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Heat of Hydration in the Placement of Mass Concrete

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***Abstract** – The factor distinguishing between normal concrete and mass concrete is the thermal characteristics. Mass concrete is defined as "any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking." Use of mass concrete has been in existence over the last two centuries, and it has lately been reaching its full potential in the construction industry. The proper design and construction of mass concrete placements is essential to ensure the durability and serviceability of the structure. Mass concrete is required in massive structures containing beams, columns, piers, dams where its volume is of such a magnitude as to require special means for coping with the generation of heat and which is followed by volume change. This paper explains the factors influencing generation of heat of hydration (cracking) along with the different ways to lower the heat of hydration and then the methods to be implemented for its reduction.*

***Keywords** - Air entrainment; cracking; heat of hydration; restraint.*

I. INTRODUCTION

Mass concrete elements generate substantial thermal gradients between the core and the surface of concrete that pose a considerable risk of thermal damage. This phenomenon is called as ***Thermal Cracking.*** As a result of which, extra precautions have to be undertaken. Cracks parallel to the axis of the dam endanger its structural stability by remaining in intimate contact with its foundation and abutments. Their behaviour is as predicted by design stress distributions. There are three circumstances that contribute to cracking and reduce the durability of mass concrete elements, these are internal restraint, external restraint, and delayed ettringite formation. Proper understanding and design of mass concrete provides elements free of cracks and thermal damage.

II. RESTRAINT AND THERMAL STRESS

Cracking in mass concrete is the result of restraint, which in turn induces tensile stresses that exceed the relatively low tensile strength of the concrete. All of mass concrete is restrained both internally by the element itself, and externally by the support system of the element.

A. Internal Restraint -

When mass concrete is placed, the core of the concrete experiences large temperature increase due to the heat of hydration, and then the concrete becomes unable to efficiently transfer heat to the surrounding environment.

As a result of which temperature in the core of the concrete increases. The proximity to the surrounding environment, results in quick cooling of the surface of the concrete in comparison with the core, due to thermal expansion. The respective volume changes in the concrete causes compressive forces to develop in the core, and tension forces to develop at the surface as shown by Fig. (b). Thermal cracking is experienced when the tensile stress in concrete exceeds the tensile strength of concrete for which it is designed.

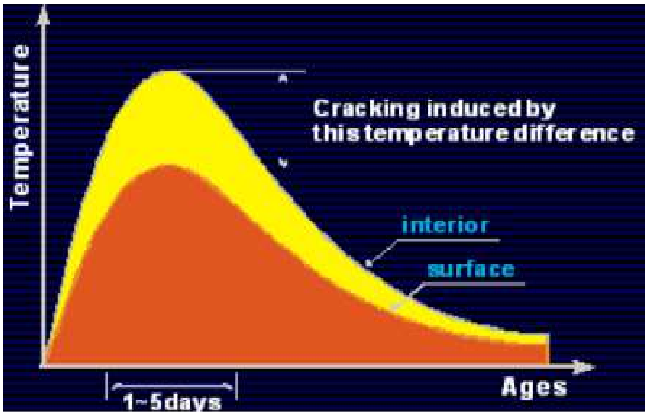

Fig. (a)

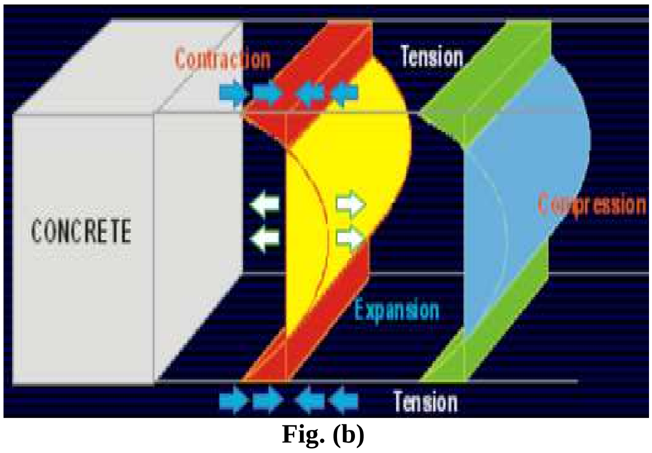

Fig. (b)

B. External Restraint –

After the concrete has reached its peak temperature the placement begins to cool, and subsequently contracts in volume. The contraction of the concrete is resisted by external restraints, such as the sub-base, rigid supports or adjoining structure supporting the mass concrete element. Fig. 3 shows how the volumetric changes of mass concrete are resisted by external restraint. The contracting volume of concrete will develop tensile stresses resulting from the resistance provided by the external restraint. If the tensile stresses are larger as compared to the developed tensile strength of the concrete, then the mass concrete placement will experience cracking. Degree of restraint is a factor

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influencing the tensile stresses resulting from an external restraint. This degree of restraint in turn depends on strength, relative dimensions and modulus of elasticity of the restraining material. ACI 207.2R defines the equation for the developed tensile strength at the centerline of the placement by the following equation -

Table I

Designation	Meaning
ft	Tensile stress at any point on the centerline of the placement
KR	Degree of restraint expressed as a percentage
Δc	Contraction of the concrete if there was no restraint
Ec	Modulus of elasticity

Refer to Equation (1);

Ft = KR Δc Ec … (1)

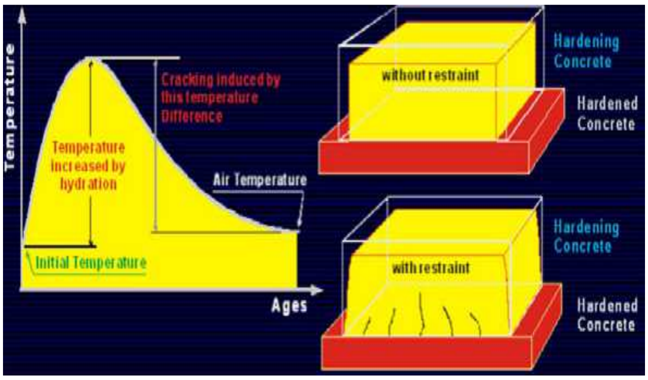

Fig. (c)

C. Delayed Ettringite Formation –

Delayed ettringite formation (DEF), is also known as heat induced delayed expansion (HIDE). It is the process of formation of ettringite in matured concrete which causes expansive pressures. Only certain concrete mixes are susceptible to delayed ettringite formation when they reach an extreme temperature. The use of fly ash and slag may help to reduce HIDE. For the prevention of DEF, specifications are undertaken that typically limit the maximum temperature of concrete to 160°F (71°C). Mass concrete elements generate extreme temperatures during hydration. If the temperature of the concrete becomes excessive, ettringite formed previously in concrete may begin to decompose, and no further ettringite is formed. After the hardening of concrete, the calcium hydrate releases the confined sulphate, which may react with calcium monosulfoaluminate in the presence of water and forms ettringite in the concrete paste. After a period of time, the accumulation of ettringite crystals in the concrete paste may build up and cause expansive pressures. If the pressures due to the expansive crystals become very high, cracking between the aggregate and the paste may be developed.

III. SHRINKAGE

Shrinkage is an effect of the hydration of concrete that cannot be avoided. As shrinkage in concrete gradually increases, stresses are developed resulting from internal and external restraint.

Types of Shrinkage -

A. Drying shrinkage.
B. Chemical shrinkage.
C. Autogenous shrinkage.

IV. WAYS TO LOWER THE HEAT OF HYDRATION

A. Cement Content –

With the help of several methods cement contents as low as 100 kg/m3 in mass concrete suitable for the interior structure of gravity dams can be achieved. With such low cement contents, even ASTM Type II Portland cement is considered adequate. 20 % pozzolan is substituted by volume of Portland cement which leads to a further drop in the adiabatic temperature.

B. Admixtures –

For cement contents as low as 100 kg/m3, it is necessary to use a low water content so as to achieve the designed one year compressive strength which falls in the range of 13 to 17 MP which is normally specified for interior concrete of large gravity structures. Around 4 to 8 % of entrained air is routinely incorporated into the concrete mixtures for the reduction of water content while maintaining the desired workability. A constant increase in water-reducing admixtures is being employed for the same purpose. Pozzolans are used primarily as a partial replacement for Portland cement for the reduction of heat of hydration; most fly ashes upon their use as pozzolans have the ability of improving the workability of concrete whereas reducing the water content by 5 to 8 %

C. Aggregate –

With concrete mixtures for dams, every probable method of reduction of water content which would eventually lead to a corresponding reduction in the cement content (i.e. maintaining a constant water-cement ratio) has to be looked upon. In this context, the two economic methods are the choice of the largest possible size of coarse aggregate and the selection of two or more individual size groups of coarse aggregate that should be combined to produce a gradation approaching maximum density after compaction (minimum void content). An example of this way is shown by the U.S. Bureau of Reclamation's investigations on mass concrete for Grand Coulee Dam. Aggregate content has a huge influence on the properties that are vital to mass concrete, such as strain capacity, coefficient of thermal expansion, elastic modulus and diffusivity. The coefficient of thermal expansion of concrete is one of the parameters determining the tensile stress on cooling. Everything else remaining the same, the choice of aggregate type can decrease the coefficient of thermal expansion by a factor greater than 2.

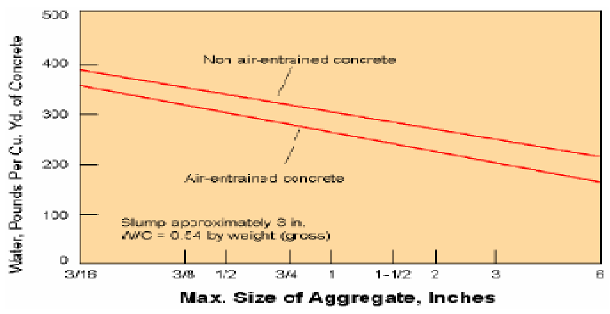

Fig. (d)

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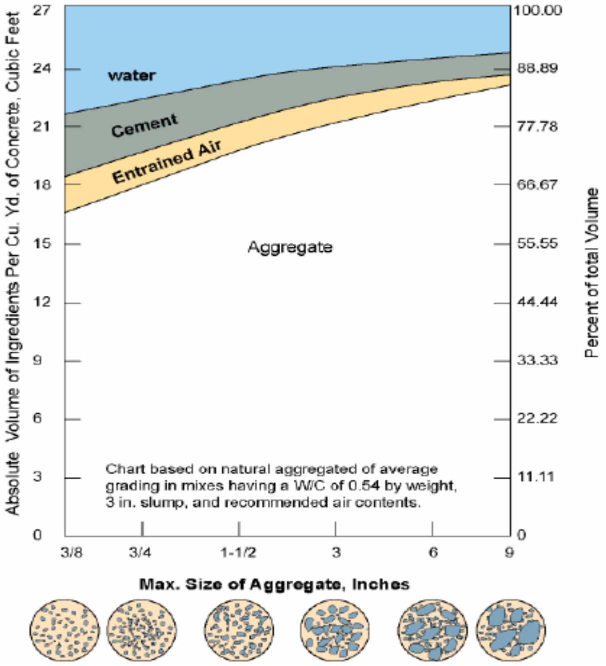

Fig. (e)

D. Strain Capacity –

According to the data shown, in comparison to mortar and concretes, the neat cement paste of the same water cement ratio has a considerably greater amount of tensile strain capacity. In practice, the tensile strain capacity increases with the period of hydration and subsequently decreases with the size of coarse aggregate. A table supporting this statement is shown as follows –

Table II

Mix	Aggregate	Maximum size of aggregate [in. (mm)]	W/C+P	Tensile strain capacity 10^{-6} 7 days	Tensile strain capacity 10^{-6} 28 days
1	Quartzite, natural	3 (75)	0.68	45	71
2	Quartzite, natural	1½ (37.5)	0.68	76	95
3	Quartzite, natural	No. 4 (4.75)	0.68	138	165
4	None (paste)		0.68	310	357
5	Quartzite, natural	1½ (37.5)	0.68	119	139
6	Quartzite, natural	1½ (37.5)	0.40^{a}	151	145

E. Mix Design –

In addition to the largest size of aggregate, determination of the water content should be on the basis of the consistency of fresh concrete that can be adequately mixed, placed and compacted. If the job-site equipment is inadequate for handling concrete alternative equipment should be sought instead of increasing the water and the cement contents of the concrete mixture. In case of precooled concrete, the laboratory trial mixtures should also be made at low temperature because less water will be needed to achieve the given consistency at 5°C than at normal ambient temperatures (20°C), due to the slower hydration of cement at low temperatures. The determination of the cement content of mass concrete is guided by the relation between water/cement ratio and strength.

V. CONSTRUCTION PRACTICES FOR CONTROLLING TEMPERATURE RISE

A. Post cooling –

The first major use of post cooling of in-place concrete was done in the construction of Hoover Dam (1930). In addition to control of temperature rise, another primary objective of post-cooling was to shrink the columns of concrete composing the dam to a stable volume so as to fill the construction joints with grout for ensuring the monolithic action of the dam. Due to the low diffusivity of concrete, it would have taken more than 100 years for dissipation of 90 % of the temperature rise if left to natural processes. Thin steel pipes typically around 25mm in diameter were used. Through these pipes, cold water was continuously circulated. This circulation of water was started when the concrete temperature had reached around 65°C. This process of cooling proved to be fruitful as a result of which the U.S. Bureau of Reclamation followed this same procedure for several other dam projects but in these projects, the circulation of cold water started simultaneously with the placement of concrete. In the first few days of inducement of cold water, the rate of cooling is generally high due to the low elastic modulus of concrete. The strength and elastic modulus generally increase at a quick rate until after the initial peak in concrete temperature been experienced. After the transformation of concrete to elastic, it is necessary to have the temperature fall as slowly as possible so to allow for stress relaxation.

B. Pre Cooling –

The first use of precooling was done by Corps of Engineers during the construction of Norfork Dam in the early 1940s. A part of the mixing water was introduced into the concrete mixture as crushed ice so as to limit the temperature of in-place fresh concrete to about 6 C. Subsequently, combinations of crushed ice, cold mixing water, and cooled aggregates were utilized by Corps of Engineers in the construction of a number of large concrete gravity dams (60 to 150 m high) so as to achieve placing temperatures as low as 4.5 C.

C. Surface Insulation –

The main purpose of surface insulation is not to restrict the temperature rise, but to regulate the rate of temperature drop so as to lower the stress differences due to steep temperature gradients between the concrete surface and the interior.

VI. PLACEMENT OF MASS CONCRETE

The location of the pump depends on the site conditions and on the optimal placement procedure. The number of pumps depends on the volume to be poured and the pump rate. The pumping sequence shall be made in a way decreasing the surface exposure to less than one hour avoiding possibility of cold joints. Municipality laws limit working time.

Stair-step is the process used for placement -

• Place concrete in layers not more than 450 mm thick.

• Extend vibrator heads into the previously placed layer of plastic concrete.

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• Immediately return to place on the freshly consolidated concrete before initial set and construct the placement in a stair stepped fashion.

VII. CONCLUSION

This paper presents various circumstances that contribute to cracking of a structure having undergone mass concreting. This paper also illustrates the various ways of preventing the structure to fail because of the increase of heat of hydration. Various important measures for the reduction of this heat of hydration are also highlighted in this paper.

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