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# The Role of Dilation in Shrinkage Cracking of Concrete

Suhaila Mattar[1] and R.S. Al-Rawi [2]

[1] Daphne Jackson Fellow, School of Civil Engineering, University of Leeds, UK
[2] Professor of Civil Engineering, College of Engineering, University of Baghdad, Iraq

**Abstract:** The aim of this investigation was to study the role of dilation in delaying shrinkage cracking of concrete and the possibility of producing shrinkage crack-free concrete. The experimental programme consisted of two parts. In the first part, end-restrained concrete beams were water-cured for one and three days before drying under controlled temperature (35 ℃) and relative humidity (25%) conditions. In the second part, concrete beams were water-cured for one and three days before drying in outdoor summer conditions in Baghdad, Iraq. For all specimens, various parameters were measured, including free-shrinkage strain, tensile strain capacity, elastic tensile strain capacity, creep in tension and cracking time.

The experimental results show that none of the concrete specimens dried under natural outdoor conditions cracked in spite of high temperatures (up to 60 ℃) and low relative humidity (less than 15%). This is due to dilation in the form of increased creep in tension with variations in temperature and relative humidity. Increasing water-curing duration usually delays shrinkage and always delays or prevents cracking; it increases tensile strain capacity, which reduces the probability of cracking for all specimens dried in natural or controlled conditions.

**Keywords:** concrete, shrinkage, creep in tension, tensile strain capacity, dilation, end restrained shrinkage.

## Introduction

Dilation can be defined as a strain opposite to shrinkage and thermal contraction. It can be expected to prevent or delay cracking and to reduce crack widths. In 1986, Al-Rawi and Al-Qassab (1) found that the observed crack width is less than the calculated maximum crack width for reinforced concrete beams cast in I-shaped moulds and subjected to drying shrinkage conditions. Many other researchers (2,3,4) and practical cases (2) have shown that crack widths observed by microscope are less than those measured by demec points and calculated by equations. Salman (5) reported that concrete beams treated with gypsum and cured for 3 days did not exhibit any cracking under outdoor exposure conditions. He attributed this to the addition of gypsum, which led to expansion and development of compressive stress along the concrete beam due to restraint at the end of the beam supported by the flanges. As a result, lower tensile stress will develop in the concrete beam which is less than the tensile strength of concrete. Another reason is that water-curing results in an increase in the tensile strain capacity of the concrete. These two effects combine to minimize restrained shrinkage stress within the concrete beam, thus delaying or preventing cracking.

Adday (2) found the same results. He indicated that covering concrete with polyethylene sheets for one day after casting, then water-curing for one week in the laboratory prevented cracking, even though the concrete beam was highly restrained and subjected to high temperature and low relative humidity for long periods. This showed that under outdoor exposure conditions, the cracking tendency of large beams seemed to be very low and the probability of cracking much less than under laboratory conditions.

Al-Rawi and Salih (6) showed that in a study of a concrete mass (850 $m^3$), no shrinkage and thermal cracking takes place despite the fact that the temperature difference between the core and the surface of the concrete mass reached 41 $^oC$ and temperature cycles (daily rise and fall) on the surface of the concrete mass cause expansion at the surface due to repeated creep cycles (dilation), which reduces the possibility of cracking.

The above-cited studies (2,5,6) conflict with the prevailing conclusion in the literature, which is that subjecting concrete to high temperatures and low relative humidity increases the probability of cracking due to increased drying shrinkage, as the beams subjected to drying in outdoor exposure conditions in the summer in Iraq did not show any cracking. This may be because the large variation in temperature and relative humidity between day and night increased creep in tension, which could be more than the increase in shrinkage. Therefore, the probability of shrinkage or thermal cracking decreases. The fact that creep increases with fluctuations in temperature and relative humidity has been studied by Al-Rawi and Kammouna (7).

Given the findings in the studies cited above (1,2,3,4,5,6,7), the term "dilation" of concrete is defined in this project to include factors that delay or prevent shrinkage or thermal cracking of concrete. These factors are:

i. Water (moisture) movement caused by water-curing concrete before drying.

ii. Increased creep of concrete in tension due to temperature fluctuations.

## Experimental Work

### *Concrete Mixes*

Four concrete mixes were designed according to ACI 211.1–91. The slump was chosen to be 100 mm for all mixes. Trial mixes were made, and slump testing was carried out according to ASTM.C143/C143M-05a to ensure the desired workability. Adjustments then were made to the calculated properties. Table 1 shows details of concrete mixes employed in this study. Mixes then were cast in special moulds and vibrated and trowelled to obtain an even surface.

**Table 1. Details of concrete mixes.**

| Mix | Mix proportion (by wt.) | Water/cement (by wt.) | Cement (kg/m$^3$) | Sand (kg/m$^3$) | Coarse aggregate (kg/m$^3$) | Water content (kg/m$^3$) |
|---|---|---|---|---|---|---|
| A | 1:2.8:3.64 | 0.75 | 288 | 791 | 1020 | 216 |
| B | 1:2.06:2.93 | 0.62 | 350 | 720 | 1020 | 216 |
| C | 1:1.74:2.66 | 0.55 | 400 | 667 | 1020 | 216 |
| D | 1:1.32:2.18 | 0.48 | 520 | 637 | 1020 | 216 |

### *Moulds*

Moulds used were made of a steel channel section fabricated into I-shapes, as shown in Figure 1. Concrete was cast into them and subjected to drying shrinkage restrained by the flanges (8). Naturally, the restraint is not complete, and some contraction of concrete will take place. The mould is designed such that this contraction is relatively small, and the restrained shrinkage induces cracking across the web of the beam. Shallow mould depth enables fast drying, without significant differential shrinkage. To minimize friction between the steel mould and the concrete, the web part of the mould is greased and lined with a sheet of polyethylene.

For each mix, three moulds were cast and then dried, either in a room with controlled temperature and relative humidity, or exposed to the weather outdoors. For each mix, one of the three moulds was cast with an artificial opening in the middle of the web to allow determination of free shrinkage, and the two others were used for the restrained shrinkage test.

Note: Each specimen was given a set of letters and numbers to describe it.

A, B, C, D: Concrete mixes shown in Table 1; i: indoor exposure conditions; o: outdoor exposure conditions; 1 and 3: water-curing durations.

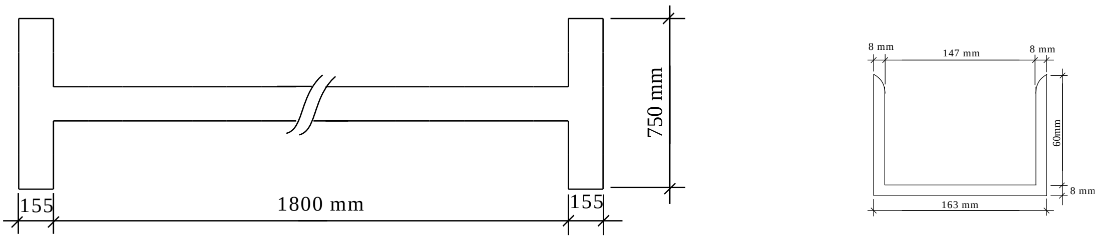

**Figure 1. I-Shaped mould (not to scale).**

## Curing and Exposure

Generally, the surface was covered with polyethylene sheets for 24 hours to prevent plastic shrinkage cracking. Curing was effected by covering the concrete beam with canvas sheets wetted with water for the specified curing period. After curing, the concrete beams are left in the moulds to achieve restraint and dried either in a room with controlled temperature and relative humidity or outdoors, subjected to natural drying conditions. For those beams dried indoors, the temperature was constant at 35 °C ± 5 °C, and the relative humidity was 25% ± 2%.

## Free Shrinkage Strain Measurement

Free shrinkage was defined as the average strain over the length of the web of concrete beams. A diaphragm was introduced in the middle of the web prior to casting, dividing the beam into two halves. The diaphragm was removed the next day, leaving an artificial opening. This arrangement allowed free shrinkage to take place, as there was no restraint. demec points were fixed on either side of the artificial opening, 100 mm apart. The increase in gauge-length between these points was measured by demec extensometer when the beams were exposed to shrinkage conditions, with 100 mm in length in an accuracy of 0.002 mm/division, and it was taken as free shrinkage along the whole web length less the 100 mm distance between the demec points. This was based on the assumption that the coefficient of the thermal expansion of steel is approximately equal to that of concrete. The difference, if any, is usually not great, and in any case, it also exists in restrained shrinkage. The fact that free shrinkage strain was averaged over a fairly long length (1700 mm) minimized experimental errors.

## Restrained Shrinkage Strain Measurement

The restrained concrete beams were water-cured in the laboratory for the specified curing periods. During that period, demec points were fixed at 100 mm intervals on the surface along the centre of the web and on the steel moulds. Then the beams, still in their moulds, were transferred either to a room with controlled temperature and relative humidity or outdoors to dry. The concrete was allowed to shrink until either cracking occurred or until it reached a fairly stable state, and demec readings were taken continuously by a demec extensometer until the end of the test. Then, parameters were calculated, as described below.

### Loss of Restraint (LOR)

In most practical cases, full restraint does not exist, i.e., not all the shrinkage of concrete is restrained. This means that some movement of moulds takes place and leads to some loss of restraint. In the moulds used in the present study, loss of restraint was measured as the mean contraction of the steel mould or, alternatively, contraction in the web length of the beams at the time of cracking.

### Tensile Strain Capacity (TSC)

Tensile strain capacity was defined as the difference between the free shrinkage strain during cracking time and the strain due to loss of restraint.

$$TSC = Fsh - LOR \qquad (1)$$

where:

TSC = Tensile strain capacity (mlths).

Fsh = Free shrinkage strain (mlths).

LOR = Loss of restraint (mlths).

### *Elastic Tensile Strain Capacity (ETSC)*

This was defined as the observed free contraction of concrete at the onset of cracking. In the present study, this was found by measuring the change in the strain at either side of the crack at the onset of cracking. This means that the elastic tensile strain capacity is equal to the difference between the strain just before cracking and the strain just after cracking.

ETSC= Strain just before cracking – strain just after cracking (2)

### *Creep in Tension (Creep Prior to Cracking)*

Concrete was subjected to very high tensile stress prior to shrinkage cracking, and the stress/strength ratio might have been close to unity for a considerable period of time. Under these conditions, significant creep can take place. This is because creep is time-dependent and it increases sharply with the increase in stress/strength ratios. It also increases under the environmental conditions that promote drying. This phenomenon can be termed relaxation, because it takes place at a practically constant length and is effective in reducing tensile stress in the concrete. Relaxation can be viewed as increasing the tensile strain capacity of concrete and consequently reducing the possibility of cracking. In addition, it can decrease crack width. Creep in tension is defined as tensile strain capacity less elastic tensile strain capacity.

Creep in tension = TSC – ETSC (3)

### *Cracking Time*

Cracking time is defined as the number of days required for cracking to occur. Cracking time has received little attention in other research. It seems, however, that cracking time can be used as an index to compare the possibility of cracking of various mixes exposed to differing conditions.

## Results and Discussion

### *Free Shrinkage Results*

Figures 2–5 illustrate the effects of prolonged water-curing on free shrinkage of concrete specimens. In general, long-term shrinkage of concrete specimens that have been water-cured for three days and then subjected to drying is higher than shrinkage of those water-cured for one day. However, in the first few days, the shrinkage of specimens cured for one day is higher than those cured for three days. The reason for this is that specimens cured for three days absorb more water than those cured for one day. During the three days, there is expansion of specimens rather than shrinkage. After water-curing, when the concrete begins shrinking, it reaches its original length (zero expansion) within three to six days. After a few more days, the shrinkage of specimens cured for three days usually exceeds that of those cured for one day.

Figures 2–5 also show that drying conditions affect shrinkage. All specimens subjected to natural outdoor conditions have higher shrinkage than specimens dried in controlled temperatures and relative humidity indoors. The final (one-month) shrinkage values show the same trend, because the specimens subjected to natural outdoor conditions were exposed to maximum temperatures exceeding 60 $^{o}$C and relative humidity of less than 15%, in contrast to the moderate conditions of 35 $^{o}$C temperature and 25% relative humidity for specimens dried indoors.

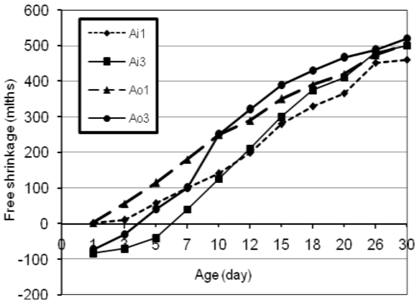

**Figure 2. Effect of water-curing duration and exposure conditions on free shrinkage development with age for concrete beams (mix A).**

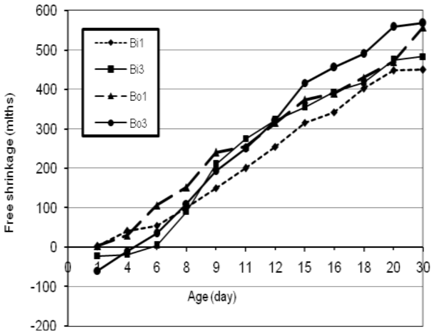

**Figure 3. Effect of water-curing duration and exposure conditions on free shrinkage development with age for concrete beams (mix B).**

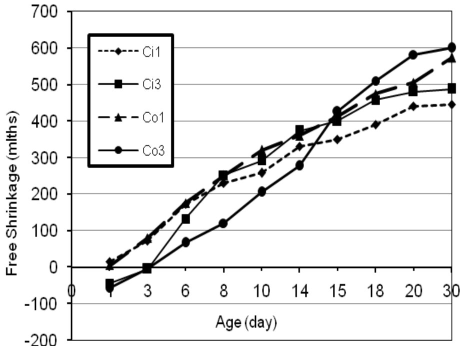

**Figure 4. Effect of water-curing duration and exposure conditions on free shrinkage development with age for concrete beams (mix C).**

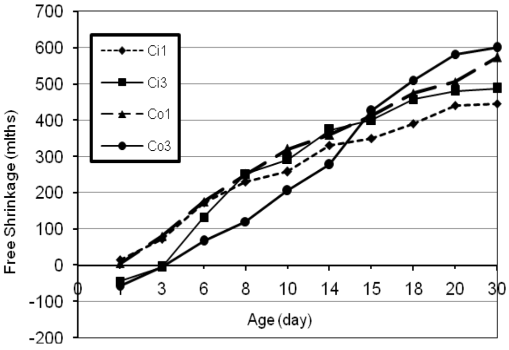

**Figure 5. Effect of water-curing duration and exposure conditions on free shrinkage development with age for concrete beams (mix D).**

## *Restrained Shrinkage Results*

### *Indoor Concrete Specimen Results*

Table 2 shows the restrained shrinkage results of indoor concrete specimens. Results show that prolonged water-curing increases the tensile strain capacity of the various mixes of concrete up to 47%. This is because the necessity for curing arises from the fact that the hydration of cement is greatly reduced when the relative humidity within the capillary pores drops below 80% (9). Furthermore, water lost internally by self-desiccation must be replaced by water from outside. Therefore, the quality of the concrete depends on the gel/space ratio of the paste. Greater hydration will lead to a higher-strength concrete. In addition, prolonged water-curing delays the advent of shrinkage and produce stronger concrete that is able to withstand a larger shrinkage without cracking.

Table 2 shows that the trend of elastic tensile strain capacity is similar to that of tensile strain capacity, because the same factors affect them both. The elastic tensile strain capacity of concrete specimens cured for three days was not measured, because no cracks occurred in these specimens. Creep strain of concrete subjected to restrained shrinkage is the difference between tensile strain capacity and elastic tensile strain capacity. This has been ignored by some researchers , while others have attributed to it as much as 75% of free shrinkage. The results of Al-Rawi (8) show that the creep strain is quite significant and therefore must not be ignored.

Table 2 shows the creep values of concrete specimens water-cured for one day before drying. In general, creep increases with increased cracking time, and factors that increase cracking time also increase creep strain. Its value, however, depends to a large extent on test conditions. The creep of specimens water-cured for three days was not measured because the increase in curing time delays shrinkage and prevents cracking. This gives enough time to develop creep, which means higher creep than the specimens water-cured for one day.

Cracking time is defined as the number of days required for cracking to occur; it can be used as an index to compare the possibility of cracking of various mixes. Table 6 shows the cracking time of concrete exposed to indoor drying conditions after being water-cured for one day.

The reduction in water/cement ratio results in earlier shrinkage cracking, in spite of increased tensile strain capacity. This is consistent with increased drying shrinkage (rapid drying shrinkage does not allow relief of stress by creep and leads to cracking). This trend confirmed results reported by Al-Ali (4), who showed that the cracking tendency of concrete (cracking age) was affected by the mix richness; concrete with a higher cement content suffered a higher cracking tendency (earlier cracking age). Shah and Weiss (10) found that the reduction in water/cement ratio decreased cracking time. They explained this as a result of increased total shrinkage, decreased stress relaxation and increased brittleness and stiffness.

Table 2 shows that prolonged water-curing prevents cracking of concrete. Drying the specimens for 30 days resulted in no cracks in specimens water-cured for three days. Figures 2–5 show that shrinkage in specimens water-cured for three days exceeds that of those cured for one day. At the same time, water-curing increases concrete strength and tensile strain capacity.

This shows as incorrect the supposition that the higher the shrinkage of concrete, the higher the probability of cracking, because it ignores the possible increase in tensile strain capacity, as in the present case. In addition, the literature calls for low shrinkage of concrete to avoid shrinkage cracking, but this is not always correct, as the present results show that higher shrinkage leads to less probability of cracking.

**Table 2. Results of indoor concrete specimens.**

| Specimen notation | Cracking time (day) | Free shrinkage (mlths) | Loss of restraint (mlths) | Tensile strain capacity (mlths) | Elastic tensile strain capacity (mlths) | Creep (mlths) |
|---|---|---|---|---|---|---|
| Ai1 | 18 | 330 | 30 | 300 | 178 | 122 |
| Ai3 | No cracking | 500 | 70 | >430 | --- | --- |
| Bi1 | 17 | 344 | 34 | 310 | 189 | 121 |
| Bi3 | No cracking | 483 | 45 | >438 | ----- | --- |
| Ci1 | 13 | 331 | 20 | 311 | 200 | 105 |
| Ci3 | No cracking | 487 | 30 | >457 | --- | ---- |
| Di1 | 11 | 350 | 20 | 330 | 266 | 64 |
| Di3 | No cracking | 510 | 40 | >470 | ---- | ----- |

## *Outdoor Concrete Specimen Results*

Restrained shrinkage movements were measured for outdoor specimens cast for one month in the summer (July and August) in Iraq without any cracking. After 30 days, the specimens (water-cured for one day) were artificially cracked to measure the properties, as shown in Table 3.

Table 3 show the tensile strain capacity of outdoor specimens, which exhibit the same trends as indoor specimens. The tensile strain capacity of concrete increases with increased cement content. Longer water curing increases the tensile strain capacity of concrete specimens more than 6.0%, as illustrated in Table 3. This, as discussed previously, is because prolonged curing delays the advent of shrinkage and produces stronger concrete, which is able to withstand greater shrinkage without cracking.

The tensile strain capacity measured in outdoor specimens was greater than that of indoor specimens, and the increase in tensile strain capacity reached more than 75%. This is expected, because outdoor temperatures reached more than 60 °C, which means faster development of strength (accelerated curing), which means faster development of tensile strain capacity.

Generally, the tensile strength capacity of concrete achieved much higher values than those reported in the literatures, which generally are 100–200 mlths. Tensile strength capacity values found in the present work were more than 597 mlths. None of the specimens exposed to outdoor conditions cracked. The researcher cracked those specimens water–cured for one day at 30 days of age and then measured the elastic tensile strain at the time of cracking. Table 3 shows the elastic tensile strain capacity for cracked mortar and for the uncracked specimens that were cracked by the researcher. This means that the values obtained for elastic tensile strength capacity are greater than the values reported here. The creep of outdoor specimens was measured as the difference between tensile strain capacity and elastic tensile strain. Creep was measured when the specimens were artificially cracked at 30 days of age. Table 3 shows that creep values are relatively high. They also are greater than the creep values of indoor specimens because of the longer cracking time (30 days). The creep developed during the 30 days period is higher than the creep of indoor specimens.

**Table 3. Results of outdoor concrete specimens**

| Specimen notation | Cracking time (day) | Free shrinkage (mlths) | Loss of restraint (mlths) | Tensile strain capacity (mlths) | Elastic tensile strain capacity (mlths) | Creep (mlths) | Average Temperature and R.H** |
|---|---|---|---|---|---|---|---|
| Ao1* | No cracking | 503 | 26 | 477 | 221 | 256 | Temp=65 °C<br>R.H=12% |
| Ao3 | No cracking | 520 | 30 | 490 | ---- | ---- | |
| Bo1* | No cracking | 557 | 33 | 524 | 277 | 247 | Temp=65 °C<br>R.H=12% |
| Bo3 | No cracking | 568 | 28 | 540 | ---- | ---- | |
| Co1* | No cracking | 588 | 43 | 545 | 292 | 253 | Temp=56 °C<br>R.H=17% |
| Co3 | No cracking | 600 | 42 | 558 | ---- | ---- | |
| Do1* | No cracking | 603 | 40 | 563 | 305 | 258 | Temp=56 °C<br>R.H=17% |
| Do3 | No cracking | 633 | 36 | 597 | ---- | ---- | |

* The specimens were artificially cracked at 30 days of age.
** These data were recorded by the researcher.

## *Results of Dilation*

The previous results show that dilation is associated with restrained drying shrinkage and is found in many forms. The effects of various factors on dilation are described below.

### *Effect of Water Curing*

It can be seen from the results of both indoor and outdoor specimens that prolonging water-curing to three days prevents cracking. This is because increased water-curing duration causes expansion, which also can be called dilation. Dilation due to water-curing reduces the probability of cracking. It can prevent cracking or at least decrease crack width. In this case, dilation delayed early shrinkage of specimens, and consequently, the cracking resistance of the concrete was increased because water-curing increases the strength of concrete. The tensile strain capacity increased so that shrinkage strains remained less than the tensile strain capacity, as shown in Figure 6. No crack occurred in any concrete specimen water-cured for three days.

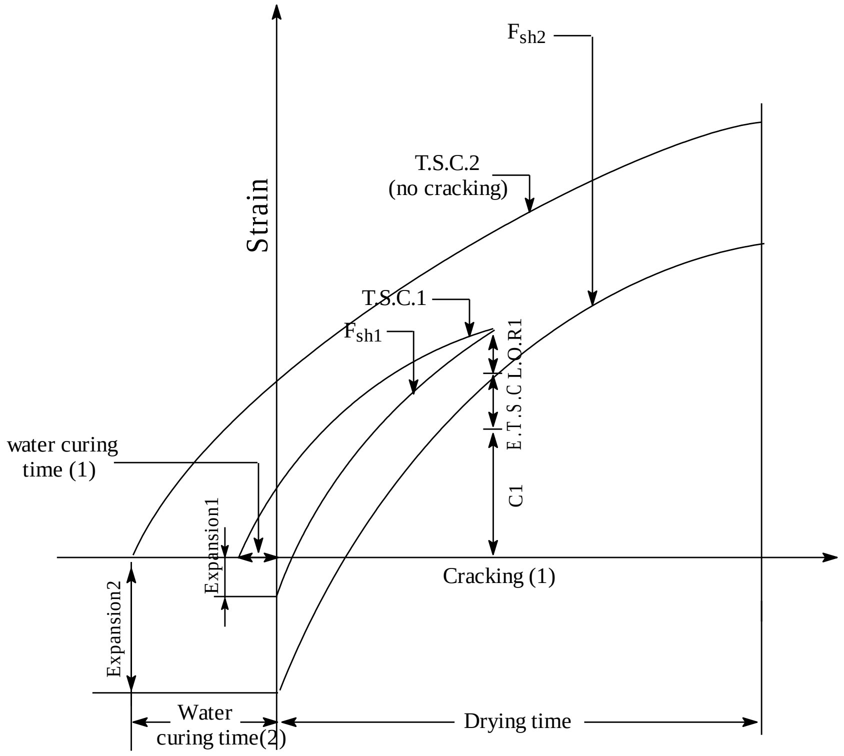

**Figure 6. A sketch of tensile strain capacity and related concrete parameters for various water-curing periods under outdoor exposure conditions.**

TSC$_1$: Tensile strain capacity for specimens water-cured one day.

F$_{sh1}$: Free shrinkage for specimens water-cured one day.

LOR$_1$: Loss of restraint for specimens water-cured one day.

ETSC$_1$: Elastic tensile strain capacity for specimens water-cured one day.

C$_1$: Creep for specimens water-cured one day.

TS$_2$: Tensile strain for specimens water-cured three days.

F$_{sh2}$: Free shrinkage for specimens water-cured three days.

Note: In outdoor exposure conditions, no cracking took place whether water-curing was for one day or three, i.e., in both cases curves (2) are applicable.

### *Effects of Fluctuations in Temperature and Relative Humidity*

Specimens subjected to outdoor exposure did not crack whether cured for one day or three. This means that other factors affect the cracking tendency of outdoor specimens. Results reported in Table 3 show the maximum and minimum temperature, average relative humidity and wind speed of exposure durations in summer in Baghdad. It can be seen that the change in temperature between day and night is more than 40 °C. The relative humidity ranged from 12% during the day to 23% at night in July and from 17% during the day to 28% at night in

August. These fluctuations in temperature and relative humidity led to higher rates and magnitude of creep, as shown in Figure 5, partially relieving the restrained shrinkage stress.

In this case, dilation occurs because of increased creep due to relatively large fluctuations in temperature and relative humidity. This agrees with the argument proposed by Al-Rawi and Kammouna (7), who claimed that the temperature rise increases the rate of creep, resulting in higher creep values. They found that changes in temperature and relative humidity from 21 °C and 50% to 42 °C and 23% caused a sudden increase in creep of approximately 280 mlths. The increased creep of concrete in tension with increased variation in temperature is attributed to the fact that the coefficient of thermal expansion of water is much higher than the coefficient of thermal expansion of concrete. Therefore, with increases in temperature, the water in concrete pores expands much more than the concrete. This causes pressure, leading to expansion of the concrete. With decreases in temperature, the water in concrete pores contracts but obviously does not lead to contraction of the concrete. Repeated heating and cooling of the concrete means repeated expansion, but no contraction, which means higher creep (transitional thermal creep) of the concrete in tension.

## Conclusions

The following conclusions can be drawn.

1- Concrete water-cured for three days after casting shows significant expansion. When such concrete is dried indoors for one month, it shows shrinkage higher than concrete water-cured for one day followed by one month of drying indoors. Concrete dried outdoors shows similar trends as concrete dried indoors, but it shows higher shrinkage due to higher temperatures (more than 60 °C) and lower relative humidity (less than 15%).

2- All specimens subjected to natural drying conditions outdoors have tensile strain capacity higher than the specimens dried in rooms with controlled temperature and relative humidity. This is because outdoor temperatures reached more than 60 °C, which causes faster development of strength (9), resulting in increased tensile strain capacity.

3- Prolonged water-curing increases the tensile strain capacity of various mixes of concrete, whether they are exposed to indoor or outdoor drying conditions. Specimens water-cured for three days gain greater strength during these three days, and higher tensile strain capacity is gained compared with specimens water-cured one day.

4- Prolonging water-curing to three days prevents cracking of concrete. Concrete specimens subjected to outdoor conditions did not crack whether water-cured for one day or three. This is due to the higher rate and magnitude of creep (dilation) and to partial relief of restrained shrinkage stress. This dilation occurs due to relatively large fluctuations in temperature, which cause higher creep, resulting in relief of tensile stress on the concrete and prevention of cracking.

5- Fluctuations in weather conditions between day and night in the summer in Iraq could be an advantage regarding shrinkage and thermal cracking of concrete. This is because such weather increases tensile creep significantly (up to more than four times the tensile creep achieved in steady moderate weather), thus increasing tensile strain capacity of the concrete by more than 46% and reducing the possibility of cracking.

6- Considerable savings in steel reinforcement of concrete can be made in fluctuating, hot, dry weather.

7- Magnitude of shrinkage is not the only factor affecting cracking of concrete. Tensile strain capacity, including dilation, is another factor.

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