IMPROVEMENT OF CONCRETE SERVICEABILITY IN HOT WEATHER ENVIRONMENT

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ABSTRACT

This paper is being presented to help improve the understanding of the effect of hot weather on concrete and to suggest measures which can offset the adverse effects of such severe exposure conditions.

The cumulative effect of elevated ambient temperatures, drying winds, fluctuating humidity levels and strong solar radiation influences the properties of concrete, both in its plastic and hardened states.

The main areas of concrete distress relate to shrinkage (plastic and drying), differential thermal cracking and strength loss. At the soil/concrete interface, considerable damage can occur due to disintegration of concrete by salt crystallization and this leads to subsequent corrosion of steel reinforcement.

The measures which can be taken to protect concrete from the effect of hot weather can be broadly categorized as 'measures from without' and 'measures from within'.

The measures from 'without' are basically intended to protect concrete by blocking the direct access of hot weather elements to the concrete surface. This may be done by shading, barriers, surface treatment products, by rescheduling concreting operations or by combinations of all four.

For improving concrete resistance to hot weather from 'within', the mix needs to be formulated with the provision of integral materials which can mitigate the adverse effects. Specifically, measures such as reduction of water content for a given consistency, retention of workability for a longer duration, curtailment of moisture movement, improvement of pore-blocking characteristics and reduction of susceptibility to shrinkage cracking, all help to increase the service life of a concrete structure in a hot weather environment.

KEYWORDS

Hot weather, concrete serviceability, protection, shrinkage, cracking, mix formulation, moisture movement, admixtures, curing, polypropylene fibre, polymers.

INTRODUCTION

The arid regions of the Middle East experience prolonged spells of hot weather characterised by high air temperatures, humidity fluctuations, drying winds and intense solar radiation.

To successfully cast concrete in hot weather, difficulties in operations like mixing, placing and curing, mainly due to an increased rate of moisture loss from wet concrete, need to be overcome. Hot ambient environments also cause a rise in the temperature of the freshly-placed concrete, leading to an acceleration in the hydration of the cement paste. Strength loss, dimensional instability, thermal cracking and reduced service life are the common adverse effects observed in concrete subjected to long hot weather exposure, as discussed by various authors in publications like (Al-Tayyib and Mirza, 1984), (Mirza and Al-Noury, 1988), (Cebeci, et al, 1989), (Mirza and Bahkali, 1994) and (Samman et al, 1996) and in the regular regional conferences, symposia and seminars which have taken place over the years.

Knowledge of the damaging influence of hot weather on concrete is essential, but it is not an end in itself. It is the preventative measures, built around this knowledge, which acquire greater significance in order that the maintenance-free service life of concrete structures is extended.

In arid countries, hot summer months constitute a 'severe exposure condition' for both the plastic and the hardened concrete.

After mixing, concrete should remain sufficiently mobile and mouldable to be transported, placed and finished as desired. Moisture loss whilst the material is still being worked may cause permanent damage in terms of increased porosity, shrinkage and cracking.

During the stiffening period, the cement paste needs an environment conducive to the production of dense and impervious hydration products and the development of strong surface bonds around each aggregate particle in the mix.

Cement-water reactions are chemical in nature and are temperature-sensitive. Any increase in temperature either of the freshly-mixed concrete mass or of the surrounding air results in the acceleration of the reaction activity, producing loosely-bound, porous hydration products.

Accelerated hydration is known to cause a short-term gain in strength but it is the strength development at 28 days and beyond which is of greater significance for designers and supervisory technical personnel. According to (Gaynor, et al, 1985), if the initial 24 hours curing of concrete is at 38°C, the 28-day compressive strength of the test specimens may be 10 to 15 percent lower than if cured at the required ASTM C31 curing temperature of 23 +/- 2°C.

HOT WEATHER COMPONENTS

In order to study the influence of hot weather on the performance of concrete, it is important that the influence of the hot weather components is understood both individually and cumulatively. Only a brief appraisal will be presented here and the reader may consult ACI Committee, Report S305 R-91 (1993) for more details.

(i) Air Temperature

The capacity of air to absorb water vapour is a function of its temperature and a high air temperature can cause the rate of water evaporation from concrete to increase considerably. For example, if air and concrete are at 32°C, the rate of evaporation loss from within the concrete is almost twice that which would otherwise occur if both were at 20°C.

(ii) Humidity

The lower the relative humidity of the ambient environment of the concrete, the greater will be the rate of water evaporation. A decrease in relative humidity from 90% to 50%, without changes in any other weather condition, will increase the rate of evaporation from an unprotected concrete surface fivefold.

(iii) Wind Speed

Still air can quickly saturated with water vapour, but its movement due to wind provides a constant renewed supply of air into which more moisture can be absorbed. For example, in a wind of 15 km/hr, the rate of evaporation is nine times that in still air.

(iv) Solar Radiation

Solar radiation greatly influences the temperature of stored constituent materials, particularly the aggregate, for making concrete. If the heat absorbed during the day by a stockpile of aggregate is not lost completely during the night hours, the internal temperature may gradually rise to a level which, in turn, can raise the temperature of freshly-mixed concrete and adversely affect curing.

When concrete is directly exposed to sunlight, its surface temperature is usually 7°C to 12°C higher than the temperature of the surrounding air. This may increase the evaporation loss significantly.

(v) Daily Temperature Fluctuations

A fall in temperature overnight has the beneficial effect of cooling both the stored material and the mixing equipment. However, lowered night-time temperatures may seriously affect unprotected concrete in the early stages of hardening. While losing heat to the cool night-time environment, the concrete contracts. Because of the low thermal conductivity of concrete, its interior mass retains its temperature and dimensions. The resultant tensile stress in the exterior of the concrete is liable to be relieved by the formation of cracks.

CUMULATIVE EFFECT OF HOT WEATHER COMPONENTS

(i) Evaporation

a) If the air temperature and humidity remain the same and the wind speed increases from 8 to 32 km/h, the evaporation rate will increase by 300 percent.

b) If the humidity and wind speed remain the same and the air temperature changes from 16 to 32°C, the evaporation rate will increase by 300 percent.

c) If the air temperature and wind speed remain the same and the humidity decreases from 90 to 70 percent, the evaporation rate will increase by 300 percent.

d) If the wind speed increases from 8 to 32 km/h, the air temperature rises from 16 to 32°C, and the humidity decreases from 90 to 70 percent, the evaporation rate will increase by 900 percent.

(ii) Compressive Strength of Concrete

The table below shows how temperature and humidity combinations can cause a loss of compressive strength.

Ambient Temp °C	Relative Humidity %	28-Day Strength Ratio (%)
23	> 75	100
23	60	73
38	25	62

(iii) Flexural Strength of Mortar

Figure 1 shows how relative humidity levels adversely affect the flexural strength of a 1:3 mortar.

(iv) Shrinkage Cracking

ACI Committee 305 R-91 (1993) lists the following temperatures with relative humidities which are potentially critical to plastic shrinkage cracking of concrete.

Concrete Temperature (°C)	Relative Humidity (Percent)
40.6	90
37.8	80
35.0	70
32.2	60
29.4	50
26.7	40
23.9	30

Potential Concreting Problems in Hot Weather

Concreting problems in hot weather are related to either the fresh state or the hardened state, but the difficulties and problems of the former category greatly influence the properties of concrete in the latter state. Hot weather problems faced at the fresh-concrete stage result in an increased:

i. water demand for a given level of consistency.
ii. rate of slump loss (with a consequent attempt by un-skilled field staff to add water at site).
iii. rate of setting posing greater difficulties in handling, compacting and finishing.
iv. risk of cold joint formation.
v. tendency for plastic shrinkage cracking.
vi. difficulty in controlling the amount of air content in an air-entrained.

The damaging influences, faced by hardened concrete exposed to hot weather, are increased:

i. permeability (if water is allowed to evaporate unchecked from the freshly-placed concrete mass).
ii. tendency for drying shrinkage cracking.
iii. differential thermal cracking from temperature differentials within the cross-section.
iv. risk of reinforcement corrosion because of the ingress of harmful substance through temperature-induced cracks.

and reduced:

i. 28-day strength and beyond.
ii. quality of appearance due to efflorescence, cracking and disintegration.

Preventative Measures During Hot Weather Concreting

The foregoing discussion illustrates that there is a need to adopt measures to control the temperature of the ambient air and that of the concrete, particularly during the early stages of the application process. Some of these precautions are external and are termed as "measures from without", i.e. steps taken to counter the hot weather effect by external means while the approaches related to lowering the temperature of the concrete from the mixture itself are the 'measures from within'.

Measures from Without

Standard practices like carrying out concreting operations without delay, shading the concrete surface, erecting wind barriers, scheduling concreting during cooler hours are to be followed. ACI Committee 305 R-91(1993) provides comprehensive guidance on these measures and will not be discussed in this paper.

Measures from Within

A number of steps, described below, can be taken to improve concrete resistance to the adverse influence of hot weather.

1. Controlling the temperature of concrete ingredients.

   - Aggregates occupy 60-80% of the volume of concrete. A reduction in aggregate temperature of 1°C will lower the concrete temperature by approximatly 0.5°C.

   - The temperature of the mixing water has the greatest effect per unit weight on the temperature of concrete because its specific heat is 4 to 5 times that of cement or aggregate. Lowering the water temperature by 2°C will lower concrete temeraturep by approximately 0.5°C.

   - The type of cement used influences both the rate and the heat of hydration. Typically, for every 100 kg of cement in a concrete mix, the increase in the intrinsic temperature of the mix can be up to 13°C. Thus for a concrete mix using 250 kg of cement per m^3, the rise in temperature due to the heat of hydration alone would be around 45°C.

   - Cements low in C_3A (Tricalcium Aluminate) and having a high C_2S/C_3S ratio (Dicalcium Silicate/ Tricalcium Silicate) are more suitable in terms of the mix temperature control as they have lower heats of hydration. The effect of internal heat generation is more serious in the early stages, as around 50% of the total heat is liberated between 1 and 3 days, about 75% in 7 days and nearly 90% in 180 days.

2. Using cement modifiers.

   The use of supplementary cementitious materials, as either additives, or for the partial replacement of cement, is becoming increasingly common and various standards have now been approved which permit and specify their use in concrete.

Pozzolanic materials, by virtue of their property of slowing down the rate of hydration, reduce the amount of heat evolved which, as a consequence, is more evenly dissipated. Pulverized fly ash, silica fume, blast furnace slag and natural pozzolanas (in powder form) have found considerable application in concrete.

Silica fume, by virtue of its extremely fine particles (typically 1/100th of the cement particle size), acts as a pore-blocking material and improves concrete durability. However, the same fineness demands that workability agents are added to improve the compactibility of the concrete mix. Also, special attention needs to be given to curing procedures, particularly with low water-cement ratio mixtures, in order to avoid shrinkage cracking.

A new generation of pozzolanic materials is now being made available commercially. Their use is supported by test data which shows their advantages over silica fume. While silica fume is an industrial by-product, the other materials are either manufactured or obtained from natural deposits.

One such product is a reactive, white alumino-silicate, called High Reactivity Metakaolin (HRM). It is manufactured by calcining purified kaolinite within a specified temperature range. Chemically HRM combines with calcium hydroxide to form calcium silicate and calcium aluminate hydrate.

Despite its particle size being 10 times greater than that of Silica fume, an addition of 10% of HRM into a concrete mix improves its modulus of rupture, reduces its drying shrinkage and reduces its heat of hydration when compared to a similar mix containing 10% Silica fume (Caldrone, et al, 1994).

3. Reducing the Water Content of the Concrete Mix

In a normal concrete mix, more water is added than is required for the hydration of cement. As a general rule, every 100 kg of cement would need only about 27 liters of water to complete the chemical reaction with cement particles. If only this quantity of water was added to a mix, the result would be little more than damp aggregate with cement powder occluded on to the surface. To ensure complete coating of individual aggregate particles by the cement paste and to produce a concrete mixture which is plastic or fluid enough to transport, handle, place, compact and finish in the desired form, concrete needs to be lubricated by the addition of about twice as much water as is necessary for cement hydration.

After performing its lubricating function, the extra water remains uncombined and makes interconnected pathways within the finished concrete mass. Some of it migrates to the surface and evaporates leaving behind a network of pores, capillaries and voids in the concrete. Later, moisture, gases and other aggressive agents will diffuse back into the concrete through these easily accessible routes.

In hot weather concreting, chemical admixtures play a very important role. Their specifications are laid down in the ASTM Standard C494-92. Of particular interest for hot weather applications are Types A,B,D, F and G. Their beneficial effects include reducing the quantity of mixing water, increasing the initial slump at a lower water-cement ratio, prolonging the slump retention and retarding the setting of concrete. Table 1 shows some typical test data for different types of concrete admixtures.

4. Enhancing the Curing of Concrete

No matter how high the quality of a concrete mix is, unless it is cured properly and effectively, the end result can still be a poor quality, low grade concrete with poor durability. Measures can be taken during curing which control the rate and degree of evaporation of water and prevent the quick drying of freshly-placed concrete. They also provide an ambient environment to concrete in which the cement-water hydration can proceed under favorable conditions.

Curing-enhacing operations should commence soon after the final finishing of the concrete surface. Ideally, this should commence with the application of a fog spray of water. Once the concrete is sufficiently hardened, it should be covered with a wet burlap. The use of expanded polystyrene or other insulating materials also tend to keep the concrete at an even temperature. Specialized techniques using impervious coatings and linings can be adopted under expert supervision and guidance. Reflective paint may be applied and wind barriers should be erected to minimize evaporation loss and hence reduce the potential hazard of cracking of large concrete areas. Curing compounds, either water-based or resin-based, are available which can be applied to form an impervious membrane on the concrete surface soon after application.

5. Improving the Tensile Strain Capacity of Concrete

Concrete is strong in compression but, being brittle in nature, its tensile strength is low. Hence, in hot weather, the shrinkage forces induce tensile strains which cause cracking. These cracks are mostly in the cement paste (the aggregate being usually sound and strong and capable of resisting tension) and therefore, the addition of materials which can improve its tensile strain capacity will increase the service life of the concrete structure.

(Wafa, et al, 1996) have shown that the use of low dosages of polypropylene fibre (0.2% to 0.5% by weight of cement) considerably reduces or even eliminates the cracking associated with plastic shrinkage or drying shrinkage of both normal-strength (23-40MPs) and high-strength (60-89 MPs) concrete mixes.

Another effective method of improving the tensile strain capacity of concrete is to add a colloidal suspension of a suitable synthetic polymer in water. The very small polymer particles (typically in the range of 0.01 to 0.001mm) increase the workability of the mix and decrease the bleeding of the paste. Their real advantage lies in the formation of a continuous polymer film within the paste matrix. Many polymers require little moisture for curing and can form a film even at a relative humidity of 50%. A flexible polymer film in concrete not only inhibits the growth of micro-cracks under tensile stress but also bridges the cracks. Additionally, a polymer film lining the capillary pores and evaporation channels will help to reduce the permeability of concrete and block the entry of external aggressive agents.

The data presented in Figure 2 shows the beneficial effects of polymer addition. The specimens were of 1:3 mortar and had been exposed to an outdoor environment for a period of 36 months. Besides the control (unmodified) mortar, specimens containing separately polyvinyl acetate (PVA), styrene-butadiene rubber (SBR) and polyacrylic materials (Acrylics) were tested for tensile strength after various durations of exposure. Figure 2 shows that while the control mortar lost tensile strength with time, due mainly to damage to the internal structure of the paste and to the paste-aggregate bond, the mortar specimens containing polymers gained tensile strength with time. The degree of tensile strength increase was a function of the type of polymer, PVA imparting the least improvement and acrylic the most, with SBR modification giving results in between the other two polymers.

Concluding Remarks

Exposure to hot weather environments has an adverse influence on the properties of concrete, both in the fresh state as well as in the hardened state. Besides causing a reduction in concrete strength and inducing cracks, such an exposure leads to a shortened service life of the structure.

While concreting in hot weather, appropriate precautionary measures should be taken to keep the concrete temperature low. Use of admixtures and pozzolanas reduces moisture loss from concrete. Additions of fibers and/or polymers improve the tensile strain capacity of concrete.

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Fig. 1 Flexural strength of 1:3 mortar as a percentage of wet-cured specimen strength.

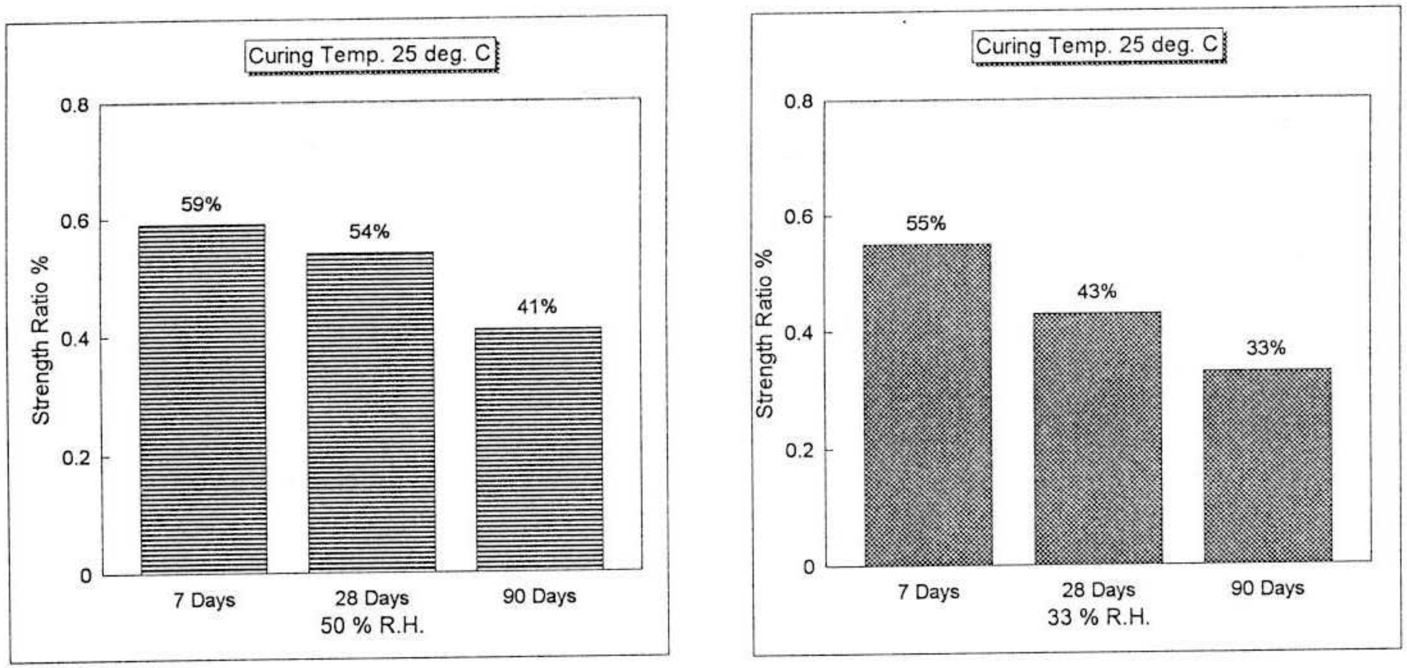

Table 1: Influence of Different Admixture Types on Concrete Slump

Admixture Type (ASTM C494)	Function	W/C Ratio	Admixture Dosage (% by wt. of cement)	Slump (mm)	
				Initital	Final
Control	-	0.55	Nil	25	-
A	Water Reducer	0.48	0.53	70	30
BD	Water Reducer, Retarder	0.50	0.40	110	60
F	High Performance Superplasticiser	0.40	1.50	180	90
G	Superplasticiser with Workability Retiontion	0.50	1.50	170	100

* Cement Content: 350 $kg.m^{-3}$ of concrete

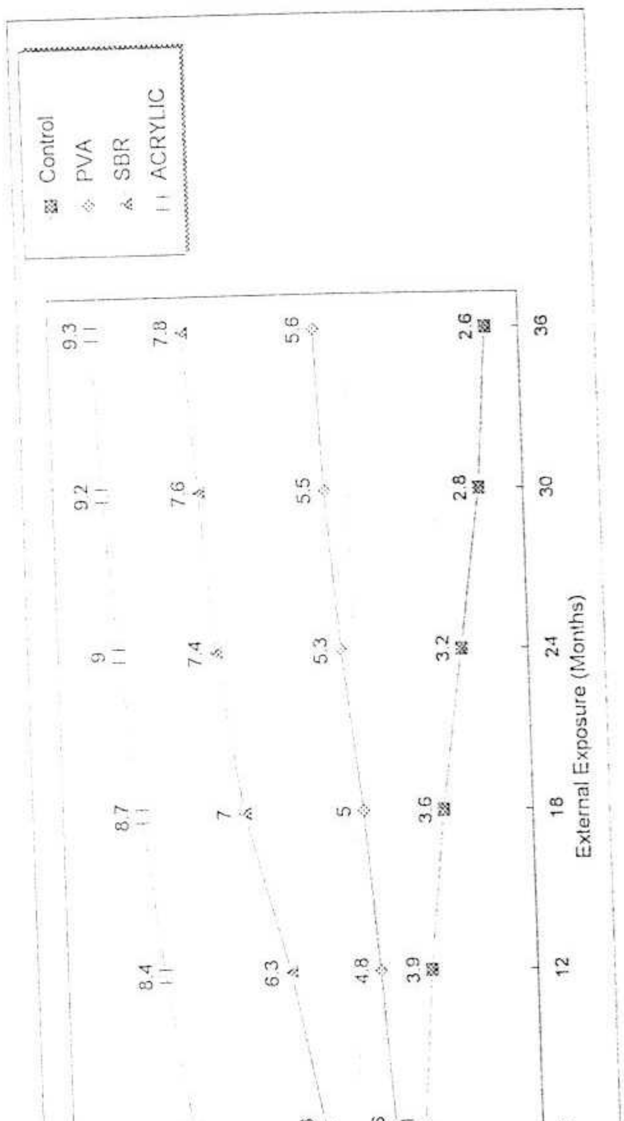

Fig. 2: Improvement of Tensile Strength of 1:3 mortar by Polymer-modification