CONTROL OF THERMAL AND SHRINKAGE CRACKING OF MASS CONCRETE IN HOT CLIMATE

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ABSTRACT

The aim of the present work is to study the possibility of controlling cracking due to differential temperature rise and differential shrinkage between surface and interior of mass concrete in hot climate.

The experimental work consisted of measuring temperature change with time on the surface and at various depths, within a mass concrete foundation of 850 cubic meters in a hot climate. Measurements of the concrete shrinkage were also taken.

The current understanding is that at a temperature difference of 20 C° between the core of mass concrete and its surface will cause cracking. In hot climate, higher temperature difference usually develops, and combined with shrinkage may cause development of wide cracks, even when precautions are taken, such as using low heat cement, large maximum size aggregate and low cement content.

The above understanding however is not applicable in all cases. It has been shown in an earlier work that concrete may be designed with a tensile strain capacity of up to 480 micro-strain, which is much higher than the values usually reported of between 100 and 200 micro-strain. Such concrete will tolerate a temperature difference much higher than 20 C° without cracking.

In the case of the present foundation such concrete was designed using the ACI method of mix design, small maximum size crushed coarse aggregate and relatively low W/C ratio. The placing temperature was lowered and plastic shrinkage cracking was prevented by covering concrete with polyethylene sheets immediately after finishing. Simultaneous occurrence of maximum temperature differential and high shrinkage differential was avoided by continuous water curing for 10 days after casting which, allows high creep to take place. As a result, a maximum temperature difference of 41 C° between the core of the mass concrete and its surface was recorded without cracking. However, 3 days after termination of water curing the maximum temperature difference decreased to 34 C°. This , combined with the shrinkage differential , lead to formation of small width cracks (not exceeding 0.15 mm) on the concrete surface. These cracks were considered to be acceptable for durability purposes.

الخلاصـــة

الهدف من البحث دراسة احتمالية السيطرة على الشقوق الناتجة عن تباين درجات الحرارة والانكماش بـــين لب الخرسانة الكتلية وسطحها الخارجي في الأجواء الحارة .

حيث تم خلال الدراسة قياس درجات الحرارة في أعماق مختلفة وكذلك قياس الانكماش على سطح خرسانة أساس كتلي بأوقات مختلفة . المعلومات المتوفرة في الأدبيات تشير الى ان تباين في درجة الحرارة بمقدار

٢٠مo بين لب الخرسانة الكتلية وسطحها يسبب فطور ولكن تبين خلال البحث أن هذا المفهوم لا يصح في جميع الاحوال حيث بالإمكان أن تصل قابلية التمدد في الشد للخرسانة بحدود ٤٨٠ (م٠ س) ٠تم تسجيل فرق في درجات الحرارة بمقدار ٤١ مo بين لب خرسانة أساس كتلي بحجم ٨٥٠ م ٣ من الخرسانة المسلحة والسطح دون حصول فطور عند استمرار الإنضاج ولكن بعد إيقاف الإنضاج وبفرق درجات حرارة بمقدار ٣٤ مo مع وجود الانكماش حصلت فطور بسمك ٠,١٥ ملم على سطح الخرسانة ٠

KEY WORDS
Shrinkage, thermal cracking, temperature differential, tensile strain capacity, creep, heat generation, cracks.□

INTRODUCTION

Numerous research works have been carried in the past on the problem of cracking of mass concrete due to temperature and shrinkage differentials between the core and the surface. In hot climate, the possibility of cracking on the surface of mass concrete is aggravated. This is because the placing temperature is usually high in hot climate. High temperature accelerates the rate of hydration of cement leading to a high rate of heat generation and high temperature differential between the mass concrete core and its surface. Furthermore, hot climate also accelerates the shrinkage on the surface of mass concrete. This also leads to a high shrinkage differential between the mass concrete core and its surface. Hence very high strain differential can accumulate at early age of concrete, which usually leads to the formation of wide cracks on the surface. Such cracks are undesirable because they adversely affect durability of concrete and reinforcement besides being unsightly.In mass reinforced concrete foundations cast in hot climate, especially that in contact with ground water or soil with high sulfate content, low W/C ratio and high strength are usually specified. This means high cement content, which further contributes to crack widening.
The present work is a study of the control of cracking of such a mass reinforced concrete foundation cast in the summer season in Baghdad.

Theoretical and Practical Considerations

Strain approach

It is thought that the strain approach is more convenient to use in the case of thermal and shrinkage cracking, because both are strain movements and they can be used directly in crack control problems (AL-Rawi 1985). This is in contrast to the stress approach where these movements have to be transformed to stresses, and several parameters have to be determined. There are however many difficulties in their determination e.g. the tensile strength of concrete is usually determined by the indirect Brazilian test. Clearly the rate of loading in this indirect test is faster than that encountered under restrained shrinkage or thermal movement conditions. The effect of the rate of loading on tensile strength of concrete is not clearly defined. The modulus of elasticity of concrete in tension must also be determined to transform the strains into stresses. The effect of age and of the rate of loading on the modulus of elasticity of concrete in tension is also not clearly defined. There is also no standard method for determination of relaxation in tension.
For these reasons it was decided to use the strain approach in earlier works (Al -Rawi 1985 , Al -Rawi 1990) and in the present study, as all needed parameters can be easily determined under conditions similar to those encountered in practice. These parameters include development of free shrinkage (Sh_{free}) or thermal strain, loss of restraint (L.O.R.) and restrained shrinkage with time (Sh_{rest}). They also include tensile strain capacity (T.S.C.), which is the restrained shrinkage at the time of cracking. Furthermore, they include the elastic tensile strain

capacity (E.T.S.C.), which is the drop in strain upon cracking. Finally they include creep of concrete in tension up to the time of cracking. The latter is defined as the difference between tensile strain capacity and elastic tensile strain capacity. A sketch of these parameters is shown in **Fig. (1)** which is presented for the first time . It may be pointed out here that in a later work (Al – Tamimi 1987) , it was shown that thermal cracking shows similar behavior to shrinkage cracking.
The above definitions may be written as follows:

$Sh_{(free)} = Sh_{(rest)} + L.O.R.$ (1)

At the time of cracking:
$T.S.C. = Sh_{(free)} - L.O.R.$ (2)

E.T.S.C. = Strain (just before cracking) – strain (just after cracking) (3)
i.e. change of strain upon cracking

Creep (in tension) = T.S.C – E.T.S.C (4)

Tensile Strain Capacity of Concrete

The values generally given in the literature for T.S.C. is between (100) micro-strain for quick loading and (200) micro-strain for slow loading (Neville 1995). For the case of mass concrete, (Fitz Gibbon 1976) suggested a limit of temperature differential of 20 C° between the core and the surface, above which cracking would occur. (European standard ENV 206 1997) has incorporated this value.
(Neville 1995) stated that for a temperature differential of 20 C°, taking the coefficient of thermal expansion of concrete as 10×10^{-6} per C°, the differential strain 200×10^{-6} He considered this as a realistic estimate of tensile strain at cracking time (i.e. tensile strain capacity). This does not seem to be correct because the differential strain in mass concrete is not the same as tensile strain capacity. This is because in mass concrete, at early age, the differential strain causes both tension on the surface and compression in the core; Hence the differential strain is much higher than the tensile strain capacity.These values of (T.S.C) , however, seem to be very low and this is probably because of adopting test methods that do not resemble field conditions because cracking was not effected by restrained shrinkage or thermal contraction of concrete. In an earlier experimental work (AL -Rawi 1985), it has been shown that under test conditions similar to these encountered in practice and adopting certain mix design considerably higher values of (T.S.C.) can be obtained (AL-Rawi 1985) .
A brief description of that work is given below:
Concrete beams were cast in I – shaped steel moulds with channel section, water curing was started at the age of one day and continued for three days at lab. temperature The beams still in their moulds were then transferred to a special room maintained at 35 ° C and at 35 % relative humidity so that relatively fast shrinkage of concrete takes place. The shrinkage of the web part of the beam was restrained by the flanges at its ends. Similar beams were cast with an opening at the center of the web. They were cured and maintained under the same conditions. Measurement of free shrinkage were taken on the latter beams.
The results showed considerable variation in the value of T.S.C. for a concrete mix designed according to ACI method of mix design (ACI 211.1 - 1991) with a W/C ratio = 0.5 and (10 mm) maximum size aggregate, the free shrinkage at the time of cracking, was 610 micro-strain. the loss of restraint was 130 micro-strain. i.e. the degree of restrained was 78.7 % . The restrained shrinkage at which cracking took place i.e. the T.S.C. was 480 micro-strain and the creep was 275 micro-

strain as shown in **Table (1).** These values called for a new look on the problem of shrinkage and thermal cracking of concrete.

Table (1) Tensile strain capacity and other properties of concrete mixes

Concrete mixes	Cracking time (days)	Free shrinkage (ms)	Loss of restraint (ms)	Tensile strain capacity (ms)	Elastic tensile strain capacity (ms)	Creep (ms)
Mix. 1 with a max. crushed aggregate size of 10 mm	10-11	610	130	480	205	275
Mix. 2 with a max. round aggregate size of 19 mm	4	260	60	200	140	60

Note :-
Mix. 1 proportions (0.5 :1 :2.2 :1.6 4) (water : cement : sand : coarse aggregate by weight)
Mix. 2 proportions (0.57 :1 :2: 4) (water : cement : sand : coarse aggregate by weight)

Design of Concrete Mixes with High Tensile Strain Capacity

The idea of designing concrete mixes with high tensile strain capacity in the present case is aimed at preventing cracking in mass concrete or minimizing crack widths. The main factors that increase tensile strain capacity are the use of relatively small maximum size crushed coarse aggregate, designing the mix according to ACI method of mix design (ACI 211.1 - 1991), use of low W/C ratio and prolonged water curing time. Water curing will delay shrinkage occurring on the mass concrete surface until after the maximum temperature differential between the core and the surface has passed i.e. there will be no concurrent maximum temperature differential and high shrinkage. This will delay or may even prevent cracking. This delay will give more time for concrete to creep leading to higher tensile strain capacity. Creep in this case will be enhanced by the high temperature usually developed in mass concrete and the high stress / strength ratio at the concrete surface. The stress is high due to the large temperature differential between the core and the surface while strength of the concrete at early age is relatively low.Furthermore, it has been shown in a recent work (Kammouna 2002) that creep is significantly enhanced if the concrete temperature is raised at the same time of load application as in the present case. Increasing creep strain, of course, will result in the same increase of tensile strain capacity of concrete. Previous literature recommends using large maximum size aggregate in mass concrete. Such use will reduce water requirement and for the same W/C ratio, lower cement content is required. This means lower shrinkage and lower temperature rise. Hence it is expected that cracking is reduced or eliminated. Cement content as low as 109 kg/m^3 were reported in mass concrete (Neville 1995) given a compression strength of 14 MPa on cylinders. This however is not always the case because large maximum size aggregate reduces T.S.C. (AL-Rawi 1985) . In many cases , high strength of concrete is required e.g. for concrete foundation in contact with soil or ground water with high sulfate concentration low W/C ratio (maximum 0.45) and high strength is specified (min 32 MPa). Furthermore, reinforcement detailing may not allow the use of large maximum size aggregate.

Use of Low Heat Cement (L .H .C .)

Low heat cement is often used in mass concrete. In this cement the ratio of C_3S / C_2S is lowered to less than unity. C_2S liberated about half the heat librated by C_3S upon hydration. Therefore low temperature difference between the core and the surface of mass concrete develops. This is usually considered to cause little or no cracking. However, this may be the case in cold humid climates, but it may not be the case in hot dry climates .This is because in the first case the concrete shrinkage is low and the temperature differential is the main cause of strain differential between the core and the surface of mass concrete. In the second case, however, the shrinkage is high and it is usually the main cause of the strain differential. It is known that the shrinkage of C_2S is about 3 times that of C_3S (Carlson 1938) and in mass concrete this will cause a large shrinkage on the surface which leads to a large increase in strain differential between the core and the surface. This increase may be more than the decrease in the strain differential due to lower heat generation. Therefore the use of L.H.C. may not have an advantage compared with S.R.P.C.Furthermore. For mass R.C foundations in contact with soil or ground water containing high sulfate content, S.R.P.C. is specified (ACI 201 2R 1992) as in the case of the present work. This cement has relatively low heat generation because of its low C_3A content. Shrinkage of concrete made with S.R.P.C. is also expected to be lower than that of L.H.C. because its C_3S / C_2S ratio is higher.

FIELD WORK

A mass concrete foundation consisting of some 850 m^3 of concrete was cast in the summer season in Baghdad. The foundation was 33 m long, 6 m width and with height varying from 3.5m to 5m. Crushed coarse aggregate with maximum size 20mm was used and both the coarse aggregate and the fine aggregate used satisfy the Iraqi specifications. The water used in the mix was drinking water. The concrete mix was designed according to the ACI method of mix design (ACI 211.1 1991). Because this concrete foundation is in contact with soil with more than 0.2% SO_4, the W/C ratio was fixed at 0.45 and S.R.P.C. was used. It physical and chemical characteristics are given in **Tables (3) and (4)** receptively. The cement content was 400 kg/m^3 of concrete, the coarse aggregate content was 1080 kg/m^3 and the fine aggregate content was 740 kg/m^3. This mix is expected to give relatively high tensile strain capacity of concrete. This is because of the use of relatively low content of small maximum size crushed aggregate and relatively high cement content. Furthermore the water curing period adopted was 10 days which is the maximum possible within the program of the work. Trial mix results show that the 28-days compressive strength of the concrete was 32 MPa. This is close to that required by the ACI code (ACI 201 2R 1992) for durability purpose in the present case.

Ten sets of thermocouples were fixed at certain points at different levels within the foundation prior to casting concrete (Salah 2001) as shown in **Table (2).** They were used for measuring concrete temperature variations with time at different locations .

The reinforcement consisted 25mm diameter bars at 150mm both ways on all six sides of the mass concrete. The internal reinforcement consisted of 16mm diameter bars at 750mm in the three dimensions. The concrete placing temperature was lowered by cooling the concrete ingredients prior to mixing and by adding ice to the concrete mix. Thus the maximum concrete placing temperature was kept in the range (25C ^{o} - 30C ^{o}) . Immediately after casting and finishing, the concrete was covered with polyethylene sheets to minimize water evaporation from its surface and also to minimizing the possibility of plastic shrinkage cracking. At the age one day , the polyethylene sheets were replaced by canvas sheets that were continuously wetted with water upto the age of 10 days. After that the concrete surface was exposed to air drying for 3 days . The sides forms consisted of steel frame and sheets in the lower part and up to 3m high, the higher part consisted of timber shuttering supported by a steel frame. These side forms were demoulded at the age of three weeks after casting concrete. The air temperature ranged from (15 C^o - 40 C^o) and the relative humidity was about 27% .

Table (2) locations of the thermocouples

Detectors number	X (m)	Y (m)	Z (m)
1	0.15	0.15	5.15
2	6.0	0.15	5.15
3	12.0	0.15	5.15
4	20	6.0	3.60
5	32.0	6.0	3.0
6	6.0	3.0	1.4
7	9.0	3.0	2.0
8	14.0	3.0	1.3
9	6.0	3.0	0.2
10	12.0	3.0	0.2

Table (3) Physical tests of cement

Test	Result	Iraqi specifications
Fineness	3150 cm^2/gm	≥ 2500 cm^2/gm
Setting time Initial Final	 2:00 hrs 4:10 hrs	 ≥ 45 minutes ≤ 10 hours
Compressive strength 3 days 7 days	 174 kg/cm^2 258 kg/cm^2	 ≥ 150 kg/cm^2 ≥ 230 kg/cm^2
Soundness(autoclave)	0.14%	≤ 0.8%

Table (4) Chemical tests of cement

Compounds	**Result**	**Iraqi specifications**
SiO_2	22 %	
CaO	62 %	
MgO	1.35 %	≤ 5.0 %
Fe_2O_3	5.48 %	
Al_2O_3	4.16 %	
SO_3	2.4 %	≤ 2.5 %
Loss on Ignition	1.42 %	≤ 4 %
Insoluble residue	1.07 %	≤ 1.5 %
Lime Saturation factor	0.86	(0.66 – 1.02)
C_3S	42.63%	
C_2S	31.2%	
C_3A	1.76%	≤ 3.5 %
C_4AF	16.7%	

RESULTS AND DISCUSIONS

Plastic Shrinkage Cracking

Close examination of the concrete surface the next day after casting showed that no plastic shrinkage cracking took place. This shows that the rate of water evaporation from the concrete surface was kept down to less than 1kg/h/m^2, which conforms to ACI requirements (ACI 305 R 1991). Prevention of plastic shrinkage cracks under hot weather conditions is very important because of their large widths (several mm) and depths. Such cracks may adversely affect the performance and durability of structure.

Temperature Measurements

Table (5) shows the thermocouples readings of concrete temperature at different locations for the first ten days after casting.

Table (5) Temperature variations at different locations with time

Location	Time after casting , days									
	1	2	3	4	5	6	7	8	9	10
1	36	37	40	38	36	35	35	34	32	32
2	38	39	41	39	37	36	36	35	34	32
3	34	37	40	37	36	35	35	35	34	33
4	38	39	41	38	36	35	35	34	33	33
5	35	37	40	37	37	35	35	34	32	32
6	50	56	65	76	76	72	69	69	69	68
7	51	53	57	72	72	68	66	66	65	63
8	48	50	55	61	68	60	60	61	60	60
9	45	50	56	54	54	50	50	51	49	49
10	47	52	53	54	54	50	50	51	48	49
Surface	32	35	40	36	35	32	32	33	31	32

Fig. (2) shows that the concrete surface temperature increased relatively slowly from (32 C°) at the first day to a maximum of (40 C°) at the age of 3 days. Then it decreased slowly to (32 C°) at the age of 10 days. The maximum temperature at the surface occurs before the maximum temperature at the core. This is to be expected because of the higher rate of heat dissipation from the surface compared with the core. This difference in the time of reaching the maximum temperature increases the maximum temperature differential between the core and the surface and this promotes the possibility of cracking. **Fig. (2)** also shows that the maximum temperature recorded at the core of the mass concrete foundation was (76 C°) . It was recorded at the age of five days after casting concrete. This maximum temperature occurred at the lower part of the concrete mass. This was expected because of the relatively low rate of heat dissipation to the earth below the foundation compared with heat dissipation from the top concrete surface to the surrounding air.

At the age of 5 days also, the maximum temperature differential between the core and the surface (41 C°) was recorded. After that the mass concrete core temperature started to decrease slowly with time. It reached (68 C°) at the age of 10 days. The temperature difference between the concrete core and its surface also started to decrease after five days. At the age of 10 days it reached (36 C°).

Temperature Differential and Strain Differential at Cracking

As stated earlier it was reported in previous literature that temperature differential above (20 C °) between the core and the surface is adequate to cause cracking on the surface of mass concrete. It was also reported that a strain differential between the core and the surface of the mass concrete of 200 micro-strain is a realistic estimate of the tensile strain of concrete at cracking (Neville 1995). An earlier work (Al-Rawi 1985) showed that very high values of T.S.C.of concrete can be obtained which means a strain differential considerably higher than (200 micro-strain) is needed to crack concrete . The results of the present work confirmed this idea as a recorded temperature differential (41C °)did not cause cracking of concrete . This corresponds to a strain differential of about (500) micro-strain . The actual temperature differential and strain differential are higher than these values because the surface temperature was measured at a depth of (5cm) from the surface . The temperature at the surface is of course much less than that at (5cm) depth . Furthermore the temperature measurements were taken in the day time and the surface temperature is less than at night while the core temperature is not affected much by ambient temperature variations . The above results are in sharp contrast with the prevailing literature as the present strain differential is more than two and half times that previously considered as a realistic value. Yet it did not cause cracking of concrete. This calls for a reconsideration of adopting a temperature differential of (20 C °) beyond which cracking will occur as in the (European standard ENV 206 1992) .The results of the present work confirm the idea of designing concrete with high tensile strain capacity by adopting certain requirements in the mix design and prolonging the water curing period as explained earlier . After termination of water curing and exposing the mass concrete to air drying for 3 days , very small cracks appeared on the top surface. The maximum width of the cracks was (0.15 mm) . These cracks appeared only between openings on the top surface i.e. in locations of stress concentration. No cracks appeared on the sides of the mass concrete because there are no openings and no stress concentrations. The widths of the cracks on the surface are so small such that they were considered as acceptable for both performance and durability of concrete. At the time of cracking the strain differential (strain between the core and the surface) exceeded that at the time of maximum temperature differential .The recorded temperature differential decreased to about (34 C °) which corresponds to a strain differential of about 415 (micro-strain) . The actual temperature differential is of course higher as pointed out above, and it may be around 465 (micro strain) . The 3 days shrinkage strain was about 250 micro-strain .Therefore the total strain differential is about 715 micro strain which is quite high compared with the 200 micro-strain adopted by (European standard ENV 206 1992) . The reasons for this large difference are pointed out above .Such large variations in the results show the need for the development of mathematical models for tensile strain capacity and related concrete properties .

CONCLUSIONS

1- Plastic shrinkage cracking in mass concrete in hot climate can be prevented by covering the surface with polyethylene sheets immediately after casting.
2- Lowering placing temperature could contribute to the prevention of cracking in mass concrete in hot climate.
3- For mass concrete cast in hot climate, S.R.P.C. may be preferred to L.H.C. because of the high shrinkage of the latter. This is specially important for foundations in contact with soil or water with high sulfate content.
4- Concrete could be designed to have a high tensile strain capacity by adopting the ACI method of mix design with relatively small maximum size crushed coarse aggregate, low W/C ratio and a prolonged water curing period.
5- In the present case, very high temperature differential (41 C °) was reached between the core and the surface of the mass concrete at the age of five days without cracking . This in contrast with previous literature, which gives (20 C°) as the maximum temperature differential of concrete

without cracking. This might be attributed to the high tensile strain capacity of the concrete in the present case.

6- When the above concrete was exposed to drying in air for 3 days (after water curing for 10 days) some small width cracks appeared in locations of high stress concentrations. Calculations show that the strain differential between the core and the surface of mass concrete in this case was above 700 micro-strain. This is clearly much higher than 200 micro-strain reported in previous literature. Again, this may be attributed to the development of high tensile strain capacity in the present case.

7- Because of the large variations in the tensile strain capacity and in the differential strain which causes cracking of concrete ,it is important to develop mathematical models for these characteristics.

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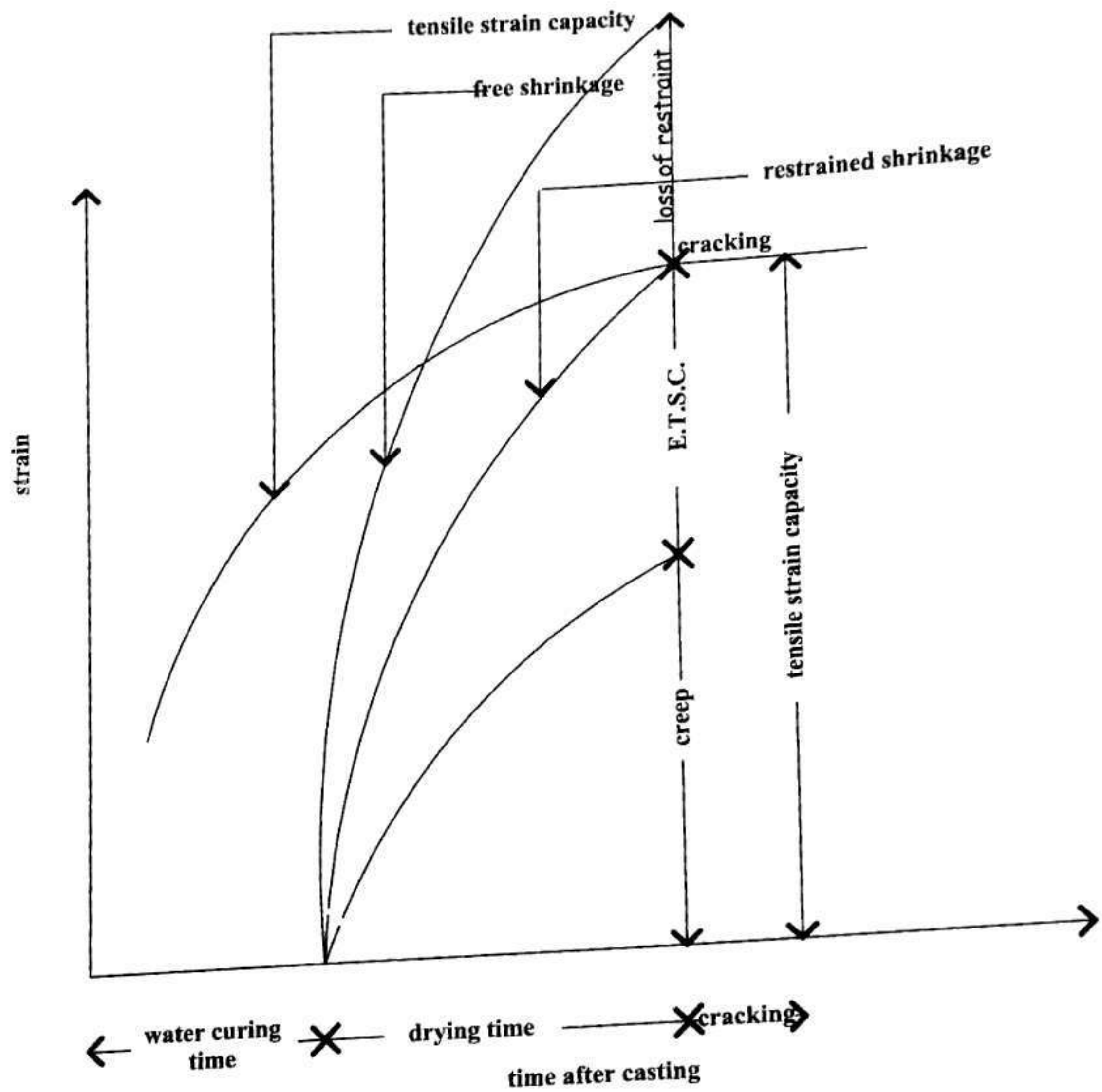

Fig. (1) Sketch of strain and crack development with time

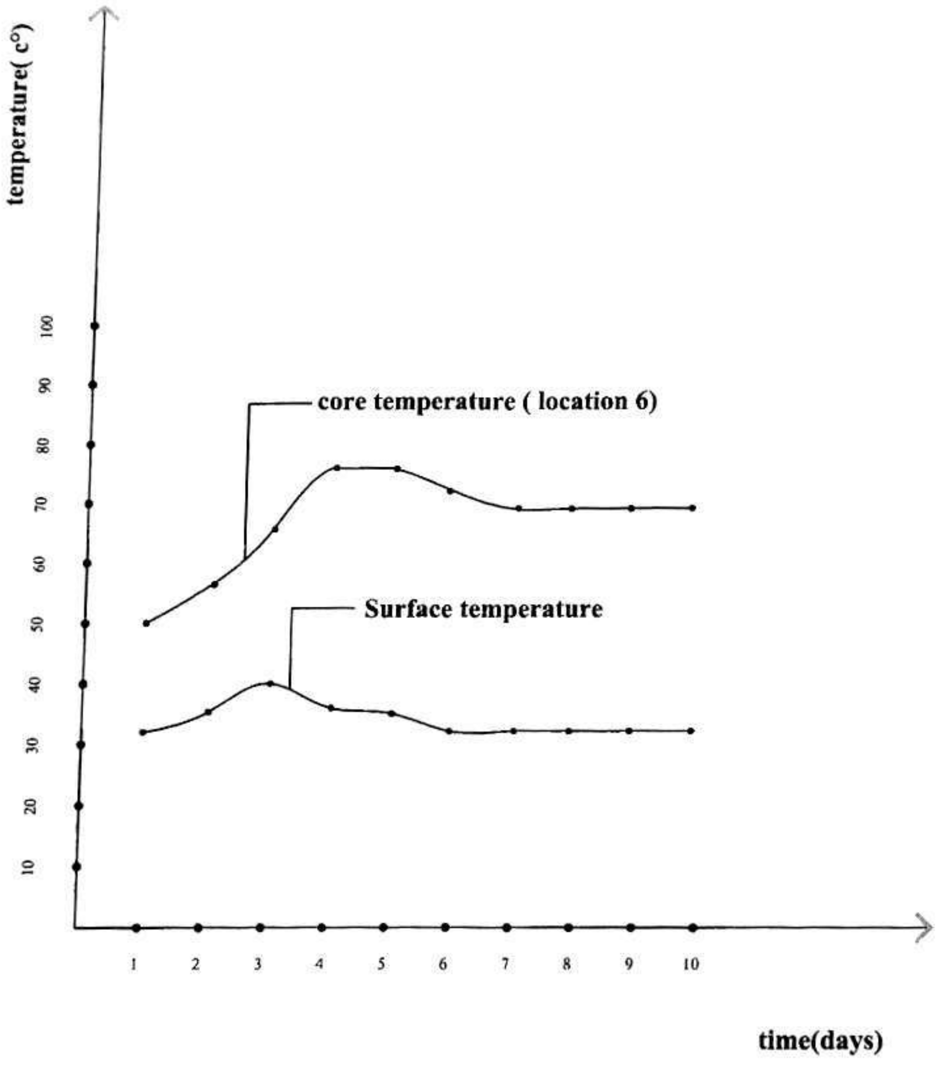

Fig. (2) Temperature variations at different locations with time