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Cement & Concrete Composites 23 (2001) 353–361

Cement & Concrete Composites

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Effect of environmental conditions on the properties of fresh and hardened concrete

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Received 28 June 2000; accepted 2 March 2001

Abstract

The effect of varying environmental conditions, at the time of casting on the properties of fresh and hardened concrete was evaluated. The influence of air temperature, wind velocity, and relative humidity on plastic shrinkage, compressive strength, pulse velocity and pore structure of concrete was investigated. Results indicate that exposure conditions at the time of casting significantly affect plastic shrinkage of concrete. As expected elevated temperature affected porosity, compressive strength, and pulse velocity of concrete. Casting of concrete at elevated temperature decreased its compressive strength. Similarly, the pulse velocity of concrete cast at 45°C was less than that of cast at 30°C. The volume of total pores in the concrete specimens cast at 45°C was more than that of cast at 30°C. The lower pulse velocity and increased pore volume in the concrete cast at 45°C than that cast at 30°C may be attributed to the coarse pore structure formed in the former than the latter. Other weather parameters, such as relative humidity and wind velocity, also influence the properties of fresh and hardened concrete.

Keywords: Concrete; Plastic shrinkage; Pulse velocity; Evaporation; Cracking

1. Introduction

Air temperature, relative humidity and wind velocity affect the properties of fresh and hardened concrete [1,2]. Elevated temperature and low relative humidity or a combination of both accelerates plastic shrinkage of concrete. If plastic shrinkage is restrained cracks are formed. These cracks are both unsightly and form a source of further concrete deterioration, mainly due to reinforcement corrosion, by allowing oxygen and moisture to diffuse to the steel surface [3]. In many arid and semi-arid areas of the world, this type of concrete distress is often noticed, understandably when proper precautions are not adopted. Elevated temperature, low humidity and high wind alone or a combination of these factors encourage rapid evaporation of the bleeding water that results in shrinkage of concrete thereby inducing tensile stresses in it. If the stresses induced due to shrinkage, at that point of time when the bleeding water is evaporating at a very rapid rate, are greater than the tensile strength of concrete, it cracks.

Although plastic shrinkage cracks develop at normal temperatures, they are frequently associated with concreting under hot-weather conditions, particularly at elevated temperatures [4–7]. Construction operations (screeding and finishing) have a very significant effect on plastic shrinkage cracking [8].

Cebeci and Saatci [9] indicated that air temperature, air velocity, relative humidity, surface temperature, geometry of the system, and flow conditions affect evaporation of water. They criticized the conclusions drawn by Berhane [10] regarding the validity of Menzel's equation to calculate water evaporation from concrete. They compared the results obtained using Menzel's equation, and the data reported by Berhane [10] with those obtained by heat and mass transfer relationship for constant drying rate and that between heat transfer and mass velocity of air for similar environmental conditions. They are of the opinion that the initial temperature of concrete should not be indiscriminately utilized for estimating later evaporation rates from fresh mortar or concrete. They also concluded that a valid criticism of Menzel's formula for calculating water evaporation from concrete or a convincing recommendation of other methods should be based on a consideration of all the factors affecting the evaporation

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of water from fresh mortar and concrete. Cebeci and Saatci [9] are of the opinion that evaporation rate formula, such as that presented by Menzel and adopted by PCI and ACI, can only be utilized when the concrete surface is completely covered with water.

Hasanain et al. [2] reported a study conducted in the hot weather of western Saudi Arabia. The results of that study indicated that, besides mix composition, the time of casting, difference in the concrete and air temperature, and moisture condition of concrete surface influence the rate of evaporation of water from freshly placed concrete surfaces.

Mora et al. [11] studied plastic shrinkage cracking of fresh concrete using restrained prisms and panels subjected to a 40 km/h wind and a temperature of 40°C. Their results indicated that incorporation of steel and plastic fibers, and a glycol-based shrinkage-reducing admixture leads to a reduction in the potential for cracking in a plastic state.

Elevated temperature, low humidity and high wind velocity or a combination of these factors may also induce problems in the preparation, placing, consolidation and curing of concrete [12]. Hot weather conditions may also affect the properties of hardened concrete. The properties of hardened concrete that may be influenced by hot-weather conditions are strength development and pore structure. Limited studies [13] conducted on this aspect have indicated that hot-weather conditions accelerate the early age strength of concrete, whereas the later age strength tends to decrease. Similar findings were reported by Kosmatka and Panarese [14]. The results of that study indicated that the higher the early curing temperature of concrete the more rapid is the rate of early age strength gain, but the later age strength is decreased.

Cather [15] indicates that in dry environments, accelerated water loss due to evaporation leads not only to a decrease in the degree of hydration in the surface or 'cure affected zone' but also to shrinkage and accompanying shrinkage stresses in the freshly placed concrete.

Al-Fadhala and Hover [16] studied the negative impact of the Arabian Gulf environment on the durability of concrete by experimental measurement of the rates of both evaporation and bleeding of concrete under a simulated regional environment. The rate of water evaporation evaluated by pan test was compared with the actual values. They concluded by pointing out the precautions that are necessary to prevent rapid and early drying of the concrete surface when placing it in a hot-weather climate.

The aforesaid literature review indicates that plastic shrinkage has been the subject of research of some studies. However, the effect of hot-weather conditions on the properties of fresh concrete, its denseness and pore structure development have not been sufficiently investigated.

This study was conducted to evaluate the effect of exposure conditions, at the time of casting, on the properties of fresh and hardened concrete. The effect of exposure conditions on the properties of fresh concrete was evaluated by measuring water evaporation, time to cracking, cracked area and plastic shrinkage strain. The effect of hot-weather conditions on the properties of hardened concrete was evaluated by assessing strength development, pulse velocity and pore size distribution.

2. Methodology

2.1. Materials and mix proportions

Type V Portland cement satisfying ASTM C 150 requirements was used in the concrete mixtures. Its chemical composition is shown in Table 1. Crushed limestone aggregate and dune sand were used in the concrete mixtures. The bulk specific gravity of the coarse aggregates was 2.46 while the water absorption was 3.0%. The specific gravity of the dune sand was 2.54 and the water absorption was 0.23%. Both the coarse and fine aggregates were thoroughly washed to remove dust prior to mixing them with cement and water. The grading of the coarse aggregate is shown in Table 2.

Table 1
Chemical analysis of type V cement

Constituent	Weight (%)
SiO_2	22.20
Al_2O_3	3.48
Fe_2O_3	3.88
CaO	65.05
MgO	2.20
SO_3	1.85
K_2O	0.28
Na_2O	0.15
Loss on ignition	0.80
C_3S	62.0
C_2S	17.0
C_3A	2.7
C_4AF	11.8

Table 2
Grading of coarse aggregates

Sieve opening (mm)	Percentage of passing	ASTM C 33 limits
19	100	100
12.5	90	90–100
9.5	50	40–70
4.75	5	0–15
2.4	0	0–5

Table 3
Weight of constituents

Constituent	Weight per cubic meter of concrete (kg)
Cement	350.0
Total water	175.0
Coarse aggregate	1156.0
Fine aggregate	708.5

The concrete mixtures were prepared with a cement content of 350 kg/m^3 and an effective water to cement ratio of 0.40. The workability of all the concrete mixtures was maintained in the range of 50–75 mm slump. A naphthalene-based superplasticizer was used to obtain the desired workability. Table 3 shows the weight of the constituent materials used in the preparation of the concrete mixtures.

2.2. Specimens and exposure

The concrete specimens utilized for evaluating the effect of exposure conditions on the properties of fresh concrete were $915 \times 915 \times 51$ mm^3 in size. The thickness of the specimens was selected to represent the surface area to volume ratio of a typical concrete slab. Aluminum and Plexiglas forms were utilized to cast the concrete specimens. These forms are not only durable, but also prohibit absorption of moisture from the mix. This improves the uniformity of conditions among all the tests, increases bleeding, forces a one-dimensional water movement and provides a worst case scenario for plastic shrinkage cracking, by simulating the casting of a slab over a plastic vapor barrier as recommended by Campbell et al. [17].

The concrete specimens were cast in a chamber with facilities to control temperature, humidity and wind velocity. The required temperature was maintained using electrical heaters controlled by thermostats. Air circulation in the chamber was facilitated by a blower. The blower was placed such that it covered the whole slab area uniformly. The direction of the air movement was parallel to the plane of the surface. The velocity of air was measured using a digital anemometer. The relative humidity in the chamber was controlled through the use of a humidifier and a dehumidifier.

The concrete constituents were mixed in an electric concrete mixer of 0.17 m^3 capacity. After mixing, the concrete was poured in the molds and vibrated on a vibrating table and leveled by a straight edge without sideways or swaying motion. Two concrete specimens were exposed to the combination of following exposure conditions:

temperature: 30°C and 45°C;
relative humidity: 25%, 50% and 95%;
wind velocity: 0 and 15 km/h.

The quantity of water evaporated was calculated as the ratio of water evaporated to the total water added to the concrete mix, while the rate of evaporation was evaluated by dividing the water evaporated in 6 h by the surface area of the slab, i.e., 450×450 mm^2. The change in mass of the concrete mix, due to water evaporation, was recorded at periodic intervals, up to 6 h by placing the mold filled with concrete on a digital balance of 0.1 g sensitivity.

Plastic shrinkage cracking was evaluated by monitoring the time to initiation of cracks and their area. The length and average width of cracks were recorded and the total area of cracks was expressed as a proportion of the surface area of the slab.

To measure plastic shrinkage strain, four studs were placed on the four sides of the specimens. The studs were embedded to half the depth of the specimen. The movement of each of the studs, due to shrinkage, was recorded through four LVDTs. Fig. 1 shows the experimental setup. The output from the LVDTs was recorded by utilizing a data acquisition system. The specimens were kept under observation for 6 h. After 24 h, the specimens were removed from the chamber and placed outdoor. They were covered with wet burlap followed by a plastic sheet to prevent evaporation of water. After 28 days of curing, pulse velocity readings were taken at several locations on the slabs. Six representative core specimens, 50 mm in diameter, were obtained from the slabs to evaluate the compressive strength and pore size distribution. For pore size distribution concrete specimens from the middle of the core were obtained.

The effect of exposure conditions, at the time of casting, on the pore size distribution was evaluated by conducting mercury intrusion porosimetry. The pore size distribution in the representative concrete specimens was evaluated using Carlo Erba Model 2000 high-pressure mercury intrusion porosimeter. The pressure in the porosimeter was slowly increased from 0.1 to 200 MPa. The measurements of the pressure and the introduced volume of mercury were recorded and used to draw the pore volume against the pore radius. The surface tension and angle of contact of mercury were assumed to be 480 MN/m and 130°, respectively.

3. Results and discussion

3.1. Effect of exposure conditions on plastic shrinkage

The effect of exposure conditions at the time of casting on plastic shrinkage was evaluated by assessing the quantity and rate of water evaporation, time to cracking, crack area and shrinkage strain.

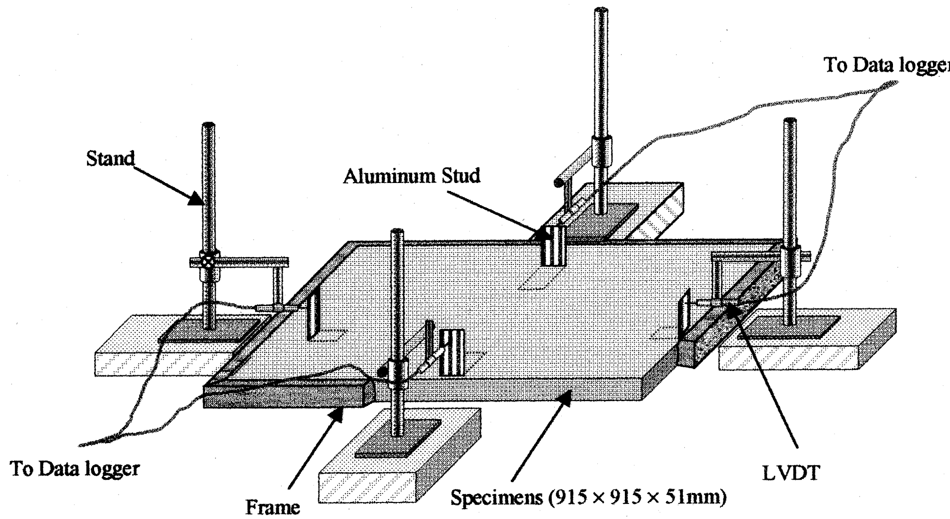

Fig. 1. Schematic representation of the experimental setup utilized to measure plastic shrinkage strain.

3.1.1. Quantity of evaporated water

Fig. 2 shows the effect of exposure conditions on the quantity of water evaporated. The quantity of evaporated water increased with increasing exposure temperature. In the concrete specimens exposed to a relative humidity of 25%, temperature of 30°C, and wind velocity of 15 km/h, the quantity of water evaporated was 42% of the mix water and it increased to 49% when the exposure temperature was increased to 45°C. An increase in the evaporation, with increasing temperature, was also noted in the concrete specimens exposed to other exposure conditions. Also from Fig. 2 it can be seen that the quantity of evaporated water in the concrete specimens exposed to normal conditions, i.e., when there was no wind was less than that in the specimens exposed to windy conditions. The relative humidity also significantly affected the evaporation of the water under non-windy conditions. Under non-windy conditions, the quantity of evaporated water was 31% when the RH was 50% and the exposure temperature was 45°C, and it was 3.0% when the RH was 95% and the exposure temperature was 45°C. The decrease in the quantity of evaporated water with increasing relative humidity may be attributed to increased volume of water vapor in the atmosphere at high humidity that reduces the evaporation of water from the concrete surface.

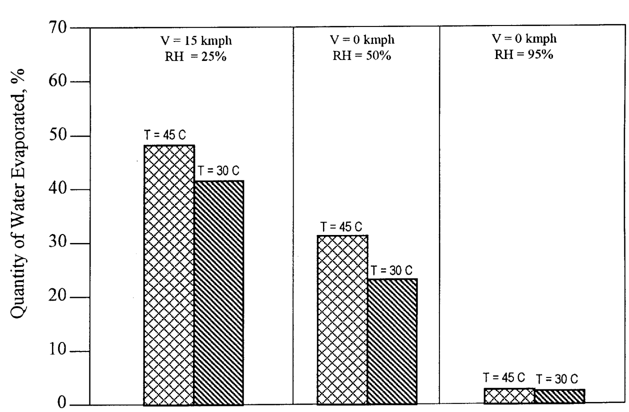

Fig. 2. Effect of exposure conditions on the quantity of water evaporated.

Higher rate of water evaporation means that sufficient water may not be available for hydration of cement. A water-to-cement ratio of 0.26 is required for hydration of cements. In the concrete mixes prepared with a w/c ratio of 0.4, as in the present case, water evaporation of 35% does not significantly influence cement hydration. However, the combined effect of elevated wind and low relative humidity leads to a water evaporation of more than 35% even though the temperature may be as low as 30°C. Therefore, to avoid excessive evaporation, wind barriers should be erected under windy conditions. Similarly, the concrete can be kept humid by applying a curing compound. Alternatively, the environment can be kept moist, for at least 6 h, by the use of a mist spray.

3.1.2. Rate of water evaporation

Fig. 3 depicts the effect of exposure conditions on the rate of water evaporation. As expected, the rate of water evaporation increased with increasing exposure temperature. In the concrete specimens exposed to a wind velocity of 15 km/h and an RH of 25%, the rate of water evaporation increased from 0.77 to 0.90 kg/m^2 h when the exposure temperature was increased from 30°C to 45°C.

From Fig. 3 it is also apparent that the rate of water evaporation decreased with increasing relative humidity. The rate of water evaporation in the concrete specimens

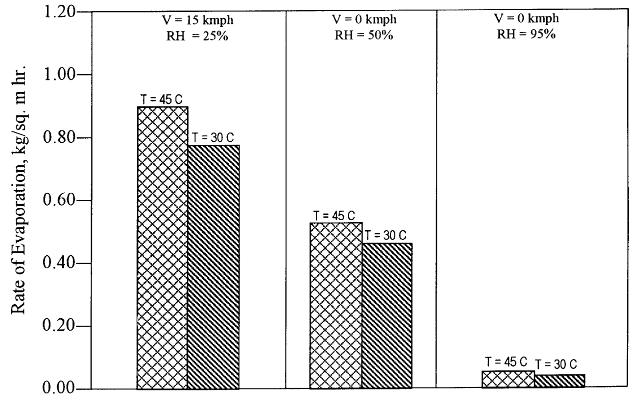

Fig. 3. Effect of exposure conditions on the rate of water evaporation.

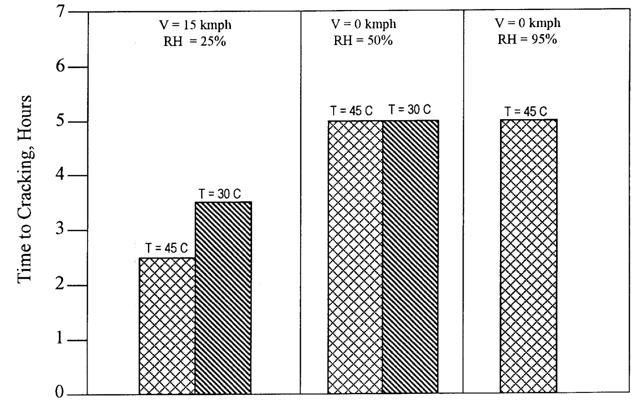

Fig. 4. Effect of exposure conditions on time to cracking of concrete.

exposed to a temperature of 45°C and an RH of 50% was 0.52 kg/m^2 h which is about 10 times the value in the concrete specimens exposed to an RH of 95% and temperature of 45°C.

This indicates that the rate of evaporation under hot-dry condition is about 10 times that under hot-humid conditions. The effect of varying exposure conditions on the rate of water evaporation from fresh mortar and concrete specimens was also evaluated by Berhane [10]. In that study also the measured water loss in a hot-humid environment was considerably lower than that in a hot-dry climate. It was noted that the water loss in a hot-dry climate was $7\frac{1}{2}$ times that in a hot-humid environment. It was shown that cracking is possible for an evaporation rate as low as 0.4 kg/m^2 h. In another investigation Almusallam et al. [18] evaluated the effect of mix composition on the rate of evaporation. In that study, cracking of concrete was noted between 0.2 and 0.7 kg/m^2 h, while ACI 305 notes that hot-weather precautions should be exercised when the rate of evaporation is more than 1 kg/m^2 h.

3.1.3. Plastic shrinkage cracking

The effect of environmental conditions at the time of casting on the plastic shrinkage was assessed by noting the time for appearance of first crack and the total crack area. The total crack area was calculated as a percentage of the total area of the concrete surface.

Fig. 4 shows the effect of ambient temperature, RH, and wind velocity on the time to cracking of concrete panels. When the exposure temperature was increased from 30°C to 45°C, the time to cracking decreased from 3.5 to 2.5 h in the concrete specimens exposed to a wind of 15 km/h and RH of 25%. In the concrete specimens exposed to no wind and an RH of 50%, cracks were noted after 5 h in the concrete specimens exposed to 30°C and 45°C. Cracks were not noted in the concrete specimens exposed to a temperature of 30°C, RH of 95% and wind velocity of 0 km/h, while they were noted after 5 h in the concrete specimens exposed to 45°C.

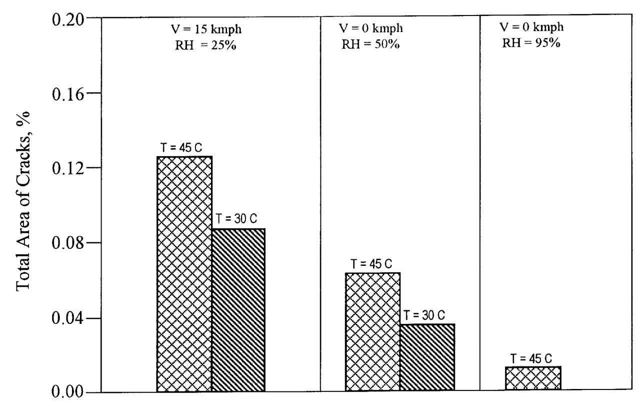

Fig. 5. Effect of exposure conditions on total area of cracks.

Fig. 5 shows the effect of varying exposure conditions on the total area of cracks. The total area of cracks increased with increasing exposure temperature. In the concrete specimens exposed to 30°C, 25% RH, and a wind of 15 km/h the total area of cracks was 0.087% and it increased to 0.13% in the concrete specimens exposed to 45°C. On the other hand, the total area of cracks decreased with increasing RH. Under non-windy conditions, the total area of cracks was 0.063% when the RH was 50% and the exposure temperature was 45°C, and it was 0.012% when the RH was 95% and the exposure temperature was 45°C. However, no cracks were noted in the concrete specimens exposed to RH of 95% and temperature of 30°C.

The above data indicate that the combined effect of elevated temperature, windy conditions and low relative humidity creates wider and longer cracks in concrete than when it is exposed to moderate conditions.

3.1.4. Shrinkage strain

Figs. 6–8 depict the effect of exposure conditions on plastic shrinkage strain. The plastic shrinkage strain increases almost linearly with time up to about 6 to 10 h and then the rate decreases.

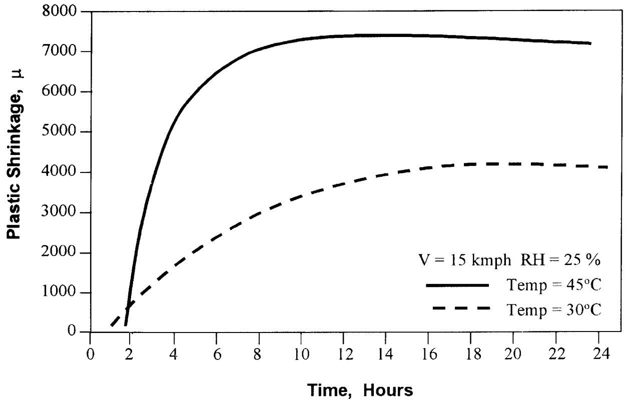

Fig. 6. Variation of plastic shrinkage strain in the concrete exposed to RH of 25% and wind velocity of 15 km/h.

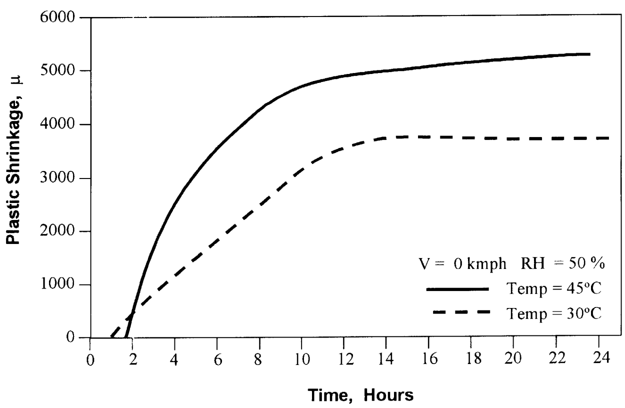

Fig. 7. Variation of plastic shrinkage strain in the concrete exposed to RH of 50% and no wind.

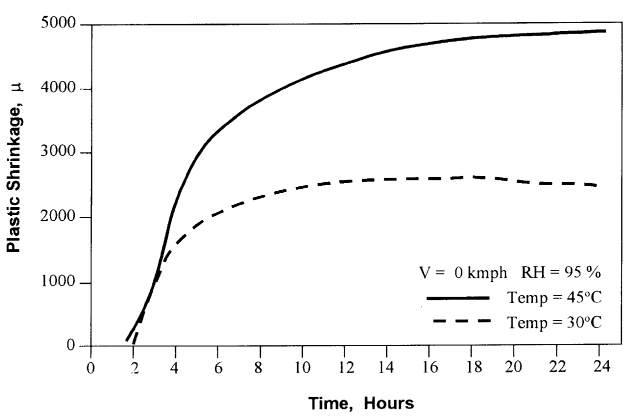

Fig. 8. Variation of plastic shrinkage strain in the concrete exposed to RH of 95% and no wind.

Fig. 9 summarizes the effect of exposure conditions on plastic shrinkage strain after 24 h of casting. In the concrete specimens exposed to non-windy conditions and an RH of 50%, the plastic shrinkage strain was 5300 and 3640 μ for the exposure temperature of 45°C

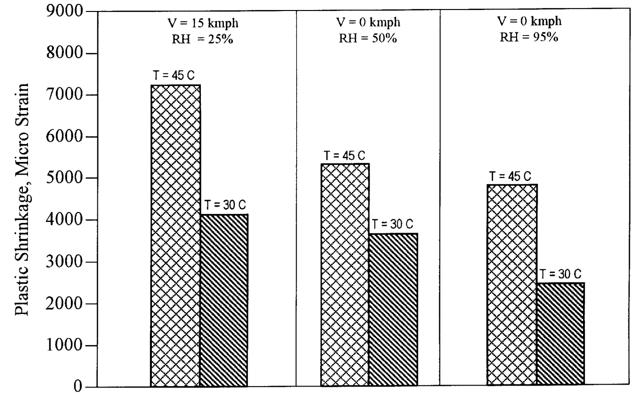

Fig. 9. Effect of exposure conditions on plastic shrinkage strain in concrete.

and 30°C, respectively. The plastic shrinkage strain decreased with increasing RH. In the concrete specimens exposed to a temperature of 45°C, the plastic shrinkage strain decreased from 5300 to 4780 μ when the RH was increased from 50% to 95%. The plastic shrinkage strain in the concrete specimens exposed to 30°C, no wind and an RH of 50% and 95% was 3800 and 2200 μ, respectively. The highest shrinkage strain in the concrete specimens exposed to either elevated temperature or low humidity enhances the chances of cracking if there is a restraint to the movement of concrete. Further, shrinkage strain in the concrete exposed to hot and arid conditions will be more than that in the concrete specimens exposed to arid conditions with moderate temperature.

4. Effect of exposure conditions during casting on the properties of hardened concrete

The effect of exposure conditions during casting on the properties of hardened concrete was evaluated by measuring the compressive strength, denseness and pore structure. The denseness of hardened concrete was assessed by measuring the ultrasonic pulse velocity while the pore structure was evaluated by measuring pore size distribution utilizing mercury porosimetry.

4.1. Compressive strength

The effect of exposure conditions on the compressive strength of concrete is depicted in Fig. 10. The compressive strength of the concrete specimens exposed to 30°C was more than that of the concrete specimens exposed to 45°C. An average change of 5 MPa, due to an increase in the exposure temperature from 30°C to 45°C, was measured in the concrete specimens exposed to all the exposure conditions. The effect of varying wind

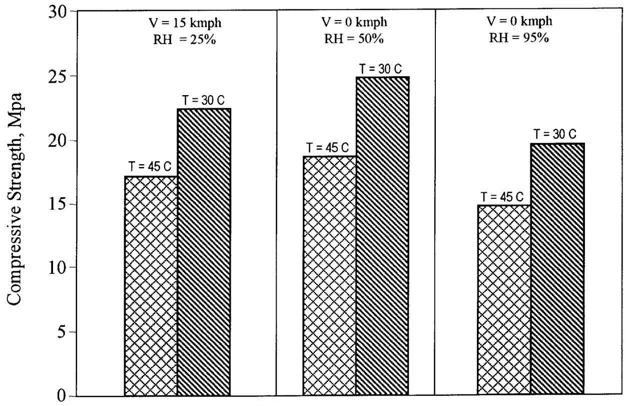

Fig. 10. Effect of exposure conditions on compressive strength of concrete.

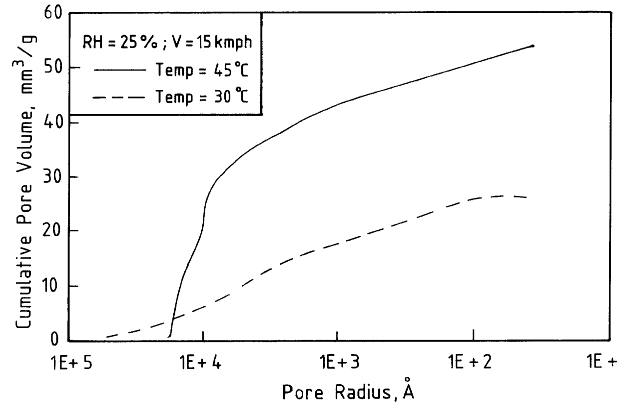

Fig. 12. Effect of exposure conditions on pore size distribution in the concrete specimens exposed to an RH of 25% and wind velocity of 15 km/h.

velocity and relative humidity on the compressive strength was, however, insignificant.

4.2. Pulse velocity

The effect of exposure conditions on the pulse velocity in concrete is depicted in Fig. 11. The pulse velocity data in Fig. 11 indicate that concrete specimens exposed to 30°C were denser than those exposed to 45°C. The reduction in pulse velocity of concrete specimens exposed to elevated temperature may be attributed to both the formation of microcracks, presumably due to increased shrinkage strain and the reduced moisture content of the specimen. The other factor that may contribute to the decrease in the pulse velocity may be the formation of microcracking due to differential thermal movements of the concrete constituents, namely, cement and aggregates.

4.3. Porosity

Fig. 12 shows the effect of ambient temperature on the pore size distribution in the concrete specimens exposed to an RH of 25% and a wind velocity of 15 km/h. The volume of coarse pores in the concrete specimens exposed to 45°C was more than that in the concrete specimens exposed to 30°C. The cumulative pore volume in the concrete specimens exposed to 45°C was 55 mm^3/g, whereas it was 23 mm^3/g in those exposed to 30°C. A similar trend was noted in the concrete specimens exposed to an RH of 50% and 95%, as shown in Figs. 13 and 14, respectively.

Fig. 15 summarizes the effect of exposure conditions on the cumulative pore volume. As discussed earlier, the cumulative pore volume in the specimens exposed to 45°C was more than those exposed to 30°C. In the concrete specimens exposed to no wind, the increase in the cumulative pore volume was more prominent in the concrete specimens exposed to an RH of 50% than those exposed to an RH of 95%. This increase in the pore volume may be attributed to the reduced humidity that may lead to increased evaporation, thus retarding cement hydration. Alternatively, the increased

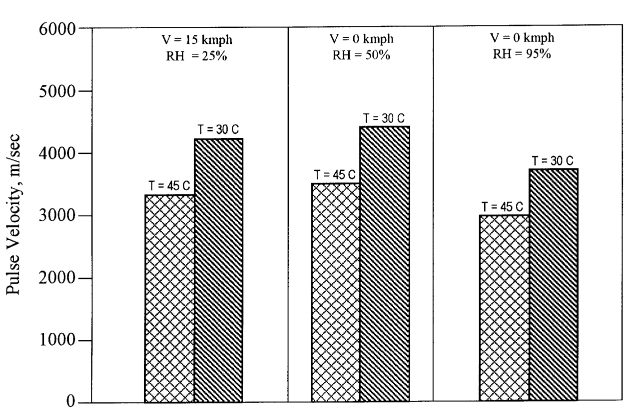

Fig. 11. Effect of exposure conditions on pulse velocity through concrete.

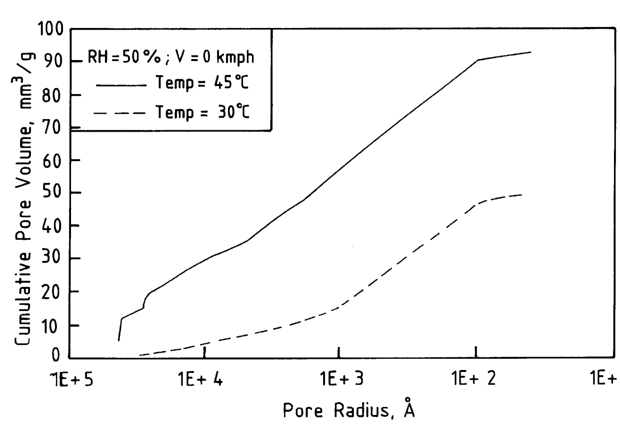

Fig. 13. Effect of exposure conditions on pore size distribution in the concrete specimens exposed to an RH of 50% and no wind.

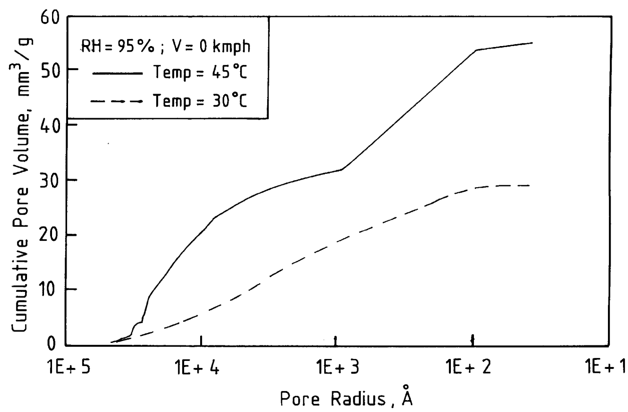

Fig. 14. Effect of exposure conditions on pore size distribution in the concrete specimens exposed to an RH of 95% and no wind.

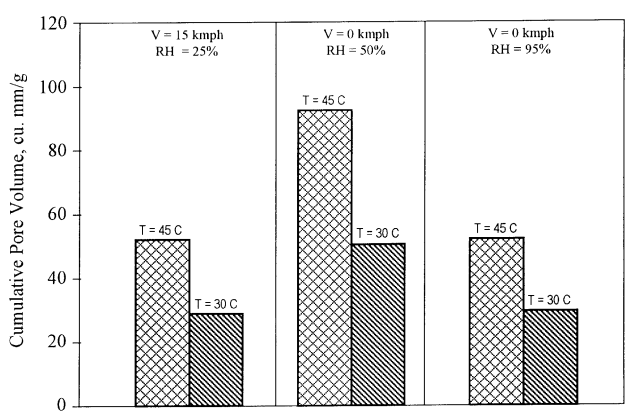

Fig. 15. Effect of exposure conditions on cumulative pore volume in the concrete.

evaporation leads to the formation of microcracks that may contribute to increased pore volume.

The data in Figs. 12–15 indicate that the cumulative pore volume increases with increasing exposure temperature. This may be attributed to the fact that, at low temperatures, the hydration products have sufficient time to diffuse throughout the cement paste matrix thereby precipitating uniformly. However, at higher temperature, the rate of hydration reaction is much faster than the rate of diffusion, due to which the hydration products remain near the cement grains, leaving the interstitial space relatively open. The results also indicate that exposure temperature significantly affects the finer pores. It can thus be concluded that high exposure temperature has a detrimental effect on the pore volume and hence the porosity. The increase in the quantity of coarse pores either due to elevated temperature or lower humidity or high wind contributes to an increase in the permeability of concrete.

5. Conclusions

The data developed in this study indicate that exposure conditions at the time of casting significantly affect the properties of both fresh and hardened concrete. The rate of water evaporation, shrinkage strain and the area of cracks increased with increasing exposure temperature and wind velocity, and decreasing relative humidity. Plastic shrinkage cracks were noted earlier in the concrete specimens exposed to elevated temperature and low relative humidity, compared to specimens exposed to low temperature and high humidity. Similarly, cracks were noted earlier in the concrete specimens exposed to windy conditions than those exposed to no wind.

The exposure conditions also influence the properties of hardened concrete. Elevated temperature exposure decreased the compressive strength and pulse velocity. The compressive strength of concrete specimens cast and exposed to 30°C was more than those exposed to 45°C. Similarly, the pulse velocity of the concrete specimens cast at 30°C was more than those cast at 45°C.

The exposure conditions significantly affect the pore structure of concrete. Coarse pores were noted in the concrete specimens cast at 45°C than those cast at 30°C. The proportion of coarse pores (pore size more than 1000 Å) in the concrete specimens cast at 45°C was more than that in the specimens cast at 30°C. A coarse pore structure in the concrete specimens exposed to 45°C indicates that the permeability of these concrete specimens will be higher resulting in a decrease in their durability.

Acknowledgements

The author acknowledges the support provided by the Department of Civil Engineering, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

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