Properties of concrete containing different type of waste materials as aggregate replacement exposed to elevated temperature – A review

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Abstract. Concrete is the chief material of construction and it is non-combustible in nature. However, the exposure to the high temperature such as fire can lead to change in the concrete properties. Due to the higher temperature, several changes in terms of mechanical properties were observed in concrete such as compressive strength, modulus of elasticity, tensile strength and durability of concrete will decrease significantly at high temperature. The exceptional fire-proof achievement of concrete is might be due to the constituent materials of concrete such as its aggregates. The extensive use of aggregate in concrete will leads to depletion of natural resources. Hence, the use of waste and other recycled and by-product material as aggregates replacements becomes a leading research. This review has been made on the utilization of waste materials in concrete and critically evaluates its effects on the concrete performances during the fire exposure. Therefore, the objective of this paper is to review the previous search work regarding the concrete containing waste material as aggregates replacement when exposed to elevated temperature and come up with different design recommendations to improve the fire resistance of structures.

1. Introduction
Concrete is the feasible material that can be exposed to high temperatures during the fire or near to the furnaces [1]. Whereas exposure to high temperature during the fire can be a potential threat for any construction buildings that can cause a major damage to reinforced concrete structures [2]. Despite that concrete is a non-combustible material, the effect of fire on concrete structure still can change physical, chemical, and mechanical properties of the concrete once it exposed to elevated temperatures. Moreover, it will also cause the strength reduction, volume stability and modulus of elasticity of the concrete [3]. Thus, the concrete properties exposure to fire is significant, while considering the load carrying capacity and restoring fire-damaged buildings [4].

It is generally known that concrete is a composite material that made from cement, water and almost 65% to 75% volume of concrete is occupied by aggregates. Currently, the depletion of raw materials in concrete such as natural aggregates becomes a serious problem all over the world and it was caused by the rapid industrial development [5]. One of the best solutions to reduce this problem is to utilize recycled waste material and industrial by-product in the concrete production such as palm oil clinker,
bottom ash, fly ash, granite powder, rice husk ash, marble and dolomite powder, furnace slag and so on as alternative materials for natural aggregate. According to Iffat & Bose (2016), the exceptional fire-proof achievement of concrete is might be due to constituent materials of concrete such as its aggregates [6]. Sakr & Hakim (2005) stated that the strength degradation of concrete with the different types of aggregates is not same at high temperatures [7]. According to Hager (2013), the commonly used aggregate is steady up to a temperature range of 200°C to 350°C but when the temperature rises up to 600°C, the physical and chemical changes of the aggregate will occur and contributed to a lower strength of concrete [8]. Since the aggregate is one of the main materials in concrete production, the properties and type of aggregate play a significant role in the behaviour and properties of concrete when it is exposed to the high temperatures [9].

Accordingly, various research attempts were committed against the assessment of materials’ performance in concrete when exposed to elevated temperature. These attempts show a perceptive about the change of materials properties of concrete and propose a guideline to improve the solution in such events [2]. In addition, structures that exposed to elevated temperatures are commonly examined to assess their structural performance [2]. Ideas for fire protection should be done to reduce the effect of fire on concrete structures. The change of materials behaviour and the reduction of the structure rigidity require the broad assessment of the structure’s achievement to propose the following actions [2]. Hence, the main objective of this study is to review the properties of concrete containing different types of waste materials utilized as aggregates replacement after exposed to high temperature. Recommendation to improve fire resistance and decrease the effects of fire events on construction buildings has been discussed in this paper. In addition to that the code requirements and recommendations of design are also highlighted for the future research.

2. A Factor affecting the properties of concrete at elevated temperature

According to Iffat & Bose (2016), few aspects can affect the properties of concrete when exposed to fire such as spalling, cracking, density of concrete, moisture content, fire intensity, transverse reinforcement placing, type of aggregates, fibre reinforcement, concrete strength and water-cement ratio [6]. Since the type of aggregate used in concrete is one of the aspects that influence the concrete properties, the selection of aggregate must be a major concern in concrete design when subjected to fire. There are two types of aggregate that commonly used in construction, carbonate aggregate and siliceous aggregate [10]. Siliceous aggregate affords higher thermal conductivity and expansion, higher fire resistance, and improved spalling resistance in concrete compared to carbonate aggregate [10]. Furthermore, concrete with compressive strength more than 55Mpa is more responsive to spalling and may have a lower resistance [2]. The spalling of concrete normally occurs at initial stages of fire due to the expansion of water pressure or the effect of thermal expansion in concrete mixes. High strength concrete may have a very lower permeability and water-cement ratio that causes moisture escapes with a slow rate and pressure of pore will be increased. Consequently, this will contribute to a major reduction in load-bearing capacity during fire exposure. Concrete density also has a significant impact on concrete properties when exposed to fire. For example, high strength concrete has a dense paste and low water-cement ratio which is liable to spalling when exposed to fire. The rate of transmission of high temperature to the concrete core is high that leads to rapid loss of concrete surface [11]. Figure 1 and 2 show the spalling and cracking of concrete due to high temperatures.

![Figure 1. Spalling of concrete [6].](image1)

![Figure 2. Cracking of concrete [6].](image2)
3. Effect of fire on concrete properties

3.1 Chemical and microstructure properties

The chemical composition of the concrete will change significantly after exposed to fire. The dehydration such as the release of chemically bound water from the calcium silicate hydrate (C-S-H) becomes significant above about 110 °C [12]. Calcium hydroxide [Ca(OH)2], which is one of the most important compounds in cement paste, disengage around 530 °C resulting in the shrinkage of concrete [13,14,15]. This is caused by the fire that is usually extinguished by water and CaO turns into [Ca(OH)2] causing cracking and crumbling of concrete [15]. Hence, the effects of high temperatures are commonly detectable in the form of surface cracking and spalling [16]. Therefore, the properties of the microstructure also change and the concrete will lose its strength and durability. The Scanning electron microscopy (SEM) was done on concrete samples containing recycled aggregate exposed to elevated temperature [17]. The samples texture of concrete becomes coarse and several micro-cracks appeared after subjected to high temperatures as shown in Figure 3. This might be due to the total pores increase and volume of water attached to the microstructure evaporated after heating at high temperature. In summary, the concrete strength becomes lower and causes a higher strain in concrete after being exposed to high temperatures.

3.2 Physical properties

The evaluation of fire-damaged, concrete commonly starts through the visual observation such as a change in colour, cracking and spalling of surface texture may also appear during the fire exposure [14, 19]. The changes of colour and surface texture resulted by high temperatures are more obvious when the temperature exceeds 500 °C. The permanent changes in the concrete were observed at this level of temperature [1]. The cracking and spalling of concrete were also observed in addition to the loss of devotion between the aggregates and cement paste [16].

3.2.1 Thermal analysis. Thermogravimetric analysis (TGA) is usually used to determine the selected characteristics of materials either loss or gain of mass due to decomposition, oxidation or loss of volatiles such as a moisture content. Based on the studies by Jumaat et al., (2015), thermogravimetric analysis (TGA) was executed with a computer-controlled furnace to determine the thermal analysis using differential scanning calorimetry between oil palm shell and palm oil clinker as a sand replacement in concrete after exposed to high temperatures [19]. The results reveal the TGA curve of oil palm shell shows an exothermic peak in the DSC curve which represents the heat released from the oil palm shell aggregates at 285°C. However, it was found that oil palm shell aggregate loses about 63% of its weight when the temperatures increase up to 478°C. Meanwhile, the TGA curves for palm oil clinkers had
shown a small variation which is less than 1% loss in weight at the temperature within 500°C. Therefore, the palm oil clinker as a sand replacement has shown an excellent high-temperature resistance compared to oil palm shell as there was a minor weight loss (1%) even at elevated temperature.

3.2.2 Colour, cracking pattern and spalling. A study conducted by Arioz (2007), presented the surface texture of the concrete samples containing crushed limestone as aggregate replacement exposed to elevated temperatures ranging from 200 to 1200 °C for 2 hours [9]. The damage to the concrete can be coarsely identified by observing the concrete surface after being subjected to high temperatures as shown in Figure 4. There was no clear effect on the surface of the samples heated up to 400 °C but the concrete started to show some crack when the temperature increased to 600°C but the effect was not significant at that temperature level. Afterward, the cracks became obvious at 800 °C and comprehensively increased at 1000 °C. Spalling of the samples was observed due to excessive cracking after exposure up to 1200°C and the specimens completely decayed and lost their binding properties. According to Sakr & Hakim (2005), the failure of the heated concrete surface occurs possibly by the crack formation that parallels to the hot surface, degradation of concrete strength and pressure of concrete pores. It is shown that spalling may cause a poor effect to fire-exposed concrete which is it can reduce the load-bearing capacity of a construction [4]. Furthermore, the explosive thermal spalling is characterized as explosively breaking of concrete into pieces, often without advance notice [20].

![Figure 4. Cracking pattern of crushed limestone exposed to elevated temperature [9].](image)

Furthermore, the changes in the physical properties were investigated by Jumaat et al., (2015) and it was perceived that the palm oil clinker (POC) and oil palm shell (OPS) can be utilized as a sand replacement (0-100% replacement) in concrete subjected to elevated temperatures [19]. Figure 5 shows the color changes of concrete mixtures after exposed to 500°C for 60 minutes of fire duration. The surface of concrete was usually light grey in color at ambient temperature; however, the surface of concrete containing 100% of OPS and 0% of POC (P0) turned into reddish color when the temperatures up to 500°C due to the partial burning of OPC in concrete. In addition, the burning smell also could be smelled during the exposure in the furnace. It can be seen from the result of Jumaat et al., the increase of POC content in concrete has reduced the effect of temperatures as there is no change in color was observed for the concrete containing 0% of OPS and 100% of POC (P100). The changes of physical and chemical experienced by the concrete after exposure to the elevated temperatures were influenced the color change in the specimens [21]. Meanwhile, the crack pattern of concrete also was observed and found there is no crack visible by naked eyes observations. However, some cracks appeared when observed through the crack measuring microscope with an accuracy of 0.001mm on specimens exposed to 300°C. But, several hairline cracks were detectable by naked eyes on specimens exposed to 500°C. Wider and deeper cracks were observed continuously on specimen surface when the temperature increases up to 500°C for 60 minutes of fire duration as shown in Figure 6. In conclusion, it can be seen from Figure 3, the crack width decreases as the POC content increase up to 100% replacement. On the
other hand, the cracks width reduces with the increases in POC content as a vapor pressure decline due to the pores in POC aggregate.

![Figure 5. Colour changes of palm oil clinker concrete exposed to 500°C [19]](image1)

![Figure 6. Crack pattern of palm oil clinker concrete exposed to 500°C [19].](image2)

3.2.3 Weight loss. At the higher temperature of 800°C and above, phase transformation of aggregate and disengagement of cement was associated with the major loss in weight of concrete [22]. A study conducted by Orioz (2007), found that the weight of the concrete containing crushed limestone reduced significantly as the temperature increased. These losses were about 5% and 45% after subjecting to 200°C and 1200 °C, respectively. This reduction was gradually increased up to 800 °C and high losses in weight were observed when the temperature beyond 800 °C. The weight loss in concrete during exposure to high temperatures can be related to the change in the mechanical properties of the concrete [9]. Topcu et al.,(2002) stated that the evaporation of water in C-S-H structure will cause losses of the binding property of cement paste while the effect of water-cement ratio and type of aggregate on the weight loss of the concrete samples was not found to be substantial [23].

Apart from that, there is no substantial weight loss in palm oil clinker concrete when it subjected to elevated temperatures of 150°C; however, the weight descends to 12% was found when the temperature increases up to 500°C [19]. The result has shown, concrete containing 100% of palm oil clinker as the aggregate replacement had the lowest rate of mass loss compared to concrete containing 0% of replacement. This indicates that with the increase in the palm oil clinker content, there is the decrease in weight loss when subjected to elevated temperature.

3.3 Mechanical properties

3.3.1 Compressive strength. The compressive strength of concrete subjected to high temperature is a major concern in the design of fire resistant. The strength degradation in concrete is changeable and there are significant variations in strength loss. Concrete should be made in controlled conditions to minimize the factors that may affect the thermal expansion coefficient, for example, the relative humidity [6]. The mix proportion of the concrete should also be closely regulated, especially the water-cement ratio [24]. According to Yuzer [18], the loss of strengths of concrete at elevated temperature can be associated to the thermal incompatibility between the cement paste and the aggregates [18]. The effects of additives, such as silica fume and fly ash, on the mechanical properties of concrete at elevated temperatures, was evaluated and found to improve the concrete properties when compared to the normal concrete not containing these additives [25, 26]. The type of aggregate was also found to have a significant impact on the fire performance of concrete [27]. Concrete made with aggregates that do not contain silica, such as limestone, basic igneous rocks, crushed bricks, and blast furnace slag was found to have a reduction in strength. On the other hand, dolomitic limestone is found to be advantageous in
improving the fire performance of concrete because the calcinations process absorbs heat, and the lower density of ‘‘calcined’’ material provides a greater insulating effect [27].

The rate of heating is also related to the changes in the mechanical properties of concrete exposed to high temperature. Free water evaporates slowly and no structural damage is detected when concrete is heated between 100 and 200 °C. However, rapid heating rate results in higher vapor pressure and causes cracks in concrete. Concrete starts to reduce its compressive strength when heated between 200°C and above [14]. Meanwhile, Malhotra [27] investigated the compressive strength of various high temperatures exposed to concrete and found that the high early temperatures also have negative influences on the strength of concrete and concluded that the residual strength of the concrete at high temperatures was influenced by the aggregate/cement ratio [28].

A study was conducted by Jumaat et al., (2015) which shows that the residual compressive strength of the concrete containing palm oil clinker as an aggregate replacement at ambient and 60°C of temperatures increase the strength compared to concrete without containing palm oil clinker [19]. The result shows the strength of concrete at 60°C containing 0% replacement of palm oil clinker is 41.47Mpa while the strength of concrete containing 100% replacement is 58.77Mpa. However, when the temperatures rise up to 500°C, the compressive strength becomes decreased at both replacements percentage which is from 41.47Mpa to 10.38Mpa and 58.77Mpa to 56.12Mpa at 0 and 100% replacement respectively. It was indicated that the reduction of strength in the specimens was influenced by the aggregate content when exposed to elevated temperatures. The higher the aggregate content, the higher the strength of concrete can withstand high temperatures. It can be concluded that the high replacement of palm oil clinker as aggregate in concrete is still able to endure the high temperatures since it shows a slight decrease in strength at 500°C [19].

In addition to that recycled glass has been used as an aggregate replacement in concrete. The influence of recycled glass content as a fine aggregate replacement in concrete after exposure to elevated temperature was investigated by Ling et al., (2012) as they were investigated that the influence of curing conditions (water and air curing) on recycled glass concrete after being subjected to high temperatures [29]. The result demonstrated that the strength of recycled glass concrete specimens decreased as the temperature increased which is at 300°C, the residual strength drop from the initial compressive strength at ambient temperatures ranged from 89% to 84% and 88% to 82% for water and air cured specimens, respectively. According to Zhou & Khoury (2001, 1992), the reduction of strength in concrete after exposed to high temperatures was due to the dehydration of ettringite, C-S-H gel, calcium carboalumination hydrates and the evaporation of capillary pore water [30,31]. The significant decrement of strength has been observed at the temperature above the 800°C. The more reduction in strength was probably due to the de-hydroxylation of calcium hydroxide or the portlandite [31]. Meanwhile, based on Alarcon (2005), the formation of micro-cracks in the specimen was caused the declination in concrete strength which can weaken the interfacial transition zone and bonding between the aggregate and the cement paste [33]. Referring to El jazairi (1980), the main hydration products of hydrated cement paste and C-S-H gel decomposed extensively and resulted in a significant drop in strength as the heating temperature rise up to 800°C and above [32]. It is shown that the decomposition of C−S−H prominently affected the loss of strength in concrete, which is resulted in about 75% loss of strength as compared to the initial strength values of unheated specimens (ambient temperature). As a conclusion, the results reveal that all the water cured specimens had higher residual strength as compared to air cured specimens at all tested temperatures. However, the effect of curing method became less important with the increase of temperature. Nevertheless, the influence of recycled glass as a sand replacement in the concrete mixes helped to maintain the concrete properties due to the melting and re-solidification of the recycled glass in the concrete after exposed to high temperatures.

The residual compressive strength of waste materials such as silica fume, bottom ash, recycled aggregate, dolomite powder also give a similar result as palm oil clinker and recycled glass as replacement materials in concrete. According to the study by Arivumangai & Felixkala, (2015), the residual compressive strength of concrete containing granite powder as a sand replacement was decreased as the temperature increased [34]. They were studied on granite powder concrete exposed to
70ºC, 140ºC, 210ºC, and 280ºC for 1 hour and 2 hours duration and the replacement level of granite powder was 0%, 25%, and 100%. The result shows that the granite powder concrete is more resistance to high temperature as the percentage of granite powder increased up to 25% and afterward, the resistance to temperature gradually drops with the increase of granite powder percentage. As per investigated by Arivumangai & Felixkala (2015), the inclusion of granite powder contributes to increment in strength at lower temperature [34]. The results evidently shows that granite powder as a partial sand replacement has beneficial effects of concrete as the strength was increased compared to control specimens, even though its strength decreased after exposed to high temperatures. 25% of replacement of granite powder as a sand replacement was found to be an adequate replacement and enhances the fire resistance of concrete at a lower temperature.

In summary, the loss in mechanical properties and degradation of concrete is due to the effect of elevated temperatures and caused by the formation of cracks and micro-cracks on the surface of concrete [34]. As reported by Phan and Carino (2000), the explosive spalling on the concrete surface at high temperature is due to the internal pore pressure and thermal stresses [36]. Meanwhile, Arioz (2007) reported that type of aggregate used in concrete has a significant effect on mechanical properties of concrete and as Kizilkanat et al., (2013) reported that thermal conductivity of concrete containing calcareous aggregate was lower compared to concrete containing siliceous aggregate at high temperatures as it has higher level of crystallinity than carbonate concrete [9, 37].

4. Conclusion and recommendations
This critical review provides a conclusion, based on the previous experimental studies. This review also determines the behaviour of concrete which is commonly used construction materials under elevated temperature. It can be concluded that the influence of the different type of waste material as an aggregate replacement in concrete can be reduced the strength during fire events. Utilization of carbonate aggregate instead of siliceous aggregate must be considered during design a concrete. Some of the waste aggregate in concrete still has a high of strength which can endure at a lower temperature; however, the strength dropped significantly when the temperature increased. Some recommendations that can be proposed through this study are the reduction of concrete density by replacing normal weight aggregate with lightweight aggregate as it less vulnerable to fire. Other than that, the introduction of steel fibres in concrete that can increase the elastic modulus and tensile strength of concrete to perform better resistance during fire events. Hence, the addition of polypropylene fibres could be the viable solution, to reduce the spalling of concrete. Finally, ASTM Standard E 119 which is Standard Methods of Fire Tests of Building Construction and Materials was designated as a design code requirement of fire test methods and its procedure was nationally accepted to determine the fire-resistant properties of building components.

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