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EFFECTS OF NOVEL CONCRETE MIX DESIGNS ON FIRE RESISTANCE OF CONCRETE MASONRY – COMPUTATIONAL ANALYSIS

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ABSTRACT

There are many new tests being done to improve the physical properties of concrete and concrete masonry by changing the concrete mix design. These new mix designs create concrete with different thermal properties, which may improve or reduce the total fire resistance of the material. Determining the effects of these new mix designs on the overall change in fire resistance is important for deciding on the real-world efficacy of those new mix designs. In order to accomplish this, the findings from several tests using novel mix designs were collated, investigated, and analysed, then a thermal model of a concrete masonry unit was created within Abaqus in order to determine the new fire resistance of the novel mix designs in terms of their insulation failure criteria. The mix designs focus mainly on the use of recycled materials such as rubber, fly ash, or recycled concrete aggregate. These new mix designs are compared to traditional mix designs, and recommendations based on the findings are given.

KEYWORDS: *concrete masonry, elevated temperatures, fire resistance, mix design, modelling*

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INTRODUCTION

When members are being tested for fire resistance, they are exposed to a standard fire which dictates the exact furnace temperature-time profile. The test ends when the member fails one of the three failure criteria. The three failure criteria are stability, integrity, and insulation. In terms of thermal modeling, insulation is the deciding factor. For a member to fail the insulation criteria the unexposed side of the member must exceed an average temperature increase of 140°C, or a temperature increase of 180°C at a single point [1].

For concrete masonry, the different block shapes have approximate fire resistances based on their equivalent thickness and mix design. However, these estimated fire resistances do not take into account many variations in the mix design or block geometry. For example, a 20cm normal weight concrete unit has a fire resistance rating of around 2h [2]. This paper will endeavour to review different mix designs to determine their effect on the fire resistance of concrete masonry units.

Material thermal performance is mainly dependent on three material properties: thermal conductivity, specific heat, and density [3,4]. Those thermal properties are reasonably well established for most common materials, however concrete properties can vary significantly due to different concrete mix designs. Even so, there are ranges of values for each thermal property that normal weight/strength concrete normally falls within at ambient conditions. For normal weight concrete, the thermal conductivity ranges from 1.4-3.6 W/mK, specific heat ranges from 840-1800 J/kgK, and density ranges from 2100-2300 Kg/m^3 [3,4]. For lightweight concrete, the thermal conductivity ranges from 0.5-1.5 W/mK, specific heat ranges from 600-1100 J/kgK, and density ranges from 800-1500 Kg/m^3 [3,4].

Each of the properties change with respect to temperature (Figure 1), which means that accurate values at each temperature range are required in order to accurately model the materials fire resistance. The density of concrete usually decreases by 100 Kg/m^3 after 100°C as the moisture inside is evaporated [4]. The thermal conductivity decreases as temperature increases, and the thermal conductivity values at 900 °C are about half of what they were at ambient conditions [4,5].

The specific heat capacity changes with temperature and is affected by physical and chemical changes within the concrete. The first change is an increase in specific heat at 100°C due to the evaporation of free water [6,7]. Another increase in specific heat occurs between 400-500°C due to the evaporation of crystallized water [6,7]. The third change is from the transformation of quartz above 600°C [6]. Nguyen et al. created an equation (Equation 1) for finding the specific heat peak due to the evaporation of free water [8].

$$\Delta C_{peak} = \frac{\omega H_{vap}}{2\Delta T}\,. \tag{1}$$

Where: ΔC_{peak} is the change is specific heat, ω is moisture content, H_{vap} is the latent heat of vaporization of water (=2260 kJ/kg), and ΔT is half the evaporation interval (5°C).

There are many issues with testing procedures used to evaluate the thermal properties of materials at elevated temperatures. Different tests may use different heating rates, specimen sizes, specimen conditions, moisture content, measurement techniques, and more [3,4]. For example, thermal conductivity can be found through the "hot-plate" or the "hot disk" methods, and each method can give different results for thermal conductivity [3]. For this reason, using thermal properties from one test in order to compare them to another test will give qualitative results, but they are unlikely to give quantitative results. While thermal properties measurements may vary between researchers, thermal properties from one test with the same testing method are very useful for determine trends.

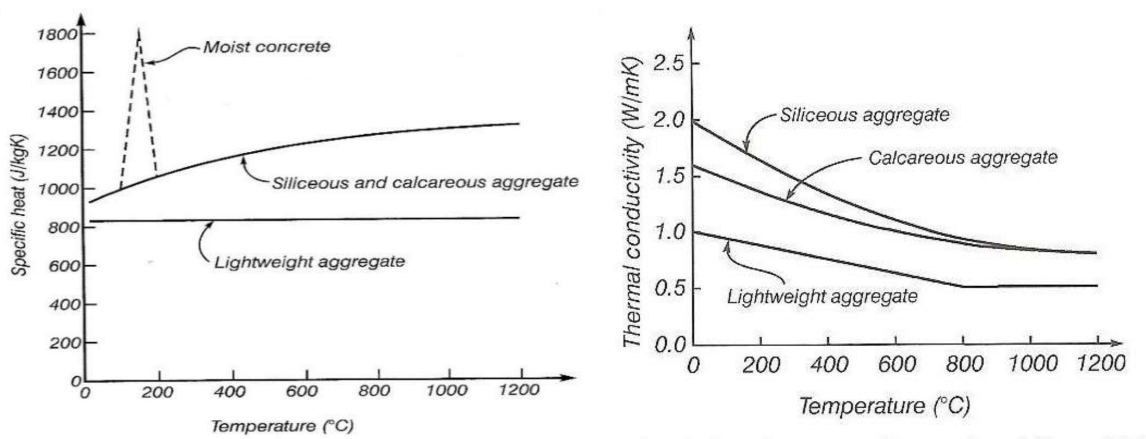

Figure 1: Specific heat and Thermal Conductivity at varying temperatures [7]

Concrete is formed through the combination of binder, water, coarse aggregate, fine aggregate, and special additives. Normal concrete is usually made with cement, water, siliceous/calcareous aggregate, and sand. Block mixes can be changed in a variety of ways by either changing the ratio between these components, or by changing the materials within each component. When speaking of mixes with a percentage replaced, this is not a percentage of the whole concrete mix, but rather a percentage of the individual components.

There are several new concrete mix designs that include recycled materials in order to be more environmentally friendly. These include recycled concrete aggregate (RCA), fly ash and rubber aggregate. These materials benefit the environment because they allow waste materials to find a new use, which keeps them from polluting the earth [10,11]. The addition of these recycled materials can have a beneficial or detrimental effect on the fire resistance of concrete. There is some research done on the mechanical properties of such materials, but their thermal performance is not as well studied. If materials have a reduction in mechanical properties but improved thermal properties, then they may still be beneficial for use in non-loadbearing partitions where the reduction in mechanical properties are less important.

METHODOLOGY

Thermal properties collation

The thermal properties published in various journal papers were collated. Most papers had complete data on the three thermal properties at various temperatures or temperature ranges. In cases when the thermal conductivity, specific heat, or density were missing from the journal results, values from the model created from the Pope 2020 data was used [2]. Some of the specific heat results accounted for the spike in specific heat due to the moisture within the concrete, others did not. In order to ensure that the results could be better compared, the effects of moisture were included in all of the models (except when the effect of moisture content was being used as a method of comparison).

Model Creation

A thermal model of a 20cm normal weight hollow concrete masonry units were created using finite element software and validated with physical testing results from Pope2020 (Figure 2) [2]. The model was created to compare the results of a standard fire test on a masonry wall, and so the model is subjected to the CAN ULC S101 standard fire for up to 4 hours [1]. The thermal properties of the concrete in the model were altered in order to match the thermal properties of each new test mix. This means that the results can be compared to each other and the estimated fire resistance of different mix designed can be determined. The results allow for the comparison of different thermal properties, as well as aggregate type, fine/coarse aggregate substitution, and the addition of different fibers. The thermal model did not take into consideration the mechanical properties, and as such only the insulation failure was determined for each mix design.

Temperature data was mainly taken from either the surface of the hollow cell, or the surface of the solid web. This is because they are the two distinct areas on the masonry block. In general, the hollow cell fails before the solid web due to the increase in convection and radiation at elevated temperatures. The solid cell data is still important to determine how large the temperature difference is between the hottest and coldest part of the masonry block.

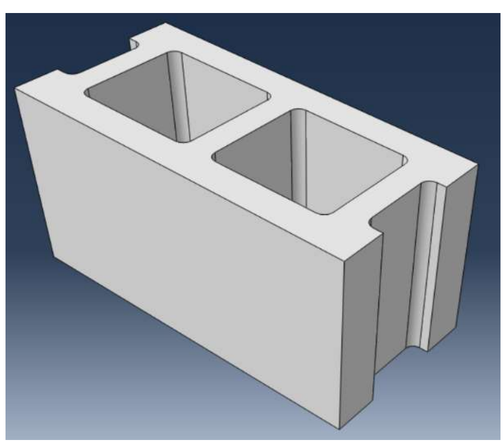

Figure 2: Thermal Model of the 20cm unit

RESULTS

Baseline normal weight concrete

The first stage of the modeling was to get a baseline of the time-temperature profile normal-weight concrete without the addition of special additives. Figure 3 compares the models of several different normal concrete mixes from various tests. It can be seen that even amongst concretes that are described as normal-weight and normal-strength, the time temperature curves can vary. This is part of the reason why quantitatively comparing novel mix designs can difficult, as the reference concrete mixes used in different tests may have variable thermal performances.

There are many concrete mixes that use the term normal-weight or normal-strength concrete. In general, the aggregates used can be either Calcareous (such as limestone) or Siliceous (such as granite). The thermal performance of each mix can vary, siliceous aggregates usually have higher thermal conductivity as well as higher specific heats when compared to calcareous aggregates [4, 6]. Calcareous aggregates usually have better fire resistance; however, as can be seen from Figure 3 with the results of Naser 2019, this is not always the case [4].

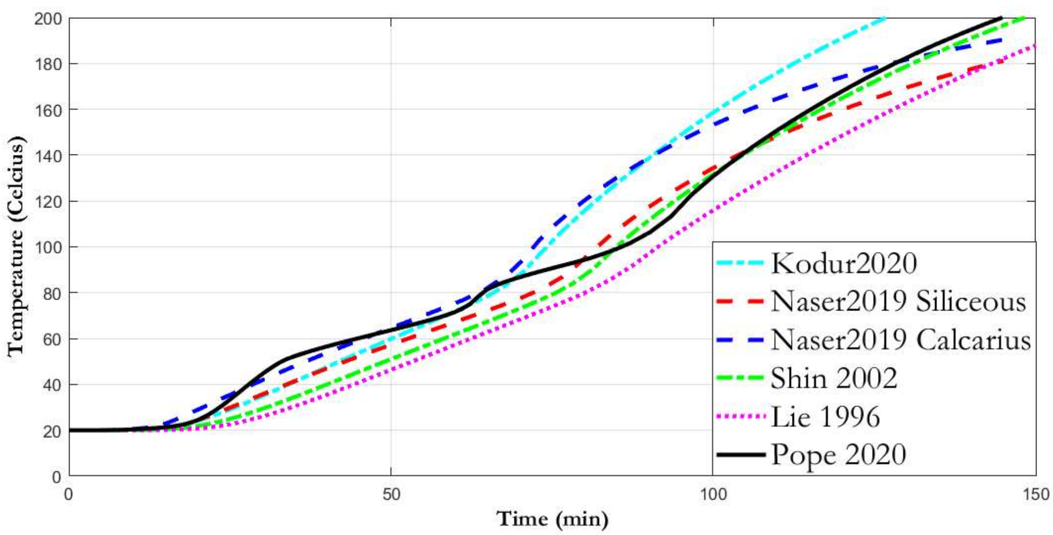

Figure 3: Modeling time temperature curves of normal weight concrete mixes.

Effect of changing different thermal properties

The three thermal properties of concrete can vary between mix designs, but it is important to know just how much the variation in thermal conductivity, specific heat, or density effects the fire resistance of a concrete masonry unit. A series of blocks were modelled in order to determine how changing one thermal property while leaving the other two the same would affect the failure time. The thermal conductivity was varied from 0.4-3.2 W/mK, the specific heat was varied from 500-2400 J/kgK, and the density was varied from 1800-2500 kg/m3. The failure times for each point was found and plots were created to compare the effects of the different thermal property ranges.

Figure 4a demonstrates the change in thermal conductivity. It be seen that the lower the thermal conductivity the higher the fire resistance (longer failure time). The effect of thermal conductivity is not linear, and so the increase in fire resistance between 3.0-2.5 W/mK is much lower than the increase in fire resistance between 1.5-1.0 W/mk. Figure 4b demonstrates the change in specific heat. It can be seen that the higher the specific heat the higher the fire resistance. For this model the effect of moisture was kept constant throughout. It can be seen that the effect of specific heat is linear, so any increase in specific heat will yield roughly the same increase in fire resistance. Figure 4c demonstrates the change in density. The higher the density the higher the fire resistance. While denser materials normally have worse thermal properties, density itself improves the thermal performance due to there being more material to absorb heat.

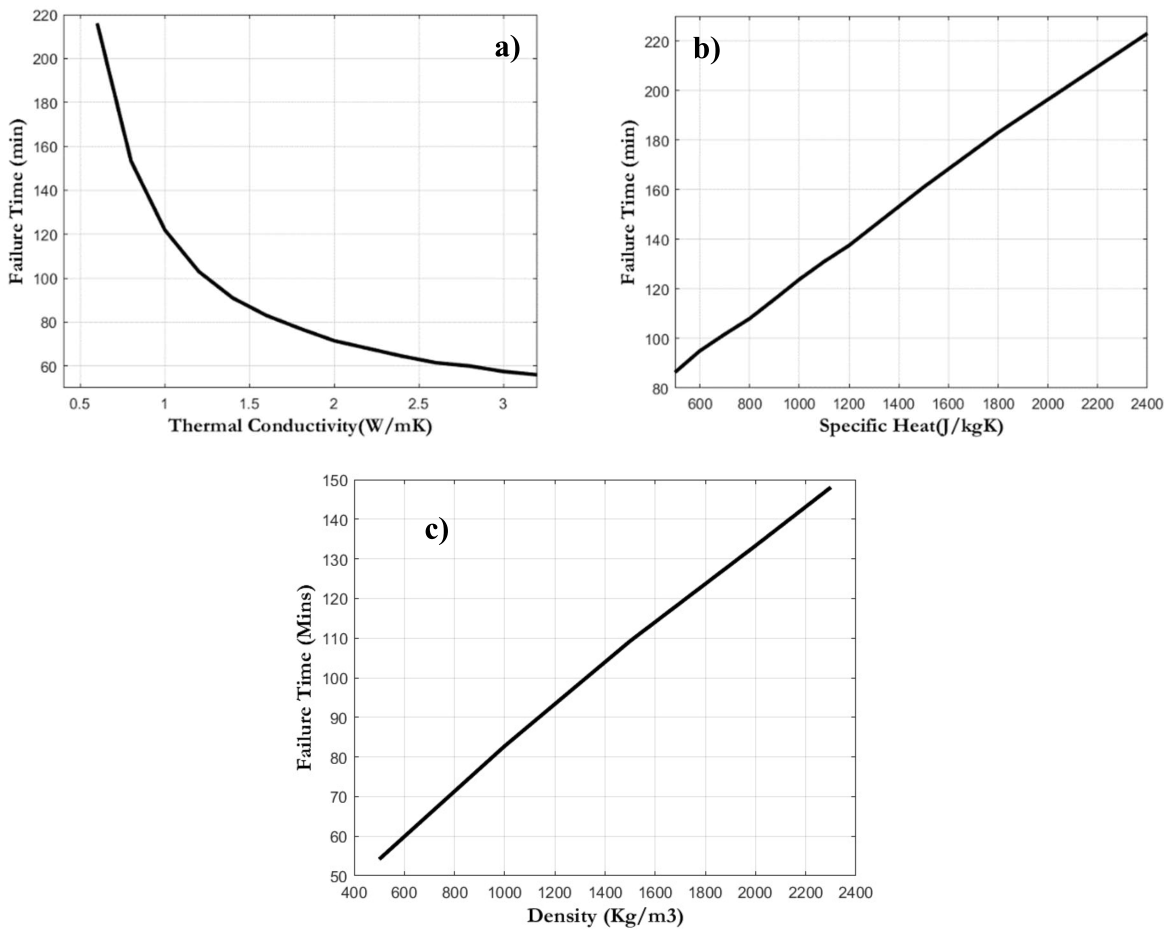

Figure 4: The effect of thermal properties on the failure time. a) thermal conductivity b) specific heat c) Density

Changing the mix design will result in different thermal properties. If all the thermal properties of the new mix are better than the reference mix, then the new mix will have an improved fire resistance. However, when the change involves many different changes to the thermal properties at different temperatures, it can be difficult to determine the fire resistance without modeling or physical tests.

Effect of Rubber

Zaleska et al. 2019 tested the effects of replacing some of the siliceous aggregate within the concrete with rubber of varying sizes and quantities [10]. The test used rubber aggregate to replace the fine aggregates within the range of 0-4 mm (C4) and/or the coarse aggregate within the range of 4-8 mm (C8) with percentage replacements of either 10%, 20% or 30% (Table 1) [10]. As rubber has a lower density than concrete, the more rubber used the lower the density of the final mix. The addition of rubber also caused a reduction in compressive strength, with the maximum strength loss being at 30% replacement [10]. There are several reasons for the reduction in strength such as the increase porosity in rubberized concrete, as well as the lack of bonding between rubber and cement paste. Also, the cement paste containing rubber is softer than the paste without rubber, and cracks form around the rubber particles during loading [10]. Due to this reduction in strength, rubber is more suited to non load bearing walls. The addition of the rubber also reduces the bulk density of the concrete which could classify it as lightweight concrete.

Table 1: Rubber Mixes

Mix Name	Ref	C4-10	C4-20	C4-30	C8-10	C8-20	C8-30	C4+8-10	C4+80-20
Fine Agg replacement	-	10%	20%	30%	-	-	-	10%	20%
Course Agg replacement	-	-	-	-	10%	20%	30%	10%	20%

For the thermal properties, it was found that the mixes with more rubber had lower thermal conductivity values, to a minimum of 0.65 W/mK [10]. This lower thermal conductivity was due in part to the lower thermal conductivity of the rubber itself, as well as the non wetting effects of the rubber which reduced the effects of moisture on the thermal conductivity [10]. This decrease in thermal conductivity is beneficial for the fire resistance of the concrete. The higher the rubber content, the lower the specific heat [10]. This is a negative effect of the rubber addition. The reduction in density is low up to 300°C, and after this temperature the rubber begins to combust which causes a decrease in the concrete density [10]. The lower density in general is a positive for fire resistance.

The thermal values were modeled both with and without the effects of moisture on the specific heat, as the addition of rubber causes a reduction in free moisture. The exact effect of moisture on the specific heat is unknown and is most likely somewhere in between both profiles. Also, the effect of moisture is most likely prevalent in the mixes with lower amounts of rubber. When comparing the two test types in Figure 5, it can be seen that the major change occurs below 100°C. The moisture effect caused a lower slope until the concrete has heated above 100°C. The tests without moisture had a more linear slope at the beginning of the test. The end temperature values after 4 hours were very similar, with only a few degrees separating the final points. However, since the moisture affects the start of the test, it meant that the time to reach the failure temperature was delayed. Figure 6 shows the difference in failure time between the concrete with and without free moisture, and it can be seen that in every case the concrete with free moisture failed second.

For the different concrete mixes, it was found that any amount of rubber improved the fire resistance. The fine aggregate replacement in the range of 0-4 mm had the largest benefit at the 30% replacement. The mixes where both fine and coarse aggregate were replaced were found to have a fire resistance between that of the mixes which replaced only one of the aggregate sizes. The addition of 10% of the coarse aggregate improved the fire resistance by over 15%, but the addition of 10% of the fine aggregate improved the fire resistance by over 35%. This indicates that the replacement of some of the fine aggregates is more beneficial than the replacement of the coarse aggregates. It was found that during the 4h run of the model the mixture with 30% fine aggregate replacement never reached the insulation failure temperature.

Since rubber aggregate decrease the strength of the concrete, lower replacement could be used for loadbearing member and large replacement would be more suitable to partitions that are non-loadbearing. However, as a 4h fire resistance rating requirement is not as common, a smaller block size could be used in order to cut costs and save space. Further research should be done to determine appropriate block sizes for the optimal mix designs, as well as to determine any negative structural effects that might occur due to the combustion of the rubber at elevated temperatures.

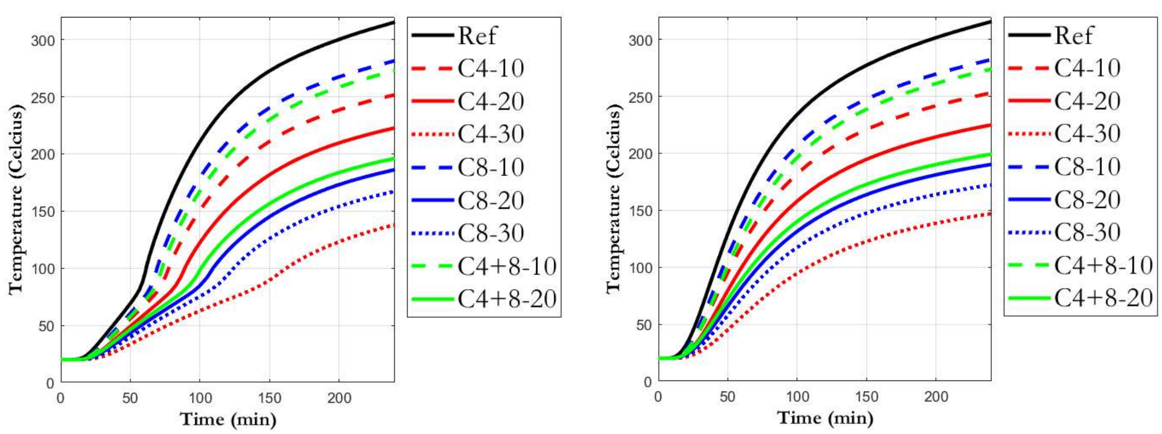

Figure 5: Effect of different rubber aggregate mixes. Left) assuming free moisture is present Right) assuming no free moisture is present

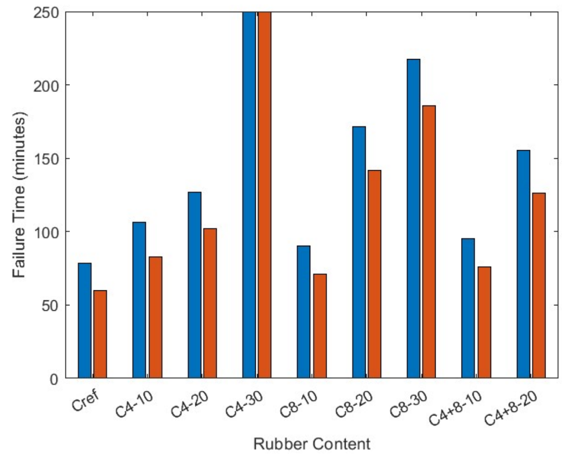

Figure 6: Comparing the failure times of rubber aggregates with free moisture (blue) and without free moisture (red).

Fly ash

Wang et al. 2017 tested the effects of relative humidity on thermal conductivity using both regular concrete and concrete with 30% fly ash replacement [11]. The relative humidifies tested were 25%, 45%, 75% and 100% [11]. It is important to note that this humidity research was done after the concrete was removed from a furnace. So, its usefulness in determine the effects at elevated temperatures less exact, since there are no moisture effects after the free moisture has been evaporated. The addition of fly ash increased the compressive strength of the concrete at all temperatures (including ambient) and the increase in pore size reduced the thermal conductivity of the concrete [11]. This means that fly ash is beneficial both for loadbearing and non-loadbearing members.

It was found that as the temperature increased thermal conductivity decreased for both mixes [11]. This is partly due to the increase in pore size that occurs when concrete is heated. The larger the pores the more air is inside, which lessens the thermal conductivity. In terms of relative humidity, higher relative humidity led to higher thermal conductivity values [11].

From the thermal modeling it can be seen that in every case the fly ash performed better than the reference concrete (Figure 7). As the relative humidity of the testing room increased the fire resistance of the modelled concrete decreased. During a fire, the relative humidity of the room would not play as large a role on the thermal properties, as the free moisture is evaporated out at the beginning of the test. However, relative humidity can have a large impact on the recorded values of conductivity, which in turn may skew modeling results. This is part of the reason why thermal properties vary between different tests, and results from the same testing method but measured in different atmospheric conditions can yield different results.

From the results of the modelling, fly ash is a beneficial addition to concrete, as it is an improvement to both the ambient mechanical and thermal properties, but also both properties at elevated temperatures.

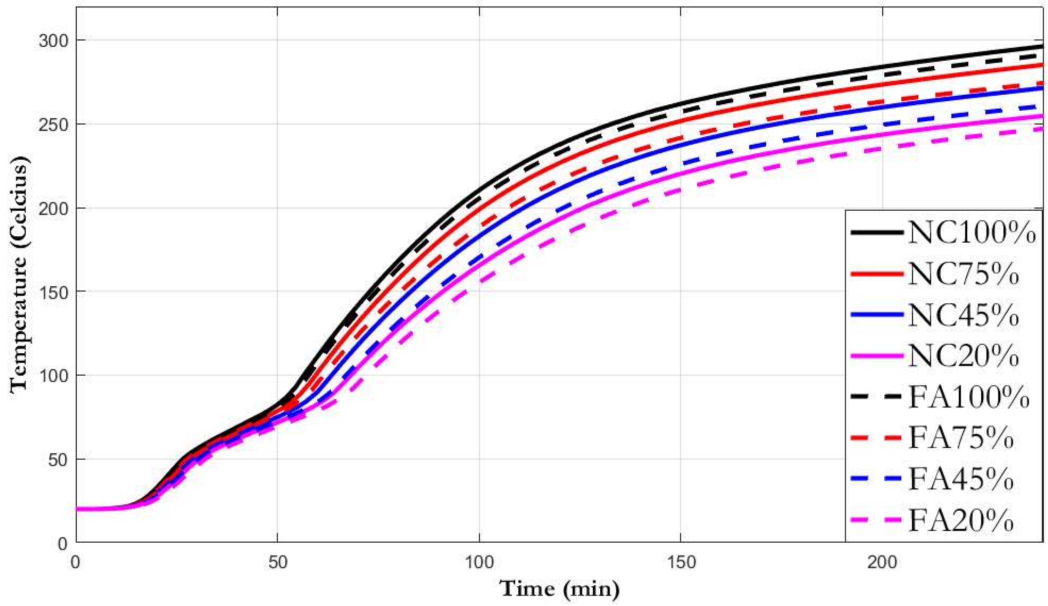

Figure 7: The effect of humidity (%) on Normal Concrete (NC) and Fly Ash concrete (FA)

CONCLUSIONS

Reducing the thermal conductivity and density improve the fire resistance, increasing the specific heat also improves the fire resistance. Specific heat and density effect the fire resistance linearly, whereas thermal conductivity effects the fire resistance non-linearly, with much greater improvements at lower values of thermal conductivity.

Normal weight concrete can have a varied fire resistance depending on the exact mix design and aggregate type. Two concretes that are being used as references for different tests may in face have large differences in their failure times.

Rubber aggregate were found to improve the fire resistance of concrete; however, they reduced the compressive strength. Small rubber replacement might be suitable for loadbearing members, but any large percentage rubber replacement is more suited to non-loadbearing partitions.

Fly ash was found to improve the mechanical and thermal properties of concrete, which makes it a great addition for both loadbearing and non-loadbearing members.

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