EXPERIMENTAL STUDY OF AMBIENT TEMPERATURE AND MOISTURE CONDITIONS ON FATIGUE RESISTANCE OF CONCRETE

YASUHIRO KODA [*], SHOHEI MINAKAWA [†] AND ICHIRO IWAKI [††]

[*] College of Engineering, Nihon University
1 Nakagawara, Tokusada, Tamura-machi, Koriyama, Fukushima, Japan
e-mail: koda.yasuhiro@nihon-u.ac.jp

[†] Nexco-Engineering Tohoku Company
13F Kakyoin Plaza, 2-1-65 Kakyoin, Aoba-ku, Sendai Japan
e-mail: s.minakawa.sb@e-nexco.co.jp

[††] College of Engineering, Nihon University
1 Nakagawara, Tokusada, Tamura-machi, Koriyama, Fukushima, Japan
e-mail: iwaki.ichirou@nihon-u.ac.jp

Abstract: It is known that the fatigue resistance of concrete decreases when it becomes saturated with water, and that its compressive strength increases at low temperature. However, there have been few systematic investigations of the influence of the environmental temperature and moisture conditions on the fatigue resistance of concrete. In the present study, static loading and fatigue tests were carried out on concrete cylinders to determine their fatigue resistance under compression. The results indicated that at room temperature, the static compressive strength decreased with increasing moisture content. In contrast, at low temperature, it increased with increasing moisture content. On the other hand, regardless of the temperature, the fatigue resistance decreased as the moisture content increased.

1 INTRODUCTION

The fatigue resistance of reinforced concrete (RC) members is affected by the fatigue strengths of both the reinforcing steel bar and the concrete. The fatigue resistance of concrete varies substantially with the water content. The fatigue resistance under compressive stress is particularly affected by the water content; it has been confirmed that the fatigue strength of RC in water is 20% less than that in dry air [1]. Furthermore, when the ambient temperature is below the freezing point of water, the compressive strength increases with decreasing temperature or increasing water content [2].

However, few studies have involved the systematic evaluation of how the water content at low temperatures affects the concrete fatigue resistance. In the present study, static loading and fatigue tests were conducted on concrete cylinders to determine their fatigue resistance under compression.

2 TESTING AND MEASUREMENT PROCEDURES

2.1 Experimental parameters

Table 1 gives the experimental parameters for each tested specimen. Each type of

Table 1 Experimental parameters

Specimen	Type of loading test		Temperature		Water content		
	Static S	Fatigue F	Normal N	Low L(-20℃)	Dry I d1(50%)	Dry II d2(75%)	Saturation s(100%)
S-N-d1	○		○		○		
S-N-d2	○		○			○	
S-N-s	○		○				○
S-L-d1	○			○	○		
S-L-d2	○			○		○	
S-L-s	○			○			○
F-N-d1		○	○		○		
F-N-d2		○	○			○	
F-N-s		○	○				○
F-L-d1		○		○	○		
F-L-d2		○		○		○	
F-L-s		○		○			○

Table 2. Mix proportion of concrete

Maximum size (mm)	W/C (%)	Air content (%)	s/a (%)	Unit content (kg/m³)					
				W	C	S	G	AE1	AE2
								Admix.	
20	69.0	4.5	48.0	170	246	899	1000	3.696	0.004

Figure 1. Large environmental chamber

Figure 2 Loading test at low temperature

specimen is identified by three test conditions: the type of loading test, the environmental temperature, and the moisture content. Specimens were tested using static (S) and fatigue (F) loading tests. The considered environmental temperatures were normal room temperature (N), which was approximately

20 °C, and a low temperature (L) of −20 °C. Finally, the considered water contents were 50% (d1), 75% (d2), and 100% saturated (s).

2.2 Specimens and test program

Table 2 shows the mass proportion per unit volume of the concrete mixture. The water–

Table 3 Results of compressive strength test

Symbol	n	Compressive strength (MPa)	Average (MPa)	CV (%)	Young's modulus (GPa)	Average (GPa)	CV (%)
N-d1	1	28.6	28.0	3.9%	27.1	28.4	7.8%
	2	29.0			31.5		
	3	26.5			26.6		
N-d2	1	22.3	21.3	3.6%	28.8	27.9	4.1%
	2	20.5			26.3		
	3	21.0			28.6		
N-s	1	22.7	23.0	2.5%	30.6	30.1	4.9%
	2	23.8			28.1		
	3	22.5			31.6		
L-d1	1	27.3	27.3	-	31.6	31.6	-
L-d2	1	35.2	36.7	4.0%	32.1	32.7	2.1%
	2	38.2			33.4		
L-s	1	42.1	42.3	0.6%	33.9	34.5	2.0%
	2	42.2			34.0		
	3	42.7			35.4		

cement ratio (W/C) was set to 69.0% for a target average strength of 25 MPa. The dimensions of the cylindrical specimens were 75 mm in diameter and 150 mm in height. Specimens were water cured for seven days and then moved to a different room that is 20°C.

The conditioning to establish the water ratio was carried out when the specimens were 28 days in age. To predict the water content, the mass of each specimen was measured, and the moisture content was measured using a concrete moisture meter through the high-frequency capacitance method. Moisture content of dry condition (d1) is became about 50% that the specimens set in the room at 21 days or more from removal formwork. On the other, Moisture content (d2) is about 75% that the saturation concrete dried under a controlled dry process.

To prevent water loss by evaporation during the loading test, wax was applied to the specimen surface after conditioning. The loading tests at the normal (N) and low (L) temperatures were conducted in an experimental room and a large environmental chamber (Figure 1), respectively. Specimens prepared for the low-temperature (L) loading tests (Figure 2) were relocated to the large environmental chamber approximately 24 h prior to testing.

The static and fatigue loading tests were conducted on pairs of specimens from identical batches concrete under the same temperature conditions and with the same water contents. The loading speed during the fatigue test was 1 Hz with the load applied by sine wave. The upper limit of the stress S1 was 70% of the compressive strength, and the lower limit S2 was 10%. During the loading tests, the load applied by the load cell, the compressive strain, and the number of load cycles (fatigue test only) were measured.

3 TEST RESULTS AND DISCUSSION

3.1 Results of static test

The first page must contain the Title, Author(s), Affiliation(s), Key words and the Abstract. The Introduction must begin immediately below, following the format of this template.
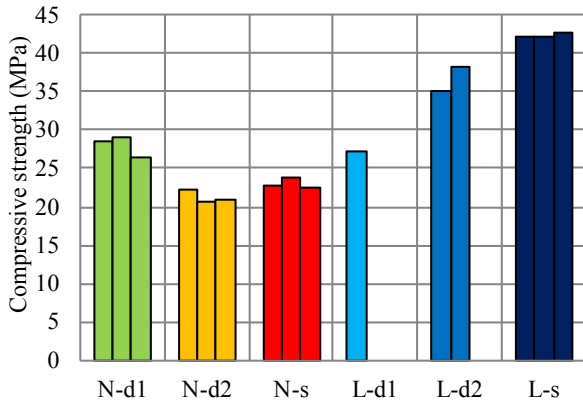
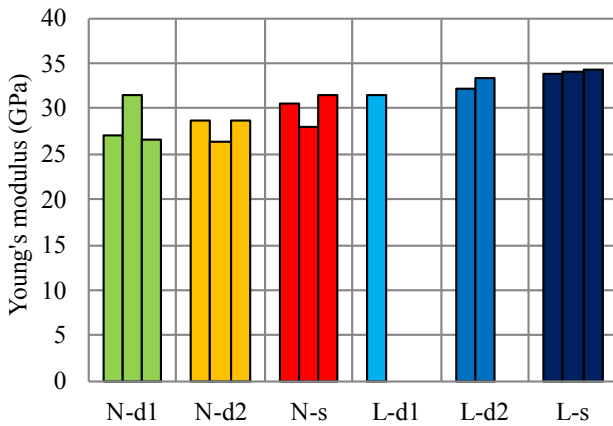**Figure 3** Compressive strength of specimens obtained under static loading tests

Figure 4 Young's modulus of specimens obtained under static loading tests

Table 4 Results of the fatigue test

Symbol	Stress ratio (%)	r	N_r	logN	P(N_r) (%)
N-d1		1	439	2.64	75.0%
		2	14906	4.17	50.0%
		3	33106	4.52	25.0%
N-d2		1	10837	4.03	80.0%
		2	17306	4.24	60.0%
		3	29673	4.47	40.0%
		4	118520	5.07	20.0%
N-s	10～70	1	100	2.00	75.0%
		2	391	2.59	50.0%
		3	2781	3.44	25.0%
L-d1		1	16998	4.23	50.0%
L-d2		1	1714	3.23	66.7%
		2	3692	3.57	33.3%
L-s		1	4	0.60	83.3%
		2	46	1.66	66.7%
		3	100	2.00	50.0%
		4	1393	3.14	33.3%
		5	17210	4.24	16.7%

r : Ranking of number of fatigue failure

Figure 5 Nnumber Nr of cyclic loads at fatigue failure

3.1 Results of static test

Table 3 gives the results of the compressive strength test conducted under static loading (S), including the compressive strength and Young's modulus of each specimen and the corresponding averages and coefficients of variation (CVs) for each set of testing conditions.

Figure 3 shows the compressive strength of each specimen obtained from the static loading tests. At room temperature, the strengths of the d1, d2, and s specimens were 28.0, 21.3, and 23.0 MPa, respectively; the strengths of the specimens with 75% and 100% water content were lower than that at 50% water content. In contrast, under the low temperature condition, the strengths of the d1, d2, and s specimens were 27.3, 36.7, and 42.3 MPa, respectively; the concrete strength of the L-s specimens was

approximately 1.5 times than the N-d1 specimens. Such increased strength at a low temperature and high water content have been obtained in static tests in previous studies [3].

3.2 Results of fatigue test

Table 4 gives the results of the fatigue test. The number Nr of cyclic load at fatigue failure are given for each specimen.

Figure 5 shows the number Nr of cyclic loads at fatigue failure for each specimen. The test results were evaluated relative to the

4

average value Nr value of the N-d1 specimens, which was 16,150. For N-d2, the number of cycles was 17,300–118,520, which was not very different from that for N-d1. In contrast, at the low temperature, the number of cycles for L-d1 (17,000 cycles) was unchanged from N-d1, but that for L-d2 (2,700 cycles) was lower than the number of cycles for N-d1. The numbers of cycles for the five tested L-s specimens (4–17,210 cycles) were widely

scattered. However, the results indicate that the number of cyclic loads for L-s was lower than that for N-d1. The compressive strengths of the L-d2 and L-s specimens were greater than that for the N specimens. However, the fatigue resistance of the concrete samples was lower at low temperatures.

Figure 6 shows stress–strain curves obtained during the fatigue tests at different cycle numbers N along with the curves obtained
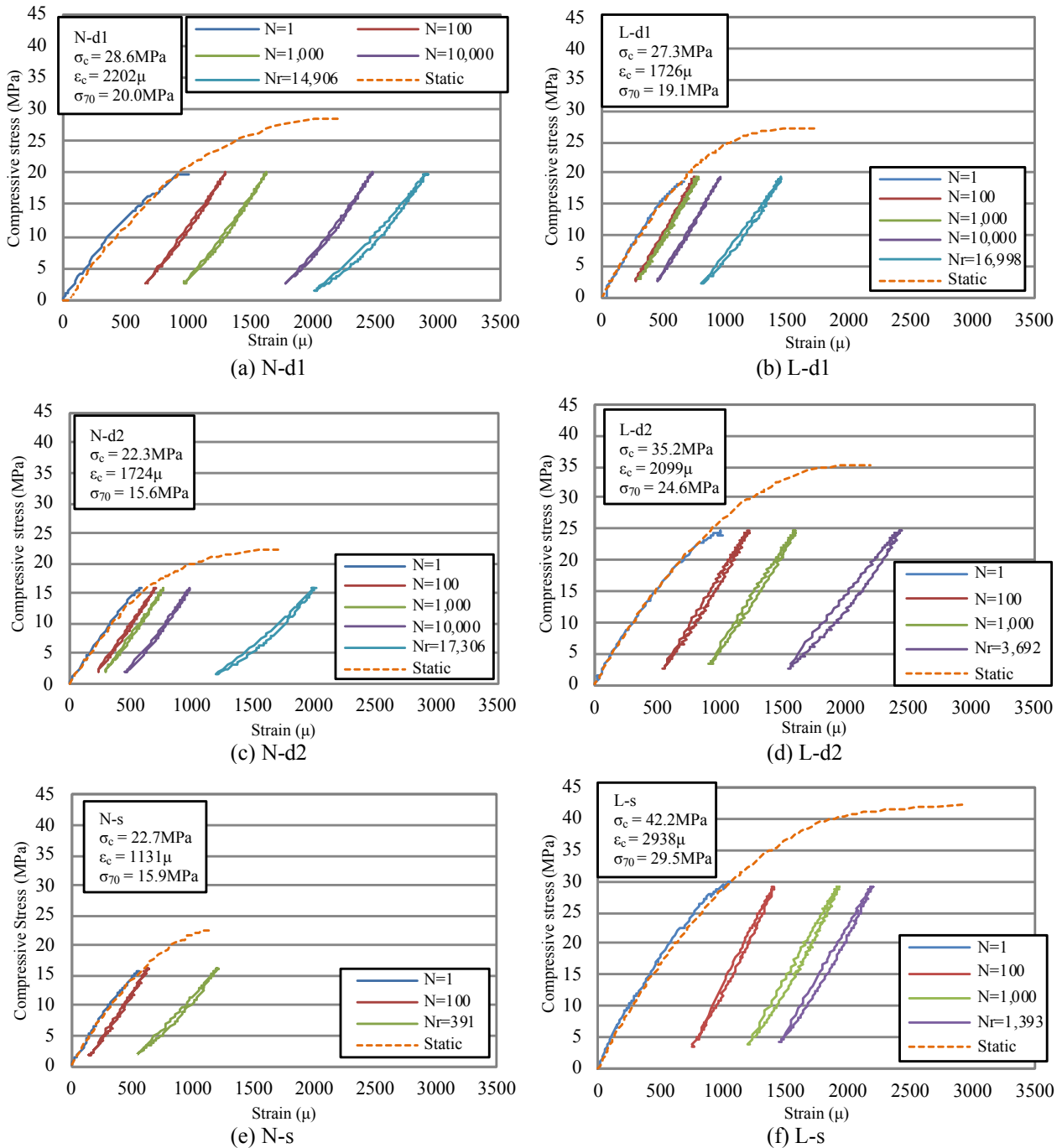

Figure 6 Stress–strain curves obtained from the static and fatigue tests

during the static tests. The stress–strain curves for the fatigue tests showed trends similar to those from the static tests in the early stages. The strain at the upper and lower stress limits S1 and S2 increased slowly with increasing cyclic load number. The fatigue failure of concrete occurred at a compressive strain of 2000 µstrain.

From the fatigue results, under saturated conditions at room temperature (N-s), the fatigue resistance of the concrete was decreased by accelerated crack progress due to the surface tension of free water in the concrete voids [4]. In contrast, at the low temperature, the compressive strength increased with increasing moisture content. However, the strength of ice is lower than that of concrete; as a result, the frozen concrete failed because of the preceding fatigue failure of the ice.

3.3 Estimation of affected fatigue failure due to environmental action

Number of fatigue failure N_r had been varies greatly that it showed Table 4. Fatigue test results estimated according to statistical processing that various water contents and environmental temperature affect to concrete fatigue resistance under the compressive stress based on research of the past[5]. Expected value of survival function P(Nr) of r th specimen from smaller one of number of fatigue failure show equation (1).

$$P(N_r) = 1 - \frac{r}{n+1} \tag{1}$$

Figure 7 show the relationship of between number of fatigue failure and survival ratio. Those relationships are recognized linear relationship. As the results of variance analysis whether it has significant difference between experimental parameters, in case of 5 % risk ratio grouping, it revealed that the data were divided into two group what are N-d1, N-d2 in dry condition and N-s, L-s in saturated condition respectively. In case of L-d2, it identified to belong both group. Therefore, it is possible that there is boundary to induce the
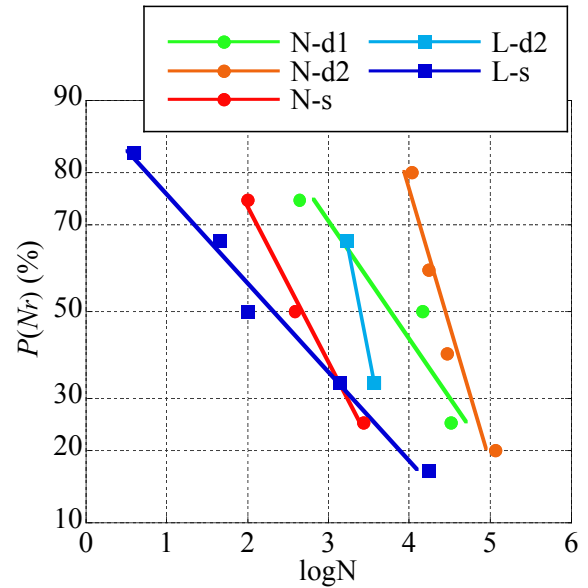

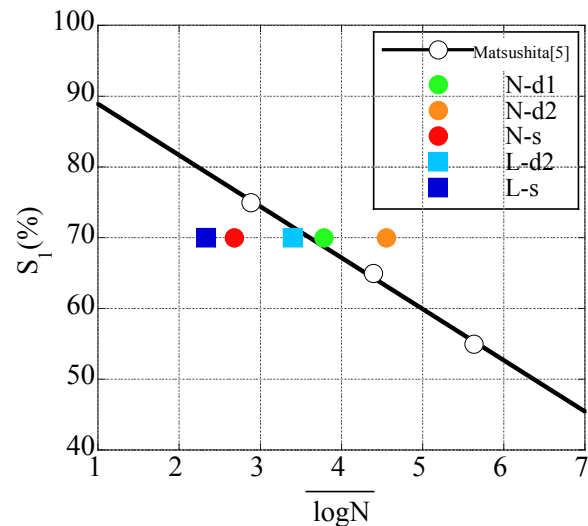**Figure 7** Relationship between P(Nr) and log N

Figure 8 Relationship between S and N

reducing fatigue resistance about 75 % water content.

Figure 8 show relationship between stress (S) and the number of cycles to failure (N) [5], and it is presented the average number of cycles to failure (P(Nr)=50%) of each experimental parameters in this figure. The data of N-d2 specimen was plotted on the right of relationship between S-N, the data of N-d1 specimen and L-d2 specimen were plotted on relationship between S-N. Thus, at least number of fatigue failure of N-d1 increased than the condition of water penetration action during all the time. On the other hands, the data of N-s

specimen and L-s specimen were obviously plotted on the left of relationship between S-N. The fatigue resistance of saturated concrete was decreased not only water supply but also in air like a N-s. In addition, the fatigue resistance of frozen concrete was decreased. In this way, the decreasing case of concrete fatigue resistance was included   saturated condition and low temperature such as freeze.

4 CONCLUSIONS

(1)   The compressive strength of the concrete samples investigated in this study increased with increasing moisture content under low temperature conditions but decreased with increasing moisture content at room temperature. The compressive strength of saturated concrete samples at low temperature was approximately 1.5 higher than that of concrete samples with 50% water content at room temperature.

(2)   The Young's modulus obtained from the static test at low temperature was approximately 1.2 higher than that of the 50% saturated concrete at room temperature. Therefore, in the static tests, the influence of the ambient temperature and moisture conditions on the compressive strength were greater than those on the Young's modulus.

(3)   The fatigue resistance of the saturated concrete was lower than that with 50% water content at both the normal and low temperatures.

(4)   Even if the kept saturation condition in air, the fatigue resistance of concrete may decrease. Furthermore, it was revealed that free water in concrete has an effect on the fatigue resistance.

REFERENCES

[1] F. Masayuki, S. Yasuhiko, K. Yoshio, 2000. A study on compressive fatigue behavior of concrete in water, *Proceedings of the Japan Concrete Institute*, 22, No.3, 205-210

[2] Japan Society of Civil Engineers, Standard Specifications for Concrete Structures [Design], 2012.

[3] G. Yukimasa, M. Takashi, 1979. Mechanical properties of reinforced concrete members at very low temperature, *Proceedings of the Japan Society of Civil Engineers*, 285, 121-134

[4] 4. O. Atsushi, M. Hiromichi, O. Kouzou, W. Mikio, 2005. Influence of Surface Tension of Liquid Stored in Internal Void on Compressive Fatigue Strength of Concrete, *Proceedings of the Japan Concrete Institute*, 27, No.1, 361-366

[5] M. Hiromichi, 1980. A study on compressive fatigue strength of concrete in the water, *Journal of JSCE*, 296, 87-95