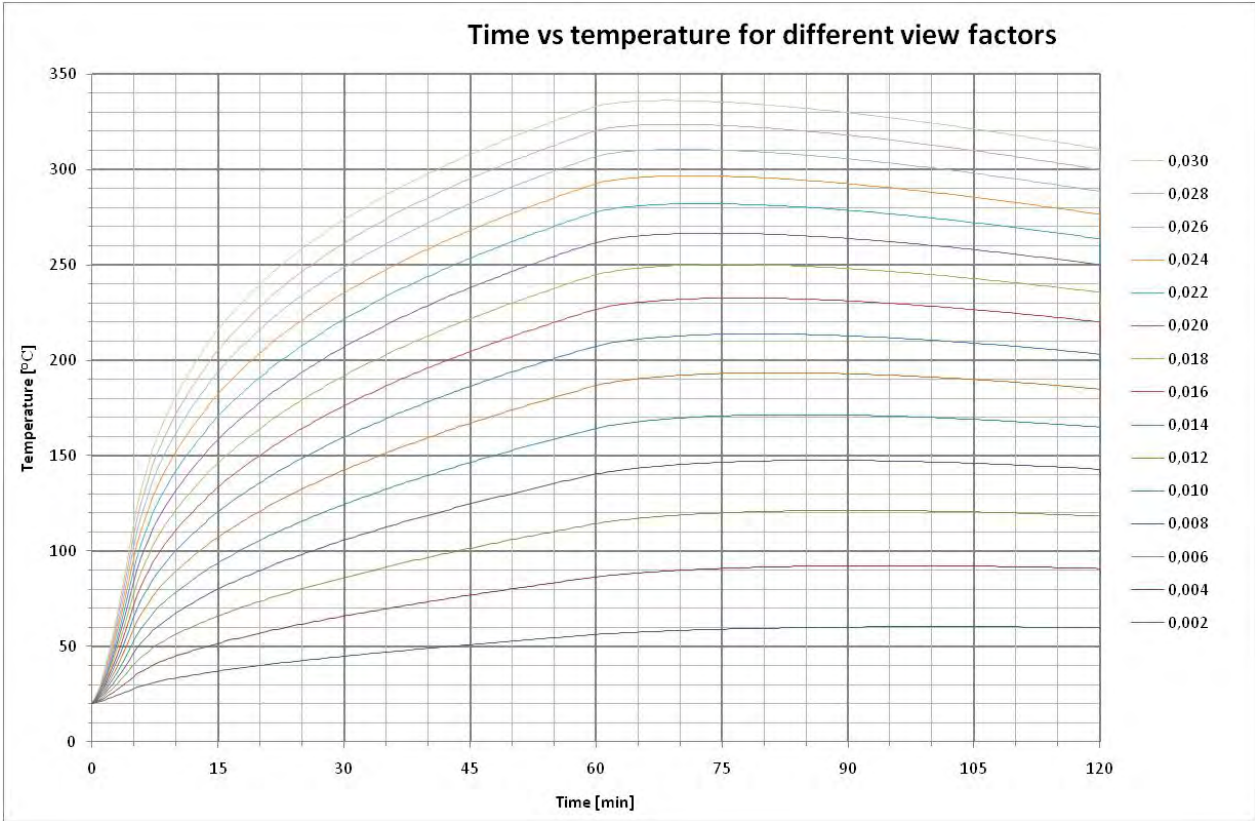Calculations with PCTempflow gave the following theoretical time-temperature relations for different view factors:

figure 6: Time-Temperature relations calculated by PCTempflow

APPENDIX D: RECORDED VS. THEORETICAL TEMPERATURES AT GASKET
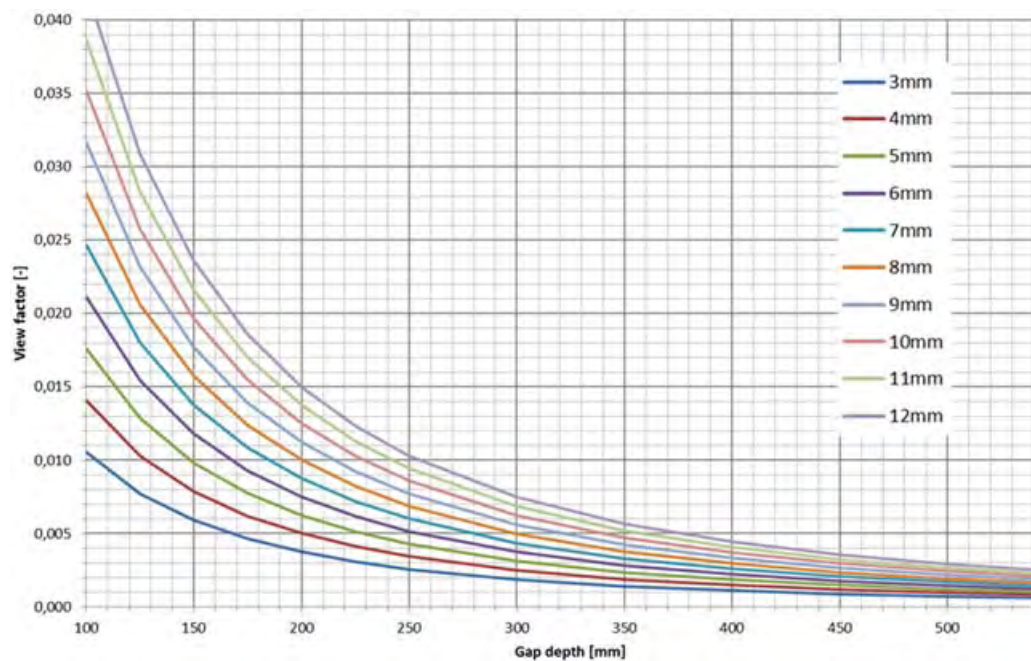
Recorded temperatures

An experiment was performed on the temperature development at several depths between two concrete plates. Time temperature-relations were therefore recorded for several theoretical gaps in segment joints.

The depths of these theoretical gaps can be corrected for flame intrusion, thereby finding the flame-gasket distances.

The recorded temperatures and the flame intrusion levels can be found in appendix A of this thesis.

Calculated temperatures

Temperature development has also been calculated for different flame-gasket distances (appendix C of this thesis). The temperature development is calculated for different view factors. View factor values depend on gap dimensions:

Comparison

The recorded and calculated time-temperature relations are plotted side by side in the following graphs. The recorded temperatures are plotted in a thick red line, the lower and upper bound theoretical temperature development are the upper and the lower thick lines. The most likely view factor is plotted in a yellow dashed line. If the most likely view factor coincides with the estimation, the yellow dashed line is plotted. The accurateness of the calculation is then assessed.

Time vs temperature 1-250
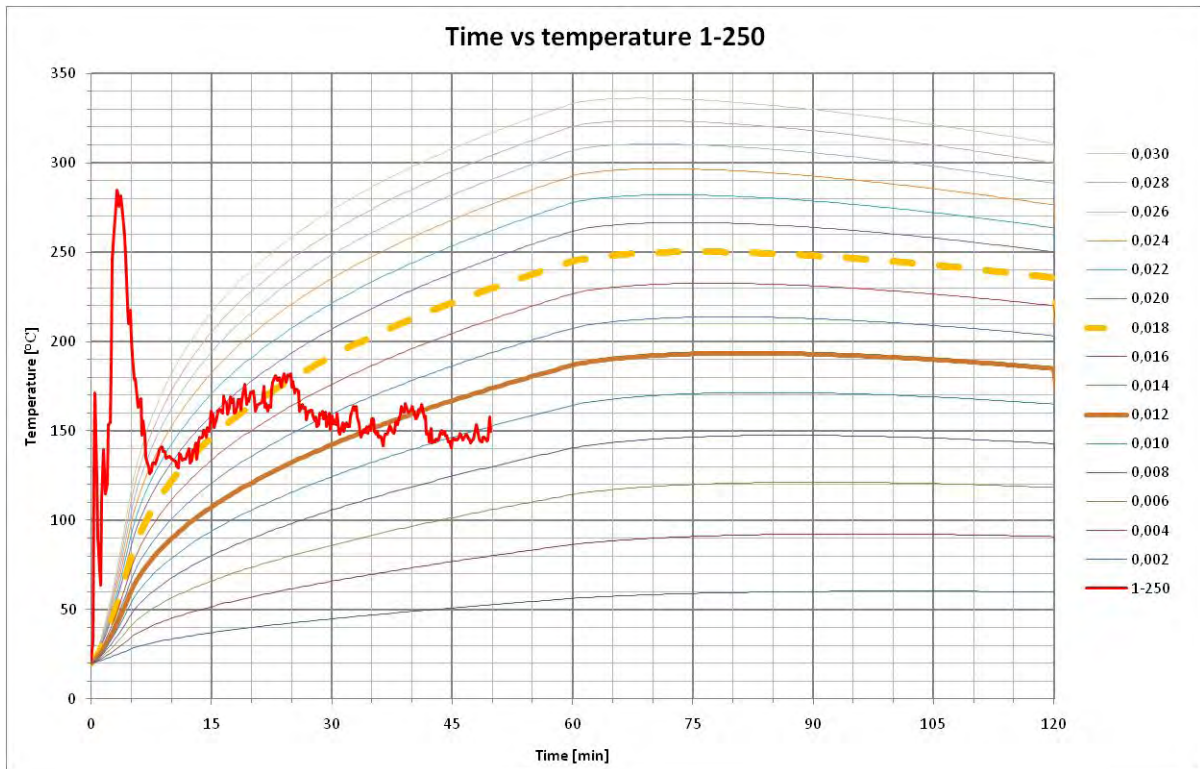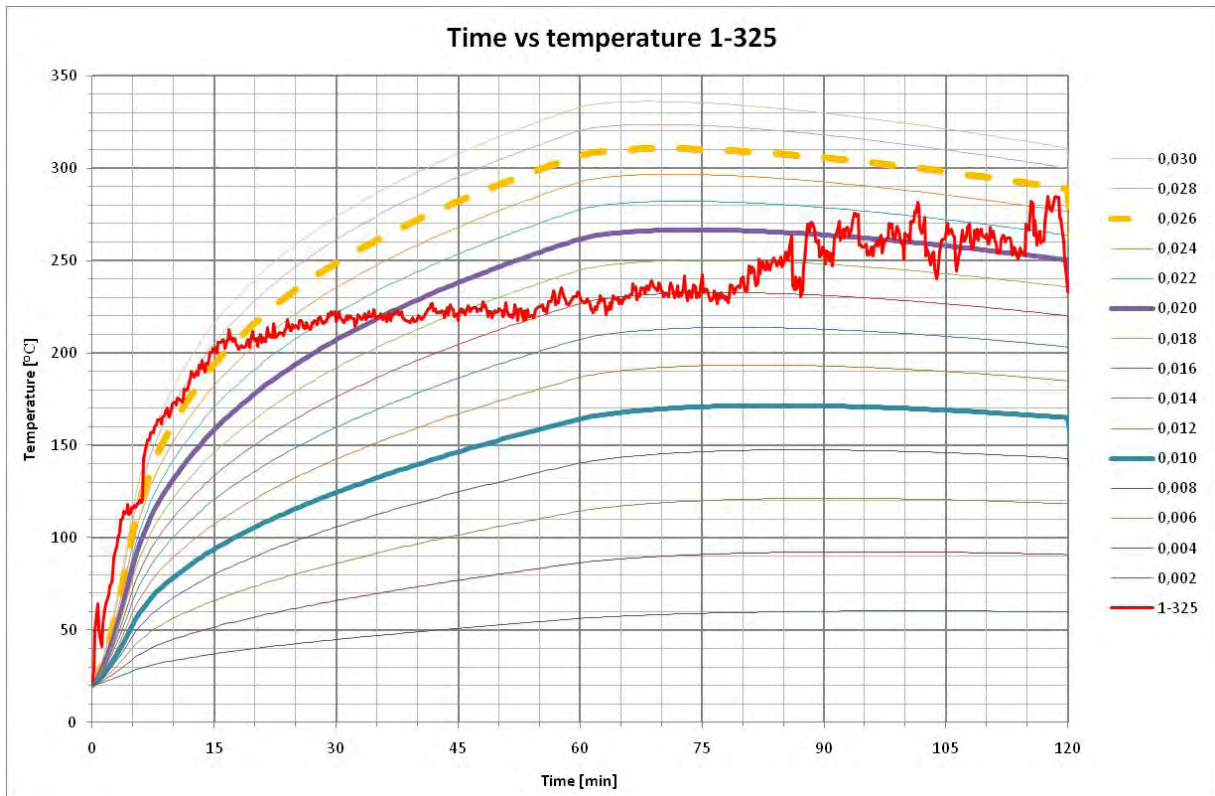
Theoretical gap depth: 250mm
Theoretical view factor: 0.00925
Gap depth after intrusion: 166-218mm
View factor after intrusion: 0.018 – 0.012
Severity of leakage: +++

Most likely view factor: 0.018

Relation most likely view factor to view factor after intrusion: **fairly accurate**

Peak in first 5 minutes: Most likely to be the result of a gas leak. The connection between the concrete and the heat resistant board was flawed at the 250mm gap. Steam was noticed to escape at the start of the test. The concrete blocks were glued together by a thermo expansive glue. It is believed that this glue was activated after some time in the test, sealing the gap and ending the gas leak.

Time vs temperature 1-325
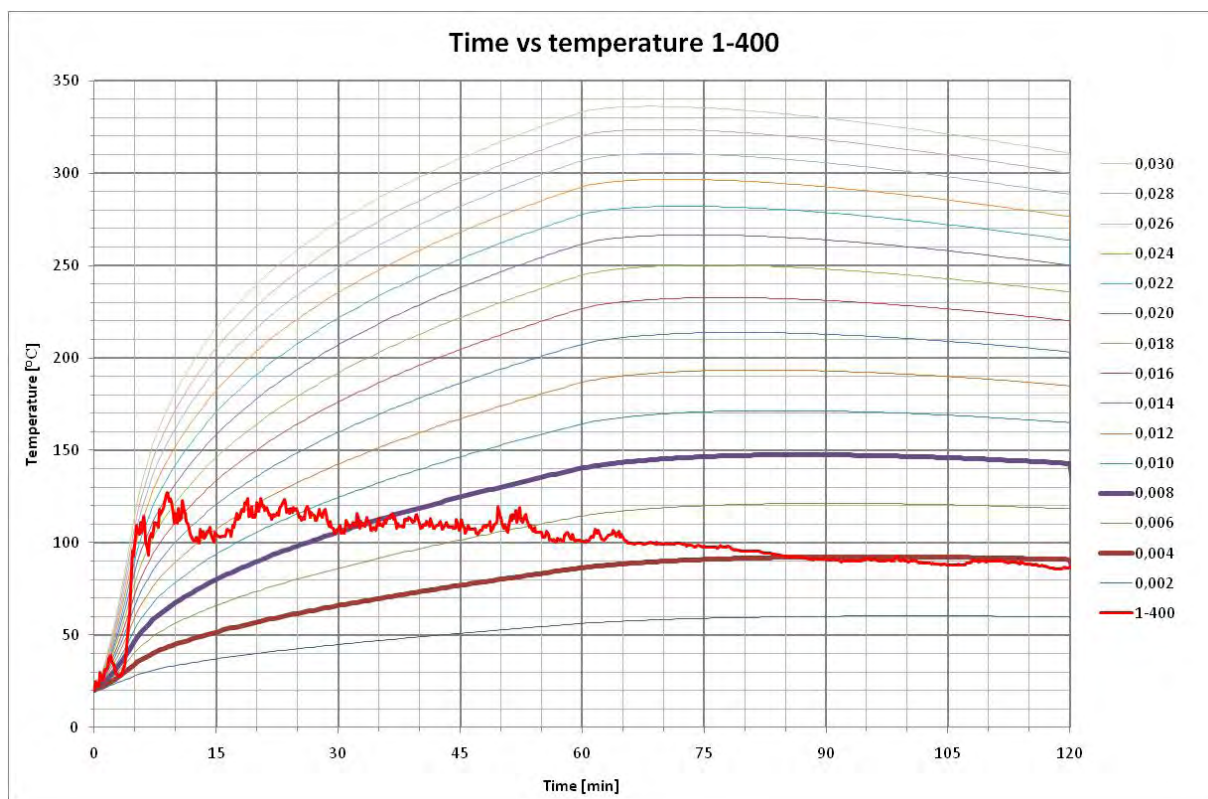
Theoretical gap depth: 325mm
Theoretical view factor: 0.006
Gap depth after intrusion: 162-258mm
View factor after intrusion: 0.020 – 0.010
Severity of leakage: +⁺/.

Most likely view factor: 0.025

Relation most likely view factor to view factor after intrusion: **slight underestimate (17mm)**

Slightly underestimated because: as the view factor values increase, incremental difference in gap depth decreases. The difference between calculated view factor and most likely view factor is about 20mm.
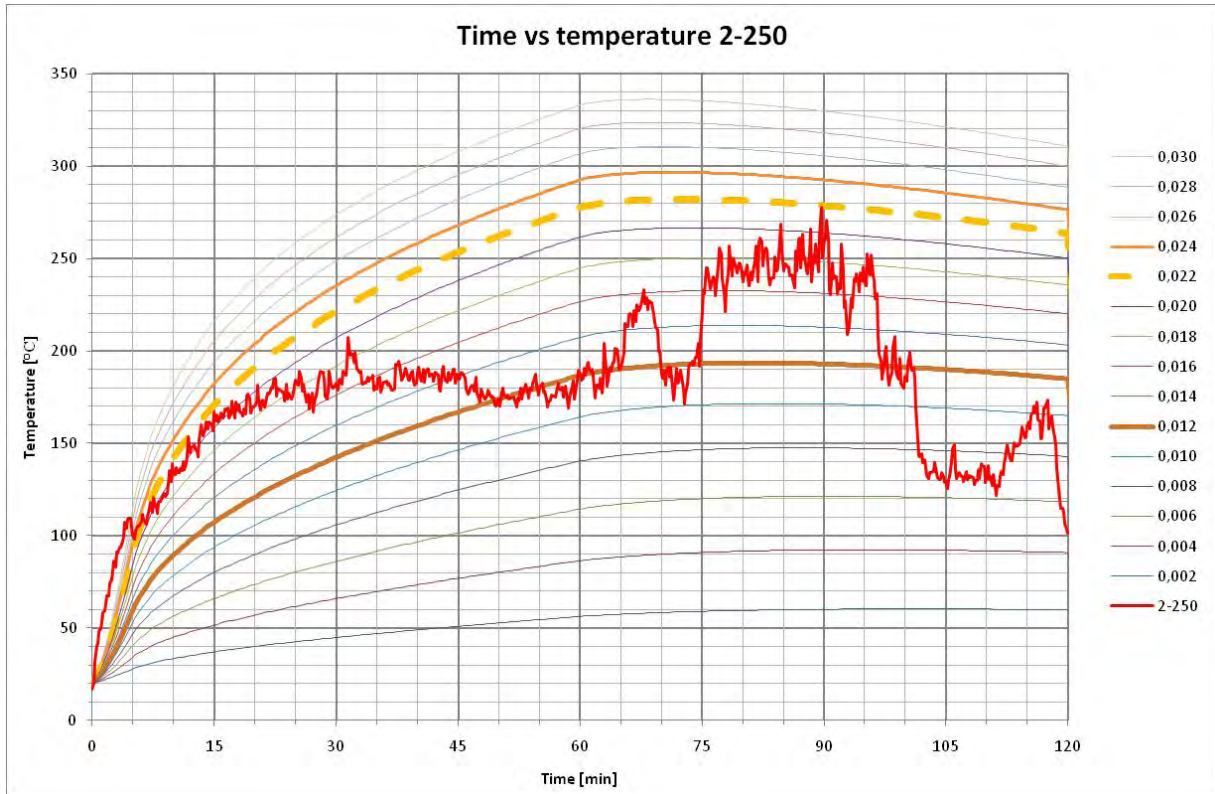
Time vs temperature 1-400

Theoretical gap depth: 400mm
Theoretical view factor: 0.004
Gap depth after intrusion: 302-353mm
View factor after intrusion: 0.008 – 0.004
Severity of leakage: --

Most likely view factor: inconclusive

Relation most likely view factor to view factor after intrusion:**inconclusive**

Inconclusive because: as soon as the temperature reaches 100°C, the curve does not follow the theoretical curve but remains at temperatures slightly higher than 100°C.

Time vs temperature 2-250

Theoretical gap depth: 250mm
Theoretical view factor: 0.00925
Gap depth after intrusion: 140-208mm
View factor after intrusion: 0.024 – 0.012
Severity of leakage: -

Most likely view factor: 0.022

Relation most likely view factor to view factor after intrusion: **slight overestimate (10mm)**

Slightly overestimated because: as the view factor values increase, incremental difference in gap depth decreases. The difference between calculated view factor and most likely view factor is about 10mm.
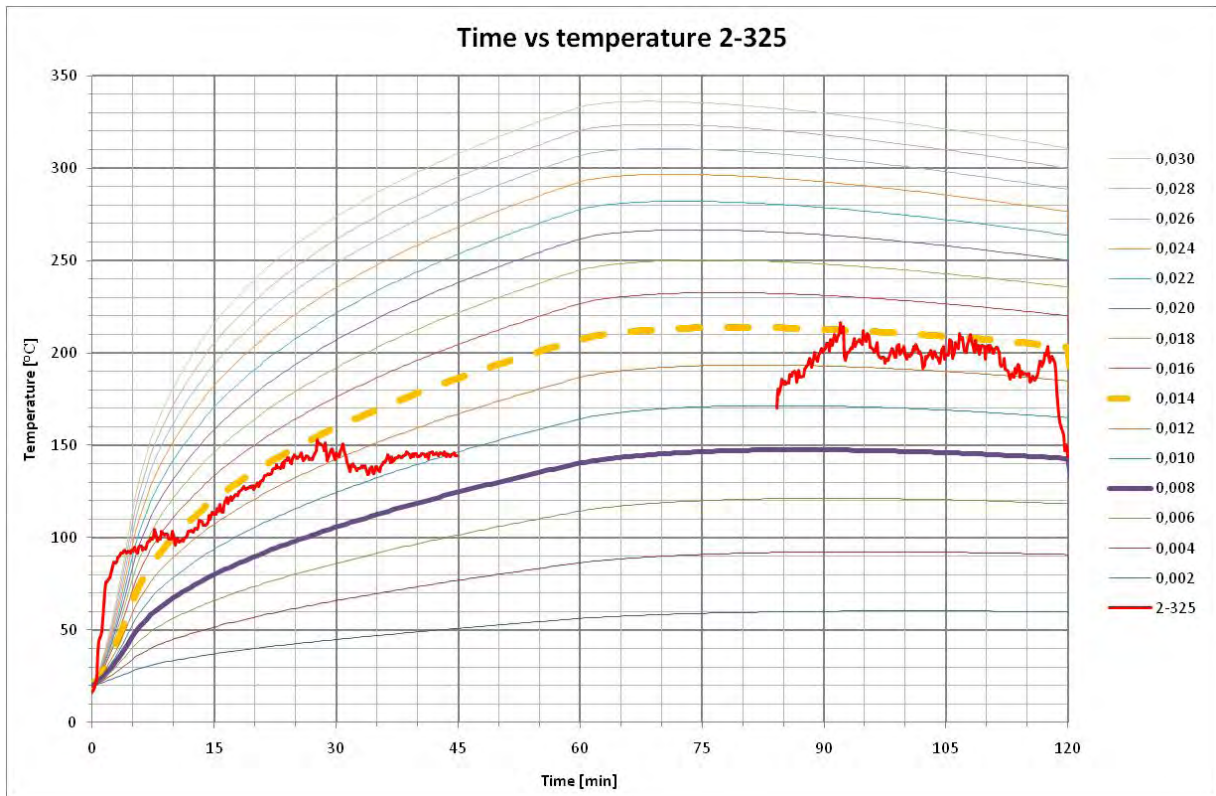
Time vs temperature 2-325

Theoretical gap depth: 325mm
Theoretical view factor: 0.006
Gap depth after intrusion: 200-280mm
View factor after intrusion: 0.014 – 0.008
Severity of leakage: +$^+$/$_-$

Most likely view factor: 0.014

Relation most likely view factor to view factor after intrusion: **<u>fairly accurate</u>**

Time vs temperature 2-400
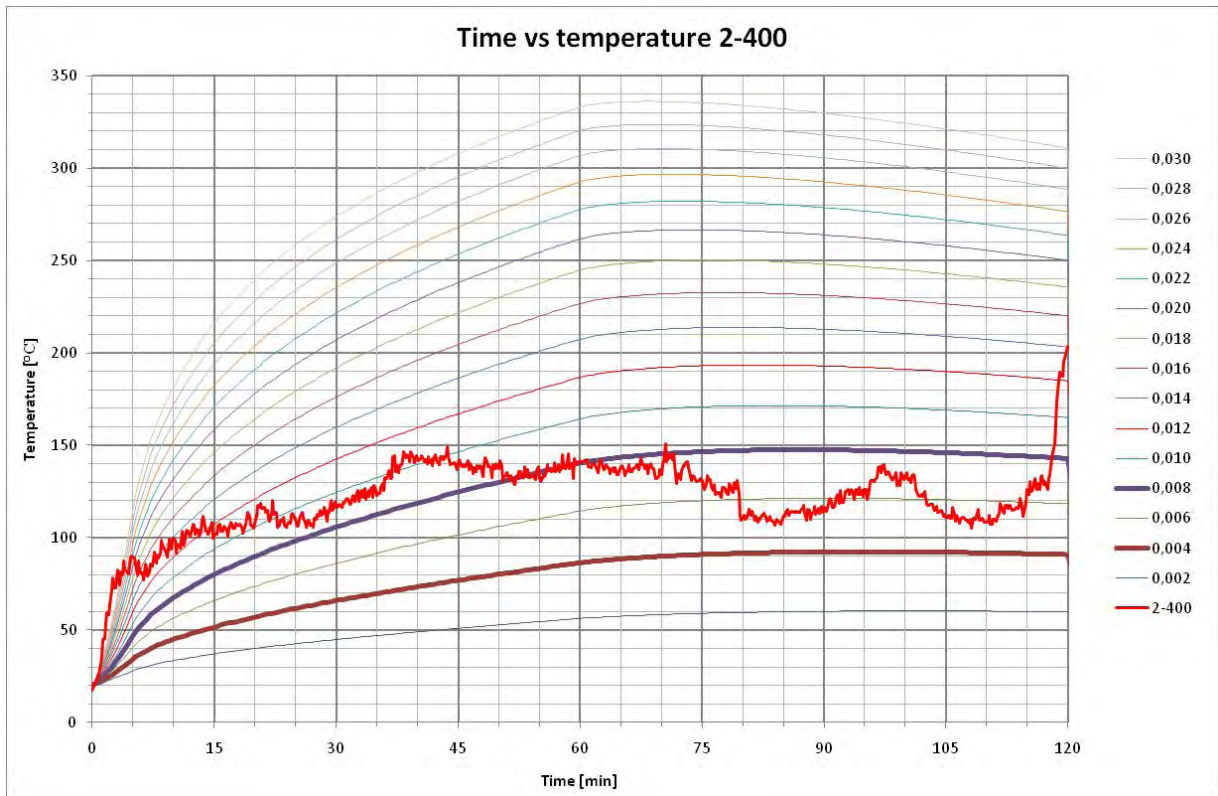
Theoretical gap depth: 400mm
Theoretical view factor: 0.004
Gap depth after intrusion: 282-357mm
View factor after intrusion: 0.008 – 0.004
Severity of leakage: +

Most likely view factor: inconclusive

Relation most likely view factor to view factor after intrusion:**inconclusive**

Inconclusive because: as soon as the temperature reaches 100°C few similarities can be found with the theoretical curves. Therefore a comparable theoretical curve cannot be chosen.

APPENDIX E: VENTILATION TYPES

Natural ventilation

Natural ventilation is based on density differences of gases. Because fires create high temperatures, gases produced by fire generally have a lower density than cold air. An upward movement of gases is therefore to be expected. Cold air is used by the fire to produce hot gases. The exhaust of hot gases therefore causes cold air to be drawn towards the fire.
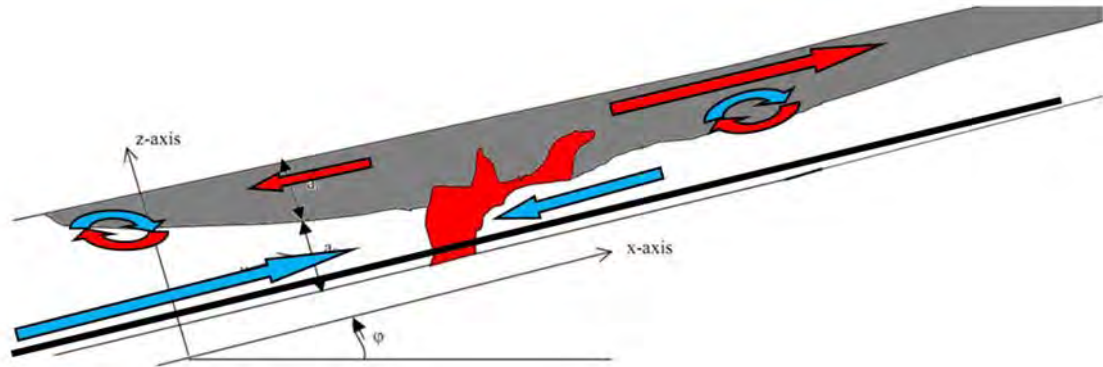

FIGURE 1: SMOKE-AIR STRATIFICATION IN TUNNELS [1]

The light hot smoke is accumulating at the ceiling and is transported out of the tunnel, the fresh heavy air is entering the tunnel in the lower part of the tunnel. An equilibrium between the smoke and fresh air layer therefore develops during the fire: gases in the tunnel become stratified. Slopes in tunnels influence this process. Speed and direction of the exhaust of smoke and supply of air can be governed by the slopes in a tunnel (figure 1). Because the supply of fresh air takes place at the lower part of the tunnel cross-section, ventilation capacity may be hindered by vehicles in the tunnel.

Another important problem of natural ventilation is destratification. This may occur at greater distance from the fire and is caused by cooling of the smoke. Destratification will eventually lead to underventilated fires and increases the risk of the presence of explosive gases in other parts of the tunnel.

Mechanical ventilation

Mechanical ventilation systems can be divided into longitudinal and transverse systems. The conceptual differences are presented in figure 2. Longitudinal ventilation is often used in one-way traffic tubes shorter than four kilometres and preferably blows air in the same direction as the traffic flow. Two-way traffic tubes and tunnels longer than four kilometres mostly use transverse ventilation. By directing hot gases away from tunnel users and new fuel sources, mechanical ventilation can be used to prevent loss of life and fire spread in the tunnel.

Hot smoke in a tunnel will always try to follow the path of natural ventilation. This means that if the mechanical ventilation capacity is insufficient, smoke will flow in the opposite direction of the mechanical ventilation. This phenomenon is called backlayering and should be avoided to provide a safe escape route for tunnel users, and to prevent fire spread to other vehicles.
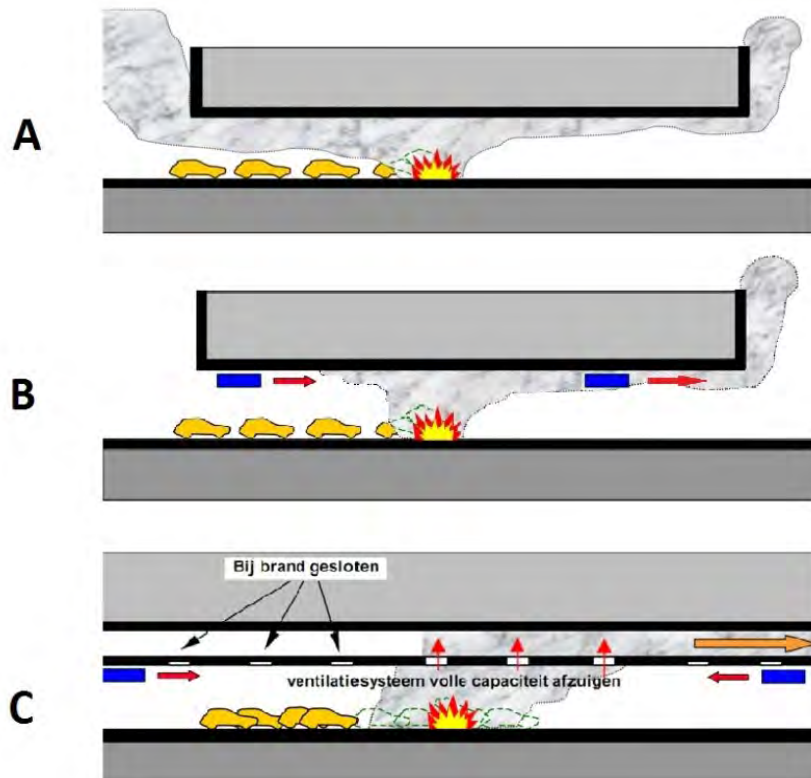
A: natural ventilation
B: longitudinal ventilation
C: transverse ventilation

FIGURE 2: TUNNEL VENTILATION METHODS [2]

References

[1]   Rigter, B.P.
        Two layer theory applied on the phenomenon of backlayering
        11th International symposium on Aerodynamics & Ventilation of vehicle tunnels
        Luzern, Switserland, 7-9 July (2003), p191-218

[2]   Huyben, J.W.
        Lecturenotes: Ventilatie van Weg Tunnels
        PAO 2006, The Netherlands
        http://www.rijkswaterstaat.nl/rws/bwd/home/pdf/tunnel/pao/VOV_11a_Huijben.pdf

APPENDIX F: DESIGN FIRES

T² design fire (pre-flashover)

The mathematical expression of the relationship can be found in equation 1. The relation is based on the peak HRR of the fully developed fire, and the characteristic growth time. The characteristic growth time represents the time needed to grow from ignition to the fully developed fire.

$$\text{t}^2 \text{ design fire:} \qquad HRR = HRR_{max}\left(\frac{t}{t_g}\right)^2$$

HRR:	Heat release rate	[W]
HRR_{max}:	Peak heat release rate (fully developed fire)	[W]
T:	time	[s]
t_g:	Characteristic growth time	[s]

slow fire growth rate	$t_g=$	600 (s)
medium fire growth rate	$t_g=$	300 (s)
fast fire growth rate	$t_g=$	150 (s)
ultra-fast fire growth rate	$t_g=$	75 (s)

EQUATION 1:PRE-FLASHOVER DESIGN FIRE: "T²"[1]

Cellulosic curve (ISO-834, flashed over)

The curve is based on a mathematical relation found in equation 2.

$$\text{ISO} - 834 \text{ curve:} \qquad T = 20 + 345 \times \log_{10}\big((8 \times t) + 1\big)$$

T	Temperature	[°C]
t	Time	[s]

EQUATION 2: FULLY DEVELOPED DESIGN FIRE: "ISO-834 CURVE" [2]

Hydrocarbon curve (flashed over)

$$\text{HC curve:} \qquad T = 20 + 1080 \times (1 - 0.325 \times e^{-0.167t} - 0.675 \times e^{-2.5t})$$

$$\text{HCM curve:} \qquad T = 20 + 1280 \times (1 - 0.325 \times e^{-0.167t} - 0.675 \times e^{-2.5t})$$

T	Temperature	[°C]
t	Time	[s]

EQUATION 3: FULLY DEVELOPED DESIGN FIRE: "HC AND HCM CURVE" [2]

HC curve = hydrocarbon

HCM curve = hydrocarbon modified

RABT-ZTV curve (flashed over)

The RABT-ZTV curves are the result of a series of test programmes. They were developed in Germany and are the only commonly used curves that incorporate a cooling phase. The curves cannot be written as a simple mathematical expression. The curve is therefore described by a set of points in the time-temperature space (table 1). The curve follows a linear path between the points. The RABT-ZTV curve reaches temperatures of 1200 degrees Celsius and shows a high temperature gradient in the first five minutes of the fire. It is the only design fire that incorporates a cooling phase.

RABT-ZTV (train)		RABT-ZTV (car)	
Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	15	0	15
5	1200	5	1200
60	1200	30	1200
170	15	140	15

TABLE 1: FULLY DEVELOPED DESIGN FIRE: "RABT-ZTV CURVE" [2]

RWS-curve (flashed over)

The RWS curve is developed by the Dutch Ministry of Transport and is used across the globe. It is the most severe fire loading scheme for tunnels at the time of this writing. The curve is based on a worst case scenario hydrocarbon fire. It is assumed that an incident with a fuel, oil or petrol tanker with a volume of fifty cubic meters has occurred, and that a pool fire of one hundred fifty square meters has resulted from the incident. Like the RABT-ZTV curve, the RWS curve is described by a set of points in the time-temperature space (table 2).

RWS	
Time (minutes)	Temperature (°C)
0	20
3	890
5	1140
10	1200
30	1300
60	1350
90	1300
120	1200
180	1200

TABLE 2: FULLY DEVELOPED DESIGN FIRE: "RWS CURVE" [2]

The RWS curve reaches a maximum temperature of 1350 degrees Celsius and shows a high temperature gradient in the first five minutes. The course of the RWS design fire has been confirmed by full scale fire tests in the Runehamar tunnel in Norway [2].

The duration of the fire has been estimated in the following way [3]:

- A load factor of 80% to 90% is considered, leading to a fuel volume of 45000 l
- Gasoline has a specific gravity of 0,72 kg/l, so 32400 kg of gasoline is present in the tanker
- The specific heat of gasoline is 43,5 MJ/kg, the tanker therefore contains 1409400 MJ
- A fire with an average HRR of 200 MW can therefore burn for 118 minutes

In order to simulate larger fires, the duration of the RWS design fire is sometimes prolonged to one hundred and eighty minutes.

References

[1]   European Thematic Network: Fire in Tunnels
        Fire in Tunnels – Technical report part 1 – Design fire scenarios
        2006

 [2]   Promatb.v.
        http://www.promat-tunnel.com/en/index.aspx

[3]   Rijkswaterstaat (Dutch ministry of public transportation)
        VRC-Documents: Veiligheids richtlijnen deel C
        2010