International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 8 Issue 02 Series. I || Feb 2019 || PP 13-17

Concrete behaviour under elevated temperature

K.M. Sakkas, N. Vagiokas, A. Kallianiotis & G. Loupa
Laboratory for Environmental Engineering, Democritus University of Thrace, Xanthi, Greece
Corresponding Author: K.M. Sakkas

Abstract: *A crucial element of a tunnel lining design in metro tunnels is the time and the way till the final lining will begin to spall due to the high temperatures, which may be developed during a fire. Although the structural elements of the tunnel lining are considered inflammable, in a real fire situation the concrete lining can be spalled largely, sometimes perhaps entirely, with very serious consequences on cost and safety of people. The spalling rate of concrete as well as the spalling depth are two main values that cannot be measured since they are affected by a series of factors including mechanical properties, permeability of concrete and age of concrete. A lot of research has taken place in order to calculate the spalling of the concrete using numerical models, which however is not validated sufficiently by the test results. So the target of the specific research is to investigate experimentally the rate and the depth of spalling for several types of concrete under high temperatures. On this purpose specimen of all types of concrete that can be found in metro tunnels were manufactured and exposed at high temperature in a special furnace which has the ability to simulate all kind of fire scenarios and at the same time monitor the spalling depth and time. The temperature of the exposure was selected after modelling of a 25 MW fire in a metro tunnel. The modelling simulated the distribution of the temperature along the tunnel in case of a 25MW fire and representative values of the temperature for 10, 20, 50 and 100m away from the fire ignition were selected.*
Keywords: *tunnel evacuation, tunnel fire assessment, tunnel linings, tunnel safety*

Date of Submission: 24-01-2019 Date of acceptance: 08-02-2019

I. Introduction

1.1 General

A number of serious metro tunnel fire incidents have been reported worldwide that have led to injuries and life losses, heavy damage in the concrete lining, excess material damage, and significant time periods of tunnel restoration during which the tunnels were unavailable for traffic. Fires in tunnels can seriously damage their concrete lining rendering it to collapse. The damage is caused particularly by the spontaneous release of great amounts of heat and aggressive fire gases, resulting to spalling of concrete. Spalling is described as the breaking of layers or pieces of concrete from the surface of a structural element when it is exposed to the high and rapidly rising temperatures experienced in fires. The most severe spalling phenomenon is the so called explosive spalling, be described as a violent showering of hot pieces of concrete, which beyond to the detrimental effect on concrete lining can additionally cause very serious problems to the firefighting service personnel rendering their work substantially more difficult and dangerous (Jöhnson & Herrera, 2010). The spalling phenomena are expected at several temperatures depending on the strength of the concrete. The American Society for Testing and Materials (2001) mentions that explosive spalling can be expected at temperatures between 300^{o}C and 450^{o}C, while it is generally accepted that concrete exposed at temperatures higher than 380^{o}C is considered as damaged and should be removed and repaired (Khoury, 2000). This temperature is near to the calcium hydroxide dehydration temperature (400^{o}C) which is a process that causes a significant reduction in the mechanical strength of the concrete (Fletcher, 2007). The latter is considered to be significantly reduced at exposure temperatures higher than 300^{o}C (Sakkas, 2013). The spalling rate of concrete as well as the spalling depth and time are two main values for the numerical analysis, which are very difficult to assume or calculate. The reason is that spalling is affected by a series of factors including apart from the compressive and tensile strength, also the following: a) permeability of concrete, b) age of concrete, c) accurate mix of concrete, d) size of aggregates, e) pore pressure, f) existing cracking on the concrete, g) reinforcement of the concrete and h) size and shape of the exposed specimen (Boström and Jansson, 2004). A lot of research has taken place in order to calculate the spalling of the concrete using numerical models, which however is not validated sufficiently by the test results. First of all, the spalling theory is not yet clear. Others support that spalling is attributed to the pre-existing cracking, others to the moisture content and others to the thermal stresses (Shuttelworth, 2002). In the last years, scientists have concluded that spalling is a combination of thermal stresses and pore pressure. According to the opinion of various international experts, the current numerical modelling capabilities for predicting the possibility of concrete spalling under a temperature scenario at the intrados of the tunnel lining, is very limited. Recently, some thermo-poro-mechanical constitutive models have been appeared in the literature, but all these require extensive validation procedures before applied in practice. Also, no constitutive model has been published in the literature which is able to account all the factors leading to concrete spalling (Akhtaruzzuman & Sullivan ,1970). A numerical procedure that can be followed in order to estimate the spalling vulnerability of a specific concrete has been suggested by Kodur (Kodur, 2008). According to this, the model is based on pore pressure calculations in concrete, and spalling is considered to occur by comparing the computed pore-pressures with the temperature dependent tensile strength of concrete. A similar (and perhaps a little more advanced) procedure has been used by the Hatch Mot McDonald engineers by using FLAC3D (Franssen et al, 2007).Both Kodur and HMD engineers validated their models with the experiments of Phan (2008). However even these models worked great in specific types of concrete but in other types seemed to overestimate the spalling vulnerability of concrete. Also, the models that have been developed for the calculation of the spalling show great weakness at concrete with high moisture content and low permeability because the moisture migration due to pressure gradients leads to a completely saturated state of the concrete pores and as a result the required thermodynamic laws do not apply any more. Also, according to other studies the calculation of the spalling is a very complicated issue, since is not very easy to simulate the behavior of concrete under fire conditions. On the other hand an essential issue on the design of the evacuation of a metro tunnel is the spalling time. It is one of the main values which define the available time of the passengers to evacuate safely the tunnel. As a result and in order to measure the spalling values and design the evacuation of a metro tunnel it is proposed to test the concrete at several temperatures for the spalling depth and time.

II. Experimental

1.2 Types of concrete

In total, three different types of concrete were investigated, which were found to be the most usually used in metro tunnels. More specific these types of concrete were C20/25, C30/37, and C35/45 with latter two to be the most usual. The syntheses of these three types of concrete are described below:

i) Category C20/25

After a test mix, it was found that the composition for the concrete required consists of 40% gravel, 10% fine grain gravel, 50% sand by weight of dry materials with 320 kg/m^3 cement CEM II / AM (WL) 42.5R and additive superplasticizer at a rate of 0.63 kg per 100 kg of cement. The W/C ratio was equal to 0.60. The compressive strength of the 15 cm cubic edge sample made from this mixture was found to be 42.8 MPa at 28 days of age.

ii) Category C30 / 37

After a test mix, it was found that the required concrete composition consisted of 40.4% gravel, 10.4% fine grain gravel, 49.2% sand by weight of dry materials with 350 kg/m^3 cement CEM II / AM (WL) 42.5R and an additional superplasticizer at a rate of 0.6 kg per 100 kg of cement. The W/C ratio was equal to 0.51. The compressive strength of the 15 cm cubic edge sample made from this mixture was found to be 46.7 MPa at 28 days of age.

iii) Category C35 / 45

After a test mix, it was found that the composition for the concrete required consists of 40.4% gravel, 10.4% fine grain gravel, 49.2% sand by weight of dry materials with 380 kg/m3 of CEM II / AM cement) 42.5R and an additional superplasticizer at a rate of 0.6 kg per 100 kg of cement. The W/C ratio was equal to 0.48. The compressive strength of the 15 cm cubic edge sample made from this mixture was found to be 53.5 MPa at 28 days of age

1.3 Temperature of investigation

The temperature and time of exposure was selected by modelling a 25 MW (fig.2) fire in a single and double tube metro tunnel. The tunnel length is 762 m, which is the maximum limit of tunnel length without cross passage obligation. The evolution of the fire is based on the FIT project – fire curve which is the worst case. The power of fire was selected to be ignited in the middle of the metro tunnel. The modelling of the fire simulation the distribution of the fire along the tunnel in case of fire and representative values of the temperature for 10, 20 50 and 100m away from the fire was selected.

1.4 Equipment of the tests

The tests were performed in the laboratory by using a test furnace (fig.1) which was designed according to European Federation of National Associations representing producers and applicators of specialist building products for Concrete (EFNARC) guidelines. The furnace has the ability to simulate the temperature-time curves employed in several international standards. For this test a 30 cm x 1 cm x 5 cm specimen was prepared. The test was performed 28 days after the production of the specimens.

Figure 1 : Set up of fire test

III. Results

1.5 Fire tests

Initially the most severe fire test was conducted for each concrete type. The most severe scenario referred to 10m distance from the fire ignition in a single tube tunnel. The temperature increased at 600 °C after 22 min and remains at that temperature for 30 min. In the C20/25 and C30/37 concrete types no spalling occurred. This was attributed to the fact that it was very low time for the concrete to be fully thermally treated. This can be easily understood from fig. 2 where the temperature of the back surface of the specimen was measured during the test. As it can be easily observed the temperature did not exceed the temperature of 50 °C, meaning that the concrete created a gradient of 55°C/cm, which is attributed to the low thermal conductivity value of the concrete. As a result the concrete was not treated uniformly at the whole specimen and this avoided the spalling phenomena. In order to find the temperature that the specific type of concretes undergoes spalling phenomena, specimens from C20/25 and C30/37 were subjected to higher temperatures. More specific three more tests were conducted, at temperatures of 700 °C, 800°C and 900°C. From the testing of the specific concrete types it was realized that the C30/37 spalled at the temperature of 800 °C while the C20/25 concrete type spalled at the temperature of 900 °C. The type of spalling was similar to the C35/45 with a sudden explosion at 25 min after the beginning of the test for the C30/37 and 18min for the C20/25. This is something that it was expected mainly according to Khoury (Khoury, 2000) who mentions that one of the most crucial parameters for the occurrence of spalling is the high compressive strength. Concrete with high compressive strength is more dense and as a result the entrapped water does not find the suitable void to be evaporated and explodes making the explosive spalling.

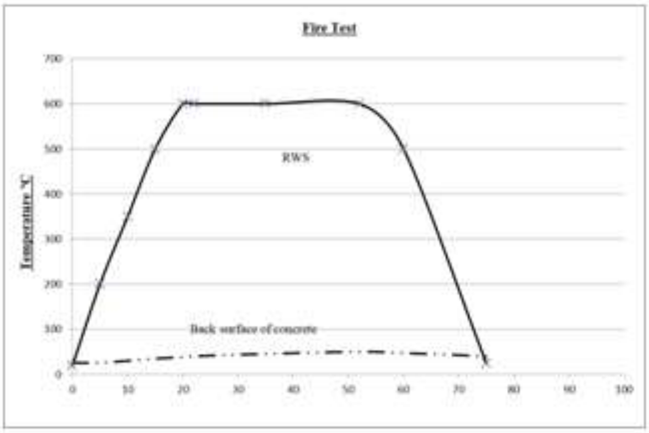

Figure 2: Temperature profile for fire test

In the case of the C35/45 spalling phenomena occurred 22 min after the beginning of the test, while the temperature was at 600 °C (fig.3). The spalling that occurred was typically explosive spalling with a piece of 10 cm to be removed from the surface of the concrete specimen at a depth of 1 cm. The same type of concrete was then subjected to another fire curve referring to a distance from the fire ignition (20m – max temp. 500 °C). As it can be observed in fig. 3b the concrete did not undergo spalling phenomena. This result is very crucial for the design of the evacuation. Based on these results the engineer should also take into account the spalling of the concrete by proposing two solutions: a) to evacuate in less than 20 minutes to ensure that all the users will evacuate the tunnel b) Oblige users close to the fireplace (a) ough the train and reach the point where the temperature is lower (20 m) and therefore there is no risk of spalling the concrete with the corresponding wound users.

In general, in order to avoid spalling phenomena at the concrete various methods of passive fire protection have been developed which however have not yet been applied to metro tunnels. At this point it should also be mentioned that apart from the concrete steel rebars necessitate protection because at temperature over 600 °C loose part of their load bearing capacity.

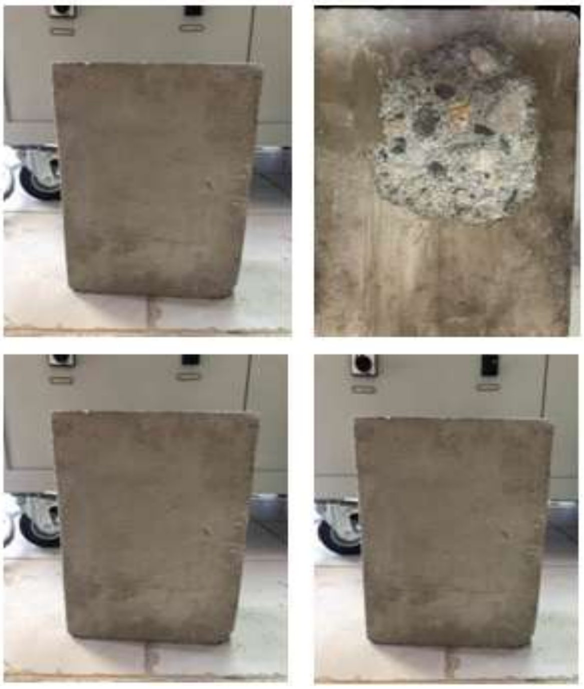

Figure 3: a) Spalling phenomena at C35/45 after 600°C, b) No Spalling phenomena at C35/45 after 500°C,

Therefore, steel and concrete are both fire sensitive construction elements requiring passive protection against fire in order to be capable of withstanding of fire for an appropriate period of time without loss of stability (Fletcher, I. 2007). Passive fire protection methods are generally divided in two categories: external (insulation) and internal (concrete design). The former are more advantageous being applied in new as well as in existing tunnels and consist of the cladding of the concrete by a fire resistant material which creates a protective external insulation envelope. These methods are a) cementious fire protection material applied either sprayed or as a board which, due to its low thermal conductivity, keeps the temperature of the concrete below the requirements and b) adding during the production of the concrete, polypropene fibers which during the thermal exposure melt thus creating passage to the evaporated water to be removed from the concrete without acting explosively.

1.6 Conclusions

From this study the following conclusions were excluded:

a) Concrete with the smallest strength did not show signs of spalling, which is also comes in accordance with the references. For this reason various methods and materials have been developed to prevent spalling, but this has not yet been applied to metro tunnels. This is a) coating the concrete with a fire protection material which, due to its low thermal conductivity, keeps the temperature of the concrete low and b) adding during the production of the concrete, polypropene fibers which during the thermal exposure melt thus creating passage to the evaporated water to be removed from the concrete without acting explosively.

b) In the case of concrete C35 / 45 it appeared that the design of the evacuation should also take into account the spalling of the concrete by proposing two solutions: a) to evacuate in less than 20 minutes to ensure that all the users will evacuate the tunnel b) Oblige users close to the fireplace to walk through the train and reach the point where the temperature is lower (20 m) and therefore there is no risk of spalling the concrete with the corresponding wound users.

c) Concrete types C20/25 and C30/37 appeared spalling phenomena under higher temperatures. More specific the C30/37 spalled at the temperature of 800 °C while the C20/25 concrete type spalled at the temperature of 900 °C . The type of spalling was similar to the C35/45 with a sudden explosion at 25 min after the beginning of the test for the C30/37 and 18 for the C20/25.

Acknowledgement

This research was funded by the project encoded EDVM 34 and title "Support of researchers with emphasis on young researchers" of the priority axis "Development of Human Resources, Education and Lifelong Learning" in Priority Axes 6, 8 and 9, co-funded by the European Social Fund (ECT) and the National Strategic Reference Framework.

References

[1]. Jönsson, J. & Herrera, F. 2010. HGV traffic – Consequences in case of a tunnel fire. Fourth International Symposium on Tunnel Safety and Security, Frankfurt am Main, Germany, 17-19/3.
[2]. American Society for Testing and Materials, 2001. Standard Methods of Fire Test of Building Construction and Materials. Test Method E119-01. West Conshohocken, PA, 2001.
[3]. Khoury, A. 2000. Effect of fire on concrete and concrete structures. Progress in Structural Engineering and Materials: 429–447.
[4]. Fletcher, I., Welch, S., Torero, J.L., Carvel, R.O. & Usman, A. 2007. Behaviour of concrete structures in fires. Journal of Thermal Science: 37–52.
[5]. Sakkas, K., Nomikos, P., Sofianos, A. & Panias, D. 2013. Inorganic polymeric materials for passive fire protection of underground constructions. Fire and Materials, 37: 140–150.
[6]. Boström, L. & Jansson, R. 2004. Spalling of Concrete for Tunnels. Proceedings from the 10th international Fire sience & Engineering Conference (Interflam '04), Edinburgh, Scotland.
[7]. Shuttelworth, P. 2002. Fire Protection of Concrete Tunnel Linings. Tunnel Management International, Vol 3, Issue: 239-244.
[8]. Akhtaruzzuman, A.A. & Sullivan, P.J.E. 1970. Explosive spalling of concrete exposed to high temperature. Concrete Structure and Research Report, Imperial College, London, UK.
[9]. Kodur, V.K.R. & Dwaikat, M. 2008. A Numerical model for predicting the fire resistance of reinforced concrete beams. Cement and Concrete Composites 30(5):431–443.
[10]. Franssen, J.M., Hanus, F. & Dotreppe, J.C. 2007. Numerical evaluation of the fire behaviour of a concrete tunnel integrating the effects of spalling. Proceedings of the Fire Design of Concrete Structures from Materials Modelling to Structural Performance Workshop, 8-9/11, Coimbra, Portugal.
[11]. Phan, L.T. 2008.Pore pressure and explosive spalling in concrete. Materials and Structures, 41(10): 1623-1632.
[12]. EFNARC. 2009. European Federation of National Associations Representing producers and applicators of specialist building products for Concrete, Specification and Guidelines for Testing of Passive Fire Protection for Concrete Tunnels Linings.

K.M. Sakkas" Concrete behaviour under elevated temperature" International Journal Of Engineering Science Invention (Ijesi), Vol. 08, No. 02, 2019, Pp 13-17