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INFLUENCE OF NON-STANDARD CURING ON THE STRENGTH OF CONCRETE IN ARID AREAS

A. Arafah, R. Al-Zaid and M. Al-Haddad
Civil Engineering Department, College of Engineering, King Saud University, PO Box 800, Riyadh, Saudi Arabia.

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ABSTRACT

The influence of non-standard curing practice on the strengths of specimen and in-situ concrete is evaluated by experimental testing. Samples were collected randomly from construction sites distributed over two areas of distinct climatic conditions: 1) hot and dry (arid) climate, and 2) hot and moist coastal climate. The in-situ strength of concrete was evaluated by strength testing of cores taken from slab, beam, and column elements. The curing methods were simulated by water sprinkling twice a day for 7 days with and without burlap cover. The strength results for cubes and cores so cured indicate that curing employing water sprinkling, twice a day, and without burlap cover is far below the ACI-318 requirements. The results also indicate the need to account for the high variability of the strength ratio of field to standard cured concrete in the assessment of curing procedures specially in arid areas. It is recommended that the curing procedures shall be improved when strength of field cured cylinders is less than 85 percent of that of companion laboratory-cured cylinders in coastal humid areas and 75 percent in arid areas.

Background

The temperature of concrete, as placed, is affected by the surrounding air, absorption of solar heat, heat of hydration of cement and initial temperature of materials. In the parlance of concrete technology, hot weather is defined as any combination of high air temperature, low relative humidity, and wind velocity [1]. The effects of hot weather are most critical during periods of rising temperature or falling relative humidity, or both. The undesirable hot weather effects on concrete in the plastic state may include: (a) increased water demand, (b) increased rate of slump loss, (c) accelerated rate of setting and (d) increased tendency for plastic shrinkage cracking [1]. Thus, continuous curing, particularly during the first few hours, is acutely needed.

ACI 318 [2] and ACI 308 [3] recommend that concrete be maintained in a moist condition for at least the first 7 days after placement. Alternate cycles of wetting and drying promote the development of pattern cracking and should be avoided. Spears [4] indicated that proper curing maintains relative humidity above 80 percent and, thereby, advances hydration to the maximum attainable limit. Proper curing decreases concrete permeability, surface dusting, thermal-shock effects, scaling tendency and cracking. It ncreases strength development, abrasion resistance, durability, pozzolanic activity and weatherability. Haque [5] investigated the strength development of concrete under the conditions of fog, temperate dry, warm-wet and warm-dry weather conditions. He found that the lack of any moist curing adversely affects the compressive strength of plain concrete at all ages.

Martin [6] demonstrated that rising placing temperatures does not, as a rule, lead to lower strengths. With favourable combinations of cementitious materials and admixtures, the strength performance of concrete can remain unaffected by higher placing temperatures, or it can even improve over that at lower temperatures. Malvin and Odd [7] conducted a large-scale field investigation of high-strength light-weight concrete and concluded that maximum curing temperatures of up to 85°C (153°F) did not adversely affect the mechanical properties of the concrete. On the contrary, they observed a slight increase in compressive strength at age of 10 days.

Khan and Ayers [8] quantified the effect of interrupted curing. They found that the losses in strength of concrete due to an interruption in moist curing can be regained significantly by recuring the concrete.

Carrier [9] indicated that a short period of drying early in the curing life of concrete specimens prevents water molecules from reaching unhydrated cement particles and prevents concrete from gaining full strength. He also indicated that much of the concrete deterioration that takes place each year should be blamed on inadequate curing. Early and rapid drying can lead to shrinkage cracks, crazing, wear, dusting, scaling, and spalling. Once the surface has cracked, dusted, scaled or spalled, the entire member is more susceptible to other types of deterioration.

A mass of freshly mixed concrete as deposited in a form is usually honeycombed with entrapped air. Consolidation process is essential to remove the entrapped air and densify the concrete. The choice of the method depends upon the workability of the mix and the placing conditions. In developing countries, it is prevalent in small jobs to use rodding for concrete compaction. Curing of concrete by water sprinkling twice a day is also common [10].

Research Significance

High temperatures, up to 45°C, and low relative humidities with an average of 4.0% during summer are prevalent in some regions of the world including many countries in the Middle East [11]. Sub-standard procedures of curing are employed in some construction sites. This calls for studying the effects of these factors and their combinations on the strengths of concrete specimens and in-situ cocnrete.

Objective and Scope

The main objective of the study is to investigate the influence of the sub-standard curing practice, prevalent in some developing countries on the cube and in-situ strengths of concrete placed during hot and dry climate. The curing methods were simulated by water sprinkling with and without burlap cover twice a day and for 7 days. The sampling was done during two distinct periods of time, September to June, and July and August. The first period of ten months (the off-summer period) represents the average climate and the latter (the summer period) represents the extremes of summer climate in Saudi Arabia.

TABLE 1
Curing Methods Used and Their Designation

Designation	Curing method
SWC	Twice a day sprinkling without cover for seven days
SBC	Twice a day sprinkling with burlap cover for seven days
STD	ASTM C31 standard curing

Experimental Work

The experimental work comprises two parts. The first part evaluated the influence of sub-standard curing practices on the compressive strength of concrete specimens. Concrete samples were collected and cast into standard cubes of 150 × 150 × 150 mm from construction sites in two regions of Saudi Arabia representing hot and dry (arid) climate and hot and moist (coastal) climate.

During the off-summer period (September to June), 124 samples were collected from 62 construction sites, two trucks per site, in the two regions. Each sample consisted of three pairs of cubes taken from a ready mix concrete truck. The cubes were left at the site for about 24 hours and then transferred to the laboratory. One pair was cured by SWC, the second by SBC and the third by STD methods described in Table 1.

During the summer period (July and August), the number of samples collected from sites in the arid and coastal areas were 62 and 24, respectively. Each sample consisted of three pairs of cubes which were cured as specified in Table 1 and testedfor strength at the age of 28 days.

The second part of the experimental work investigated the influence of curing practices on the in-situ strength of concrete during the summer time in arid areas. Casting of concrete was done outdoors of the concrete laboratory during the summer period when the average outdoor temperature and relative humidity were about 42°C and 6% , respectively.

A total of 18 elements were cast. Six of them in upstanding position as columns, 6 in horizontal position as beams and the remaining were cast as slabs. The column and beam elements were 200 × 400 mm in section and 2 m long while the slabs were 1.0 m-square and 200 mm thick. Concrete of grade 35 MPa having a slump of 100 mm was used. Consolidation was accomplished by mechanical vibration with an ordinary flexible shaft vibrator. The concrete mix proportions are presented in Table 2.

TABLE 2
Mix Design of C35-Grade Concrete

Material	Batch Quantity /m^3
Cement (kg)	400
Water (Litre)	170
Aggregate, (20 mm) (kg)	640
Aggregate, (10 mm) (kg)	430
Fine Aggregate (kg)	720
Admixture, P509 (Litre)	1.0

TABLE 3
Basic Statistics of the Strength Ratios R_i for Specimens Tested in the Off-Summer Period

Climate (No. of specimens)	R	Mean	COV%	Pr ($R \leq 0.85$)
Hot and dry	R_1	0.84	12.6	0.54
(58)	R_2	0.93	9.80	0.20
Hot and Humid	R_1	0.92	4.95	0.10
(38)	R_2	1.00	3.20	0.0001

The different structural elements were divided into two groups of 9 specimens each. The first group was subjected to SWC while the second was subjected to SBC method of curing. At age of 28 days, five cores of 95 mm diameter and 200 mm length were obtained from each specimen and tested for strength. Cores were designated as C1 and C2 for SWC and SBC curing methods respectively.

Analysis and Discussion of Results

Effect of Curing on Cube Specimens. For the off-summer testing program, the ratios R_1 and R_2 of the strengths of the SWC and SBC cured specimens to those of the companion STD cured ones, respectively, are subjected to statistical analysis and plotted on normal probability forms along with the best fit normal distributions. Results are presented in Table 3.

Results of specimens from arid areas, hot and dry climate, are presented in Fig.1. The mean values of the ratios R_1 and R_2 are 0.84 and 0.93, respectively indicating the beneficial

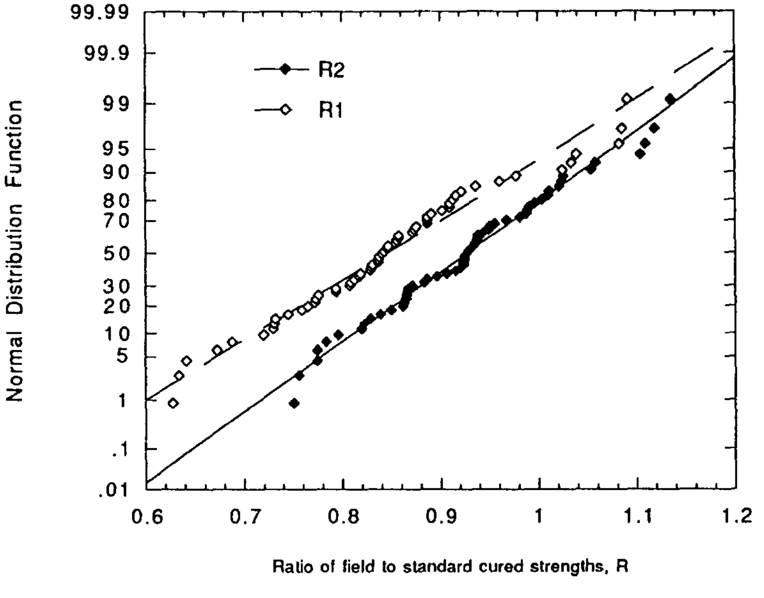

FIG. 1.
Influence of curing methods on concrete strength in arid areas during off-summer period. R1 and R2 relate to curing methods SWC and SBC respectively.

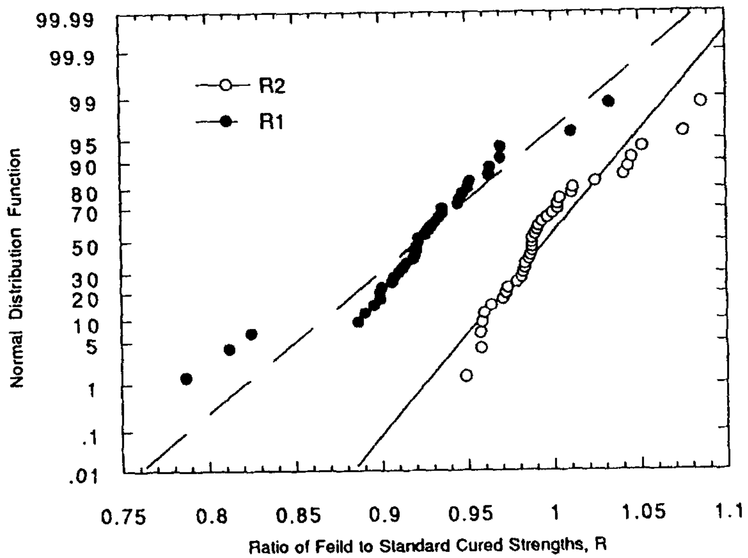

FIG. 2.

Influence of curing methods on concrete strength in coastal areas during off-summer period. R1 and R2 relate to curing methods SWC and SBC respectively.

effect of curing with burlap cover in dry weather. The COVs of R_1 and R_2 are 12.6 and 9.8 percent, respectively, indicating the effect of the burlap cover in reducing the strength variation. It is interesting to note that these ratios for some individual specimens were higher than unity which is attributed to the variabilities in the concrete strength and the curing process.

Results of specimens from the coastal area, hot and humid climate, are presented in Fig. 2. The mean values of the ratios R_1 and R_2 are 0.92 and 1.00 which are higher than the corresponding values in arid areas as shown in Table 3. The COVs of R_1 and R_2 are less than those observed in the arid areas. The results indicate the beneficial effect of a higher relative humidity on the 28 day strength.

In the summer period, the ratios R_1 and R_2 were evaluated in the arid climate. The results were subjected to statistical analysis and plotted on normal probability forms along with the best fit normal distributions as shown in Fig. 3. As shown in Table 4, the mean values of the ratios R_1 and R_2 are 0.88, and 0.98, respectively. These values are higher than those from off-summer period. The higher strength is attributable to the effect of high temperature in accelerating the rate of hydration and consequent gain in 28-day strength.

The results for specimens from the coastal area are also presented in Table 4 and plotted in Fig. 4. The mean values of the ratios R_1 and R_2 are 0.92 and 1.00 which are close to those obtained during the off-summer period and higher than those results obtained in arid areas.

The COVs of R_1 and R_2 in arid areas during the off-summer period were observed to be higher than those duirng the summer period. This is main attributed to high temperature variation during the long off-summer period (between 2°C and 40°C) compared with the short summer period. Fig. 5 presents the one standard deviation error bars for R_1 and R_2 under different climatic conditions.

ACI 318 [2] specifies that "procedures for protecting and curing concrete shall be improved when strength of field cured cylinders at test age designated for determination of f'_c is less than 85 percent of that of companion laboratory-cured cylinders. The 85 percent

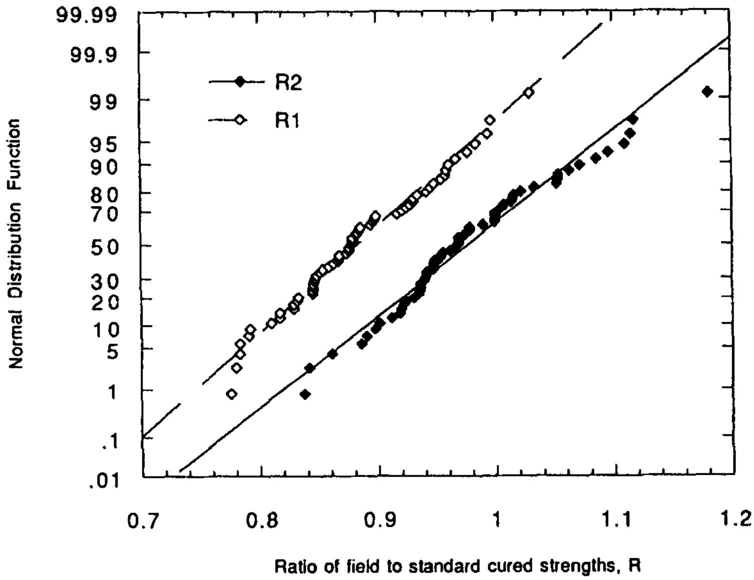

FIG. 3.
Influence of curing methods on concrete strength in arid areas during the summer period. R1 and R2 relate to curing methods SWC and SBC respectively.

limitation shall not apply if field-cured strength exceeds f'_c by more than 3.5 MPa". This criterion can be interpreted, from a statistical point of view, as that the ratio R shall be larger than 0.85 and the probability that this ratio being less than 0.85 shall not be more than 1 percent. For good curing practice, this probability will be less than 1 percent, however, the probability increases when poor practices are employed. The probability that the ratio R being less than 0.85 depends on its statistical characteristics, i.e., the values of mean and coefficient of variation and the type of distribution function.

Results, in all data sets, indicate that the mean values of R_1 are less than those of R_2 while the COVs of R_1 are higher than those of R_2. In the off-summer period, the probabilities that R_1 being less than 0.85 in arid areas and humid areas are 0.54 and 0.10, respectively. In summer period, these probabilities are 0.30 and 0.15, respectively. All of these values are higher than the acceptable probability of 0.01 indicating that the SWC curing method does not meet the ACI-318 requirement in both arid and coastal areas.

In the off-summer period, the probabilities that R_2 being less than 0.85 in the arid areas and coastal areas are about 0.20 and 0.00, respectively indicating the role of the ambient

TABLE 4
Basic Statistics of the Strength Ratios R_1 for Specimens Tested in the Summer Period

Climate (No. of specimens)	R	Mean	COV%	Pr ($R \leq 0.85$)
Hot and dry	R_1	0.88	6.92	0.30
(62)	R_2	0.98	6.90	0.05
Hot and humid	R_1	0.92	6.90	0.15
(21)	R_2	1.00	5.27	0.005

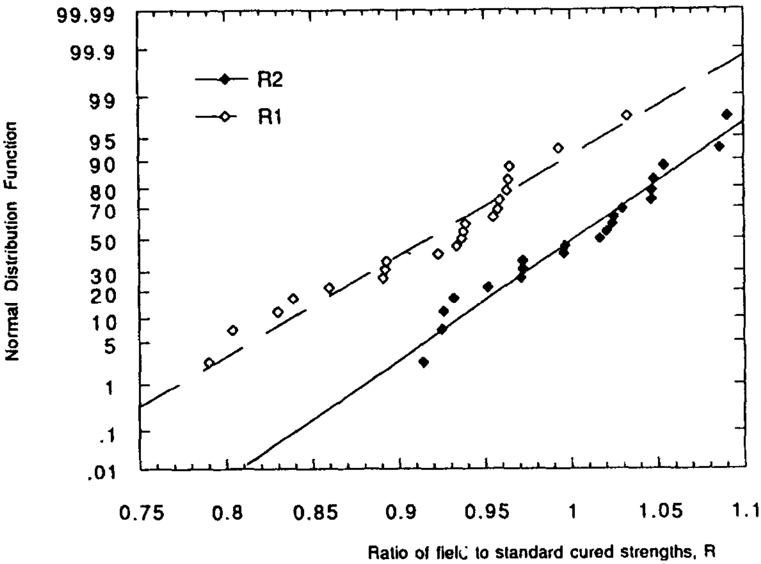

FIG. 4.
Influence of curing methods on concrete strength in coastal areas during summer period. R1 and R2 relate to curing methods SWC and SBC respectively.

relative humidity in improving the curing process. In summer period, these probabilities are 0.05 and 0.005, respectively. Thus SBC satisfies the ACI-318 requirements in coastal areas while it does not meet the requirements in arid areas.

Effect of Curing on In-Situ Strength. The 28-day compressive strengths of the cores C_1 and C_2 taken from column, beam and slab elements were subjected to statistical analysis plotted

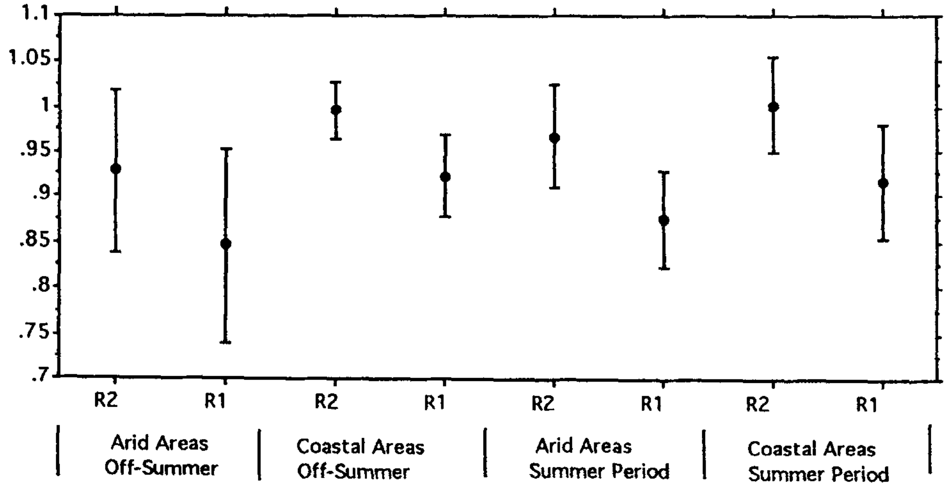

FIG. 5.
One standard deviation error bars for curing methods under different climatic conditions.

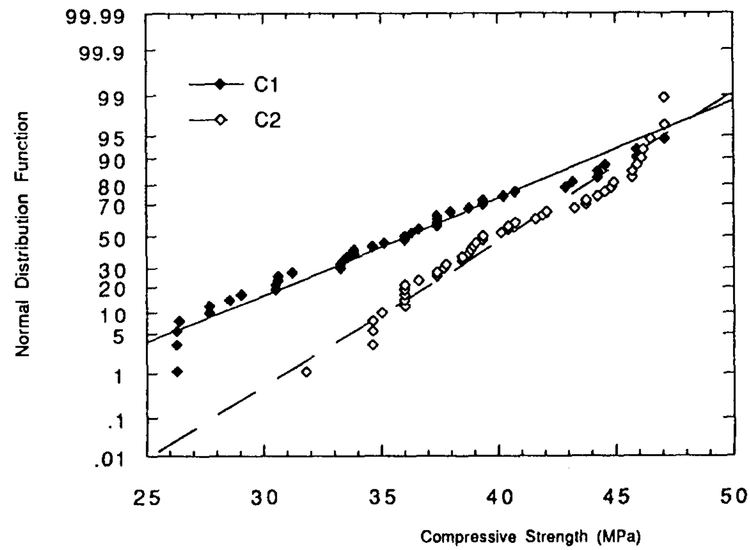

FIG. 6.
Variation of in-situ concrete strength as affected by curing methods. C1 and C2 relate to curing methods SWC and SBC respectively.

on normal probability forms as shown in Fig. 6. The nominal compressive strength is 35 MPa. The mean to nominal ratios, l, of the compressive strengths of C_1 and C_2 are 1.12 and 1.15, respectively. The average strength ratios of C_1 to C_2 is 0.97. The coefficients of variation of C_1 and C_2 are 17.48 and 9.27, respectively. Results indicate to the adverse effect of SWC on the mean and variation of in-situ concrete strength. These results are comparable with those obtained from cube specimens.

Plastic shrinkage cracks started developing in slabs cured with SWC within 2 hours of casting and incresed with time. Some of these cracks were 650 mm long and 120 mm deep. The cracks in slabs cured with SBC were fewer, shorter in length and depth. This is indicative of the beneficial effect of SBC curing in reducing the rate of moisture evaporation and reducing concrete cracking.

Proposed Criteria for Curing Efficiency. The ACI-318 criterion for concrete curing is found to be rational in assessing the efficiency of concrete curing in humid areas, however, there are two points which should be considered: (1) the criterion does not account for the climatic effect on the curing process. In arid areas, where water resources are limited, it is difficult and costly to attain the ACI criterion, and (2) the criterion states that the 85 percent limitation shall not apply if field-cured strength exceeds f'_c by more than 3.5 MPa which allows poor curing procedures if the concrete mix design is conservative. Good curing of concrete is important for several durability aspects as well as strength .

Results indicate that curing methods in arid areas (with low mean values and high COVs) should not be evaluated by the same criterion as in the humid areas. In arid areas SBC can be considered as a feasible method of concrete curing. The authors recommend that the ACI-318 minimum value of the ratio R should be reduced in arid areas. Fig. 7 indicates that, in arid areas and during the summer and off-summer periods, the ratio R_2 is well presented by a normal distribution with mean and COV of 0.95 and 8.8 percent, respectively. The value of

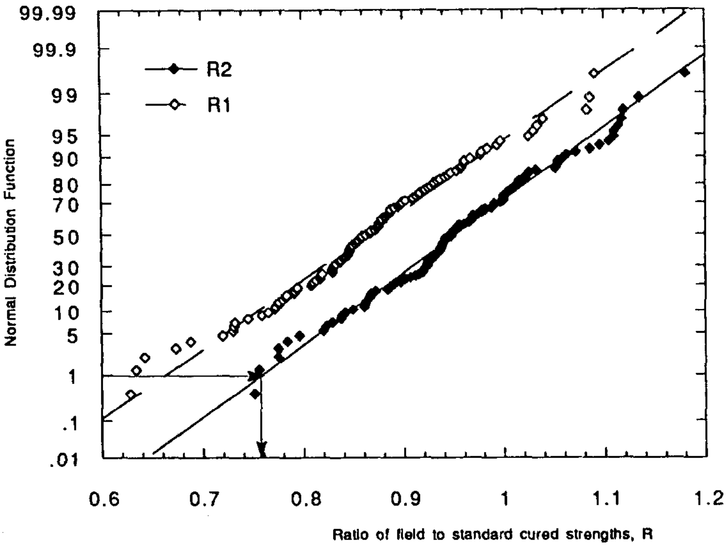

FIG. 7.

Influence of curing methods on concrete strength in arid areas. R1 and R2 relate to curing methods SWC and SBC respectively.

R_2 corresponding to one percent of the distribution function is about 0.75. This value is recommended to be considered in the evaluation of curing process in arid areas.

The proposed criterion for curing is stated as follows "procedures for protecting and curing concrete shall be improved when strength of field cured cylinders at test age designated for determination of f'_c is less than 85 percent of that of companion laboratory-cured cylinders in coastal humid areas and 75 percent in arid areas". To insure good curing the criterion shall not allow for less values of this ratio even when the mean strength of the field-cured specimens is higher than the nominal compressive strength.

Conclusions

The effect of non-standard curing practice is evaluated by statistical analysis of strength ratio of the field cured to that of the standard cured cubes. The field curing methods used were sprinkling with and without burlap cover twice a day for 7 days. The conclusions drawn from the study are as follows:

1. The results of the off-summer program in the arid area showed that the mean values of R_1 and R_2 corresponding to SWC and SBC curing methods are 0.84 and 0.93, respectively. The higher value of R_2 indicates the effectiveness of burlap cover during the curing process. The probability of having R_1 less than 0.85 (as specified by ACI-318) is 54 percent.
2. Higher values of R_1 and R_2 were observed in the coastal areas with high relative humidity.
3. The results of summer program conducted in the arid area yielded mean values of the ratios R_1 and R_2 of 0.88 and 0.98, respectively. The higher values of the ratios point to

the role of high temperature in accelerating the rate of the hydration process and consequently increasing the concrete compressive strength at 28 days.

4. The variations in the ratio R can be represented by the normal distribution function. The coefficient of variation of R_1 is higher than that of R_2 in all the cases.
5. The SWC curing method does not meet the ACI-318 requirement in both arid and coastal areas while SBC satisfies the ACI-318 requirements in coastal areas while it does not meet the requirements in arid areas.
6. Results from in-situ strength are comparable with those obtained from cube specimens.
7. In arid areas, where water resources are limited, the SBC method can be considered as a feasible method of concrete curing. the ACI-318 minimum value of the ratio R should be reduced to 0.75. The proposed modification accounts for the natural variation of the ratio R employing SBC method.
8. The criterion for assessing the efficiency of concrete curing shall not allow for ratios less than 0.85 and 0.75 in humid and arid areas, respectively, even when field-cured strength exceeds nominal strength by more than 3.5 MPa.

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