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Nano-silica as the go material on heat resistant tunnel lining

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Abstract. This paper is concerned with passive fire protection method of protective concrete mix that is made up of fly ash, polypropylene fibre, and nano-silica. Nano-silica is focused on as the innovative material to be used in the composition of the protective concrete mix. The previous experimental studies which analyse the performance of passive fire protection on tunnels are discussed. This paper also discusses passive fire protection. The fire protection materials and behaviour analyses of tunnel structure are also presented. At the end of the paper, the recommendation of the optimum composition concrete material with fly ash, polypropylene fibre and nano-silica as tunnel lining fire protective materials is proposed.

1. Introduction

Since the early 1970s, there have been numerous minor, and several major fire incidents in underground transportation systems are increasing the interest in structural fire safety of underground facilities. The high temperature in a very confined space is able to damage the concrete lining and threaten the safe operation of the tunnel. In a major fire, the high temperature may also cause the tunnel lining to collapse.

When structures such as tunnels are exposed to a high temperature of 1000°C in a short span of time the structural, physical, and mechanical properties of the structure could be affected and consequently leads to irreversible loss of strength and instability of the tunnel structure. These effects could be due to the micro-cracking and spall generated by high vapour pressure from the temperature of the smoke and the radiation from the fire. These effects can be prevented, or at least minimised, by choosing the right material to provide fire protection. Massive amounts of wastes, such as fly ash and silica fume produced by the industries daily, can be added to or replaced a certain percentage of cement in a concrete mix.

2. Protective Concrete Mix

The three primary failures in tunnel fire are a failure of segments and segmental joints and yielding of the joint bolts [1]. These failures are mostly caused by the explosive spalling that takes place during sudden elevating temperature of fire in the tunnel. Few methods can be used to reduce the chances of explosive spalling such as protective concrete mix, boards and heat resistant segments. Bottomline is that focus should be given to the protective concrete mix. The right ratio of materials in the concrete mix will be able to suppress the possibility of spalling and subsequently avoid the failure aforementioned. The usage of supplementary cement replacements such as fly ash, polypropylene fibres, air-entraining agent, admixtures, silica fumes, and nano-silica is highly recommended while to minimise the effect of elevated temperature, the correct preventative measures with suitable material and proper insulation methods should be carried out.

Concrete is a porous material formed by combining cement, aggregates & steel reinforcements. Compared with steel structures, concrete structures have excellent fire resistance characteristics and are often used to protect steel from fire effects. Concrete has a low heat flow rate and high specific latent length compared to steel. The conductivity values of iron and steel are between 16 W / mK and 43 W / mK while the conductivity values of concrete are 0.62 W / mK to 3.3 W / mK [2]. The advantage of concrete when exposed to fire is to store strength if the exposure is not too long, and does not produce smoke and toxic waste at the end of the combustion. High-temperature exposure affects all concrete components which ultimately result in severe concrete loss strength. Detailed studies showed that the strength of the concrete is almost unaffected until the temperature is 200 ° C to 300 ° C, but starts to decrease at a higher temperature [3].

Fly ash is a waste material from coal-burning power plants. It has been used extensively as supplementary material in high strength concrete due to its exceptional performance as a pozzolanic material. When 50% of the cement is replaced with fly ash, the fly ash will act as a pozzolanic material and micro filter in concrete [4]. Adding 15 to 25% fly ash in a concrete mix help to increase the tensile strength of the concretes. However, adding a higher percentage of fly ash reduces the tensile strength of concrete mix slightly [5]. Regarding compressive strength, however, compressive strength decreases with the increase of fly ash content [4]. To show that fly ash’s strength increases with age, the highest increase in strength from 28 to 365 days was a specimen with 40% fly ash by 45% and the lowest increase in strength from 28 to 365 days was a specimen with 45% fly ash with only 39.27% [4]. This is due to the cement that continues to hydrate. Under the high heating condition, fly ash shows superior performance than pure cement concrete at temperatures below 600℃ [6]. After being exposed to heat, the specimen containing fly ash only produced fine cracks and did not spall. To maintain maximum strength and durability after exposure, replacing cement with 30% fly ash is recommended [6].

Polypropylene (PP) fibre is famous for its fire-resistant properties. In a normal condition, adding PP fibre to the mix does not affect the concrete’s compressive strength positively because of the weak interfacial bond between the fibre and cement fly ash grains [7]. Regarding indirect tensile strength, on the other hand, the inclusion of a high volume of fly ash and 0.75% PP fibre resulted in an increase of 53% at 28 days of curing [8]. This is due to the microstructural densification in the transition zone between the matrix and the fibre [8]. In elevated temperatures, PP fibres create pores in concretes when they disintegrate at approximately 160 ℃ [9]. The powerful vapour pressure will then be released into the additional pores or voids formed by the PP fibre, thereby reducing cracking and spalling. PP fibre is added into the concrete mixture with quantity between 1 to 2 kg / m^3 of concrete. However, for real tunnel development projects, a 1.5 kg / m^3 PP fibre is recommended [10]. Note that rates greater than 1.5 (kg of fibre PP) / (m^3 concrete), however, result in severe reduction of workability and densification ability and, therefore, increase in pore space[11]. Studies found that although fibre enhancement improves concrete performance, it also reduces workability by 2-8% [12]. This problem can be avoided by adding fly ash. Figure 1 shows the image of scanning electron microscopy (SEM) of control specimen with significant cracks after heated to 750℃. Figure 2 then shows that after the PP fibre specimen being exposed to 500℃ however, only microcrack can be seen as the fibres have completely melted and vaporised.

Nano-silica (NS), the focus of this paper, is a material which exhibits advanced pozzolanic properties that enhance the microstructure of cement. During cement hydration, nano-silica reacts with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrate (CSH) gel [13][14]. CSH gel is the main component responsible for the high strength of siliceous mixed specimens. The primary purpose of using nano-silica is to enhance a material’s hydration, thus raising pozzolanic activity, and to act as a micro-filler in cement [14][15]. Since nano-silica can produce high-density calcium silicate, it can accelerate hydration process and thus increase the initial strength of fly ash and nano-silica mix. Since there is a risk of the mixture undergoing exaggerated self-desiccation and cracks, high amounts of nano-silica compensated with the right water and superplasticisers ratio are recommended [14].

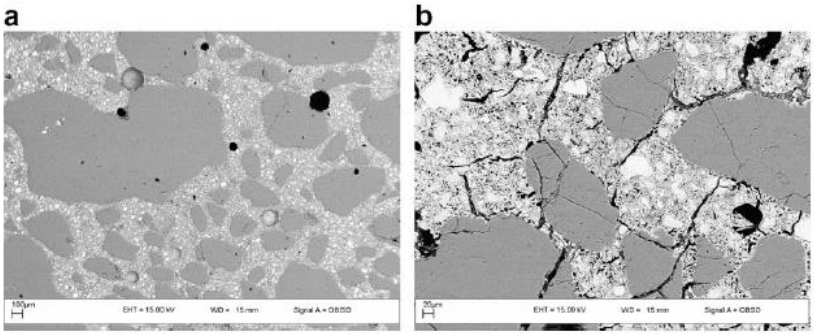

Figure 1. SEM images of control specimen at (a) 20°C and (b) 750°C [9].

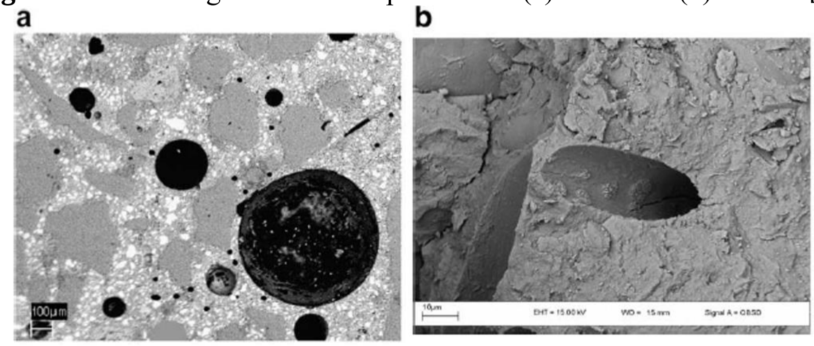

Figure 2. SEM Images of PP fibres RC (a) 20°C and (b) after exposure to 500°C [9].

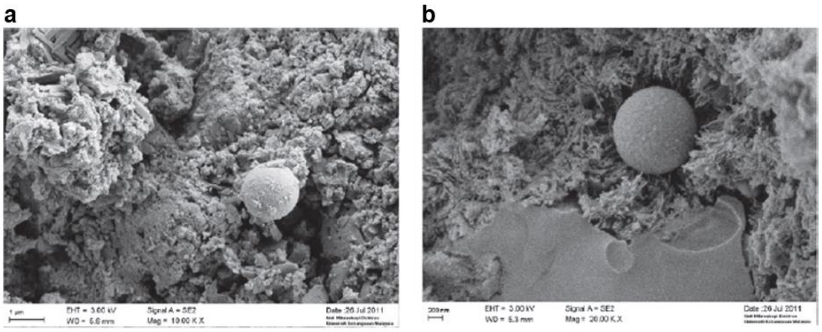

Figure 3. SEM images of fly ash and nano-silica specimen a)27°C and b) after exposure to 700°C [16].

An experiment was carried out to investigate the behaviour of nano-silica when added in a high volume of fly ash specimen and resulted in no improvement in strength when only 60 and 70% fly ash was used [15]. However, when 2% nano-silica was added to the mixture, the 28-day compressive strength of the specimen increased to 33 and 48%, respectively. This shows that the correct ratio of all substances is crucial to ensure that maximum strength is obtained. As a result of these observations, the addition of 2% nano-silica is recommended as the optimum value to achieve the highest compressive strength.

As a result of the better particle packing of the extremely small-sized nano-silica and the high pozzolanic activity of nano-silica reacting with fly ash as shown in Figure 3, the nano-silica and fly ash can enhance the strength of the calcium silicate hydrate structure, the specimens containing 37.5% fly ash and 7.5% nano-silica exhibited a maximum increase in strength [16]. When heated, all specimen containing nano-silica showed an obvious increase in compressive strength because of the filler effect of nano-silica and the enhancement of hydration process which then produced more high-density calcium silicate hydrate that will increase the reactivity of nano-silica and subsequently boost the strength [16]. Nano-silica, however, has a more negative influence on flexural strength when exposed

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to higher temperature [16]. High temperature causes the specimen to crack due to the vapour pressure. The addition of tensile stresses increased the expansion of cracks thus reducing the strength. These effects are believed can be improved with the addition of PP fibre to increase the tensile strength of the specimen thus reducing cracks and spalling. Therefore a combination of fly ash, PP fibre and nano-silica could provide the best protection method for concrete exposed to high temperature.

3. Discussion

Due to all the advantages that siliceous materials have to offer, this paper proposes using nano-silica together with fibre and fly ash to ensure the fire resistance of cementitious concrete mix. The composition of 30% of fly ash, 1.5 kg / m^3 of PP fibre and 5-10% of nano-silica is suggested to replace the cement composition. This can be used as a basis for investigating the performance of the concrete mix in tunnel lining.

The previous studies that were explained previously were from experimental studies on normal structural specimens. However, note should be taken that there is yet an experiment, reduced-scale or full-scale that investigates the usage of nano-silica in a heat-resistant tunnel segments.

Due to all the advantages that siliceous materials have to offer, this paper proposes using nano-silica together with fibre and fly ash to ensure the fire resistance of cementitious concrete mix. The effect of thermal, axial and combined loading should be investigated further to ensure that the chosen material is the best for the safety of the tunnels and tunnels users. This paper also recommends that more study should be carried out on the strength and mechanical, thermal and structural properties of nano-silica as it is believed that nano-silica can be an excellent fire protection instrument. A full-scale fire test should be done on new materials containing fly ash, fibre and nano-silica along with numerical simulation using CFD software and parametric study as to investigate the properties of the materials. A full-scale structural analysis should not only to examines the properties of segments but also the properties of the joint between segments and the segments with surrounding soils by taking into account initial load, construction load, service load, and thermal load.

4. Conclusion

This paper presented a collection of a literature review of passive fire protection materials to be used as tunnel lining fire protection. Gaps and recommendations are highlighted for future research. Since very few studies have been done on the benefits of nano-silica as a tunnel fire protection instrument, research on this topic could be very helpful to tunnel designers since the use of nano-silica has been proven to strengthen structures. To further understand the behaviour of nano-silica as a tunnel lining subjected to thermal loading, a very detailed study which involves analytical, experimental, and numerical simulation needs to be carried out.

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