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Effect of Hot Weather Conditions on the Microcracking and Corrosion Cracking Potential of Reinforced Concrete

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Synopsis: This study focuses on the damaging implications of the daily temperature fluctuations in the aggressive climatic conditions of hot-arid regions due to strain incompatibility resulting from the widely differing coefficients of thermal expansion of the local crushed limestone aggregate and the hardened cement paste. The data developed strongly indicates that temperature fluctuations cause microcracking in concrete which would increase its permeability and lower its tensile strength and cracking time to a noticeable degree. In this investigation, concrete specimens of water-cement ratios 0.40, 0.50, and 0.65 with a cement content of 550 lb/yd^3 (330 kg/m^3) were subjected to cyclic heating in programmed ovens which carried out 120 temperature fluctuations, each simulating the temperature regime of a typical summer day in Eastern Saudi Arabia. The thermal regime was characterized by a temperature swing from 27 ^{O}C to 60 ^{O}C within a 24 hr period. This included the effect of concrete surface heating by direct solar radiation. Pulse velocity, permeability, and time-to-cracking data were developed in reference and cyclic heat-treated specimens at 20, 40, 60, 80, and 120 heating cycles. It was observed that the cyclic heat treated specimens had a significantly reduced pulse velocity, a noticeably increased permeability, and, depending on water-cement ratio, a 55 to 70 percent reduction in cracking time due to reinforcing bar corrosion. It is inferred from this data that a significant degree of microcracking is induced in concrete due to the thermal incompatibility of concrete components.

Microcracking of concrete increased with the number of heating cycles and there was a systematic improvement in the performance of concrete with a reduction in w-c ratio.

Keywords: Corrosion; cracking (fracturing); cyclic heat; hot weather construction; microcracking; permeability; reinforced concrete; strains; temperature; tensile strength; thermal expansion; velocity; water cement ratio

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INTRODUCTION

The exposure conditions for concrete in the Middle East constitute one of the most aggressive climatic environments in the world. In the Arabian Gulf States, interaction between concrete and the environment controls material performance (1-4) and has resulted in premature deterioration and low durability of concrete construction to a level of major concern.

In terms of its sensitivity to its service environment, concrete has been likened to a living organism. Contrary to its plain rock-like appearance and deceptive simplicity, concrete is a highly complex diphasic or three-component (cement, water and aggregate) pseudo-solid system which is affected by many external actions such as variation of pressure, temperature, or humidity. In the Gulf States, many problems of concrete durability have been encountered which are related to the adverse effects of climatic conditions during mixing, placing, curing and the service life of structures.

EFFECT OF HOT WEATHER CONDITIONS ON FRESH AND HARDENED CONCRETE

Climatic conditions in the Gulf region may cause increased water demand and slump loss, premature setting resulting in cold joints and insufficient compaction and enhanced tendency for plastic shrinkage and pre-setting cracking in fresh concrete. Concrete cast and cured under hot weather conditions and not cured sufficiently thereafter may show as much as 25%

reduction in strength (5). Any deficiency in curing which has a negligible effect in mild climatic conditions may permanently impair the quality of concrete skin in hot weather conditions, thereby weakening the protective shield against the ingress of chlorides, sulfates, moisture and oxygen into the concrete matrix. High rates of evaporation of mix and curing water cause significant sulfate and chloride salt concentrations near the surface and may result in sulfate attack and early initiation of rebar corrosion if steel is located near the surface. Thermal and drying shrinkage cracking are a common feature of concrete damage in this region. Corrosion and solubility of salts are accelerated with an elevation of temperature which on the surface of the concrete may be as high as 70 to 80 °C due to the direct solar radiation effect on a typical summer day. Fluctuations of temperature cause cycles of expansion/contraction and hydration/dehydration resulting in microcracking and damage due to thermal incompatibility of concrete components.

All these effects interact concomitantly and cumulatively and significantly increase concrete permeability and reduce its durability.

TEMPERATURE FLUCTUATIONS AND MICROCRACKING IN CONCRETE

It is being increasingly recognized that the aggregate-paste bond strength forms the weakest link in the heterogeneous concrete system (6-8). Studies focusing on direct observations of microcracking in concrete show that microcracks can be divided into two categories: bond cracks which exist at the aggregate-paste interface, and mortar cracks which exist within the mortar. These studies also show that considerable microcracking at the aggregate-paste interface exists in concrete even before it is subjected to any external load. Interfacial microcracking is partly due to segregation and partly due to volume changes during hydration and setting. When microcracking is confined to the transition zone, as happens before loading, it is essentially discontinuous. However, when concrete is subjected to external load and thermal/humidity gradients, specially to cycles of temperature and humidity changes, then mortar cracks start bridging and spanning between bond cracks, thereby making the microcracking system within concrete continuous (9). Such a continuous system of microcracks in concrete gives rise to distinct paths and conduits for the ingress of aggressive ions from outside and will play a decisive role in the durability performance of concrete. Also, the existence of considerable microcracks in concrete due to segregation, volume changes during hydration, and setting and cyclic thermal/humidity changes will lower its tensile strength. This will advance cracking failure due to reinforcement corrosion which is caused by the tensile mechanical pressure from the expansive corrosion products.

One aspect of the hot weather condition which has not been adequately researched and yet may cause considerable physical disintegration and microcracking is the large fluctuation in the daily and seasonal temperature conditions. For example, on the coastal flats of the Gulf region the temperature easily varies as much as 20 ^{o}C during a typical summer's day. This rapid and continuous variation in the temperature causes continual expansion and contraction which may result in considerable microcracking. The expansion-contraction cycle becomes all the more damaging due to the thermal incompatibility of concrete components. The differential expansion and contraction movements of aggregate material and the hardened cement paste may set up tensile stresses far beyond the tensile strength of concrete resulting in microcracking. Limestone, the predominantly used aggregate, is exactly the rock type having the widest spectrum of coefficient of thermal expansion values (1 to 10 x $10^{-6}/^{o}C$). The coefficient for hardened cement paste is much higher (usually between 10 x 10^{-6} and 20 x $10^{-6}/^{o}C$). With the fall of temperature tensile and compressive stresses are set up in the cement paste and the aggregates respectively. With a rise of temperature the stresses are not exactly reversed but tensile stresses are set up at the aggregate-paste interface tending to cause interface bond failure and significant microcracking in and around the transition zone (10). It has been shown by Hsu(11) that a volume change of 0.3% is enough to generate tensile stresses of the order of 1800 lb/in^2 at the aggregate-paste interface. Slate and Matheus (12) have determined volume changes of cement paste and concrete from the time of casting to an age of 7 days. This work shows that volume changes even larger than 0.3% occur during setting and hardening of concrete. The authors, on the basis of a simple mathematical model, have inferred that for a commonly occurring value of 6 x $10^{-6}/^{o}C$ for limestone, tensile stresses of more than 250 lb/in^2 for every 10 ^{o}C fall of temperature are set up in the concrete. These stresses are cumulatively interactive on the shrinkage and microfissure stresses already present due to other causes.

RATIONALE FOR THIS STUDY

This study focuses on the effect of cyclic thermal changes on the microcracking in concrete and the lowering of its tensile strength which may significantly advance corrosion cracking. The thermal changes imposed on concrete simulate the daily fluctuations of temperature typical of the ambient conditions during summer months in the Gulf region. Increase in microcracking due to thermal cycles is determined indirectly by two techniques: firstly, by the additional water absorbed under pressure by cyclic heat-treated specimens and secondly, by the changes in the pulse velocity measurements. In this study the lowering of the tensile strength is measured directly by recording the reinforcement corrosion cracking time in accelerated corrosion tests on reference and heat-treated specimens.

EXPERIMENTAL PROGRAM AND TECHNIQUES

Materials and Specimen Preparation

Investigation on microcracking due to cyclic heating was carried out on concretes made with w-c ratios of 0.40, 0.50 and 0.65. Accelerated corrosion tests to evaluate the effect of cyclic heating on corrosion cracking time were carried out on two concretes having w-c ratios of 0.40 and 0.65. All mixtures were made with a cement content of 550 lbs/yd^3 and a coarse to fine aggregate ratio of 2:1. The coarse aggregate used was local crushed limestone with 3/4 in. maximum size having a bulk specific gravity of 2.37 and average absorption of 2.3%. The fine aggregate was beach sand with a specific gravity of 2.70 and absorption of 0.27%. The beach sand had a grading significantly finer than the ASTM C 33 limit for sand. Both coarse and fine aggregates were washed free of dust with sweet water which had combined Cl^- and SO_4^{--} less than 100 mg/l. After washing the aggregates were air dried at 110 °C for a period of 20-24 hours. The aggregates were air cooled before use. Desalinated water was used for mixing.

Concrete was mixed in a 1/2 ton electrically operated revolving drum type mixer. The molds were filled in three equal layers and vibrated at a rate of 3600 vibrations per second till complete consolidation was assumed when a uniform thin film of mortar appeared on the concrete surface. After casting, the specimens were kept in air for 24 hours and then demolded and stored in water for 28 days. Thereafter the test specimens were transferred to the programmed ovens for cyclic heating whereas reference specimens were retained in water.

All specimens were 4-inch cubes. In order to evaluate the effect of microcracking on concrete resistance to corrosion cracking, 4 inch cubes were prepared with 1/2 in diameter mild steel bar embedded centrally with a clear cover of 1 inch from the bottom. The bar protruded 2.5 inches out of the concrete cube.

Simulation of Daily Temperature Fluctuations

In order to provide a realistic simulation of daily temperature fluctuations, the actual ambient temperature variation in Dhahran for the six summer months of April to September were analyzed for a 7-year period and are shown in Fig. 1. It is seen that the daily temperature variation is very similar for the summer months of June, July and August. Therefore, an average temperature variation of these three months over a 7-year period, shown in Fig. 2, was adopted as a possible regime to simulate the daily fluctuations of temperature during the peak summer months. To the maximum ambient temperature must be added the effect of direct solar radiation which raises the temperature of concrete surfaces significantly in excess of the ambient temperature.

An experiment was performed to evaluate the effect of solar radiation on typical concrete surfaces. On several days in the month of July, ambient and concrete surface temperatures were recorded concurrently at hourly intervals from 10 am to 2.30 pm. Based on this test and on data developed on solar radiation effect by Mironov et al (13) and Jaegermann et al (14), a 20 ^{O}C addition was made to the maximum ambient temperature for a 4 hour period from 11 am to 3 pm to take into account the effect of direct solar radiation. The somewhat idealized regime adopted for simulating daily temperature fluctuations for summer months is shown in Fig. 3.

The heating and the electrical systems of two ovens were then modified to automatically trace the proposed 24-hour heating cycle. About forty-two 4-inch cubes and steel embedded specimens were then located in each oven in a manner to allow adequate air circulation within the oven. Temperatures were repeatedly checked at different locations within the oven and were found to be fairly uniform in the whole range of the regime. These ovens performed cyclic heating with excellent precision in accordance with the proposed temperature regime of Fig. 3. Fig. 4 shows the ovens with specimens and with mechanical and electronic fixtures to automatically control the cyclic heating. A strip chart recorder was hooked to the ovens to monitor the heating cycle continuously.

The compressive strength, pulse velocity and permeability data developed in this study are up to 120 cycles of heating after a 28 days' curing period for the specimens. Parallel data have been obtained for reference specimens which were kept under water for 120 days after a 28 day curing period.

Permeability Testing

In this study the objective of permeability determination is to develop a relative measure of the degree of microcracking which occurs in concrete as a result of cyclic heating. With increased microcracking the permeability would be enhanced thereby reducing the barrier-effect against the ingress of chloride ions and oxygen to the steel-concrete interface. This will reduce concrete protection against corrosion. There is therefore an important relationship between permeability caused by microcracking and concrete durability.

A special apparatus shown in Fig. 5 was developed and fabricated for high pressure permeability testing which is similar to those developed by Lindsay [15] and Tyler and Erlin [16]. It consists essentially of a water-tight pressure vessel for two 3/4 x 4 inch cylindrical test specimens, a hand pump for applying hydraulic pressure, high quality pressure gauge for measuring hydraulic head, and a graduated glass cylinder for measuring the amount of water pumped into the pressure vessel. The pressure chamber is just large enough to accommodate two 3/4 x 4 inch cylindrical specimens, thus keeping the volume not occupied by a specimen to a minimum. Water flows by gravity from the graduated glass cylinder into the hand pump.

The two 3/4 x 4 inch cylindrical specimens used for the high pressure permeability tests were cored from the reference and cyclic heat treated 4 inch cubes. The reference and cyclic heat-treated cored specimens were brought to a similar state of internal dryness by oven drying at 80° C till the reduction in weight due to loss of water ceased to occur. The cylindrical concrete specimen was then placed into the water-filled pressure vessel and a hydraulic pressure of 1000 psi (6.9 N/mm^2) was applied through a hand pump. The rate and the total amount of water forced into the specimen was recorded. The method provides a useful comparison of the relative permeabilities of various concretes used in this program. The apparatus and the procedure are fully described elsewhere (17). The water absorption data developed are based on averages of three specimens for each mixture.

Pulse Velocity Measurements

Proprietary Pundit equipment was used with 82 KHZ transducers coupled to the opposite faces of the cubes with the help of a sticking grease to obtain pulse velocity readings along all three axes. Care was exercised in ensuring good acoustic coupling between transducer face and the surface of the cube.

Resistance to Concrete Cracking

This test was designed to evaluate the effect of microcracking on the resistance against cracking caused by the expansive mechanical pressure generated due to the growth of rebar corrosion products. Specimens with w-c ratios of 0.40 and 0.65 and treated with 164 simulated cycles of daily temperature fluctuations after 28 days of curing were subjected to this accelerated corrosion test where time taken to first corrosion cracking was determined. Concrete with increased microcracking as a result of cyclic heating should crack earlier.

For this test 1/2 inch diameter steel bars embedded in concrete specimens of the type shown in Fig. 6 were used. These specimens were sawn to the 2 x 4 x 4 inch size from the steel-embedded 4 inch reference and cyclic heat-treated cubes (Fig. 7). The proposed size of the specimen ensured that the crack due to rebar corrosion would always occur vertically along the bar on the 4 x 4 inch faces of the specimens. To simulate the corrosion process, direct currents of 20 and 15 milliamperes were impressed on the bar embedded in the cube using a system incorporating a small rectifier power supply coupled with an ammeter to monitor the current, and a potentiometer to control the current intensity. Each specimen was placed on plastic chairs under water in a galvanized steel tank. The direction of the current was arranged so that the reinforcing steel served as the anode, while the galvanized steel tank body acted as the cathode. To facilitate an even spread of the corrosion current over the bar surface the specimens were soaked in water for at least 2 hours prior to the test. The current supplied to each specimen was checked on a regular basis and any drift was corrected by the adjustment of the potentiometer.

Appearance of the first crack in each specimen was monitored precisely by installing 2 inch SR-4 strain gauges horizontally near the top on the opposite sides of the 4 inch square faces of the specimen. The gauges were fixed very carefully on prepared concrete surfaces and were protected with an epoxy coating to avoid moisture penetration. The gauges were connected to a strain recording system which was hooked to a strip chart recorder to record strain continuously with time. As soon as the crack occurred, the strain gauge was damaged which was instantaneously recorded by the strip chart recorder. The accelerated corrosion test instrumentation is shown in Fig. 8.

Compressive Strength

Compressive strengths of reference and cyclic heat-treated specimens were determined after every 20 days/cycles in accordance with ASTM C 39 with a strain rate of 144 kN/minute.

RESULTS AND DISCUSSION

Results

Fig. 9 shows the effect of cyclic heating on the compressive strength of specimens made with w-c ratios of 0.4, 0.5 and 0.65. The strength data have been developed for 148 days for the reference specimens and for 120 heating cycles for the heat-treated specimens.

Fig. 10 shows the effect of cyclic heating on the pulse velocity measurements for reference and heat-treated specimens made with the three w-c ratios.

The permeability data for the cyclic heat-treated specimens for 120 cycles in comparison with the reference specimens for the three concretes are shown in Fig. 11 Fig. 12 shows a comparison of the water absorption capacities of 0.40 w-c concrete specimens subjected to 80 and 120 heating cycles.

Table 1 shows the effect of cyclic heating on the time taken for the concrete to crack as a result of tension developed due to the mechanical pressure exerted by the corrosion products. The specimens tested in this series were made with two w-c ratios of 0.40 and 0.65.

Discussion

The compressive strength of specimens subjected to cyclic heating increased with the number of heating cycles up to about 60 cycles, after which it almost stabilized or showed slight reduction. Such reduction' which in any case has not exceeded 3%, may be considered insignificant for all practical purposes and may be attributed to the unavoidable lack of uniformity associated with concrete making and testing. The increase in compressive strength during the first 60 cycles is significantly higher for the heat-treated specimens compared to reference specimens, and may be attributed to accelerated hydration of cement at higher temperatures.

Inspite of the fact that compressive strength has increased during the first 60 heating cycles, it is note-worthy that the structure of concrete has been deteriorating during this period due to the daily fluctuations of temperature. This is concomitantly shown by the three different techniques used in this study: firstly, by a progressive reduction in the pulse velocity measurements, secondly, by an increase in the permeability and thirdly, by a reduction in the cracking time of concrete for specimens subjected to cyclic heating.

The pulse velocity data of Fig. 10 for reference and heat-treated specimens up to the age of 148 days show increasing values of pulse velocity with time for reference specimens signifying a densification of the structure of concrete with the progress of hydration. However, at the same time pulse velocity measurements for specimens subjected to cyclic heating show a reduction in pulse velocity values for concretes of all the three w-c ratios, signifying an increase in the microcracking due to the thermal incompatibility of concrete components.

This position is also supported by the water absorption data presented in Fig. 11. It is seen that for each of the three w-c ratios the absorptive capacity, signifying permeability, is higher for cyclic heat-treated specimens than for the parallel reference specimens. Also, the absorptive capacity and hence permeability of specimens subjected to 120 heating cycles is somewhat higher in comparison with those subjected to 80 heating cycles (Fig. 12).

Table 1 shows the time taken for concrete specimens to crack as a result of induced rebar corrosion for reference and cyclic heat-treated specimens made with w-c ratios of 0.40 and 0.65. Time-to-cracking indirectly signifies the tensile strength of concrete. The time-to-cracking data show that the cyclic heat-treated specimens for the two mixes cracked significantly earlier than the reference specimens. The time taken for the cyclic heat-treated specimens to crack was half to one-third of the time taken by the reference specimens of the corresponding mixtures. This shows that the microcracking in the internal structure of concrete lowered its tensile strength thereby advancing its corrosion cracking time.

Another significant observation was the exudation of liquid corrosion products at the bar concrete junction which happened in the accelerated corrosion test for the cyclic heat-treated specimens only. The control specimens did not show the exudation of corrosion products and it is possible that the bars in the heat-treated specimens were undergoing corrosion through a modified mechanism. The exudation of corrosion products appeared to suggest a deterioration of the rebar-concrete bond thereby allowing noticeable exudation of rust products to take place.

The effect of concrete quality on its durability performance is clearly shown by the pulse velocity, permeability and the time-to-cracking data. All the three techniques show a systematic improvement in the performance of concrete in permeability, pulse velocity and time-to-cracking tests with a reduction in the w-c ratio. For example, after the cyclic heat-treatment, the 0.40 w-c concrete specimens took twice as much time for corrosion cracking as the 0.65 w-c concrete specimens.

CONCLUSIONS

1. Pulse velocity, permeability and time-to-cracking data are developed on reference and cyclic heat-treated concrete specimens. These data show that cyclic heating, simulating the fluctuations of temperature of a typical summer day in Eastern