Examination of the Causes and Effects of Thermal Crack in Concrete Structures with Solution

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Abstract

Thermal crack is known by civil and structural engineers hundred years ago. However, the phenomenon does not solve completely yet. This project examines the causes and effects of thermal crack with some common solution for the problem. The study starts with definition for some words, then presents causes and effects of the problem and finally, shows some common solution to reduce the thermal crack. It is concluded that the series of action that are taken place to cause thermal crack are very complex. Therefore, there are many factors must be beheld to avoid thermal crack; especially when a concrete structure is planned, designed and constructed.

CONTENTS

Introduction

The phenomenon of thermal cracking in concrete structures recently has become a serious problem among civil and structural engineers as well contractors. Today, although the technology has been developing, this problem can not be solved totally. This is because also the concrete structures are developed and become more complex.

Although, the thermal cracks were known since more than a century, first time it was mentioned in the books during the 1920 (Emborg 1989:1). Springenschmid (1998) mentions that the first testing laboratory machine for cracking was developed in 1969 to carry out sample testes.

The purpose of this paper is to examine the causes and effects of thermal cracks in concrete structure, with some significant solutions for this problem. Non-common words will be defined firstly. The main causes of thermal cracks then will be presented, with a focus on thermal stresses. Also, the effects of thermal crack will be showed with some common solutions and evaluations for the problem. However, this treatise does not contain design ways for the solutions. Since the thermal cracks are become rife in most concrete structures, it is felt that this examination will underline some areas that are important to be taken into consideration when any concrete structures are constructed.

1. Definitions:

i- **Crack:**

American Concrete Institute ACI (2000:116R-19) defines crack as a whole or partial split of concrete resulted by breaking according to stress.

ii-**Pozzolan:**

It is defined as a siliceous or siliceous and aluminous material; it does not have Properties of cement, only it has very fine particles and chemically react with calcium hydroxide at normal temperature with presence of water as catalyst to form a substance that has cementitious properties (Malhotra and Mehta 1996:2).

iii- **Concrete creep:**

Creep in concrete is defined as the change in shape or the displacement of any concrete structure due to a stress or pressure, usually this will be in the same direction of the force that is generated by the stress (Soft Technologies 2010).

iv- **Mass concrete:**

American Concrete Institute ACI (2000:116R-16) define mass concrete 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".

v- **Aggregate:**

In this project aggregate means ‘construction aggregate’ which is a wide group of granular material that includes relatively fine material and coarse material such as sand, gravel, crushed stone, slag and crushed old concrete. Aggregate is a major component of concrete mixture which gives a considerable strength to concrete (Yes Cape Verde 2012).

vi- **Liquid Nitrogen:**

Helmenstine (2012) defines Liquid Nitrogen as: “is nitrogen that is cold enough to exist in liquid form”.

vii- **Epoxy:**

Epoxy or epoxy resins “is a class of organic chemical bonding systems used in the preparation of special coatings or adhesives for concrete or as binders in epoxy-resin mortars and concretes” (American Concrete Institute ACI (2000:116R-25).

viii- **Modulus of Elasticity:**

American Concrete Institute ACI (2000:116R-39) defines Modulus of Elasticity as a ratio that is calculated by dividing the amount of pressure or stress applied to any material to the deformation or the strain that caused by the stress; sometimes is named as elastic modulus, Young’s modulus, and Young’s modulus of elasticity; denoted by the symbol (E).

2. Causes of Thermal Crack.

Thermal cracking is related to the high temperature that is emitted during the chemical reaction of the cement (Cement Hydration) and is the result of increasing and decreasing the dimension of a concrete section during heat emission and cooling (concrete curing) the concrete section (Bamforth 2007:17).

According to the concrete section, this type of crack happens during different periods of time, for mass concrete sections need more time with compare to the normal concrete section (Bamforth 2007:41).

When the process of cement hydration occurs, the heat that is produced at the beginning will be more than the heat losses of the concrete (Bamforth 2007:41). The effect of this makes an internal stress that tries to make an expansion in the concrete section (Bamforth 2007:41). After a period, the process inverts because the rate of heat generation reduces, at the same time the heat losses are relatively increased, the effect of this it leads to shrinkage of concrete section (Bamforth 2007:41). These two different situations in an unrestrained section are happened without any effects, but practically any concrete section is restrained fully or partially (Emborge 1989:7). This means the concrete section is exposed to two different forces, which are different in value and direction. Also, Emborg (1989:7) and Bamforth (2007:41) are mentioned that if the characteristics and mechanical behaviour of the concrete (which represented by Modulus of Elasticity) remain constant during the hydration process this differential expansion and contraction will not occur.

As well as the main cause that explained above, there are some factors that contribute to make the problem worst. These factors can be summarized as follows (Bamforth 2007):

- Ratio of cement in the concrete mixture.
- Type of cement.
- Other materials used in concrete and the type of mixing
- The surrounding temperature during casting concrete.
- Type of temperature control.
- The dimension of the concrete section, the degree of restrain and the sequence of casting
- Type of formwork.
- Some estimated factors that use for design purpose.

It is clearly that both Bamforth (2007:41) and Emborg (1989:7) agree in that the main causes of thermal crack are the stresses that produce during the process of hydration. Also they are in agreement that if the Modulus of Elasticity of concrete remains constant as well as free restrains concrete section the thermal cracks will not occur.

3. Methods of Determine Thermal Stresses.

As indicated in the previous section, the main causes of thermal cracks are the stresses that generated in the concrete sections. In this section will emphasize on the main causes, which are the thermal stresses, and methods of determination.

1- Simplified approaches and rate of creep method.

Emborg (1989:40) stats that a considerable difficulty to understand a whole evaluation of thermal stresses and cracking, with regard to all possible effects. Therefore, the analysis of thermal stresses and the prophecy of thermal cracking have to be simplified (Emborg 1989:40). As a result, most of design codes have considered only the effect of concrete creep (Emborg 1989:40).

As mentioned before, the temperature is on of the factors that affects on cracking as well as thermal stress. Therefore, Emborg (1989::40) and Bamforth (2007:34) agree that the difference between casting temperature and ambient have not to exceed 20 degree centigrade. For more clarification, it is important to compare the restricted tensile strain with the tensile strain capacity of concrete (Emborg 1989:40). Consequently, the minimum tensile strain for fully restrained concrete section calculated by the following equation (Bernander 1973, 1980 cited in Emborg 1989:41):

$\varepsilon^{+} (t) = \Delta T (t1) [\alpha_c - \alpha_e (1\text{-}K1)] + \alpha_c \Delta T0$

Where:

$\varepsilon^{+} (t)$: is the tensile strain.

α_c and α_e : are coefficients of thermal expansion and contraction respectively.

ΔT (t1): is the difference between placing temperature and temperatures of adjoining structures.

K1: is a factor expressing the relation between the viscoplastic compression and total thermal expansion at the time of maximum temperature (i.e. a factor expressing the relaxation of concrete).

The above equation is a simple method for estimating the risks of thermal cracking. Harrison [(1981) cited in Emborg (1998:184)] gives similar equations for determining the risks of thermal crack with more simplification and related to the restriction of the concrete section. Emborg (1989:41) indicates that the accurate data is not available in terms of early-age behaviour or restrained conditions in most concrete structure yet. Also, Bernander and Gustafsson [(1981) cited in Emborg (1989:42)] develop a theoretical type of equation for analyzing thermal stresses by the rate of creep and the modulus of elasticity of concrete.

2- Superposition of thermal stresses and rate type formulation.

The use of fundament of this method is a way to evaluating the thermal stresses (Emborg 1989:42). van Breguel [(1980,1982) cited in Emborg 1989] establishes an equation for early-age repose based on the principle of this method.

3-In situ measurement of thermal stresses.

The measurement of thermal stresses in field is difficult and has various problems (Emborg 1989:45); such as the gauges that use for reading the stresses have not be affected by the stresses of other structures that contacted with the new one. Also, Emborg (1989:45) says that the gauges, for accurate result, must have the same or very close modulus of elasticity and thermal expansion coefficient as the concrete. This practically can not be obtained or achieved. Further, the unwanted stresses in the gauges that produced during the curing process must be recovered (Emborg 1989:45). Although, the problems that mentioned this method of measurement is continuously used (Emborg 1989:45).

Emborg (1989:42) former experiments, which based on first and second methods, finds that the principle of the second method has more accuracy results compare with the first method. However, some tests based on this method might have inaccurate results because the principle of this method is inadequate for evaluating of large structure with finite element method, which is an analyzing method (Emborg 1989:43). Therefore, with finite element method the equations based on principle of superposition should be transformed to basic equations (Emborg 1989:43).

4. Effect or Result of Thermal Crack.

Generally speaking, cracks are the result of fatigue for any element. The first effect of thermal crack in concrete structure, like any other types of cracking, is normally a visible problem (The Pennsylvania State University 2008). Ghali and Faver (1994:344) are named this problem as “aesthetic appearance”. When Engineers, builders and even people see cracks in any structure, they will have a negative notion about the structure (The Pennsylvania State University 2008). Furthermore, reaching water and air to steel bars that use for reinforcement is another effect because these two elements are the main factors of causing corrosion, which is the result of chemical decomposition of steel (The Pennsylvania State University 2008) and it is a serious problem that engineers try to avoid it. However, Ghali and Faver (1994:343) claim that the width of crack has not a serious effect on a significant corrosion in steel reinforcement. As well as the negative notion and corrosion, when water move into the cracks, in cold weather condition, could generate a stress due to freezing (The Pennsylvania State University 2008). Consequently, the width of the cracks becomes wider. In addition, Ghali and Faver (1994:343) indicate that cracks can be a good nest for developing microbes.

Although, Ghali and Faver (1994), and The Pennsylvania State University (2008) are in agreement to most of the effects of cracking but it seems that Ghali and Faver (1994) claims different view in terms of crack width effect on corrosion.

5. Solution of Thermal Crack Problem.

5-1. Solution by Reducing the Causes of Thermal Crack.

In order to reduce the effect of any problem, the causes of the problem must be determined. As in previous sections these causes are represented. The most common reducing factors can be indicated as follows:

1- One of the ways is controlling the effects of concrete component in terms of property and ratio. Which can be illustrated as follows:

   a- Aggregate, which is the large proportion of concrete mixture, with a low coefficient of thermal expansion, reduces the thermal expansion of the concrete (Springenschmid and Breitenbucher 1998:43). Furthermore, the shape of the aggregate has a main influence on thermal crack because the use of non-smooth surface aggregate leads to high tensile strength in concrete, which helps reducing cracks (Springenschmid et al. 1998:45). Also, using the maximum allowable aggregate size in concrete contributes to high tensile strength (Springenschmid et al. 1998:45). As well as type, shape and size of aggregate, the ratio of it also reduces the problem because the maximum allowable proportion of aggregate, which is indicated by design of concrete mixture, help to reduce the ratio of cement in the mixture, which is another factor to reduce cracks (Springenschmid et al. 1998:45).

b- Cement, which is the main ingredient in concrete mixture, with relatively low ratio theoretically causes little hydration, which means less heat generation. However, this is unusual practically (Springenschmid et al. 1998:45). In stead of using low ratio of cement to reduce the problem, different types of cement, with different chemical components, are used (Springenschmid et al. 1998:45). Furthermore, using fly ash, with a proper ratio in concrete mixture, reduces the ratio of cement, (Bamforth 2007:41). As well as using various type of cement and adding fly ash, Emborg (1989:2) suggests adding Pozzolans to concrete mixture in order to decrease the ratio of cement.

It seems that Springenschmid et al. (1998), Bamforth (2007:41) and Emborg (1989:2) suggest different idea to reduce thermal crack in terms of controlling the effects of concrete component but their ideas have the same aim, although, Springenschmid et al. (1998:45) emphasizes on aggregate more than the others.

2- Temperature is another factor that can be controlled to reduce the problem. Rising in temperature assists the chemical reaction of the cement. Hydration already produces high temperature. For solving this, there are many ways to reduce the temperature of concrete mixture, which represent by:

a- One of the most common ways is using cold water in concrete mixture and cooling aggregate (Mihashi, H., Nishiyama, N., Kobayashi, T. &

Hanada, M. 2002 cited in Bentz, D. P. 2009:III-12). Similarly, Bamforth (2007:90) believes that the cheapest way to reduce the temperature of concrete mixture is cooling the concrete mixture component. Bamforth (2007:90), for the reason that aggregate is the large proportion of concrete, adds that the cooling of it will have a considerable effect to reduce concrete temperature. This can be achieved by inundating the aggregate in cold water, drizzling it by water or blowing cold air through aggregate store (Bamforth 2007:90). Also, Emborg (1989:48) concurs with the idea that it is better to control the concrete temperature by cooling its components.

b- Another way to reduce the temperature is rained the concrete mixture by liquid nitrogen, which has a very low boiling point, before casting (Bamforth 2007:92). This technique specially is used before pouring when the pouring place relatively far from the concrete plant because during transferring the concrete temperature is increased by the process of hydration (Bamforth 2007:92).

c- The third process of reducing temperature is named by Emborg (1989:48) as "Post Cooling Technique", which is the way to ensure an immediate cooling for the section of concrete. This is achieved by laying a network pipe inside the concrete section and pumping cold water or any other cooling liquid to it. Whereas, Bamforth (2007:92-93) defines this way in two different technique. The first one is by cooling the outer face of framework, which is depend on the type of framework and not suitable for thick sections (thickness more than 500 millimeters); and the second, which Bamforth (2007:92-93) believes that it has more productive, is by using embedded pipes such as mentioned by Emborg (1989:48). In addition, Bamforth (2007:92-93) promotes plastic pipe to be use in this technique because it is a suitable conductive material among other materials. Emborg (1989:48) and Bamforth (2007:92-93) are in agreement with that the design process must consider the existence of pipelines.

3- Another way to reducing crack problem is reducing dimensions of the concrete structure by constructing joints. When concrete is poured in large dimension, such as construction of car park floor, airplane paths at airport or any other slab, cracks are occurred due to the internal restrain during thermal expansion. Simply, joints are already cracks but in a planned and geometric way (National Ready Mixed Concrete Association NRMCA 2011). Likewise, ACI (2000:318R-19) defines Contraction joint as ”Formed, sawed, or tooled groove in a concrete structure to create a weakened plane and regulate the location of cracking resulting from the dimensional change of different parts of the structure”. NRMCA (2011) divides joints to three types, which are “Isolation or Expansion joints, Contraction joints and Construction joints”. Whereas, Bamforth (2007) names the joints as “Expansion joints, Full or Free Contraction joints and Partial Contraction joints”.

5-2. Solution by Using Common Methods.

1- Using reinforcement steel bar is the most common way to prevent the phenomenon of thermal cracks. Thermal crack in concrete can be reduced or controlled by laying a suitable layer of steel bars, especially for thin concrete sections (Bernarder 1998:307). Bernarder (1998:307) adds that the reinforcement is usually laid as 10 millimeters bar diameter every 30 centimeters center to center of the bars (space between bars is measured from centre to centre of the bars), which means (3.33 square centimeters per each meter length). Further, Bernarder (1998:307) says that this number does not surpass (6 to 10 cm^2/m). Whereas, ACI (2000:318R-75) recommends minimum ratio of total steel bars area in any concrete section to the area of same concrete section must not be less than (0.0014).

2- As mentioned before, one of the problems of thermal crack, such as any other type of crack, is appearance problem. When the cracks are not having a structural problem, there is an easy and cheap way to solve the appearance problem (concrete network.com 2012). This is by inserting some special material to the crack space such as epoxy (concrete network.com 2012). Epoxy resin is one of the suitable grouting materials for crack maintenance (ACI 2000:503R-10). Also, ACI (2000:503R-10) recommends using epoxy as liquid for cracks (6 millimeters) wide and epoxy mortar must be used for wider cracks. As well as epoxy solve the appearance problem; also prevent the moisture reach the steel reinforcement, which is another problem that causes corrosion.

Conclusion

Thermal cracks are not only a simple crack in concrete structures but it is a serious problem that must be considered. This is because a considerable number of factors might be gradually increased or changed in future according to the situation of concrete structures. This treatise boosts the importance of having knowledge about the causes and effects of thermal cracks, and what are the ways to minimize the problem.

It can be concluded that the process of thermal crack is completely complex and there are many factors to be taken in consider avoiding thermal cracks when planning, designing and constructing any concrete structure. This is based on a considerable number of researches and tests that have been carrying out the last 50 years.

It is important to mention that there are other causes of thermal cracks problem that are not addressed in detail in this paper as well as many other solution because of narrowness of the treatise. Therefore, more researches can be done in this subject.

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