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CYCLIC LOADING TEST OF REINFORCED CONCRETE (RC) BEAMS INCORPORATING ALTERNATIVE CEMENTITIOUS MATERIALS

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The focus of this study is to examine flexural fatigue durability of RC beams, which were made with various cementitious materials. The cementitious materials tested in this study were blast furnace slag powder, fly-ash, silica-fume, and an artificial admixture of rich SiO_2 and Al_2O_3. Fifteen RC beams for each admixture were prepared in addition to a control mixture (without admixture). The dimensions of the RC beams without stirrups were 160 × 160 × 1200 mm. Three beams for each mixture were soaked into a water-tank until the cyclic loading test. The study conducted static and cyclic four-points bending test. The paper aims to report the effect of the alternative cementitious materials on the fatigue durability of RC beams, which were exposed to the dry and wet environmental conditions.

Keywords: Admixture, Fatigue, Shear failure, Load cycle, Dry and wet.

1 INTRODUCTION

It is well known that alternative cementitious materials can improve fresh and hardened properties of concrete. Some cementitious admixtures are finer than Portland cement, so concrete, incorporating the powder material, has denser pore structures. Hence, the concrete with the admixture often indicates higher durability than the conventional concrete. The authors had examined the strength properties and material durability of concrete, mixing various cementitious admixtures (Yoshitake *et al*. 2017, Yoshitake *et al*. 2019). Yamato *et al*. (2020) focused on the concrete incorporating an admixture of rich SiO_2 and Al_2O_3; they reported the excellent durability of the concrete. These studies confirmed that the concrete with mineral admixtures has adequate strength properties and superior material durability.

Fatigue durability, an important structural resistance to repeated loadings, is a concern for structural concrete. Researches on the fatigue of reinforced concrete (RC) member made with various admixtures are few while cyclic loading tests using concrete materials have been widely conducted. To improve durability, concrete made with cementitious admixture is often used in RC members such as bridge deck slabs. It is well known that the fatigue is affected by microscopic pore-distributions of the concrete. Note that the pore structure characteristics are varied by the cementitious materials mixed in the concrete. Hence, the fatigue durability of RC members using concrete of cementitious admixture should be examined carefully.

The study aims at investigating the flexural fatigue durability of RC beams made with various cementitious materials: fly-ash, blast furnace slag powder, silica-fume, and an artificial admixture of rich SiO_2 and Al_2O_3. Fifteen RC beams for each admixture were prepared in addition to a control mixture (without admixture). The RC beams (160 × 160 × 1200 mm) without stirrups were tested to compare the effect of each concrete mixture on fatigue performance. Three beams for each mixture were soaked into a water-tank until cyclic loading test, and three other beams were exposed to freeze-thaw (F-T) cycles in a large freezer room. The study conducted static and cyclic four-points bending test and reports the effect of alternative cementitious materials on the fatigue durability of the RC beams, which were exposed to dry and water environmental conditions. Note that the fatigue durability of the RC beams exposed to F-T cycles cannot be reported here. Further research will be reported in another paper.

2 TEST MATERIALS AND SPECIMENS

2.1 Materials and Mixture Proportions

Materials used for the RC beams are given in Table 1. Steel deformed, longitudinal bars of 13 mm nominal diameter and yield strength of 345 MPa were used for the concrete beam. In addition, the mixture proportions of concrete are summarized in Table 2. Each 1.0 m^3 of the concrete mix were prepared at a ready-mix batch plant and transported within 60 minutes to the laboratory in a transit mixer. All concreting for the RC beams was completed in 5 weeks while each concrete was made on a different day.

Table 1. Materials for concrete incorporating admixture.

Material	**Type**	**Property**
Water	Tap-water (***W***)	Density 1.00 g/cm^3
Cement	Ordinary Portland cement (***OPC***)	Density 3.16 g/cm^3, Blaine fineness 3280 cm^2/g
Cementitious admixture	Blast furnace slag powder (**B**)	Density 2.90 g/cm^3, Blaine fineness 4840 cm^2/g
	Class II Fly-ash (**F**)	Density 2.22 g/cm^3, Blaine fineness 3530 cm^2/g
	Silica-fume (**S**)	Density 2.21 g/cm^3, BET fineness 16.9 m^2/g
	Chloride resistance admixture (**C**)	Density 2.36 g/cm^3, BET fineness 13.3 m^2/g
Fine aggregate	Crushed limestone sand (F_1)	Density 2.69 g/cm^3, Size 5-0 mm
	Crushed sandstone sand (F_2)	Density 2.58 g/cm^3, Size 5-0 mm
	Crushed limestone sand (F_3)	Density 2.60 g/cm^3, Size 5-0 mm
Coarse aggregate	Crushed stone (G_1)	Density 2.73 g/cm^3, Size 20-15 mm
	Crushed stone (G_2)	Density 2.73 g/cm^3, Size 15-5 mm
Chemical admixture	Water reducing agent (***WRA***)	Primary component: Lignin sulfonate
	Air entraining agent (***AEA***)	Primary component: Rosin

Table 2. Mixture proportion of concrete.

ID	***w/cm***	**Unit-weight kg/m^3**								**g/m^3**		***Air***** %
		W	***OPC***	***P****	F_1	F_2	F_3	G_1	G_2	***WRA***	***AEA***	
Con.	0.55	164	299	0	362	181	363	571	381	2392	8.1	3.7
B10	0.55	164	269	30	361	180	361	571	381	2392	34.1	3.9
F10	0.55	164	269	30	357	179	357	571	381	2392	7.2	3.9
S10	0.55	164	269	30	357	179	357	571	381	3439	0.0	3.8
C10	0.55	164	269	30	358	179	358	571	381	3289	9.0	4.1

* Cementitious admixtures (**B**; **F**; **S**; **C**), **Test value (designed air content: 4.5 %).

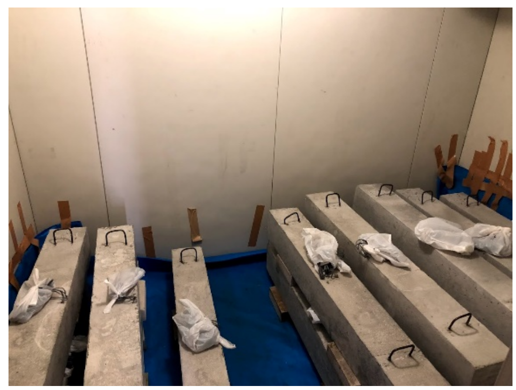
2.2 RC Beam Specimens

The study prepared 15 RC beams for each concrete mixture. Dimensions of the RC beams were 160 mm wide × 160 mm high × 1200 mm long. All RC beams had been wrapped with a curing-film for 91 days or longer. The curing conditions are shown in Figure 1(a). After the film curing, three RC beams for each test condition had been stored in a laboratory (air-conditioned), in a water-tank (water-conditioned), and in a freezer room (freeze-thaw conditioned) until the loading test. These environmental conditions were illustrated in Figure 1(b) and Figure 1(c).

a) Curing with plastic-film

b) Room-temperature environment

c) Water environment (20 ºC)



d) Freeze-thaw environment (-15 ºC~ air temp.)

Figure 1. Environmental conditions of the RC beams.

3 FLEXURAL LOADING TESTS

3.1 Test Set-up for Loadings

A monotonic and cyclic loadings system using a hydraulic jack system (maximum 1000 kN) is shown in Figure 2. The study conducted a four-point bending test, the beam-span of 1000 mm length and the loading-span of 300 mm length. The static load of 2 kN/min was applied to the beam specimen in the monotonic loading test. A linear variable displacement transducer (LVDT), strain gauges, and a load cell (maximum 500 kN) were used to examine flexural deformations. In the fatigue test, the cyclic load of 3 Hz was applied to the beam specimens. The detail of the loading is described in the following section. To maintain the water-saturated condition during the fatigue test, the tested RC beam was covered with plastic films (see Figure 2).

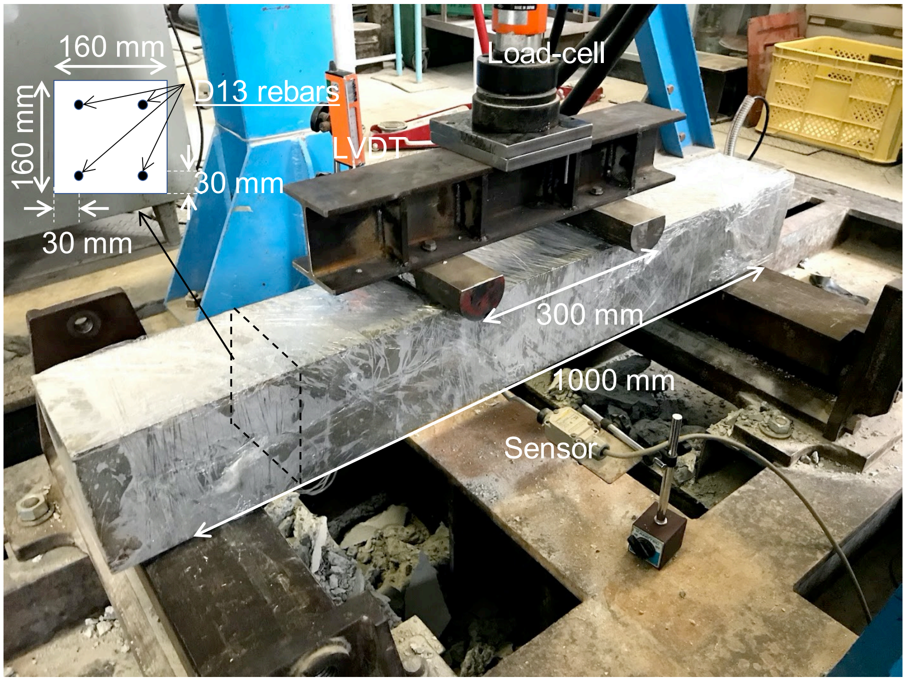


Figure 2. Test set-up for monotonic and cyclic loading.

3.2 Equivalent cycles

Load-carrying capacities ($\boldsymbol{P_0}$) of the RC beams were varied by concrete made with each admixture though the water-cementitious material ratio (***w/cm***) being constant (0.55). To assess the flexural fatigue durability of each parameter, equivalent loading cycles were calculated by Eq. (1).

$$\boldsymbol{S} = \frac{\boldsymbol{P_{max}}}{\boldsymbol{P_0}} = 1 - \boldsymbol{k} * \log \boldsymbol{N} \tag{1}$$

where $\boldsymbol{S}$ is the load-ratio, $\boldsymbol{P_0}$ is the load-carrying capacity, $\boldsymbol{P_{max}}$ is the maximum load in cyclic loading test, $\boldsymbol{N}$ is the fatigue failure cycles, and $\boldsymbol{k}$ is a coefficient of the empirical equation.

The maximum load in all cyclic loading test was constant, which was decided as 80% of the averaged load-carrying capacity, $\boldsymbol{P_0}$ (Con.), of the control RC beam. Note that the load-ratios ($\boldsymbol{S}$) were slightly varied in accordance with the load-carrying capacities ($\boldsymbol{P_0}$) of each admixture.

It is well known that Miner's rule can be used for designing fatigue life of RC structures. When the maximum load ($\boldsymbol{P_{max}}$) were applied repeatedly ($\boldsymbol{n_i}$ cycles) to the RC beam having the load-capacity ($\boldsymbol{P_0}$), the accumulated fatigue damage is defined as $\boldsymbol{n_i}$ / $\boldsymbol{N_i}$. Even if the load-ratio ($\boldsymbol{S_i}$) varied, fatigue failure of the the RC beam occurs when the accumulated fatigue damage reaches 1.0. Based on the Miner's rule, fatigue cycles of each RC beam can be assessed by using Eq. (2).

$$\boldsymbol{S_i} - \boldsymbol{S_j} = -\boldsymbol{k} * \log \boldsymbol{N_i} + \boldsymbol{k} * \log \boldsymbol{N_j} = \boldsymbol{k} * \log \frac{\boldsymbol{N_j}}{\boldsymbol{N_i}} \tag{2}$$

where subscripts $\boldsymbol{i}$ and $\boldsymbol{j}$ represent each admixture.

Hence, the equivalent fatigue life (N_{eq}) of an RC beam with each admixture can be calculated by applying the fatigue life of the control RC beam as given in Eq. (3).

$$N_{eq} = N_i \times 10^{\frac{S_i - S_j}{k}} \tag{3}$$

where subscript i means control concrete (Con.), and j represents B10 / F10 / S10 / C10.

4 TEST RESULTS AND DISCUSSION

4.1 Load-carrying Capacity

The cracking loads and load-carrying capacities of each RC beam are summarized in Table 3. The table presents the averaged data obtained from three loading tests. The strength and load-capacity were almost equivalent, though the admixture concretes (B10, F10, S10, C10) had 10% lower cement than the control concrete without admixture.

Table 3. Load-carrying capacity.

I.D.	Com. strength (MPa)	Young's mod. (GPa)	Cracking L_{cra}		Capacity $L_{cap.}$	
			load (kN)	Moment (kNm)	load (kN)	Moment (kNm)
Con.	44.4	31.5	24.4	4.27	82.6	14.5
B10	48.0	34.3	21.6	3.79	82.0	14.4
F10	41.5	34.0	21.5	3.76	77.7	13.6
S10	42.5	33.0	23.2	4.05	87.7	15.4
C10	44.7	36.5	19.2	3.36	73.9	12.9

a) Typical failure under dry condition

b) Typical failure under wet condition

Figure 3. Fatigue failures.

4.2 Fatigue Durability

The applied load range in the fatigue test was set as 80% to 20% of the static loading test of the control RC beam. Figure 3 illustrates typical failures of RC beam under the cyclic loadings. The tested RC beams had no shear reinforcement, so diagonal cracks occurred and developed under the cyclic loading. All RC beams indicated the shear failure induced by the cracks.

Figure 4 shows the semi-logarithm relations between the load-ratio (S) and cycle (N). Note that the load-ratios (S) were slightly different by each test. The different load-ratios (S) were due to the constant applied load (80% of L_{cap} of the control beam) and the varied load-capacity of each RC beam. The previous ***S-N*** relation proposed by Higai (1978) was also shown in the graph. The fatigue test results confirm that RC beam indicated various fatigue life (***N***) regardless of the mixtures. Figure 5 presents the equivalent cycles (N_{eq}) that was calculated by using Eqs. (1)-(3). A dried RC beam (S10) indicated fatigue failure under significantly lower cycles than other the dried RC beams (S10). Hence the equivalent cycles (N_{eq}) under dry conditions was lower. Except for the results of S10, the equivalent cycles (N_{eq}) under wet conditions were lower than the fatigue durability of the dried RC beam. The fatigue test confirms the differences of the dried and wet RC beams made with various admixture while the lower fatigue durability under wet condition is well known. Noteworthy is the excellent fatigue durability of wet RC beams mixing silica-fume (**S**) or the chloride resistance admixture (**C**).

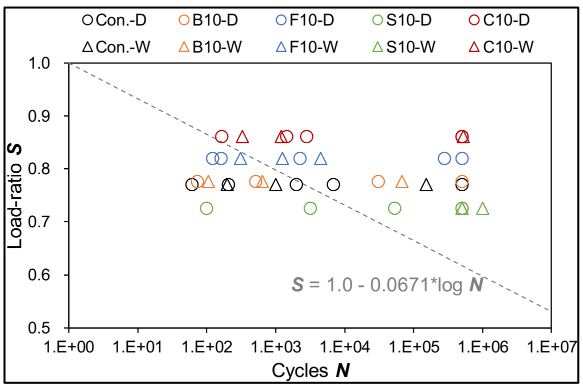


Figure 4. Semi-logarithm ***S-N*** relations.

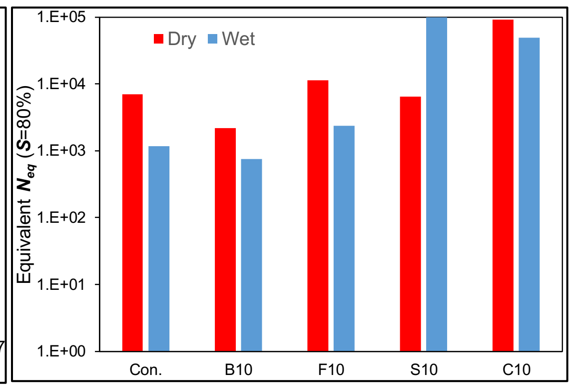


Figure 5. Equivalent ***N*** (***S*** = 80%).

5 SUMMARY

The paper reported the effect of alternative cementitious materials on the fatigue durability of RC beams exposed to the dry and wet environmental conditions. To compare the fatigue durability of various test conditions, the equivalent loading cycles (N_{eq}) were used in the study. The test results showed that the fatigue life of RC beams varied regardless of the mixture proportions of concrete. Nevertheless, the observation confirmed the lower fatigue durability of wet RC beams. The excellent fatigue durability of RC beams incorporating superfine powder materials such as silica-fume (**S**) and the chloride resistance admixture (**C**) was noteworthy.

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