Forensic engineering of fire damaged concrete structures– a review –

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Abstract. Malaysia has put numerous efforts in producing standards and guidelines for firefighting systems in building. However, with rising statistics of fire incidents in Malaysia, developing the standards and guidelines on forensic engineering for fire damaged concrete structures is a pure challenge. Since the durability of fire damaged concrete depends on many factors including the types of concrete materials used and the thermal actions, a performance-based method should be considerably adopted besides prescriptive method that are currently being used. To overcome this, an attempt has been made to study and review papers on the durability of concrete structures damaged by fire according to the performance-based method, the assessment and its’ rehabilitation. Few methods of assessment and investigation have been discussed briefly in this paper such as non-destructive test like Hammer Test, UPV and Core Test. Various of fire-damaged building rehabilitation method had been implemented in the industry however FRP plates stands out among them. Reviews on the behavior of fire damaged concrete structure repair with FRP composite plate and new improvement in fire resistance of FRP composite materials will be conducted. Other than that, a new composite material, TRM composite for fire damaged concrete strengthening and a chemical treatment method, realkalisation method for restoring fire damaged concrete strength are also discussed. Therefore, the understanding in this field is useful in evaluating and improving the building structural integrity of fire damaged concrete structures to ensure the rectified structure could fulfill the initial function and restore the original mechanical properties.

1. Introduction
Concrete has low thermal conductivity and therefore transfer heat very slowly when subjected to fire. Although concrete provides good fire resistance, concrete structures must still be designed for fire effects. According to Jabatan Bomba dan Penyelamat [1] statistical report for 2012, 29,484 fire incidents were reported. From the statistics, 5,447 cases involved structural building with 98 were reported death. It was also reported that fire causes damage and lost in assets worth more than RM 1 billion for the year 2012 in Malaysia. Therefore, the understanding of the behaviour of concrete subjected to fire is essential in developing the standards.

While most countries are moving towards performance based codes that in such a way give more flexibility in design and allowing cost-effectiveness as stated by Hadjisophocleous & Bénichou (2000), Malaysia according to Zainudin et al (2003) however still adopting fire-resistance design philosophy based on a prescriptive approach. In the prescriptive method, the behaviour of structures is evaluated and normally expressed in units of time (1-hour, 1.5-hour, 2-hour fire resistance) rather than the actual performance of the structure. This method is adopted in the Uniform Building by Laws Malaysia which is based on the ISO Standard Fire.
In general, Erlin, Hime, & Kuenning (1972), Wong et al. (1992) and Ingham (2009) explained that the temperature of 300°C been used as benchmark or critical temperature where concrete is deemed to have significantly damaged. However, the residual strength of concrete after fire is significantly influenced by types of material used such as mix proportions, types of aggregates as well as the applied loading during heating.

Over the years, numerous studies have also been conducted on thermal actions including the cooling process either by natural or forced process. Ingham (2009) also explained that the compressive strength of concrete also effected by the duration of fire and the temperature. However, data on the effect of concrete mechanical properties on the duration of fire is limited.

As for the assessment, a classic method for estimating the maximum surface temperature reached by reinforced concrete elements is based on the observation of the permanent colour variations undergone by concrete containing aggregates of siliceous or limestone rock after exposure to high temperatures. According to Neville A.M (1975) and Lea FM, Davey N (1949), such colour changes depend upon the maximum temperature: the surface takes on a pink or red hue when exposed to temperatures of 300-600°C; dark grey, if the temperatures are in the range of 600-900°C; brown, if the maximum temperature reached is between 900 and 1200°C; and finally, yellow if it exceeds 1200°C. Unfortunately, this simple method is so approximate as to be absolutely inapplicable when the information is required to constitute the basis for precise analysis.

In recent years fire accident has rapidly occurred, numerous of strategies been undertaken to resolve the fire damaged building such downgrade the service loading, demolish and reconstruction. However, due to time and cost consideration, immediate repair and rehabilitation technique on the localised damaged area is more favourable in the industry. Strengthening and repair fire-damaged concrete structure using high strength composite material has been commonly implemented since composite material such as fibre reinforce polymer (FRP) been introduced a few decades ago. Steel plates or reinforced concrete jacketing were also being use in concrete structure repair however FRP provides more advantages such as light weight, high strength, corrosion resistance, better repair efficiency and easy application.

Reinforced concrete structures offer well fire resistance due to its low thermal conductivity properties. However, studies have proven that when concrete exposed to rapidly increased temperature, the properties will decrease and intended to reduce the durability. Hence, FRP composite materials stands out among the other materials in playing an important role in repair and increase the fire-damaged concrete load capacity. Various of new form FRP composites is rapidly developed and improved due to increasing knowledge and common implement in the construction repair industry. For the past few years, many research have been conducted on improving effectiveness of using FRP composite materials in repairing fire damaged reinforced concrete structure as well as increasing the fire resistance of FRP composite material.

Therefore, with a vast transformation from the conventional cast in-situ concrete to a modern concrete technology, it is essential to study the performance based design on the durability of several types of concrete materials when exposed to high temperature/ fire, the assessment and the rehabilitation. Hence, these information and knowledge will be used to develop the code of forensic engineering for fire damaged concrete structures as well as perfecting the current code for fire safety engineering which is binded in the Uniform Building by Law Malaysia.

2. Durability of Concrete After Fire
When concrete exposed to high temperature, it will undergo a series of chemical and physical changes that will result in deterioration of its mechanical properties. (Ma, Guo, Zhao, Lin, & He, 2015). The changes in concrete mechanical properties is strongly influenced by many factors such as of material used including types of aggregate, proportion of mixture and the thermal actions.
2.1. Types of aggregate

Malaysia is rich with limestone and has commonly been used as a primary source of aggregate to mix concrete. Numerous study has been conducted on the effect of different types of aggregates used in the concrete mix when subjected to fire. Abrams, M.S. (1971) found that siliceous aggregate loses its capacity by half at 650ºC (1200ºF) while carbonate and lightweight aggregate concretes retains nearly its original compressive strength at the same temperature.

Lightweight aggregates have low heat conductivity, therefore exhibit high resistance to heat. This is mainly because they are formed by volcano eruption or incineration. Therefore, the concrete mixed with such aggregates should perform higher resistance towards high temperature compared to normal aggregates concrete (Ashley, B.E, 2007).

In Malaysia, besides the commonly used expanded clay, numerous studies have been conducted on an oil palm shell (OPS) as an alternative lightweight aggregate. Johnson Alengaram, Al Muhit, bin Jumaat, & Jing (2013) through their research have found that the lowest thermal conductivity for structural OPS concrete is of 0.57 W/mK. The value is relatively lower than 0.8 W/mK explained by Ashley B.E (2007) and also the lowest among other aggregates such as 1.6 W/mK for siliceous concrete and 1.3 W/mK for calcareous concrete. To simplify, the lower the thermal conductivity of the concrete, the higher the resistance towards the rise in temperature when exposed to a fire.

2.2. Types of material

While carbonate and lightweight aggregates under normal concrete strength performs relatively well in fire, the same residual strength doesn’t reflect in the High Strength Concrete (HSC) (Eurocode 2). Studies by Kodur VKR (2000) and Jahren, P. (1989) have found that HSC has been found to be more prone to spalling failure than normal strength concrete (NSC) under high temperature. The high strength concrete often relates to low permeability due to lower water/cementitious ratio and higher density. Because of this, during high temperature, the pore will exert pressure on its surrounding leading to spalling. The spalling will result in the reduction of cross sectional area of the structural member. Therefore, the process accelerates the heat penetration to the steel reinforcement leading to early failure of structural member.

Over the years, numerous study has been conducted on the behaviour of concrete when different types of supplementary cementitious materials are used. The supplementary cementitious materials used to produce higher strength of concrete as well as to increase its durability. One of the most commonly used additive is fly ash.

Xu, Wong, Poon, & Anson (2001) studies the behaviour of concrete made with pulverized fly ash (PFA) when subjected to fire. In this research, concretes made with PFA replacements of 25% and 55% with the water/cement ratios were 0.5 and 0.3 respectively when subjected to temperature up to 800ºC were investigated. They found that concrete made with a 55% PFA replacement exhibited a residual strength higher than other concretes by about 10% after being subjected to 450ºC and 650ºC. Simply put, when PFA is included, fire resistance of the material is improved compared to non PFA concrete.

Besides fly ash, silica fume has been widely used to produce high strength concrete. Although silica fume performs outstanding mechanical properties at room temperature, however it is highly prone to explosive spalling when subjected to fire compared to normal strength concrete (Ju, Tian, Liu, Reinhardt, & Wang, 2017), (G. Sanjayan and L. J. Stocks, 1993) and (Jahren, P., 1989).

Apart from the supplementary cementitious materials mentioned above, the addition of fibres often used in the concrete mixture for producing high performance concrete. There are two types of fibres that are commonly used in the industry, which are polypropylene and steel fibres. According to Akca & Zihnioğlu (2013), polypropylene fibre shows improvements of residual compressive strength below 400ºC. However, no significant influence was identified beyond the temperature.

In recent study, Serrano, Cobo, Prieto, & González (2016) carried out an experiment to investigate the behaviour between concrete with addition of polypropylene and steel fibre by 1% to 2% when
subjected to fire. Through their study, they found out that, under normal temperature, concrete with addition of polypropylene fibres reaches higher strength values than those with steel fibres. Polypropylene fibres have lower thermal conductivity than steel fibres. Hence, concrete with addition of polypropylene fibres has a higher resistance to the heat than steel fibres. However, both fibres show greater compressive strength at 400°C than the traditional mixture of cements and aggregates.

2.3. Water cementitious ratio
Lower water to cementitious (w/c) materials ratio often relates to higher strength of concrete. It is favourable technique used in the construction industry as it produces workable concrete without the need to use excessively high cement contents. However, according to Xu, Wong, Poon, & Anson (2003), Xu et al. (2001) and Akca & Zihnioglu (2013), lower ratio of w/c leads to lower porosity and decreases permeability of concrete. During the elevated temperature, water in the concrete pores evaporates, leads to the increase of pressure within the cement paste until eventually causes spalling.

Xu et al. (2001, 2003) through their experiment has proven that the w/c ratios of 0.3 when subjected to fire showed fewer cracks than w/c of 0.5, but the crack are wider and longer. This explain the tendency of concrete experiencing spalling as a result of high vapour pressure.

2.4. Thermal Actions
Over the years, numerous studies have been conducted on the relationship of temperature and strength loss. Studies by Erlin et al. (1972) and Ma et al. (2015) has concluded that at room temperature to 300°C, concrete strength keeps constant or increase due to the effect of concrete paste hardening. Concrete compressive strength decreases dramatically at temperature beyond 300°C until it lost almost its capacity at 800°C.

When concretes are exposed to high temperatures, there are changes in the mechanical properties and the durability of concrete. Apart from the material’s thermal conductivity, the compressive strength is influenced by the cooling process and heating rate. Dos Santos & Rodrigues (2016) have studied the effect of cooling on residual strength of concrete. They have concluded that the higher the temperature and the fastest the cooling process are and the greater the negative impact on the residual strength of a concrete.

The strength was also affected by heating rate. Studies by Xiong & Liew (2016) in their study have found that the higher heating rate, the lower strength the concrete could carry, although the former author conclude that the rate of heating has little effect on the residual strength for temperature gradients lower than 10°C/cm. The reduction in the concrete strength will eventually induce spalling.

3. The Fire Concrete Damaged Assessment
The original properties must be obtained by performing certain assessments such as Visual Inspection, Non-Destructive Tests (NDT) and Semi Destructive Tests (SDT), in order to restore the mechanical properties of the affected structure. Figure 1 show the flow chart of the assessment process, starts with site environment verification, preliminary investigation, detailed evaluation and analysis of the results to produce a proper repair design.
Figure 1. The Assessment Flow Chart (Narendra K. Gosain, 2008).

3.1. Visual Inspection
Although concrete is designed to withstand fire to certain extend, BS8110:1997, Table 3.4, Nominal Cover to All Reinforcement to Meet Specific Fire Resistance, intense heat may affect the concrete and chemical reaction due to fire will cause the change in colour (Tovey, A.K, 1986). Table 1 shows intense temperature or fire effects on concrete which changes the colour, pink to buff and physical appearance, cracks and spalling. This table can be used as guideline to evaluate the current state of affected structure.

According to Roy G. Kinnear (2007), the investigator will start the inspection by evaluating the structure from a reasonable safe distance in the risk of his own safety. With the current technology visual inspection can be conducted using drone (Figure 2) which will capture the footage of the fire affected structure from a very close angle without risking the investigator’s safety.

3.2. Non-Destructive Test (NDT)

3.2.1 Rebound Hammer. Rebound Hammer is the cheapest and fastest test to obtain compressive strength of concrete and to compare the surface hardness of concrete to locate potential damage (Narendra K. Gosain, 2008). Figure 3 shows the schematic view of the Schmidt Rebound Hammer and procedure of test.
**Table 1.** Physical Effects of Temperature on Concrete (Narendra K. Gosain, 2008).

| Temperature   | Colour Change | Changes in Physical Appearance and Benchmark Temperatures | Concrete Condition |
|---------------|---------------|----------------------------------------------------------|---------------------|
| 0 - 290°C     | None          | Unaffected                                               | Unaffected          |
| 290 – 590°C   | Pink to Red   | Surface crazing: 300°C; Deep Cracking: 550°C; Popouts over chert or quartz aggregate: 575°C | Sound but strength significantly reduced |
| 590 - 950°C   | Whitish Grey  | Spalling, exposing not more than 25% of reinforcement bar surface: 800°C; Powdered, light coloured, dehydrated paste: 575°C | Weak and friable    |
| 950+°C        | Buff          | Extensive Spalling                                       | Weak and friable    |

**Figure 2.** Drone (Google image).
3.2.2. Ultrasonic Pulse Velocity Test (UPV). Ultrasonic Pulse Velocity Test usually performed to visualize a cross section of a structure to identify any possible cracks, voids, delamination and bond loss between cement and aggregate within hardened concrete Figure 4 & 5, (Fire Protection Planning Report, 1994).

High Frequency sound waves will be introduced to the affected structure/surface and the waves will be reflecting back to its receiver, oscilloscope creating a graph of reflected sound waves vs time (The Collaboration for NDT Education, The American Society for NDT).

Figure 3. Schematic View of the Schmidt Rebound Hammer (Awoyera P.O, 2014)

Figure 4. UPV Tester (Google image)
3.3. Partially-Destructive Test

3.3.1 Core Test. Although NDT can give information on the compressive strength of the structure, Core Test will allow the examiner to conduct systematic investigation on the crack pattern caused by fire (Paolo Cioni, 2000) while determining compressive strength, modulus of elasticity and Poisson’s Ratio. Using this core test (Figure 6, 7 & 8), the penetration depth of the characteristic irreversible thermos-chemical reactions in the concrete aggregates can identify the maximum temperature induced by fire. (Paolo Cioni, 2000).

Petrographic analysis can be performed on the core to obtain information on bond loss between cement and rebar, crack orientation and their relationship to the aggregate, micro cracking, extend of concrete dehydration, chemical compositional changes in cement and aggregate and temperature distribution in the specimen (Fire Protection Planning Report, 1994)

Figure 5. Oscilloscope, or flaw detector screen (The American Society for NDT)

Figure 6. Core Drill Equipment (Google image).

Figure 7. Concrete Core Sample (Google image).
4. Rehabilitation

4.1. External Bonded FRP composite plate method

Once fire accident occurred in a building, the concrete structure intends to lose design capacity due to exposure to high temperature. Hence, in order to strengthen the existing concrete structure capacity to be able to support existing service load, various repair and rehabilitation methods were introduced and external bonded FRP composite plate is the most widely used method since it was introduced a few decades ago.

Since repair and rehabilitation of fire damaged building has been a concern, many research and studies have been conducted to support the FRP effectiveness and advantages in fire damaged concrete structure repairs [24,25,31,32]. These studies including the investigation of the axial capacity and flexural strength of fire damaged concrete structure specimens strengthening with external bond FRP composite plates. In these papers, the investigation shows positive results as FRP composite increase axial capacity and flexural capacity with jacketing method.

For axial load studies, the concrete column specimens lose 42-44% of its compressive strength after exposed to high temperature 500°C and applying external bonded FRP composite plate jacketing method increase compressive load capacity of the fire damaged concrete structure effectively [31,32].

On the other hand, the flexural strength behaviour of repaired fire damaged concrete beam is investigated by strengthening the concrete beams which was damaged with high temperature up to 700°C with external FRP composite and subjected to testing loads [24,25]. From the papers, the investigation shows promising results where the load capacity and stiffness of concrete beams specimens increased and enhanced.

4.2. New fire resistance composite materials for external bond repair

As repair fire damaged concrete with externally bonded fibre reinforced composite plates is well applied, the fire resistance of FRP repaired concrete structure had been a major concern and widely studied due to FRP composite material low fire resistance properties. In the recent years, a new fire resistance FRP for external bond repair had been studied and developed by Ji, Li, & Alaywan (2013).
This new fire resistance FRP technology involves using the nanoclay reinforced intumescent coating. The nanoclay is mixed with the epoxy resin to form an exfoliated nanoclayed reinforced epoxy and this epoxy is used to prepare the FRP sheets for the externally bonded repair to damaged concrete specimens. Once the nanoclay enhanced FRP external bonded repair is complete, an intumescent coating is applied on the surface to form the new fire resistance FRP repair technology. Nanoclay enhanced FRP and intumescent coating forms multiple insulate layers that reduce the thermal conductivity yet does not affect the FRP sheets mechanical properties. In this paper, the repaired concrete structure specimens will be tested with fire exposure and the result residual strength capacity is investigated. The residual strength capacity of test specimens shows positive result as well the fire resistance which test results show that the fire resistance of repaired specimens with pure epoxy and nanoclay enhanced epoxy are 132.54°C and 138.75°C.

Nevertheless, the new fire resistances technology provided positive result, this new improved FRP less effective in fire resistance compare to TRM which will be discussed in item 4.4. Other than that, in order to maintain the mechanical properties of FRP sheets, exfoliated nanoclay reinforced epoxy is selected due to its high interfacial interaction and this composite material require certain mixing procedure and equipment. Hence, development of the new fire resistance FRP requires specify equipment and technical skills otherwise required strength capacity may not be able to achieve as poorly developed nanocomposite resulting reduction of mechanical properties. Apart from that, this paper serves as a good guideline and reference for new fire resistance technology of FRP composite materials which benefit for future research.

4.3. Re-alkalisation Method
Since many researches had been carried out in repair and rehabilitation of the fire damaged concrete structure and in the recent years, majority FRP composite plates was implemented in the concrete repair. However, other than the FRP composite plates, an alternative method had been carried out by Y. Xiong, Deng, & Wu (2016) which is re-alkalisation treatment.
They discussed that when the high strength concrete exposed to high temperature, the concrete durability tends to reduce due to chemical reaction of concrete that involves carbon dioxide in air and calcium hydroxide subsequently the reduction of concrete alkalinity. Hence, in order to restore the concrete alkalinity, realkalisation treatment is carried out to concrete specimen which undergoes high temperature exposure from 300°C to 700°C for 2 to 3 hours. Refer to their test result, the residual compressive strength of concrete is able to be recovered, ranged from 17.5% to 42.4% for concrete grade 50 and 9.3% to 21.2% for concrete grade 70. This shows that the treatment is more effective to lower concrete grade.

However, despite of the positive result of this method, this electrical treatment is not practically convenient in the industry as the treatment time involve up to 14 days and requires various equipment compare to the FRP composite plate that able to provide immediate strength increase and easy installation.

4.4. External Bond TRM composite Method

As fibre reinforced polymer composite materials for concrete repair works been introduced throughout the years, a new cement based composite material known as textile reinforced mortar (TRM) was develop in recent years. The TRM composite is formed by combining textile form advanced fibres with cement-based mortar. This composite is low in cost, high fire resistance and easy installation even for wet surface compare to FRP composite material. A research was done on the comparison of TRM versus FRP jacketing in shear strengthening of concrete members subjected to high temperature by Tetta & Bournas (2016).

![Figure 11. TRM for Shear Strengthening of Concrete Member (Tetta & Bournas, 2016)](image)

In the paper, the concrete specimens were strengthen using the TRM or FRP jacketing subjected to various high temperature from 20°C to 250°C. The result shows that TRM is serves better for enhancing the fire damaged RC beams shear capacity than FRP jacketing. However, apart from subjecting to high temperature, FRP has more advantages in term of strengthening compare to TRM (Raoof, Koutas & Bournas, 2017) because TRM require multiple layers in strengthening of concrete structure in order to achieve the required strength which subsequently increase in self-weight. Therefore, although TRM have more advantages in strengthening the concrete structure subjected to fire, FRP is more in favour and effective due to its light weight and high strength capacity.

5. Conclusion

The approach of adopting fire engineering based on the performance based is a big challenge as it requires the good understanding in the design process, the building material, the fire scenarios acting on the building, the assessment and the most suitable rehabilitation works that should be adopted. The following main conclusions are withdrawn:
• Siliceous aggregate loses its capacity by half at 650°C (1200°F) while carbonate and lightweight aggregate concretes retains nearly its original compressive strength at the same temperature;
• The lower the thermal conductivity of the concrete, the higher the resistance towards the rise in temperature when exposed to a fire;
• When superplasticizers such as PFA is included, fire resistance of the material is improved compared to non PFA concrete;
• However, silica fume is highly prone to explosive spalling when subjected to fire compared to normal strength concrete;
• The addition of both polypropylene and steel fibres show greater compressive strength at 400°C than the traditional mixture of cements and aggregates. However, polypropylene fibres have a higher resistance to the heat than steel fibres;
• Lower water to cementitious (w/c) materials ratio relates to higher strength of concrete. However, lower ratio of w/c leads to lower porosity and decreases permeability of concrete;
• The higher the temperature and the fastest the cooling process are and the greater the negative impact on the residual strength of a concrete;
• The higher heating rate, the lower strength the concrete could carry;
• In order to restore the mechanical properties of the affected structure, site environment verification, preliminary investigation, detailed evaluation and analysis of the result are crucial.
• For evaluating the structure’s mechanical properties, NDT and SDT which are rebound hammer, UPV and core test were used.
• Among various of repair and rehabilitation method for fire damaged concrete structure, externally bonded FRP composite plates is more effective due to its light weight properties, instant increase of concrete strength capacity, high tensile strength and easy installation.
• Due to FRP composite materials low fire resistance properties, sufficient fire protection is required in order to maintain its effectiveness in strengthening purpose when subjected to potential fire hazard in future.

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