FAILURE ANALYSIS OF A SEMI STRUCTURAL PAVEMENT USING A MECHANISTIC TOOL – CASE STUDY FOR A PROVINCIAL ROAD

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ABSTRACT

Pavement design is a vital part in new road construction and in rehabilitation projects. Conventional flexible pavements are layered systems with high stress intensity on top and low intensity at the bottom. AASHTO method is widely used by most of the road agencies to design pavements while the Transport Research Laboratory (U.K) Road Note 31 (TRL RN-31) specifies for the tropical countries. Both these design guidelines are based on empirical formula or experimental studies conducted in extreme weather condition. Road Note 31 specifies the layer thicknesses of specific materials. It does not specify a method to adopt the materials that does not fit the specifications, which is the commonly encountered problem due to the varying site condition and availability of materials. Empirical design methods do not have any provision for analysing road failures and propose most suitable rehabilitation method. Therefore this research focused on evaluating the suitability of a mechanistic empirical pavement design tool to investigate a pavement failure. In this study, failure of a Sri Lankan rural road which is failed immediately after completing the construction was selected for the analysis. This road was designed according to the Overseas Road Note 31(ORN 31) as a Double Bitumen Surface Treatment (DBST) road and it has shown longitudinal cracking on the surface followed by the depression and the settlement, approximately after six months from the completion. Heavy axle load applied on the pavement due to transporting of construction materials to a new project has increased the propagation of cracks and potholes. Soil samples collected from the critically damaged locations were tested and the results showed that the inadequate strength of the pavement structure as the cause to the failure. Failure investigations were done using a mechanistic tool called CIRCLY and reliable reclamation method was proposed.

Keywords: Mechanistic-Empirical pavement design, Pavement failure, Failure investigation

1. INTRODUCTION

There are three types of pavement design procedures as empirical, mechanistic and mechanistic-empirical. Empirical method is based on past experiments and results while the mechanistic method is based on physical phenomena as stresses, strains and deflections. In mechanistic empirical method, pavement structure is analysed by evaluating physical phenomena and defining the Cumulative Damage Factor (CDF) by using empirically derived equations.

In current practice, TRL Road Note 31 is widely used in Sri Lanka for designing flexible road pavements. It gives recommendations for road pavements by using design traffic volume in ESAL (Equivalent Standard Axle Load) and subgrade strength. RN 31 specifies layer thicknesses for specified materials and it does not specify a method to adopt the materials with various properties. This is the main problem encountered due to the varying site conditions and non-availability of

standard materials. Meanwhile those empirical guidelines are developed for the worst possible condition. Therefore this might not give an economical design. Hence there is a need to use a mechanistic tool to analyse pavement designs.

2. BACKGROUND

The design of new and rehabilitated roads has relied on empirical procedures that have been incremented over time. But there are some limitations of those procedures due to its empirical nature. Therefore road designing agencies have been looking forward to overcome those limitations by combining the knowledge and experience gained from empirical procedures with the real time performance, traffic loading, material properties and environmental conditions of the pavement structures. In February 2004, a recommended Mechanistic Empirical Pavement Design Guide (MEPDG) was delivered to NCHRP under project 1-37 A. This project provided a major advancement for the pavement design and directed the traditional empirical based design procedures to the mechanistic empirical based procedure which has advantages of analytical modeling capabilities and real time performance of in service pavements (Chen, Pan, & Green, 2009). Premature road pavement failures occurs when the particular road can no longer perform its traditional purpose of carrying traffic safely, conveniently and economically over its anticipated design life. Therefore the failure is defined as an unacceptable difference between the expected design life and the observed performance (Leonard, 1983). When the road failure has occurred, it is important to know the reasons for the failure, to propose the relevant rehabilitation method. There is a research that was conducted in Ghana-west Africa to investigate the causes leading to the early deterioration of the road pavement. The selected road was designed for fifteen (15) years design period but it was failed less than six months. By carried out insitu field tests and laboratory tests they have encountered that the inclusion of substandard material is one of the reason for that early failure of the road. (Achampong, Boadu, Agbeko, & Anum, 2013). In present there are several number of computer aided softwares use to analyses the pavement structures. KENLAYER is one of the popular mechanistic tools which have been used for determining the damage ratios using distress models. HDM-4 is a computer software which has been used for predicting the performance using pavement deterioration models. A research was done to compare the performance of flexible pavement using KENLAYER and HDM-4 and they found that the life of the pavement predicted by HDM-4 is less than that predicted by KENLAYER (Gedafa, 2006).

2.1 Available mechanistic tools

The elastic solution for two- and three-layer axisymmetric systems was first developed by Burmister (1943, 1945) and later extended by Mehta and Veletsos (1959) to multilayered systems. Several computer programs have been developed based on the multilayer elastic theory to solve stress conditions in pavements. The most commonly used ones are CHEVRON (Michelow 1963), BISAR (Koninklijke/Shell Laboratorium 1972) and JULIA and WESLEA developed at WES. CHEVRON is limited to a single-wheel load and the others can be used for multiple-wheel loads. The CHEVRON program was later extended by Chou (1976) and Ahlborn (1972) to account for the effect of the nonlinear properties of pavement materials on pavement responses. The BISAR program was also adopted by Baker and Brabston (1975) and Parker et al. (1979) for the design of rigid pavements. In using the layered elastic computer program, the elastic moduli and Poisson's ratio of each layer of the pavement structure are needed as input. The applied loads to the pavement are considered as static, circular, and uniform over the contact areas. The basic principle of the design procedure is to select a pavement thickness to limit the vertical strains (compressive) in the subgrade and the horizontal (tensile) strains at the bottom of the bituminous concrete induced by design vehicular traffic loads at selected levels (Chou, 1992).

2.2 CIRCLY software as a Mechanistic tool

CIRCLY is an integral component of Austroads Pavement Design Guide (2010) which is widely used in Australia and New Zealand. By comparing with the available mechanistic tools, CIRCLY have some special features. It enables to use any combination of vehicle types and load configurations, use of any wheel layout, braking or vertical loads, use any damage model, any combination of layer thicknesses and elastic modulus etc.

The system calculates cumulative damage induced by a traffic spectrum consisting of any combination of vehicle types and load groups. Most of the mechanistic pavement design methods, including the Austroads method (Austroads, 1992), typically use layered elastic analysis to calculate traffic-induced elastic strains in pavements. Then those critical strains are empirically related to the deterioration rate of the pavement which is calibrated against performance observed from the test pavement or in service pavement. The vertical compressive strain at the top of the subgrade level is related to the repetitions to cause surface rutting and the horizontal tensile strain at the underside of the asphalt and stabilized layers is related to the repetitions to cause cracking of those layers. These critical strains are referred to as 'pavement performance indicators' and the empirical performance relationships are called as 'failure criteria'. In Austroads guild they introduced two types of failure criteria, rutting and cracking. (Austroads, 2008)

Equations (1)-(10) are taken from Austroads guide, 2008.

Failure criteria is of the following form of eq. (1);

$$N = (K/\epsilon)^b \tag{1}$$

Where,
N = Allowable load repetitions to failure (predicted life)
K = material constant
ϵ = Critical strain
b = damage exponent
Damage indicators (critical stresses or strains) can be chosen as required

CIRCLY is supplied with a comprehensive range of performance models and it facilitates to use own performance models by specifying values for 'K' and 'b' and the particular component to be used as vertical strain, vertical deflection etc.

CIRCLY introduced different fatigue criterion models for asphalt, cement treated and subgrade with the same form of damage model.

Fatigue criteria for asphalt material is of the form of eq. (2);

$$N = RF (K/\epsilon)^5 \tag{2}$$

Where,
RF = Reliability Factor
K depends on the stiffness
ϵ = Horizontal tensile strain on underside of the asphalt layer

$$N = RF \left[\frac{6918 \left(0.856\, V_B + 1.08 \right)}{S_{mix}^{0.36}\, \mu\varepsilon} \right]^5 \tag{3}$$

$\mu\varepsilon$ = maximum tensile strain (in units of micro strain)
S_{mix} = asphalt mix stiffness (MPa)
V_B = volume of binder in asphalt mix (%)

Fatigue Criteria for Cement treated material:

$$N = RF \, (K/\epsilon)^{12} \tag{4}$$

K depends on modulus etc
ϵ = Horizontal tensile strain on underside of the cement treated layer

$$N = RF \left[\frac{113\,000 \big/ E^{0.804} + 191}{\mu\varepsilon} \right]^{12} \tag{5}$$

Rutting Criteria for subgrade material:

$$N = (0.0093/\epsilon)^{7} \tag{6}$$

ϵ = Vertical strain at top of subgrade

Cumulative damage factor

Cumulative damage concept does not mentioned in the Austroads flexible pavement design method, but it has been adopted in CIRCLY to presenting results in both numerically and graphically. Cumulative damage concept is required to predict the total pavement damage which is occurred through its design life. Cumulative damage factor (CDF) is calculated by summing damage factors which are induced by all of the vehicles contributes to the failure of the pavement section according to the strain imposed by the individual vehicles. Damage factor for the ith loading is defined as eq (7);

$$DF = \frac{n_i}{N_i} \tag{7}$$

Where,
n_i - Number of repetitions of the load
N_i - Allowable repetitions of the response parameter that would cause failure

Cumulative damage factor is obtained by summing the damage factors induced by all the vehicle loading in the traffic spectrum using Miner's hypothesis. The Cumulative Damage Factor is defined by eq (8):

$$CDF_{Total} = \sum_{i=1}^{LoadCases} CDF_i \tag{8}$$

Pavement has reached its design life when the CDF reaches 1 and if the CDF is less than 1 that means the pavement has excess capacity and the CDF represents the proportion of design life consumed by the design traffic. If the CDF exceed 1, pavement section fails before all of the design traffic has been applied.

The design traffic for flexible pavement design is stated in Austroads pavement design method as; the total number of Standard Axle Repetitions during the design period which causes the same damage as the cumulative traffic. As mentioned in Austroads guide, light vehicles contribute very little to the pavement deterioration therefore design traffic only accounts for heavy vehicles. Standard axle defined by the Austroads guide is a single axle with dual tyres which is applying an 80 KN load to the road pavement.

The design traffic can be calculated by eq (9):

$$N_{DT} = 365 \times AADT \times DF \times \frac{\%HV}{100} \times N_{HVAG} \times LDF \times CGF \tag{9}$$

Where,

N_{DT} = cumulative number of heavy vehicle axle groups (When axles are less than 2.1 m apart they are considered as axle group)
AADT = annual average daily traffic
DF = direction factor
%HV = percentage of traffic that are heavy vehicles
N_{HVAG} = average number of axle groups per heavy vehicle
LDF = lane distribution factor
CGF = cumulative growth factor

AUSTROADS uses a factor called the Standard Axle Repetitions (SARs) to provide a measure of the damage caused to the road in terms of a standard axle. The SAR is evaluated by eq (10);

$$SAR_{ilm} = \left[\frac{L_{ij}}{SL_i} \right]^m \tag{10}$$

Where,

SAR_{ijm} = number of standard axle repetitions which causes the same amount of type m damage as a single passage of axle group type I with load L_{ij}
SL_i = standard load for axle group type I
L_{ij} = load on the axle group
m = damage exponential which is specific to the mechanism of failure

Design Equivalent Standard Axles (DESA) can be obtained by N_{DT} multiplied by ESA/HVAG.

3. CASE STUDY

3.1 Selecting road and description of the failure

A road section which was failed immediately after construction was selected for the failure investigation by using CIRCLY. It is a C class road in Northern Province, which is 1.38 Km length was rehabilitated by overlaying the existing road with additional layers of sub base (type | and type ||) and ABC followed by DBST. After completion of the road surfacing, three individual locations, within first 100 m length showed longitudinal cracks followed by depression and settlement.

In accordance with the normal practice in Sri Lanka, the composition and layer thickness of pavement layers had been designed from Overseas Road Note 31 (ORN 31) which is specify as the road pavement design guide for tropical countries. This design guidelines uses subgrade strength class and traffic class in designing pavement structures. Subgrade strength class is defined according to the subgrade CBR value and traffic class is defined by the Cumulative Equivalent Standard Axles (CESA) over the design life of the pavement. For this road, design subgrade strength class is S-3 and traffic class is T-2. Selected pavement structures for the selected road section is shown in Figure 1.
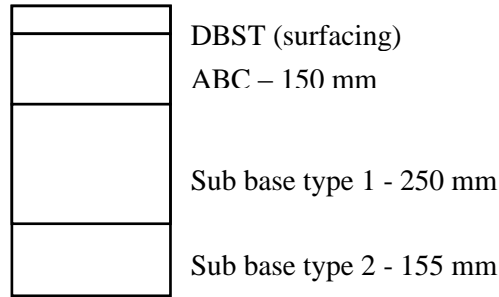
	DBST (surfacing)
	ABC – 150 mm
	Sub base type 1 - 250 mm
	Sub base type 2 - 155 mm

Figure 1: Road pavement structure *(Overseas road note 31, 1993)*

Inadequate strength has first caused to pavement cracking on the wheel path and creating potholes. After that penetrating rain water through those cracks and potholes to the underneath layers has been accelerated the damage. Abnormal heavy traffic transporting concrete sleepers and other construction materials has exaggerated the pavement damage. Designed road section for this road is in the underside of the pavement strength and it is not suitable for the frequently use of heavy vehicles. Failure location is shown in Figure 2.

Figure 2: Failure location

3.2 Investigation of material properties and field measurement

For the investigation purposes several test pits were dug near the heavily damaged areas and necessary soil testing were carried out and following results were obtained.

Table 1: Material properties of the sub base soil

Test	Upper sub base		Lower sub base		Remarks
	Tested values %	Limit specified %	Tested values %	Limit specified %	
Liquid Limit (LL)	48	<40	53	<40	Higher than specified
Plasticity Index (PI)	19	<15	22	<15	Higher than specified
CBR	4	>30	14	>15	Below specified

Passing 0.075 mm sieve	32	5 - 25	27	Not specified	Higher than specified

Results of aggregate testing (aggregate impact value, flakiness index and gradation test) are well compliance with the specifications and there is no evidence to show that the aggregate used for the pavement construction has any deterioration which is caused to the road failure. But when considering sub base material, though the Atterberg limits and fine content are within the specified limits, CBR value is lower than the specified limit in both upper and lower sub base. Stress level at the sub base is high and sub base with 4% CBR is not able to with stand for high stress level. So, road has failed due to excessive deformation at the sub base layer. Deformation of each layer was plotted in Figure 4 and 5.

Design and actual layer thicknesses are shown in Table 2 and it is revealed that the specified layer thicknesses are not encountered throughout the section.

Table 2: Design and actual layer thicknesses

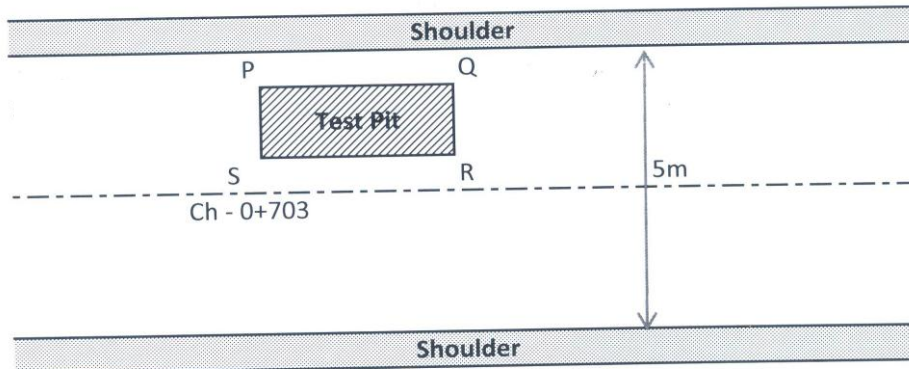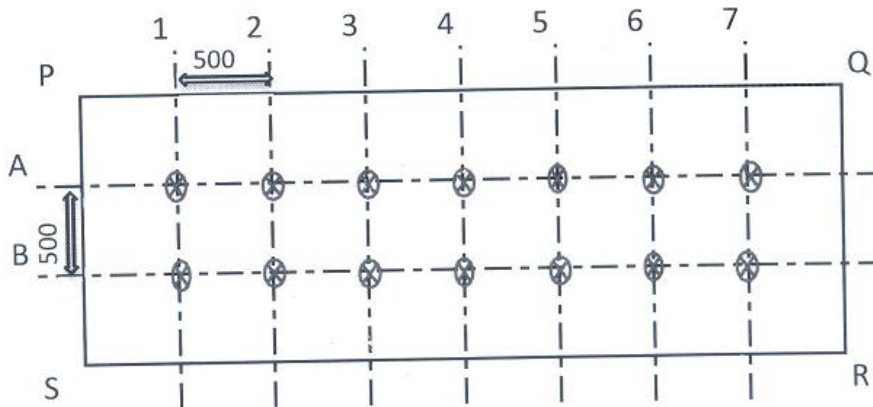| Layer	Design thickness (mm)	Actual thickness (mm)
DBST surfacing	20 – 25	20 -25
ABC	150	150
Sub base type 1	250	390
Sub base type 2	155	
Total sub base thickness	405	390

Figure 3: Layout of the test pit

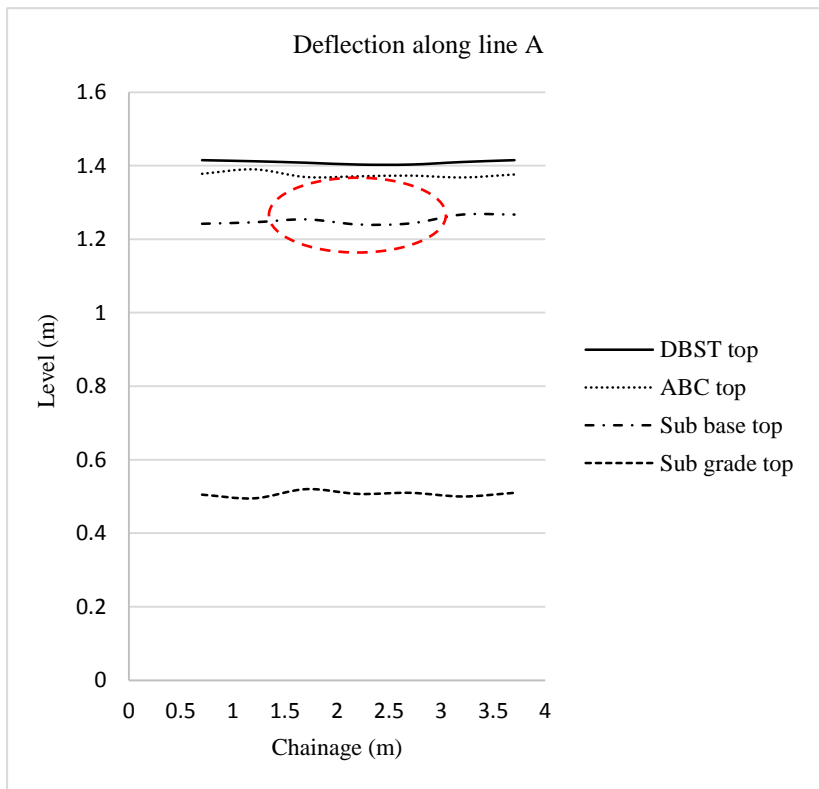Figure 4: Grid lines marked on the test pit area
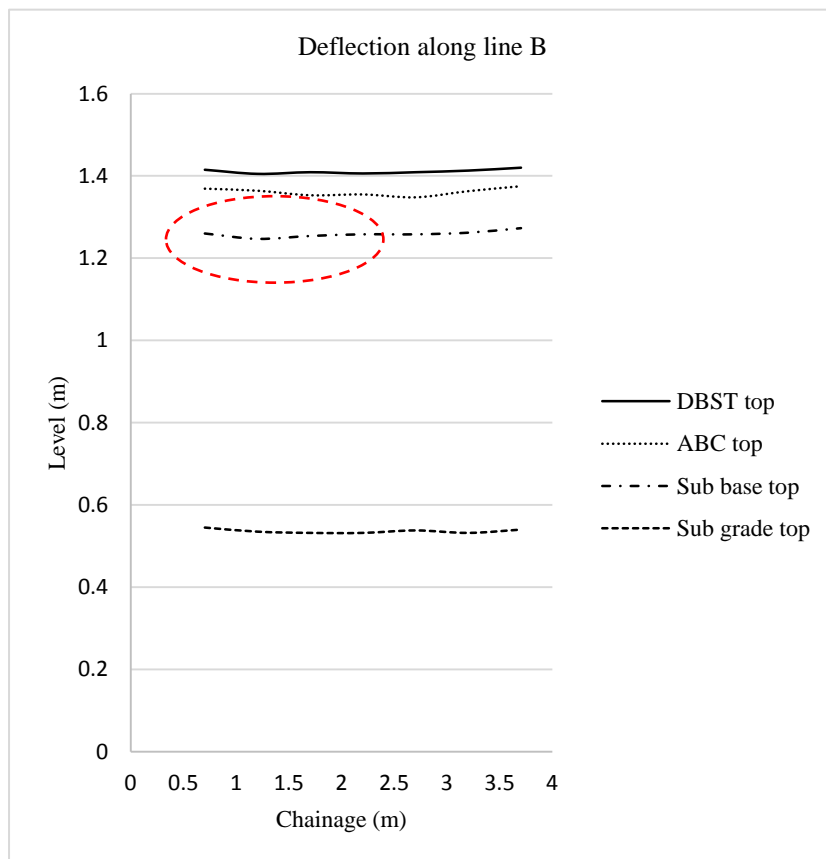
Figure 5: Cross section along grid line A

Figure 6: Cross section along grid line B

Field measurements indicates that the strength of sub base material is a substantially low and it has contributed to the low strength of the pavement structure. Vertical deflection of the individual layer for one loading cycle in CIRCLY is indicated in Figure 6 and it confirms that the sub base layer have the maximum deflection value. Abnormal heavy axle load applied on the pavement could be another reason for the failure. Therefore the pavement structure was analysed using a mechanistic tool to investigate the failure and select a suitable method for rectification.
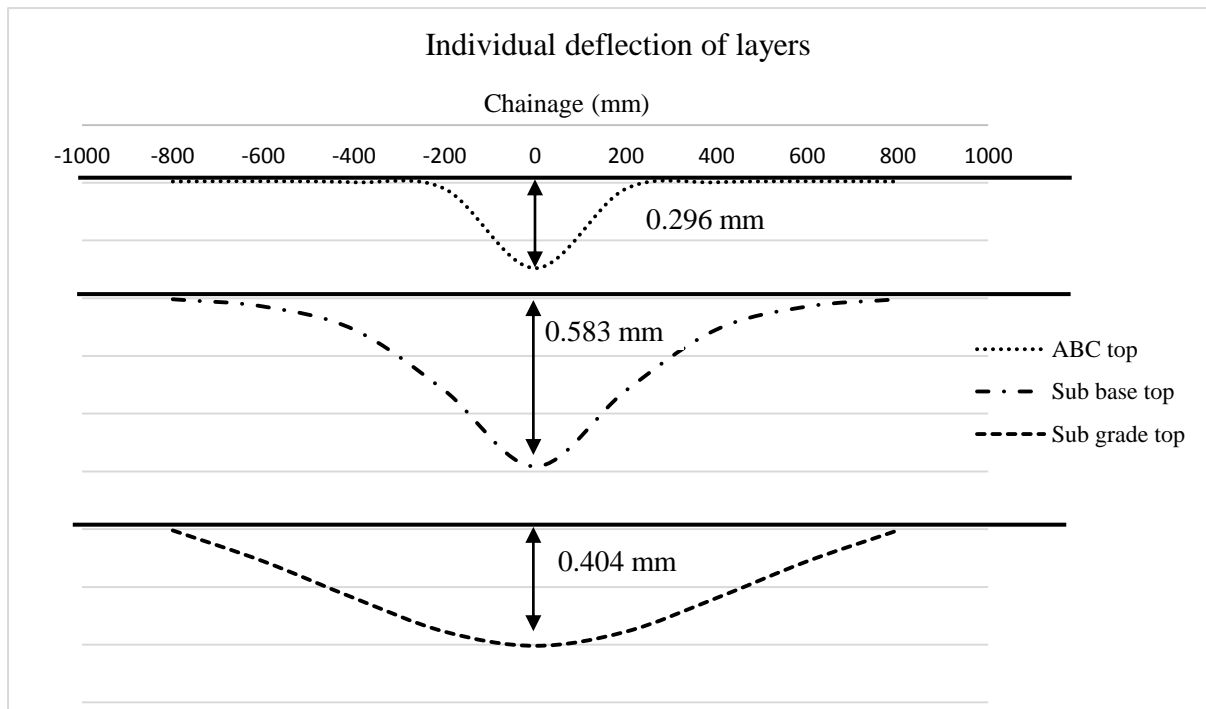

Figure 7: Individual deflection of layers (CIRCLY results)

3.3 Model development using CIRCLY

Pavement analysis model was developed using CIRCLY for both road sections. Additional heavy vehicle loading was assumed and total design traffic was calculated according to that. Two failure criteria, rutting in sub grade and fatigue cracking in DBST layer were considered.

Design material properties (Modulus of elasticity) (huang, 2009)**:**

DBST   - 1035 MPa
ABC   - 193.2 MPa
Upper sub base   - 34.5 MPa
Lower sub base   - 81.42 MPa
Sub grade   - 34.5 MPa

Failure criteria:

Sub grade: K= 0.0093

DBST   K= 0.0044
        [V_B %   = 11 (Asphalt content)]

Design Parameters – Traffic

Particular road has been used for transport of construction materials for the nearby railway construction site. Therefore overloaded trucks were recently used this road. A heavy truck with sand loaded was considered as the design vehicle for this road. According to the axle load survey data, gross weight of an overloaded truck would be around 22 tons. For the axle load configuration, front and rear axle weight were considered as 6 tons and 16 tons respectively. The allowable limit for a two axle (6 wheel) truck is 15.275 tons as per the motor traffic act.

For the analysis, 30 number of trucks were assumed per day in the road and design traffic was estimated using 5% of heavy vehicle growth rate.

 Design Parameters (RN 31)

Design Period (years)	= 10
Annual Average Daily Traffic (AADT)	= 30
Direction Factor (DF)	= 0.5
Percentage heavy vehicles	= 100%
Lane distribution factor (LDF)	= 1
Cumulative Growth Factor (CGF)	= 12.56
Number of heavy vehicle axle groups (N_{HVAG})	= 2
Heavy vehicle growth rate (compound)	= 4.97

N_{DT} =   137,535.22

DESA (Movements) = 1,124,633.13

Design Period (years)	Movements
5	494,461.74
10	1,124,633.13

Sample ESA	= 17.98
ESA (per day)	= 539.29
ESA(design life=10)	= 2,472,373.59
DESA	= 1,236,186.80

4. RESULTS

(CIRCLY 5.0 user manual, 2012)

Table 3: Damage ratios for 10 years design traffic

	Specified design				Actual design			
	Layer thickness (mm)	Good material		Poor material		Layer thickness (mm)	Good material		Poor material	
		CBR %	Damage Ratio	CBR %	Damage Ratio		CBR %	Damage Ratio	CBR %	Damage Ratio
DBST	25					25				
ABC	150	80		80		150	80		80	
Sub base - Upper	250	30	6.51E-02	4	6.14E+00	250	30	6.78E-02	4	6.19E+00
Sub base - Lower	155	15	2.85E-02	14	4.53E-02	140	15	3.72E-02	14	5.73E-02
Sub grade		4	5.24E-01	4	9.90E-01		4	6.85E-01	4	1.26E+00

According to the table 3, it can be seen that the upper sub base with poor materials will fail when the ten years traffic is applied on the road pavement. But the actual design thickness of the lower sub base is lower than the design thickness, therefore the actual road section will fail due to the failure in both upper sub base and subgrade.

Then analysis was done to investigate the section's behavior after two years. Results shown in table 4.

Results in table 4 shows that the design life of the road section is less than two years when the same traffic is applied on the road.

Table 4: Damage ratios for 2 years design traffic

	Layer thickness (mm)	CBR %	Damage Ratio	Layer thickness (mm)	CBR %	Damage Ratio
DBST	25			25		
ABC	150	80		150	80	
Sub base - Upper	250	4	1.00E+00	250	4	1.01E+00
Sub base - Lower	155	14	7.99E-03	140	14	9.35E-03
Sub grade		4	1.75E-01		4	2.06E-01

4.1 Analysis of proposed design

Proposed ABC thickness was calculated by using the design thickness facility supplied by CIRCLY, such that the pavement section will not fail even after the ten year design traffic applied on the road.

Table 5: Damage ratio for the proposed design (for 10 years design traffic)

	Layer thickness (mm)	Proposed Layer thickness (mm)	CBR %	E (MPa)	Damage Ratio
DBST	25	25		1,035.00	
ABC	150	*212.39*	80	193.20	
Sub base - Upper	250	250	4	34.50	9.87E-01
Sub base - Lower	140	140	14	81.42	1.07E-02
Sub grade			4	34.50	2.40E-01

4.2 Recommended design for 10 Years Traffic

Recommended ABC thickness for 10 years traffic for the RN 31 design and as built design with poor materials are shown in Table 5. It can be seen that 212.5mm ABC layer is required. Currently 150mm of ABC is available. So it is proposed to increase the layer thickness by 75mm. However, 75 mm layer is not recommended since the maximum aggregate size of ABC is 37.5mm. Therefore it is proposed to introduce 150mm of new layer for the rectification of the road section.

Individual deflections of layers for the actual and the proposed design is shown in Table 7 (CIRCLY results). Surface deflections of sub base and sub grade were decreased after introducing the new layer of ABC.
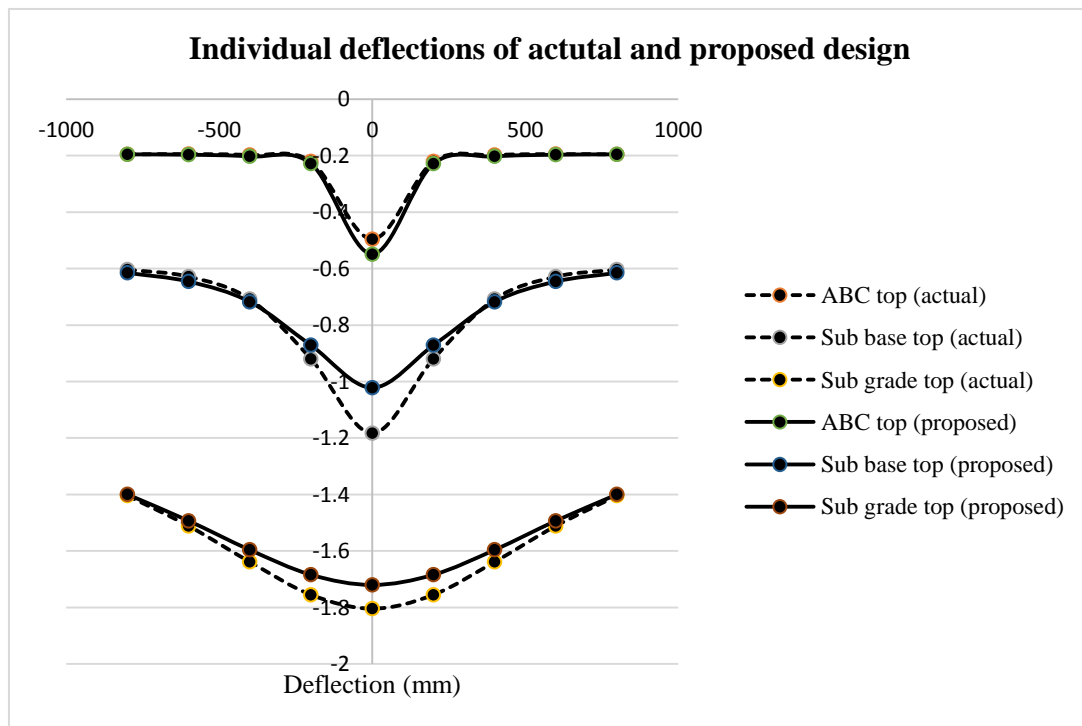

Figure 8: Individual deflections of actual and proposed design

5. DISCUSSION

In TRL RN 31 design, pavement structures are designed using the subgrade CBR value and the Cumulative Design ESA value. In this design guideline basic soil properties as Atterberg limits and maximum dry density are also considered. But the elastic modulus of the materials are not considered as main input. But in AASHTO design procedures, Structural Number (SN) is calculated using elastic modulus and layer thicknesses. In mechanistic approach, pavement performance is evaluated based on physical phenomena as strain, stress and deflection. Calculated results greatly depend on the elastic modulus of the materials specially the asphalt. Elastic modulus of the bitumen is very much sensitive to the temperature. The mechanistic tool CIRCLY facilitates to analyse the pavement structures by dividing the same layer in to any number of sub layers with applying different elastic modulus values. So it is very important that the analysis to be carried out considering the seasonal variations rather than getting the same properties throughout the year. Because material properties, specially the elastic modulus values depend on the temperature. For the analysis, modulus values were obtained from the charts developed by "pavement design by Young hung". A local road situated in Northern Province was considered in this study. In there the ambient temperature is much higher throughout the year. Therefore the consideration of the temperature dependency is much important.

Layer thicknesses should be changed according to the available material properties when the substandard material is used. But the RN 31 does not facilitate to alter the layer thicknesses consistent with the material properties. Therefore the mechanistic tool CIRCLY was used to analyse road failures based on Cumulative Damage Factor. This tool enables to use available materials and we can get design thicknesses using thickness design facility of the software.

6. CONCLUSION

Pavement failure was observed in Sri Lankan provincial road which failed immediately after construction. This road was constructed using RN 31 design guide. Soil tests, Atterberg test and CBR test were conducted for the soil samples which were collected from the field. According to that test results and field deflection measurements, it was found that the CBR value of the sub base material is less the specified material and also the sub base soil layer has excessive surface deflection. Therefore it can be shown that the road has failed as the results of using lower strength sub base material. Same failure was analysed using a mechanistic tool, CIRCLY and it was also revealed that using lower strength material is the caused for the failure. Two sub base layers, upper sub base with 4% CBR and lower sub base with 14% CBR were also considered in the CIRCLY model as the actual design. According to the damage ratio, CIRCLY showed that the road has not failed when using the actual layer thicknesses with specified materials for the higher design traffic. But when using the poor materials damage ratio of the sub base layer is greater than 1. That means the road was failed due to the use of poor materials. Individual deflections of all layers for the one loading cycle in CIRCLY is shown that the maximum deflection has observed in sub base layer. This also indicates that the strength of sub base material is a substantially low and it has contributed to the low strength of the pavement structure.

When proposing the suitable rehabilitation method it is important to know whether the proposed design is strong enough to withstand the higher design traffic. Therefore the proposed design should be analysed to confirm it. CIRCLY has a facility to design the layer thickness of the relevant material which is required to prevent any failures. CIRCLY provides the proposed layer thickness which is required to get the damage ratio equals 1. For the particular provincial road, CIRCLY has introduced another ABC layer of 62.39 mm thick, as the rectification method. So it is proposed to increase the layer thickness by 75mm. However, 75 mm layer is not recommended since the maximum aggregate size of ABC is 37.5mm. Therefore it is proposed to introduce 150mm of new layer for the rectification of the road section. Deflection values which were taken from the CIRCLY analysis also proved that the deflection of the surface of sub base and sub grade was decreased after introducing the new layer of ABC.

Mechanistic tool, CIRCLY can be used to investigate the road failures. If the cause for the failure is low strength of the pavement structure or unbearable traffic load, this software can be determine which the actual reason for the failure is.

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