Comparative Analysis Of Pothole Formation From Longitudinal And Transverse Crack Using Mechanistic Model

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***Abstract*—Crack distress is a common problem of structural damage for pavements. The typical crack distress include transverse and longitudinal cracks. This study compare the extent of deterioration in terms of deepening of longitudinal and transverse cracks to form potholes, when subjected to equal traffic load, pavement thickness, modulus of elasticity of subgrade material over a period of time. The study modifies an existing mechanistic model that predict deflection (deepening) of transverse cracks and also developed a mechanistic model for deflection of longitudinal cracks. Vehicle axle load, time interval, modulus of elasticity of subgrade and thickness of pavement were considered as factors in formation of pothole in the two models. The models were verified and found effective before comparison. Transverse and longitudinal deflection were compared using independent t-test having t-value of 0.657 and p-value of 0.515 at 20 degree of freedom. The analysis indicated that p-values is greater than 0.05, hence there is no significant difference between transverse deflection (deepening) and longitudinal deflection in pothole formation. From the analysis, both longitudinal and transverse crack should be given attention when developed on pavement. The developed models can be used to predict pothole formation in flexible pavement.**

Keywords—Transverse crack, longitudinal crack, deepening, pothole, pavement.

I. INTRODUCTION

Cracks in flexible pavements have continued to be a major failure mechanism to both developed and developing countries. This type of pavement distress when left untreated, deteriorate into pothole formation, hence, affecting traffic flow and safety leading to poor performance of flexible pavement. Cracks in flexible pavements are caused by deflection of surface over an unstable foundation, shrinkage of the surface, thermal expansion and contraction of the surface, poorly constructed lane joints, or reflection cracking [1].

Pothole is a form of disruption in the surface of a roadway where a portion of the road material has broken away, leaving a hole [2]. As severity of cracks increases, potholes are formed. Cracking propagates from the bottom or the top of the layer to form a combination of transverse and longitudinal cracks that extend over the width of the pavement and crates hazardous conditions for the road uses [3]. A number of factors such as traffic loading, specific standards of service and design, climate change risk factors, temperature, rainfall, and other factors affect pavement cracking over a pared of time. Longitudinal crack is crack in the surface of a road pavement that runs longitudinally along the pavement as shown in fig. 1. It is formed in the direction of the traffic flow. Longitudinal crack can occur for a number of reasons, including, the reflection of a crack or joint in the road pavement, poorly constructed joints in the asphalt surface, asphalt hardening, temperature fluctuations. It can consist of a single crack or as a series of parallel cracks.

Fig. 1: Longitudinal crack on flexible pavement.

Transverse cracks occur roughly perpendicular to the center line of the pavement and traffic flow direction as shown in fig. 2. This type of crack is causes by shrinkage of the hot mix asphalt due to low temperatures or asphalt binder hardening, reflective crack due to crack beneath the surface of Hot Mix Asphalt layer and top-down cracking. Initiation of potholes can be expressed as a function of time since it starts 2 to 6 years after wide cracking [4].

Fig. 2: Transverse crack on flexible pavement.

Fig 3 presents pothole formation due to different types of cracking. Deformation, breaking of pavements and bending stress develop as each type of crack undergoes traffic loading.

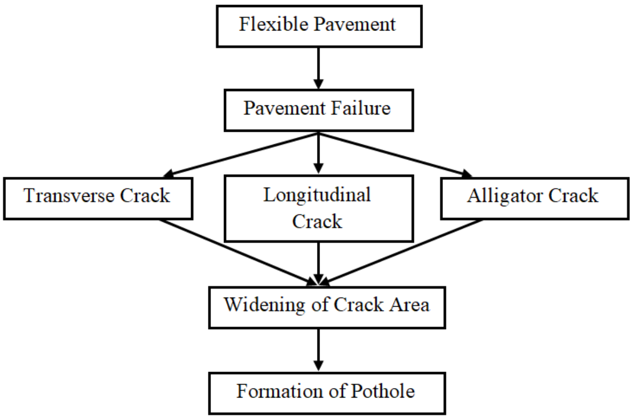

Fig. 3: Flow Chart for pothole formation

Source: Kulbir [5].

Several studies have been conducted on mechanistic modeling of cracks in pothole development.

Jongeun [6] examined the behavior of traffic induced reflective cracking using finite element (FE) model for an HMA overlay with and without interlayer system and evaluated the performance of interlayer systems in controlling reflective cracking. The author concluded that the said mix interlayer system extended the service life of the HMA overlay regarding reflective cracking due to its relatively high fracture energy.

The study developed a three dimensional FE model for a typical HMA overlay constructed over Joint Concrete Pavement (JCP). A linear viscoelastic model and a bilinear cohesive zone model (CZM) were incorporated with the FE model to characterize continuum and fracture behavior of the HMA.

Anthony [7] studied crack propagation in high modulus Asphalt mixtures. The author investigated the fatigue cracking behavior of twelve High Modulus Base (HMB) binders and mixtures. The study found that crack propagation is dramatically affected by both binder hardness and temperature.

Review of modelling crack initiation and propagation in flexible pavements using the finite Element method by Mostafa, Jongeun and Nirmal [8]. They presented two approaches, the first approach focused on Finite Element to simulate the crack initiation and propagation phases. The second approach focused on simulating propagation using FE and cohesive zone model (CZM). The study concluded that both approaches have merits in modeling cracking in flexible pavement.

Mechanistic modeling of potholes development from cracks due to axle loads and time was presented by Thawat et al [9]. The study was based on transverse crack and considered Euler lagrange equation for dynamic beam to develope a model to predict pavement performance with respect to pothole deepening due to crack. They assumed that pothole formation is a function of the elastic modulus of the pavement (EP) and the elastic modulus of the subgrade (ts).

This study is aimed at comparing the extent of deterioration of pothole from longitudinal and transverse cracks due to traffic load and time interval.

Existing mechanistic models on flexible pavement.

Since the study is aimed at comparing the extent of determination in terms of deepening of longitudinal and transverse cracks to form pothole due to traffic load and time interval. The study will be based on existing mechanistic models for transverse cracks in flexible pavement, modification of existing longitudinal cracks deflection model by introducing time as a variable. The extent of deflection for both longitudinal and transverse cracks determination model will be compared by carrying out verification.

II. CRACK DEFLECTION MODEL

A. Transverse crack deflection model

Transverse cracks which extend across the centre-line of pavement are caused under several conditions. When cracks are formed on flexible pavement, moisture tends to enter the base of the asphalt and weakens the soil beneath the pavement. As traffic loads applies on the cracked point, the stress on the pavement surface will cause it to break, hence deflection will occur. With the growth of traffic volume over a period of time, asphalt pavement will be subjected to repeated vehicle load which will cause long-term stress and strain on the cracked pavement, resulting in pothole formation. Fig 4 simulates the action of wheel load on transverse crack.

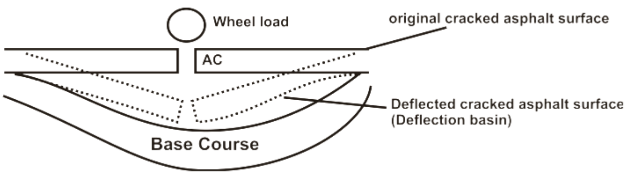

Fig. 4: Action of wheel load on transverse crack

Odumade and agunwanba [8] developed a model for pothole formation from cracks due to axle loads and time. The model which was based on transverse crack, was formulated on certain assumptions:

- The development and progress of potholes is a function of time of usage of the road in days after the development of cracks.
- There is a constant precipitation cycle over the period.
- The rate of increase of the deepening of the pothole is directly proportional to the magnitude of the axle load
- Rate of pothole deepening is a function of the elastic modulus of the pavement and the subgrade.

They considered total deflection of pavement from crack (y_c) to be deflection as a function of load (y_x) and a function of load (y_t) of time (y_t).

Hence $y_{(c)} = y_{(x)} \times y_{(t)}$ (1)

They developed general equation of deflection from Euler-lagrange equation for dynamic beam. Where load (P) and time (t) as factors of pothole deflection y

Where

$$y_{(x)} = \frac{Pe^{-\measuredangle x} \cos\measuredangle x}{2EI \measuredangle^3} \quad (2)$$

And

$$y_{(t)} = \frac{Pt^2}{2} - Pt \quad (3)$$

Hence the deflection equation of flexible pavement from crack developed by Odumade and Agunwanba is as presented below.

$$y_{(c)} = \frac{Pe^{-\measuredangle x} \cos\measuredangle x}{2EI \measuredangle^3} \times \left(\frac{Pt^2}{2} - Pt\right) \quad (4)$$

But modulus of Elasticity, E = $Es + Ep$ (5)

Substituting E in (5) into (4).

$$y_{(c)} = \frac{Pe^{-\measuredangle x} \cos\measuredangle x}{2\,(Es + Ep)I \measuredangle^3} \times \left(\frac{Pt^2}{2} - Pt\right) \quad (6)$$

Where $y_{(c)}$ = transverse deflection of pavement from crack

P = wheel load.

$\measuredangle$ = constant = $\sqrt[4]{\frac{\beta}{4EI}}$

x = length of contact area

t = time (month)

Es = Elastic modulus of asphalt

Ep = Elastic modulus of Subgrade.

I = Movement of inertia.

B. Longitudinal crack deflection model

Like the transverse crack, longitudinal cracks formed on the surface of flexible pavement allows the water to go inside the crack. Continuous traffic load together with accumulated water inside the pavement, exert pressure on the pavement. The pressure produces bending stress and deflection on and around the crack location. Consider a wheel load acting on a longitudinal crack as shown in fig 3. The contact position of the wheel load will act on the inner and outer of the longitudinal crack.

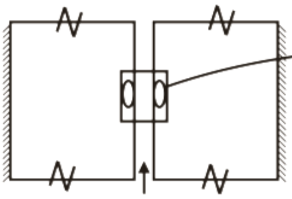

Fig. 5: wheel Load on Longitudinal Crack

C. Deflection of Longitudinal Crack Due to Load

Julbir [9] in his thesis, studied development of potholes from cracks in flexible pavements.

He considered transverse, longitudinal and alligator cracks and generated a model to compute stresses and deflections associated with these cracks in flexible pavement and the formation of potholes. The study obtained a complete solution consisting of homogeneous solution as presented in (12) since wheel load passing through longitudinal crack also produces bending in the pavement.

$Y = e^{\measuredangle x}\,[\,C_1 \cos \measuredangle x + C_2 \operatorname{Sin} \measuredangle x] + e^{-\measuredangle x}\,[\,C_3 \cos \measuredangle x + C_4 \operatorname{Sin} \measuredangle x]$ (12)

He considered a length of beam resting on an elastic foundation and subjected to a load p at any point at section X = 0.

At X = ∞, $Y = M = 0$

Therefore from equation (12) $C_1 = C_2 = o$

Under load P

X = 0, dy/dx = 0 therefore, $C_3 = C_4 = C$

Hence, Y = $Ce^{-\measuredangle x}\,(\sin \measuredangle x + \cos\measuredangle x)$ (13)

The constant C is determined from condition that shear force (Q)

Q = $-\,{}^{P}\!/_{2}$ for $X = 0$ (14)

From beam deflection equation

$$EI\,\frac{d^2y}{dx^2} = -M \quad (15)$$

Where E = Elastic modulus

I = second moment of Area of the beam’s cross section

$$EI\,\frac{d^3y}{dx^3} = \frac{dM}{dx} \quad (16)$$

$$Q = {}^{dm}/_{dx} \quad (17)$$

$$EI \frac{d^3y}{dx^3} = -Q \quad (18)$$

$$Q = -\frac{d^3y}{dx^3} = -{}^{P}/_{2} \quad (19)$$

From (13) and (14)

$$C = -{}^{P}/_{8 \lambda^3 EI} = \frac{P\lambda}{2\beta} \quad (20)$$

The deflection of longitudinal crack with respect to load is given as

$$Y = \frac{P\lambda}{\sqrt{2\beta}} e^{-\lambda x} \left[\sin\left(\lambda x + \frac{\pi}{4}\right)\right] \quad (21)$$

D. Deflection of longitudinal crack with respect to time.

Since deflection of both longitudinal and transverse cracks occur by a period of time, according to Thawat et al. [9], initiation of pothole (deepening) can be expressed as a function of time since it start 2 to 6 years after white cracking. Equation (22) shows that the deflection function is a function whose second derivative is equal to load intensity.

$$\frac{d^2y}{dt^2} = P \quad (22)$$

Integrating (22) and further integrating the result gives (23) and (24).

$$\int \frac{d^2y}{dt^2} \int Pdt$$

$$\frac{dy}{dt} = Pt + C_1 \quad (23)$$

$$y_{(t)} = \frac{Pt^2}{2} + C_1 t + C_2 \quad (24)$$

Considering that

Deflection is zero at t =o; substituting in (24)

$$C_2 = 0$$

Considering $\frac{dy}{dt}$ = o, when t = 1; substituting in (23)

$$o = P + C_1$$

$$C_1 = -P$$

Substituting for C_1 and C_2 in equation 24

$$y_{(t)} = \frac{Pt^2}{2} = Pt \quad (25)$$

The Final longitudinal deflection with respect to load and time is given by

$$y_{(L)} \frac{P\lambda}{\sqrt{2\beta}} e^{-\lambda x} \left[\sin(\lambda x + {}^{\pi}/_{4})\right] x \left(\frac{Pt^2}{2} - Pt\right) \quad (26)$$

Where P = wheel load

III. VERIFICATION OF LONGITUDINAL AND TRANSVERSE CRACK DEFLECTION MODEL FOR COMPARISON.

The following data is assumed in order to compare the deflection (deepening) of longitudinal and transverse crack in flexible pavement that can develop to pothole when load acts on the edge of the crack.

Thickness of the pavement layer, h = 0.10m

Wheel load, P = 44.8kN

Tire pressure, P = 480kN/m^2

Contact area = $\frac{\text{wheel load}}{\text{Tire pressure}} = \frac{44.8}{480} = 0.093m^2$

The contact area is assumed to be rectangular

Width of tire = 0.34m

Length of contact area = 0.27m

Pavement strip of 0.025m width and 0.27m length is considered

Load on the strip = 3.33kN

Breath of beam, b = width of tire = 0.34m

Elastic Modulus of pavement E_P = 600.5∧10^3kN/m^2

Elastic Modulus of pavement, E_s = 89x10^3kN/m^2

E = E_s + E_p = 689.5 x 10^3kN/m^2

Modulus of beam, k = 68346.6N/m^2

Reaction of foundation, β = 23.27x10^3kN/m^2

Cross – section of pavement layer is w = 0.025 and h = 0.10

Moment of inertia, I = $\frac{wh^3}{12} = 0.0000v22m^4$

$$\lambda = \sqrt[4]{{}^{B}/_{4EI}} = 7.87m^{-1}$$

Considering $y_{(t)} = \frac{Pe^{-\lambda x}\cos\lambda x}{2\,(Es+Ep)1\lambda^3}\ x \left(\frac{Pt^2}{2} - Pt\right)$ as transverse crack deflection model

And

$y_{(L)} \frac{P\lambda}{\sqrt{2\beta}} e^{-\lambda x} \left[\sin(\lambda x + {}^{\pi}/_{4})\right] x \left(\frac{Pt^2}{2} - Pt\right)$ as longitudinal Crack deflection model

Assuming there is constant application of axle loads on the crack and taking time (t) from day 2 to day 21 (20 samples), deflection for longitudinal and transverse crack are presented in table 1.

IV. RESULT AND DISCUSSION

TABLE 1: Verification of the Models

S/N	Time (days)	Transverse deflection (m)	Longitudinal deflection (m)
1.	2	0	0
2.	3	0.1344	0.1115
3.	4	0.3584	0.2974
4.	5	0.672	0.5577
5.	6	1.0752	0.8924
6.	7	1.568	1.3014
7.	8	2.1504	1.7848
8.	9	2.8224	2.3425
9.	10	3.584	2.9747
10.	11	4.4352	3.6812
11.	12	5.376	4.4620
12.	13	6.4064	5.1251
13.	14	7.5264	6.2469
14.	15	8.736	7.2508
15.	16	10.0352	8.3292
16.	17	11.424	9.4819
17.	18	12.9024	10.7089
18.	19	14.4204	12.0104
19.	20	16.128	13.3862
20.	21	17.8752	14.8364

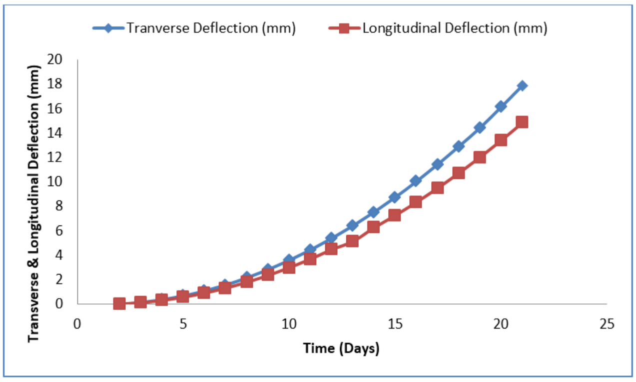

Fig. 5: Graph of Transverse and Longitudinal Deflection (mm) against time (days).

The results of predicted deflection from longitudinal and transverse crack models as presented in table 1 show that deflection (deepening) in transverse crack is 18% higher than deflection developed in longitudinal crack for the selected days when subjected to the same wheel load intensity, pavement thickness, modulus of elasticity of subgrade, moment of inertia and time interval. This percentage is practically insignificant. Both transverse and longitudinal deflection decreases as time (days) of application of axle load increases. It is also observed that deflection on flexible pavement for longitudinal and transverse cracks increases with days assuming there is constant application of axle load as shown in fig. 5. The rate of increase in deflection for both longitudinal and transverse are the same. This rate of increment decreases as period of exposure of crack to vehicular load increases. It can be seen in table 1 that change in deflection (deepening) for both longitudinal and transverse crack from day 3 to day 4 is 90% but decreases to 10.27% in day 21.

TABLE 2: Descriptive Statistic for Independent t-Test.

Group	N	Mean	Std. Dev.	Df	t-statistic	p-value
A	20	6.3828	5.7314	38	0.657	0.515
B	20	5.2888	4.7560			

Table 2 shows the descriptive statistics for the independent t-test. The result suggest that there is no significant difference (mean 6.3828, SD = 5.7314) for transverse deflection and (mean = 5.2888, SD = 4.7560) for longitudinal deflection, t (20) = 0.657, p = 0.515, d = 0.208, 95% confidence interval (u) (4.804). This further implies that there is no statistical significance between transverse deflection and longitudinal deflection. Hence the deepening of pothole does not depend on the direction of the crack. This agrees with the study [10] that the main cause of vertical surface deflections and the horizontal tensile strains in layer of flexible pavements were vertical loads. When a crack initiates, the structural capacity of the pavement section is reduced. The crack decreases the section of the asphalt layer available to resist tension, resulting in pavement deflection [11].

V. CONCLUSION

From the results of the study, it can be found that there is no significant difference between deflection (deepening in pothole formation from longitudinal and transverse cracks when subjected the same load intensity, modulus of elasticity of subgrade material and pavement thickness over a period of time. With constant application of axle load, longitudinal and transverse cracks will be subjected to bending stress and deflection. This deflection will deteriorate into pothole formation since the structural capacity of the pavement section will be reduced. It is important for highway engineers to quickly identify cracks distress (either longitudinal or transverse crack), and seal the cracks to prevent crack propagation.

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