The Evaluation of Deflection and Tensile Stress in Jointed Plain Concrete Pavement for a Damaged Road

Wibowo¹, Ary Setyawan¹, Yusep Muslih P², Bambang Setiawan³, Farikh Fajri Muandululman³, Abel Galang Setiawan³, Galih Rizky Adi Prabowo³

¹Roadmate Research Group, Universitas Sebelas Maret
²Geotehnic Laboratory, Engineering Faculty, Universitas sebelas Maret.
³Student of Civil Enginering Graduate Program, Universitas Sebelas Maret, Jln Ir Sutami 36 A, Surakarta 57126

E-mail: wibowo68@staff.uns.ac.id

Abstract. Most local governments in Indonesia experienced problems in developing pavements on expansive soil as observed in the damages to the road segment due to the conditions of the soil and excessive traffic loads. This has led to the rehabilitation of the road pavement by designing a continuous rigid structure without reinforcement. Therefore, this study aimed to analyse and evaluate the condition of a jointed plain concrete pavement (JPCP) structure without reinforcement based on the results of deflection and tensile stress. The process involved the application of Manual Road Pavement method to determine the pavement thickness as well as the use of analytical and numerical analysis to produce tensile and deflection values at CBR variations of 2% to 6%. Moreover, loads were applied at the edge and centre of the concrete plates and the results from the two methods of analysis were compared to determine the usefulness of different types of reinforced rigid pavement on the conditions of expansive soil subgrade. Meanwhile, the jointed plain concrete pavement analysis without reinforcement produced a 25 cm thick concrete plate and the thickness was further analysed analytically and numerically using variations in CBR values from 2% to 6%. The deflection and tensile stress values, however, met the maximum limit required.

1. Introduction
Highway is an infrastructure consisting of building and other complementary designs to maintain traffic above and below the surface of the land and water. It is usually constructed to play an important role in the transfer of people, goods, and services from one place to another. It is also important to note that roads are designed to support the economic growth of an area through their significant contribution to production process.

The focus of this study is on Sragen Regency which has highlands in the north and southeast and lowlands in the middle with Solo Bengawan River flowing through the area. The regency, however, has a soil structure which tends to be unstable and this led to the construction of the Surakarta-Gemolong-Geyer road section which borders the Grobogan Regency using concrete technology. This was intended to minimize the damage to the road but some functional and structural damages practically persist possibly due to vehicle load, reinforcement used in the concrete, and the unstable soil conditions. This, therefore, makes resilient modulus, shear strength, erosion, and permanent deformation of the non-bonded layer or subgrade important factors in rigid pavements. Several
previous studies have shown problem solving in similar cases. In this case, the rigid pavement is damaged due to the subgrade behaviour of the expansive soil [1][2].

The main structure of a rigid pavement is the concrete plate sheet which is equivalent to the wear, surface, and foundation layers of a flexible pavement. The name ‘rigid pavement’ is used because the concrete slab never deflected under traffic loads and is designed for a service life of up to 40 years before a major reconstruction is required.

Several previous studies have produced empirical theories on rigid pavement design. For example, Cristian Gaedicke studied concrete slabs above the ground and found the use of a three-dimensional cohesive crack model approach was able to predict the flexural capacity of a rigid pavement slab. The model involved the production of test objects measuring 2m x 2m with the thickness varied between 150 mm and 63 mm using load vs displacement curve as observed in the FEM software [3].

The plate geometry has a significant influence on the potential for longitudinal cracking, particularly when traffic consists of more tandems and tridem axles. It is, however, possible to use field data to develop empirical models to predict longitudinal cracks and this further showed the possibility of developing a mechanistic-empirical model for these cracks in future mechanistic-empirical pavement design with the slab length, width, and thickness included in the geometry [1][4].

The load transfer efficiency was improved in the 3D FEM model by increasing the elasticity module of the concrete slab and base layer or the slab thickness in order to reduce joint deflection and damages to the pavement joint. Meanwhile, the removal of the dowel rod has a detrimental effect on the load transfer [5][4] while the stress modulus of the existing concrete pavements was found to be affecting the overlay performance with respect to cross-fracture, joint fracture, and pavement roughness. The cross fracture was discovered to be the most affected parameter with a change of 0.27% e2.31% and a unit change in stressed modulus. It was, however, possible to minimize the adverse effects of the compressed modulus by reducing the joint distance or increasing the coating plate thickness [6].

The greatest stress was reached during the impact load or first touchdown at both the maximum vertical and horizontal speed and this means reinforcement is required in the concrete. A close correlation was also observed to exist between transverse crack distances and steel reinforcement spacing while there was no consideration for the effect of concrete initial life and creep behaviour on crack initiation [7][8].

2. Experimental
A quantitative analytical method was used to analyse the continuous rigid pavement without reinforcement. Moreover, a structural modelling experiment was conducted through the use of finite element method while the analytical solution was determined using the Westergaard equation. The data used were in 2 groups and the first is the primary data such as the dimensions of road sections and segments and existing conditions of the rigid pavement. The second is the secondary data which consist of the CBR and LHR values used to evaluate the continuous rigid pavement without reinforcement [9][4].

2.1. Analytic Solution
The use of analytical solutions is possible in the context of this rigid pavement problem and this commonly involves the application of the Westergaard equation. However, the difficulty usually observed with this equation is the non-inclusion of the effect of the reinforcing bars in the rigid pavement plate and this leads to some differences when compared with the results of numerical solutions which normally include this factor. Equations (1) and (2) were used when load was applied at the middle of the plate while (3) and (4) were used when the load was applied at the edge.

Center Load:

\[ \sigma = \frac{3(1 + \mu)P}{2\pi bd^2}(\ln \frac{1}{b} + 0.6159) \]  

(1)
2.2. Numerical Analysis
The numerical analysis was conducted on the rigid pavement plates using the finite element method. The specimen used was designed in the form of a single square rigid pavement plate which discretizes into a small rectangular element and supported by a spring at the corner point of each element.[10]

![Figure 1. The meshing of a rigid pavement plate specimen](image)

The finite element method was used to produce the stress map and displacement of each joint in the plate after which the maximum values obtained were compared with the results of the analytical solution to determine the limit of the flexural capacity of the rigid pavement plate [11][12].

2.3. Soil support as a subgrade
Soil supports were assumed to be expansive with extremely swelling variation based on the dry and wet seasons. The effect of the soil swelling was simplified in this study by varying soil support using field minimum and maximum CBR test [13][14][15].

3. Results and Discussion
The results of the numerical analysis and analytical solutions are presented in a series of tables and graphs to have a clearer picture of their differences and strengths [16].

| CBR | Edge Load | Centre Load |
|-----|-----------|-------------|
|     | Tensile Stress (σ) (kN/m²) | Displacement (Δ) (mm) | Tensile Stress (σ) (kN/m²) | Displacement (Δ) (mm) |
| 2%  | 2811.5495 | 0.0032490   | 2132.3508 | 0.0003911   |
The difference in the CBR magnitudes represents the simplified swelling model of the soil subgrade as previously mentioned. Table 1 shows the increase in the CBR led to the loss of subgrade support and more deflection in the slab of the rigid pavement and the difference in the subgrades were further used to explain the swelling problem on the edge of the slab, especially on expansive soil.

**Table 2.** Displacement result of analytical and numerical solution due to edge loading

| CBR | Analytical Solution Displacement (Δ) (cm) | Numerical Solution Displacement (Δ) (cm) | Allowed Displacement (cm) | Note |
|-----|-------------------------------------------|-------------------------------------------|---------------------------|------|
| 2%  | 0.324905                                  | 0.387221                                  | 1.6667                    | OK   |
| 3%  | 0.262518                                  | 0.281594                                  | 1.3704                    | OK   |
| 4%  | 0.236121                                  | 0.241988                                  | 1.3030                    | OK   |
| 5%  | 0.222245                                  | 0.221726                                  | 1.2703                    | OK   |
| 6%  | 0.207796                                  | 0.201339                                  | 1.1905                    | OK   |

**Table 3.** Displacement result of analytical and numerical solution due to centre loading

| CBR | Analytical Solution Displacement (Δ) (cm) | Numerical Solution Displacement (Δ) (cm) | Allowed displacement (cm) | Note |
|-----|-------------------------------------------|-------------------------------------------|---------------------------|------|
| 2%  | 0.039113                                  | 0.120038                                  | 1.6667                    | OK   |
| 3%  | 0.031636                                  | 0.083721                                  | 1.3704                    | OK   |
| 4%  | 0.028457                                  | 0.070467                                  | 1.3030                    | OK   |
| 5%  | 0.026781                                  | 0.063995                                  | 1.2703                    | OK   |
| 6%  | 0.025033                                  | 0.057607                                  | 1.1905                    | OK   |

The gap observed from comparing the analytical and numerical deflection using limited allowable displacement as shown in Tables 2 and 3 explains the inability of the static loading to provide a maximum impact due to the damage in the rigid pavement. This means there is a need for more explanation on the soil as a subgrade and rigid pavement. Meanwhile, the behaviour of the pavement has been reported to have a very strong influence on stress distribution and deflection of slab [4][17] as illustrated in Tables 4 and 5.

**Table 4.** Maximum tensile stress due to edge loading using analytical and numerical solutions

| Nilai CBR | Analytic Solution | Numerical Solution |
|-----------|-------------------|--------------------|
|           | Tensile Stress (kN/m²) | Tensile Stress (kN/m²) |
| 2%        | 2811.54953        | 2300.4903          |
Table 5. Maximum tensile stress due to centre loading using analytical and numerical solutions

| CBR (%) | Analytic Solution | Numeric Solution |
|---------|-------------------|------------------|
|         | Tensile Stress (kN/m²) | Tensile Stress (kN/m²) |
| 2%      | 2132.35077         | 433.6906         |
| 3%      | 2060.48818         | 419.7945         |
| 4%      | 2024.92232         | 412.1144         |
| 5%      | 2004.64481         | 407.4348         |
| 6%      | 1982.17998         | 401.9358         |

The maximum tensile stresses due to edge and centre loading for the concrete road pavement were determined using analytical and numerical analysis and the results are presented in Tables 4 and 5. Meanwhile, the significance difference in the two methods is observed in Table 5 but the similarity recorded when static loading was used theoretically indicate an inaccurate calculation or analysis [18] with the numerical solution discovered to be more precise.

Figure 2. Displacement result of edge loading (vertical displacement)
Figure 3. Maximum tensile stress result of edge loading

The relationship between Figures 2 and 3 is the most interesting part of this research and this is represented by the linear relationship between the mechanical load and the displacement in the zone elastic analysis. Meanwhile, the same values of loading produced a different result in tensile stress but the same result in the vertical deflection and this means there is a need for a wider development of the analytical approach to include some variables not considered in the equation. The weakness observed in Equations 1, 2, 3, and 4 of this study was the inability to provide results outside the point where loadings were applied on the rigid pavement.

Figure 4. Maximum tensile stress result of centre loading
The results shown in Figures (3) indicate the analytical and numerical analysis have the same trend for both displacement and tensile stress but there is a significant difference in the values obtained using the two methods. Meanwhile, the failure or damage observed in the rigid pavement structure was not caused by traffic loads but due to the loss of subgrade support in the form of expansionary soil [19][13][20].

4. Conclusion
The conclusions drawn from this research are summarized as follows:

- There was a significant difference between the results obtained from the analytical and numerical analysis results due to the non-consideration of the variations in the modulus of elasticity in the analytical solution.
- There was no excess tensile stress or displacement due to the load applied and this means the road structure was not damaged by traffic loads.
- The damage on the field as observed with the crack pattern was found to be most likely due to the loss of the subgrade bearing capacity.
- The use of reinforcing bars as internal reinforcement for rigid pavement plates is considered a potential solution to prevent premature damage but there is a need for more in-depth studies on this assumption.

Acknowledgements
The author shows the highest appreciation and gratitude to all colleagues in the Roadmate research group that provided suggestions and input to improve the research and writing of this article.

References
[1] D. X. Xiao and Z. Wu, “ScienceDirect Longitudinal cracking of jointed plain concrete pavements in Louisiana : Field investigation and numerical simulation,” Int. J. Pavement Res. Technol., vol. 11, no. 5, pp. 417–426, 2018.
[2] R. Lytton, C. Aubeny, and R. Bulut, “Design Procedure for Pavements on Expansive Soils: Volume 2,” Texas Deparment Transp., vol. 7, no. FHWA Report No. 0-4518-1 Vol. 2, p. 232, 2004.
[3] C. Gaedicke, J. Roesler, and F. Evangelista, “Three-dimensional cohesive crack model prediction of the flexural capacity of concrete slabs on soil,” vol. 94, pp. 1–12, 2012.
[4] S. Kim, Y. Kyo, and J. Ho, “Advanced reinforced concrete pavement : Concept and design,” Constr. Build. Mater., vol. 231, p. 117130, 2020.
[5] V. Sadeghi and S. Hesami, “Investigation of load transfer efficiency in jointed plain concrete pavements (JPCP) using FEM,” Int. J. Pavement Res. Technol., vol. 11, no. 3, pp. 245–252, 2018.
[6] G. Sabih and R. A. Tarefder, “ScienceDirect Effects of existing concrete pavement condition on performance of unbonded jointed plain concrete overlay,” J. Traffic Transp. Eng. (English Ed.), pp. 1–10, 2018.
[7] I. L. Al-Qadi and M. A. Elseifi, “Mechanism and modeling of transverse cracking development in continuously reinforced concrete pavement,” Int. J. Pavement Eng., vol. 7, no. 4, pp. 341–349, 2006.
[8] K. A. Abaza, “Simplified empirical approach for predicting the remaining strength factor used in pavement rehabilitation applications,” Cogent Eng., vol. 6, no. 1, pp. 1–21, 2019.
[9] Ilpandari, “Analisis Desain Struktur Rigid Pavement dengan Metode Empirik, Evaluasi dan Permodelan dengan Software Kenpave-Kenslabs (Studi Kasus : Jalan Tol Semarang - Solo, Seksi III Bawen - Salatiga),” no. 1993, p. 14914023, 2018.
[10] V. A. Patil, V. A. Sawant, and K. Deb, “Finite element analysis of rigid pavement on a nonlinear two parameter foundation model,” Int. J. Geotech. Eng., 2012.
[11] L. A. G. Bitencourt, O. L. Manzoli, Y. T. Trindade, E. A. Rodrigues, and D. Dias-da-Costa,
“Modeling reinforced concrete structures using coupling finite elements for discrete representation of reinforcements,” *Finite Elem. Anal. Des.*, 2018.

[12] T. Sok, Y. K. Kim, and S. W. Lee, “Numerical approach to predict zero-stress temperature in concrete pavements,” *Constr. Build. Mater.*, vol. 262, p. 120076, 2020.

[13] M. A. Bhatti, J. A. Barlow, and J. W. Stoner, “Modeling damage to rigid pavements caused by subgrade pumping,” *J. Transp. Eng.*, vol. 122, no. 1, pp. 12–21, 1996.

[14] D. M. Setiawan, “The role of temperature differential and subgrade quality on stress, curling, and deflection behavior of rigid pavement,” *J. Mech. Behav. Mater.*, vol. 29, no. 1, pp. 94–105, 2020.

[15] A. Mateos, J. Harvey, J. Bolander, R. Wu, J. Paniagua, and F. Paniagua, “Structural response of concrete pavement slabs under hygrothermal actions,” *Constr. Build. Mater.*, vol. 243, p. 118261, 2020.

[16] Y. H. Parjoko, “Sensitivity Analysis of Concrete Performance Using Finite Element Approach,” *J. Civ. Eng. Forum*, vol. 21, no. 1, 2012.

[17] A. Jindal, G. D. R. N. Ransinchung, and P. Kumar, “International Journal of Transportation Behavioral study of self-compacting concrete with wollastonite microfiber as part replacement of sand for pavement quality concrete (PQC),” *Int. J. Transp. Sci. Technol.*, no. xxxx, 2019.

[18] V. A. Sawant and M. S. Norazzlina, “Flexural Stress Analysis of Rigid Pavements Using Axisymmetric and Plane Strain Fem,” *ASEAN J. Sci. Technol. Dev.*, vol. 24, no. 4, p. 443, 2017.

[19] B. Kermani, S. M. Stoffels, M. Xiao, and T. Qiu, “Experimental simulation and quantification of migration of subgrade soil into subbase under rigid pavement using model mobile load simulator,” *J. Transp. Eng. Part B Pavements*, 2018.

[20] B. Kermani, S. M. Stoffels, M. Xiao, and T. Qiu, “Experimental simulation and quantification of migration of subgrade soil into subbase under rigid pavement using model mobile load simulator,” *J. Transp. Eng. Part B Pavements*, vol. 144, no. 4, 2018.