ISSUES WITH MASONRY AND FIRE: SPALLING AND THERMAL BOWING

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ABSTRACT
Masonry elements have long been known to possess excellent fire protection qualities. Masonry is well suited as a fire barrier because it works effectively to isolate and contain fire, heat, and smoke. Masonry is also able to keep its strength and resist collapse when put under a fire load. For these reasons, masonry is commonly used as a fire barrier in buildings. While masonry does have several positive attributes when exposed to fire, there are some issues that occur when masonry is heated, other than simple loss of strength. One common issue is concrete spalling (pieces of the concrete falling off or violently exploding). The second common issue is thermal bowing (when the wall bends during fire exposure). These issues can have an impact on the fire resistance rating of the member, so it is important to know why they happen and how to mitigate their effects. This paper discusses how concrete masonry behaves when it is heated and how its various properties change with higher temperatures. The effect of these property changes is described, and recommendations are made. An explanation on how spalling and thermal bowing occur is given, and the damage they cause during and after the masonry walls are heated is described. Methods of reducing the likelihood of these two major issues occurring in masonry are discussed.

KEYWORDS: *fire, heat transfer, masonry, spalling, thermal bowing*

INTRODUCTION
In order to determine the fire resistance rating of a masonry member, it needs to be tested with a standard test. The Canadian standard test is performed by exposing the member to CAN/ULC-S101 standard fire in order to determine how the member behaves once heated, Equation 1 [1]. When tests are preformed, the three failure criteria assessed include stability, integrity, and insulation (temperature rise). The test is terminated once the member has failed any one of the failure criteria. The specimen fails stability if the structural element is no longer able to carry the applied load. The specimen fails integrity if any cracks or fissures form which allow smoke or hot

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gasses to pass through. The specimen fails insulation if the unexposed side exceeds an average increase of 140°C or a maximum increase of 180°C at a single point [1].

CAN/ULC-S101-14:

$$T_g = T_o + 750(1-\exp(-0.49\sqrt{t})) + 22.0\sqrt{t} \quad (1)$$

T_g = Furnace temperature, T_o = ambient temp (˚C), and t= time (min) [1].

One of the problems with the standard fire curves is that they do not represent a real fire. Its purpose is to create a standard for materials testing and to determine when the member fails. The standard fire also reaches temperatures of around 500°C within three minutes, so it limits what can be researched at low temperatures. For this reason, when researchers are to determine the effect of a certain factor at elevated temperatures they do not always use the standard fire. The common method of testing an element is to use a specified heating rate until a maximum temperature is reached, then keep the member at that maximum temperature for a specified amount of time. The advantages of these testing methods are that they give researchers more control on the testing methodology, and allow them to study the behaviours at lower temperatures as well as higher temperatures.

Properties of Masonry

Differences in properties between the mortar and the masonry at ambient and elevated temperatures can have beneficial or detrimental effects depending on how they are combined. Many material properties change with temperature such as compressive strength, specific heat, thermal expansion, and moisture content. These properties can be changed by the use of different aggregates (such as normal weight or lightweight aggregates) or the use of different mix designs.

Compressive strength and modulus of elasticity

The compressive strength of concrete is one of the most important mechanical properties of concrete masonry. When concrete is exposed to elevated temperatures, factors such as the decomposition of aggregates and loss of moisture eventually reduce the compressive strength of the concrete. The difference in strengths under elevated temperatures mainly depends on the type of aggregates used in the production of concrete. The decomposition of normal weight concrete begins at a temperature of about 400ºC while lightweight concrete begins at about 500ºC, Figure 1 [2]. The normal weight concrete will lose most of its compressive strength at 900ºC, while the lightweight concrete does not lose its compressive strength until 1,000ºC [2].The density of lightweight concrete is lower than normal weight concrete and is expected to produce a lower compressive strength. However, under elevated temperatures lightweight concrete undergoes a lesser loss of strength than normal weight concrete [2]. Similar to the compressive strength, the modulus of elasticity of masonry reduces with an increase in temperature, making the masonry more brittle. Even after the masonry has cooled, the compressive strength and modulus of elasticity are permanently reduced [3].

Specific heat capacity

Specific heat is the amount of energy that is required to raise the temperature of a certain mass by one degree Kelvin (J/kgK). Materials with low specific heat values require very little energy to raise their temperature, whereas materials with high specific heat require more energy and will heat up slowly. Water's specific heat is 4,185.5 J/kgK and concrete's specific heat is around 800-1,000 J / Kg K, which means that it takes more energy to heat up water than concrete [2]. The concrete aggregates can have a large impact on the specific heat of the concrete masonry. As the temperature increases, the specific heat of normal weight aggregates (siliceous and calcareous) will also increase; whereas the specific heat of the lightweight aggregate remains constant. This means that normal weight concrete requires more energy to heat at higher temperatures. The moisture content and chemically bound moisture greatly increases the specific heat of concrete as the moisture requires more energy to vaporise (dotted spike in). Since mortar has more moisture than concrete, it takes more energy to increase the mortar temperature above 100°C than it does for the concrete block.

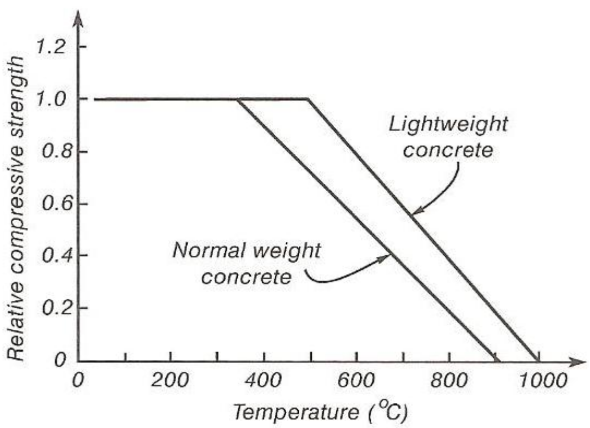

Figure 1: Relative Compressive Strength of Concrete [2]

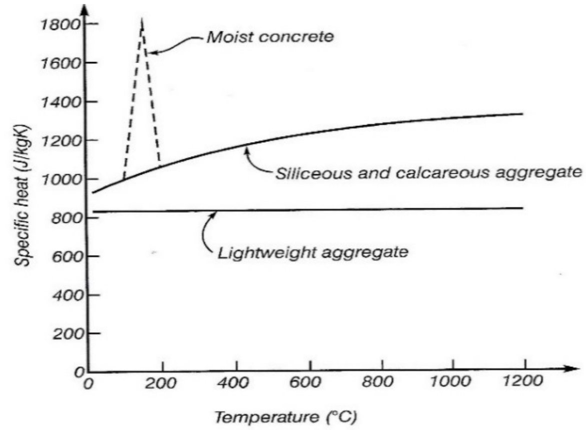

Figure 2: Specific heat of concrete [2]

Thermal expansion

Thermal expansion is the change in material size and/or shape with respect to temperature (units 1/K). A material with a high coefficient of thermal expansion is one that increases its size significantly with an increase in temperature, a material with a low coefficient is one that increases in size minimally with an increase in temperature. A material with a negative thermal expansion is one that decreases in size with an increase in temperature. The coefficient of thermal expansion changes based on the material, as well as with different temperature ranges.

Thermal expansion for most aggregates increases linearly with temperature [4]. After 570°C the thermal expansion suddenly increases due to the transformation of quarts (which swells) [4]. Siliceous aggregates like flint have higher thermal expansion than other aggregates (around twice as much), which causes cracking to occur around the aggregates due to the mismatch in thermal expansions of the aggregate and the cement [4]. After cooling residual thermal strains are much higher for siliceous aggregates.

The thermal expansion of masonry can cause thermal stresses as well as unequal thermal expansion. Masonry expands when heated, and so it exerts a force on the frame surrounding it. If the frame is rigid enough to withstand this force, the wall is put into compression and added confinement restraints are imposed. Concrete masonry is strong in compression so there is usually no concern when the forces are even [5]. However, masonry is made up of different materials that have different values of thermal expansion. The mortar does not usually expand as much as the blocks it holds together. This, coupled with shrinkage from loss of moisture, can cause cracks to form at the mortar to block interface. These cracks reduce the bonding between blocks and can reduce the strength of the wall [6].

Moisture

Moisture exists in masonry in two forms, free moisture in the voids, and chemically bound moisture. These can have a large effect on the temperature profile of the wall, as energy is required to vaporise the moisture. Each part of the wall has a different amount of moisture in it, and so the temperature on the unexposed side of the wall varies at different points on the masonry unit, Figure 3a. The three temperature locations on the unexposed side in Figure 3a are the mortar, the web, and the hollow cell. At the beginning of the fire exposure the mortar heats up faster than concrete block due to the higher thermal conductivity of the mortar [2]. Once the mortar reaches 100°C the temperature rise slows drastically due to an endothermic peak. Whenever a part of the wall reaches 100°C, that part of the wall forms a plateau, which is caused by the free moisture in the block and mortar being heated and driven out in a steam form, Figure 3b. The plateaus are beneficial since they increase the specific heat of the unit while the moisture is evaporating [7]. The more moisture available to evaporate, the longer the plateau. The longest plateau occurs in the mortar, because it has a higher moisture content than the block. The loss of moisture in the mortar increases its strength, but it also shrinks the mortar. This could cause problems with the mortar to block bonding. The second longest plateau occurs in the solid part of the block as it has all of the moisture in the web section. The shortest plateau occurs in the hollow part because the only moisture available is in the face shells. The moisture also helps reduce the radiation in the cavities because the moisture migrates to the cavity space and creates an opaque barrier which reduces the radiation [7]. Since the plateau remains for such a long time in the mortar, the mortar goes from being the hottest part of the wall to the coolest part. Once a point on the wall runs out of moisture the temperature starts to increase again. This means that the moisture content of the materials is one of the most important factors for fire resistance as it affects the fire rating of the assembly.

Moisture affects the strength as well as the temperature of concrete at high temperatures. Concrete loses weight as it is heated due to the release of water. When bound water is released from the cement paste, more air voids are formed in the concrete. This deteriorates the structural integrity of the concrete. The weight loss based on temperature is 4% at 400°C, 6% at 600°C, and 8% at 800°C [8]. A way to reduce the mass loss and keep the integrity is to add pozzolans. Pozzolans are materials that are either siliceous or siliceous and aluminous materials which can react chemically with calcium hydroxide and water to form compounds possessing cementitious properties [8]. These compounds can add to the compressive strength of the material. This reaction process is known as the pozzolanic action. For this reason, adding aggregates and mixtures, which have silica contents (e.g. fly ash), will provide a good pozzolanic action and improve the strength of the concrete.

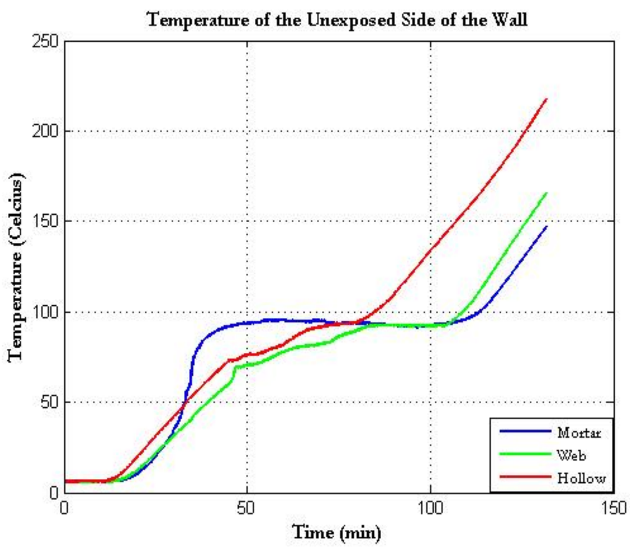

Figure 3a: Temperature of the wall (unexposed side)

Figure 3b: Moisture bleeding off of the walls

THERMAL BOWING

Thermal bowing is caused when one side of a wall is exposed to fire and heated while the other side is unexposed. The temperature difference causes an uneven expansion inside the wall, due to the fire exposed side expanding more than the unexposed side. This causes the wall to bend out towards the fire, with the maximum curvature being at the wall's centre, Figure 4. Data on thermal bowing is limited since standard testing does not require the measurement of samples' displacements during testing. This is an important phenomenon since it can lead to premature failure due to the curvature of the wall. The curvature occurs rapidly at the start of the fire and then recovers during the fire. This rapid change happens due to the increase in the temperature difference between the exposed and unexposed side. The reason the wall recovers is that the unexposed part eventually heats up as well and reduces the temperature difference between the two sides [9]. Another reason the wall recovers is that the Young's modulus decreases at high temperatures [9]. Thermal bowing causes eccentric loads, which adds stress to the wall. If the deflections are large enough they may cause the wall to fail earlier. Large deflections from thermal bowing usually occur in unrestrained brick walls and concrete floors, and the deflections are increased when the element is subjected to a faster heating rate [10].

When masonry walls are heated and undergo thermal bowing, they go through three phases. The length of each phase depends on the loading and the slenderness ratio. Phase 1 is a rapid increase in deflection, which is caused by thermal bowing. Phase 2 has no increase in deflection which is caused by the applied loads counteracting thermal bowing. This phase is lengthened if the applied load is higher. Phase 3 is a further increase in deflection, which is caused by the eccentricity of the applied load. This phase is shorter if the applied loads are higher [11]. In general, the higher the slenderness ratio the faster the walls collapse. Lightly loaded walls with high slenderness ratios take longer to fail, whereas walls with a low slenderness ratio and with an applied load of approximately 50% of the permissible design load fail the fastest. Walls with low slenderness ratio and with the applied load above or below the 50% load also take longer to fail [11].

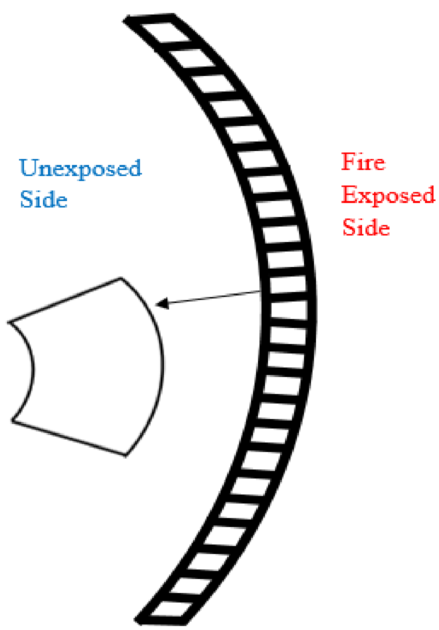

Figure 4: Thermal Bowing

Figure 5: Circular crack formation due to thermal bowing

Masonry materials with a low coefficient of thermal expansion can help to reduce thermal bowing, but if the values are too low it may cause the wall to fail prematurely due to integrity failure (when a member allows that passage of smoke or flames). When walls were tested with scoria aggregate (an aggregate with low thermal expansion), several walls failed in integrity [5]. The reason for this is that the mortar undergoes shrinkage when heated, and if the blocks do not expand, to some degree, cracks will form where the mortar and block meet and the wall will have integrity failure. In non-load bearing tests, the specimens are built to fit tightly into a semi-rigid rectangular frame and the resistance provided by the frame makes it unlikely for any cracks to open up [5]. This means that, in testing of non-load bearing walls integrity failure is less likely to occur. When non-load bearing walls are tested, the restraint from the frame causes the wall to curve in a spherical shape with cracks across the four corners, Figure 5.

Load bearing walls exposed to high temperatures do not usually undergo crushing failure because of thermal bowing [3]. Instead, instability failure occurs due to the horizontal displacement in the wall [3]. It has been found that failure is most likely to occur when the displacement at midspan reaches 0.8 times the thickness of the wall [3]. Equations to calculate the midspan deflection with respect to temperature have been created for simply supported and cantilever walls, Equations 2 and 3 respectively [3]. It can be seen that the deflection for a cantilever wall is four times that of a simply supported wall. The supports help to reduce thermal bowing by resisting movement and providing confinement forces, with fixed supports being the most effective. While loading can mitigate the effect of thermal expansion, the mechanical decay induced by high temperatures on the exposed side can force the compressive stress to migrate towards the unexposed side [3] . If the load is high enough, reverse bowing can occur. Reverse bowing occurs when the structural response is dominated by the decay of mechanical properties.

$$\Delta_m = \frac{\alpha L^2 \Delta T}{8d} \quad (1)$$

$$\Delta_m = \frac{\alpha L^2 \Delta T}{2d} \quad (2)$$

Δ_m = displacement at midspan, α = thermal expansion coefficient, L = height of the wall, ΔT = change in temperature, and d =thickness of the wall [3].

SPALLING

Spalling can result in a significant loss of concrete during fire. This exposes the deeper layers of the concrete to the fire, which in turn increases the heat transmission to the inner layers. This can cause members to fail sooner than anticipated. It is a special concern for masonry walls that are ungrouted since the inner cavity can heat up very quickly once the face shell spalls off. This heated inner cavity can cause part of the wall to spall and fail due to integrity, or even cause the unexposed side to reach the critical failure temperature much sooner than anticipated.

There are two different types of spalling. Explosive spalling occurs earlier on, and involves chunks of concrete exploding from the concrete member. Slower spalling (sloughing off) occurs later as cracks form parallel to the fire-exposed surfaces, which causes the separation of the concrete layers and part of the concrete falls off [12]. An example of the slower spalling can be seen in Figure 6a. Cracks formed in between the web and the face shell of the masonry units and after some time the face shells began to slowly fall off. In Figure 6b it can be seen that the remaining face shell has had some loss of material, either from explosive spalling during heating, or slower spalling after cooling.

When concrete is heated to 105°C-160°C the free water vaporises and causes a rise in pore pressure [13]. Another rise in pore pressure occurs between 160°C - 180°C and is caused by the release of the chemically bound water [13]. After 180°C the pore pressure continues to rise slowly until the concrete reaches 220°C-245°C where it reaches the maximum pore pressure [13]. Once the maximum pressure is reached cracks form and the concrete either explodes because of the pore pressure, or the pressure is allowed to escape through the cracks and the system reaches an equilibrium [13]. Even when there are some paths for moisture to escape, spalling may still occur due to the phenomena of moisture clog [14]. Moisture clog occurs when the moisture in the concrete closest to the fire exposed surface evaporates and results in the significant increase in the pore pressure. This pore pressure increase causes part of the vapor to migrate to the surface, and the remainder migrates deeper into the concrete [14]. The vapor deep within the concrete condensates and results in the saturation on the concrete and can significantly increase the pore pressure of the concrete [14].

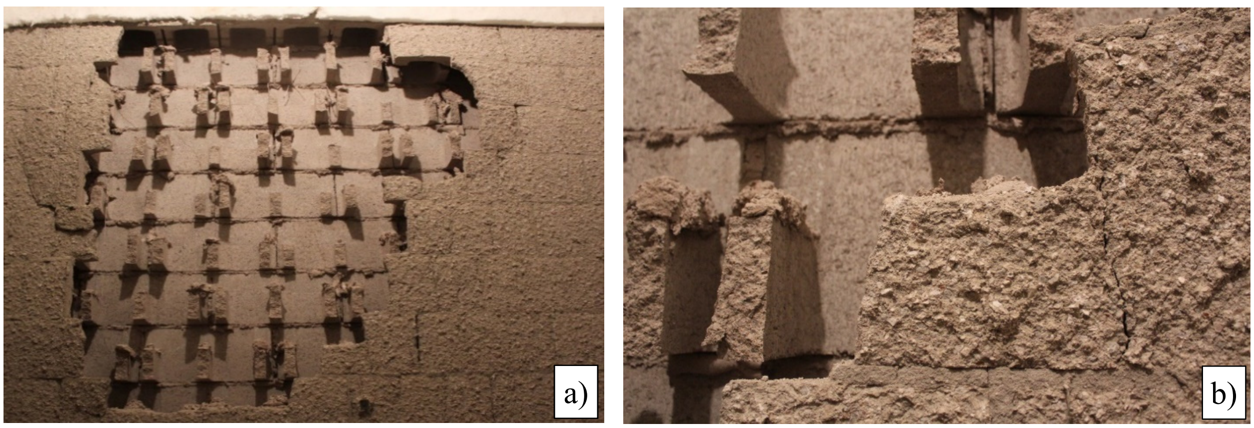

Figure 6: a) Masonry Spalling (Exposed Surface), b) Close up of Masonry Spalling

While it is difficult to predict exactly when and where spalling will occur, factors that increases the likelihood of spalling are known. The higher the strength of the concrete, the higher the chance of spalling. This is because higher strength concrete has lower porosity, which means that the vapour pressure cannot escape due to the higher density [15]. The probability of spalling occurring is also increased when the moisture content is higher because it causes a higher vapour pressure under fire conditions [13]. It is important to note that larger specimens have a greater chance of spalling, so if smaller specimens are used in testing it can lead to incorrect results.

Another method of reducing the occurrence of spalling is to change the type of aggregate used. Carbonate aggregate has better fire resistance and better spalling resistance than siliceous aggregate. This is due to the fact that carbonate aggregate has a higher specific heat, better strength, ductility, thermal expansion, and thermal stability [15]. However siliceous aggregate like flint may reduce spalling by forming micro cracks when they expand, [4]. These micro cracks can increase the permeability of the concrete and allow the vapours to escape, however they also decrease the strength of the concrete [4].

Also, the heating rate can be beneficial or detrimental, depending on the temperature increase used. Some researchers have found that higher thermal gradients can be beneficial since it can create micro cracks in the concrete which allows pore pressure to escape [4, 13]. When samples were tested with a 5°C/min heating rate vs a 25°C/min it was found that the higher heating had consistently lower pore pressure due to the increased number of micro cracks [13]. However, other researchers found that when heating rates are too high (over 150°C/min) they can cause an increase in spalling of concrete [15, 16, 17]. This means that there is a point where the heating rate goes from creating beneficial micro cracks, to increasing the likelihood of harmful spalling.

Spalling may be caused not only from the pore pressure, there is also potential for spalling due to the high thermal gradients that occur due to high heating rates [16, 17]. These thermal gradients cause thermal stresses in the concrete and can cause cracking or spalling. It has been found that when concrete was heated to 500°C after three minutes, the cracks in un-spalled concrete were mainly formed by the thermal stresses from the large temperature gradient [17]. To put this into perspective, the standard fire is 487°C after three minutes [1]. It can be inferred from these results that when concrete is heated quickly the temperature gradient might be a more important factor than the pore pressure. Researchers are still debating the exact circumstances that determine whether the pore pressure or thermal stresses are the dominant cause of spalling.

Tests have been done with low heating rates (0.1°C/min) to determine if spalling will occur [16]. The low heating rate did not produce any spalling, partially because there were very minimal stresses from thermal gradients, and partially because the pore pressure had much more time to attenuate. Tests have also been done with no free moisture by baking the sample to 80°C in order to evaporate all the free moisture [4]. When the sample was put in several different heating rates and no spalling occurred. These tests proved that high thermal gradients and pore pressure are both required in order for spalling to occur, however it is still unclear the exact role each plays.

SUMMARY AND CONCLUSION

The choice of aggregates can have a large impact on the thermal and mechanical properties of masonry. Lightweight aggregates retain their strength at high temperatures for longer period than normal weight aggregates. However, the specific heat of normal weight aggregates improves more than lightweight aggregates as temperature increases. The aggregates and cement need to have similar thermal expansions in order to reduce cracking during heating. It is also important for the mortar and the blocks to have complementary thermal expansions in order to minimize the cracking that can occur at the interfaces. In general, more moisture present in the masonry member improves its fire resistance by increasing the specific heat (as long as it does not lead to spalling).

To mitigate thermal bowing a material with a low coefficient of thermal expansion should be chosen. Thermal bowing can also be reduced by increasing the distance between the exposed and unexposed surfaces, or decreasing the slenderness ratio. Also, the use of fixed supports as opposed to pin, roller, or cantilever supports greatly reduces the thermal bowing because even at large deflections the specimens are stable due to the confinement forces from the frame. While the applied loads on a masonry wall can reduce the effects of thermal bowing, high loading can cause reverse bowing and structural failure.

Moisture can have a large impact on the fire resistance of concrete masonry member, but it can also cause harmful spalling at lower heating rates. It is important to choose the proper aggregates and mix designs in order to ensure a higher porosity in order to reduce the likelihood of spalling. High heating rates can either reduce spalling by creating micro cracks to relieve pore pressure, or increase spalling because of the high temperature gradients depending on the heating rate used. Spalling caused by high heating rates is usually caused more by thermal gradient-induced stress instead of the increased pore pressure, but there is some debate over how much each factor contributes to spalling.

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