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Fatigue Characteristic of Reinforced Concrete Member in Mineral Oil

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Synopsis

The present paper describes flexural shear cyclic loading test results of reinforced concrete member in mineral oil, with focusing on fatigue characteristic due to liquid permeation into cracks of the member. In case of no fatigue failure reached, monotonic load was again applied up to failure after cyclic loading. For comparison, similar loading tests were also conducted in water and no liquid (normal) conditions. Cyclic loading and liquid dependent failure behavior, i.e. crack progress, stiffness reduction and displacement increase are discussed.

KEYWORDS: Fatigue, Reinforced Concrete Member, Flexural shear, Mineral oil permeation.

1. INTRODUCTION

In recent years, deterioration has been found in the concrete foundation for pressing machine of steel production factory. In these facilities, circumferential temperature reaches up to 40 to 50 C degree around the concrete foundation. As the result, accelerated evaporation of entrained water provides negative pressure and leads absorption of mineral oil into concrete. In addition, repeated cyclic load is applied during normal operation. These facts suggest fatigue orient deterioration of concrete. Chemical attack by plant oil has been well known, but not by mineral oil. Rain water dependent deterioration of concrete slab subjected to repeated vehicle load is also well known.

As the first step, authors conducted compressive fatigue test with concrete cylinders in the three different circumstances, i.e. in mineral oil, in water and in no liquid, i.e. normal condition. Focusing points are load cycle and liquid dependent strength and hysteretic stress strain relationship [1]. However significant effect of liquid permeation into cracks was not observed. One of causes was that micro crack provided insufficient permeation of more viscous mineral oil.

In these backgrounds, fatigue loading test has been conducted focusing on flexural shear fatigue characteristic of reinforced concrete member. Test specimens designed as post yielding shear failure, are similarly in the three different circumstances, i.e. in water, mineral oil and normal (no liquid) conditions. Focusing points are load cycle and liquid type dependent crack progress, load displacement characteristic and residual displacement increase. In case of no fatigue failure reached, monotonic load is again applied up to the ultimate after fatigue test.

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2. EXPERIMENTAL TEST

2.1 Test Specimens

As illustrated in **Fig.1**, test specimen has dimension of B120mm×H150mm×L1000mm, shear span ratio of 3.75 and has single tensile reinforcement allocated with no shear reinforcement. As for specimen production, once work form removal, one day after the concrete placement, test specimens were sprayed water cured during 28 days in the curing room under 20□ temperature. Material properties are illustrated in **Table 1**.

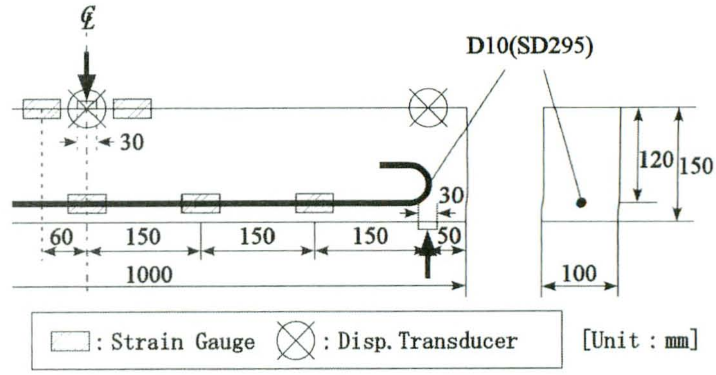

Fig.1 Specimen Dimension and measurement

2.2 Test Procedures

Three points loading is illustrated in **Fig.1**. Measurements are relative displacement between loaded and supported points, reinforcement strains at three points from center at 150mm distance and concrete strains at both sides of loading point.

Test variable is circumferential condition, in mineral oil, in water and no liquid. As illustrated in **Photo 1**, a part of test specimen where crack distributes is soaked in the liquid. Test specimens are listed in **Table 2**, where for each circumferential condition; one is for essential monotonic loading while another three or four are for cyclic loading test. Essential monotonic loading specimen is referenced for upper and lower load limit of the cyclic loading test. 10% of yield strength obtained in that essential loading test will be utilized as lower limit and 80% of that as upper limit for the following cyclic loading test.

Table 1 Material Properties

Concrete			Reinforcement			
f_c' (MPa)	E_c (GPa)	νc	f_{sy} (MPa)	ε_{sy} (μ)	E_s (GPa)	f_{su} (MPa)
28.8	25.8	0.191	372.7	2165	172.2	515.1

Table 2 List of Test Specimens

Specimen	Test Condition		Age	Obtained Essential Yield Load (kN)
	Circumferentional	Applied Load	(day)	[Applied Upper and Lower Load Ratio (%)]
N-0	No Liquid	Monotonic	70	16.7
N-1		Cyclic	93	[10～80]
N-2			143	
N-3			156	
O-0	Oil	Monotonic	112	15.8
O-1		Cyclic	113	[10～80]
O-2			127	
O-3			170	
O-4			225	
W-0	Water	Monotonic	102	16.0
W-1		Cyclic	106	[10～80]
W-2			141	
W-3			163	

In the fatigue test, controlled load was sine wave with 0.5Hz velocity due to applied load capacity and provided displacement. Because of rather slow velocity controlled, 250,000 load cycles was employed as a maximum number except O-4 specimen. If no failure reached in the fatigue test, it was again monotonically loaded up to failure after 250,000 cyclic loading experienced. It is noted that O-4 specimen was additionally tested for potential fatigue shear failure (failed in shear at 461,000 cycles during cyclic loading).

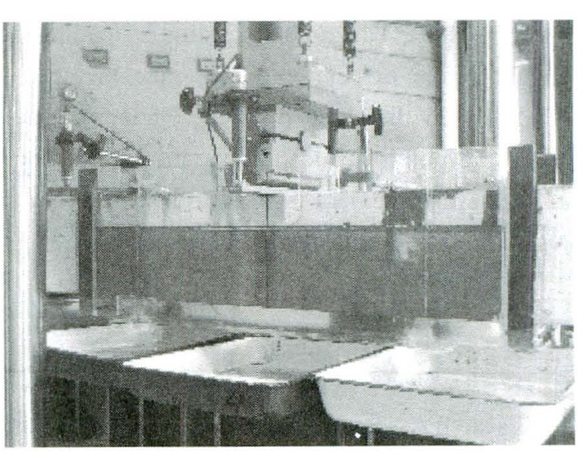

Photo 1 Test Specimen Set Up

3. FAILURE BEHAVIOR IN THE ESSENTIAL MONOTONIC LOADING TEST

Fig.2 illustrates load-displacement relationship in the essential monotonic loading test specimens for three circumferential conditions and **Fig.3** represents crack distribution in the mineral oil specimen. There is no significant difference in yielding and maximum load capacity between three circumferential conditions. Also commonly observed in three specimens was flexural crack progress up to diagonal shear through out the loading point in the ultimate stage. There is some difference in the failure displacement between three specimens due to flexural shear crack propagation, where shear crack in the water and mineral oil specimen progresses up to the right side of bearing plate, while that in the no liquid specimen progresses up underneath the loading plate.

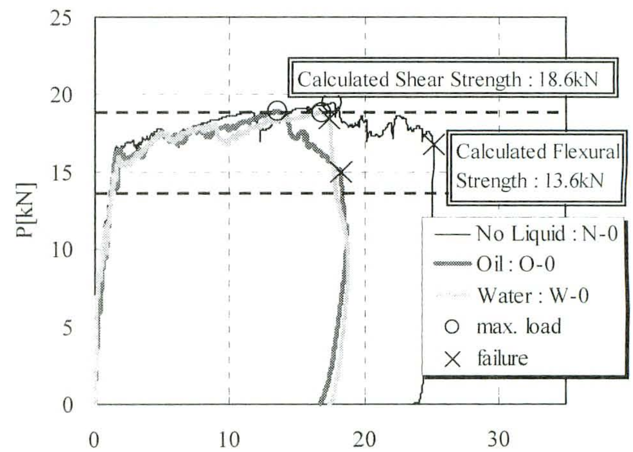

Fig.2 Load-Displacement Relationship

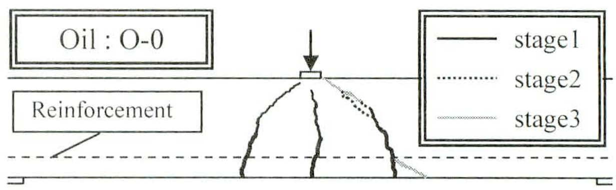

Fig.3 Crack Distribution

Fig.4 represents load strain relationship of concrete at compressive flange, in which loading history is respectively provided as stage 1 before yielding, stage 2 before maximum loading and stage 3 after that. In the stage 1, compressive strain, mainly due to flexural compression, increases more due to dominant flexural cracks, while in the stage 2, less due to predominance of diagonal shear crack. In the stage 3, this compressive strain decreases in the load descending branch because of ultimate shear failure, no flexural deformation increase. Although shear to flexural strength ratio of 1.37, these specimens ultimately failed in flexural shear and experimental maximum loads reached up to around the calculated shear strength due to strain hardening of reinforcement.

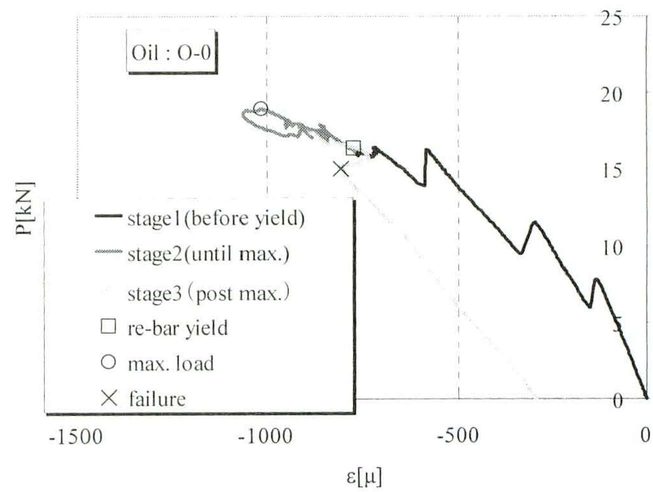

Fig.4 Load-Strain Relationship

4. FATIGUE TEST

4.1 Failure Behavior in the Cyclic Loading Test

Experimental test results are summarized in the **Table 3** including essential monotonic loading test specimens. Among them, water specimens W-2 and W-3 and mineral oil specimen O-4 were failed in shear during cyclic loading. The cyclic number at failure is shown in the parentheses of the table. Other test specimens were failed in post yielding shear during final monotonic loading stage after cyclic loading application. The yielding load

Table 3 Summary of Test Results

Specimen	P_{yi}^{exp}	$P_{yi}^{exp}/P_{y0}^{exp}$	P_{ui}^{exp}	$P_{ui}^{exp}/P_{u0}^{exp}$	$P_{ui}^{exp}/P_{vu}^{cal}$	R_{ui}^{exp}	$R_{ui}^{exp}/R_{u0}^{exp}$	Applied Load		Failure Mode
								Cyclic	Monotonic	
N-0	16.6	—	19.4	—	—	0.0558	1.00	—	○	Post Flexural Yeilding Shear Failure
N-1	16.5	0.99	21.4	1.10	—	0.0638	1.14	○	○	
N-2	17.6	1.06	18.8	0.97	—	0.0402	0.72	○	○	
N-3	16.7	1.01	18.7	0.96	—	0.0620	1.11	○	○	
O-0	16.3	—	19.0	—	—	0.0429	1.00	—	○	
O-1	17.4	1.07	20.7	1.09	—	0.0747	1.74	○	○	
O-2	17.3	1.06	19.3	1.02	—	0.0347	0.81	○	○	
O-3	17.1	1.05	18.1	0.95	—	0.0509	1.19	○	○	
O-4	—	—	12.6	0.67	0.68	0.0080	0.19	○(461,152)	—	Shear Failure During Fatigue loading
W-0	16.0	—	18.8	—	—	0.0453	1.00	—	○	Post Flexural Yeilding Shear Failure
W-1	17.6	1.10	18.1	0.96	—	0.0376	0.83	○	○	
W-2	—	—	12.8	0.68	0.69	0.0066	0.15	○(25,280)	—	Shear Failure During Fatigue loading
W-3	—	—	12.8	0.68	0.69	0.0147	0.32	○(32,807)	—	

Note: P_{yi}^{exp} : yeilding strength, P_{ui}^{exp} : maximum experimental strength, P_{vu}^{cal} : estimated strength, R_{ui}^{exp} : ultimate rotation
For Oil, R_{u4}^{exp} : rotation of 461,000 cycle
For Water, R_{u2}^{exp} and R_{u3}^{exp} : rotation of 25,000 cycle and 32,000 cycle respectively

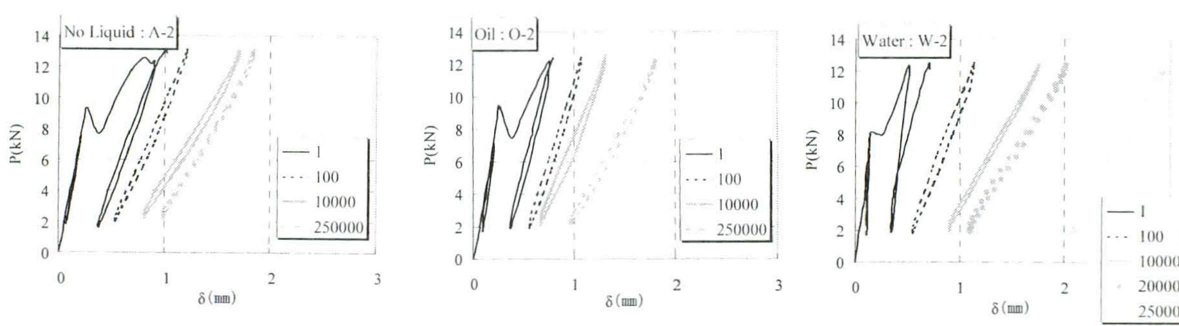

Fig.5 Load-Displacement History

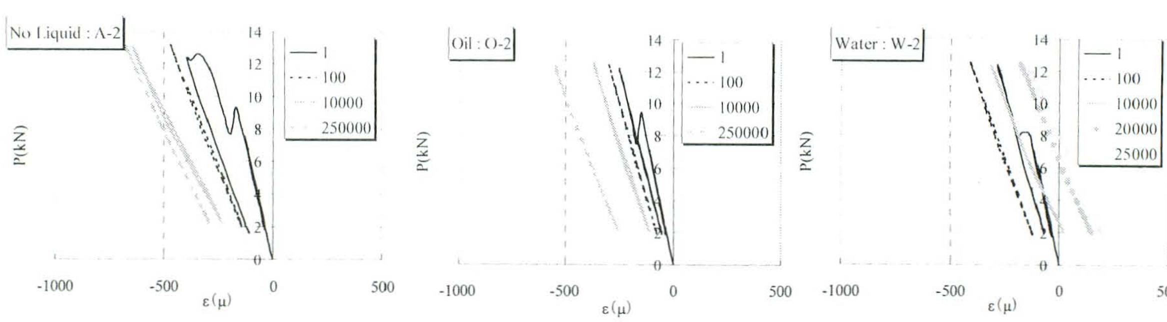

Fig.6 Load-Strain History

ratio which is defined as the yield capacity at cyclic loading divided by that at essential monotonic loading, provides no significant effect of fatigue deterioration except above mentioned two water specimens.

Fig.5 and **Fig.6** represent displacement and concrete strain histories of the cyclic loading test specimen respectively for each circumferential condition. And crack distribution until 1,000th cyclic loading, the end of cyclic loading and post fatigue monotonic loading is respectively illustrated in **Fig.7**, where in the water specimen W-2 failed in shear, crack distribution is shown until cyclic loading number of 25,000. It is noted that in the **Fig.5** and **Fig.6**, the 1st cycle history is affected by cracking because applied upper limit load is more than the flexural tensile strength of the member. **Fig.5** suggests cyclic number dependent increase of displacement, where in the water specimens failed during cyclic load application, larger displacement reached even at 10,000th and displacement at 20,000th is larger than that at 250,000th of both mineral oil and no liquid specimens.

Fig.7 suggests that in comparison between no liquid and mineral oil specimens, flexural crack followed by flexural shear crack is similarly observed, however flexural shear crack of the water specimen distributes up at earlier stage. In the water specimen, it distributes much earlier, say at around 10,000th cycle, up to as same extent of that at 250,000th cycle of the mineral oil specimen.

As for the strain history at compressive concrete flange shown in **Fig.6**, it seems to correspond with displacement history except water specimen where strain at 10,000th cycle is smaller that that at 100th, and cyclic number dependent decreases is observed for further cycles. This strain decrease phenomena of the water specimen is explained by significant shear deformation increase and flexural stress release as a result at the progressive shear failure stage. It is noted that for no liquid specimen, predicted design fatigue strength [2] defined below eq.(1) provides 9.46kN at 250,000 cycles (13.4kN as upper load applied in the present test), that means all specimens are predicted as possible fatigue failure during cyclic loading stage.

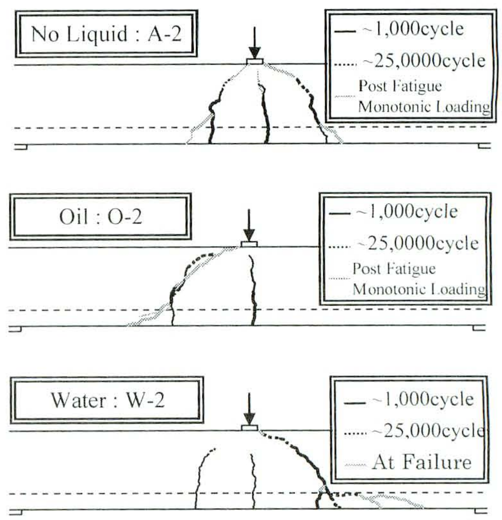

Fig.7 Comparison of Crack Distribution

$$V_{rcd}=V_{cd}\,(1-V_{pd}/V_{cd})\,(1-\log N/11) \qquad (1)$$

V_{rcd} : Fatigue shear strength V_{cd} : Shear strength

V_{pd} : Applied shear force N : Fatigue life(Load cycles)

4.2 Displacement History

Fig.8 provides load cycle dependent stiffness reduction, where the stiffness is defined as load amplitude divided by responded displacement amplitude for each loading cycle and stiffness ratio defined as the prescribed stiffness divided by initial stiffness at the first loading cycle. Each specimen provides significant reduction of stiffness, however after 10th cycle, some difference is observed due to circumferential condition. In the no liquid specimen, stiffness ratio gradually decreases until 1,000 load cycles but is rather stable after that. In contrast, both water and mineral oil specimens continuously decrease even after that cycle. However in the shear failed specimens, two water specimens W-2 and W-3 and the mineral oil specimen O-4, the history does not provide sudden reduction even toward shear failure.

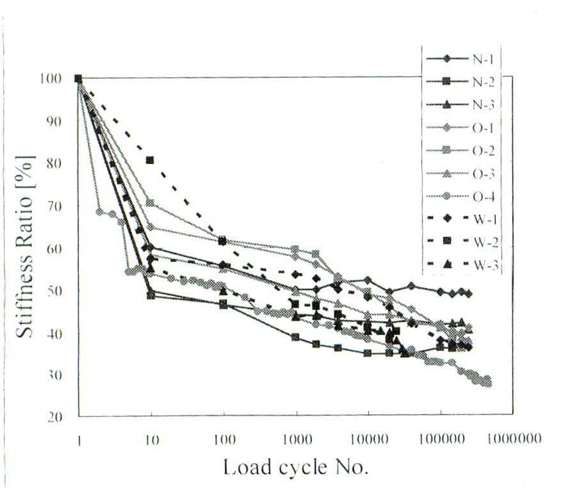

Fig.8 Load Cycle Dependent Stiffness Ratio

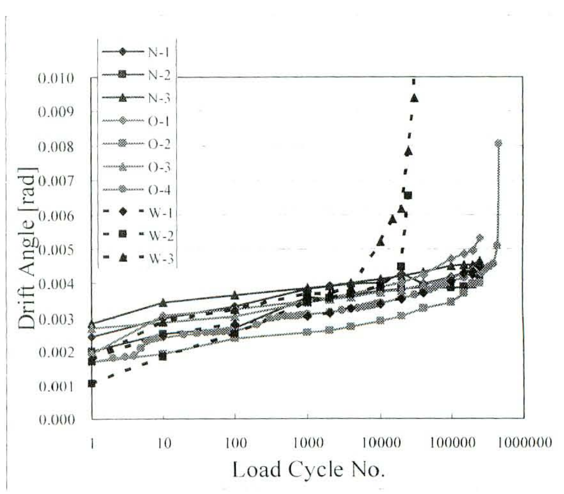

Fig.9 Load Cycle Dependent Displacement

Fig.9 provides load cycle dependent displacement response, where drift angle is defined as the displacement at each cycle upper load divided by shear span L=450mm. No liquid (normal) specimens tend to increase linearly, while water specimens provide similar increase until around 4000 cycles, but provide significant increase after that cycle except W-1 with no shear failure reached. Among mineral oil specimens shown as thick solid line, O-4 specimen provides significant increase after 400,000 cycles and others some increase after 100,000 cycles.

4.3 Damage Potential with Liquid Pressure

Two of three water specimens provided shear failure during cyclic load application, while one of four mineral oil specimens shear failure. In general, with liquid existence, crack especially flexural shear crack tends to be enhanced. That enhancement is more in water than in mineral oil with higher viscosity. In the eye observation, both at water and mineral oil specimens test, paste was pushed out of existing cracks and flew out in the acryl storage with increase of load cycles. However more amount of paste flow out was observed in the water specimen than mineral oil specimen. This fact suggests difference of liquid permeation and pressure dependent on liquid viscosity.

4.4 Post Fatigue Monotonic Loading Test

Monotonic load was applied up to failure for survived specimens. Obtained load displacement relationship is represented in **Fig.10** where the results of same specimens is provided for no liquid and mineral oil condition, and the result of W-1 specimen provided for water. With some difference in maximum load capacity and ultimate displacement, it is commonly said that load increases up to 17~18kN at yielding and after that displacement increases until ultimate shear failure. As shown in Fig.7 some flexural shear cracks were distributed but no flexural yielding was reached. Flexural shear crack enhanced during cyclic load application, progressed toward the compressive flange section.

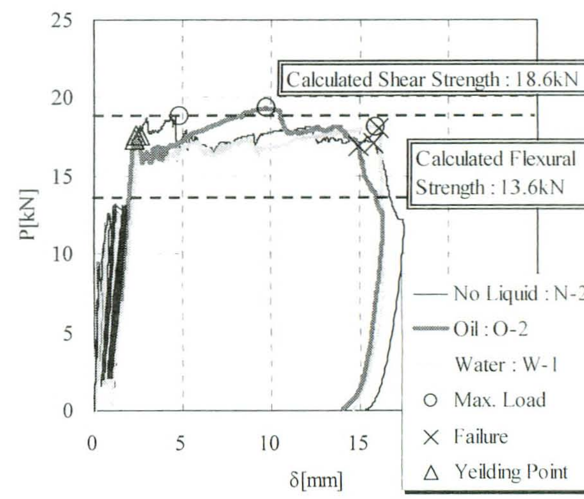

Fig.10 Load Displacement Relationship after Fatigue Load Experienced

4.5 Ultimate Strength and Ultimate Displacement

Obtained ultimate strength and ultimate displacement is respectively summarized in **Fig.11** and **Fig.12**. **Fig.11** provides no significant difference in ultimate strength except liquid specimens failed in shear during cyclic load

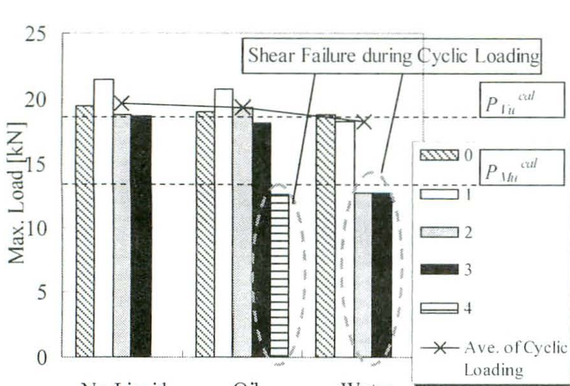

Fig.11 Comparison of Ultimate Strength

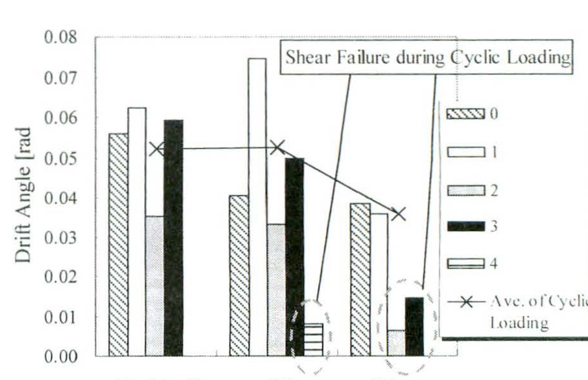

Fig.12 Comparison of Ultimate Displacement

application. Shear strength of these latter two water specimens provide 69% of calculated value, further less compared with obtained flexural strength in other specimens, where averaged value is provided only for post yielding shear failure specimens.

Fig.12 provides ultimate displacement, where some difference is observed between specimens because all of them were ultimately failed in shear; i.e. some of them in shear during fatigue loading and most of them in flexural shear. In general, mineral oil specimens provide less value than no liquid (normal) specimens and water specimens least value among all specimens failed in flexural shear.

5. Concluding Remarks

Cyclic loading test has been carried out in order to study liquid permeation dependent fatigue characteristic of reinforced concrete beam. Obtained results are concluded as followings.

1) Flexural shear crack develops during cyclic load application.
2) Load cycle dependent displacement increases more in water and the next, mineral oil than normal(no liquid) condition, and two of three specimens in water and one of four those in mineral oil failed in shear during cyclic loading.
3) In the post fatigue monotonic loading test, observed is post flexural yielding shear failure at ultimate.
4) Displacement ductility decreases more in water and the next, mineral oil than normal conditions.
5) For practical design of reinforced concrete member with mineral oil permeation, it seems to be conservatively designed with fatigue strength predicted by current design standard considering water permeation.

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