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Nonlinear Structural Deformation Modelling of Asphalt Layers using Artificial Neural Networks

Sunny Deol G [1], Vikas Kumar Reddy T[2]

[1]Assistant Professor, Department of Civil Engineering, National Institute of Technology, Raipur, Chhattisgarh, 492010
[2]PhD Scholar, Department of Civil Engineering, National Institute of Technology, Raipur, Chhattisgarh, 492010

Abstract

Structural deformation commonly known as rutting (permanent deformation) in Asphalt pavements is the most familiar and major form of distress in soft subgrade soils which results in premature failure and impairing its serviceability criteria. Conventional distress prediction models account only direct in-situ measurements rather than material characterization and its responses under realistic dynamic loading. This study develops in-situ response based modified constitutive 2-D model to predict rutting in terms of estimated vertical compressive strain and radial strain. The influence of calculated responses estimated from 30 tests locations of various road sections having diverse traffic loading and soil characteristics has been thoroughly assessed by developing the correlation with conventional volumetric and index properties along with backcalculated moduli of granular and subgrade layers. Results depicts that poor correlation of 0.65 between vertical compressive strain and material parameters with radial basis function network and comparatively good correlation of 0.79 with multi linear perceptron network. Similarly, poor correlation of 0.55 between radial strain and material parameters with radial basis function network and comparatively good correlation of 0.82 with multi linear perceptron network. Further the final 2-D rut prediction modified constitutive model shows a satisfactory result with a correlation value of 0.732. The application of these developed models in the developing countries like India accelerates the decision-making process of various stakeholders in understanding the realistic mechanistic behaviour of pavement structural deformations rather than simple conventional rut measurements.

Keywords: Asphalt Pavements, Backcalculated Moduli, Distress, Rutting.

I. INTRODUCTION

Structural deformation (Rutting) is one of the most serious distresses in asphalt pavements affecting the pavement performance and service life. Unfortunately, there does not exist any quantitative engineering basis for determining the rut depth threshold for pavement maintenance or rehabilitation. As a result practically all highway agencies classify rut severity on the basis of engineering judgment or past practical experience for the purpose of pavement maintenance and rehabilitation [4]. To provide a fundamental analysis of mechanics of the rutting of asphalt pavement, the constitutive characterization and modelling of the Pavement material as well as the interactions among its constituents are needed [7]. Hence, the validity of response models is an important prerequisite for reliable evaluation of structural pavement condition. Though there were some questions about the assumptions made in the layered elastic theory in pavement applications, such as uniform contact pressure, isotropic layers, interface conditions, loading pattern etc., the layered elastic theory predict pavement responses reasonably well [1,2,3,6, and 9]. [12] compared the available software results with the measured response and the comparison shows that the layered elastic packages predict the pavements responses reasonably well in most cases. Currently, many available computer packages help the pavement designer to calculate pavement responses by inputting the load configuration and material properties. WESLEA, VESYS, KENLAYER, CIRCLY4, BISAR, VEROAD, ELSYM, PDMAP, JULEA, ILLIPAVE, FENLAP are some of the important available computer programs that are used in pavement analysis and design [10]. In some cases, the models have been further refined to estimate pavement performance in terms of rutting and fatigue by incorporating appropriate transfer functions (e.g., WESLEA for Windows 3.0 and KENLAYER) [8]. As noted, the pavement responses has being studied widely. From these studies, a series of empirical relationships that were proposed to predict pavement responses are summarized in table I.

Table I. Empirical relationships for predicting pavement responses

Equation	**Model**	**Author, Year**	Parameters
1	$\text{Log RR} = -1.173 + 0.717\log(d) - 0.658\log(N_{18}) + 0.666\log(\sigma_c)$	Finn et al., 1977	
2	$\mathrm{N}_p = 6.15 \times 10^{-7} \times \varepsilon_c^{-4}$	Claussen, 1977	
1	$\varepsilon_p = N \times \left(\frac{q}{a}\right)^b$	Brown and Bell, 1979	Permanent strain, deviatric stress, Load repetitions
	$\text{Log}\ \varepsilon_p = C_0 + C_1(\log N) - C_2(\log N)^2 + C_3(\log \mathrm{N})^3$	Allen &Deen Model (1980)	axial permanent strain, Load repetitions
2	$\mathrm{N}_p = 1.365 \times 10^{-9} \times \varepsilon_c^{-4.477}$	shook, 1982	
	$\varepsilon_p = A \times N^B + C$		
	$\varepsilon_p = A\left[1 - \left(\frac{N}{100}\right)^{-B}\right]$ $\mathrm{A} = \left[\frac{\frac{q}{(p+p^*)}}{a - b\frac{q}{(p+p^*)}}\right]$	Paute et.al, 1988	
	$\text{Log}\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = -0.631 + 0.435(\log N) + 2.767\log\mathrm{T} + 0.110(\log\mathrm{S}) + 0.118\log\eta + 0.930\log V_{beff} + 0.501 logV_a$	Leahy's Model (1989)	Accumulated Permanent strain, resilient strain, load repetitions, mix temperature viscosity.
3	$\varepsilon_p = A \times N^B$	Sweere, 1990	
4	$\varepsilon_p = (m.N + A)(1 - e^{-B.N})$	Wolf and Visser, 1994	
	$\varepsilon_p = (A_1 \times N^{B_1}) + (A_2)(e^{-B_2.N} - 1)$	Francken et.al.1987, Kaloush et.al 2002, Huurman et.al, 1996, Werkmeister et.al, 2003 arnold, 2004	
	$\varepsilon_p = (m \times N) + (A_2)(1 - e^{-B_2.N})$	Theyse et.al, 1997	
5	$\gamma^p = ae^{(b\times\tau^e)}\gamma^e N^c$	Hand et al., 1999	plastic shear strain, elastic shear stress, elastic shear strain, load repetitions,
6	$\mathrm{RD} = \Big\{[-0.016H_{AC} + 0.033\ln(SD) + -0.011T_{annual} - 0.01\ln(KV)] \times \Big[-2.703 + 0.657\left(\varepsilon_{v,base}\right)^{0.097} + 0.271\left(\varepsilon_{v,SG}\right)^{0.883} + 0.258\ln(N) - 0.0341 ln\left(\frac{E_{AC}}{E_{SG}}\right)\Big]\Big\}$	Kim 1999	Rut depth, asphalt layer thickness surface deflection temperature, vertical elastic compressive strain of different layers, load repetitions resilient modulus of layers.
	$\rho_p = 0.00011 \times h_{AC}\left[\sum_{i=1}^{k} n_i\left(\varepsilon_{i,AC}\right)^{1.111}\right]^{0.9}$	Ali et al., 1998	Rut depth, HMA layer thickness, vertical compressive elastic strain
	$\varepsilon_p(n) = \mu \times \varepsilon_e \times n^{-\propto}$ $\rho_p = h_{AC}\frac{\mu_{AC}}{1-\propto_{AC}}\left(\sum_{i=1}^{k}(n_i)^{1-\propto_{AC}}(\varepsilon_{ei,AC})\right) + h_{base}\frac{\mu_{base}}{1-\propto_{base}}\left(\sum_{i=1}^{k}(n_i)^{1-\propto_{base}}(\varepsilon_{ei,base})\right) + h_{SG}\frac{\mu_{SG}}{1-\propto_{SG}}\left(\sum_{i=1}^{k}(n_i)^{1-\propto_{SG}}(\varepsilon_{ei,SG})\right)$	Ali and Tayabji, 2000	Rut depth, number of ale groups, number of load repetitions, vertical elastic compressive strain, proportionality between plastic and elastic strain
	For Asphalt layers, $\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = 0.0007\beta_r T^{1.734\beta_{r2}} N^{0.39937\beta_{r3}}$ For unbound layers, $\delta_a(N) = \beta_{s1}\varepsilon_v h\frac{\varepsilon_o}{\varepsilon_r}\left[e^{-\left(\frac{\rho}{N}\right)^{\beta}}\right]$	NHCRP 1-37A	Plastic strain, resilient strain, layer temperature, load repetitions, Thickness of layer

$\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = K_1\beta_{r1}10^{-3.1552}T^{1.734\beta_{r2}}N^{0.39937\beta_{r3}}$	MEPDG, 2004	accumulated permanent strain, resilient strain, mix temperature, number of load repetitions
Primary stage rutting, $\varepsilon_p = A \times N^B$ Secondary stage rutting, $\varepsilon_p = \varepsilon_{ps} + C(N - N_{ps})$ Teritiary stage rutting, $\varepsilon_p = \varepsilon_{st} + d(e^{f(N-N_{st})} - 1$	Zhou et al., 2004	Permanent strain, number of load repetitions
$\mathrm{Rut}_i = \mathrm{Rut}_{i-1} + \lambda_0(N_i{}^{(\lambda_1\times\gamma_i)})$ $\mathrm{Rut}_i = \mathrm{Rut}_{i-1} + \beta_0(N_i{}^{(\beta_1\times\varepsilon_i)})$	Selvraj, 2007	Shear strain, Vertical base or subgrade strain

Therefore, the accurate simulation of rutting in asphalt pavements is essential for improving their performance and management. Therefore, an evaluation of a simplified numerical model with efficient and realistic loading conditions and material constitutive models that can simulate the pavement rutting performance for a very large number of loading cycles is desirable [11]. The permanent deformation is defined hereto mean only the vertical permanent deformations in the unbound, granular material including also the subgrade. Even though only the vertical permanent deformations are calculated, they include also the radial strain, and shear strains, pertinent for accounting for permanent deformation [5].

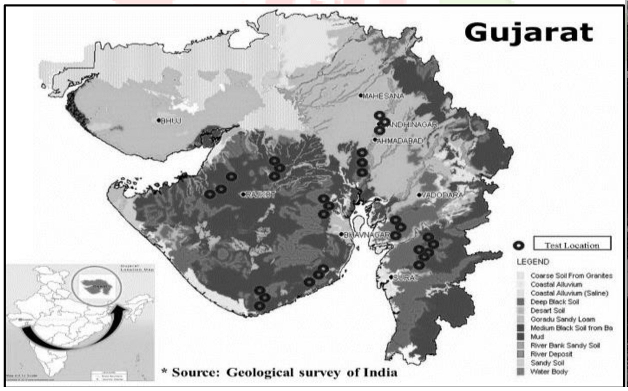
The present study aims at developing response based 2D constitutive model for predicting rut depth using estimated vertical compressive strain and radial strain with number of load repetitions. This study also aims to develop independent response material empirical models between vertical and radial strain with conventional volumetric and index properties of pavement layers.

II. MATERIALS AND METHODS

Detailed experimental investigations have been performed on the selected 10 different road stretches. 10 different category of road stretches were selected having distinct traffic loading and soil characteristics as shown in Fig.1a. The entire field and laboratory investigations have been performed on the three selected pavement section of each road stretch. Therefore 30 different test location was selected undergone with permanent deformation.

A. *Field investigations*

Field investigations were very significant for the development of correlations in order to simulate the field conditions. All the field investigation have been performed as per the guidelines suggested by the Indian and ASTM standards. Field investigations such as rut measurement, trial pit for sample collection, In-situ density assessment, and layer deflections and backcalculated pavement layer moduli using portable falling weight deflectometer (PFWD) were performed at the distress locations on selected pavement test stretches as shown in Fig. 1b. The test results obtained were analysed as shown in Fig. 2, 3 and used in the development of models and correlations.



* Source: Geological survey of India

Fig. 1 (a). Test locations

Fig. 1 (b). PFWD test

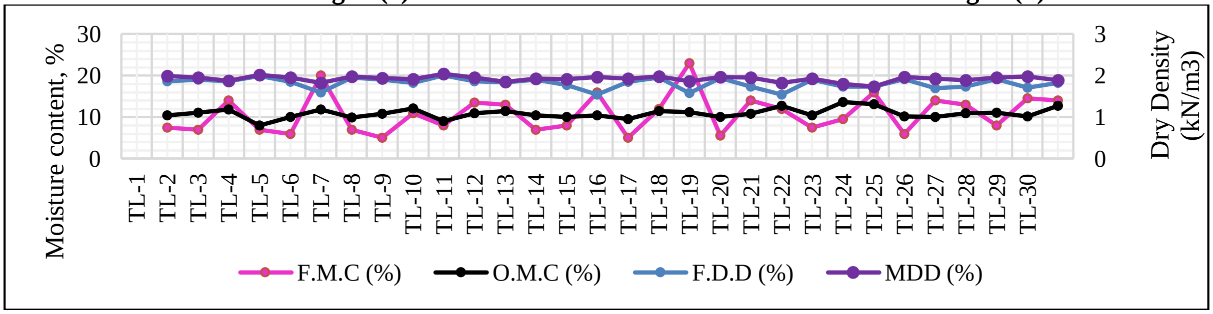


Fig. 2. Density and Moisture content

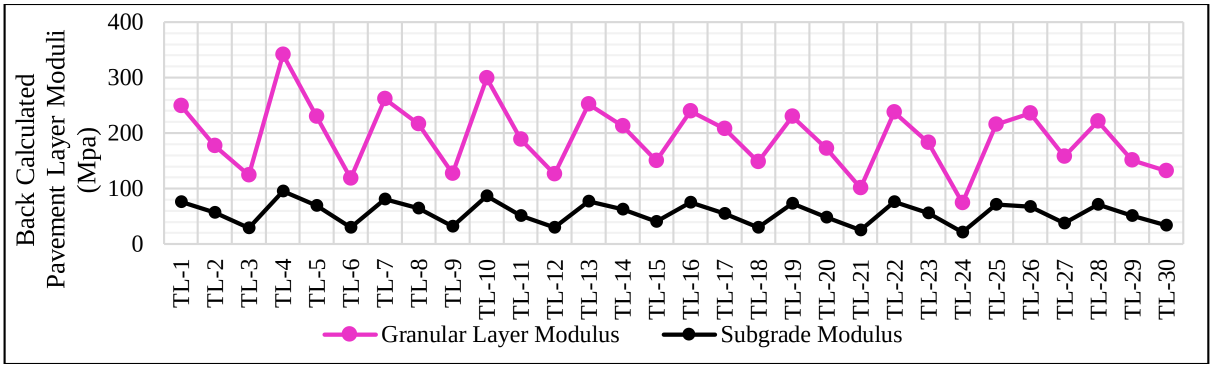


Fig. 3. Backcalculated Pavement layer moduli for Subgrade and Granular layers

B. *Laboratory Investigations*

Tests performed in the laboratory for both physical and strength properties. Tests for the physical properties such as grain size analysis, index properties, soil classification and free swell index were performed to assess the detailed physical characteristics of the collected soil samples from various locations. Tests for the strength properties such as CBR, density levels at optimum moisture content were also performed in the laboratory to developed empirical correlations and to assess the detailed strength characteristics of the collected soil samples from various locations. The test results from physical and strength tests were analysed as shown in Fig. 4, 5.

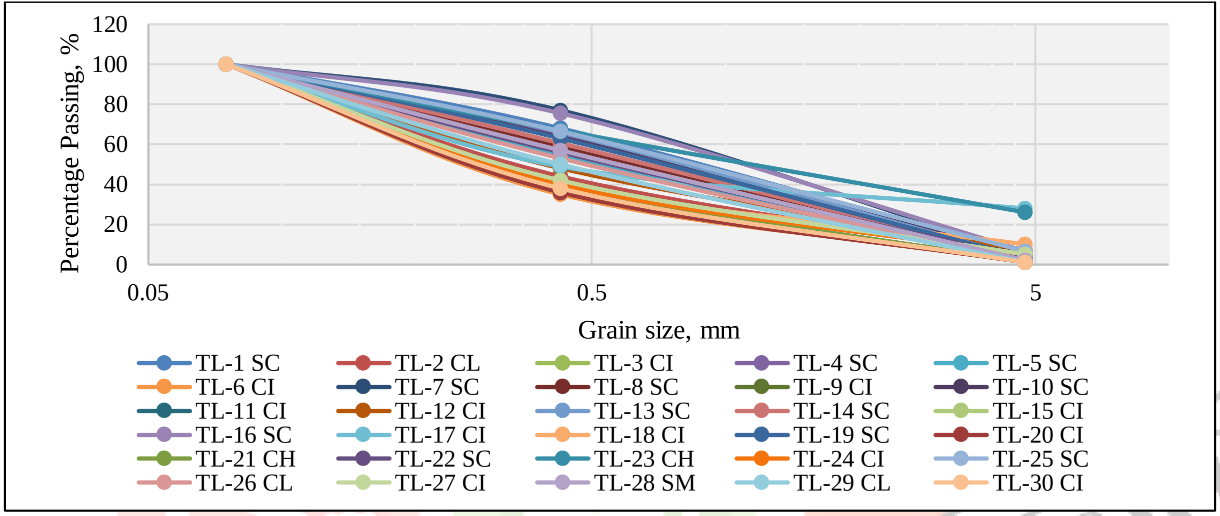


Fig.4. Grain size analysis for subgrade

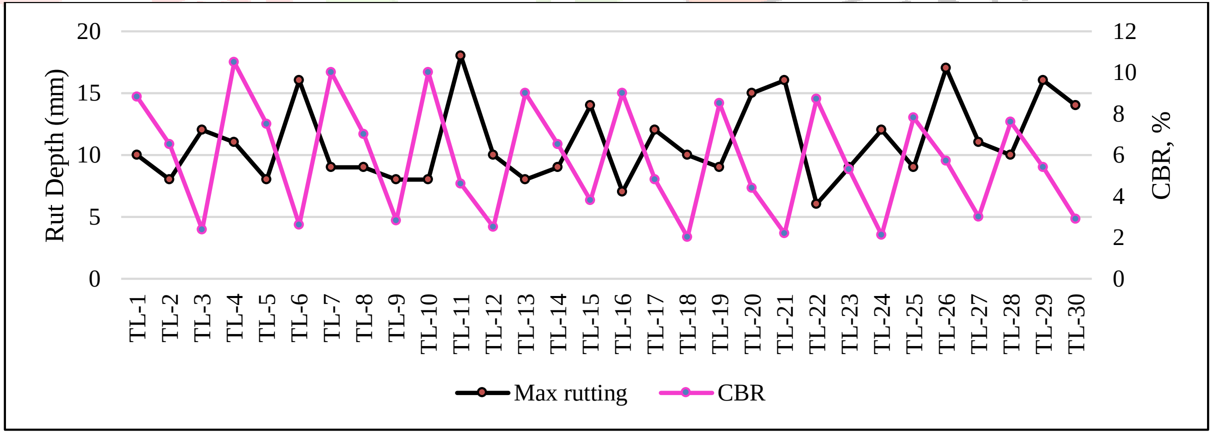


Fig. 5. Rut depth and Subgrade CBR

III. DEVELOPMENT OF MATERIAL BASED RESPONSE MODEL

A. Measured Pavement responses

Pavement responses such as vertical compressive strain and radial strain were estimated for various load groups having at distinct locations of the pavement crossection using KENLAYER program based on the backcalculated layer moduli and measured crust thickness along with vehicular loadings. The strains obtained for different load groups from the KENLAYER program were analysed and final cumulative vertical compressive and radial strains were estimated for various test locations as shown in as shown in Fig. 6.

B. Empirical modelling for predicting strains

The estimated vertical compressive strains were correlated with conventional volumetric properties like dry density ratio (DDR) and moisture content ratio (MCR), index properties like Plasticity index (PI) and backcalculated subgrade modulus. Estimated Radial strain is correlated conventional volumetric properties like dry density ratio (DDR) and moisture content ratio (MCR), index properties like Plasticity index (PI) and backcalculated subgrade and granular layer modulus. Empirical modelling for predicting Vertical compressive strain and radial strain has been carried out distinctly for each type of strain using radial basis function network (RBFN) and multi linear perceptron network (MLPN). Detailed correlation analysis has been carried with multiple iterations for each type of algorithm and best correlation value is selected. The correlation results obtained from each type of network is compared and once again best fit correlation value is selected for this study. The developed empirical correlations were validated for the given data set and the correlation are quite acceptable as shown in Table.II and Fig. 7a,b.

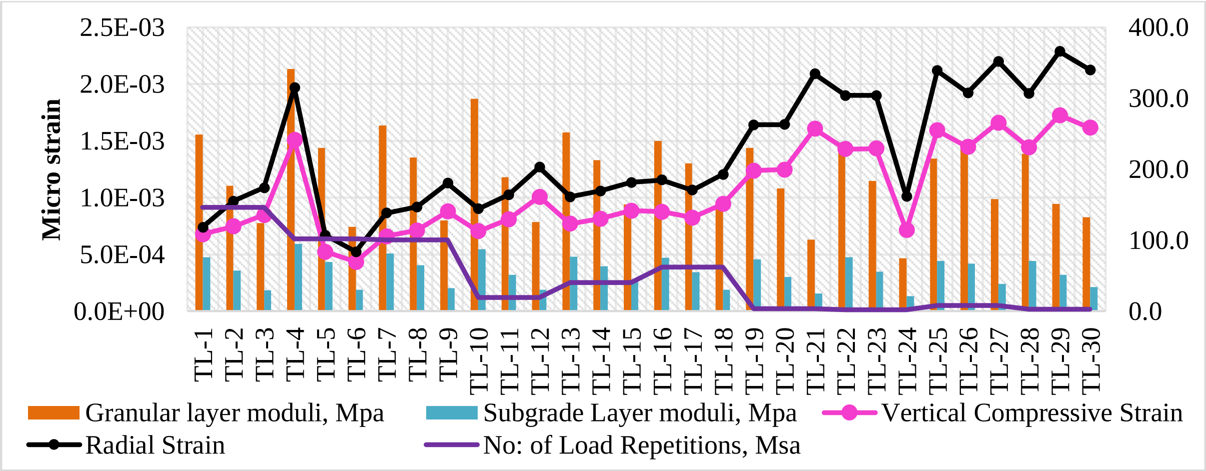


Fig. 6. Vertical compressive and radial strain with Load repetitions

Table II: ANN modelling results

Dependent variable	Independent variable	Global Sensitivity	Algorithm	R^2 Training	R^2 Testing	R^2 Validation	Final Correlation
Vertical Compressive Strain	Subgrade modulus	6.91237	MLP 4-6-1	0.7614	0.9544	0.7789	0.7930
	PI	4.60453					
	DDR	5.64333					
	MCR	4.48380					
	Subgrade modulus	1.29159	RBF 4-12-1	0.5686	0.7622	0.9172	0.6499
	PI	1.37194					
	DDR	1.49450					
	MCR	1.24903					
Radial Strain	PI	3.01480	MLP 5-6-1	0.7481	0.9427	0.9992	0.8150
	DDR	1.81468					
	MCR	3.83685					
	Granular modulus	5.48081					
	Subgrade modulus	5.94731					
	PI	1.04502	RBF 5-11-1	0.4135	0.7625	0.9980	0.5535
	DDR	1.66886					
	MCR	1.06291					
	Granular modulus	0.97099					
	Subgrade modulus	0.99927					

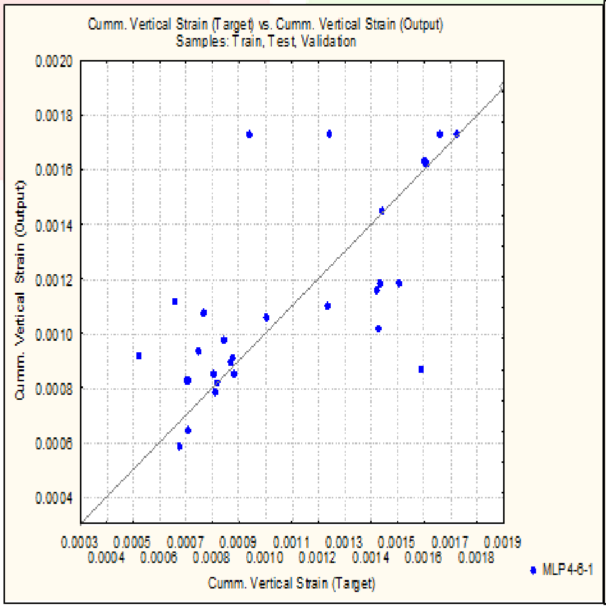


Fig. 7(a). Measured vertical strain vs predicted strain

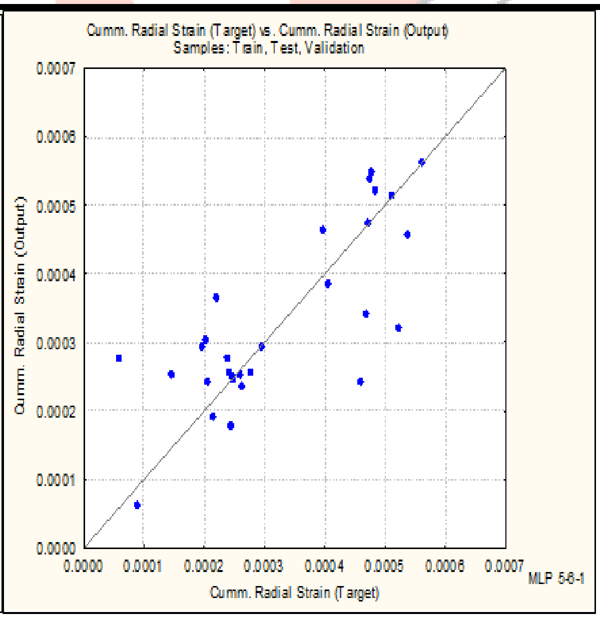


Fig. 7(b). Measured Radial strain vs predicted strain

IV. RESPONSE BASED 2D CONSTITUTIVE MODELLING

Two-dimensional response based constitutive model was developed based on the estimated or predicted strains i.e. vertical compressive strains and radial strain. As the structural deformation most commonly known as permanent deformation or rutting includes not only vertical compressive strain but also radial strain [5]. Therefore, the basic form of the vertical strain-based model has been adopted as shown in Eq. 1 from the historical theories and further the base model is modified to 2D model.

$$\text{Rut Depth} \; = \beta_0 \, N_i^{\,(\beta_1 \times \varepsilon_i)} \qquad (1)$$

Where, N_i = Total number of axle passes at time ‘i', ε_i = Vertical base or subgrade strain calculated at time ‘i’ from strain prediction models, β_0, β_1= Regression constants for traffic and strain respectively.

The modified 2D constitutive model comprises of estimated or measured strains of a elastic half space i.e. vertical compressive strain and radial strain accumulated, number of load repetitions, and modulus ratio with rut depth as shown in Eq.2. Multi linear regression analysis has been carried out to assess the correlation of developed model between rut depth and response parameters along with the load repetitions. The results obtained from the regression analysis gives best fit correlation value of 0.7325. The results obtained from the ANNOVA test and the corresponding model coefficient values are shown in Table III. Further the model coefficients was analysed to assess the reliability and it is quite acceptable. The validation of the developed model with the 10 test data set has been carried out and the correlation between the measured and predicted rut depth is quite acceptable as shown in Fig.8.

$$\text{Rut Depth} \; = K \times \beta_0 \times N_i^{\,[(\beta_1 \times \varepsilon_v)+(\beta_2 \times \varepsilon_r)]} \qquad (2)$$

$$K \; = \left(\frac{E_{granular}}{E_{Subgrade}}\right)^{\alpha} \qquad (3)$$

Where, N_i = Total number of axle passes at time ‘i’, ε_v = Vertical compressive strain calculated from strain prediction models, ε_r = radial strain calculated from strain prediction models, β_0, β_1, and β_2 = Regression constants for traffic and strain, K= Modulus ratio, α = Regression coefficient respectively.

Table III: Rut prediction model coefficients

Parameter	Coefficients	Standard Error	t-Stat	P-value
β_0	0.7917	1.0138	0.780923	0.464534
α	0.57069	0.782562	0.729259	0.493316
$\beta 1$	108.1726	41.2761	2.620708	0.039549
β_2	-189.991	103.1871	-1.84123	0.115182

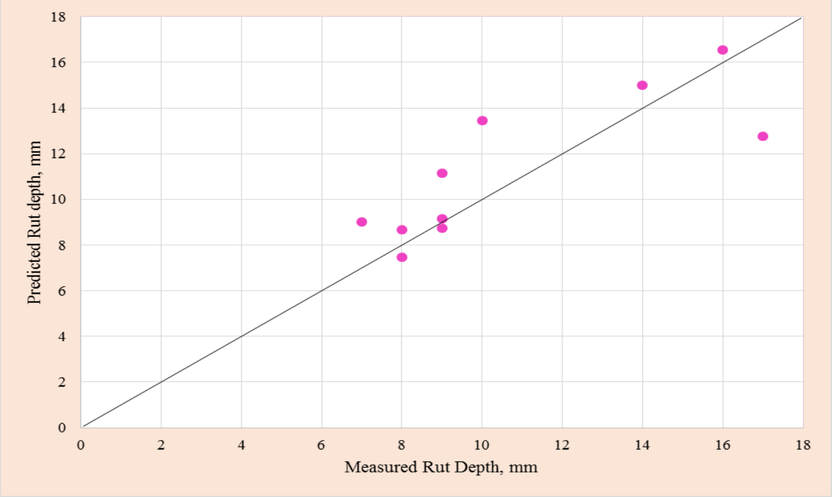


Fig. 8. Predicted rut depth vs measured rut depth

V. CONCLUSION

In this paper, 2-two dimensional response based rut prediction constitutive model has been developed based on the calculated vertical and radial strains along with number of load repetitions. Vertical and radial strains for the test location were calculated using KENLAYER program based on the backcalculated pavement layer moduli which is obtained from the portable falling weight deflectometer test on the test location. The calculated vertical and radial strains on the test locations were correlated with conventional material properties using MLPN and RBFN network algorithm. Results shows that RBFN algorithm gives poor correlation rather than MLPN algorithm.

The developed rut prediction model and independent strain prediction models provides quick and reliable engineering judgement and accelerates the decision making process in predicting rut depth of pavements during feasibility and maintenance stages of the project under similar traffic, soil strata and climatic conditions and also used for predicting the residual life of in-service pavement during maintenance phases on the pavement.

However, the performance of the developed models can further be enhanced with larger data sets and with in-situ measured strains under realistic vehicular loading conditions.

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