Abstract
Efectis Nederland is developing a mobile furnace, which is capable of determining the concrete spalling sensitivity of existing concrete tunnel linings. The aim of this mobile furnace is to qualify and quantify the spalling sensitivity of the concrete under typical tunnel fire loads, such as the RWS fire curve.

This paper describes the minimum requirements of a mobile furnace based on the fundamental background of the phenomenon of concrete spalling. Furthermore, the design of the mobile furnace is shown in combination with the spalling results achieved with different concrete mixes. In addition a calculation is shown which compares the internal concrete temperatures achieved with the mobile furnace and with the RWS fire curve.

1. INTRODUCTION
For new tunnels there are extensive fire testing methods, which in general imply that a special test specimen is manufactured and tested in a fire laboratory. However, for existing tunnels a reliable and cost-efficient testing method for fire resistance testing still does not exist.

The urgency of an adequate and reliable test method for the spalling sensitivity of concrete tunnel linings under a fire load is very clear. A big share of today’s tunnels have been constructed about 40 years ago, which implies that these tunnels will soon need renovation. When renovating tunnels questions arise such as “What is the current fire resistance rating of the concrete lining?” or “How sensitive is the concrete to spalling?”. Several testing methods for existing tunnels have been proposed, such as fire testing on small concrete cores extracted from the tunnel. However none of these methods is able to study a substantial area of the tunnel and preserving the most important boundary conditions present in a real tunnel, such as compression stress on the concrete and relative humidity.

2. REQUIREMENTS
In order to design an appropriate mobile furnace for testing the spalling sensitivity of an existing concrete tunnel lining the influencing parameters of concrete spalling should be well understood. Therefore the first paragraph in this chapter gives a brief background of concrete...
spalling. The second paragraph concludes with the heating requirements for the mobile furnace. The last paragraph gives some additional requirements.

2.1 Determining parameters of concrete spalling in relation to a mobile furnace

The occurrence of the phenomenon spalling under fire loading is based on three main mechanisms according to most authors: (1) deterioration of the cement paste, (2) thermal stresses and (3) pore pressures. In theory each of the mechanisms can lead to spalling. In practice a combination of the mechanisms will determine the spalling behaviour in a given situation. The mechanisms have a number of contributing factors that can increase the probability of spalling, for example the type of aggregates, moisture content, type of cement, heating rate, restrained thermal expansion, etc.

Firstly, many authors agree that the heating rate is very important because it influences the thermal stresses and the pore pressures. Secondly, the maximum temperature is important as well. The maximum temperature influences aggregate failure (e.g. Thames River gravel & limestone), corner spalling (not significant in tunnel fire tests) and dehydration of the CSH & CH in the concrete. Aggregate failure does not happen often due to the fact that failure temperatures of most aggregate types are far above 1000°C, so the main concern is the deterioration due to the dehydration. The dehydration leads to a shrinkage of the cement paste and coupled with the expansion of the aggregates internal cracking will occur. According to Harmathy the dehydration of CSH is nearly completed at 800°C.

Furthermore, it is well-known that a higher compressive stress in the concrete makes the concrete more sensitive to spalling, as does a boundary condition with restrained thermal expansion.

When the concrete tunnel lining under study is protected with insulation material (i.e. fireproof spray mortar or board material) the maximum temperature of the mobile furnace should be according to the maximum expected fire temperatures in the tunnel. This is due to the fact that some common spray mortars show a chemical phase change above 1100°C Celsius, which influences the thermal behaviour of the insulation material.

2.2 Required heating conditions

From the previous paragraph it is concluded that the following requirements for the mobile furnace should be met when checking the spalling behavior of concrete:

1. a steep heating curve similar to RWS fire curve to create conservative thermal gradients inside the concrete AND
2. a maximum furnace temperature of at least:
   a. roughly 800°C for unprotected concrete
   b. 1350°C for protected (=insulated) concrete (when testing according to RWS fire curve)

3. DESIGN OF THE MOBILE FURNACE

This chapter describes the design of the mobile furnace. The first part describes the general design, followed by a more detailed description of several parts of the furnace.

3.1 General design

With an eye on practical aspects and flexibility the choice have been made for 3 standard propane tanks of 25kg each which are coupled. The gas flow then goes through a mass flow meter for determining the heat flux. Just after this mass flow meter the gas flow is splitted in 4 tubes. On each of these 4 tubes 5 Sievert power burner heads (nominal power: 26 kW), type
293401 are mounted. The Sievert burners are placed in a grid of 4 x 5 with 80 mm centre-to-centre distance. The furnace chamber is delimited with 27mm thick Promatect-H and covered with 30mm ceramic blanket. In the current design there is flame impingement with the surface, which leads to a higher heat transfer coefficient. As a result of this higher heat transfer coefficient the current furnace will demonstrate a worst-case scenario for the object under study as the fire conditions will be more severe. The exact increase of heat transfer will be part of further research.

![Figure 27: Photos of the mobile furnace. Left: a top view. Right: front view.](image)

### 3.2 Furnace temperature monitoring
The temperatures inside the furnace are monitored with 2 K-type wire thermocouples on two different heights. Both thermocouples are placed at a distance of 100mm from the concrete surface. One of these thermocouples is located in the midpoint of the heated area and the second thermocouple is located 200 mm above the midpoint of the furnace. This choice is made as a result of the convection of the flames.

### 3.3 Heating rate
The heating rate is determined with a mass flow meter from Brooks instruments type 5853E, which is placed just after the 3 propane tanks. The operating pressure of the propane tanks is reduced to 3 bar using pressure reduction valves.

### 4. DESIGN OF EXPERIMENTS
In total 2 experiments have been carried out to demonstrate the performance of the mobile furnace: (1) spalling test on a spalling insensitive concrete mix and (2) spalling test on a spalling sensitive concrete mix. These experiments are described in more detail below. The tests will focus on the occurrence of spalling, time of initial spalling and spalling depth.

#### 4.1 Experiment A: Spalling insensitive concrete slab
This experiment was done using a standard C28/35 concrete slab (dimensions: 1.6 x 1.9 x 0.15 m³) in vertical orientation which is exposed to fire by the mobile furnace for 10 minutes. The concrete mix of this slab contained silicious river gravel with a maximum grain size of 32mm and 340 kg/m³ CEMIII. This concrete mix is also known as the RWS-concrete mix for immersed tunnel linings, as this concrete mix is approved by the Dutch Ministry of Transport as a spalling insensitive concrete mix. Fire tests with an RWS fire curve on large preloaded concrete slabs (4 x 4 m²) with this concrete mix have shown that spalling does not occur.
4.2 Experiment B: Spalling sensitive concrete slab
This experiment is almost identical to the previous experiment only difference is the concrete slab, which is made of a higher grade concrete (C50). For such high concrete grades it is well-known that the concrete is very sensitive to spalling. Spalling depths will be measured with a sliding caliper and measured in relation to the non-exposed concrete surface, which will remain intact. The depths will be measured in a grid of 10 x 10 cm.

5. RESULTS
This chapter shows the results of the performed experiments described in the previous paragraph. The first paragraph shows the general heating conditions for all experiments, followed by the results of spalling test. Thereafter a comparison is made using a Eurocode calculation of the expected temperatures inside the concrete for a RWS fire curve and the mobile furnace.

5.1 Heating conditions
The heating conditions for all 2 experiments were similar. The heat rate was set to 225 kW. The resulting heating curve of the mobile furnace for experiment B is shown in Figure 2. The graph shows that the maximum temperature of the mobile furnace was limited to about 1250 °C. Besides, the graph also shows that a very rapid increase of temperature is achieved with the mobile furnace. The heat rate in the first 1000°C is equal to 35 °C/s, which can most probably be dedicated to the reaction time of the thermocouples. By comparison the RWS fire curve requires only 5°C/s.

Figure 28: Temperature curve of the mobile furnace during the experiment performed on the spalling insensitive concrete slab (diamonds). The temperature curve is compared to the RWS fire curve (squares).

5.2 Experiment A: Spalling insensitive concrete mix
The spalling insensitive concrete slab (C28/35) did not show any spalling during the first 10 minutes of the experiment. For further research the duration of the experiment was extended
with an additional 20 minutes, which stretched the total fire exposure up to 30 minutes. In this extended test period the concrete slab also remained intact.

5.3 **Experiment B: Spalling sensitive concrete mix**

In the second experiment (B) the spalling sensitive concrete initiated spalling after 3 minutes. The heating of the concrete slab was stopped after 10 minutes and the spalling depths were measured, see Figure 5. The figure shows clearly that an area of about 70 cm in width and 40 cm in height is affected by the fire. The fact that this affected area is larger than the area covered by the Sievert burners is mainly a result of the flames spreading at the concrete surface. This can also be seen clearly on the photos in Figure 1. Spalling depths up to 23 mm were measured. The average spalling depth (dashed square in Figure 3) is 11 mm.

A solid validation of the spalling depth with an identical test on a traditional furnace has not yet been performed. However, based on the experience of Efectis with similar concrete slabs under RWS fire conditions, the current result matches the expectations.

![Figure 29: Measured spalling depths in mm of the C50 concrete slab after heating for 10 minutes with the mobile furnace. The average spalling depth is taken from the dashed square.](image)

5.4 **Temperature calculation within the concrete**

In the current version of the mobile furnace the temperature is limited to approximately 1250°C. The RWS fire curve increases up to 1350°C in 60 minutes. The difference in temperature development within the concrete can be calculated using the standard Eurocode calculation for concrete and the time-temperature data shown in Figure 4.

A 1D-heat calculation is performed based on the assumption of a concrete slab with 3% moisture content, siliceous aggregate and 2350 kg/m³ concrete density. Furthermore, the slab has a thickness of 15 cm and has infinite width and height. Two calculations are performed with different fire curves exposed to the unprotected concrete: (1) Mobile furnace fire curve
and (2) RWS fire curve. The resulting temperatures in the concrete are shown in Figure 4. The difference between the temperature developments for the two fire curves is shown in Figure 5 (negative temperatures means that the mobile furnace fire curve is ahead of the RWS fire curve).

![Figure 30: Calculated concrete temperatures for the RWS fire curve and the mobile furnace fire curve at various time steps.](image)

![Figure 31: Difference in concrete temperature between the RWS fire curve and the mobile furnace temperature (ΔT = T_{RWS} - T_{mobile}) at various depths in the concrete.](image)

Figure 5 shows clearly that in the first half hour the temperatures in the concrete are higher for any depth when using the mobile furnace. The majority of fire tests in the lab of Efectis Nederland demonstrate that spalling of unprotected concrete subjected to the RWS-fire curve occurs in the first 15 minutes. This makes the mobile furnace acceptable for unprotected
concrete undergoing the RWS-curve, but further research needs to be done concerning the use for concrete with fire protection covers.

6. CONCLUSION AND RECOMMENDATIONS

Experiments performed with different concrete grades showed that the developed mobile furnace is able to determine the spalling sensitivity of an unprotected concrete lining when subjected to typical tunnel fire conditions. It is shown that the current version of the mobile furnace can determine the spalling sensitivity in a qualitative way. Although the achieved spalling depths are similar to the expected spalling depths of the concrete under study in a standard furnace, further validation is needed in this respect. Calculations according to the Eurocode standard have shown that the mobile furnace is able to show more severe concrete temperatures than the RWS fire curve in the first half hour. Due to the limited mobile furnace temperature of 1250 oC temperatures will fall behind after 30 minutes when compared to the RWS fire curve. On the other hand it is known that in most cases spalling of unprotected concrete will occur in the first 15 to 30 minutes.

For concrete tunnel linings protected with fireproof material further development of the mobile furnace is needed, in order to achieve the required 1350oC for a RWS fire curve. This peak temperature is needed to show the behaviour of the fireproof material under such high temperature loading. For determining concrete spalling behaviour of unprotected concrete such high temperatures are not needed. Further research for the mobile furnace will also focus on validation with test results on a traditional furnace, including tests on a wider variety of concrete grades. In addition, a closer look will be given to the effect of resulting compressive stresses when the concrete slab is subjected to local heating with a cold boundary as well as the thermal effect of flame impingement on the concrete slab.

REFERENCES