Effect of Expansive Agents in Improving Fatigue Durability of Concrete Bridge Deck under Wet Condition

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ABSTRACT

Cracks in concrete bridge decks provide easy access for water to penetrate. Infiltration of water accelerates the deterioration of reinforced concrete bridge decks by wearing crack surfaces when under fatigue loading. Transportation of chlorides through penetrating water is known to cause corrosion of reinforcement which shortens the life time of the structure. The effect of expansive agents in mitigating crack occurrence and improving the fatigue durability RC bridge slabs has been observed in previous research carried out by the authors. Fatigue tests were carried out on fix supported slabs made from expansive concrete under wet and dry conditions using the Wheel Running Machine. The results are compared with the previous fatigue test results of normal RC slabs tested under wet conditions.
Keywords: expansive agents, fatigue durability, wet condition, Wheel Running Machine

1. INTRODUCTION

The formation of cracks in RC bridge decks is known to reduce its service life. Cracks also provide easy access for water to penetrate into the concrete. Infiltration of water accelerates the deterioration of reinforced concrete bridge decks by wearing crack surfaces when under fatigue loading. Transportation of chlorides through penetrating water is known to cause corrosion of reinforcement which shortens the life time of the structure. Penetrating water through cracks in the concrete has been known to cause spalling of concrete resulting in the formation of potholes. Thus it is reasonable to assume that the reduction in crack occurrence will reduce water penetration, increasing the durability of the slab. Effect of water on the fatigue durability of normal RC slabs under wheel loads has been documented by previous research [1]. This research also found that the life time of a bridge slab reduces to less than 1/200 of the life of a dry slab when tested under wet condition.

The effect of expansive agents in mitigating crack occurrence and improving the fatigue durability of RC bridge slabs was investigated through earlier research carried out by the authors [2]. The addition of expansive agents to concrete has been found to provide a volumetric expansion during early setting thus compensating for plastic and drying shrinkage. Although expansive agents are extensively used in mitigating early age crack occurrence, the effect of expansive concrete on the fatigue durability of RC bridge decks, especially under wet conditions, has not been clearly studied.

The failure mechanism of RC bridge decks under wheel loads has been well documented by fatigue tests using the wheel running machine [3]. The present tests were carried out on expansive concrete bridge slabs under both wet and dry conditions. In order to simulate actual conditions the slabs were cast with steel girders and tested under fixed support conditions at the girder positions.

The results of the fatigue tests are presented and compared with the test results of a wheel running test for a normal RC slab with steel girders under fixed support conditions tested under dry conditions and also previous research results for simple support normal RC slabs tested under wet conditions.

2. EXPERIMENTAL PROCEDURE

The fatigue tests were carried out on full-size models of real concrete bridge decks. The reinforcement details as well as slab dimensions of the tested slabs are shown in Fig.1. A general concrete mix design adhering to manufacture specifications was used and is given in Table 1. The expansive admixture amount utilized was of the shrinkage compensating type according to the specifications provided by JSCE. The expansive admixture was of the lime based type and was added in place of equal cement content.

Table 1 Characteristics of concrete mix

Concrete Type	W/(C+E) (%)	s/a (%)	Weight per unit volume (kg/m^3)						Slump (cm)	Air (%)
			Water	Cement	Gravel	Sand	Water reducer	Expansive agent		
Normal	55	44.5	165	300	1019	803	3	-	16.5	4.5
Expansive	55	44.5	165	280	1019	803	3	20	18.3	5.2

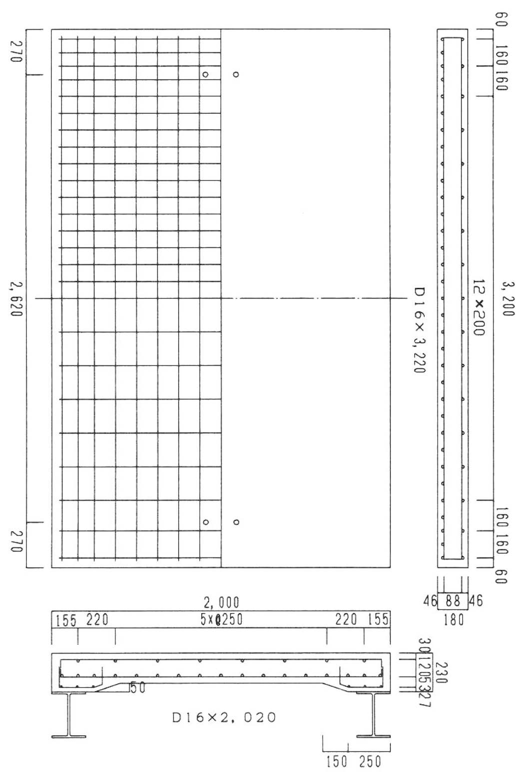


Fig.1 Slab details

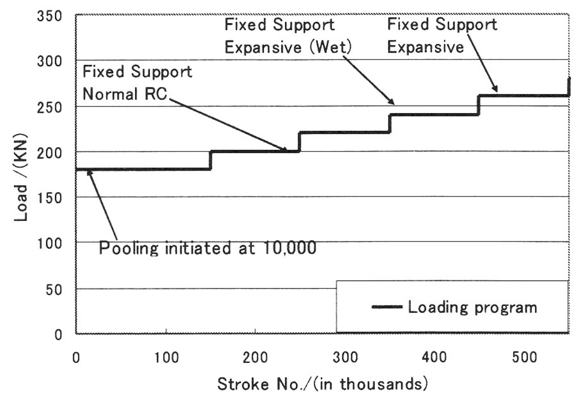


Fig.2 Loading Program

All slabs were cast and cured for 10 days. The sides of the slabs were waterproofed during the curing period to prevent evaporation. Strain gauges were attached at predetermined locations on the main and distribution bars before casting. The loading program was designed using the punching shear load equation for RC slabs [4]. The running load was calculated to be 180kN for a normal RC simple supported slab to fail at the predetermined 200,000 loading cycles. Due to the reduction of bending moment expected by fixed supports a higher durability was anticipated, and thus, a step loading program was utilized in the fatigue testing. The initial load was set at 180kN and the load was increased by 20kN every 200,000 cycles after the initial 300,000 cycles. The loading program is depicted in Fig. 2 along with the ultimate failure position of each slab.

At regular intervals the wheel was stopped at the slab center and two other predetermined locations along the running direction and displacement along the transverse and longitudinal slab axis were recorded under static loading using dial gauges set under the slab surface. Strain readings were obtained from the attached strain gauges on the main and distribution reinforcements. Crack occurrence on all surfaces was documented with the corresponding load cycle number. Following the wheel load running tests all the slabs were cut along the transverse and longitudinal center lines in order to evaluate the mode of failure.

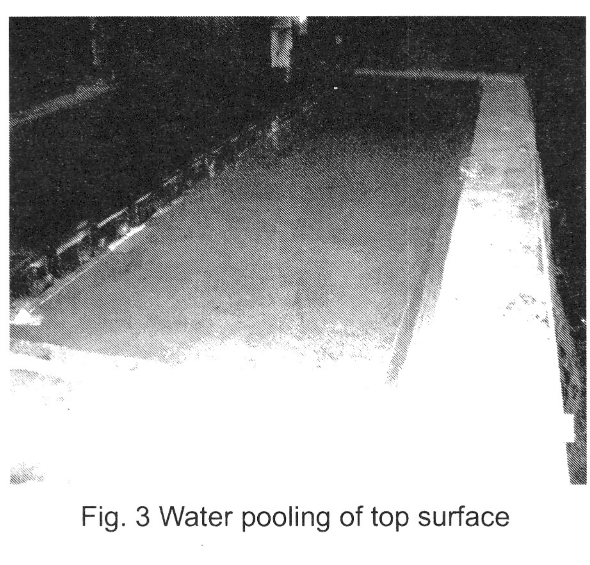


Fig. 3 Water pooling of top surface

The boundaries of the pool in the expansive RC slab tested under wet conditions were made from plastic triangular pipes as shown in Fig. 3. Water pooling was initiated after 20,000 load cycles under the initial load of 180kN. Water pooling was not initiated from the start of loading in order to check for the comparability of the present slab with that of the fix supported expansive slab tested under dry conditions. The edges of the pool were made approximately 20cm from the edge of the slab and the water level was kept constantly above a depth of 5mm.

3. RESULTS

3.1 Fatigue Durability

Previous wheel load running tests on simple supported concrete slabs showed that fatigue life could be extended substantially by the addition of expansive agents [2]. From the mechanical material tests carried out 28 days after casting and before the start of the wheel load running test it was seen that the addition of expansive agents did not affect the compressive strength of concrete. The Young's modulus and Poisson's ratio was also found to be very similar for both concrete types.

The present fix supported expansive RC slab under wet condition was found to have fatigue strength of 4,269,000 cycles in 180kN equivalent load. The durability of this slab is compared with the fix supported expansive RC slab under dry conditions and also the normal RC slab under dry state in Fig. 4. The two lines represent the S-N relation for normal RC slab under simple supported dry and wet conditions [1].

The fixed supported expansive RC slab tested under dry condition failed at 16,004,000 180kN equivalent cycles. It is interesting to note that in expansive concrete slabs the difference between wet and dry state fatigue life is only approximately 1/4 whereas in normal RC the drop in fatigue durability due to presence of water was found to be less than 1/200 [1]. Therefore expansive concrete slab tested under wet conditions is seen to also have a longer service life than the normal RC slab tested under dry conditions which had a fatigue life of 921,400 cycles. The extension of service life when compared with simple supported normal RC slabs under wet conditions as seen in the S-N curve is more than 1000 times.

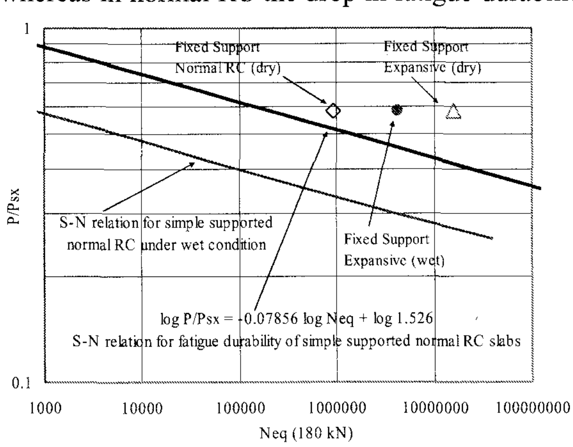


Fig. 4 S-N Relation

3.2 Deflection

The variation of the live load deflection at the slab center with increasing load cycle number is plotted in Fig. 5. From the graph it is seen that the stiffness of both expansive concrete slabs is larger than the normal RC slab. Even though one slab is being tested under wet condition, both expansive concrete fix supported slabs show similar live load deflections until the failure of the slab tested under wet conditions.

In Fig. 6 the live load, residual and total deflections at the slab center for the two expansive concrete slabs are compared. It is seen that the live load deflection is similar but the residual deflection of the slab under wet conditions becomes negative soon after pooling of the top surface at 20,000

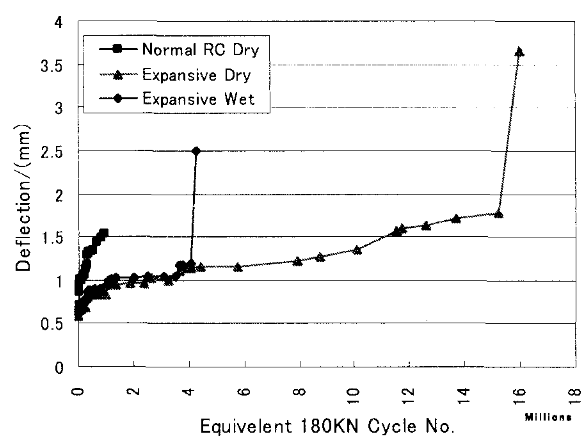


Fig. 5 Live load deflection at center

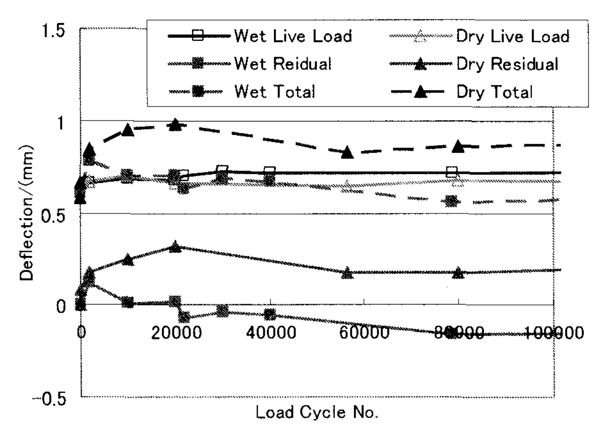


Fig. 6 Wet and dry deflection of expansive concrete slabs up to 100,000 cycles

cycles. One explanation for this phenomenon is thought to be that expansive concrete expands further due to the presence of water. Another theory is that water seepage into the top surface of the slab progress the hydration of residual concrete within the slab. One or the combination of these two ideas is thought to provide a local prestrain to the reinforcement around the cracked area, and thus an expansion of the slab is thought to occur near the top reinforcement. This is thought to result in the slab curving upwards and reducing the residual deflection.

3.3 Strain

The residual deflection change at 20,000 load cycles when under wet conditions is verified by the residual strain variation of the reinforcement. Fig. 7 shows the residual and live load strain change during the initial 80,000 load cycles at two points 270mm apart in the upper main bar 600mm from the center of the slab tested under wet conditions. Fig. 8 depicts the residual strain variation in the

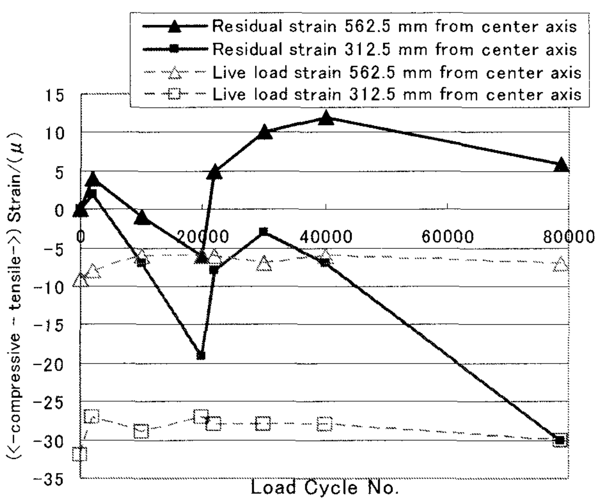


Fig. 7 Expansive wet slab strain variation in upper main bar 600mm from slab center

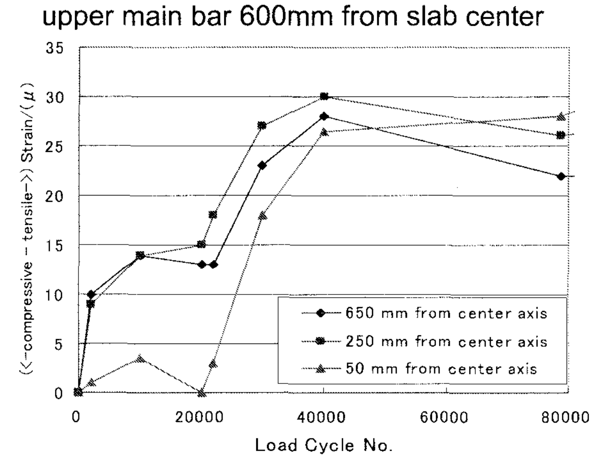


Fig. 8 Expansive wet slab residual strain in upper distribution bar 375mm from slab center

upper distribution bar 375mm from the slab center when tested under wet conditions. It is clear that soon after 20,000 load cycles in each bar there appears to be a sudden increase in tensile strain. It is found to be only in the residual strain as the live load strain is found to constant without decreasing as seen in Fig. 7. Thus it can be confirmed that a prestraining of the reinforcement does occur soon after pooling of the top surface as such changes are not visible in the slabs tested under dry conditions.

3.4 Crack Occurrence

The crack development under cyclic loading, especially on the bottom surface of the slabs, has been found to be less in expansive concrete slabs when compared with the normal RC slabs [2]. Fig. 9 shows the crack development with time on the bottom surface of the normal RC and the two expansive concrete slabs tested under fix support conditions. It is clear from this figure that the development and propagation of cracks is less in expansive concrete even when under wet conditions. The experiments results indicate that the slab tested under wet condition has less number of cracks than the slab tested under dry condition.

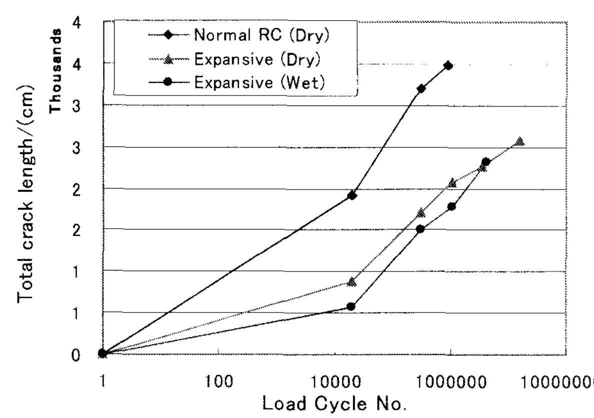
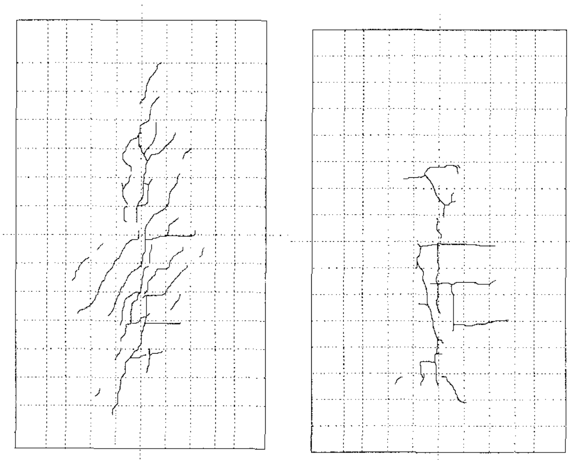


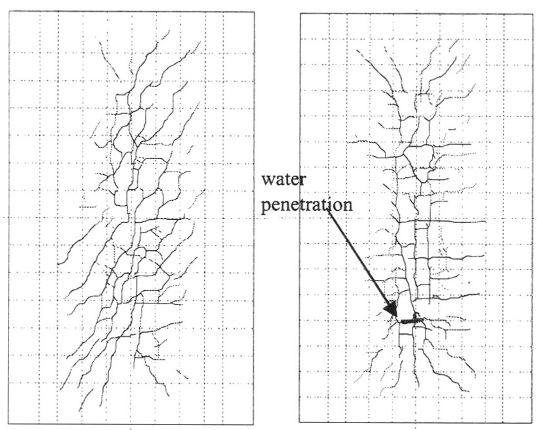
Fig. 9 Crack occurrence history



(a) Dry slab (b) Wet slab

Fig. 10 Cracks at 20,000 cycles

The crack occurrence at 20,000 cycles on the bottom surface of the two expansive concrete slabs is shown in Fig. 10. Since both slabs were tested under dry state during this period it is thought that the greater occurrence of cracks in the dry slab is an occasional occurrence. Fig. 11 shows the crack pattern on the bottom surface of the two expansive concrete slabs at 3.65 million equivalent cycles in 180kN load, which is just before the failure of the slab tested under wet condition. As seen water has already started to penetrate the entire depth of the slab, yet the crack density is seen to be similar to the dry slab.



(a) Dry slab (b) Wet slab

Fig. 11 Cracks at 3.65 million cycles

Following water penetration the slab was seen to fail in punching shear. Water was seen to penetrate through the cracks that appear near the slab haunch parallel to the wheel running direction just before failure. These cracks are considered to be the toes of the shear cracks within the slab. The top surface as seen in Fig. 12 had several areas where concrete spalling had occurred. Most locations were at the edge of the running wheel, and course aggregate was seen to have been released from the concrete matrix. The appearance of potholes on many bridges has been found to contain the same phenomenon [1].

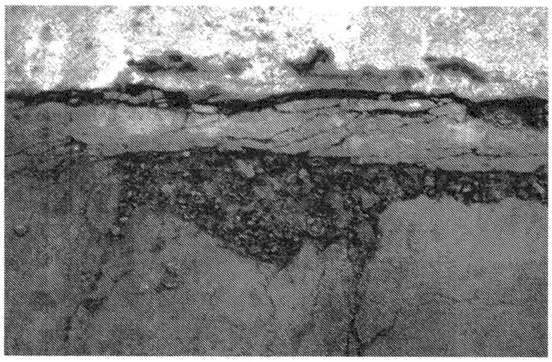
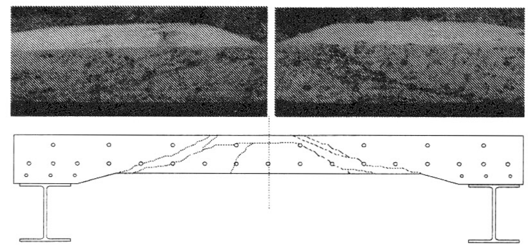


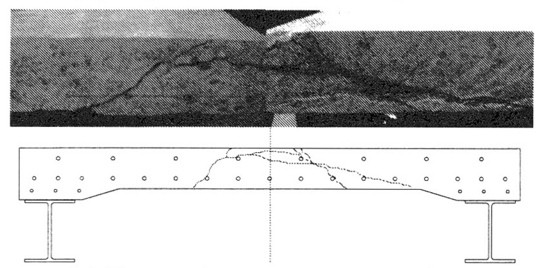
Fig. 12 Aggregate released from the deteriorated concrete matrix

3.5 Punching Shear

Cutting the slabs along the longitudinal and transverse axis revealed that the slabs had clearly failed by punching shear. Previous research has shown that the punching shear angle decreases due to prestressing [5]. Research carried out by the authors has found that the addition of expansive admixture also reduces the punching shear angle in RC slabs [2].



(a) Expansive concrete dry slab



(b) Expansive concrete wet slab

Fig. 13 Punching shear crack sections

In the slab tested under wet conditions the shear cracking was not symmetric as normally expected. While one side had multiple cracking on the shear surface as seen in Fig. 13(b), the other surface had only a single crack. Multiple cracks were observed in the expansive slabs under dry conditions as seen in Fig. 13(a). The reason for the difference in angles on either side of the slab is not clear. Weak concrete sections and slight unsymmetrical loading is thought to have lead to this phenomenon. It is not clear if the penetration of water had any effect on the symmetry of the shear cracks. Additional tests need to be undertaken to verify this behavior.

4. DISCUSSION

The same loading program was used to test fixed supported slabs of expansive concrete under wet and dry conditions to evaluate the fatigue durability. Water pooling was done at 20,000 cycles, after this the residual deflections were found to decrease under cyclic wheel loads indicating that the slab was curving upwards. The phenomenon is supported by the residual strain readings indicating a tensile straining of the top reinforcement soon after pooling of the top surface.

It is thought that the penetration of water either causes expansive concrete to further expand or to hydrate residual concrete mixture which has not reacted with water during curing. The expansion of the concrete is thought to prestrain the surrounding steel which will in turn provide local prestress to the concrete. This effect is thought to reduce further crack occurrence and is clear when comparing the crack formation with the slab tested under dry conditions, especially during the early stages of loading.

Spalling of concrete was observed on the top surface with aggregate seen to be released from the concrete matrix. As the top surface was pooled during this period it was not possible to evaluate crack occurrence on the top surface. Since a number of cracks were found on the top surface after the test, it is thought possible that the water could have penetrated through these cracks.

Punching shear angles on the slab sections of the slab tested under wet conditions were not symmetric, which could have been due to weak concrete sections or unsymmetrical wheel loading.

5. CONCLUSIONS

The following conclusions were drawn from the results of the fatigue durability test for expansive concrete fix supported slab tested under wet condition.

1. The durability of expansive concrete slabs tested under fixed supports and wet condition was found to be more than 4 times less durable when compared with the slab tested under dry condition.
2. The durability of the expansive concrete slab tested under wet condition was more than 4 times durable than a similar normal RC slab tested under dry condition and more than 1000 times more durable when compared with the existing S-N relation for normal simple supported RC slabs under wet condition.
3. The residual deflections after pooling of the top surface was found to become negative, while residual strains in the reinforcing were suddenly found to become tensile indicating local prestreesing of concrete due to penetrating water.
4. The crack occurrence under wet condition was found to be slightly less than the slab under dry condition until just before failure.
5. Spalling of concrete was observed near the edges of the wheel forming "potholes" on the top surface of the slab.
6. The punching shear cracks were found to be unsymmetrical.

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