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Effect of Hot Climate on Shear Strength of Concrete

A.F. ABBASI AND A.J. AL-TAYYIB

Many construction projects are being carried out in countries known to have a hot climate during the major part of the year. High-temperature conditions create problems in preparation, placement, and curing of concrete and adversely affect the properties of concrete. Results are presented of tests on reinforced-concrete beams of different sizes prepared and cured at various temperatures; the tests were performed under both natural atmospheric conditions and controlled laboratory conditions. Tests have shown that even if the concrete mix is so designed to give the required compressive strength of concrete in high-temperature conditions, the shear strength of the concrete is still reduced by 7 to 20 percent in the temperature range of 90 to 113°F.

It is generally known that special problems are created when concreting is done in hot climatic conditions and that the quality of the concrete is adversely affected by high temperature during mixing, placing, and curing. Rapid evaporation of water at the time the hot ingredients are mixed occurs at high temperatures; this results in lower slump, which is generally restored by adding more water. This increased demand for water is considered to be largely responsible for the reduced strength of the concrete (1,2).

Furthermore, under high-temperature conditions cement sets faster, and it becomes difficult to compact and finish the concrete (3). The American Concrete Institute (ACI) Manual of Concrete Practice (4) gives the harmful effects of concreting under high-temperature conditions, and the necessary precautions to be taken in advance to minimize these effects are also given in various books and publications (1-5). In the construction specifications for regions with hot climates, it is required that the concrete temperature not exceed 90°F; hence either ice is added to reduce the temperature of the concrete or concreting is done in the evening when the atmospheric temperature is low enough so that the concrete can be prepared and placed at a temperature not exceeding 90°F. Sometimes it is impossible to avoid concreting under high-temperature conditions; precautions are then required, which not only are difficult to follow but add to the cost of the concrete. Even if the temperature of the concrete is lowered to 90°F or less and the workability is restored by adding the proper amount of extra water, the curing problem remains, because the process is to be carried out in hot weather for at least 7 days, preferably longer.

The compressive strength of concrete is the most important property for designing concrete structures. The shear, tensile, and bond strengths of concrete are expressed in terms of its compressive strength (6), which in turn is greatly influenced by the effective water/cement ratio. Although the extra quantity of water required at high temperatures can be estimated by using the information given in the ACI Manual of Concrete Practice (4), it

is difficult to do so accurately under changing atmospheric conditions; the result is that too much extra water is added, which yields a higher effective water/cement ratio and lower compressive strength.

Moreover, it must be emphasized that natural atmospheric conditions in a hot climate are different from controlled laboratory conditions, mainly because the atmospheric temperature does not remain constant throughout the day. The high-temperature conditions prevail for only a few hours during the middle of the day, whereas the temperature at night may even be lower than 86°F. Therefore, the test specimens must be cured at varying daily temperatures. This is perhaps one of the main reasons for the conflicting results obtained about the effect of high temperature on the compressive strength of concrete (3,5,7-11).

Tests conducted at the University of Petroleum and Minerals, Dhahran, Saudi Arabia (12), have shown that if just sufficient extra water is added to compensate for the loss caused by evaporation in high-temperature conditions, which keeps the effective water/cement ratio unchanged, and if curing of the concrete is done properly at varying daily temperatures, the compressive strength of the concrete is unaffected even at concrete temperatures as high as 113°F. On the other hand, even if the concrete temperature is lowered by taking necessary precautions, improper curing in hot climatic conditions results in lower concrete compressive strength.

Therefore, if a concrete mix could be so designed to give the specified compressive strength when the mix is prepared at the prevailing high temperature and in the curing conditions of the natural atmosphere, the other properties of concrete that are known to depend on the compressive strength, such as bond strength (development length), shear strength, modulus of rupture, and tensile (split-cylinder) strength, should remain unaffected. Tests on reinforced-concrete beams with varying lengths of embedment (13) have shown that when beams are prepared and cured in hot weather, a reduction in the bond between steel and concrete results. This reduced bond causes a reduction in the moment capacity of these beams compared with that of beams prepared and cured under normal laboratory conditions even if the moment capacity is computed by using the actual compressive strength of the concrete prepared under both conditions, which eliminates the effect of hot weather. Consequently, the following test program was carried out to determine the effect of hot weather on the shear strength of concrete.

TEST PROGRAM

Two series of specimens were prepared at different

temperatures and different mix proportions as described in the following.

Series I

Beams 5x5x25 cm reinforced with one 10-mm-diameter deformed bar in the tensile zone were prepared in the laboratory and tested over a simple span of 20 cm. The concrete temperatures at preparation and placement ranged from the normal laboratory temperature of 75° to 113°F. Curing of specimens prepared at higher temperatures was done in an oven with a 24-hr cycle of varying temperature. The specimens prepared at normal laboratory temperature were cured at the same constant temperature. For each temperature at which the mix was prepared, three beams were formed.

Three 2-in. cubes were also prepared from the same mix and cured in the same way as the beams to determine the compressive strength of the concrete and hence compute the nominal shear strength of the concrete according to the ACI code. In the concrete mixes for high-temperature specimens, an extra quantity of water was added to compensate for evaporation and hence get approximately the same kind of workable mix.

Series II

Beams 4x4.5x30 in. and 6x6x30 in. reinforced with two No. 4 deformed bars in the tensile zone were prepared and cured in the natural atmosphere in hot weather as well as at normal laboratory temperature and tested over a simple span of 24 in. The same mix proportions were used for all the specimens of this series, but an extra quantity of water was added to the mixes at high temperatures to compensate for the loss of water due to evaporation. Cylinders 3x6 in. were also prepared from the same mix and compacted and cured in the same way as the beams to determine the compressive strength of the concrete.

The specimens are described in Table 1, and the properties of the materials are given in Table 2.

Table 1. Description of specimens.

Specimen No.	Size (in.)	Effective Depth (in.)	Span (cm)	Concrete Temperature at Preparation (°F)	Type of Curing
Series I					
1	2x2x10	1.303	9	75	Inside laboratory
2	2x2x10	1.303	9	99	
3	2x2x10	1.303	9	102	
4	2x2x10	1.303	9	110	Inside oven
5	2x2x10	1.303	9	113	
6	2x2x10	1.303	9	75	
Series II					
1	4x4.5x30	3.5	24	75	Inside laboratory
2	6x6x30	5.0	24	91	
3	4x4.5x30	3.5	24	100	Outside in natural atmosphere
4	4x4.5x30	3.5	24	102	
5	4x4.5x30	3.5	24	111	

Note: $^{\circ}\text{F} = (^{\circ}\text{C} + 0.55) + 32$; 1 in. = 2.5 cm.

^aSize = b x h x L,

where

b = width of section,

h = overall depth of section,

d = effective depth of section, and

L = length of beam.

Table 2. Material properties.

Property	Series I	Series II
Cement	Type I	Type I
Water/cement ratio	0.55	0.54 to 0.59
Aggregate/cement ratio	4.0	3.0
Coarse aggregate		
Type	Limestone from Dhahran area	Limestone from Dhahran area
Percent passing		
3/8-in. to No. 4 sieve	70	40
3/4- to 3/8-in. sieve	-	50
No. 4 to No. 8 sieve	30	10
Fine aggregate		
Type	Dune sand near Halfmoon Beach	Dune sand near Halfmoon Beach
Fineness modulus	1.60	1.60
Ratio fine aggregate to coarse aggregate	2/3	2/3
Reinforcement		
No. of bars	One	Two
Diameter	0.39 in.	1/2 in.
Yield stress	55,300 psi	50,500 psi
Clear cover to bars	1/2 in.	3/4 in.
Relative humidity (%)	-	30-50

Note: 1 in. = 2.5 cm; 1 psi = 145 MPa.

Preparation of Specimens

Series I

The ingredients for all the specimens of this series were first mixed dry in the required proportions with a hand trowel. For the high-temperature specimens, the dry, mixed ingredients were put in an oven and heated to a temperature such that for different specimens different concrete temperatures were obtained after the specimens were mixed with water. The required amount of water was added to the dry mix and the ingredients were mixed thoroughly with a hand trowel for about 3 min until a uniform mix was obtained. The concrete temperature was noted after the ingredients were mixed. The beam and cube molds were then filled in three layers. Each layer was compacted by placing the molds on a small vibrating table. After the specimens were finished, the concrete temperature was again recorded. The average of the two temperatures was taken as the concrete temperature during the preparation of the specimens. The normal laboratory specimens were also prepared in the same way with all the ingredients at the normal laboratory temperature of 75°F. After being finished, the specimens were covered with thin polyethylene sheets; the normal-temperature specimens were left in the molds in the laboratory and the high-temperature specimens, in the oven; the oven temperature had been adjusted to the range 113° to 122°F. The specimens were removed from the molds after 18 to 24 hr.

Series II

The ingredients for the high-temperature specimens of series II were kept outside in the sun for about 3 hr to heat them before mixing. The materials for all the specimens were mixed for about 3 min in a portable mixer outside in the natural atmosphere in the early afternoon between 1:00 and 2:00 p.m. Concrete was placed in the molds in three layers and compacted by vibration on a vibrating table. The temperature of the concrete was recorded in the middle of the concreting operation. The normal-laboratory-temperature specimens were prepared in the same way inside the laboratory at about 75°F. After being finished, the specimens were covered with thin polyethylene sheets and left in the molds

at the casting place until removed from the molds on the next day. The relative humidity ranged between 30 and 50 percent during the period of the test program.

Curing of Specimens

All the specimens of series I were moist cured up to the age of 14 days by being kept in polyethylene bags containing water. For the remaining 14 days, the specimens were kept in air. The normal-laboratory-temperature specimens were cured in the laboratory at a constant temperature of about 75°F, whereas the high-temperature specimens were cured in an oven at daily varying temperatures as given in the next section.

All the specimens of series II were moist cured up to the age of 7 days and in air for 21 days in the same way as those of series I except that the high-temperature specimens were cured by being kept in the natural atmosphere instead of the oven.

Oven Temperatures

The high-temperature specimens of series I were cured in an oven at varying temperatures to simulate the temperature conditions in the natural atmosphere. The temperature of the oven was changed four times in a cycle of 24 hr, i.e., 8:00 to 11:00 a.m., 95° to 104°F; 11:00 a.m. to 5:00 p.m., 113° to 122°F; 5:00 to 8:00 p.m., 95° to 104°F; and 8:00 p.m. to 8:00 a.m. (the next day), laboratory temperature of 75°F.

Testing of Specimens

All the beams were tested at 28 days under a concentrated load at midspan. The typical diagonal tension failure occurred in the beams. The beams were tested in triplicate for each of the specimens of series I and in duplicate for series II. The compressive strength of the concrete was determined by testing three 2-in. cubes for series I, the corresponding cylinder strength being taken as 80 percent of the cube strength, and three 3x6-in. cylinders for series II.

TEST RESULTS

For all the specimens, the shear force at failure (V_u) was determined from the average of the load at failure (P_u) for each set of beams. The shear strength of the specimens (V_c) was calculated from the average compressive strength (f'_c) obtained for each set of three cubes or cylinders by using Equation (11-3) from the ACI code (6):

$$V_c = 2(f'_c)^{1/2}bd \quad (1)$$

where b is the width of the beam and d is the effective depth of the beam.

The ratio V_u/V_c was calculated for each specimen and compared with that of the corresponding normal-temperature specimen of each series to determine the effect of high temperature on shear strength of concrete. Table 3 gives a summary of the test results and comparison of shear strengths for all the specimens.

DISCUSSION OF TEST RESULTS

Because the compressive strength of concrete varied from specimen to specimen--the range was 3,000 to 5,000 psi--it was not possible to directly compare the experimentally determined shear strengths (V_u) of specimens at different temperatures. Hence to eliminate the effect of compressive strength, the ratios of V_u to V_c (the shear strength estimated as recommended by the ACI code) have been compared at different temperatures as shown in Figures 1 and 2 for series I and II, respectively. This has another advantage in that the effect of temperature on compressive strength is also eliminated because the actual compressive strength of concrete at different temperatures has been used in calculating V_c .

Figures 1 and 2 show that for both series of specimens, prepared and cured under the controlled laboratory conditions as well as in natural atmospheric conditions, the ratio V_u/V_c decreases with an increase in temperature. In order to compare the results of series I with those of series II and also to determine the percentage of reduction in shear strength at different temperatures, the ratios of V_u/V_c for each specimen to that of the corresponding specimen at normal laboratory temperature of 75°F

Table 3. Test data.

Specimen	Temperature of Concrete (°F)	Avg Compressive Strength of Concrete ^a (psi)	Avg Load at Failure ^b (lb)	Shear Force at Failure (lb)	Shear Strength (lb)	V_u/V_c	[(V_u/V_c) for Specimen at T_c °F] ÷ [(V_u/V_c) for Specimen at 75° F]	Reduction in Shear Strength (%)
Series I								
1	75	3,950	2,183	1,092	328	3.33	1.0	0
2	99	3,837	1,992	996	323	3.08	0.925	7.5
3	102	4,458	2,000	1,000	348	2.87	0.863	13.7
4	110	4,205	2,000	1,000	338	2.96	0.888	11.2
5	113	3,847	1,633	817	323	2.63	0.790	21.0
6	75	5,407	2,372	1,186	383	3.10	0.930	7.0
Series II								
1	75	5,411	8,770	4,385	2,060	2.13	1.0	0
2	91	5,022	16,580	8,290	4,252	1.95	0.915	8.5
3	100	5,000	7,550	3,775	1,980	1.91	0.897	10.3
4	102	4,607	6,970	3,485	1,900	1.83	0.859	14.1
5	111	2,928	5,763	2,881	1,618	1.78	0.836	16.4

Notes: Temperature of concrete, T_c ; average compressive strength of concrete, f'_c ; average load at failure, P_u ; shear force at failure, $V_u = P_u/2$; shear strength, $V_c = 2(f'_c)^{1/2}bd$.

$^{\circ}\text{F} = (^{\circ}\text{C} \div 0.55) + 32$.

1 psi = 145 MPa. 1 lb = 0.45 kg.

^a Average of three specimens for both series.

^b Average of three specimens for series I and two specimens for series II.

Figure 1. Comparison of shear strength of concrete at different temperatures: series I.

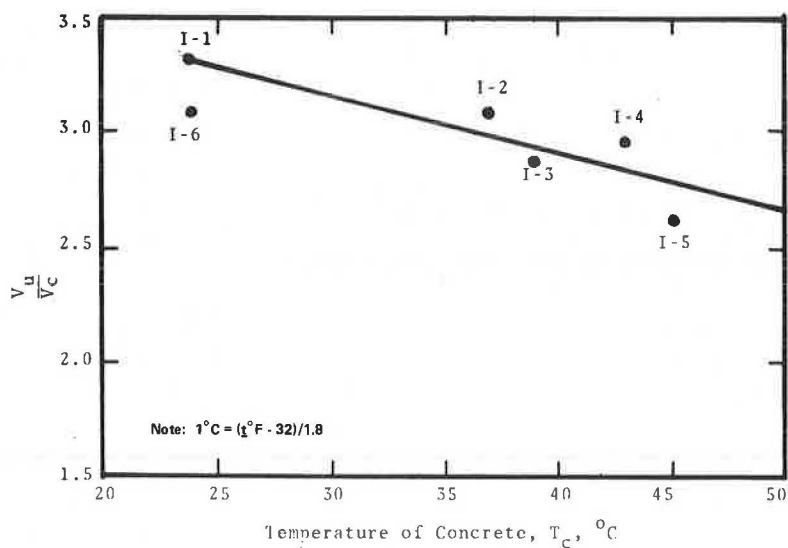


Figure 2. Comparison of shear strength of concrete at different temperatures: series II.

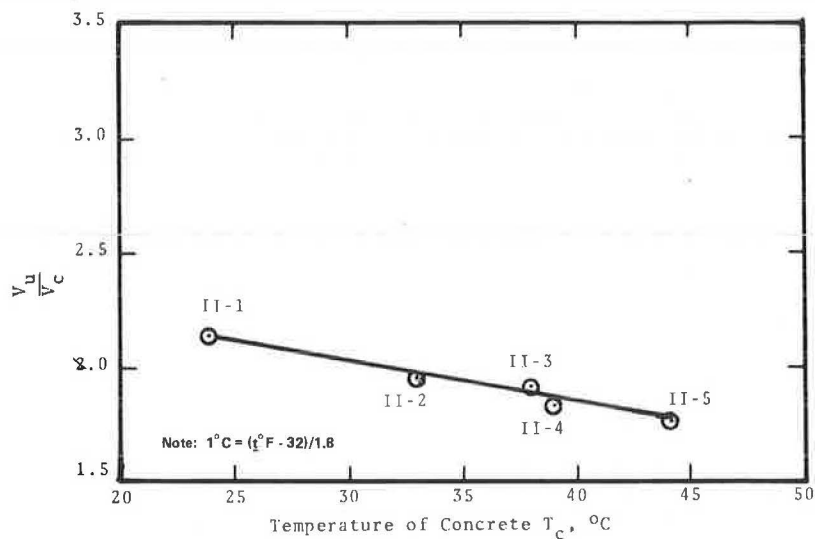
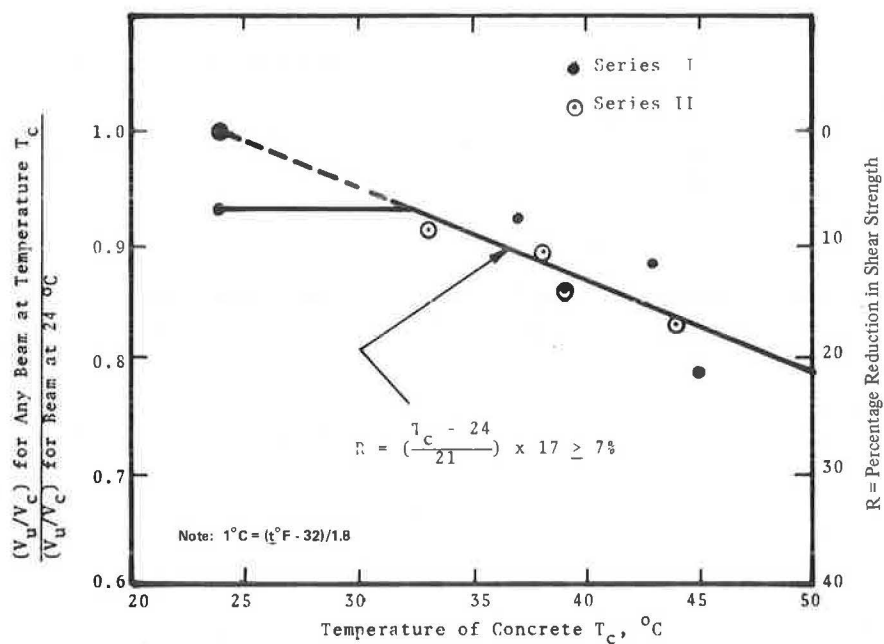


Figure 3. Reduction in shear strength of concrete at different temperatures.



have been calculated as given in Table 3 and are shown in Figure 3, which also shows the percentage of reduction in shear strength at different temperatures. It can be determined from Figure 3 that the percentage of reduction in shear strength at any temperature T_c °C of concrete is given as follows:

$$R = [(T_c - 24)/21] \times 17 \quad (2)$$

It is pertinent to emphasize here that because the actual f_c' of concrete at different temperatures was used in analyzing the test results, the previously mentioned reduction in shear strength will be obtained even if necessary precautions are taken or the concrete mix is so designed to give the required compressive strength in a hot climate.

The test results for specimen I-6, which was prepared at the normal laboratory temperature of 75°F but cured in the oven at high temperature simulating hot climatic conditions, show that the shear strength is reduced by 7 percent. This corresponds to the reduction obtained at 90°F by using Equation 2. Thus, even if all the necessary precautions are taken to reduce the temperature of the concrete to 90°F as laid down in the construction specifications, the shear strength of the concrete will still be reduced by about 7 percent, mainly due to the curing effect in hot climatic conditions. Thus, Equation 2 can be restated as follows:

$$\text{Percentage reduction in shear strength of concrete at any temperature } T_c \text{ °C} = [(T_c - 24)/21] \times 17 \geq 7 \text{ percent} \quad (3)$$

Hence, the shear strength (V_{ct}) of concrete at any temperature T_c can be expressed by any of the following equations:

$$V_{ct}/V_c = 1.0 - [(T_c - 24)/21] \times 0.17 \leq 0.93 \quad (4)$$

$$V_{ct}/V_c = 1.194 - 0.0081T_c \leq 0.93 \quad (5)$$

$$V_{ct} = V_c(1.194 - 0.0081T_c) \leq 0.93V_c \quad (6)$$

where V_c is the shear strength of concrete obtained from Equation (11-3) of the ACI code.

CONCLUSIONS AND RECOMMENDATIONS

The shear strength of concrete prepared and cured under hot climatic conditions is reduced with an increase in the temperature of the concrete. This is true even if all the necessary measures are taken to obtain the required compressive strength of concrete under hot climatic conditions.

The shear strength of concrete (V_{ct}) at any temperature of concrete (T_c) between 75° and 113°F can be obtained from Equation 6.

It is recommended that Section 11.3 of the 1977 ACI code be suitably amended to incorporate Equation 6 to modify Equation (11-3) of the code for shear strength of concrete in hot climatic conditions.

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Discussion

Waheed Uddin*

The authors should be commended for initiating laboratory research in Saudi Arabia on the effects of local environment on the quality and placement of portland-cement concrete. I have worked for several years as a materials engineer on civil aviation projects and in pavement research in Saudi Arabia and therefore am interested in this research. There are several points that need further clarification from the authors.

They mention the practice of adding water to improve the workability of concrete in hot weather conditions. I recall that while I was supervising the construction of a portland-cement concrete apron at Dhahran International Airport in 1978, addition of water in the transit mixer was strictly prohibited once it had left the batch plant. The workability of the low-slump concrete on such jobs was attained within desirable limits by designing a concrete mix with suitable admixtures, e.g., plasticizers. It is common practice, followed in all parts of Saudi Arabia, to use plasticizer in the concrete mix designed for any major construction where the quality is controlled through a materials testing laboratory.

The authors fail to describe the concrete mixes that were used in the preparation of laboratory specimens. It is well known that coarse aggregate is the most important component of the concrete mix that is affected by temperature variation. Was the same type of aggregate used in all specimens?

I have had wide experience in the availability of aggregate types in the quarries around Dhahran, which are evidently the source of the aggregates used in this study. Basically limestone, dolomite, or dolomitic limestone are the rock types crushed in the quarries of the Dhahran region. The limestone can be very soft and highly water absorptive. The dolomitic limestone is scarce, relatively hard, less water absorptive, and if used in concrete yields higher compressive and flexural strength. It has been reported that the percentage loss from the sodium sulfate soundness test (AASHTO T-104) for soft limestone is as high as 27 percent, and for dolomitic limestone it can be as low as zero (14). It is suggested that the authors include a data summary on the physical and engineering properties of the aggregate types used in their study.

The authors recommend amending the ACI code of 1977 [Equation (11-3)] based on the equation developed in their paper. It is pointed out that their relationship may not be unique. Apparently they did not consider three important variables in their testing program, namely, aggregate type, mix type, and presence of plasticizers.

The inferences made by the authors are obviously limited to the aggregate samples and testing conditions used in their study. Additional work is desirable before any amendment to the existing ACI code is considered.

*Transportation Engineering, University of Texas at Austin, 3367-B Lake Austin Boulevard, Austin, Texas 78703.

Authors' Closure

We appreciate the valuable comments by the discussant. No doubt suitable admixtures are used to improve the workability of concrete in hot weather. With regard to the practice of adding extra water to a concrete mix to compensate for evaporation of water from the mix, which was mentioned in our paper, the discussant may refer to papers by Scanlon (1) and Newman (2). Furthermore, if no extra water is added and if workability is not a problem, the net effective water/cement ratio is reduced due to evaporation of water. The results of the tests conducted at the University of Petroleum and Minerals (12) have shown that in this case the compressive strength is increased. In any case the results of the shear tests have been so analyzed and presented in our paper that the effect of hot weather on compressive strength is eliminated.

The necessary information on concrete mixes has been given in Table 2 of our paper, which gives the type and size of the coarse aggregate used in the mixes. The coarse aggregate used is limestone available in the quarries around Dhahran, which is used extensively in construction work. Its mineralogical composition is calcite, 73 percent; quartz, 10 percent; and dolomite, 13 percent.

Different mix proportions were used in the two series of tests. The water/cement ratio and the conditions for preparation and curing were varied to obtain compressive strengths from 3,000 to more than 5,000 psi. Equation 6 is developed on the basis of the test results obtained. Although not unique, it is believed to give a reasonable relationship considering the highly unpredictable conditions in hot weather. Any additional work will probably give similar results.

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