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Effect of high temperature on hardened concrete

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ABSTRACT

Consider these factors when designing concrete for high temperature exposure. Construction materials suffer in fire. Deterioration of material characteristics and structural performance highly depend on constituents and on the temperature history. Design for high temperature requires additional aspects of material composition and material characteristics. Present paper provides information on effect of concrete composition at high temperature including selection of appropriate cement, aggregate and fibres and its chemical transformations and the codal provision.

Keywords : high temperature, fire, spalling, cement, aggregate, fibres, pozzolanic materials.

As fire has been known since ancient times as one of mankind's greatest enemies we intend to draw attention to fire, as well as to its impact on structural elements. During design, in several cases the fact is ignored that a building may also be exposed, to the effect of high temperature, when the properties and the bearing capacity of materials also change. Therefore it is very important to get acquainted with the behaviour of the different materials under high temperature, as a consequence of which a building may also collapse.

Concrete must at times resist the effects of artificially induced high temperatures such as might be encountered near furnaces or in atomic reactors, in pavements subjected to jet engine blast, and in areas exposed to fire. Applications of concrete involving extremely high temperatures, such as landing pads for missiles, are considered expendable, but in most instances it is desired to avoid deterioration of the concrete's physical properties as much as possible.

Effect of high temperature on hardened concrete

A number of factors will enter into a decision regarding the type of concrete to use under conditions of elevated temperature. These include the following: length of exposure, rate of temperature rise, temperature to which the concrete mass will be raised, temperature of concrete at initiation of exposure to high temperature, degree of water saturation of the concrete, age of the concrete , type of aggregate used, type of cement used, aggregate / cement ratio, and loading conditions at time of exposure.

These failure behaviours are due to:

(a) Thermal stresses induced by thermal gradients.
(b) Decomposition of calcium hydroxide (CH) in the cement paste.
(c) Calcination or phase transformation of aggregates.
(d) Vaporization of free moisture.

Effects of ingredients

Cement: Preliminary studies indicate that the amount of calcium hydroxide in concrete is of great importance in the resistance to high temperatures. Cements which release the least amounts of calcium hydroxide during hydration and hardening of the concrete are certainly to be favored. For this reason slag cement or portland blast furnace slag cement are sometimes specified for this type of work.

Aggregates: Studies of concrete heated to high temperatures indicate that the type of aggregate employed is critical. Nevertheless no standard specifications have been developed to define the aggregate properties desired for high temperature exposure. It seems obvious that aggregates with low coefficients of thermal expansion in the range of temperatures that the concrete is expected to experience would be preferable to those with high coefficients. A sizeable amount of expansion of the aggregates within the confines of a shrunken hardened cement paste would result in a disruption of the concrete mass. The conductivity of the aggregates employed will also be an important factor in determining the stability of the concrete.

Predominantly limestone (carbonate aggregate) provides higher fire resistance and better spalling resistance than that of siliceous aggregate predominantly quartz. This is mainly because carbonate aggregate possesses substantially higher heat capacity (specific heat), and this is beneficial for mitigating spalling and also increasing fire resistance. This increase in specific heat is caused by an endothermic reaction occurring around 600-750 deg centigrade due to dissociation of dolomite in carbonate aggregate concrete. This endothermic reaction absorbs energy supplied by fire and enhances the specific heat of concrete in that temperature range. In general, the fire resistance of the HSC columns made with carbonate aggregate concrete is about 10% higher than those made with siliceous aggregate concrete. Generally speaking, aggregates that contain a comparatively high proportion of silica exhibit a higher coefficient of thermal expansion. Therefore they should be avoided in concrete which is to be exposed to high temperatures.

Studies indicate that light weight aggregates, especially those manufactured in high temperature kilns or furnaces, exhibit greater dimensional stability under heat. In a comprehensive study reported in Volume 63 of the ASTM Proceedings expanded shale aggregates were the most stable. The expanded shale type retained approximately 20 percent of its original compressive strength after being heated to 1,000 degrees Fahrenheit; its thermal conductivity in concrete was also much lower than the other three types. This is probably explained by its glasslike composition and high porosity . This type, therefore, retains a comparatively high amount of moisture, which is beneficial in dissipating heat within the concrete mass . Of course retention of water can be carried to an extreme wherein the generation of steam would be detrimental. The aggregate/ cement ratio appears to have an important effect on concrete strength exposed to high temperatures, the proportional reduction in strength being less for a lean mix than for a rich one.

Addition of Fibers
The addition of polypropylene fibers minimizes fire induced spalling in the high strength concrete (HSC) members. One of the most accepted theory is that by melting at a relatively low temperature of 170 deg centigrade polypropylene fibers create ‘channels’ for the generated steam pressure (within the concrete) to escape, thus preventing the small ‘explosions’ that cause spalling. The amount of polypropylene fibers needed to mitigate spalling is about 0.1-0.15% (by volume). This technique is highly effective for concrete used in tunnel linings as tunnels are susceptible to fires with very high heating rates. Alternatively steel fibers can also be used to enhance fire resistance of HSC members. The addition of steel fibers enhances the tensile strength of concrete and reduces spalling.

Also, hybrid (mixture of polypropylene and steel) fibers have been shown to be effective in minimizing spalling and thus enhancing the fire resistance of concrete structures.

Pozzolanic materials
The effect of high temperature on concrete containing fly ash or natural pozzolans has not been investigated in detail. Researchers and investigators differ in their opinion regarding the changes in the properties of concretes, particularly in the range of 100– 300oC, whereas for temperature above 300 oC, there is uniformity in opinion concerning a decrease in mechanical characteristics.

The pozzolanic material such as silica fume, slag and ground clay bricks (homra) have been shown to improve the microstructure of cement paste by densifying the cement paste matrix and improving interfacial zone.

This is due to the reaction between the amorphous silica of the pozzolana and the calcium hydroxide produced by the cement hydration reactions. In addition, the physical effect of the fine grains allows denser packing within the cement and reduces the wall effect in the transition zone between the paste and aggregate.

This weaker zone is strengthened due to the higher bond developed between these two phases, improving the concrete microstructure and properties. In general, the pozzolanic effect depends not only on the pozzolanic reaction, but also on the physical or filler effect of the smaller particles in the mixture. Therefore, the addition of pozzolans to Portland cement increases its mechanical strength and durability when compared to the blank paste, because of the interface reinforcement. The physical action of the pozzolans provides a denser, more homogeneous and uniform paste. Natural pozzolans have been used since antiquity with excellent results for production of durable concrete

The hydrates, such as calcium silicate hydrate (CSH) phases produced as a result of consumption of free Ca(OH)2 by active silica fume, are deposited within the pore system and around the grains of the concrete constituents. This leads to the formation of a denser concrete microstructure.

Chemical transformations of concrete at high temperature
Concrete is a composite material, that consists mainly of mineral aggregates bound by a matrix of hy-drated cement paste. The matrix is highly porous and contains a relatively large amount of free water unless artificially dried. When exposed to high temperatures, concrete undergoes changes in its chemical composition, physical structure and water content. These changes occur primarily in the hardened cement paste in unsealed conditions. Such changes are reflected by changes in the physical and mechanical properties of concrete that are associated with temperature increase.

When concrete is subjected to elevated temperatures, the incompatibility of thermal deformations of the constituents of concrete initiates cracking. Internal stress is caused by a microstructure change due to dehydration and steam pressure buildup in the pores. The maximum exposure temperature, exposure time, heating and cooling rates are among the most important factors. In these processes, the removal of free water, absorbed and chemically bounded water affected the porosity, capillary and the microstructure of cements. In the temperature range (100 – 300oC), free and bound water from C-S-H gel is evaporated. Above 300°C a reduction in strength in the range of 15 – 40 % occurs. At 550oC, the reduction of strength in the range 55 – 70 % and dehydroxylation of Ca(OH)2 takes place. The dehydration of calcium silicate hydrated and the thermal expansion increase internal stresses and micro cracks which are induced through the cementing material. Fire is generally extinguished by water and CaO turns into Ca(OH)2 causing cracking and crumbling of concrete. The alterations produced by high temperatures are more evident when the temperature surpasses 500oC. CSH gel, which is the strength giving compound of cement paste, decomposes further above 600 – 800oC. At 600°C, Ca(OH)2 is dehydroxylated, and CaCO3 dissociates to CaO and CO2 accompanied with the recrystallization of non-binding phases from hydrated cement under re-combustion are dominant processes between 600°C and 800°C. This stage of concrete is characterized by the collapse of its structural integrity, revealing residual compressive strength.

Codes and standards
1S:456 provides tabulated data on required minimum dimensions and minimum cover thickness to achieve desired fire resistance in structural members, such as beams, columns and slabs.

The fire resistance of a continuous reinforced concrete beam is generally significantly longer than that of a simply supported beam having the same cover and loaded to the same moment intensity.

Concrete structures in the US are to be designed in accordance with the specifications as per AC1 216.1 (2007) standard which gives specifications for fire resistance ratings of concrete and masonry structural members. Similarly NBC (2005) for Canada, Eurocode 2 (2004) for Europe and AS 3600 (2001) for Australia provide fire resistance specifications.

Conclusion
When a designer is faced with the need to develop concrete which will be exposed to high temperatures, the following points should be kept in mind.

- If the temperature will not exceed 200 OC, a high-quality ordinary concrete will usually be sufficient If the temperature will reach 260 to 315 degrees, special steps must be taken.
- For the higher temperatures use ordinary portland cements which release the least amount of calcium hydroxide upon hydration. If available, use slag cement or portland blast furnace slag cement.
- siliceous aggregates, which at very high temperature also undergoes physical changes accompanied by a sudden expansion in volume, thus sometimes causing aggregates splitting and / or spalling.
- The physical compatibility between matrix and the aggregate with regard to deformability and expansion characteristics is also much better in light-weight concrete than gravel concrete.

- Provide ample concrete cover for steel reinforcement .
- Replacing cement by pozzolanic material like fly ash, silica fume, blast furnace slag and metakaolin , not only its strength gets enhance but serviceability and durability characteristic can also be improve.
- A continuous beam or slab provides more resistance against fire than that of simply supported one.

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