

# Thermal Deterioration of Wear Coat: A Paving Path to Corrosion of Concrete Structures



Engineering

KEYWORDS :

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## ABSTRACT

*Concrete structures such as bridges, runways and harbour decks etc., have been subjected to heavy vehicular traffic and the area exposed to such traffic are finished with a wear coat. As these concrete wear coats are open to atmosphere, they are subjected to heating during day time and to cooling during night. As a consequence of thermal cycles, thermal stresses are set up within the materials leading to the cracking of wear coat. These cracks reaching the interface of wear coat and the base concrete, serve as a paving path to all the aggressive species to accumulate and concentrate in it and at the interface, thus supplying the same to the base concrete and thereby initiating the corrosion. In this paper an attempt has been made to quantify the thermal stresses developed due to thermal stresses developed due to thermal swing and suitable remedial measures to overcome this this serious problem have been suggested.*

## INTRODUCTION

The purpose of providing a wear coat on exposed concrete surface is to provide protection to the structure beneath. The wear coat is normally a thin layer (2.5 to 50 mm) of plain concrete to offer protection to base concrete from heavy vehicular traffic, thermal deterioration and attack by aggressive species such as CO<sub>2</sub>, chlorides, sulphates etc. The base concrete structure may be of reinforced or pre-stressed type. The wear coat will be spread over several length and breadth with construction joints at some interval. The wear coat exposed to open atmosphere absorbs the heat from the radiating sun during the day and gradually cools down during night. As a result of this heating and cooling, the wear coat expands and contracts to sizeable amount. When such free elongation or contraction due to temperature swing is restrained, temperature stresses are set up within the material.

The wear coat is normally of ordinary Portland cement concrete which is a composite material consisting of cement paste (binder) and stone aggregates, whose thermal properties vary widely. Among the thermal properties of these materials such as thermal conductivity, thermal diffusivity, specific heat capacity, coefficient of linear thermal expansion, the last one determines the expansion and contraction of the material and the rest of the properties are used for computing the heat transfer through the concrete [1]. As there is a large difference between the values of linear thermal coefficient of expansion or contraction among cement paste and aggregates, differential expansion/contraction takes place within the concrete on exposure. This non-uniform expansion/contraction introduces the restrained stresses when the free elongation or contraction is prevented, and the nature of this stresses will be tensile. When this tensile stresses exceeds the tensile strength of concrete, cracking takes place. The cracks thus initiated will, however, propagate or grow as the concrete is exposed continuously to the environment [2]. Once the concrete (wear coat) is cracked the serviceability and durability is decreased or lost.

### Coefficient of thermal expansion/Contraction ( $\alpha$ ) of concrete

Coefficient of thermal expansion or contraction of a material ( $\alpha$ ) is a measure of quality, which represent the change in volume with temperature. Similar to most other materials, cement concrete also tends to

expand with the rise in temperature and contracts when the temperature falls down. This expansion or contraction varies in concrete with the amount of cement paste aggregates, water to cement ratio, temperature range, age of concrete and relative humidity of concrete (degree of saturation of concrete). Of these, the percentage of volume of cement paste and the aggregate is a very important factor that influence the expansion/contraction to a great extent [2].

The coefficient of thermal expansion/contraction of cement paste (binder) is many times more than that of stone aggregates used in concrete. Values of coefficient of thermal expansion/contraction may vary from  $10 \times 10^{-6} / ^\circ\text{C}$  to  $22 \times 10^{-6} / ^\circ\text{C}$  for cement paste and from  $3.5 \times 10^{-6} / ^\circ\text{C}$  to  $13 \times 10^{-6} / ^\circ\text{C}$  for stone aggregate [3].

Stone aggregates with higher quartz (SiO<sub>2</sub>) content such as quartzite, chert and sand stones have the highest coefficient of thermal expansion. Aggregates containing little or no quartz such as lime stone have the lowest coefficients, and the aggregates with medium quartz contents such as igneous rocks (granite, basalt etc.,) have intermediate values as shown in Table 1.

**Table 1 Average linear coefficient of thermal expansion values for different rocks and concrete (Within normal temperature range) [Ref.1]**

S.No	Types of Rock Material	Average linear coefficient of thermal expansion ( $\times 10^{-6} / ^\circ\text{C}$ )	
		Rock aggregate	Concrete
1	Quartzite, Cherts	11.2-12.8	12.1-13.0
2	Sand Stone	10.2-12.3	10.2-11.9
3	Quartz sands & gravels	10.0-12.3	11.0-16.0
4	Granites, Greisses	5.8-9.7	6.9-9.7
5	Diorite, Basalt	5.5-8.2	8.0-9.7
6	Lime stones	3.6-6.6	6.2-9.3
7	Marbles	4.0-7.1	4.2
8	Expanded slag	-	7.9-11.3
9	Blast furnace slag	-	9.3-10.8
10	Pumice	-	9.5-11.0
11	Perlite	-	7.7-11.9
12	Vermiculite	-	8.4-14.5
13	Limonite, Magnetite	-	8.4-11.0
14	Cellular concrete	-	9.1-12.8
15	Sulphur concrete	-	8.5

The coefficient of thermal expansion/contraction is found to vary from  $5.5 \times 10^{-6} / ^\circ\text{C}$  to  $14 \times 10^{-6} / ^\circ\text{C}$  for concrete, from  $6.6 \times 10^{-6}$

/ °C to  $11 \times 10^{-6}$  / °C for light weight concrete from  $10 \times 10^{-6}$  / °C to  $22 \times 10^{-6}$  / °C for cement paste and from  $7.9 \times 10^{-6}$  / °C to  $12.6 \times 10^{-6}$  / °C for cement mortars [2]. For structural steels thermal expansion is taken as  $11.1 \times 10^{-6}$  / °C [4].

**Estimation of Internal Stresses**

From the thermal expansion/contraction of concrete materials discussed above, it can be seen that the cement paste will show more elongation than aggregates on temperature increase of concrete. This free elongation of the cement paste is partially prevented by the aggregates present in the concrete, and as a result of this, restrained stress set up on the aggregates and the cement paste. This restraining stresses also causes elongation/contraction in the material in addition to the expansion/contraction caused by the temperature swing.

Let a concrete member of length 'l' is subjected to a temperature increase t °C. The net expansion of the member in the longitudinal direction is δl. The components of expansion of concrete materials due to this temperature increase can be written as follows.

Free elongation of aggregate due to increase in temperature =  $(\delta l)_t = l \alpha_a t$  ..... (1)

Free elongation of cement paste due to increase in temperature =  $(\delta l)_t = l \alpha_p t$  ..... (2)

Elongation of aggregate due to restrained stress =  $(\delta l)_\sigma = P_a l / A_a E_a$  ..... (3)

Contraction of cement paste due to restrained stress =  $(\delta l)_\sigma = P_p l / A_p E_p$  ..... (4)

$P_a$  and  $P_p$  are the axial restraining forces and they are equal in magnitude and opposite in nature and thus equilibrium is maintained.

$P_a = - P_p$  (or)  $P_a + P_p = 0$  ..... (5)

The net change in length of the cement member will be δl.

$\delta l =$  Free elongation of the aggregate due to temperature increase + Elongation of aggregate due to restrained stress.

Also,  $\delta l =$  Free elongation of the cement paste due to temperature increase - contraction of cement paste due to restrained stress.

$\delta l = (\delta l)_t + (\delta l)_\sigma$  and } ..... (6)

$\delta l = (\delta l)_t + (\delta l)_\sigma$  }

(or)  $(\delta l)_t - (\delta l)_t = (\delta l)_\sigma + (\delta l)_\sigma$  ..... (7)

Substituting the relevant values in eqn. (7) from equations 1 to 4,

$(l \alpha_p t) - (l \alpha_a t) = (P_p l / A_p E_p) + (P_a l / A_a E_a)$

$t (\alpha_p - \alpha_a) = P [(1 / A_p E_p) + 1 / A_a E_a]$  ( $P_p = P_a$ )

$P = [ (\alpha_p - \alpha_a) A_p E_p A_a E_a / A_p E_p + A_a E_a ] t$  ..... (8)

This is the restraining force developed within the concrete due to differential expansion of cement paste and aggregate. The corresponding stress in cement paste ( $\sigma_p$ ) and aggregate ( $\sigma_a$ ) can be written as,

$\sigma_p = \frac{P}{A_p} [ \frac{(\alpha_p - \alpha_a) A_a E_a E_p t}{A_p E_p + A_a E_a} ]$  ..... (9)

$\sigma_a = \frac{P}{A_a} [ \frac{(\alpha_p - \alpha_a) A_p E_p E_a t}{A_p E_p + A_a E_a} ]$  ..... (10)

**DISCUSSION**

While selecting the stone aggregate, care must be taken to select stronger aggregate than the harder one as the hardness of aggregate is not an absolute quantity to represent the strength of the aggregate. Stronger aggregates can be selected by studying the deformability characteristics which is given by Modulus of elasticity of the aggregate (Young's Modulus). This is the most important single factor that represent the strength of the material [2]. Table 2 shows the values of modulus of elasticity of some rocks normally used in concrete. Although the modulus of elasticity does not play any role towards stress development of change in temperature, the strength of the stone aggregate against cracking by tensile force is determined by the value of modulus of elasticity. For a good stone aggregate, the tensile strength will be about 2.5 N/mm<sup>2</sup> and the restrained stress developed should not exceed this value. The volume of paste and the stone aggregate present in concrete influence the stress development. In general 70 to 85 % of stone aggregates and 15 to 30 % of cement paste occupy the concrete. The volume of fine aggregate (sand) used in the concrete also has some influence on the thermal properties of concrete (Table 3). As sand content increases, the coefficient of thermal expansion decreases [2].

**Table 2 Modulus of Elasticity (Young's Modulus) of some common rocks [Ref. 5]**

S.No	Type of Rock	Modulus of Elasticity (N/mm <sup>2</sup> )
1.	Igneous rock	$0.50 \times 10^5 - 1 \times 10^5$
2.	Sedimentary rock	$0.25 \times 10^5 - 0.75 \times 10^5$
3.	Siliceous gravel	$0.60 \times 10^5$
4.	Portland cement	$10^5$

**Table 3 Influence of fine aggregate content on coefficient of linear thermal expansion [Ref.3]**

S.No	Cement to sand ratio	Linear coefficient of thermal expansion at the age of 2 years ( x 10 <sup>-6</sup> /°C)
1.	Neat cement	18.5
2.	1:1	13.5
3.	1:3	11.2
4.	1:6	10.1

When the stress developed in aggregate or in cement paste exceeds the interfacial bond strength of aggregate and cement paste, bond rupture takes place. Therefore, to increase the interfacial bond strength, proper aggregate grading is important and the aggregates must be angular in shape.

Use stronger stone aggregate than the harder one. Therefore, the selection of aggregate must be based on elastic modulus so as to offer enough tensile strength against restrained forces.

If aggregates are strong and the cement paste is weak, crack will pass through the cement paste. To increase the strength of the cement paste, fully hydrated and void free/dense cement paste must be achieved.

While selecting the materials for concrete, value of the coefficient, value of the coefficient of thermal expansion of cement paste and the stone aggregates must be almost equal or  $(\alpha_p - \alpha_a)$  must tend to zero. In other words  $(\alpha_p / \alpha_a) \approx 1$ .

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