Effect of mineral admixtures on the properties of mass concrete - A review

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Abstract: This study addresses the various aspects of massive concrete construction and one of the major problems associated with such type of concreting i.e. thermal cracking. A detailed review has been presented on the mitigation strategies of various researchers in controlling the problem of thermal cracking and temperature gradients caused during massive concrete structures. The mineral substitution techniques used in current day research have been qualitatively assessed and a better judgement has been proposed while utilizing the capabilities of such mineral substitutions. The experimental techniques adopted to investigate the thermal gradients established within massive concrete members have also been reviewed and a synopsis is presented. The behaviour of mineral admixtures with respect to their dosages in mass concrete specimen has been critically looked upon and the variation in the performances in establishing respective temperature thresholds are analysed. Moreover, the beneficial role of various mineral substitutions in controlling the cracking propensity of the concrete structures have been put forward by presenting a real-time case scenario for adaptation in future research studies in addressing the cracking behaviour of mass concrete specimen. Adiabatic temperature rise, rate of adiabatic temperature rise and the cracking temperatures in mass concrete specimen have been selected as primary point of research interest and the dosage rates of mineral admixtures kept as the variable while addressing the behavioural characteristics of crack generation and existence of steep temperature gradients.

Keywords: Massive concrete, Thermal cracking, Temperature gradients.

Introduction:
Since the beginning of twentieth century, early-age cracking caused within massive concrete construction has been identified as the most common form of deterioration associated with such type of concrete construction. Concrete structures like dam walls, abutments of bridges and foundations are generally classified as mass concrete structures as shown in Figure 1. The Florida Department of Transportation (FDOT) defines mass concrete structures as “any large volume of cast-in place or precast concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change so as to minimize cracking” [1]. Similarly, another classification has been put forward by the Texas Department of Transportation (TxDOT) as “placements with at least one cross-sectional dimension greater than or equal to 5 ft” [2]. With the increase in number of days elapsing after the placement of concrete, the heat generated as a result hydration reaction subsides and the concrete structure starts to cool in order to create equilibrium. The concrete present on the exterior side of the member undergoes temperature drop in a much faster pace as compared to the interior, which results in the establishment of thermal gradient. This thermal gradient as a result of the non-uniform cooling of the concrete member creates strains in the member and eventually the concrete cracks [3].

The composition of cement has a prime role in contribution towards the development of heat during the hydration reaction in a concrete mix. The composition of cement primarily involves the chemical composition of cementing material and its fineness level. Generally, Type II and IV cements are low-heat generating cements. Similarly, the higher the fineness of the cementing material the more surface area the cement has to react with the water and thus hydrate it.

Mineral substitution
In order to reduce the amount of heat released during the hydration reaction in a concrete mix, some amount of mineral admixtures or most commonly known as supplementary cementing materials (SCM’s) are incorporated in the batch of the concrete as a partial replacement of cement [4]. It is current practice to reduce the cement content to an extent that is both stoichiometrically and practically possible in order to overcome the heat evolved during the phase of hydration. As a result, various mineral substitutions e.g. fly ash, silica fume, ground...
granulated blast furnace slag and bentonite have been adopted in the current day research practice for the purpose of lowering the heat of hydration, and their detailed review is presented as follows:

2.1 Fly Ash:
Fly ash has been widely used in the modern day concreting practice for its vast utility in enhancing the workability as well as lowering the heat of hydration of concrete mixes. There is a great variation in properties of fly ash obtained from different sources; therefore the primary indicator of its cementitious nature has been attributed to the amount of CaO content in the ash. The amount of CaO reported in the class C type of fly ash is more than 20% whereas in class F type of fly ash the amount of CaO is less than 15%. Sakai et al. 2005 [5] established an experimental procedure to determine the effect of different fly ash classes on the amount of heat liberated as a result of the hydration reaction.

The results reported in Figure 2 and Figure 3 has provided a relationship among the various replacement dosages of class C fly ash in a concrete mix and their effect on the amount of heat liberated thus recorded as the adiabatic temperature rise of the specimen. It is noted that the 35% dosage of class C fly ash provided lesser heat liberation as compared to the other dosages.

Schindler et al. 2005 [6] provided further experimental evidence to the possible utility of class C fly ash in controlling heat of hydration by optimizing the dosage of class C fly ash to 30% with an adiabatic temperature rise in the concrete mix as 9°C recorded during the initial 10 days of curing. Thielen et al 2006 [7] reported that the effect of class C fly ash on lowering the heat of hydration almost ceases when the replacement dosage is increased to as much as 45%, after which there is no significant reduction in the amount of heat liberated within the massive concrete member. The 45% dosage of class C fly ash corresponded to almost the same amount of adiabatic temperature rise as obtained from the 35% replacement conducted by Schindler et al. 2005.

Sioulas 2007 [8] provided a means of providing a better understanding of the microstructural phases occurring during the pozzolanic reaction of class C fly ash with the hydrating cement mixes. The research concluded that the micro pores associated within the crystal lattice of the fly ash provided the inherent behaviour of chemical intermixing with the particles of cement that created a strong effect on the inter-molecular forces. This resulted in a reduction in the heat thus liberated when the chemical reaction undergoes.

Figure 2: Total temperature rise using class C fly ash (Sakai et al. 2005)

Figure 3: Rate of temperature rise using class C fly ash (Sakai et al. 2005)

Figure 4: Total temperature rise using class F fly ash (Sakai et al. 2005)
The results reported in Figure 4 and Figure 5 has provided a relationship among the various replacement dosages of class F type of fly ash in concrete mixes and their effect on the amount of heat liberation during the hydration reaction. It was observed by Sakai et al. 2005 that with increasing the dosage of class F type of fly ash, there has been a substantial amount of reduction in the rate of heat liberation with the progress of hydration reaction. The research concluded that after initial 10 hours of concrete placement, the higher the dosage of class F fly ash, the better is the performance in adiabatic temperature rise i.e. at 20 hours of concrete placement, the 35% dosage of class F fly ash reported temperature values of 20 °C whereas at the same age, the class C fly ash mixes were at 28 °C adiabatic temperature levels. 

Sakai Ohshawa, 2005 [9] reported the behaviour of class F fly ash when incorporated in a concrete mix subjected to adiabatic calorimeter testing and stated that the optimized values of heat liberation were obtained at 50% replacement of class F fly ash with cement. This optimized dosage is 5% increased as compared to the conclusions of Thieilen et al. 2006, for the class C fly ash replacement. Paulinious et al. 2006 [10], presented a detailed microstructural behaviour of the pozzolanic potential and chemical reactivity of class F fly ash. The chemical results put forward by Paulinious et al. 2006, were used as guideline by Middleson 2006 [11], and presented an experimental evidence of the better performance of class F fly ash in controlling heat of hydration as compared to the class C fly ash.

2.2 GGBF Slag

There has been an effective use of ground granulated blast furnace slag to mitigate the temperature rise in massive concrete structures, Sioulos and Sanjayan 2000 [12]. It has been reported that there is a direct relationship between the reduction in early-age heat generation to the amount of ground granulate blast furnace slag quantity used a partial replacement of cement. The rise of the temperature values and formation of peaks in the adiabatic temperature curves is greatly delayed by the addition of ground granulated blast furnace slag in to the hydrating concrete mixes. Bamfosh 2001 [13] reported that ground granulated blast furnace slag delays the formation of peak temperature gradients due to the activation energy of the slag. Depending on the curing temperature, the presence of such an amount of activation energy influences the heat of hydration thus liberated. Schindler and Follard 2005 [14] reported that the dosage of ground granulated blast furnace slag can reach up to a maximum of 75% to liberate the same amount of heat of hydration as liberated by 30% dosage of class F fly ash. This behaviour is strictly observed during the initial 7 days of concrete hardening and the behaviour diminishes with the progress of hydration reaction.
Bazant 2007 [15] expressed a numerical model of the heat inflow and outflow within the hydrating cement mixes in a closed chamber of specified dimensions. Bazant concluded that the use of mineral admixtures such as ground granulated blast furnace slag enhances the performance of massive concrete members in terms of thermal cracking thus imparted due to temperature gradients. The key synopsis of the research was that slag dosage of up to 80% contributed to adiabatic temperature levels of 10 °C after the initial 20 days of concrete mix placement. This result was better than the results reported by Schindler and Folliard 2005. The results of Schindler and Folliard 2005 reported an adiabatic temperature gradient that ranged to a maximum of 15 °C at 20 days of concrete placement.

Fulton Emborg 2007 [16] provided a measurement technique of determining the temperature gradients occurring within a hydrating concrete mix however, the important conclusion that the research put forward was the utilization of ground granulated blast furnace slag in amounts much lesser than what was stated by Schindler and Folliard 2005. The research implemented a new technique of synergic effect of ground granulate blast furnace slag with other supplementary cementitious materials. This was the governing factor of reducing the temperature gradients to a level of 8 °C at 20 days after the hydration of concrete. This important conclusion gave way to further research of utilizing the synergic properties of various supplementary cementitious materials in order to address problems associated with concreting industry.

Fulton Emborg 2007 reported that the replacement of cement with ground granulated blast furnace slag provided slightly lower cracking temperatures at placement of 50 °F and 95 °F which are shown in Figure 8.

At 73 °F placement temperature, the ground granulated blast furnace slag mixture were about the same as that to the control mixes that were prepared in the study. There was no considerable change in the cracking tendency thus reported however, when compared with the 95 °F placement temperature, the cracking temperatures of the 30% reduction in cement content and 50% reduction in cement content were reduced by approximately 12 °F by lowering the placement temperature to 73 °F.

![Figure 8: Effect of GGBF dosage on cracking temperature (Fulton Emborg 2007)](image)

Figure 8: Effect of GGBF dosage on cracking temperature (Fulton Emborg 2007)

The reduction of the placement temperature to 50 °F yielded a 20 °F reduction in the cracking temperature, which is reported in Figure 9.

![Figure 9: Effect of placement temperature on GGBFS mixes (Fulton Emborg 2007)](image)

Figure 9: Effect of placement temperature on GGBFS mixes (Fulton Emborg 2007)

Conclusions:

Early-age cracking in massive concrete construction has remained a severe problem that poses a threat to the structure’s functional life. In literature, there have been active efforts to develop the scientific reasoning and logical explanation towards the cracking propensity of massive concrete construction. The underlying phenomenon of increased rate of hydration has been widely discussed among researchers and strategies have been developed to cope with this characteristic of a hydrating concrete mix.

However, there is a deficiency of the microstructural evaluation procedures that give a more reliable source of results as compared to physical testing and the conclusions made on such justifications. It has also been concluded that the use of supplementary cementitious materials provide an economical method of controlling the temperature gradients established within a massive concrete structure. A number of researchers established relationships among the various dosages of supplementary cementitious materials during the concrete mix batching and their effects on the mechanical and thermal properties of mass concrete members. There has been confidence among the researchers on the use of mineral admixtures.

In the coming years, there is a need of computer aided modelling techniques to strengthen the utility of supplementary cementitious materials in mass concrete members. There has been limited amount of research done on assessing the potential of alternatives to reduce the thermal cracking propensity of mass concrete members.
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