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TECHNICAL NOTE

Fire Damaged Reinforced Concrete – Investigation, Assessment And Repair

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INTRODUCTION

The purpose of this Technical Note is to summarize levels of damage to and effects of fire on concrete and to describe technical requirements for the satisfactory investigation, assessment and repair of fire damaged reinforced concrete bridges and other structures.

LEVELS OF FIRE DAMAGE TO CONCRETE

Concrete can sustain various degrees of damage depending on the severity of the fire and the high temperature levels reached.

The effects on concrete components of high temperature fire includes:

- reduction in compressive strength;
- micro-cracking within the concrete microstructure;
- colour changes consistent with strength reductions;
- reduction in the modulus of elasticity;
- various degrees of spalling;
- loss of bond between concrete and steel;
- possible loss of residual strength of steel reinforcement and possible loss of tension in prestressing tendons [1, 2, 3, 4, 5]

The more severe fire damage would also involve the total exposure of main bars, significant exposure of prestressing tendons, significant cracking and spalling, buckling of steel reinforcement and even significant fracture and deflection of concrete components [1, 2, 3, 4, 5].

Fire damage to bridges is not a frequent occurrence compared to fire in commercial, domestic or industrial buildings. A fire in a building can be fuelled and maintained by an abundance of combustible materials. A bridge usually has no inherent fuel load and a fire may be the result of a vehicle collision, particularly involving fuels, cargo, tyres or other flammable materials. Fire can cause significant disruption to the operation of a bridge and the travelling public, depending on the extent and severity of damage and whether pre-stressing steel is involved. Immediate safety measures may include totally or partially closing a bridge, reduced speed limits as part of an overall traffic management response, posting a load limit or placing netting to collect fragments of spalling concrete.

EFFECTS OF FIRE ON CONCRETE

Changes in Colour and Temperature of Concrete

The colour change of concrete is a very important indication of the effect of fire. Colour change provides a very good visual guide to estimating the temperature range to which concrete has been exposed at various depths during the fire. Elevated temperatures result in significant modifications to the concrete microstructure, associated with dehydration of the cementitious paste, modifications to the aggregate/paste interface, and micro-cracking. These modifications are detrimental to concrete performance. The common changes in concrete properties associated with various peak temperatures are as follows:

- Up to 120°C: Oven-drying temperature has negligible effect or damage on the pore system or microstructure of concrete. There is no change in colour. Only free moisture is lost from within the concrete microstructure. There is no significant change in the properties of concrete up to these temperatures. For temperatures lower than 120°C, concrete porosity varies very little and the shape and pore size distribution curves shows no significant modification [6, 7].
- Up to 250°C: Characterised by localised cracks and dehydration of the cementitious paste with complete loss of free moisture and a reduction in paste volume. Commencent of strength reduction (Fig 1).
- 300°C - 600°C: Significant cracking of both the cementitious paste and aggregates due to expansion. Colour of concrete changes to pink (Fig 2).
- At 400 °C: Decomposition of calcium hydroxide.
- Greater than 600°C: Complete dehydration of the cementitious paste with considerable shrinkage cracking, honeycombing and generally concrete becoming friable, very porous and easily broken down. Colour of concrete changes to grey. Strength lost.
- Greater than 900°C: Colour of concrete changes to buff.
- Greater than 1200°C: The various components of concrete start to melt.
- Greater than 1400°C: Concrete melts completely.

At approximately 300°C the cementitious paste and aggregates containing iron salts, which are commonly present in concrete aggregates, turn pink (Fig 2). According to research this is also the point at which a significant loss of strength takes place due to the heating of the concrete. Siliceous aggregates are characterised by a colour change to pink under these extreme temperatures, although it is important to note that concrete which has not turned pink does not mean that it has not been damaged by fire. Any investigation must be undertaken with caution.

The above fire effects on concrete apply to all types of fires irrespective of the initiating and propagating fuel (for example, rubber tyres, tanker fuel, bush and grass fires). However, the intensity and duration of the fire may vary depending on the availability and combustible nature of the fuel. The extent of the resultant distress also depends on the proximity of the fire to the concrete surface. Appropriate fire retardant chemicals may be used for the protection of road and bridge assets from bushfires (TN 67) [(8)].

Spalling

Spalling of the concrete will occur when the intensity of the fire is such that moisture trapped within the concrete microstructure, (Fig 1), achieves bursting pressures, due to the generation of superheated steam, sufficient to crack and spall the concrete. Unequal rates of thermal expansion between the aggregates, cementitious paste and reinforcing steel, and water quenching during fire suppression, can also increase spalling due to thermal shock, strain differences and pressure causing micro-cracking and further strength losses. The two types of spalling that generally take place are the explosive type (Fig 2) due to moisture trapped within the interconnected void space of the concrete microstructure and a gradual detachment, of the concrete surface skin from a plane of weakness (Fig 3).

Soot and Smoke Deposits

Soot blackening and smoke deposits on concrete components are a direct by-product of an intense fire (Fig 2). These can be deposited during the height of the fire although soot can also be deposited while the intensity of the fire is abating.

TEMPERATURE EFFECTS ON CONCRETE

Strength of Concrete

A significant loss of strength in the order of 30% - 40% takes place once the temperature of concrete has reached 300°C. This is the result of significant internal cracking of the cementitious paste and aggregates due to thermal expansion, as well as the incompatibility between the paste and the steel reinforcement within the concrete. Above about 500°C - 600°C more than 70% to 80% strength reduction takes place due to the resultant friable and porous microstructure which lies in the grey to buff colour range. In the temperature range of 150°C - 300°C the loss of strength ranges between 5% and 30%.

Modulus of Elasticity

In the temperature range of up to 300°C the loss in modulus of elasticity of concrete is similar to the loss in strength and in the order of 40%. At around 550°C the loss in modulus of elasticity is in the order of 50%.

TEMPERATURE EFFECTS ON STEEL

Steel reinforcement

Steel reinforcement (depending on the type) can lose up to 50% of its yield strength while at elevated temperatures of the order of 600°C. However, it can fully recover its yield strength on cooling from temperatures of up to 450°C for cold worked steel and up to 600°C for hot rolled steel. At temperatures higher than these, the loss in yield strength is permanent, reducing to mild steel levels on cooling. The modulus of elasticity of steel is also significantly reduced while steel is at elevated temperatures.

Pre-stressing Tendons

Pre-stressing steel is more susceptible to fire damage and elevated temperatures, compared to normal steel reinforcement because the loss in strength of the order of 50% occurs at the lower temperature of about 400°C. Loss of tension in the pre-stressing tendons can be a combination of the elevated temperature effects on strength and loss in the modulus of elasticity of the concrete.

Bond between steel and concrete

The bond between steel and concrete can be adversely affected at temperatures higher than 300°C because of the greater thermal conductivity of steel compared to the cover concrete and differences in thermal expansion properties.

INVESTIGATION AND ASSESSMENT OF FIRE DAMAGED CONCRETE

The investigation and assessment of fire damaged concrete comprises both visual inspection and the use of various tests to establish the full extent of damage and the residual quality of the in-situ concrete. The visual inspection should be supplemented with consideration of temperature effects of fire damage on concrete, the physical properties, petrographic examination, temperature effects on reinforcing steel and prestressing strands and the temperature effects on the concrete/steel interaction.

Extraction of Concrete Cores

During the inspection, concrete cores may be extracted from both fire damaged areas and from sound concrete further away from the damage (Fig 4). The purpose of obtaining the concrete cores is to:

- Enable compressive strength testing and relative comparison between fire-affected and unaffected areas, and petrographic examination of the fire damaged concrete.

- Establish visually the depth of fire-affected concrete with respect to both steel reinforcement and prestressing tendons (Fig 2 and 5).

  Cores are usually 75 mm or 100 mm diameter for strength and petrology testing, although they can be smaller. Cores as small as 20 mm may be required from between pre-stressing tendons, often located at 50mm centres both vertically and horizontally. Accurate positioning of the drilling equipment must be achieved, probably within an accuracy of better than 2 mm.
- Enable a visual inspection of any internal surfaces of voided superstructure components using suitable lighting through adjacent cored holes.

Strength Assessment

Strength assessment can be based on actual concrete core compressive strength testing (including conversion to equivalent cylinder strength based on corrected core strength), consideration of Schmidt Hammer test results (in accordance with ASTM C805)[9] and physical appraisal using a hand-held hammer during the inspection of the fire affected concrete structure. Knowledge of the original design compressive strength can be very useful in the overall strength assessment. Hand-held hammer testing during the visual inspection, both on fire-damaged concrete and sound concrete, can provide some initial indication of the relative quality compared to undamaged concrete.

The estimated compressive strengths at the various locations can be utilised for structural analysis purposes.

Structural Analysis

Structural analysis should be undertaken to establish the residual capacity of the structure in satisfying the prevailing loading conditions, having regard for the concrete strength and condition of the steel reinforcement in the fire affected zone.

Petrographic Examination

The purpose of the petrographic examination is to more accurately delineate the extent of the damaged area and to identify any significant micro-cracking developed in the cementitious paste. The extent of micro-cracking can be determined in the coarse aggregate pieces in the fire affected zone and in adjoining sound concrete. Any material that may exist within these cracks should be identified. The petrographic examination may provide further confidence in relation to the depth of fire-damaged concrete determined from site observations together with the visual inspection of the concrete cores shortly after extraction from the affected concrete. Scanning electron microscopy may also be used to identify both the material that may fill these cracks and the cause of these cracks [10].

REPAIR OF FIRE-DAMAGED CONCRETE

Following the investigation and assessment of visual and temperature effects of the fire damage on concrete and steel, a detailed repair process can be developed (TN 72) [11]. Standard practice for fire-damaged concrete requires that all the severely fire affected concrete be removed from behind the steel reinforcement and pre-stressing tendons, to a depth of at least one bar diameter. The removed concrete is then replaced with flowable or hand/trowel applied polymer modified cementitious materials or spray applied gunite cementitious repair materials (Fig 5, 6).

However, it is considered that although the fire-damaged concrete must be removed behind the normal steel reinforcement to afford a good mechanical key and effect a good concrete repair, the pre-stressing tendons may not have to be exposed any further if they are not physically damaged or unravelled. It is considered that leaving prestressing tendons undisturbed in somewhat lower quality, yet bonded concrete is a better result rather than replacing that concrete with repair materials. The effectiveness and efficiency of the prestress transfer to the existing fire-affected concrete would be superior to that developed after removal of the fire-affected concrete and replacement with a material which will not provide composite prestress action after the repair.

A step-by-step repair procedure should be undertaken in accordance with the requirements of VicRoads Specification, Section 689 “Cementitious Patch Repair of Concrete” [12]. Such repair of concrete must include:

- breaking back all the fire affected concrete to sound and dense concrete and exposing as much of the steel reinforcement as possible;
- preparation of steel reinforcement and concrete substrate;
- application of an appropriate steel primer and substrate bonding coat; and
- rebuilding to the original surface profile using either flowable, hand/trowel applied polymer modified cementitious materials or spray applied gunite cementitious repair materials.

SUMMARY

When a concrete structure or component is damaged by fire, a thorough investigation to assess the structural damage should be conducted as soon as possible after the fire. Careful and considered interpretation of visual observations and any testing that may be conducted is essential to enable a correct diagnosis and prognosis of the problem in fire affected areas, and thus enable appropriate corrective measures to be taken. In contrast to construction materials such as timber and steel, concrete has superior fire resistance and therefore even in severe fires it may offer effective in-situ repair options or partial removal and replacement options compared to the alternative of complete demolition and reconstruction.

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Fig 1 - Scarred and spalled underside of flat slab concrete beam (temperature about 150°C - 200°C)

Fig 2 - Explosive spalling, pink tint, exposure of steel ligatures, main corner bars and pre-stressing tendons. Temperature above 300°C

Fig 3 - Concrete surface skin detached from upper part of beam

Fig 4 – Removal of cores from fire damaged concrete

Fig 5 – Preparation to sound and dense concrete, exposure and protection of steel, shows coring holes

Fig 6 – Saw cutting of perimeter of repair area , application of steel primer, formwork in place, and repair with free flowing micro concrete in formwork

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