

Analysis of Fatigue and Crack Properties of High-Performance Concretes for Application in Nuclear Power Plants

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Abstract— The design of concrete structures used in nuclear power plants should be suitable to protect against accidents caused by different factors, one of them being temperature. Stress due to temperature can be classified as a secondary stress, which is different from the primary stress caused by an external load. This stress can create a bending moment as a result of a temperature gradient inside walls, which is caused by the difference of indoor and outdoor temperatures, or an axial force can be exerted depending on restraint conditions. In addition to seismic loads, the temperature load is a dominant factor in the design of concrete structures used in nuclear power plants considering their thickness should be at least 4 ft. to ensure radiation shielding. In particular, the tensile stress around large passing-through reinforced parts or the tensile strength at cylinder-foundation slab joints may induce concrete cracks at an early stage. Moreover, the use of high-strength concretes and reinforced bars that can be designed with a relatively small amount of reinforced bars may lead to rapid reduction in rigidity after SSE. In addition, safety of nuclear power plant structures against accidents caused by high temperature and seismic loads is a mandatory permit and authorization issue that must be reviewed; moreover, the fatigue and crack properties of high-performance concretes must be determined. Thus, this study analyzed the fatigue and crack properties of high-performance concretes that can be used in nuclear power plants.

Keywords—HPC; Fatigue; Crack Property; Blast Furnace Slag; Fly Ash; Mineral Admixture;

I. INTRODUCTION

Concrete structures used in nuclear power plants should be designed to protect against various accidents and one of them is temperature. Similar to ACI 349-06, ACI 349-12 does not permit the use of structural plain concretes in nuclear power plant facilities for safety purposes. The minimum compressive strength of concretes has been increased from 2500 psi to 3000 psi. According to Section

6.3.14 in ACI 349-06, the temperature on the surface cannot exceed 150°F during normal operation and locally it cannot exceed 200°F. According to ACI 349-12, if the actual test strength of the mix design concrete at age 28 days is higher than the design strength by 115% or larger, then the temperature criterion can be alleviated to 180°F and 230°F respectively [1].

In 1934, Lynam defined autogenous shrinkage as “a shrinkage differentiated from ones that occur due to moisture loss into temperature or the atmosphere”. Following this, in 1940, Davis defined the autogenous shrinkage as a “phenomenon of changes in concrete volume as a result of changes in physicochemical structure inside the mass caused by other than stress due to moisture migration from the outside, temperature change, and external load or restraint”. The technical committee on autogenous shrinkage of concrete at Japan Concrete Institute defined autogenous shrinkage as “volumetric reduction of binders that occurs when cements are hydrated after initial set” and specified that it did not include shrinkages due to loss or permeation of a substance, temperature change, and external load or restraint [2, 3].

In the regulations in ASME and SNB, there are no specific descriptions about concrete creep as well as no specific mention about fatigue in relation to the use permit of new materials. Thus, this study reviewed existing techniques used for evaluating concrete shrinkage. Subsequently, it evaluated the concrete autogenous shrinkage, drying shrinkage, and ring test according to high strengthening of concretes and use of various admixtures to acquire foundational data for required quality guarantee. To this end, we analyzed fatigue and crack properties of existing nuclear power plant mix (6,000 psi) and a standard mix of 8,000 psi and 10,000 psi prepared in this study.

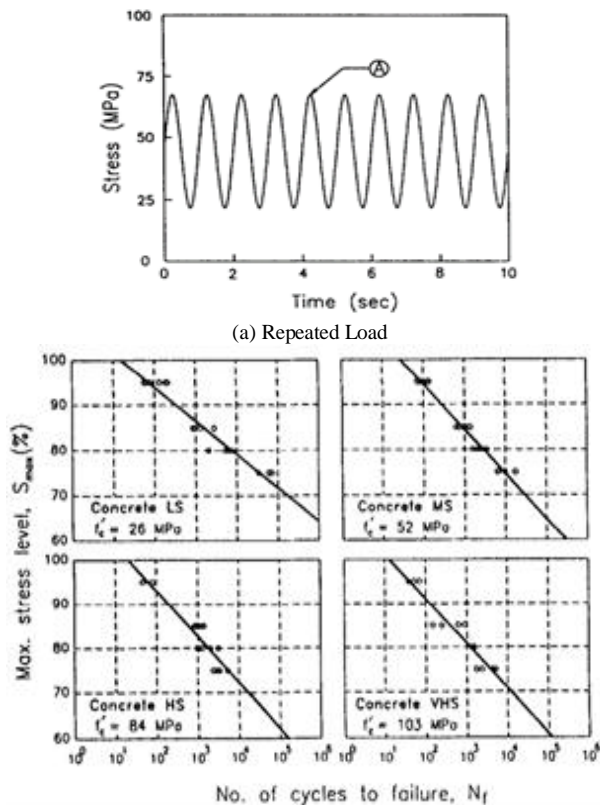
II. FATIGUE PROPERTY OF HIGH-PERFORMANCE CONCRETES USED IN NUCLEAR POWER PLANTS

A. Analysis of the Fatigue Behavior of Concretes

The analysis of the fatigue behavior of concretes showed that although the fatigue properties of the structures were different depending on tension, compression, and shear stress, the structures were usually in a state of compressive stress for containment buildings; this is because they were compressed from all directions as a result of two-way pre-stressing

In a study by Kim et al., a fatigue experiment was performed with concretes of strengths 26, 52, 84, and 103 MPa by applying repeated loads as shown in Figure 1(a); the results obtained are shown in Figure 1(b). As the magnitude of the maximum stress was increased, a failure occurred with a smaller number of repeated loads; moreover, as the concrete strength increased, the number of repeated loads tended to decrease [4].

However, considering the trend line in the experiment result, if a stress equal to 60% of the highest concrete strength of 103 MPa is applied as the maximum stress of repeated loads, the concrete would not fracture below 105 MPa of repeated load. In general, the compressive stress applied to concretes under the service state of structures is less than 30% of the strength so that the probability of failure due to fatigue during the service period is very low.



(b) Number of Repeated Loads during Failure Due to the Maximum Stress of the Repeated Load

FIGURE 1. FATIGUE PROPERTY ACCORDING TO CONCRETE STRENGTH (J.K. KIM, CCR, 1996)

B. Fatigue Design of Concretes

In reference to the concrete fatigue design regulation in Eurocode 2, in Eq. (1) represents fatigue strength; further,

if calculated using Eq. (1) satisfies Eq. (6.77) shown in Figure 2, it was deemed appropriate for this study.

$$f_{cd,fat} = k_1 \beta_{cc}(t_0) f_{cd} \left(1 - \frac{f_{ck}}{250}\right) \quad (1)$$

(2) The fatigue verification for concrete under compression may be assumed, if the following condition is satisfied:

$$\frac{\sigma_{c,max}}{f_{cd,fat}} \leq 0.5 + 0.45 \frac{\sigma_{c,min}}{f_{cd,fat}} \quad (6.77)$$

≤ 0.9 for $f_{ck} \leq 50$ MPa
 ≤ 0.8 for $f_{ck} > 50$ MPa

where:

$\sigma_{c,max}$ is the maximum compressive stress at a fibre under the frequent load combination (compression measured positive)
 $\sigma_{c,min}$ is the minimum compressive stress at the same fibre where $\sigma_{c,max}$ occurs. If $\sigma_{c,min}$ is a tensile stress, then $\sigma_{c,min}$ should be taken as 0.

FIGURE 2. EUROCODE 2: FATIGUE DESIGN REGULATION OF PART 1 - 1

Figure 3 shows the number of repeated loads during the service period according to structure. For nuclear power plants, at least 104 or smaller repeated loads are expected even with a conservative calculation. Even with the conservative assumption that the compressive stress applied to concretes is 30%, it satisfied Eq. (1).

Low-cycle fatigue			High-cycle fatigue			Super-high-cycle fatigue		
1	10 ³	10 ⁶	10 ³	10 ⁴	10 ⁵	10 ⁶	10 ⁷	10 ⁸
Structures subjected to earthquakes			Airport pavements and bridges			Highway and railway bridges, highway pavements		
						Mass rapid transit structure		
						Sea structures		

FIGURE 3. NUMBER OF REPEATED LOADS DURING SERVICE PERIOD ACCORDING TO STRUCTURE

A part of the reports on evaluation of nuclear power plant structures by the IAEA mentioned about fatigue. Concretes have very high resistance against fatigue and show no fatigue failure in general. However, the report suggested that damage due to fatigue can occur around equipment or pipe supports. In the report, damages due to fatigue were investigated at 10 locations of real nuclear power plants; however, only one location developed cracks due to fatigue. Moreover, cracks were not found in containment buildings but in the internal structure.

C. Analysis of Fatigue of HPC

In the case of containment buildings of nuclear power plants, tensile stress is not exerted in all directions owing to two-way pre-stressing and the compressive stress actually exerted is evaluated as 30% or less of the actual strength. The number of repeated loads in the structures of nuclear power plants is not as large as that in other structures, and failure due to fatigue is not expected to occur according to our review of design methods or previous study results. With regard to HPC for new nuclear power plants, the compressive stress that is actually exerted is expected to be lower than 30% of the compressive stress. Under such circumstances, no experiment studies on fatigue are needed in particular. However, note that it is necessary to evaluate safety accurately in reference to previous studies on fatigue properties.

III. ANALYSIS OF CRACK PROPERTIES

A. Experimental Design and Mixes

The materials used in the experiment were as follows: Type 1 Portland cement, Type 2 fly ashes, Type 3 blast furnace slag and silica fume as binders; sea sand as fine

aggregates; and ungraded crushed rock as coarse aggregates (maximum dimension: 20 mm). Table 1 shows concrete mixes used in this study as experimental mixes. 6000-FA20 mixes with a goal strength of 6000 psi (41.36 MPa) are those currently used for nuclear power plants and the other mixes are standard mixes with goal strengths of 8,000 psi (55.17 MPa) and 10,000 psi (68.97 MPa), respectively, prepared in this study

B. Experimental Method

Five specimens—three for compressive strength measurement and two for elastic modulus measurement — were manufactured as per mix according to KS F 2403. Experiments were conducted in accordance with the KS F 2405 regulations.

TABLE 1. CONCRETE MIX DESIGN

Compressive Strength (psi)	Mix Type	W/C	W	C	BS	FA	SF	S	G
6000	FA20	40	162	324	-	81	-	747	963
8000	FA25	34	155	342	-	114	-	732	942
	BFS50		155	228	228	-	-	742	956
	SF5		155	433	-	-	23	735	942
	BS25FA25		155	228	114	114	-	701	899
	BS30FA30		155	182	137	137	-	696	893
	BS65SF5		155	137	296	-	23	702	901
10000	SF5	28	155	526	-	-	28	710	914
	FA25SF5		155	388	-	139	28	687	885
	BS30FA25SF5		155	222	166	139	28	682	878
	BS45SF5		155	277	249	-	28	702	904
	BS65SF5		155	166	360	-	28	698	899
	BS25FA20SF5		155	227	139	111	28	619	794

For autogenous shrinkage measurements, an acrylic mold as shown in Figure 4 was used as an improvement of the KS F 2586 regulation and two specimens were manufactured as per mix to measure changes in autogenous shrinkage. For drying shrinkage, experiments were conducted in accordance with the ASTM C 596 regulation and two specimens were manufactured as per mix to measure changes in drying shrinkage. For the ring test, cracks were measured after manufacturing specimens in accordance with the AASHTO T 334-08 (2012) regulation and potential for cracking was assessed according to ASTM C 1581/ C 1581M-09a [5-8].

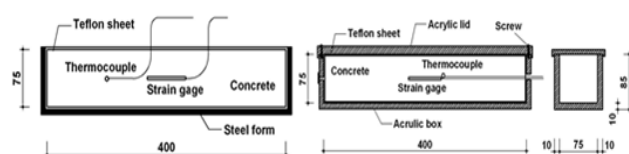


FIGURE 4. SPECIMENS FOR AUTOGENOUS SHRINKAGE

C. Analysis Results of Crack Properties

The test result of compressive strength and elastic modulus satisfied the goal strength in the design standards at age 91 days. In particular, a mix with 5% SF showed the largest initial compressive strength. All standard

mixes showed elastic moduli higher than that of the existing nuclear power plant mix (6,000 psi grade). In particular, all standard mixes had large initial elastic moduli up to age 7 days (Table 2).

TABLE 2. ANALYSIS RESULTS OF CRACK PROPERTIES

Goal Strength (psi)	Mix	Crack Occurrence Time (day)	No. of Cracks	91-Day Crack Width (mm)		Assessment of Potential Crack		
				Max	Aver.	G	S	Potential for Cracking
6000	FA20	22	2	0.25	0.183	35.83	0.11	Moderate-low
8,000	FA25	50	3	0.50	0.276	35.83	0.05	Low
	BS50	70	2	0.10	0.068	35.83	0.05	Low
	SF5	12	3	0.30	0.146	35.83	0.13	Moderate-highlow
	BS25FA25	66	4	0.15	0.075	35.83	0.06	Low
	BS30FA30	85	2	0.08	0.042	35.83	0.05	Low
	BS65SF5	after 91	1	0.15	0.120	35.83	-	Low
10,000	SF5	35	1	0.04	0.033	35.83	0.06	Low
	FA25SF5	10	2	0.30	0.163	35.83	0.14	Moderate-highlow
	BS30FA25SF5	36	2	0.06	0.040	35.83	0.05	Low
	BS45SF5	76	1	0.35	0.250	35.83	0.05	Low
	BS65SF5	29	1	0.30	0.202	35.83	0.08	Low
	BS25FA20SF5	after 91	1	0.40	0.196	35.83	-	Low

For autogenous shrinkage, prediction equations of autogenous shrinkage of CEB, Tazawa, and Jonasson were compared. The experimental values for the standard mix of 8,000 psi grade were smaller than the predicted values for Tazawa and showed a similar trend as the predicted value for CEB. For the standard mix of 10,000 psi grade, the result was similar to or smaller than the predicted values for CEB and Jonasson, respectively, and was approximately half the predicted value for Tazawa [9-10].

IV. CONCLUSION

In this study, the fatigue properties of high-performance concretes used in nuclear power plants were analyzed. For containment buildings in nuclear power plants, tensile stress was not exerted in all directions owing to two-way pre-stressing; further, compressive stress that was actually exerted was evaluated as 30% or less of the actual strength. Thus, the number of repeated loads in the nuclear power plant structures is lower than that of other structures; moreover, according to our review of the design method or previous study results, failure due to fatigue is not expected to occur.

Furthermore, the effect of the admixture was larger than the effect of the water binder in terms of autogenous shrinkage, and shrinkage admixed with fly ashes was relatively smaller than mixes without fly ashes. In particular, mixes with a 5% SF admixture increased autogenous shrinkage at an early age followed by expansion; for these mixes, the experimental values were similar to or smaller than the predicted values for CEB, Tazawa, and Jonasson. For drying shrinkage, the experimental values were small when the 5% SF admixture was used and shrinkage crack reduction (below -800 $\mu\epsilon$) was achieved to ensure durability defined in JASS5 by the Architectural Institute of Japan. The drying shrinkage values were similar to or larger than the predicted values for CEB, ACI, and B3.

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