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Spalling of concrete – influence of porosity and specimen size and its critical factors regarding safety

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Abstract. The influence of porosity and of the specimen geometry and its stiffness on the behaviour of spalling in an event of fire is investigated. Fire resistance is heavily depending on the w/c and air void content values. Thinner specimen with possibility of elongation and higher air void content is generating better laboratory testing results in case of fire resistance.

1. INTRODUCTION

Within the last few decades the number of built tunnels increased. Especially if you compare this to the early years of the last century. Of course one reason is the cumulative technical development in all sectors of construction. It is a matter of fact that not only the number but also the length of the tunnels increased and the geological challenge of the surrounding overburden and rock mass while construction make great demands on the planning and processing.

Reasons for that can be found in the importance of these facilities as an essential part of the transport infrastructure. However, this is an economic factor all over the world most of the challenging constructions can be found in Europe. On the way to be finished till the end of 2016, the Gotthard Base Tunnel can be listed here. It will be the longest railway tunnel in the world and will be used not only for passenger trains but also for freight trains. A mixed usage of a tunnel also for the usage for freight carriage will increase the risk of damage in cases of incidents.

In the past ten years several huge tunnel accidents can be mentioned with huge economic or human impact. The incidences in the Euro Tunnel 1996 and 2008 caused only damages to the structure with the result that one of the tubes was closed for seven months at the first and several weeks at the second accident. In the road tunnels of Tauern, Austria and Mont Blanc, France, both in 1999 as well as in the Gotthard Road Tunnel in 2001 all together more than 60 people lost their lives. After the incidents the tunnels were closed for repair works, the Gotthard Road Tunnel for some months, including the resultant influence.

2. CAUSE OF DAMAGE AND CHARACTERISTICS

The characteristic of the damages shown in all the tunnels were similar. Starting with displacement and stripping of the concrete surface to the point of huge spallings. All these are results of the fire and its temperatures higher than 1300 °C which in the end may cause a total structural collapse. The worst case of total failure is not of such a high importance in buildings like the Gotthard Base Tunnel because the structure of the whole tunnel is partly borne by the ambient lump of rock. Nevertheless, the efforts for the complex and expensive rework caused by the spallings and displacements have to be taken into account.

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Figure 1. Prop support of structure after fire.

2.1 Fires in tunnel as an example

This description is not giving finally a hint why a tunnel shall be recognised in a different way of surface and high building structures. Fires in tunnels are different from fires at the surface or above the ground. The main difference is the development and propagation of the heat. On the one hand the inside of a mountain offers no possibilities for the heat quantity to be discharged and get reduced. The conductibility of rock formation as well as of the construction itself does not allow a temperature compensation. Dependent on the available combustible material, e.g. freight like tires or other synthetical products, temperatures above 1400 °C are reachable. On the other hand the heat emission in buildings above ground level is achieved by the walls, windows and other openings. This is also a reason for the ISO standard temperature time curve used for fire reaction tests. It can be assumed that within 90 minutes a temperature not higher than 1000 °C is reached. For the tests of systems used in tunnels the estimated temperatures go up to 1350 °C and an attitude of temperature drifting which is much higher, e.g. temperature time curve RWS (Netherlands) or EBA (German Railway). More important for the behaviour of concrete is the fast increase in temperature within 5 minutes than the maximum temperature of 1000 °C.

The challenge of standard concrete is the immanent water which is one of the main additives to produce it but on the other hand also one of the biggest issues. The water is bonded chemically and physically. During the fire it will expand and vapourise within a few minutes after the temperature reached its critical point inside the concrete structure. The volume is increasing with a factor higher than 1000 times. Spallings of the concrete occur if the pressure of the vapour is not able to be released fast enough. Within a short period of time huge areas of the structure will be destroyed. Also partial damage into deep section down to the reinforcement is possible which finally loses its bearing function and reaching a critical state if the fire heats it up over 400 °C.

Another complexity is given by the increasing use of concrete with high strength in building structures above ground and especially in tunnels. It seems to be that this is getting an argument for sales and marketing more and more without recognizing the consequences. Beginning 20 years ago in the 90s of the last century the use of high performance concrete is getting more and more of importance. In the building and construction sector the opinion “the more strength and solid the better” is rampant with all its negative aspects for the fire protection; in this case for the structural fire protection just as much for the fire defence.

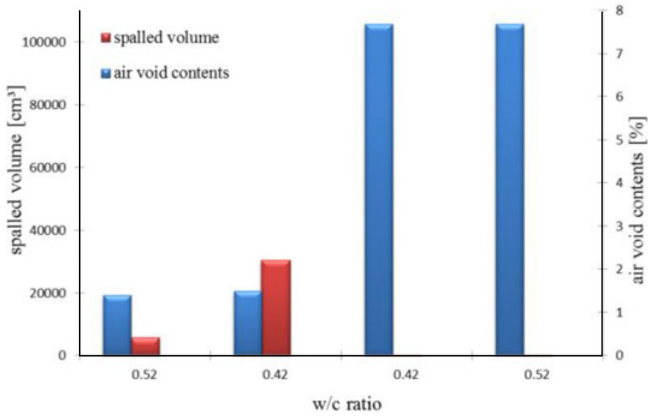

Figure 2. Dependency of fire resistance from porosity with 150 mm specimen.

2.2 Influencing factor on fire resistance

Furthermore a typical intended use of high performance concrete is in the tunnel sector for the use of tubbing or in general for precast elements. The dense and firm structure abet widespread displacements caused by the high vapour pressure.

It is well known that that the following (technical) aspects have an influence on the resistance to fire of a used product.

- Fire load
  More and more tunnels are not only used for the movement of travellers only but also for cargo. This freight often having high fire loads and causes huge damages on the structures.
- Porosity
  It is an important quality criteria for concrete. Different types of pores in concrete exists with variable influences. Capillary pore within a huge impact on the strength and the modulus of elasticity and can be influenced by the water–cement ratio (w/c-ratio) and responsible for the transport process.
- Humidity of specimen
  This depends on the humidity of the structural components and the climatic ambience conditions.
- Aggregate
  This parameter describes the highest volume of material within the heterogeneous concrete. Hence the effect to fire has to be rated as high.
- Stiffness
  The stiffness has an in important influence on the results of a fire test. The greater the stiffness of a tested specimen the higher the vapour pressure inside and the resulting damages.

Different research studies, technical specialist literature and own surveys gave references to the porosity and the stiffness and its influence towards to aspects of displacements and spallings of concrete under the influence of high temperatures. Many years of experience with accredited fire tests reassure that the avoidance of spalling is depending on the amount of vapourised water and the possibility to exhaust through the matrix of pores and capillary tubes. Based on these aspects the VSH did a research study on behalf of the ASTRA, Switzerland (Federal Roads Office – FEDRO).

3. TEST SET UP AND PROCEDURE

The investigation focused on two main questions. It should point out the influence of porosity and the influence of the specimen geometry and the stiffness on the behaviour of spalling in an event of fire.

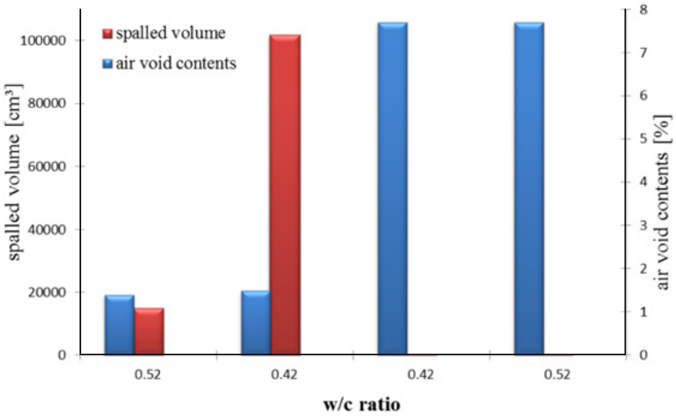

Figure 3. Dependency of fire resistance from porosity with 350 mm specimen.

It was the aim to point out what could be the right way to test specimen under realistic test conditions. This is of importance for the reproducibility and comparability for the different involved testing institutes and hereon depending customers.

3.1 Chosen parameters

The porosity was chosen for the investigation because it abet the expansion of the vapourising water through the pore matrix. Moreover it can be influenced in a good manner by the w/c-value. Together with an adequate amount of polypropylene fibres (pp fibres) this generates pores (melting at approx. 140 °C) and it could be an economic way of producing concrete which last a fire a sufficient time.

The stiffness is important in order to demonstrate the interdependency between test specimen of different dimensions. It is to be assumed that thinner and therefore more flexible specimen have a faster crack formation. Due to it the pressure will decrease faster and the risk of spalling is lower. This will potentially help to understand the needs of tests under comparable conditions where the specimen is used later.

The oven used in the Hagerbach Test Gallery is capable to achieve temperatures up to 1400 °C. So all necessary and useful fire curve for testing products in the field of structural fire protection are covered. The used temperature time curve in the experiments was in accordance with the regulations ZTV ING (Germany). It specifies a maximum temperature of 1200 °C after 5 minutes. The time period for each test was 30 minutes. The reason to choose this temperature profile was that its distribution is between the maximum of RWS (Netherlands, used in the tunnelling sector) of 1350 °C after 60 minutes and the ISO curve which reach nearly 1000 °C after 90 minutes (civil engineering surface sector). Corresponding to the test configuration and the increase of temperature over 1000 °C within the first 5 minutes this is recognised as the critical phase. Hence 30 minutes is seen as an adequate time period for a single test sequence.

3.2 Test preparation

The intended experimental run insists upon two series of tests. In test series (A) the influence of the porosity as a function of the w/c ratio is regarded. In this case the w/c value and the air void contents are the variable parameters. The specimen geometry and specimen stiffness is object of investigation in test series (B). The test in this case is done according to different w/c-ratios and the air void contents

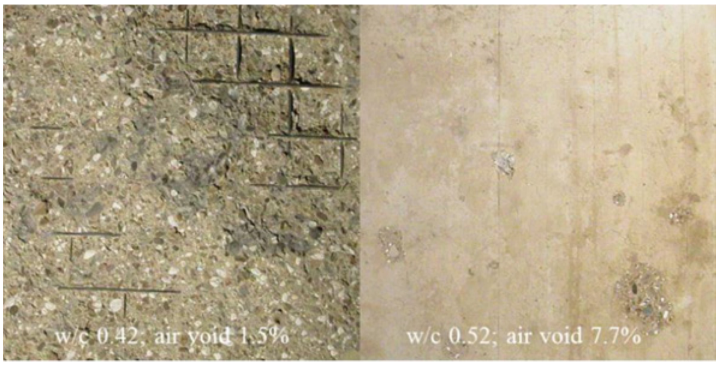

Figure 4. Test series (A) with specimen thickness 150 mm.

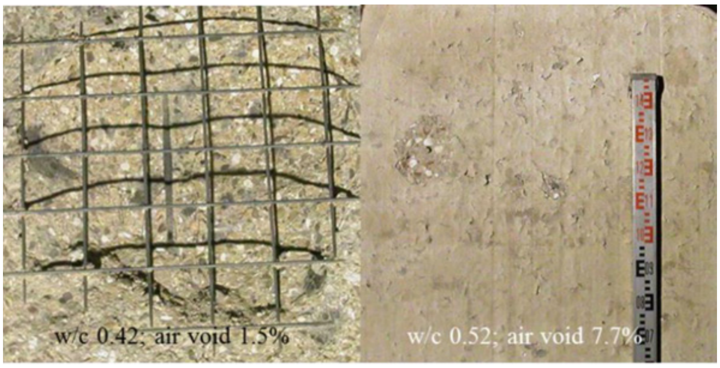

Figure 5. Test series (B) with specimen thickness 350 mm.

likewise series (A). To reveal the phenomenon of specimen stiffness the reference body of series (A) had a thickness of 150 mm in contrast to 350 mm for the reference body of series (B).

For both series of tests the thermocouples were embedded in concrete during construction of specimen to maximise the thermal link. The metering point were in the depths of 50 mm, 70 mm and 90 mm, measured form the testing surface which will be exposed to the high temperatures. Based on the to date fire testing experience a significant temperature profile is given by this setup. In order to reveal the influence of an elongation disability a steel frame is used for the series (B) among the additional higher thickness of 350 mm. The armouring iron (diameter 20 mm) of the specimen is joined integrally with the steel frame. On the welded armouring iron the reinforcing mesh is installed.

Of high importance for these experiments was the conformability of the testing results based upon equal concrete mixtures. This helps to eliminate any uncertainty based on the specimen production process. For all reference bodies the same recipe was used with 1 kg of polypropylene fibres (pp fibres) per m^3 of concrete. The variable parameters w/c and air void content were identified via fresh concrete testing.

4. TEST RESULTS

On the following selection of pictures the main results of the fire tests are illustrated. In order to evaluate the results in terms of the fire resistance the spalled volume is identified. The correlation between w/c-ratio, air void content and spalled volume is diagrammed to show the interdependence with the fire resistance. Here the spalling is a direct result of the proportion of w/c and air void content within the specimen.

Reference body two and three with a w/c ratio of 0.42 depict by contrast with reference body one and four with a w/c-ratio of 0.52 that a value difference of just 0.1 reduce the affinity of spallings. Even more obvious this characteristic is by considering the air void content as well. The least spalling recognizable is with specimen four with the highest w/c and air void content value (w/c 0.52 and 7.7%).

In consequence of the results of test series (A) the influence of the specimen geometry is analysed (elongation disability and stiffness of reference body). The w/c and the air vapour content values kept identic.

Again the spalled volume is identified to draw conclusions in the fire resistance of the specimens. Therefore the correlation between w/c-ratio, air void content and spalled volume is diagrammed.

On the pictures it is obvious to recognise the effect of the steel frame if specimen two of test series (A) is compared with specimen two of series (B). As already mentioned under the same test conditions including w-c and air void content value. Almost the whole concrete cover is gone and the whole reinforcement is exposed to the flame impact with all its negative implications. The spalled volume is more than three times higher than in series (A). Even the spalled volume of reference body one is more than doubled.

Nevertheless on specimen four the influence of the proportion of the w/c and the air void content values can be seen. Compared to specimen two or one nearly no displacement is obvious. On specimen three with lower w/c-ratio but a higher air void content the surface is still firm, only slight displacement can be recognised. On both specimen, number three and four, no spalled volume is measurable.

5. CONCLUSION

Summing up the results of both test series it can be shown that the fire resistance is heavily depending on the w/c and air void content values. In spite of the adapted test configuration in series (B) with the steel frame the above mentioned dependency can be verified. None the less it was obvious that the elongation disability is a not dispensable factor for the fire resistance. This is clearly noticeable in the following figure for both specimen with the low air void content of 1.5 % abated by a low w/c-ratio (vide specimen one and two in test series (A) and (B)).

As a matter of principle displacements and as a progression spallings occur on all tested specimen. Reference blocks with high air void content and w/c ratio were not taken into account because these were nearly not measurable. Important to mention in here is the fact of cold spallings.

For testing institutes as well as for the gaining of knowledge of customers it is important that a thinner specimen with a higher air void content is generating better results in case of fire resistance. Through the small cracks the vaporised water can exhaust easily. This will cause into lower spalling behaviour. As an extreme example too good results can be produced.

Also it is a result that a high performance concrete in case of strength is not always a good decision. According to the application in surface or underground construction it can be the right solution but always is has to be kept in mind that the structural fire protection need again more importance.

Durability and strength of concrete require finally a low porosity. The low porosity supports all characteristics of concrete with exception of fire resistance. The lesser the porosity the higher the risk of spalling and finally having an impact on the safety of the infrastructure users.

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