EFFECT OF CONCRETE COMPONENTS ON THE TEMPERATURE ENDURANCE OF TUNNEL LININGS

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1. Introduction, scientific precedents

Last quarter century’s incidents in road and railway tunnels turn the attention to the risk of the tunnel fires. The investigation of the disasters is motivated by the on-going development and expansion of traffic networks, as well as to improve the resistance of structures to extreme effects of such catastrophes.

1.1 Tunnel catastrophes, tunnel fires

The traffic load of international railway and road networks has increased considerably during the last decades, especially with regards to the number of freight trains and heavy trucks. Transport efficiency has been improved by the construction of high-speed railway lines and the development of highway networks. As a consequence of standard design of the longitudinal sections, it has been necessary to construct tunnels and tunnel networks in mountainous areas. Observations make it clear, that the increasing traffic requirements in cities can be possibly best fulfilled by improving or constructing underground traffic networks.

By forcing traffic – railway, road or public transport – into tunnels, i.e. into closed spaces, the requisite safety requirements are increasing considerably. In the case of abnormal operating conditions, despite safety systems (previous information signs, smoke and fire detection, automatic alarm and fire-extinguisher systems, emergency escapes etc.) the most dangerous situation, either to human life or to the tunnel structure is fire (Fig. 1.). There are essential differences between the consequences of accidents in closed or in open spaces. In closed spaces, fire is more threatening because of the close proximity of persons and the effects on materials of the load bearing structural elements because of the quick development of temperature (Fig. 2.)

1.2 Behaviour of tunnel linings during fire

The huge amount of evolving heat is loading directly to the load bearing linings, on which the underground pressure effect unaltered. To maintain the stability of structures it is necessary to improve the resistance of the structure to the bumping heat load. Therefore the recognition of physical and chemical changes in concrete during heating and cooling is
needed: Increasing the temperature at definite temperature the physically and chemically bounded water discharges, becomes steam (Schneider and Horvath, 2002). Other components decay with gas forming. Through the decomposition of the substituents the strength of the material decreases (MSZ EN 1992-1-2; 2005).

The accumulation of steam forming near the surface and the thermal expansion of concrete respond to the spalling which is the detachment of surface layers. The main reason of spalling is the local failure in strength. Therefore the change of splitting tensile strength, which is close to pure tensile strength, to the elevated heat was tested. The effect of spalling is similar to the scaling of concrete due to frost. Because of the similarity the effect of air-entraining admixture on the residual strength of concrete was tested. The main problem and danger of the spalling is the decrease of concrete cover (Høj, 2000). The strength parameter of the exposing rebars decreases rapidly because of the high temperature (Fig. 3.).

2. Present investigations, aims and methods

2.1 Aim of the dissertation

During my present investigations I have been looking for the answer of the influence on the temperature endurance, in hardened cement pastes:

- I) the specific surface area of the Portland cement (new scientific result 2.),
- II) the water/cement ratio (between 0.120-0.750) (new scientific result 2.),
- III) the type (limestone filler, dolomite filler, blast-furnace slag, quartz sand, barite) and dosage (between 20-60 m/m%) of additives (new scientific result 3.);

in concrete:

- IV) the water/cement ratio and the maximum size of aggregate (new scientific result 4.),
- V) the PP fibre, the air-entraining admixture and barite aggregate (new scientific result 4.),
- VI) the rate and method of cooling (new scientific result 5.).

2.2 Method of tests

In the investigations nearly 6500 specimens were tested to determine the influence of the concrete components on the temperature endurance (Tab. 1.). The 28 days old specimens were heat treated with bumping heat in preheated furnace with 10 temperature steps between 50 and 900 °C. According to Richter (1993) results with this temperature range the heat load of concrete exposed to tunnel fire is described well, except the near surface centimetres of the few meters close to fire. After the heat load, which duration was uniformly 120 minutes, the specimens were cooled down to the test (laboratory) condition in different speeds and methods.

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1 the definition of temperature endurance is in new scientific result 1.
The absolute and relative (correlate with not heat treated values) parameter of the specimens (splitting tensile strength and compressive strength) and their ratio (T/C value, inverse Brinke number) were compared. To study the changing curves, the temperature endurance, the area (%×°C) below the relative strength vs. temperature curve, was inducted.

**With hardened cement pastes** (30 mm cubes) was tested the effect of:
- the specific surface area of Portland cements (CEM I 32.5 R(S), specific surface area = 304 m²/kg, C₄AF content = 18.7 m/m%; CEM I 42.5 R, 353 m²/kg, 9.6 m/m%; CEM I 52.5 N white, 452 m²/kg, 0.9 m/m%),
- the water/cement ratio (0.120; 0.165; 0.195; 0.240; 0.300; 0.375; 0.462; 0.575; 0.750),
- the different type of additives (limestone filler, dolomite filler, blast-furnace slag, quartz sand, barite).
During the tests with the additives the effect of the change of water/fines ratio (fines means the cements and the additives altogether) as well as the water/Portland cement ratio (refer only to the Portland cement part) were tested.

**With concrete specimens** (cylinder: Ø60/120 and Ø60/60 mm) was tested the effect of:
- the water/cement ratio (0.38; 0.45; 0.55),
- the maximum size of aggregate (8 and 16 mm),
- the type of coagent (PP-fibre 0.1; 0.2; 0.5 V/V% and air-entraining admixture 0.15; 0.3; 0.6 m₃% → 7-9 V/V% air content)
- the special aggregates (barite 0/6 mm, two different dosages).
The barite is a remaining material of ore cleaning process come through in roasting (heat treating, 720-740 °C) with high BaSO₄ content. The effect on the temperature endurance were tested with different fractions of the barite.
On the specimens due to their small dimensions the real residual material properties were measured, without the influencing effect of the unequal heating and the spalling.

The effect of cooling method (slow cooling, cooling at laboratory conditions, forced-air cooling, cooling with water mist and quenching) on the residual compressive strength was tested with 72 mm cubes.
For the comparing tests 150 mm cubes and Ø100/200 mm cylinders were made.
The required consistency of the cement pastes and concrete was adjusted with superplasticizer.
During the investigations the effect of continuous (service) high temperature, lightweight concrete and steel fibre reinforced concrete was not tested.

**Tab 1.: Tested specimens**

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Portland cements</strong></td>
<td>30 mm cubes</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Additives</strong></td>
<td>30 mm cubes</td>
<td>2880</td>
</tr>
<tr>
<td><strong>Concrete components</strong></td>
<td>Ø60/120; Ø60/60 mm cylinder</td>
<td>1596</td>
</tr>
<tr>
<td></td>
<td>150 mm cubes and Ø100/200 mm cylinder</td>
<td>196</td>
</tr>
<tr>
<td><strong>Effect of cooling methods</strong></td>
<td>72 mm cubes</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>150 mm cubes</td>
<td>9</td>
</tr>
</tbody>
</table>
3. New scientific results

The results are summarized in 5 new scientific results and are given in bold characters and their explanations are given in normal characters. The numbers in \[\text{italic square bracket}\] indicate the corresponding own publications.

**New scientific result 1: Temperature endurance**

To compare the effect of the concrete components the temperature endurance, the definite integral of the relative residual strength vs. temperature curve \[\% \times ^\circ \text{C}\], has been indicated. The temperature endurance has been defined both to the whole temperature range and also to a section of it. According to the defined values the results could be ranked. [9, 11, 13, 14, 15, 16]

In case of tunnel fire greatly different temperature is obtained depending on the place of the fire and the distance from the concrete surface. To define the exact thermal behaviour of the concrete components, the range of 20-900 °C was divided into 11 temperature steps. From single relative strength results of the specimens tested at each temperature the strength distribution in the tunnel lining is definable in depth of the structure as well as longitudinally.

The two ways of representation of the residual strength values are the absolute and relative (compared to the start value) strength curves. While the change of the real strength parameters to elevated temperature is displayed with absolute curve, the comparison of the thermal behaviour of different materials is possible with the relative strength curves. Employing the relative values it is possible to pre-indicate or to compute in the tested thermal range the strength changes of a material from a simple test of an unheated specimen. For the characterization of the relative residual strength vs. temperature curves, beyond the simple comparison, the temperature endurance was indicated. The temperature endurance was also defined to the sections of the total temperature range (Fig. 4.). With the value of the temperature endurance, the results of the series could be ranked.

![Fig. 4.: Interpretation of temperature endurance](image)
New scientific result 2.: Temperature endurance of Portland cements

New scientific result 2.1.: From experimental results of hardened cement pastes it has been assessed that the temperature endurance is better with the decrement of the specific surface area and the increment of the C₄AF content of the ordinary Portland cement, independently of the temperature range and the water/cement ratio. [4, 7, 9, 10]

With tests on hardened Portland cement pastes it has been defined, that the temperature endurance (TE) of the hardened cement paste is reciprocally proportional to the specific surface area of the cement (Figs. 5 to 7). The cement with the least specific surface area (CEM I 32.5 R(S) gives the largest temperature endurance both in the whole temperature range (20-900 °C) and at higher temperature level (300-900 °C). The cement with the maximal specific surface area (CEM I 52.5 N white) has the lowest temperature endurance. All three tested types of cement exceed their initial strength values at 300 °C.

The greater specific surface area effect the decrement of diameter of cement particle and the mass of unhydrated clinkers, the rate of hydration is increasing, the length of CSH fibres gets smaller, the structure of the hardened paste becomes more compact, and its capillary activity decreases. The increment of the temperature endurance is also noticeable by the increment of the C₄AF content of the cement, which hardens slowly in long fibres. According to both variables, the temperature endurance increases if the hydration’s heat is smaller.

Testing the most advantageous cement types (CEM I 32.5 R(S) and CEM I 42.5 R) with nine water cement ratios (0.120-0.750) it has been found that the cement with the smaller specific surface area is favourable, independently of the water cement/ratio, both in the whole temperature range (20-900 °C) and at higher temperature level (300-900 °C).

![Graph showing the relationship between temperature and residual compressive strength of different cements](image)

Fig. 5.: Changes of the compressive strength of the ordinary portland cements

New scientific result 2.2: From experimental results of hardened Portland cement pastes it has been realized that local strength maximum near 300 °C has been effected by posthydration effect between the evolving water, hitherto physically and chemically bonded, and the unhydrated cement particles. [9, 10]

Between 150-300 °C the relative strength increment of hardened Portland cement pastes is noticeable, with some exceptions (high water/cement ratio). In this range thermogravimetric tests were carried out with three water/cement ratios to determine the change of the mass of Ca(OH)₂. The connection has been confirmed between the strength increment and the growing of the mass of Ca(OH)₂ generated by the posthydrating effect of the evolving water (Figs. 8 to 10)
Fig. 6.: Temperature endurance of the compressive strength in the whole temperature range (20-900 °C) and in the range 300-900 °C

Fig. 6.: Temperature endurance of the compressive strength of the ordinary Portland cement in the function of the water/cement ratio

Fig. 8: The change of the relative mass of Ca(OH)$_2$ in CEM I 32.5 R(S) cement pastes in the function of the temperature

Fig. 8: The change of the relative mass of Ca(OH)$_2$ in CEM I 42.5 R cement pastes in the function of the temperature
New scientific result 3: Effect of additives on the temperature endurance

From experimental results of hardened cement pastes it has been realized that replacing a part of the Portland cement in the paste with additives effects on the temperature endurance comparing to the ordinary Portland cement paste:

- greatly disadvantageous with limestone and dolomite filler,
- slightly disadvantageous with blast-furnace slag,
- advantageous (especially over 500 °C) with previously heated barite and quartz sand. [7, 8, 9, 10]

To define the effect of additives five materials were tested: limestone filler, dolomite filler, blast-furnace slag, quartz sand and barite of two finenesses. The most beneficent cement type (CEM I 32.5 R(S)) was used. The effects of the dosages of additives were tested with constant water/fines ratio (limestone filler, blast-furnace slag) as well as with constant water/Portland cement ratio (all additives). In the tests definitely 20, 35, 45 and 60 m/m% of total mass of the binder were replaced the Portland cement with the additives.

Results of the pastes with constant water/fines ratio showed, that the adding of lime stone filler and blast-furnace slag is disadvantageous to the temperature endurance than the ordinary Portland cement paste independently of dosages. (Fig. 11.)

Results of pastes with constant water/cement ratio showed, that the temperature endurance of pastes consisting quartz sand and barite are slightly advantageous than the reference values (Fig. 12.). The positive difference is experienced especially at high temperature. The temperature endurance of pastes consisting blast-furnace slag is slightly, the lime stone and dolomite filler is greatly lagged behind the reference values. Both barite additives and quartz sand effects auspicious residual compressive strength at high temperature.

The reason of the advantages is the restructuration of quartz that effect by the volume increase at 573 °C generating beneficial self stress state. The reason of the advantageous behavior of barite additive is the former tempering, roasting, that alter the strength bearing too. Up to 600 °C nearly constant residual strength value is measurable at the pastes containing the “routher” barite. The generation of gas and the rehydratation in the cooled specimens effects the explosion and/or disintegration of the hardened pastes consisting lime stone or dolomite filler.
New scientific result 4: Temperature endurance of concrete

New scientific result 4.1: Effect of the concrete technology parameters on the temperature endurance

From experimental results of concretes it has been proved that the temperature endurance of compressive strength is improving and the concrete is keeping its initial strength up to higher temperature with the decrement of the water/cement ratio.

From experimental results of hardened cement pastes it has been realized that the temperature endurance of the splitting tensile strength and the ratio of tensile and compressive strength are nearly equal independently of the water/cement ratio, the maximum size of aggregate, the content of PP fibre or air-entraining admixture. \[11, 12, 13, 15\]

The effect of the concrete technology parameters (w/c = 0.38, 0.45, 0.55; MSA = 8; 16 mm) and admixtures (PP fibre 0.1; 0.2, 0.3 V/V%, air-entraining admixture 0.15; 0.3; 0.6 m/m,%; barite aggregate) were tested with 14 different mixtures. Constant parameters
were the type and dosage of cement (CEM I 42.5 R; 400 kg/m³), and the 11 temperature steps (20-900 °C).

The effect of the water/cement ratios and the maximum size of aggregate were tested with six series. Then the connection between the dosage of PP fibre and air-entraining admixture were investigated.

The addition of PP fibre is the internationally accepted method for preventing the spalling effect. The addition of air-entraining admixture for improving the temperature endurance is not yet studied.

The results were compared by the splitting tensile strength (cylinder Ø60/60 mm), the compressive strength (cylinder Ø60/120 mm) and their ratios. The temperature endurances of the strengths were measured. Big differences are noticed between the absolute strength values of the different mixtures, so the usage of relative residual parameters was needed for the comparison.

Studying the effect of the change of the water/cement ratio on the temperature endurance of the concrete, it has been determined that the fast decrease of the compressive strength starts at higher temperature (cca. one temperature step; 200-300-400 °C) with the decrement of the water/cement ratio because of the more auspicious structure (Fig. 13) The change of the maximum size of aggregate did not effect on the relative residual compressive strength.

The compressive strength of the concrete is only the 15% of the initial value at 500-600 °C.

![Graph showing the effect of water/cement ratio and maximum size of aggregate on relative residual compressive strength](image)

*Fig. 13: The effect of the water/cement ratio and the maximum size of aggregate on the relative residual compressive strength (notation: water/cement ratio / MSA)*

The relative residual splitting tensile strength of the concretes containing only ordinary quartz aggregate are identically equal and may replaced by a bilinear function, independently of the water/cement ratio, the maximum size of aggregate, the dosage of PP fibre and entraining admixture (Fig. 14). The splitting tensile strength of concretes exhausts over 600 °C.

The ratio of the splitting tensile and the compressive strength, the stiffness of concrete, are similar by only quartz containing concrete: constant up to 250 °C, then the brittleness increases. The form of the curves may also replaced with a bilinear function (Fig 15)
Fig. 14: The effect of the water/cement ratio, the maximum size of aggregate, the dosage of PP-fibre and air entraining admixture (LB) on the residual splitting tensile strength (notation: water/cement ratio / MSA; dosage of PP-fibre V/V% and air entraining admixture m/m, %)

Fig. 15: The effect of the water/cement ratio, the maximum size of aggregate, the dosage of PP-fibre and air entraining admixture (LB) on the T/C value (notation: water/cement ratio / MSA; dosage of PP-fibre V/V% and air entraining admixture m/m, %)
New scientific result 4.2: Effect of the dosage of barite on the temperature endurance of the concrete

From experimental results of concretes it has been realized that the temperature endurance of the compressive and the splitting tensile strength of the concrete as well as the ratio of the residual tensile and compressive strength are increased in the engineering relevant range (over 500 °C), if the sand of the concrete has been replaced with previously heated, 0/6 mm barite. [11, 12, 13, 15]

0/6 mm barite fraction was tested as a sand-replacing material from the point of view of temperature endurance. However, the total temperature endurance of the compressive strength of barite containing are slightly unfavourable than the reference values, at higher temperature (over 500 °C) the temperature endurance are auspicious (Fig. 16). The effect of the replacement of 0/6 mm barite is auspicious on the temperature endurance of the splitting tensile strength (Fig. 16). The better temperature endurance of the barite is caused by the former tempering (roasting) of the aggregate.

The behaviour of the ratio of the tensile and compressive strength has been altered with the dosage of barite. The concrete keeps its initial stiffness up to 500 °C, only over 500 °C starts the increment of the brittleness (Figs. 16 and 17). The reason of the spalling, the failure in tension, occurs at higher temperature with barite than with quartz aggregate containing concrete.

![Graph showing temperature endurance of the compressive strength and splitting tensile strength](image1)

**Fig. 16:** Effect of the dosage of 0/6 mm barite on the temperature endurance (500-900 °C) and on the average of relative T/C value (500-750 °C) (notation: dosage of barite m/m, %)

![Graph showing T/C values](image2)

**Fig. 17:** Effect of the dosage of 0/6 mm barite on the T/C values (notation: dosage of barite m/m, %)
New scientific result 4.3: Repair of concrete after fire

From experimental results of concretes it has been realized that the residual splitting tensile strength of concrete are higher than 2.0 N/mm² (proposed value for repair) up to higher temperature, if appropriate concrete technology parameters has been used (e.g. low water/cement ratio). [11, 12, 13, 15]

The residual splitting tensile strength values reduce below 2.0 N/mm², belonging value of the 1.5 N/mm² of the pure tensile strength of the repair limit, from 250 to 450 °C according to the concrete technology parameters (Fig. 18). Major parts of the tunnel linings, adequate distances from the fire both longitudinally and in depth of the wall, are capable to be bounded with the repair materials (e.g. shotcrete) after the removing of the damaged concrete parts.

![Residual absolute splitting tensile strength](image)

*Fig 18: Changing of the splitting tensile strength, with the limit of reperability (notation: water/cement ratio / MSA; dosage of barite m/m₀4%)*

New scientific result 5: Effect of cooling on the temperature endurance

From experimental results of concretes it has been proved that the CEB-208 Bulletin overvalues the temperature endurance of the method of the cooling, or rather the decrement of the temperature endurance is undervalued. Connection between the rate of cooling and the temperature endurance measured at smaller specimens of slow cooling, cooling at laboratory conditions, forced-air cooling, cooling with water mist and quenching was not noticeable. [6, 14, 16]

The effect of the cooling method on the residual compressive strength were tested with five different methods (slow cooling, cooling at laboratory conditions, forced-air cooling, cooling with water mist and quenching) and two different cooling materials (air and water). The time of the cooling changed in wide range (30 to 4500 minutes). Three concrete mixtures were used (etalon, 0.1 V/V% of PP fibre and 0.3 m/m₀% air-entraining admixture).

The average curves of the slow and fast cooling method (Fig. 20) of the CEB-208 (1991) (which gave major differences of the residual strength values) are gave higher temperature endurance than as justifiable with test results. The temperature endurances of the tested concretes are not monotone regressive parallel to the increase of the rate of the cooling.
The minimum temperature endurance were found by the practically most possible cooling method of the tunnels emergency cooling methods, the forced-air cooling and the water mist.

The temperature endurances were overvalued by the CEB especially the advantage of the slow cooling’s method, because major differences between the fast or slow cooling down method were not experienced. Between the extreme methods (slow cooling and quenching) major differences were not measurable. However, the temperature endurances of the methods with the same cooling down speed but altering cooler material show differences. Connection between the speed of cooling down and the temperature endurance is not provable.

However, barely any damage was seen on concrete specimens heat loaded at 600 °C, but major structural damages were experienced on the specimens loaded at 900 °C.

**Fig. 19: Temperature endurance of the compressive strength in function of of the cooling methods, compared to the CEB-208 Bulletin**

4. **Practical use of the results of the dissertation**

The several results and establishments of the dissertation assist to the understanding of the behaviour of the concrete and concrete components of tunnel linings. The elaborated new estimation and comparing methods, with the new results, ease the way of the testing and development of advisable concrete mixture. Benefits of new aggregates, not used for this before, were demonstrated. Recommendations were worked out for the estimation of the residual strength values from the unheated strengths.

5. **Future work**

Appointed new aims based on the results are: accurate definition between the clinker content of the Portland cement and the temperature endurance; the examination on mortar of the tested parameters on hardened cement pastes; the test of the industrial usage of the quartz sand and the barite containing cements; the examination of the air-entraining admixture containing concrete with special regards on the spalling on mass concrete.
6. Notations and abbreviations

- **Air** air-entraining admixture
- \( m/m_{0/4\%} \) percentage by mass of the mass of 0/4 fraction
- \( m/m_{c\%} \) percentage by mass of the mass of cement
- **MSA** maximum size of aggregate [mm]
- **PP-fibre** polypropylene fibre
- **T/C** ratio of splitting tensile and compressive strength
- **TE** temperature endurance between 20-900 °C [%×°C]
- **TE_{α-β}** temperature endurance between \( α-β \) °C [%×°C]
- \( V/V\% \) percentage by volume
- \( w/c \) water/cement ratio [m/m]
- \( w/f \) water/fines ratio [m/m]
- \( w/pc \) water/Portland cement ratio [m/m]

7. References

7.1 References in new scientific result brochure


7.2 Publications in the subject of PhD dissertation

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[3] **Fehérvári, S.**: „A füstgázok keletkezése és kezelése alagúttüzek esetén” (Formation and handling of somke in case of tunnel fire), Közút és Mélyépítési Szemle (Hungarian Revue of Roads and Civil Engineering), Vol. 57/6, pp 11-15

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