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Material and Size Effect on Fatigue Damage of Concrete for Pavement Application

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Abstract

Highway pavements need to withstand repeated and varying traffic loads due to which they may fail at a stress level lower than their strength called fatigue. Fatigue is the progressive damage due to the propagation of cracks and is considered to be the primary cause of structural failure in concrete pavement. The propagation of cracks in concrete is resisted by the fracture toughness, which is a material property. Stress intensity factor is used to express the fracture toughness which depends upon the present state of crack tip stress, strength and geometry of the structural component. Material fracture toughness and the applied stress ratio influence the progressive damage and the fatigue life of concrete. This paper investigates analytically the progressive damage of concrete due to cyclic loading based on a stress intensity factor based fatigue damage prediction model. The effects of material property and specimen size have found to affect the propagation of cracks and the incremental damage. The varying sequence of cyclic loading was found to influence the progressive damage and fatigue life of concrete significantly.

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Keywords: *Concrete pavement; fatigue; crack propagation; stress intensity factor; incremental damage*

1. **Introduction**

Highway pavements are subjected to repeated number of traffic loads throughout their service life. In concrete pavement, the repeated loading may cause cracks at critical locations which propagate within the pavement over time. Propagation of cracks finally leads to failure of the pavement due to fatigue. Fatigue can be considered as the progressive structural damage due to cyclic loading by which the structure fails at a stress level lower than its strength.

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It is considered to be the primary cause of structural failure in concrete pavement. The fatigue life (*N*) depends significantly upon the applied stress level (*S*). More is the applied stress, less is the fatigue life. Several fatigue life equations have been developed by researchers which indicates a linear relationship between the stress ratio and the logarithm of number of load cycles (*S-N* relationship) (Darter and Barenberg, 1976; PCA, 1984; Oh, 1991; Roesler et al., 2004 etc). Recent research shows that material fracture toughness also plays a significant role in fatigue damage due to cyclic loading (Subramanian et al., 2000; Maitra et al., 2018). Fracture toughness is the property of the material which resists crack propagation and is generally expressed by stress intensity factor. It indicates the state of stress at the crack tip and is influenced by the applied stress state, present crack length and the geometry of the structural component. The present work investigates the crack propagation and incremental damage due to cyclic loading based on a stress intensity factor based damage prediction model. The effects of material property and specimen size on crack propagation are examined and the incremental damage is estimated with increase in number of load cycles till failure. The effect of varying sequence of cyclic loading has also been investigated and the cumulative damage and remaining life is determined.

2. Concrete under cyclic loading

Fatigue in concrete can be defined as the incremental damage due to initiation and subsequent propagation of cracks under repeated loading. Energy is released and when this exceeds the energy required to form two new surfaces, the crack propagates within the material (Hillerborg et al., 1976). The resistance of the material against crack propagation is termed as fracture toughness. With increase in load repetitions, the resistance decreases resulting which the crack widens and propagates through the material and consequently causes failure of the structure due to fatigue (Maitra et al., 2014). Fatigue is thus the incremental damage due to repeated application of loading.

Reinhardt and Cornelissen (1984) investigated the behavior of concrete under cyclic tension by performing laboratory tests based on fracture mechanics approach. Subsequently, researchers (Gylltoft, 1983; Hordijk, 1991) have indicated that the incremental damage due to cyclic loading is influenced by material properties. Subramanium et al. (2000) performed flexural fatigue experiments on concrete beams and studied the fatigue damage behavior based on stress intensity factor. Navalurkar and Hsu (2001) investigated high strength concrete based on fracture mechanics principles. Gaedicke et al. (2009) investigated the crack propagation of concrete slab by performing laboratory tests. A fatigue model was proposed which considers material fracture resistance. Isojeh et al. (2017) investigated compression fatigue damage due to the effects of different loading parameters in concrete and observed the influence of material properties on fatigue life.

The conventional *S-N* curve approach gives a linear relationship between the applied stress ratio (*S*) and the final fatigue life (*N*). Stress ratio is defined as the ratio of the applied stress level to the material's flexural strength. However, the relationship does not provide the incremental damage due to any intermediate stage of load repetitions. The effect of material fracture toughness, which depends upon the existing state of stress, present crack length and specimen geometry, has not been recognized in the conventional *S-N* relationships. Research has established that specimen size has a significant effect on fatigue damage of concrete (Bazant and Schell, 1996; Zhang et al., 2001; Roesler et al., 2004). For highway pavements subjected to repeated loading of various magnitudes, it is important to know the amount of the existing damage and the remaining life, so that necessary measures can be taken up for repair and rehabilitation. The existing fatigue models or the *S-N* relationships cannot estimate the present state of damage and also the cumulative damage. Therefore, it is necessary to investigate these effects on fatigue performance of concrete. This paper presents an analytical investigation to estimate the effects of concrete material properties and specimen size on crack propagation and incremental damage of concrete. The cumulative damage due to varying sequence of cyclic loading has also been investigated and the remaining life is determined.

3. Crack Propagation and Damage Estimation

It has been demonstrated in the literature that crack propagation depends upon material fracture toughness or the stress intensity factor (K_I). The variation of rate of crack propagation is sigmoidal in shape as shown schematically in Figure 1(a) (Paris and Erdogan, 1963). The stress intensity factor has a threshold value (K_{TH}) at which the crack initiates. This is a small region which is followed by a comparatively large stable crack growth region. Finally there exists a critical fracture zone, where the rate of crack propagation is very high leading to instability and consequently the failure of the structure. As the crack propagates, the stress intensity factor also increases and reaches its maximum at the failure. This maximum value is termed as critical stress intensity factor (K_{IC}) or fracture toughness and is considered to be a material property.

The variation of crack length with number of load cycles is shown schematically in Figure 1(b) for varying load (stress) levels. This type of variation has been derived from several fatigue experiments performed by researchers (Bazant and Xu, 1998; Gaedicke et al., 2009; Maitra et al., 2018 etc.). The figure shows that with increase in the number of load cycles, the crack length increases steadily till failure. Near failure condition, the crack length increases at a very high rate and finally reaches its maximum leading to failure of the specimen. For lower stress levels, the point where the rate of crack propagation changes abruptly is clearly identified and it is termed as bend over point (n_b). For higher stress levels however, there is no distinct bend over point. Also, with increase in stress levels, there is a linear decrease in the maximum crack lengths. At higher load levels, the crack propagates faster and the specimen fails more rapidly as compared to that with lower load levels.

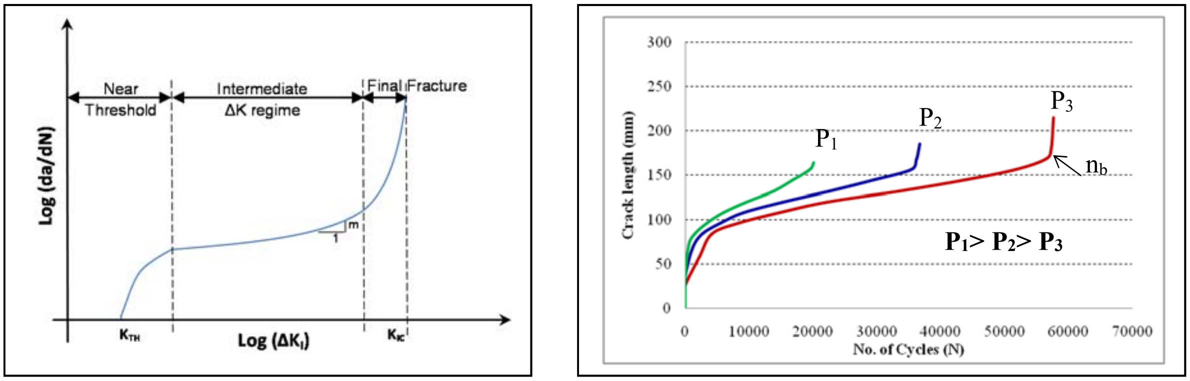

Figure 1. (a) Schematic variation of Rate of Crack Propagation (*da/dN*) with Stress Intensity Factor (K_I); (b) Schematic variation of Crack length with Number of load cycles for different Stress levels

In order to estimate the progressive cracking due to cyclic loading, the stress intensity factor based damage prediction model proposed by Maitra et al. (2018) has been considered in this work. The model estimates the state of damage in terms of fracture toughness ratio (K_{In}/K_{IC}) by considering the applied stress level (S) and the current number of load cycles (n). Fracture toughness ratio (K_{In}/K_{IC}) gives an estimate of the state of damage at any intermediate load cycle for a particular stress level. It is expressed as the ratio of stress intensity factor (K_{In}) at any load cycle (n) to the critical stress intensity factor (K_{IC}). The ratio increases with increase in number of load cycles and reaches finally to its maximum value K_{IC} at failure. The failure criterion has thus been considered when K_{In} reaches K_{IC} for which the fracture toughness ratio becomes 1.0. The value of this ratio less than 1.0 indicates the intermediate state of damage corresponding to the applied number of load cycles at a particular stress ratio (Maitra et al., 2018). The final fatigue life is the load cycle at fracture toughness ratio 1.0. The damage prediction model (Maitra et al., 2018) expresses damage in terms of fracture toughness ratio and is demonstrated by equations 1 to 3.

$$K_{In}/K_{IC} = 0.102 \times \log(n) + 0.672 \times S \qquad \textit{for } S < 0.65 \qquad (1)$$

$$\left(K_{In}/K_{IC}\right)^{0.33} = 0.107 \times \log(n) + 0.802 \times S\,, \qquad \textit{for } S < 0.65, \qquad (2)$$

$$K_{In}/K_{IC} = 0.162 \times \log(n) + 0.769 \times S\,, \qquad \textit{for } S >= 0.65 \qquad (3)$$

Equations 1 and 2 are applicable for stress ratios less than 0.65. Equation 1 is used to estimate the state of damage up to the bend over point. The bend over point can be estimated using equation 4. Beyond the bend over point, the state of damage is expressed using Equation 2 for stress ratio less than 0.65. For stress ratios greater than 0.65, equation 3 can be used for estimating the incremental damage corresponding to any applied load cycle.

$$n_b / N = 1.517 - 1.007 \times (S) \tag{4}$$

The stress intensity factor can be determined as per RILEM specifications (Shah, 1990). K_{IC} being a material property, is determined in the laboratory whereas K_{In} is estimated considering the existing crack length and geometry of the structural component at any load level (Shah, 1990).

4. Parametric Study

The state of damage in terms of crack propagation depends upon applied stress ratio, fracture toughness ratio and the present number of load cycles. Fracture toughness ratio indicates the materials fracture resistance against the applied stress ratio and number of load cycles. Stress intensity factor is used to measure the toughness characteristics of the specimen, which depends upon the property and size of specimen and the existing crack length. A parametric study has been carried out in this work in order to understand the effects of material properties and specimen size on incremental damage. In practice, wheel loads of different magnitudes are moving at varying sequences on the highways and the pavements get damaged. Therefore, the damage due to the effects of variable loads applied at different sequences is also investigated. Knowing the state of damage, the remaining life of the pavement is estimated.

4.1. Effect of material property

Concrete properties influence the material fracture toughness. For the present parametric study, three different concrete grades have been chosen. Table 1 shows the concrete elastic modulus (*E*), and the corresponding modulus of rupture (MOR) and critical stress intensity factor (K_{IC}) values for the chosen materials. The beams are assumed to be subjected to three-point bending under cyclic loading. For all the 3 grades, concrete beams of size 100 mm X 100 m X 500 mm with c/c distance between supports of 400 mm (length/depth=4) are considered. For the repeated loads, two different stress ratios of 0.62 (*S1*) and 0.70 (*S2*) are assumed to apply on the beam specimens.

Table 1: Concrete material properties

Material	Elastic Modulus (MPa)	Modulus of Rupture (N)	Critical Stress Intensity Factor ($Nm^{-3/2}$)
E1	34380	8020	2080390
E2	25780	6015	1675040
E3	20630	4815	1374065

Based on the damage prediction model, damage is estimated in terms of crack propagation for all the 3 concrete grades. For the known stress ratio (*S*), the load cycles (*n*) are increased steadily and the corresponding crack length is determined. Thus the propagation of cracks or the incremental damage is obtained for each increase in load cycle till the final failure. For stress ratio *S1*, Equations 1 and 2 are used and for stress ratio *S2*, Equation 3 is used to estimate the incremental damage and the final fatigue life. Figure 2(a) shows the crack propagation with number of load cycles for *S1* and Figure 2(b) shows the same for *S2*. For the lower stress ratio *S1*, it has been observed from the figure that the rate of crack propagation is low initially, after that there is a steady increase till the bend over point following which a rapid increase in the crack rate leading finally to the failure of the beam due to fatigue. For higher stress ratio

S2, however, there is no distinct bend over point and the crack length increases reaching to its maximum and the specimen fails rapidly due to fatigue.

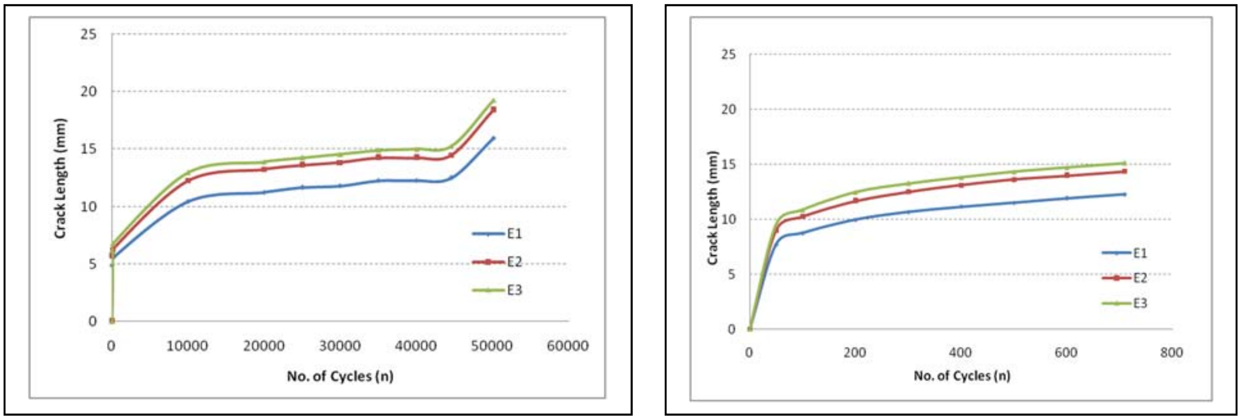

Figure 2. (a) Variation of crack length and number of load cycles (*n*) with different *E* values for Stress ratio *S1* = 0.62; (b) Variation of crack length with number of load cycles (*n*) with different *E* values for Stress ratio *S2* = 0.70

The effect of concrete elastic modulus on maximum crack length at failure is shown in Figure 3. Concrete with higher *E* value has a lesser maximum crack length as compared to that with lower *E* value for both the stress ratios. Higher *E* value designating stronger material having smaller crack length at failure indicates that the failure is more brittle as compared to that with smaller E values. The figure also indicates that the maximum crack length at failure is higher for lower stress ratio for all E values. The fatigue life (*N*) is determined and it is found to be as 50,120 for *S1* and 710 for *S2.*

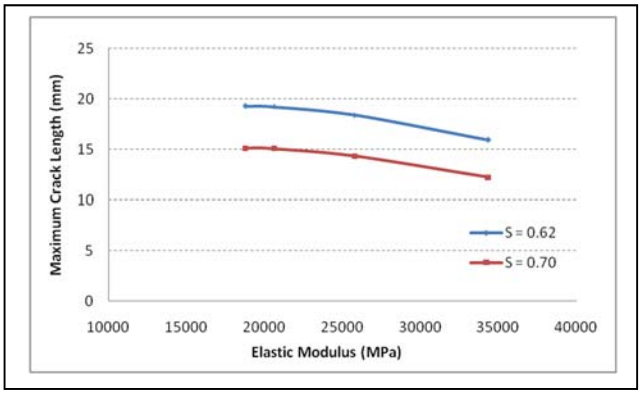

Figure 3.Variation of maximum crack length with concrete elastic modulus

4.2. Effect of specimen size

Size of concrete specimens influence the material fracture toughness and consequently the crack propagation due to cyclic loading. In the present study, 3 different concrete beam sizes having similar length to depth ratio (length/depth=4) and same concrete grade have been considered and are given in Table 2. The material properties and MOR values are also shown in the table. As in the previous case, the beams are subjected to cyclic loading with two different stress ratios of *S1* = 0.62 and *S2* = 0.70.

Table 2: Concrete specimen size and material properties

Size of Beam (mm X mm X mm)	Modulus of Rupture (N)	Elastic Modulus (MPa)	Critical Stress Intensity Factor ($Nm^{-3/2}$)
75 X 75 X 300	4510	34380	2080390
100 X 100 X 400	8020		
150 X 150 X 600	18045		

Damage is estimated due to the applied cyclic loading with two different stress ratios using the damage prediction model. Load cycles are increased steadily and from the estimated damage, crack lengths are obtained. Figure 4(a) shows the variation of crack propagation with number of load cycles for *S1* and Figure 4(b) shows the same for *S2* for all the 3 beam sizes. The variation of crack propagation with the applied load cycles is similar in nature.

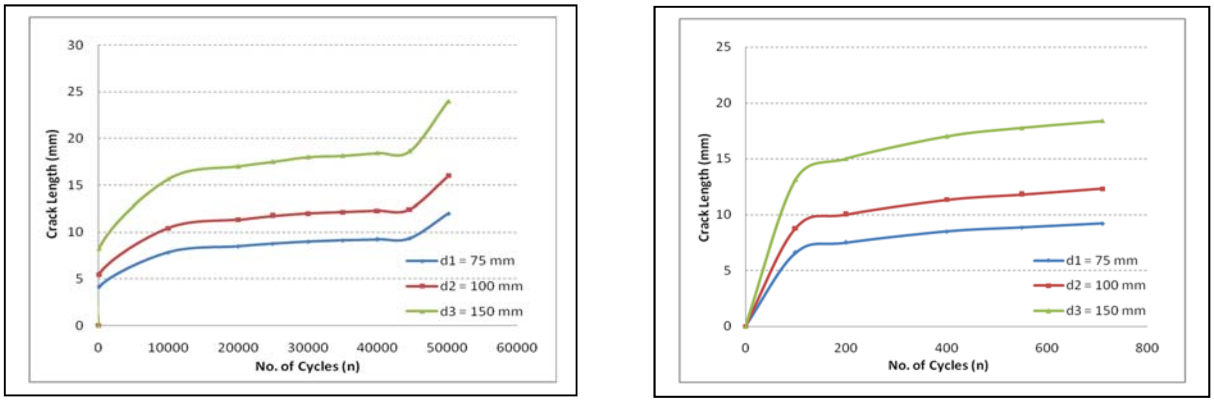

Figure 4. (a) Variation of crack length and number of load cycles (*n*) with varying beam depth for Stress ratio *S* = 0.62; (b)Variation of crack length with number of load cycles (*n*) with varying beam depth for Stress ratio *S* = 0.70

The figures show that for the same number of load cycles, the crack length increases with increase in beam depth for both the stress ratios. The maximum crack length at failure is also higher for the beams with higher depths. As before, the crack propagates with a distinct bend over point for stress ratio of 0.62 whereas no such clear bend over point is visible for higher stress ratio of 0.70. This indicates the failure is more rapid for higher stress ratios. Figure 5 shows the variation of maximum crack length at failure with beam depth. It is seen that the maximum crack length increases linearly with increase in beam depth.

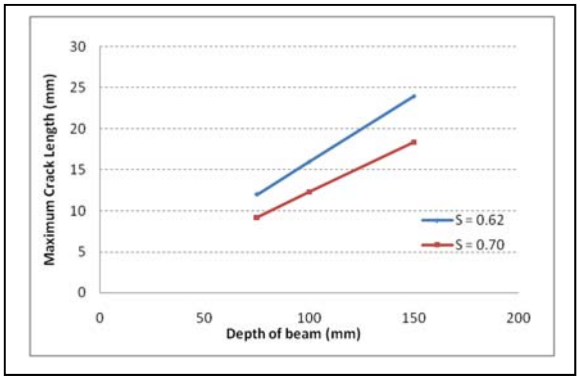

Figure 5.Variation of maximum crack length with depth of beam

4.3. Effect of sequence of loading

In practice, pavements are subjected to different loads of varying sequences. The change in sequence of load repetitions affect the overall damage of the structure. Using the damage prediction model, the cumulative damage and the remaining life can be estimated for loads applied at different sequences. By equating the damage caused by the previous load with a known cycle, the equivalent number of cycles of the next sequence of load is estimated and the total damage due to the combined effects of the loads is determined (Maitra et al., 2018). A parametric study has been carried out to evaluate the cumulative damage due to varying sequence of loading.

A beam of size 100 mm X 100 m X 400 mm with material properties *E3* (Table 1) has been considered for the present study. The beam is subjected to two stress ratios 0.62 (*S1*) and 0.70 (*S2*) with varying sequences. For the first case, *S1* is assumed to apply for 20,000 cycles followed by *S2* for 500 cycles and in the second case, the sequence is reversed. Cumulative damage in terms of fracture toughness ratio (K_{In}/K_{IC}) is estimated using the damage prediction model for both cases and the results are presented in Table 3. It has been observed that due to *S1* applied for 20,000 cycles, the damage (fracture toughness ratio) equals 0.855 which becomes 0.987 due to the subsequent application of *S2* for 500 cycles with a crack length of 14.75 mm. The remaining life is evaluated and it is found that the beam can withstand an additional 120 cycles of *S2* for complete failure. The crack length at failure is estimated as 15.15 mm.

For the next case, *S2* is assumed to apply first for 500 cycles which could cause a damage of 0.976 (K_{In}/K_{IC}) with a crack length of 14.35 mm. This is followed by *S1* for 20,000 cycles. Using the damage prediction model, it has been found that the beam is able to carry at most 8000 repetitions of *S1* till complete failure. The damage caused by 500 repetitions of *S2* is significantly high (0.976) and that's why the beam could carry much less repetitions of *S1* as compared to the first case. The results indicated that varying sequences of load cycles causes different cumulative damage and consequently the remaining lives are also much different.

Table 3: Cumulative damage for varying sequence of cyclic load

Sl. No.	Sequence of load repetitions	Stress Ratio (S)	No. of Cycles (n)	Cumulative Damage (K_{In}/K_{IC})	Crack length (mm)
1	*S1* followed by *S2*	0.62	20000	0.855	13.90
		0.70	500	0.987	14.75
		0.70	120	1.000	15.15
2	*S2* followed by *S1*	0.70	500	0.976	14.35
		0.62	8000	1.000	19.30

5. Conclusion

This paper investigates the fatigue crack propagation and incremental damage of plain concrete due to cyclic loading. A fracture based damage prediction model has been utilized for estimation of progressive damage due to repeated loading. The effect of concrete material properties and specimen size have been examined and it is found to influence the incremental damage. The effect of varying sequence of cyclic loading has also been investigated. The results indicate a significant influence of this on the cumulative damage and the remaining life of concrete. The major outcomes of the present work is summarized as follows.

- Concrete material properties influence the crack propagation due to cyclic loading. At the same load repetitions, concrete with higher elastic modulus has lower crack length. The maximum crack length at failure is also smaller with higher elastic modulus. This establishes the fact that concrete with higher grade is more brittle as compared to that with lower grade.
- At the same elastic modulus, the maximum crack length is higher for lower stress ratio.
- Specimen size influences the incremental damage of concrete. With increase in depth of beam, the maximum crack length increases linearly. At the same load cycle, the beam with higher depth withstands higher crack length.

- Effect of sequence of cyclic loading on cumulative damage of concrete is significant. The damage caused by a concrete beam subjected to a smaller load with a certain repetitions followed by another cyclic load of higher magnitude is less as compared to the damage caused by the same loads with similar repetitions in the reverse sequence. The remaining life is estimated which is distinctly different in the two cases.

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