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A Discussion of the Paper "MEMBRANE CURING OF CONCRETE: MOISTURE LOSS" by J. Wang, R.K. Dhir and M. Levitt*

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Work on the phenomenology related to concrete curing and especially the factors affecting the performance of membrane-forming curing compounds is needed and welcome. It should, however, be recalled that "curing" of concrete is defined (ACI 116R-90) as "the maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop." What constitutes a "satisfactory" moisture content must ultimately depend on whether or not the moisture content that was maintained did or did not allow the "desired properties" to develop. It should be clear that there are concretes that cannot develop the desired properties no matter how they are cured - you can't get 140-MPa compressive strength from 0.8-w/c concrete no matter what moisture content and temperature are maintained during its early stage. Similarly, there are many concretes that are so "over designed," in some cases quite intentionally, that it is almost impossible, under ordinary environmental conditions, to so do harm to curing that the concrete fails to develop "desired properties." The American Concrete Institute Standard Practice for Curing Concrete (ACI 308-92) says that "The strength and durability of concrete will be fully developed only if it is cured. No action to this end is required...when ambient conditions of moisture, humidity, and temperature are sufficiently favorable to curing." In effect, this says, under some conditions the proper time for application of a membrane-forming curing compound is never. Of course, if one is executing a contract that requires such application, the compound must be applied unless a proper exception to the requirement is authorized.

The authors, in their discussion of "Fundamentals of Moisture Loss from Concrete," remark that concretes "usually contain an amount of water in excess of that required for complete hydration" as if somehow complete hydration was regarded as desirable. I pointed out (Mather, 1993) that the relationships of water-cement ratio and potential hydration of cement should be considered when dealing with performance of concrete. I cited Philleo (1986, 1991) who pointed out that if the ratio of the volume of water to the volume of cement is 1.2, then all the water and all

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the cement can combine and all the originally mixing water-filled space can be filled with hydration product. A water-cement ratio (w/c) of 1.2 by volume is 0.4 by mass. If the w/c is higher than 0.4, even if all the cement hydrates, there will always be some residual originally mixing water-filled space. If the w/c is lower than 0.4, some of the cement will always remain unhydrated but, in theory, all the originally mixing water-filled space could be filled with hydration products. There is a misconception, often stated, that it takes only the amount of water in a 0.2 w/c paste to hydrate all of the cement. This is based on the fact that only 0.2 unit of water by mass chemically combines with cement during hydration. However, for a given volume of cement to hydrate, there must be an amount of originally mixing water-filled space equal to 1.2 times the volume of the cement. This is because the hydration product has about 30 percent pore space that must be present, and water must be available to fill it. If the amount of originally mixing water-filled space is less than that provided at a w/c of 0.4, not all of the cement can hydrate, even though only half of that water will go into chemical combination. However, concrete made at w/c's well below 0.4 by mass will not have all of the originally mixing water-filled space filled with hydration product. This is because the part of the mixing water that ends up in the gel pores undergoes a 10 percent reduction in volume because the pores are so small and the water is adsorbed. Philleo (1991) also discussed the fact that additional water may enter test specimens of very low w/c concrete while they are curing in the laboratory, but such externally available water will not get very far into larger masses of field concrete even if it is made available.

If the w/c is higher than 0.4, then the more of the cement that hydrates, the larger the proportion of the originally water-filled space that gets filled, the higher the strength, and the lower the permeability. Therefore, if it were desired that the concrete develop all the strength and reduced permeability that it can, then the longer it is kept moist, the closer it will come to having all its cement hydrated and the greater its strength and impermeability will be. There are, however, at least two possibly undesirable consequences of a concrete having all of its cement hydrated and becoming as strong as it can become. First, if there is no remaining unhydrated cement, then there can be no autogenous healing of microfractures as water enters and is available to react with unhydrated cement to accomplish the healing. Second, if the concrete is as strong as it can possibly become, it will have a higher modulus of elasticity, be more brittle, and crack at a lower strain level. Reduced strain capacity - both elastic strain and creep strain - is not a desirable property in a lot of concrete. As Philleo (1991) put it, "the desirable magnitude of creep is an issue on which practitioners have not agreed. Structural engineers find it a nuisance they could easily do without.... On the other hand, builders of unreinforced mass concrete structures find creep an indispensable property of concrete.... Creep redistributes stresses...permitting highly stressed regions to shed some of their stresses to low-stressed regions before cracking occurs.... [Mass concrete] structures could not survive if concrete behaved elastically."

The authors' display in their Fig. 1 of the three phases of drying of a solid mass describes Phase 1 of which as the "constant rate of drying from a saturated surface." I would call their attention to the evaporation rate nomograph in ACI 308-92 (and elsewhere) that I discussed (Mather, 1985) which shows the quantity of water that will be lost by evaporation in kg/m^2/hr (or lb/ft^2/hr) as a function of air temperature, relative humidity, concrete temperature, and wind velocity. The rate of such evaporation will only be constant if none of these parameters change and will only follow Dalton's law if the surface is completely covered by water as if it were the surface of a lake or pond. The authors conclude that the three-phase theory is not applicable to concrete at early ages. I believe that Dalton's law, as exemplified by Fig. 1 of ACI 308-92, is applicable to any surface covered completely by standing water, of which some of the authors' specimens should have been, since as shown by their Fig. 4, the highest w/c concrete continued to bleed for at least 80 minutes after placing. If the bleed water can readily evaporate or the bleeding rate is quite low, there may never be enough bleed water on the surface to prevent plastic shrinkage cracking, and steps must be taken to avoid such cracking. These steps, fogging, sunshades, windbreaks, evaporation-retardant films, etc., are part of curing, and when needed must be employed in the period before the membrane-forming curing compound can be applied. The authors' specimens were stored after molding at 20° C and "around" 70 percent RH. If one goes to Fig. 1 of ACI 308-92 and selects an air and concrete temperature of 20° C and an RH of 70 percent, one will follow the dashed line of the example down into the wind velocity section. If one does this and notes that the authors found about 45 mL/m^2/hr evaporation from the free water surface, it can be concluded that their results are in excellent agreement with the evaporation rate prediction of ACI 308-92, Fig. 1. All one needs to do is assume a very low wind velocity.

The authors' description of their procedures makes it clear that application of the curing compound was not delayed until the cement reached its time of initial setting and bleeding ceased. Therefore, the concrete may well have continued to bleed after the curing compound was applied. ACI 308-92 provides that "compounds must be applied after finishing and as soon as the free water on the surface has disappeared and no water sheen is visible" but not while the concrete is still bleeding. The authors report that "the curing compounds...tended to float...on the bleed water on the concrete surface." At the low evaporation rate of the storage conditions, one wonders if the membrane ever did get to lie down on the concrete surface or if the bleed water spilled out from under the curing compound film as the specimen was picked up to have its mass determined.

The authors conclude that "moisture loss increased the later curing compound was applied." However, other workers (e.g., Burnett and Spindler, 1952) showed that all water lost as bleed water that was allowed to evaporate was beneficial to the concrete by reducing the w/c at the surface and increasing strength and abrasion resistance.

Burnett and Spindler (1952) found that the optimum time for application is at the stage where the concrete reaches a set. The authors also do not state that the top edge of the specimen was sealed to prevent evaporation at the interface with the mold. When testing membrane-covered concrete surfaces for moisture loss in accordance with ASTM C 156, it is required that the 150- by 300-mm surface be grooved at its contact with the mold and the groove filled with a sealing compound.

The authors find that one should apply the curing compound quickly - the more so the "higher" the grade of the concrete. I suspect what this means is that the lower the w/c (the "higher" the "grade"), the less the amount and duration of bleeding and the earlier the bleed water sheen will disappear.

In conducting research on curing, it would appear that consideration should be given to the objectives of curing to the aspects of the phenomenology of concrete that affect the ability of the curing procedures to produce their intended effects while taking precautions against factors unrelated to curing from influencing the results.

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