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EVALUATION OF THE IN SERVICE THERMAL CYCLING EFFECTS ON THE FAST BREEDER REACTOR CONTAINMENT CONCRETES

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ABSTRACT

The degradation of the concrete characteristics due to the effects of the high temperature regimes is a matter of serious concern particularly in nuclear reactor structures. In the case of the fast breeder reactor structures the concretes are subjected only to marginally higher temperatures throughout its life span, but yet higher than that approved by the nuclear regulatory boards at present. The influence of these effects due to such marginally higher temperature differentials on the nuclear radiation shielding capability of these concretes is not yet very clear and needs a better understanding. The present paper is an effort to critically assess these effects through all the relevant parameters for a satisfactory correlation of the actual distress. These were studied through the evaluation of the changes in the internal structure due to temperature cycling as exhibited by the porosity related parameters like the sorptivities and its effects on the electrical resistivity and the ultrasonic pulse velocities.

INTRODUCTION

Concrete is essentially a heterogeneous material and the performance behavior is often dictated by its internal microstructure, influenced by a host of parameters related to its constituents, proportioning, production, curing and above all the service life environment in which it performs throughout its life span. In the present context, the degradation in the concrete internal microstructure due to in service temperature cycling is being discussed. In fact the degradation of the strength characteristics with temperature is a parameter often discussed, particularly through the dehydration and decomposition characteristics of its various constituents at the corresponding higher temperatures, typically ranging up to almost 1000^0 C. In general, these studies are aimed at an understanding the failure of the concrete structures subjected to high temperature regimes like in the case of a fire or the meltdown situation in nuclear reactors.

However, it is to be noted that even the much smaller temperature differentials that can occur in certain structures like the fast breeder nuclear containment structures could be a cause for concern. These may be due to the moderately higher in service operational temperatures as in the case of the fast breeder reactor using the molten sodium pool blanket as the nuclear reaction control medium forcing the operating temperatures to levels higher than those allowed by the ACI recommendations. The code on the Requirements for Nuclear Safety Related Concrete Structures (ACI 349-01), specifies that the temperatures shall not exceed 65^0 C (150 F) except for local areas, such as around penetrations, which are allowed to have increased temperatures not exceeding 93^0 C (200 F) during the service life. Also, in case of an accident the temperatures shall not exceed 176^0 C (350 F), though the local areas are allowed to reach 343^0 C (650 F) for very short periods.

The corresponding temperature stresses in fact are accentuated by the temperature cycling and also the temperature gradients in the concrete structural components, the differential stiffness of the component assemblage causing restraint due to the intricacies in the configuration. Most important is the fact that the associated structures have to perform the function of nuclear shielding over prolonged periods of time and any degradation of the shielding capacity over time can never be compromised for the entire life of the structure or in many cases even far beyond that operational life, though the facility is not any longer operational. But it is obvious that these long term effects due to such marginal stresses are difficult to assess even through accelerated test methods, as the characteristics that are being influenced by them also change only marginally and quantification of these minute changes to a satisfactory degree is always difficult. The present paper is an effort to critically assess these effects through all the relevant parameters for a satisfactory correlation with the actual distress.

TEMPERATURE EFFECTS ON CONCRETE

It is also well established through extensive testing on concrete samples that in concrete the free water evaporates initially (up to about 120^0 C) and the dehydration of the CSH gel will then start and will continue up to a temperature of about 800^0 C, leaving almost an inert mass. This dehydration between the temperatures of 120 - 800^0 C is also associated with other effects like the dehydration of the calcium hydroxide (400 - 530^0 C) and the decomposition of the calcium carbonates formed later until 800^0 C both leading to the destruction of the cementitious system and a further increase in temperature will result in a melt at temperatures beyond 1000^0 C depending up on the aggregate composition (Lee,2009; Xiao, 2004; Naus,2006). Some of the finer aspects of concrete degradation were also studied through the material characterization methods like XRD, SEM and DT-TGA. While these material characterization studies present an insight into the various compounds resulting at the various stages, studies on the larger concrete specimens will provide the remaining strength characteristics to ensure the stability and integrity of the total structure.

However, the present aspect about the effect of the much smaller temperature differentials near the ambient working conditions is a specific case of the above, and has assumed significance only due to the recent introduction of the fast breeder reactor technology. The corresponding stress cycling may cause an accumulation of strain, similar to the well-recognized ratcheting phenomenon in the metal components. In fact the effects of similar marginal stresses form the creep, shrinkage and temperature factors are always included in the design itself. But when these are compounded with the temperature differentials in the operational processes in a critical industry like the case of fast breeder reactor there could be reasons for concern.

The shrinkage and microcracking in concrete due to the variations in moisture and temperature gradients is a well-established fact. These effects due to the moisture and temperature variations continue to influence the internal microstructure of the concrete both during the initial hydration period and also during operational life of the structure. The corresponding strain components are reflected in the permanent deformations and cracks that exist. Also during the service life of the structure the ever changing moisture and temperature distributions often induce additional strains or deformations which keep growing due the ratcheting type effect from the moisture and thermal cycles occurring. Also the crumbling of the crack faces during these cyclic stresses in a heterogeneous medium like concrete that will never allow a complete closure of these cracks on reversal of the moisture ingress and egress. In fact these effects are accentuated by further crack growth over time mainly due to the restraints on such movements from either the substrate or the complex geometry of the members.

Lee (2009) presented a prediction model for the thermal degradation of the elastic modulus of concrete considering the phase transformations in the different temperature ranges. He also felt that the aggregates play an important role in the degradation process at high temperatures. This aspect was also reinforced by the report of Naus (2006) while discussing the results of Khoury (1996). It is also obvious from the above that particularly in the temperature range of ambient to about 200^0 C the lime stone aggregate concretes appear to show an improvement in compressive strength compared to their counter parts using gravel, while basalt concretes appears to be largely unaffected in this range. In fact Khoury (1995) suggests that some of these transient stresses in concrete can be broadly addressed through a “First heat cycle”, simulating the heating of the concrete following a hypothetical thermal transient caused by the loss of cooling water or inadequate performance of the liner thermal insulation. In a way he appears to suggest that these forced marginal distress procedure will resolve itself due to the redistribution of the stresses during the operational life.

Zadrazil (2004) studied the effect of temperature on the compressive strength and the corresponding porosity at the early ages (up to 180 days). The authors show that concrete drying in the range of 100^0 C -200^0 C led to an increase in strength, and this was attributed to the higher mobility of water in its vapour state (so-called steam curing effect) particularly at these early ages. However, the microcracking that is associated with the thermal incompatibility of the hardened cement and aggregate will increase the porosity and thus lowers the strength. The resulting balance of these contradicting influences was also found to be decreasing with age. Similar opinion was expressed by Saad (1996) regarding the effects of the physic-chemical processes occurring during heat treatment essentially due to the heterogeneity of concrete. In fact he opines that the resistance to the flow of steam creates a high pressure in the paste (pore and microcracking system) leading to conditions similar to an internal autoclaving of the cement paste. This led to the additional hydration of the unhydrated cement. The effects of temperature at a very early age on the dynamic and static elastic moduli of a couple of concretes were studied by Han (2004). While the cement type or age did not show a significant influence, it was seen that the moduli were almost the same at the higher curing temperatures of about 50^0 C.

EXPERIMENTAL INVESTIGATIONS

Presently it is obvious that it is the concrete porosity and the distribution of the internal micro-crack structure that is influenced because of the thermal cycling and temperature differentials between the matrix and the aggregate or the reinforcement. However, it is also seen that during the initial stages of concrete hydration (even up to a few months) this is often compensated due to the moisture driven hydration accentuated by the thermal effects, sometimes leading to even an increase in strength during such investigations.

In view of this the authors chose to study the effects on a few concrete specimens which are over an year old, to minimize the effects of the hydration effects that were already discussed. In specific concrete cube specimens of two grades concrete (design strength 20 and 30 MPa and target strength of 25 and 35 MPa) were chosen for this study, considering the fact that earlier nuclear containment structures adopted such concretes. The details of the concrete mixtures adopted are presented in Table 1.

Table 1: Details of concrete mixtures used for thermal cycling

Sl. No.	Constituents	M 20 (kg/m^3)	M 30 (kg/m^3)
1	Cement	266	325
2	Water	205	205
3	Fine aggregate	805	712
5	Coarse aggregate	1025	1068
6	w/c	0.77	0.63
7	Slump (mm)	165	100

These concrete specimens were subjected to a daily thermal cycling of 8 hours in a hot air oven at 105^0 C followed by immersion in water for 15 hours after the specimens have cooled reasonably for almost about an hour. The effects of thermal cycling were studied through the parameters that are most relevant to the porosity and micro-cracking as discussed earlier at the end of 0, 10, 20, 30 and 50 cycles. One important fact to be noted is that due to an inadvertent failure of the circulating fan of the hot air oven the specimens kept immersed in water after the 25th cycle for a period of about one month before the further cycling, allowing the specimens to recuperate and recover from the effects of the earlier thermal cycling.

The actual parameters studied include the variations in the wet and dry weights and absorption and desorption characteristics (to understand the overall pore volume) in these specimens due to the temperature cycling. Apart from these the electrical resistivity and the longitudinal and transverse pulse velocities in both in the wet and dry states after the specific number of cycles as given were also measured. The ultrasonic pulse velocities were measured by an Ultra Sonic Tester (Marui, Japan), having both the longitudinal and transverse 50 kHz transducers. Finally the degradation was assessed through the changes in strength at the end of the different number of cycles. These ultrasonic pulse velocities were used for calculating the variations in the Poisson's ratio, dynamic shear modulus and the dynamic Young's modulus. These parameters were calculated using the relations presented hereunder.

The propagation speed is obtained from Equation 1 below, by measuring the propagation time and distance of travel of the transverse and longitudinal waves.

$$v_1 = \frac{L}{t} \times (10) \tag{1}$$

where, v_l is the pulse velocity (km/sec); L the Distance (cm); t the propagation time (micro sec) and the number 10 a constant to adjust units.

The dynamic poisson's ratio can be obtained from the longitudinal and transverse pulse velocities using Equation 2.

$$\mu_D = \frac{{v_1}^2 - 2{v_s}^2}{2\,({v_1}^2 - {v_s}^2)} \tag{2}$$

where, μ_D is the dynamic poisson's ratio; v_l the longitudinal pulse velocity (km/sec); v_s the transverse pulse velocity (km/sec).

The dynamic shear modulus can be obtained from Equation 3.

$$c_d = \frac{{V_s}^2 \times p}{g} \times 10^7 \tag{3}$$

where, C_d is the dynamic shear modulus (kg/cm^2); v_s the transverse pulse velocity (km/sec); p the density and g the acceleration due to gravity (980cm/sec^2).

The dynamic modulus of elasticity can be calculated from the longitudinal and transversal pulse velocities, the density and the dynamic poisson's ratio through the Equations 4 and 5.

$$E_d = {v_1}^2 \times \frac{1}{g} \times \frac{p(1+\mu_D)(1-2\mu_D)}{(1-\mu_D)} \times 10^7 \tag{4}$$

$$E_d = {v_s}^2 \times \frac{1}{g} \times p(1+\mu_D)(2) \times 10^7 \tag{5}$$

where, E_d is the dynamic Young's modulus (kg/cm^2).

RESULTS AND DISCUSSIONS

The results of the various investigations on the two different concretes after the relevant number of wetting and drying cycles were presented and discussed hereunder. Table 2 presents the physical and mechanical strength characteristics of the concretes after the specified number of cycles. The wet and dry weights, the initial and final absorption and desorption values depict in some way the pore space and its distribution broadly in a concrete specimen.

Table 2. Effect of thermal cycling on the sorptivity and strength characteristics.

Sl. No.	Conc. grade	No. of Cycles	Weight		Absorption		Desorption		f_{ck}
			wet	dry	30 min	72 hours	60 min	72 hours	
			(kg/m^3)		(%)		(%)		(MPa)
1	M 20	0	2.53	2.48	0.80	4.22	0.16	4.27	27.40
2		10	2.48	2.43	0.80	4.22	0.40	5.40	23.50
3		20	2.54	2.43	0.54	3.85	0.80	5.43	25.80
4		30	2.56	2.45	0.54	5.11	0.57	5.30	26.80
5		50	2.54	2.49	---	---	---	---	16.90
6	M 30	0	2.58	2.53	0.84	4.06	0.47	4.53	34.20
7		10	2.53	2.48	0.68	2.88	0.43	4.27	36.20
8		20	2.60	2.51	0.37	2.58	0.82	5.56	33.50
9		30	2.61	2.55	0.64	2.81	0.42	4.37	37.80
10		50	2.60	2.55	---	---	---	---	33.60

Figures 1 shows the typical water absorption and desorption characteristics with time for the 20 MPa concrete studied. These in a way are the signatures of the permeable pore distributions in these concretes.

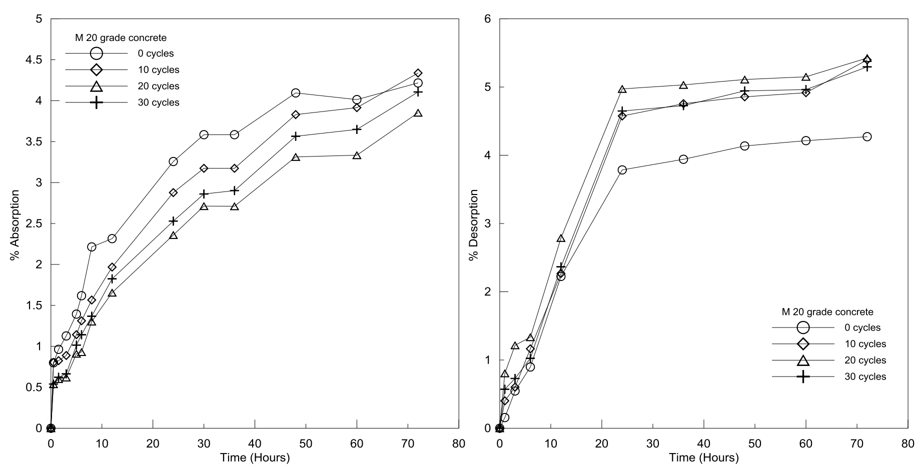

Figure 1. Typical absorption and desorption characteristics of the 20 MPa concrete

The above figures show a specific trend showing the degradation in the pore or microstructure of the concretes. However, it is easy to note that at 30 cycles the above trend is reversed, which is attributable to the recouping effect from the break in testing (with the specimens being left in water). The observations were very similar in the case of the 30 MPa concrete also. The strength values also are relatively higher at the 30 cycle stage as can be seen from Table 2 particularly in the 30 MPA concrete. In fact the individual differences between the two concretes indicate that the hydration effects are also dependent up on the strength or the permeable pore space that can be influenced by the rehydration (may one can call that also a type of autogenous healing) of concrete as was discussed previously.

After having looked through the physical and mechanical related parameters, the next part of the investigation turns to understand the effects of thermal cycling on the variations in the nondestructive parameters that are influenced by the variations in the pore / microstructure. In fact it is easy to note that the electrical conductivity and the ultrasonic pulse velocities are a measure of the continuity established or broken by the pore and microcracking structure in the concrete. Keeping this in view, the authors studied the electrical resistivity as well as the longitudinal and transverse pulse velocities in both the wet and dry states after the different cycling regimes planned earlier. The variations in these parameters and estimated values of the Poisson's ratio, dynamic shear modulus and the dynamic Young's modulus from these were presented below.

Table 3. Effect of thermal cycling on the nondestructive test parameters.

Sl. No.	Conc. grade	No. of cycles	Resistivity		UPV (L) direct		UPV (T) direct		UPV (L) indirect		UPV (T) indirect	
			Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
			(k ohm cm)		(km/sec)		(km/sec)		(km/sec)		(km/sec)	
1	M 20	0	66	---	3.44	---	1.45	---	2.17	---	1.00	---
2		10	58	75	2.61	2.61	1.19	1.20	1.85	1.82	0.97	1.32
3		20	36	56	2.93	2.69	1.16	1.32	1.90	2.41	0.97	1.63
4		30	39	227	3.54	2.96	1.44	1.16	3.76	2.85	1.32	1.88
5		50	21	188	2.97	2.78	0.99	1.22	1.61	2.19	0.78	1.51
6	M 30	0	75	---	4.05	---	1.71	---	3.42	---	1.23	---
7		10	56	34	2.61	3.13	1.21	1.45	1.99	2.07	0.98	0.78
8		20	29	7	3.28	3.19	1.12	1.28	2.38	2.80	1.00	1.05
9		30	68	146	3.80	3.11	1.51	1.14	3.59	2.91	1.63	1.22
10		50	32	134	3.65	3.33	1.19	1.36	2.40	3.16	0.84	1.39

It may be noted that the direct UPV measurements were obtained by using the opposite faces of the side of the cubes cast, while the indirect measurements were obtained from one of these sides and the bottom face of the cube specimen as cast. The DC resistivity was also measured by using the electrodes covering the full face of the specimen's opposite faces, which was a standard that was adopted for several investigations earlier.

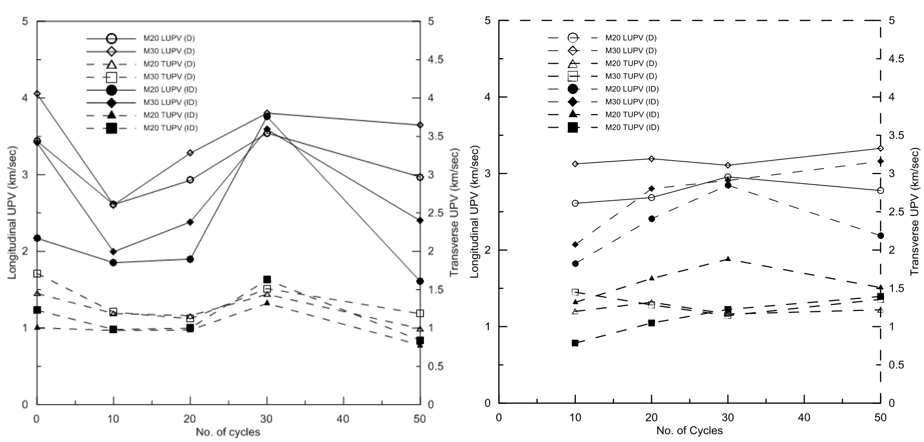

Figure 2. Variation of the longitudinal and transverse pulse velocities in wet and dry conditions.

Figure 2 presents the variation of the longitudinal and transverse pulse velocities, both in the wet and dry conditions for the concretes investigated. The decrease in the longitudinal pulse velocities with number of thermal cycles can be seen quite clearly from this Figure 2 for the 10 and 20 cycles, particularly in the wet state. The recoupment effect of the break and wet curing after that (after 25 cycles) is obvious from the recovery in the longitudinal pulse velocities. Even the transverse pulse velocities follow a similar trend. Figure 3 presents the variation of the dynamic moduli in wet condition. It was seen that the pulse velocity values in the wet condition were more stable (as observed during the experimental investigations) and were also more sensitive as can be seen from the results. For this reason the dynamic moduli from these wet pulse velocities were chosen for presentation in Figure 3.

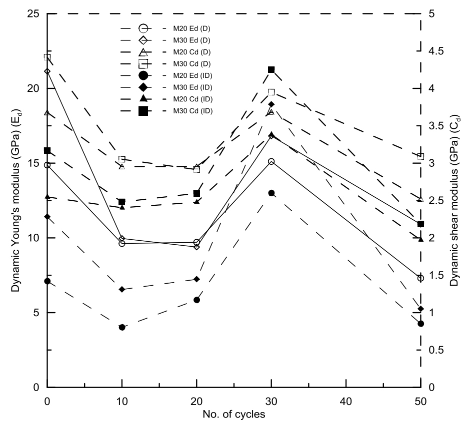

Figure 3. Variation of the dynamic moduli in wet condition.

Furthermore, it is obvious that the electrical resistivity and the pulse velocities are both influenced by the variations in the microcracking inside the concrete. In view of this the variations of the pulse velocities with the electrical resistivity in wet condition were presented in Figure 4. It may also be seen from the figure that the pulse velocities are directly related to the resistivity of the concrete and the influence of the strength of concrete was not seen.

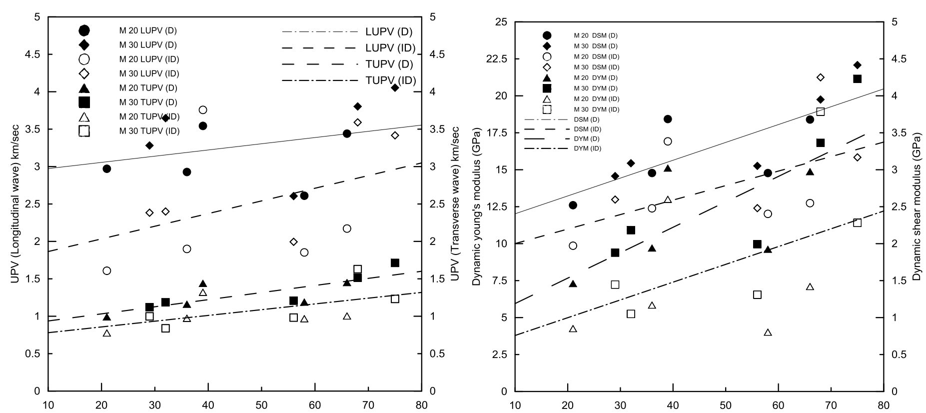

Figure 4. Variations of the pulse velocities and dynamic moduli with resistivity in wet condition.

Also, while the variations in the pulse velocities with the resistivity even in the wet state are only marginally varying, the computed dynamic moduli from the longitudinal and transverse velocities show a better spread in the variations, thus providing a more suitable avenue for the determination of the distress levels in the concrete due to the thermal cycling.

CONCLUSIONS

The investigations on the marginally high temperature thermal cycling effects on well cured normal concretes show that the imposed thermal cycling did cause a small but yet perceptible effect on the sorptivities as well as the strength of concrete. The effect of the rehydration due to an intermediate inadvertent curing was also seen from the results of this investigation.

The one important aspect that came out of this investigation is that the disruptions in the microstructure due to thermal cycling could be assessed also from the more directly related parameters like the electrical resistivity and the pulse velocities. However, the variation of the dynamic moduli obtained from the longitudinal and transverse pulse velocities with the electrical resistivity gave a comprehensive and also a better estimate of the distress due to the thermal cycling process.

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