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An experimental evaluation to determine the required thickness of passive fire protection layer for high strength concrete tunnel segments

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HIGHLIGHTS

- 30 mm layer thickness above 50 mm concrete cover limits temperature of steel below 160 °C and concrete surface below 300 °C.
- Exposure of protected high strength concrete to ZTV-ING fire load is investigated.
- Concrete cover is thermally ineffective when layer thickness is greater than 55 mm.
- Fire damage into the protection layer initiates through the shrinkage cracks.
- Design thickness must include the depth of shrinkage cracks if they are inevitable.

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ABSTRACT

The Eurasia Tunnel is a part of the Bosporus Strait Highway Crossing Project connecting the Anatolian and European shores of Istanbul. This paper evaluates the use of high strength concrete for the segments for the bored part of the tunnel under the effects of design fire conditions. High strength concrete enables the attainment of high early strength levels required for segment handling and increases the segment durability compared to segments designed by ordinary strength concrete. However, in the event of a tunnel fire, the increased concrete strength of the segments increases their likelihood of spalling compared to segments fabricated by ordinary strength concrete. Therefore, determination of the passive fire protection requirements must take into account the strength of the protected concrete. This paper will present and include a discussion of the results of small-scale fire exposure tests conducted to determine the required thickness of passive fire protection layer for the evaluated high strength concrete tunnel segments.

1. Introduction

The Eurasia Tunnel is part of the ongoing 14.6 km long Bosporus Strait Highway Crossing Project. The 3.4 km bored part of the tunnel is composed of concrete segments.

Due to its increased strength and durability, designers can use high strength concrete to design tunnel segments. Euro Norm concrete classification considers concrete grades between C50 (50 MPa) and C150 (150 MPa) as high strength [1]. During the design phase of the project, use of high strength concrete was one of the considerations for the segment design. The grade of the design concrete evaluated in this study is C70 (70 MPa).

Concrete is a material that is susceptible to the degenerating effects of long-term fire exposure. There are three structurally degenerating effects of fire exposure on reinforced concrete. The first degenerating effect is the initiation of dehydration at 100 °C and concrete strength loss at 300 °C [2,3]. The second degenerating effect is the spalling of concrete and the third is the temperature increase of the embedded steel reinforcements. Spalling not only reduces the section thickness but may also expose the reinforcements to fire without the protection of their concrete cover. This exposure rapidly increases the reinforcement temperature and reduces its bearing capacity.

The study for defining the mechanism of spalling and the development of a reliable model to estimate the initiation temperature and the extent of spalling continues. Being a homogenous material under mechanical actions, concrete behaves as a heterogeneous material under thermal actions [2,4,5]. Spalling has been observed to occur within a wide temperature interval as low as 300 °C [6] and as high as 500 °C [7]. Spalling occurs because of the development of internal stresses surpassing the direct tensile strength of

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concrete. The two main explanations for the development of stresses are the generation of thermal gradients within the restrained concrete and the rapid development of vapor pressure within the porous space of concrete [8].

Concrete is a material consisted mainly of ingredients with varying geologic origins. High strength concrete is additionally consisted of reactive industrial by-product ingredients such as silica fume and fly ash. Thermal behaviors of ingredients that constitute the aggregate and the binding paste of concrete are different. This difference could lead to relative deformations under heat exposure that can initiate the development of stress levels surpassing the direct tensile capacity of concrete [9,10]. Research also suggests a rapid increase of the internal pressures with lower temperatures due to lower porosity levels of higher strength concrete [10–13].

On the other hand, the amount of compressive loading on the fire-exposed element determines the extent and depth of spalling [7]. High strength concrete elements can carry greater loads per unit area than elements composed of normal strength concrete. High strength concrete also has a higher modulus of elasticity than normal strength concrete. The modulus of elasticity and the amount of deformation of a concrete element determines the stored potential energy. The amount of potential energy stored within the deformed concrete element can influence the intensity of the spalling. The higher stresses carried by a high strength concrete element and the higher amount of potential energy stored within is likely to increase the extent and depth of spalling.

Different methods can increase the resistance of the concrete against the degenerating effects of fire. One method is to cover the concrete element by a fire resistant coating with sufficient thickness to limit the development of critical heat levels at the concrete surface. Passive fire protection materials are usually trademarked cement based materials with a fire resistive component. The fire resistive component can be volcanic ashes and volcanic aggregates previously exposed to and survived the extreme temperatures of the earth's core. A fire protective coating consisted of such elements has the ability to provide fire protective resistance against the effects of tunnel fires, the scale of which is lower than the heat exposure conditions the volcanic material has already been exposed to. The fire resistive component can also include silicates, mica or vermiculate that in the event of fire reacts with high temperatures to produce a beneficial reaction against the adverse effects of fire on concrete [14]. Another protective measure is to produce the concrete element with polymeric fibers. When exposed to fire, as the fibers melt they give way to the formation of voids thereby increasing the porosity of concrete and lowering the development of pore pressure that leads to spalling [15].

There was a time when normal concrete strength levels were the norm in construction. Therefore, majority of the research conducted by producers about the performance indicators of their passive fire protection elements concentrated on the performance of normal strength concrete. However today, recent findings suggest that the strength of the concrete element is highly influential on its fire performance. Therefore, the performance of a protected concrete element is not only dependent on the properties of the fire protection material but also on the properties of the protected concrete material.

The present study aims to determine the required thickness of cement and volcanic ash based fire protection material for the segments produced by high strength concrete. To this end, the paper presents the mixture properties of the design concrete and the fire performance requirements based on the design specification. The paper then presents the production of the small-scale fire test samples, the testing sequence and temperature data collection at various locations within the samples. Following the evaluation of results, the study concludes with a list of findings and recommendations for the thickness requirements of the passive fire protection layer for high strength concrete tunnel segments.

2. Material and method

2.1. Design concrete mixture

Table 1 presents the content of the high strength concrete mixture specially designed for the production of the small-scale fire test samples. The main reasons for selecting such a mixture are briefly as follows:

1. The Eurasia Tunnel is the deepest bored tunnel in the world underneath the saline waters of the Bosporus Strait. The high overburden pressures reaching 12 atm required simultaneous consideration for both the strength and the durability of concrete segments. Therefore, silica fume and type F-fly ash was used in the design to decrease the permeability and increase the sulfate resistance of the segments.
2. The bored tunnel is composed of 1670 rings. The project schedule requires that the 20-Ton segments reach 15 MPa strength levels in 24 h to resist the stresses expected to develop during their removal from the formworks.

A ternary high strength and high performance design concrete mixture attained high early strength levels with limited curing and low permeability and high sulfate resistance. Cylinder samples cast along the fire exposure samples tested under compression yielded the strength development of the design concrete in time. The 3-day, 7-day and the 28-day compressive strength values of the concrete samples cured under plastic covers at room temperature were 53.3 MPa, 61.5 MPa and 72.1 MPa respectively.

The No.1 grade of aggregate refers to aggregate sizes that can pass through a square sieve with dimensions varying between 4 mm and 16 mm. The No.2 grade of aggregates refers to aggregate sizes that can pass through a square sieve with dimensions varying between 16 mm and 22 mm.

Table 2 shows the specification limitations for the binder and water contents. The total binder content is the arithmetic sum of each binding element. The equivalent binder content denoted by EQC and determined from Eq. (1), depends on the hydration activities and weights of the binder contents [16]:

$$\text{EQC} = \text{Cement weight} + 0,3 * \text{Fly ash weight} + 2 * \text{Silica fume weight} \tag{1}$$

The design concrete mixture was the highest strength yielding mixture based on the specification limits. In terms of fire susceptibility, the mixture was also the most vulnerable in terms of spalling due to its high strength. Therefore, this paper studies its interaction with the fire protection material under the action of the design fire load.

2.2. Production of fire test samples

The three small-scale fire test samples produced satisfied the EFNARC specifications. EFNARC is an acronym for *European Federation for Specialist Construction Chemicals and Concrete Systems* [17]. The samples were 40 cm wide, 40 cm long

Table 1
High strength concrete fire test sample mixture content.

Mixture content	Quantity (kg/m^3)
CEM I 52,5R cement	320
Silica fume	20
F-type fly ash	60
No.1 calcareous aggregate	550
No.2 calcareous aggregate	555
Natural sand	371
Plasticizer	3.6
Water	144
Crushed sand	384

Table 2
Project specifications for the binder content [16].

	Limits of specification	Used quantity
Total binder (kg/m^3)	Minimum 340 kg/m^3	400 kg/m^3
EQC	Not applicable	378 kg/m^3
Water/EQC	Maximum %40	39.1%
Silica fume/EQC	Maximum %5	5.0%
Fly ash/EQC	Maximum %15	15.0%