Modelling Joint Deterioration in Roller Compacted Concrete Pavement

Abstract

Joints in Roller Compacted Concrete (RCC) pavements are used to distribute traffic loading between adjacent slabs by friction. The Load Transfer Stiffness (LTS) of the joints has critical effects on RCC pavement performance near the joints. Research have shown that LTS can deteriorate over time due to traffic loading or environmental conditions. This study investigates the deterioration of LTS of RCC pavement joints and its effect on the fatigue cracking performance near the joints. To achieve that, firstly, an innovative experimental program was designed to measure LTS as a function of number of load repetition, joint width, and RCC mix properties using a cyclic shear test setup. Secondly, a mathematical model was derived to predict LTS deterioration in joints; this model was validated against the experimental data. Lastly, an RCC pavement design model was developed using the LTS deterioration model. To demonstrate the application of the developed solution, a hypothetical RCC pavement structure consisting of four slabs was considered. The analysis results show that LTS has inverse relationship and direct impact of fatigue life of RCC. In particular, the results demonstrate that fatigue damage over an analysis period of 20 years is negligible if LTS is assumed constant, which is unrealistic, but it can reach 40% if LTS deterioration is considered in the analysis. Accordingly, this study recommends considering the deterioration of RCC joint LTS when design that kind of pavement structures.

Keywords: Roller compacted concrete, Load transfer stiffness, Joint stiffness deterioration, cyclic shear, KENSLAB, Fatigue damage.

1. Introduction

Roller compacted concrete (RCC) is a kind of low workability concrete with similar ingredients to conventional Portland cement concrete (PCC): cement, aggregates, and water. Ordinary asphalt paving and vibratory compaction equipment are used to place and compact RCC which provides high strength and density concrete, ultimately long service life [1, 2]. RCC can be a very good choice pavement structure over asphalt in terms of speed of construction, durability and sustainability and cost of materials. It generally differs from PCC in the proportions of the constituents, such as: less cement, higher aggregates, and less water content than conventional PCC, which makes it a zero-slump concrete. In general, the mechanical properties of RCC are comparable to, or outperform those of conventional PCC pavements; this suggests a similar or larger structural capacity and fatigue resistance for RCC pavements relatively to PCC pavements of the same structural design [3].

RCC can be considered as a form of jointed plain concrete pavement (JPCP). Historically, to increase the economy of construction, RCC pavements have been allowed to crack naturally, and this has proven to be very successful in many applications. When RCC is allowed to crack naturally, aggregate interlock can still provide adequate load transfer across the cracks. The first cracks will appear within 24 hours of placement because of shrinkage and will typically be spaced from 10 to 25 m apart. However, to control this random cracking, it is now a common practice to introduce joints [4].

The performance of a concrete pavement depends on its ability to transfer load from one side of the joint/crack to the other. The good transferring of load will lead to smaller deflections, reduction in faulting, spalling, and corner breaks, and improvement in the riding quality [5]. Service life of jointed concrete pavements depends on the performance of the joints. To control or eliminate joint deterioration, it is necessary to understand the mechanisms of joint damage [6].

An essential role of the aggregate in RCC pavements is to provide load transfer across these joints by means of aggregate interlock which in theory can eliminate the need for load transfer devices. Joints in RCC pavement are the most critical areas as they represent weak points. Joints sawn every 8-12 meters will reduce most of the random shrinkage cracking and improve the appearance of the final RCC pavement [7]. On the other hand, Harrington et al. [8] reported that cracks typically occur at 6.1 to 18.3 m intervals, depending on the properties of RCC and pavement thickness. The Portland Cement Association (PCA) recommends that joints should be spaced no more than 6 m apart and, for slab thickness less than 200 mm, the joint spacing should be between 4.6-6 m [7, 8].

An important characteristic of concrete pavement joints affecting design is load transfer stiffness (or joint efficiency). Load transfer stiffness refers to the ability of a crack to transfer load from one slab to an adjacent slab, thereby reducing the amount of load and therefore stress which must be borne by an individual slab. Joint efficiency is a measure of load transfer, being the portion of deflection due to a load on one slab that is transferred to an adjacent slab through the joint. It has been found that load transfer is improved by limiting the spacing between joints [9, 10].

1.1 Fatigue damage in RCC

Fracture of concrete due to fatigue is one of the most frequent failure modes observed in concrete pavements. Fatigue cracking of concrete pavements has been attributed to repeated traffic loading as a result of excessive stresses and deflections [11]. The most critical stresses in RCC pavements are flexural, therefore the design of thickness is depended on fatigue due to flexural stress. Stress ratio, as used in fatigue relationships, is the ratio of flexural stress to flexural strength [8].

The concept of fatigue is important to the design of concrete pavements. It allows designers to determine what the design stress should be for a given strength of concrete and the desired number of load repetitions [9]. The ACI-327 [7] study found from results of fatigue tests on beams obtained from a full-scale test section incorporating four different RCC mixtures that the fatigue behavior of RCC is similar to that of conventional concrete.

The Portland Cement Association (PCA) has suggested that RCC has similar fatigue characteristics to conventional concrete but tends to deteriorate more rapidly at lower stress ratios than conventional concrete. In contrast, the Waterways Experiment Station (WES) has observed that RCC has similar or better fatigue characteristics as compared to conventional concrete. The PCA used their flexural fatigue data to develop a design curve used in their design procedure for RCC pavements. This design curve was conservatively set about 15% below and nearly parallel to the PCA regression line at which 95% of the PCA data was greater, as shown in Figure 1. The design curve suggests that RCC can withstand an unlimited number of load applications at a stress ratio of 0.40 [9]. In summary, RCC has same failure criteria to conventional concrete pavements related to the fatigue characteristics depending on sever tests by PCA and WES.

1.2 Joint deterioration

Load transfer occurs across cracks that form naturally after placing the concrete slab, or across joints. Load transfer is a complex mechanism that can vary with concrete pavement thickness, joint spacing, temperature, moisture content, aggregate type and size, age, construction quality, magnitude and repetition of load, and joint type [9]. Sadeghi and Hesami [12] observed that increasing slab thickness will increase load transfer between the adjacent slabs. This process can be attributed to increasing the slab thickness increasing the cross-sectional area of the joint leading to improved stress distribution over the slabs.

Wang et al. [6] investigated the joint deterioration in cold regions depending on different mechanisms such as freezing-thawing damage, salt crystallization, oxychloride expansion and interfacial transition zone (ITZ) damage. They found that ITZ between cement paste and aggregate permits more salt solution to penetrate around aggregate particles and potentially accelerates the joint deterioration.

Sadeghi and Hesami [12] studied the effect of different factors such as material properties, slab geometry, load magnitude and frictional status of the slab and base layer on load transfer efficiency. This study was investigated by a three-dimensional finite element method (3D-FEM). They found that load transfer efficiency (LTE) was improved by increasing the modulus of elasticity of the concrete slab and the base layer.

Ioannides and Korovesis [13] and Ioannides and Korovesis [14] presented a non-dimensional joint stiffness parameter in order to show the load transfer mechanism of a joint with dowel bars or aggregate interlock. Those researchers propose load transfer by shear forces over joints is desirable; this is because load transfer by bending induces further stresses when the movement is constrained.

In RCC pavements, aggregate interlock is the main mechanism of transferring traffic load; it relies on the shear force developed from the friction at the rough vertical interface of a concrete pavement joint [9]. Raja and Snyder [15] investigated the influence of different parameters, such as width of crack opening, type and size of coarse aggregate, compressive strength of concrete, applied load magnitude and number of load repetitions, and foundation support, on the rate of deterioration of load transfer capacity through aggregate interlock of transverse cracks and joints in concrete pavements. They concluded that all these parameters or some of them had a significant influence on joint deteriorations.

Maitra et al. [5] developed a finite element model to simulate the characteristics of load transfer through aggregate interlock in concrete pavements by presenting a new parameter called modulus of interlocking joint. They introduced guidelines for selecting an appropriate spring stiffness value for finite element analysis to estimate the load transfer.

Based on this brief literature review, it can be concluded that most of available studies focus on estimating load transfer capacity without considering the joint stiffness deterioration. On the other hand, only a few studies have investigated the reduction in joint efficiency mainly in cold regions. Therefore, the aim of this paper is to investigate the deterioration of joint stiffness of RCC pavements and its effects on the efficiency of load transfer stiffness (LTS) and the rate of fatigue damage. This is achieved by using a mathematical model developed in MATLAB and the finite element program KENSLAB. The results show the importance of joint deterioration calculations for RCC and for fatigue damage in pavement design.

2. Experimental work

2.1 Selection of materials

Two mixtures have been adopted in this study. The first one was used as a base layer of a two-layer RCC; this mix consisted of 0-20mm crushed Carboniferous limestone aggregates supplied from Tunstead quarry, Derbyshire, UK. The second mix was 0-10mm concrete used as a surface layer, and it contained crushed granite aggregate supplied from Bardon Hill quarry, Leicestershire, UK. The selection of this type of aggregate for the surface layer was to achieve acceptable abrasion strength and provide sufficient skid resistance whereas the limestone was used for the base layer because it provides suitable strength for pavement base layers, its relatively low cost and high availability. In both mixtures, Portland cement CEM I- 42.5/52.5N conforming to BS EN 197-1[16] was used.

2.2 Mix design

The mix design of RCC for this study was conducted according to ASTM D 1557 [17] following a geotechnical approach, which is basically by finding a relationship between the optimum moisture content and the maximum dry density. Following this approach, two mixtures were prepared for the two-layer system where the proportions were 7% water content and 12% cement content for both mixes. A square steel mold with dimensions 305 mm × 305 mm × 80 mm was used for fabricating slab samples according to British standard BS EN 12697-33 [18] a laboratory roller compactor was used in making the RCC slab simulating field compaction conditions. Since there could be a delay between placing the surface and the base layers in RCC pavement construction, then three cases were considered in this study with different bond and construction conditions. These cases were:

- Case1: the time of placing and compacting of two layers was within one hour.
- Case 2: the time of placing and compacting of the surface layer was 3 hours after constructing the base layer.
- Case 3: the time of placing and compacting of the surface layer was 24 hours after constructing the base layer.

The fabricated slabs were removed from molds after 24 hours of placing the surface layer then cured in water at 20˚C for 28 days. Strength and stiffness of each layer were measured on beam specimens sawn from the slabs, reaching 33-35 MPa and 31-33 GPa, respectively as illustrated by Mohammed [19].

3. Laboratory tests

3.1 Fatigue test

To assess fatigue cracking resistance of RCC, a four-point bending apparatus [20] was used. This apparatus has been found to give consistent and reliable results. The test frame provides free rotation at the clamp-specimen supports; this is critical to prevent the development of any internal stresses that might imposed on the specimen during testing. The test was carried out on a MAND servo-hydraulic testing machine where the load applied to the 4-point bending frame; this machine is controlled by a Rubicon digital servo control system.

Beams with dimensions 60 × 60 × 305 mm sawn from slab specimens were attached to the test apparatus and fixed by the clamped, as depicted in Figure 2. The test was conducted under load control mode at a load frequency of 2Hz. The stress ratio, which is the ratio of the applied flexural stress to the static flexural strength of the specimen, was used to express the applied load. The flexural strength of the beams was predetermined to be 6 MPa; and stress ratios of 0.75, 0.8, 0.85 and 0.9 were investigated in this study. At each stress ratio, two beans were tested until complete fracture of the beam.

3.2 Cyclic shear test

To investigate the properties of the crack interface, the cyclic shear test was conducted to two-layer RCC samples. The purpose of this test is to investigate shear stress properties of a transverse crack in order to improve the load transfer characteristics of a pavement. Since load transfer efficiency is related to the crack width, then three approximate crack widths, 0.2 mm, 0.5 mm and 1 mm were chosen to understand the dynamic shear characteristic of two-layer RCC pavements.

The experimental procedure started with inducing two cracks in each sample vertically by a small hammer as shown in Figure 3. For each notch, the average cross-sectional area was measured with a Vernier gauge. The crack existence was confirmed by visual inspection of the beam, and the crack width was obtained by DEMEC pips mounted on the face of the specimen. The optimum crack width was obtained by measuring the width inside the machine by a digital Vernier gauge before starting the test; then adjustments were made at intervals during the test. The test samples had dimensions of 60 x 60 x 305 mm and were subjected to shear stress ranges at the cracks of ±195 kPa, ±250 kPa, ±278 kPa. These were chosen by trial and error based on previous studies by Thompson [21] and Thom [22].

The load form was sinusoidal, where the positive stress represents an upward direction and the negative load downward. One thousand cycles were applied at each load level. MOOG software and a servo-hydraulic load frame machine with 100 kN capacity were used to apply and control the load, the response data were collected using data acquisition system, as shown in Figure 3. The specimen left and right sides were fixed whereas the part between the cracks was sheared by the applied sinusoidal load. This arrangement was considered a more realistic approach than the single crack test arrangement by Thompson, [21].

4. Experiment and analysis Results

4.1 Fatigue performance

Figure 4 presents the results of the fatigue performance of the three construction cases considered in this study in addition to the results of the upper and lower layer separately. In this figure, the fatigue life is expressed as the between the stress ratio (S) and the number of load application at failure (N).

These results show the fatigue performance of the upper and lower layers, relatively to their strength, is comparable to the performance of the two-layer cases considered in this study. Furthermore, the RCC materials show a performance consistent with the results of Graeff et al. [23] and Sun et al. [24] even though the mixes were different.

4.2 Results of cyclic shear test

The outcome of the cyclic shear test can be expressed by load transfer stiffness (LTS), which was determined as the applied shear stress per unit shear slip. Since the applied loads and the cross-sectional areas of both sides of the crack were constants, then any increase in the shear slip during the test can be interpreted as a reduction in the capacity of the crack to transfer load, in other words, a deterioration in the load transfer stiffness.

Figures 5 A and B show the results of LTS of the three construction cases with different crack thicknesses and applied stresses at three loading stages during each one thousand load applications was applied. These figures show that the thicker the crack the lower the LTS. Also, it can be seen that as far as the crack width is less than 1mm, the LTS deteriorates with increasing the applied load and/or the number of load applications. Furthermore, the rate of deterioration was influenced by the placement conditions where the weak bond reduced load transfer across the crack as illustrated by Mohammed [25]. This means that placing the upper layer of the RCC immediately after placing the lower layer can significantly improve the LTS, as shown in the results.

5. Modelling of Joint Deterioration and its Effect on Fatigue

5.1 Mathematical model Development

The experimental results demonstrate that load transfer stiffness deteriorates as a function of number load applications, shear stress, joint width, and the modulus of rupture of concrete. This deterioration explains the appearance of cracks near to joints; the reduction in load transfer stiffness leads to a concentration of tensile stress at critical locations which in turn leads to the formation of fatigue cracks. In order to include the impact of this mechanism on the prediction of fatigue cracking performance of RCC, the following innovative procedure was developed:

1) The first step was to model the allowable number of load applications of RCC using the following equation:

$$N_{allowable} = 10\text{^}(18.45 - (18.09 \times S)) \quad (1)$$

where $S = \frac{\sigma_t}{M_R}$

σ_t is tensile stress and M_R is modulus of rupture of concrete. This equation relates to the base layer of RCC with $R^2 = 0.997$ since the maximum tensile stress happens in this layer according to Mohammed (2018) and fits the data in Figure 4 efficiently.

2) The relationship between the load transfer stiffness and other parameters was modelled as follows as proposed by [25]:

$$LTS = 22 \times (\frac{\tau}{M_R})^{2.2}/(w \times (29 + N^{0.4})) \qquad (2)$$

where τ is the applied shear stress across a joint/ crack, w is the crack width, N is the number of load applications, and other inputs are as defined previously. The equation was estimated depending on non-linear relationships between test variables and a simple Matlab code was created to find the constants of the equations by trial and error.

Figure 6 presents the correlation between LTS computed from Eq. 2 and LTS measured, combining data for three crack widths, three shear loads and three bond conditions [26]. This figure indicates that LTS is very sensitive to crack width and number of cycle, since it is hard to control the width of cracks it was difficult to obtain more LTS data.

3) The rate of reduction in joint stiffness per load application is given by differentiating Eq. 2 with respect to N, which results in:

$$\frac{\partial LTS}{\partial N} = -44/(5 \times N^{\frac{3}{5}} \times w \times (N^{2/5} + 29)^2 \times (\tau/M_R)^{\frac{11}{5}}) \qquad (3)$$

4) In order to consider the LTS in the deterioration process, Equation 2 must be rearranged to produce N as a function of the other parameters; this resulted in the following equation:

$$N = (22/((\tau/M_R)^{\frac{11}{5}} \times LTS \times w) - 29)^{\frac{5}{2}} \qquad (4)$$

5) Substituting Equation 4 into Equation 3 and simplifying, we obtain:

$$\partial LTS/\partial N = -44/(5 \times w \times \left(\left(\left(\frac{22}{LTS \times w \times \left(\frac{\tau}{M_R}\right)^{\frac{11}{5}}} - 29\right)^{\frac{5}{2}}\right)^{\frac{2}{5}} + 29\right)^{2} \times \left(\left(\frac{22}{LTS \times w \times \left(\frac{\tau}{M_R}\right)^{\frac{11}{5}}} - 29\right)^{\frac{5}{2}}\right)^{\frac{3}{5}} \times \left(\frac{\tau}{M_R}\right)^{\frac{11}{5}}) \qquad (5)$$

6) Accordingly, the reduction in LTS can be calculated incrementally; for every certain number of load applications, the reduction in LTS can be calculated as follows:

$$R_{LTS}(i) = \frac{\partial LTS}{\partial N} \times TV(i) \tag{6}$$

where $R_{LTS}(i)$ is the reduction LTS for period (i) and $TV(i)$ is the traffic volume applied in the same period.

7) Lastly, the total fatigue damage can be estimated as follows:

$$Total\, fatigue\, damage = \sum_{i=1}^{ap} \frac{TV(i)}{10\hat{}(18.45 - (18.09 \times \sigma_{t(i)}/M_R))} \tag{7}$$

where ap is the analysis period in months and $\sigma_{t(i)}$ is the tensile stress of the ith month. To apply this concept and predict RCC fatigue performance, a Matlab code was written. The code applies the concept developed by Abed et al. [27]; the KENSLAB software was linked as a subroutine to Matlab to calculate pavement response. The code is graphically explained in Figure 7. Basically, the code sends the design inputs to KENSLAB to calculate pavement response, particularly the maximum tensile stress near the joint, then it predicts the fatigue life of RCC. After that it calculates fatigue damage by the application of Miner's law, and it calculates the reduction in the joint stiffness using Eq. 5. The code stops the simulation process when the fatigue damage reaches ~100%.

5.2 Finite element analysis by KENSLAB

KENSLAB is a two-dimensional finite element software that can be used to analyze concrete pavements with joints [28]. In this study, it was used to analyze an RCC concrete pavement consisting of four slabs with different load locations as illustrated in Figure 8. In this analysis, it was assumed that all layers are linear elastic and isotopic. In order to design based on the most critical location of the load, three critical locations on the first slab were considered in the analysis, as shown the figure. The length and width of slabs were 3.6 x 4.5 m respectively. The thickness of the top layer was 100 mm and the bottom one was 150 mm. The modulus of the first and second concrete layers were 31 and 33 GPa respectively as measured in the experimental work; the foundation layers were assumed to give a modulus of subgrade reaction of 150 kN/m^3, in accordance with previous studies [7, 9, 29]. A single wheel was considered in the analysis; the wheel load was 41.5 kN and the tyre pressure was 690 kPa as recommended by [28].

Three different locations were chosen for simulation as the most critical locations for RCC pavements:

- For the first location, the wheel load was applied at the middle edge between slab 1 and slab 2 with loading area 500x500 mm.
- For the second location, the wheel load was applied at the upper right corner of slab 1 with same loading area as in location 1.
- For the third location, the wheel load was applied 1.5 m from pavement edge right next to the joint, as shown in Figure 8.

5.3 Example Application

As an example, this method was applied to predict fatigue performance and joint deterioration of a rigid pavement consisting of two RCC layers.

The number of load applications was taken as 100,000 per month. The "initial" LTS of the joints was 10000 MN/m^3. Figure 9 shows the profile of the two-layer RCC pavement, where layer 3 in reality represents a combination of subbase, capping and subgrade layers.

Pavement performance was simulated over twenty years considering two scenarios. The first ignored the reduction in LTS; in other words, the LTS was constant and fatigue damage was predicted accordingly. The second included the impact of the reduction in LTS on the predicted fatigue cracking performance by implementing the method suggested in this study. The result of these simulations is presented in Figure 10.

Figure 10 presents the results for the three locations and shows that where the joint stiffness was constant the predicted total fatigue cracking damage after twenty years (12×10^6 wheel loads) was about 0-4%. This means that this pavement is unlikely to exhibit much cracking even after a long service life. On the other hand, where the reduction in the joint stiffness was considered in the analysis the figure demonstrates that the joint stiffness significantly reduces at the beginning of the pavement service life and then tends to decrease slowly over time. The slowing down in the rate of joint damage occurs because as the joint load transfer stiffness reduces, so, the shear stress across the joint also reduces.

However, the key finding is that this mechanism is found to have a critical impact on the predicted fatigue cracking. As shown in Figure 10, the pavement fatigue damage at two critical locations, one and three, reached 35-40% after 20 years of simulation, whilst it reached a maximum of 4% regardless the location when the deterioration in the joint stiffness was ignored. This means that fatigue cracking is expected to appear in the area around the longitudinal joints under the combined effects of traffic loading and joint stiffness reduction. Clearly, to sensibly predict fatigue cracking distress in RCC, the simultaneous reduction in LTS must be considered in the analysis.

6. Conclusions

In this study, joint stiffness deterioration of RCC pavements was investigated. An experimental procedure was developed to measure LTS and quantify its reduction. The reduction in LTS was then modelled and the derived mathematical model was applied in a Matlab code to predict fatigue cracking damage considering the effect of LTS reduction on the predicted performance. The developed solutions was applied on a hypothetical 4-slabs RCC pavement structure that was simulated for twenty years. Based on the results of this study, it can be concluded:

- The experimental results show that LTS has strong relationships between the number of load repetition, RCC modulus of rupture, and joint width, and it can be modelled as a function of these properties.
- Analyzing the relationship between the numbers of load applications and LTS reveal that there is an inverse relationship between these. The results showed that the LTS reduces as the number of load applications increases, which shows the importance of considering this mechanism in fatigue cracking performance prediction of RCC pavements.
- The bond strength between RCC layers have direct effects on LTS, the stronger the bond the larger the LTS, which should be considered when designing and constructing RCC pavements.
- The analysis result of MATLAB model built in this study presented that LTS has direct effects on fatigue life of RCC; the higher of load application the lower LTS the larger fatigue damage. If LTS is considered in modeling RCC then the fatigue life is expected to be about 35-40%, but if it is not considered then the damage is expected to be 4% which is unrealistic. Therefore, LTS deterioration should be considered in the design of RCC pavement structures.

Future work will focus on including important factors such as expansion and contraction of RCC on LTS considering factors of differential pavement temperature and shrinkage of RCC. It will be further expanded to validating the developed RCC pavement analysis model against experimental data using large RCC slabs or full scale field data.

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