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Road pavement defect investigation using treated and untreated expansive road subgrade materials with varying plasticity index

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ABSTRACT

Road pavement defect has been a major issue in the construction industry leading to a high cost of maintenance and sometimes a total reconstruction of the road. Expansive road subgrade materials are one of the major causes of these road defects. In this study subgrade materials with varying plasticity index were formulated at a ratio of 25% bentonite + 75% kaolinite, 35% bentonite + 65% kaolinite and 75% bentonite + 25% kaolinite respectively. Cement and lime were used as binders to improve the engineering properties of these expansive subgrade materials to make them usable in road construction. A road pavement defect analysis was conducted to investigate the effect of varying California Bearing Ratio (CBR) and traffic load on treated road subgrade in terms of failure. Atterberg limit, compaction, characteristics, mineral structure, California Bearing Ratio (CBR), Swell and microstructural properties (Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX)) of the subgrade were also investigated in this study. The results show an increase in CBR value with a reduction in swell values translating to lesser stresses within the pavement structure which reduced rutting, fatigue and permanent deformation of the road. The study concluded that the service life of the pavement can be prolonged by reducing road pavement defects using cement and lime as binders in subgrade stabilisation.

1. Introduction

Layers of processed materials placed over the natural ground (subgrade) are referred to as road pavement. Road pavements distribute traffic load to the subgrade providing skid resistance, low noise and smooth riding. Most times, road pavement defects occur as a result of destress developed in the pavement under the combined effect of traffic loading, environmental conditions and geotechnical issues due to expansive subgrade [1]. The strength of road subgrade can be investigated by conducting California Bearing Ratio (CBR) test on the subgrade material. The California Bearing Ratio (CBR) of road subgrade can influence the overall thickness and depth of construction of the road pavement which greatly impacts the cost of construction [2] and [3]. According to Amakye et al., 2021 [4] road pavement defects are a result of expansive subgrade and the process of maintaining or repairing the pavement comes with a huge cost. The US and China incurred a cost of $US30 billion as maintenance costs due to expansive subgrade [5]. The damage caused by expansive subgrade rums into millions of dollars and the UK spent more than £3 billion on infrastructural damages caused by expansive soils [6] and [7]. Other studies have used binders such as Construction and Demolition Waste (CDW) [8,9,10,11] and [12] Crashed glass waste [13], waste ceramic tiles and zinc-coated steel milling waste [14] and [15], and recycled construction and demolition materials in road pavement subgrade [16].

However, in this study, Cement and lime were used as binders in subgrade stabilisation due to their ability to improve the engineering properties of subgrade materials. Portland cement and lime over the years have been used in subgrade stabilisation due to the ability to form Calcium Silicate Hydrate (C-S-H) gel responsible for strength gain [17]. Calcium Silicate Hydrate (C-S-H) gel act as a binding agent which binds subgrade particle together [3]. Cement and lime are suitable for subgrade stabilisation and a cement range of 4% and 15% was used to enhance the engineering properties of subgrade materials [18] and [19]. Using lime as a binder with the help of calcium releases a cementitious product called Calcium Silicate Hydrate (C-S-H) gel which can stabilise subgrade materials with plasticity index between 20% and 30% and a liquid limit from 25% to 50% [20] and [21]. Ingles et al., (1972) [22] achieved good California Bearing Ratio (CBR) and swell values using 80% lime in subgrade treatment and 3% – 8% lime to improve high plasticity index clays. 1%, 4% and 6% lime proportions were used in

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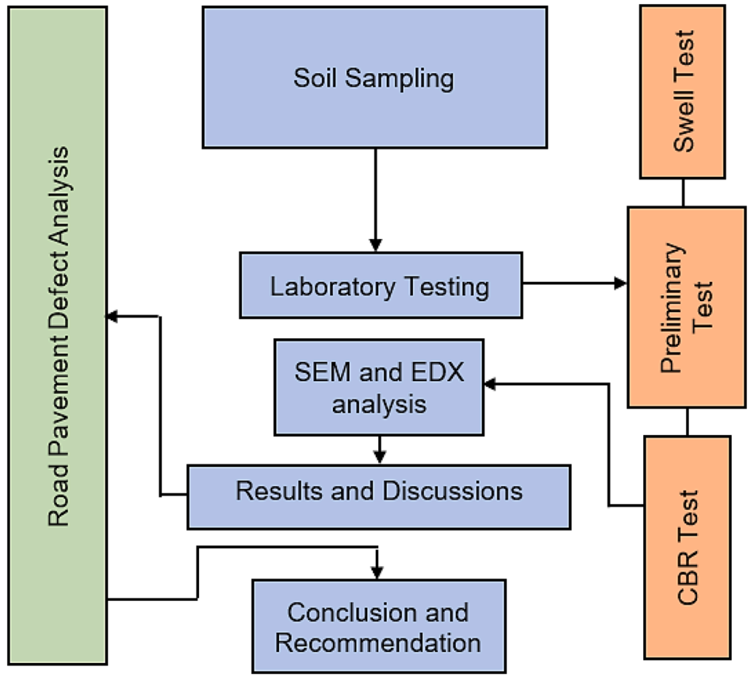


Fig. 1. Methodological process used in this study.

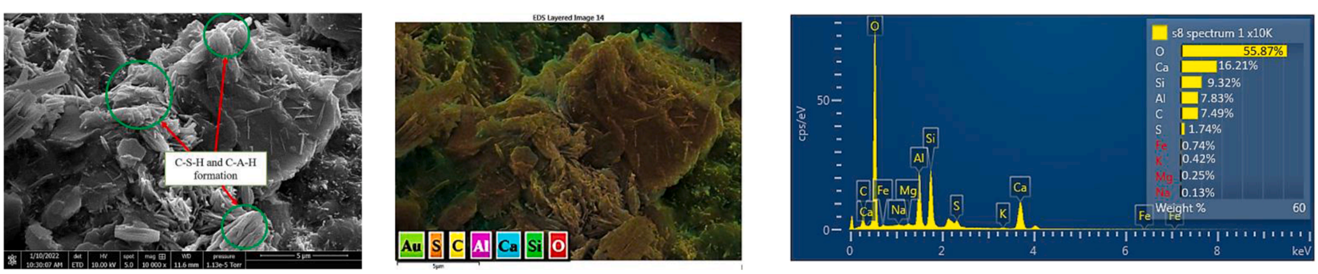


Fig. 2. SEM image, Map and EDX results for ASS1 after 7 days of curing.

various studies for subgrade treatment to achieve good performance [23,24] and [25]. The inclusion of cement increased the bearing capacity of subgrade materials during stabilisation at proportions of 10%, 15% and 20% by weight of soil. In this study road pavement defect analysis was conducted using varying design traffic load and California Bearing Ratio (CBR) values achieved in this study to determine their effect on the durability of the road pavement structure. The study seeks to explore the area of road pavement defects by investigating the causes of road pavement defects. The study investigated the factors responsible for these defects and attempt to eliminate or reduce these defects for road pavement with stabilised high plasticity index subgrade materials using chemical stabilisation techniques.

2. Materials and methods

Bentonite and kaolinite were used in this study to form subgrade materials with varying plasticity index. These Artificially Synthesised Subgrade (ASS) materials were referred to in this study as ASS 1 (25% bentonite + 75% kaolinite) high plasticity index subgrade, ASS 2 (35% bentonite + 65% kaolinite) very high plasticity index subgrade and ASS 3 (75% bentonite + 25% kaolinite) extremely high plasticity index subgrade respectively. These subgrade materials were treated using cement and lime to improve their engineering properties in accordance with relevant standards. The standards used in sample preparation, testing, details of suppliers, material oxide, mineralogical composition, chemical composition and particle size distribution of the materials used are as reported in the authors' previous study [2]. Atterberg and compaction tests were conducted on untreated subgrade materials and California Bearing Ratio (CBR) and swell test was conducted on treated and untreated subgrade materials. The study also conducted microstructural properties (Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX)) for treated subgrade materials to determine the effect of the binder after treatment. The study analysed the occurrence of a potential defect within road pavement using California Bearing Ratio (CBR) values achieved in this study and adopted design traffic loads. KENPAVE software was used to analyse stresses at various response points within the road pavement layers. Fig. 1 show the methodology used in this study.

3. Results and discussion

3.1. California Bearing Ratio (CBR) and Microstructural Properties

Artificially Synthesised Subgrade (ASS 3) composed of high bentonite content achieved the highest CBR value for untreated subgrade materials soaked and unsoaked at 9% and 2% and Untreated ASS 1 and ASS 2 recorded CBR values of 0.9%, 5% and 0.8% for untreated soaked respectively. The CBR values achieved for untreated soaked subgrade materials are unacceptable for use in road construction. According to Amakye et al. [2,26], California Bearing Ratio (CBR) values <2% are unacceptable for use in road construction. California Bearing Ratio (CBR) values achieved for treated subgrade materials both soaked

Fig. 3. SEM image, Map and EDX results for ASS2 after 7 days of curing.

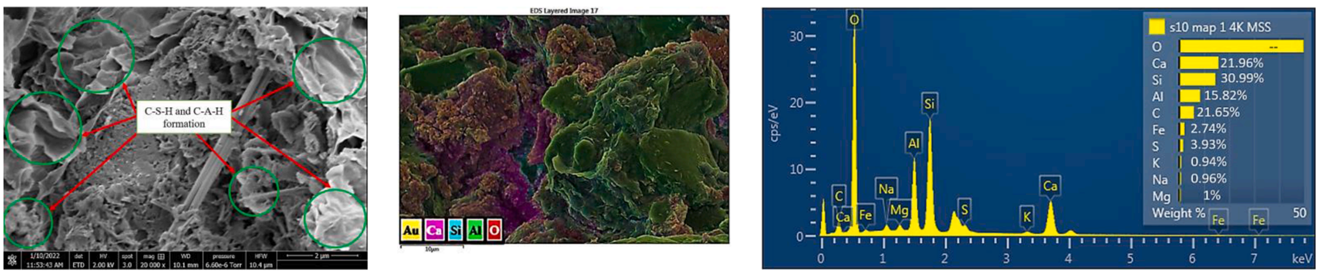


Fig. 4. SEM image, Map and EDX results for ASS3 after 7 days of curing.

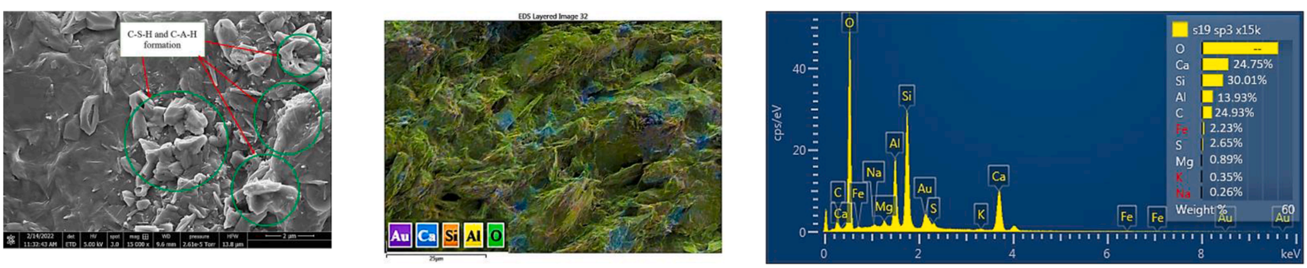


Fig. 5. SEM image, Map and EDX results for ASS1 after 28 days of curing.

Fig. 6. SEM image, Map and EDX results for ASS2 after 28 days of curing.

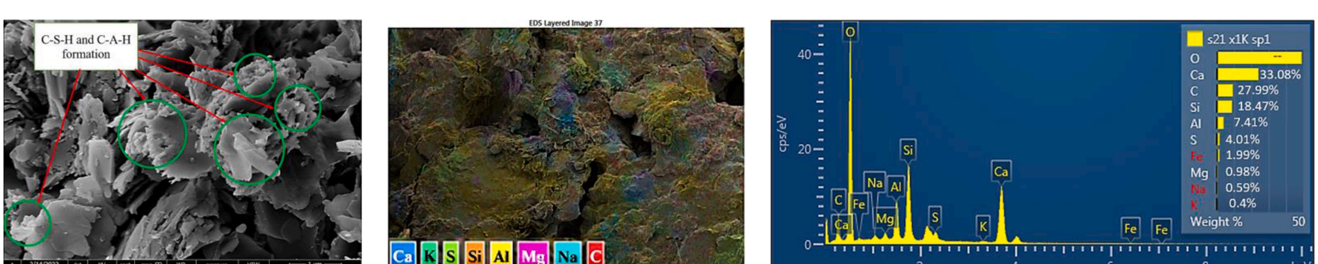


Fig. 7. SEM image, Map and EDX results for ASS3 after 28 days of curing.

Table 1
Selected CBR values used in defect analysis.

Subgrade Type	Mix Design	Treated	Soaked	Curing days	CBR (%)
ASS 1	(25%B + 75% K)	x	x	0	8
ASS 2	(35%B + 65% K)	x	x	0	5
ASS 3	(75%B + 25% K)	x	x	0	9
ASS 1	(8%L + 20% C)	√	x	7	80
ASS 2	(8%L + 20% C)	√	x	7	60
ASS 3	(8%L + 20% C)	√	x	7	30
ASS 1	(8%L + 20% C)	√	√	7	50
ASS 2	(8%L + 20% C)	√	√	7	40
ASS 3	(8%L + 20% C)	√	√	7	30
ASS 1	(8%L + 20% C)	√	x	28	90
ASS 2	(8%L + 20% C)	√	x	28	100
ASS 3	(8%L + 20% C)	√	x	28	80

Where B = Bentonite K = Kaolinite L= Lime and C = Cement

and unsoaked are greater than 2% and suitable for use in road construction. Further details on California Bearing Ratio (CBR) results are as reported in the authors' previous study [2]. The high CBR achieved for the treated subgrade in this study was a result of the formation of calcium silicate hydrate (C-S-H) gel during the hydration process of cement and lime. A gradual increase in CBR value and a reduction in swell was observed with an increase in curing age. Scanning microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis conducted on treated subgrade samples showed an obvious formation of C-S-H gel in the mix. The EDX results show an increase in the formation of calcium (Ca) responsible for the formation of calcium silicate hydrate (C-S-H) gel for strength gain in the mix as curing age increases. At the end of curing day 7, EDX for ASS 1 reported a formation of 16.21% Calcium (Ca), 30.51% Calcium (Ca), for ASS 2 and 21.96% Calcium (Ca) for ASS 3. At the end of 28 days of curing, Calcium (Ca) formation increased drastically from 16.21% Calcium (Ca), for ASS1 to 24.75% Calcium (Ca), and 30.51% Calcium (Ca) to 32.56% Calcium (Ca) for ASS 2 and from 21.96% Calcium (Ca), to 33.08% for ASS 3 respectively. Fig. 2–7 show detailed results for SEM and EDX achieved in this study for selected subgrade

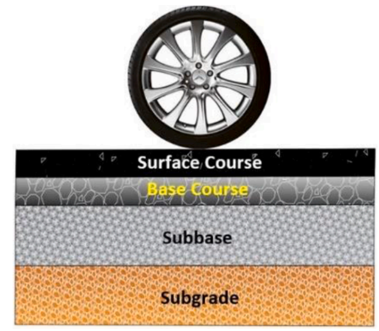


Fig. 9. Three-layer flexible composite pavement structure.

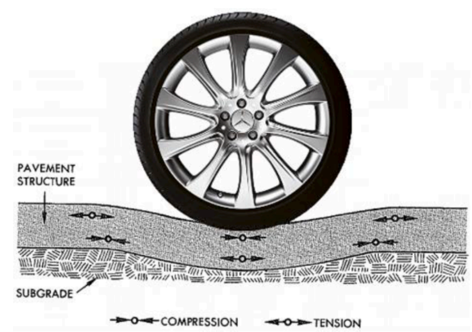


Fig. 10. Pavement deflection in tensile and compressive stress in a pavement structure [31].

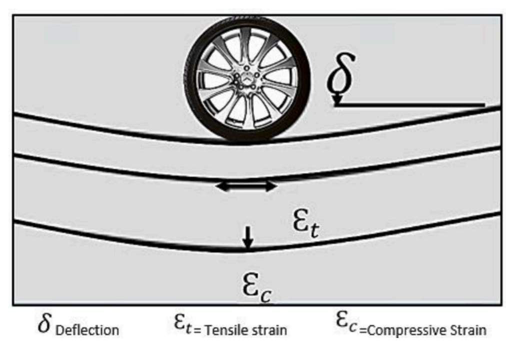


Fig. 11. Types of stress within a road pavement structure.

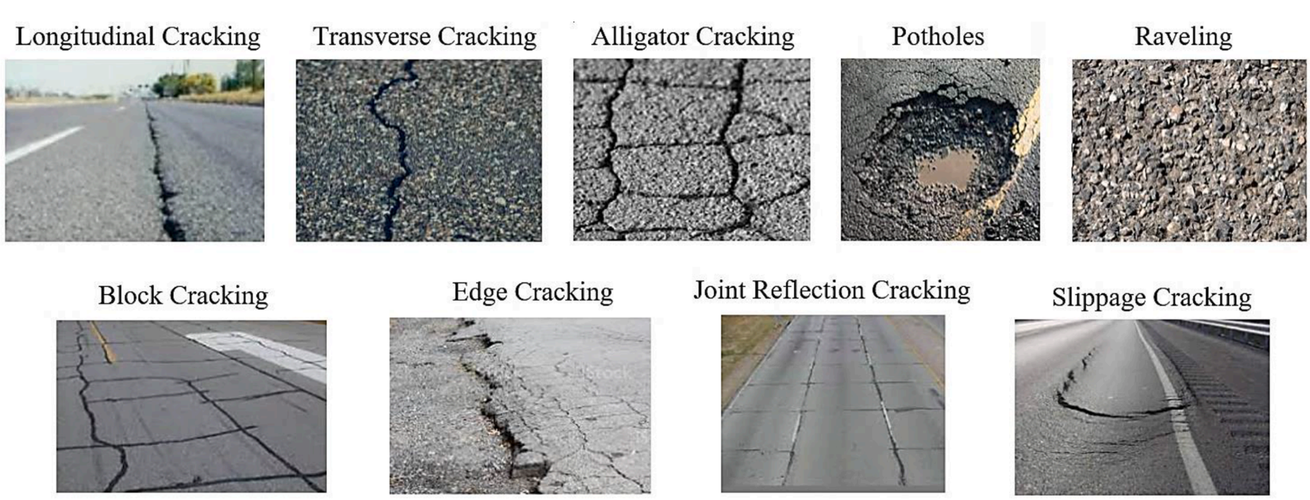


Fig 8. Types of road pavement failures [35–43].

ASS 1 Untreated -Unoaked -Light Traffic- Subgrade CBR 8% - Design Traffic 30msa				
Flexible Pavement Layers	**Material**	**Thickness (mm)**	**Elastic Modulus MPa**	**Poisson's Ratio**
Surface Course	TSCS	40	1350	0.35
Binder Course	DBM50	60	250	0.35
Subbase	DBM50	170	165	0.35
Subgrade CBR 8%	ASS	∞	67	0.4
Total pavement thickness		270		
NOTE: TSCS = Thin Surface Course System ASS = Artificially Synthesised Subgrade ASS				

Fig. 12. properties of flexible pavement layers used in this study.

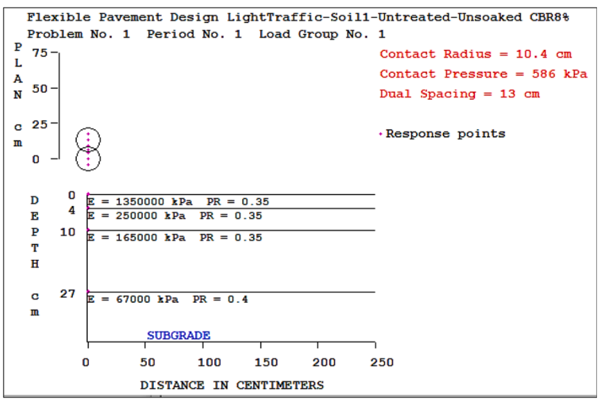


Fig. 13. KENPAVE analysis results.

materials used in defect analysis. Table 1 shows selected CBR values used in defect analysis in this study.

4. Road pavement defect analysis

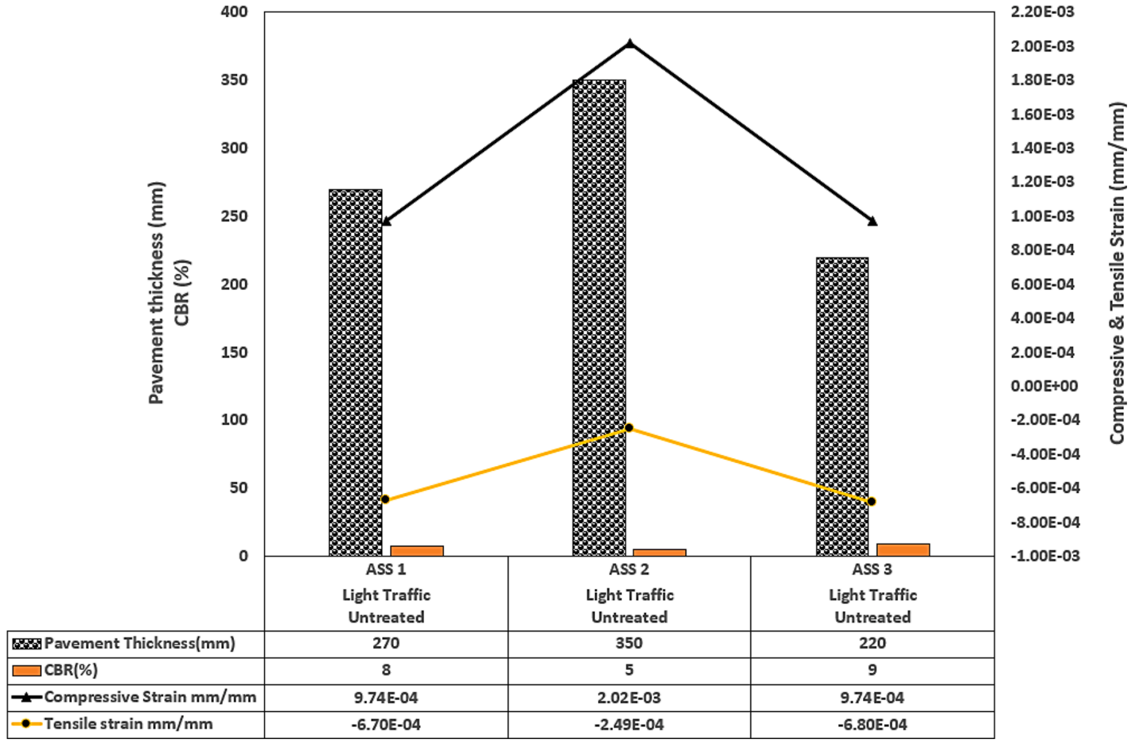
Defect analysis in this study was conducted to establish the durability of road pavement structures using varying California Bearing Ratio (CBR) values achieved in this study. Subgrade California Bearing Ratio (CBR) values of a road pavement whether high or low would determine the stress and strain behaviours within the road pavement structure [27]. The intensity of these stress and stains can cause fatigue failure and would determine the type of road pavement defect that would occur in the pavement structure and how long it would take for these defects to occur. Some of these rod pavement defects include the occurrence of fatigue, rutting and deformation in the pavement structure. Fatigue refers to the ability of an object or material to withstand concentrated stresses before it fails completely [27]. Rutting refers to the surface or longitudinal depression that occurs in the wheelpaths of flexible pavement and deformation is the change in a road surface from the originally intended profile. In this study, fatigue, rutting and permanent deformation analyses were conducted to determine the effect of varying CBR values and traffic loads and how they affect the pavement structure [27]. KENPAVE software was used to determine the stresses within the pavement structure based on the subgrade California Bearing Ratio (CBR) values achieved in this study [28]. KENPAVE provides a solution for elastic multilayer pavement systems under circular loaded areas [29]. The software is designed to analyse different wheel configurations under linear elastic, nonlinear elastic and visco-elastic layer behaviours. KENPAVE software was used to analyse a three-layer pavement system underneath the asphalt layer and the vertical compressive strain on the top of the subgrade. The loaded areas were determined using the same radius and contact pressure (tyre inflation pressure). Materials adopted for the various layers include a bituminous surfacing material - Thin Surface Course System (TSCS), granular base and subbase material - Dense Macadam Binder and subbase Course (DBM50) respectively. The subgrade CBR values achieved for high plasticity subgrade stabilised using cement and lime were used in the analyses to see the effect of stabilised or treated high plasticity subgrade material on road pavement fatigue, rutting and permanent deformation.

A traffic design of 30msa (million standard axils) for light traffic and 80msa for Heavy traffic were adopted with a single axle dual wheel load configuration. A contact radius of 10.4cm and contact pressure of 586KPa on a circular loaded area was adopted. The pavement was assumed to behave as a linear elastic structure with Poisson's ratio of 0.35 for all layers and Poisson's ratio of 0.4 for the subgrade. The critical stress and strain are estimated in the pavement layers at radial distances of 13cm away from the centre of the wheel load. Vertical compression strain above the subgrade and tensile strain at the bottom of the bituminous layer were considered to be the critical conditions for the pavement system. Resilient modulus MR1, of the bituminous layer, was considered to be 1350MPa as used for a standard UK asphalt material at temperatures 20°C and 5Hz in accordance with DMRB CD 226 [30]. Resilient modulus of the subgrade, subbase and base were estimated using CBR values of Artificially Synthesised Subgrade (ASS) materials achieved in this study and were calculated using Eqs. (1), (2) and (3) (IRC, [31]). Resilient modulus refers to a measure of elastic behaviour of pavement under repeated loadings and helps in characterising different materials used in the construction of pavement under simulated field conditions. Values for long-term elastic stiffness modules 4700MPa of standard UK asphalt material Dense Macadam Binder (DBM50) used in the analytical design were adopted in accordance with DMRB [32]. Eqs. (4), (5) and (6) used by Asphalt Institute and IRC [31] were adopted to calculate the allowable load repetition for fatigue, permanent deformation and rutting life of the road pavement. Repeated loading refers to the number of loading required to initial fatigue crack. Before fatigue crack can be initiated, three basic factors are required (i) The loading pattern must contain minimum and maximum peak values with large enough variation or fluctuation [27]. The peak values may be in tension or compression which may change over time but the reverse loading cycle must be sufficient to initiate a crack [27]. (ii) peak stress must be very high, if peak stresses are low they may not initiate crack [27] (iii) the materials must experience a sufficiently large number of cycles of the applied stress [27]. So the higher the stress concentration the more likely a crack may initiate [12,27]. Fatigues are usually associated with tensile stresses but fatigue crakes have been reported due to compressive loads, hence the greater the applied stress range, the shorter the life [33]. Observations after carrying out pavement damage analysis on selected treated and untreated ASS materials from this study are as follows;

Table 2
Pavement details and response for actual tyre contact area for selected subgrade materials.

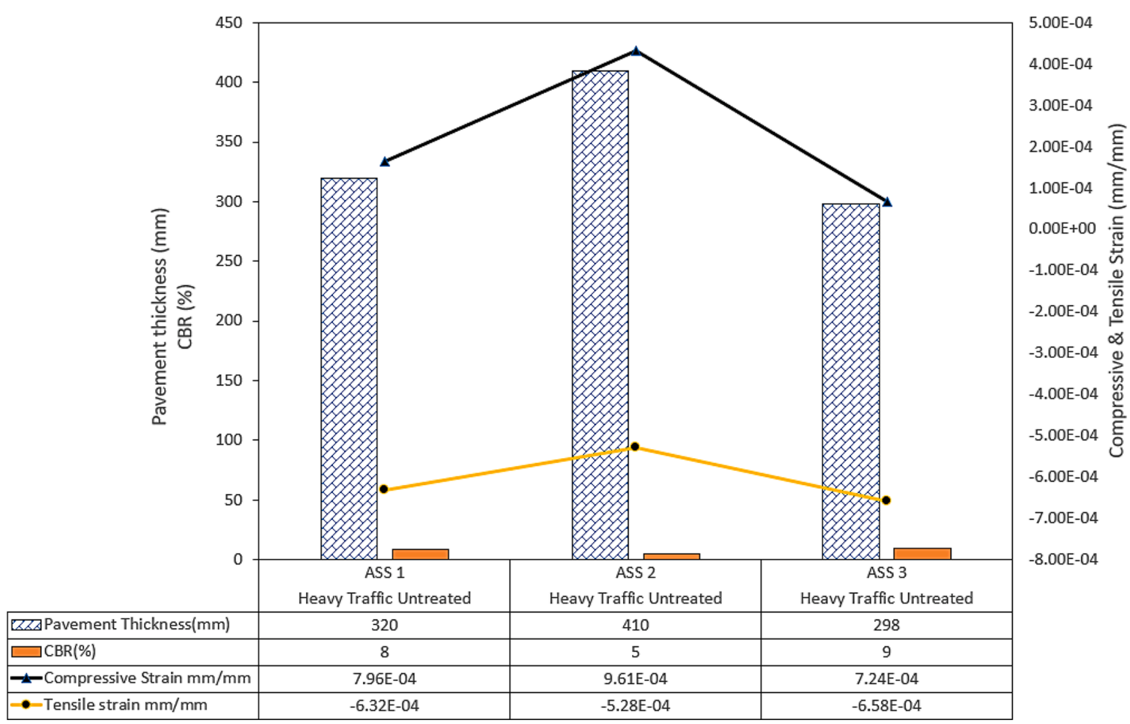
Subgrade Type	CBR (%)	Pavement Thickness (mm)	Design Traffic (msa)	Traffic Type	Tyre Inflation Pressure (kPa)	Radius of circular Contact A0rea (cm)	Tensile Strain (ε_t)	Compressive Strain (ε_c)	Allowable Load Repetition for Fatigue Prediction	Allowable Load Repetition for Permanent Deformation Prediction	Allowable Load Repetition for rutting Life Prediction
ASS 1-Untreated	8	270	30	Light	586	10.4	6.70E-04	9.74E-04	5.22E+06	2.34E+06	3.04E+06
ASS 1-Untreated	8	320	80	Heavy	586	10.4	6.32E-04	7.96E-04	5.70E+06	8.53E+05	8.62E+06
ASS 2-Untreated	5	350	30	Light	586	10.4	2.49E-04	2.02E-03	4.71E+06	4.15E+04	1.71E+06
ASS 2-Untreated	5	410	80	Heavy	586	10.4	5.28E-04	9.61E-04	4.99E+06	1.56E+05	2.30E+06
ASS 3-Untreated	9	220	30	Light	586	10.4	6.80E-04	9.74E-04	4.89E+06	7.28E+06	2.59E+06
ASS 3-Untreated	9	298	80	Heavy	586	10.4	6.58E-04	7.24E-04	5.82E+06	1.19E+06	1.09E+07
ASS 1-Treated- 7 days curing	80	50	30	Light	586	10.4	5.58E-05	1.39E-03	1.07E+12	8.35E+03	3.70E+05
ASS 1-Treated- 7 days curing	80	60	80	Heavy	586	10.4	4.46E-05	1.82E-03	1.38E+12	2.45E+04	1.10E+06
ASS 2-Treated- 7 days curing	60	70	30	Light	586	10.4	1.66E-05	2.05E-03	2.06E+11	9.92E+02	4.28E+04
ASS 2-Treated- 7 days curing	60	90	80	Heavy	586	10.4	2.27E-05	3.30E-03	9.79E+10	2.52E+03	1.10E+05
ASS 3-Treated- 7 days curing	30	120	30	Light	586	10.4	2.60E-06	2.24E-03	6.76E+10	7.00E+01	1.07E+03
ASS 3-Treated- 7 days curing	30	150	80	Heavy	586	10.4	1.21E-05	3.56E-03	4.71E+09	5.50E+02	7.92E+04
ASS 1-Treated-Soaked-7days curing	50	80	30	Light	586	10.4	5.61E-04	8.92E-04	1.00E+12	6.14E+04	2.79E+06
ASS 1-Treated-Soaked-7days curing	50	100	80	Heavy	586	10.4	2.25E-04	1.83E-03	2.33E+11	2.44E+03	1.43E+06
ASS 2-Treated-Soaked-7days curing	40	105	30	Light	586	10.4	3.04E-05	1.99E-03	1.24E+11	1.68E+03	7.29E+04
ASS 2-Treated-Soaked-7days curing	40	120	80	Heavy	586	10.4	3.21E-05	1.73E-03	1.18E+10	3.20E+03	1.40E+05
ASS 3-Treated-Soaked-7days curing	30	120	30	Light	586	10.4	1.66E-05	2.05E-03	3.05E+10	1.47E+03	6.38E+04
ASS 3-Treated-Soaked-7days curing	30	150	80	Heavy	586	10.4	1.21E-05	1.76E-03	2.17E+07	5.07E+03	7.92E+04
ASS 1-Treated-28 days curing	90	48	30	Light	586	10.4	6.47E-05	2.23E-03	1.03E+10	1.02E+03	4.41E+04
ASS 1-Treated-28 days curing	90	50	80	Heavy	586	10.4	6.01E-05	2.18E-03	1.31E+10	1.14E+03	4.91E+04
ASS 2-Treated-28 days curing	100	30	30	Light	586	10.4	4.10E-04	1.78E-03	2.25E+10	2.80E+03	1.22E+05
ASS 2-Treated-28 days curing	100	30	80	Heavy	586	10.4	4.10E-04	1.78E-03	2.25E+10	2.80E+03	1.22E+05
ASS 3-Treated-28 days curing	80	50	30	Light	586	10.4	5.58E-05	2.39E-03	2.62E+09	7.41E+02	3.18E+04
ASS 3-Treated-28 days curing	80	60	80	Heavy	586	10.4	4.46E-05	2.10E-03	1.04E+10	1.34E+03	5.82E+04

Where **ASS** = Artificially Synthesised Subgrade. **msa** = million standard axils
ASS 1= (25% Bentonite + 75% Kaolinite) High Plasticity, **ASS 2**= (35% Bentonite + 65% Kaolinite) Very High Plasticity, **ASS 3**= (75% Bentonite + 25% Kaolinite) Extremely High Plasticity



	ASS 1 Light Traffic Untreated	ASS 2 Light Traffic Untreated	ASS 3 Light Traffic Untreated
Pavement Thickness(mm)	270	350	220
CBR(%)	8	5	9
Compressive Strain mm/mm	9.74E-04	2.02E-03	9.74E-04
Tensile strain mm/mm	-6.70E-04	-2.49E-04	-6.80E-04

Fig. 14. Compressive and tensile strain results of light traffic for untreated ASS materials.

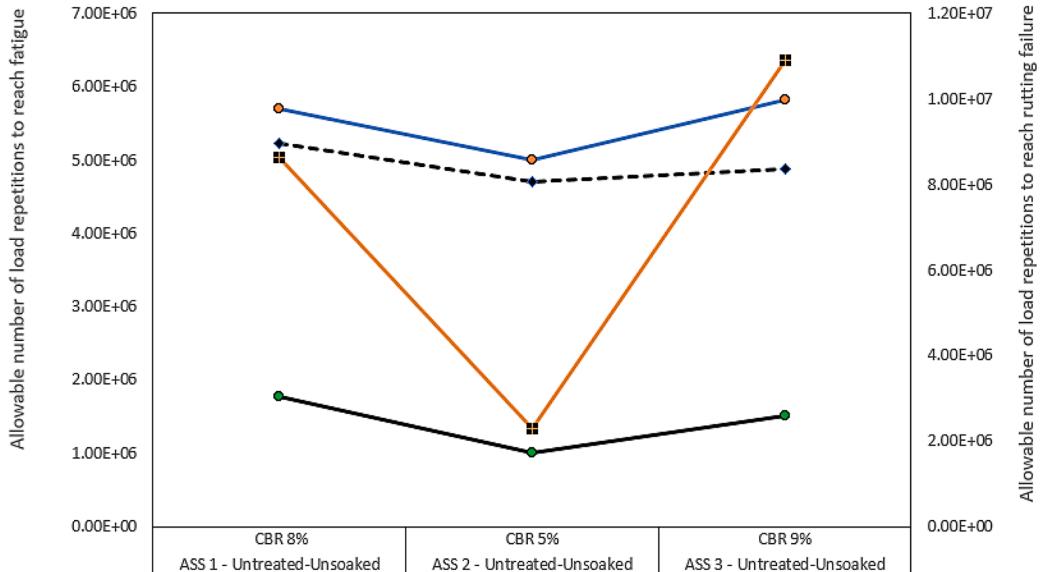


	ASS 1 Heavy Traffic Untreated	ASS 2 Heavy Traffic Untreated	ASS 3 Heavy Traffic Untreated
Pavement Thickness(mm)	320	410	298
CBR(%)	8	5	9
Compressive Strain mm/mm	7.96E-04	9.61E-04	7.24E-04
Tensile strain mm/mm	-6.32E-04	-5.28E-04	-6.58E-04

Fig. 15. Compressive and tensile strain results of heavy traffic for untreated ASS materials.

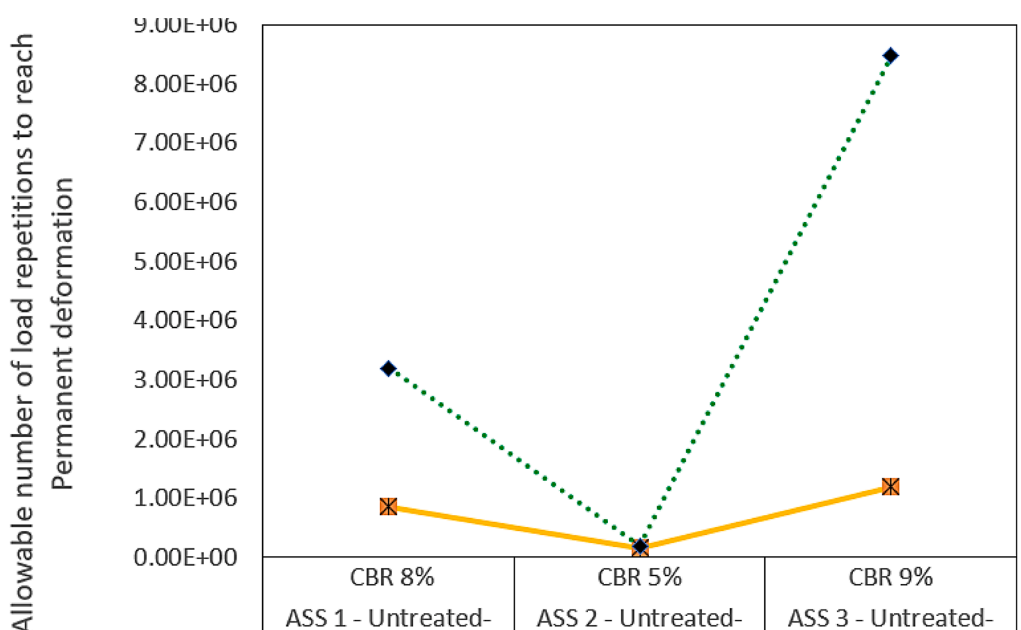
4.1. Effect of stresses on treated and untreated subgrade materials

A high potential for pavement defect was observed with an increase in compressive and tensile stresses for light traffic in untreated Artificially Synthesised Subgrade (ASS) material with California Bearing Ratio (CBR) values of 5% for ASS 2. These stresses began to decrease when California Bearing Ratio (CBR) values for ASS1 and 3 increased to 8% and 9% respectively. CBR values recorded for untreated ASS 1, 2 and 3 for heavy traffic exhibited high compressive and tensile strains responsible for pavement defects. However, these stresses reduced as CBR values increased. Overall, very high CBR values with low compressive and tensile strain responsible for pavement deformation were recorded for treated ASS materials for light and heavy traffic loads compared with that of untreated ASS materials. This means, treated ASS



	CBR 8% ASS 1 - Untreated-Unsoaked	CBR 5% ASS 2 - Untreated-Unsoaked	CBR 9% ASS 3 - Untreated-Unsoaked
Fatigue - Light Traffic	5.22E+06	4.71E+06	4.89E+06
Fatigue - Heavy Traffic	5.70E+06	4.99E+06	5.82E+06
Rutting Life - Light Traffic	3.04E+06	1.71E+06	2.59E+06
Rutting Life - Heavy Traffic	8.62E+06	2.30E+06	1.09E+07

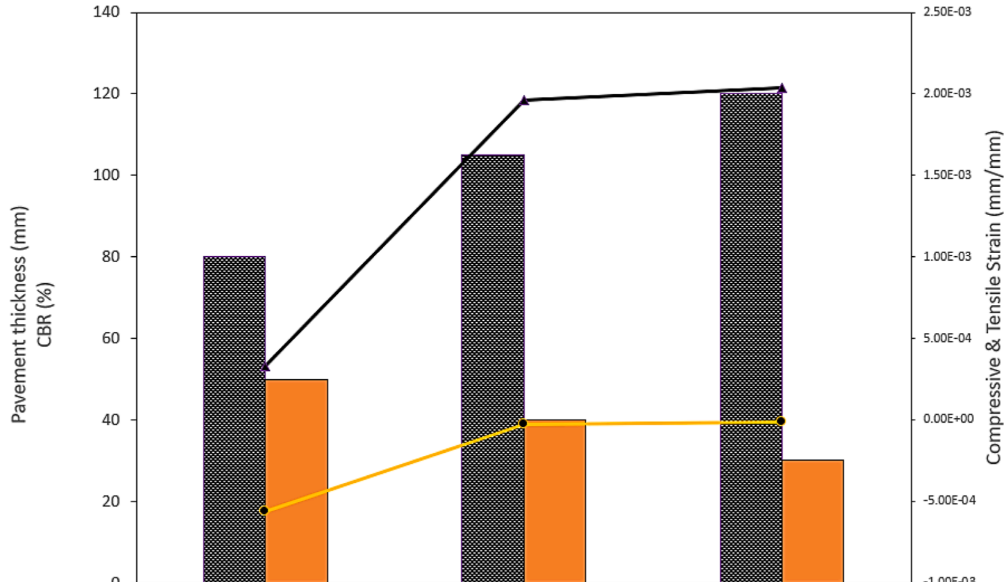
Fig. 16. Load repetition for fatigue and rutting of light and heavy traffic for untreated ASS materials.



	CBR 8% ASS 1 - Untreated-Unsoaked	CBR 5% ASS 2 - Untreated-Unsoaked	CBR 9% ASS 3 - Untreated-Unsoaked
Permanent deformation - Light Traffic	2.34E+06	4.15E+04	7.28E+06
Permanent deformation - Heavy Traffic	8.53E+05	1.56E+05	1.19E+06

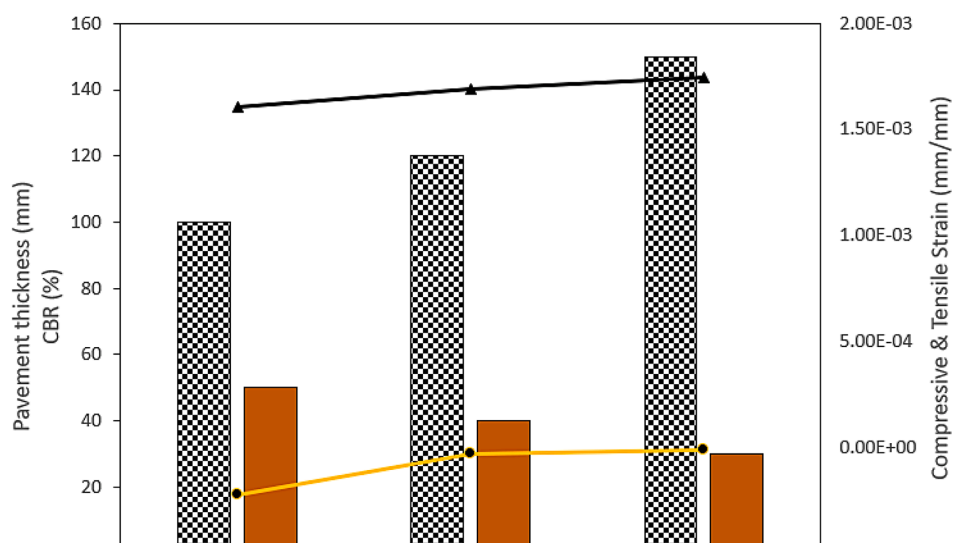
Fig. 17. Load repetition for permanent deformation of light and heavy traffic for untreated ASS materials.

materials with very high CBR values can withstand stresses in road pavement structure for a longer period before any defect occurs compared with untreated ASS with low CBR values. An increase in compressive and tensile stresses were observed with an increase in pavement thickness due to low California Bearing Ratio (CBR) values for light and heavy traffic load after 7 and 28 days of curing for treated ASS materials. For fatigue crack to initiate in road pavement structure, peak stress (compressive and tensile) must be very high, if peak stresses are low they may not initiate a crack [27]. The higher the stress concentration the more likely a crack may initiate and the greater the applied stress range, the shorter the life of the pavement structure [27] and [33]. This means the higher the subgrade CBR value the least likely a defect



	ASS 1 Treated-Soaked-Light Traffic-7 days curing	ASS 2 Treated-Soaked-Light Traffic-7 days curing	ASS 3 Treated-Soaked-Light Traffic-7 days curing
Pavement Thickness(mm)	80	105	120
CBR(%)	50	40	30
Compressive Strain mm/mm	8.92E-04	1.99E-03	2.05E-03
Tensile strain mm/mm	-5.61E-04	-3.04E-05	-1.66E-05

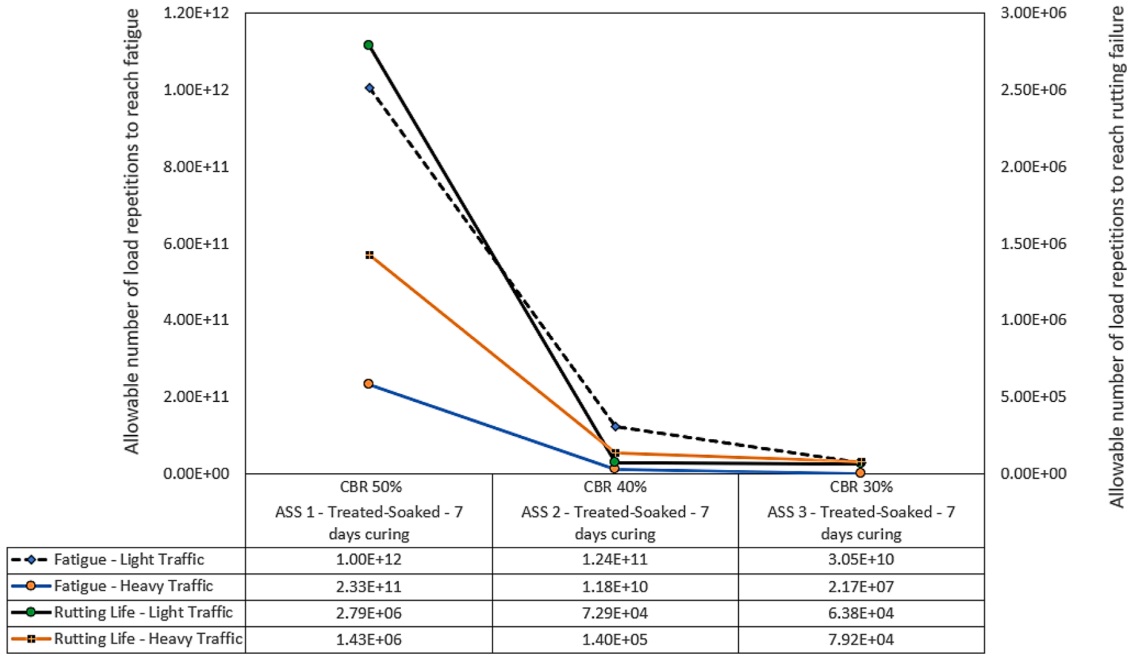
Fig. 18. Compressive and tensile strain results of light traffic for treated- soaked ASS materials 7 days curing.



	ASS 1 Treated-Soaked-Heavy Traffic-7 days curing	ASS 2 Treated-Soaked-Heavy Traffic-7 days curing	ASS 3 Treated-Soaked-Heavy Traffic-7 days curing
Pavement Thickness(mm)	100	120	150
CBR(%)	50	40	30
Compressive Strain mm/mm	1.83E-03	1.73E-03	1.76E-03
Tensile strain mm/mm	-2.25E-04	-3.21E-05	-1.21E-05

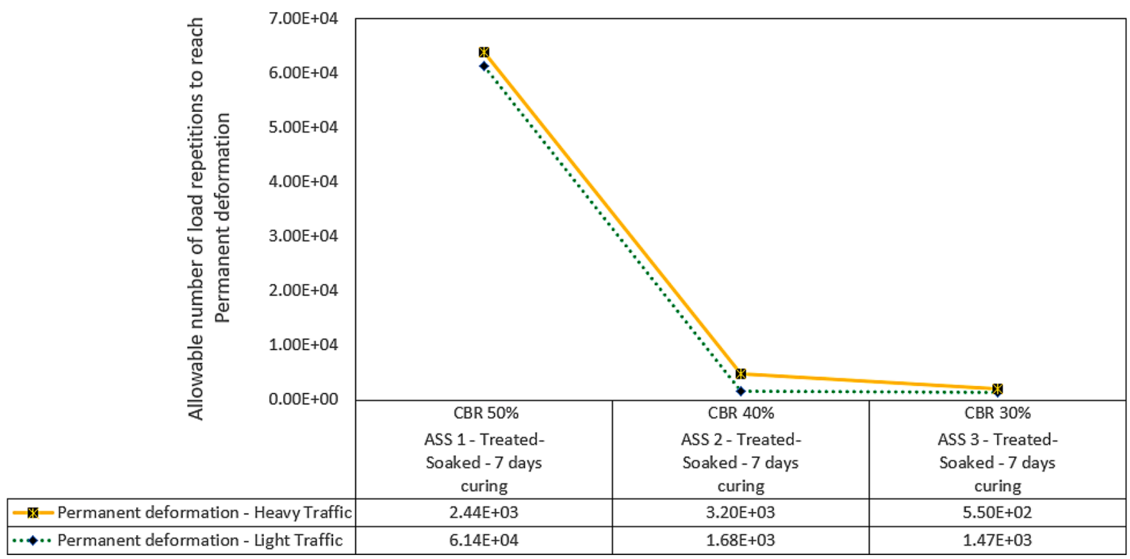
Fig. 19. compressive and tensile strain results of heavy traffic for treated-soaked ASS materials 7 days curing.

may occur in the road pavement structure. These are the reasons why pavement thickness increases with low subgrade CBR values to help cattail or reduced stresses in pavement structures to prolong the life of the road pavement. According to Nunn et al. [34], road pavement with thinner pavement thickness deforms at a higher rate compared with pavement frith thicker asphalts.



	CBR 50% ASS 1 - Treated-Soaked - 7 days curing	CBR 40% ASS 2 - Treated-Soaked - 7 days curing	CBR 30% ASS 3 - Treated-Soaked - 7 days curing
Fatigue - Light Traffic	1.00E+12	1.24E+11	3.05E+10
Fatigue - Heavy Traffic	2.33E+11	1.18E+10	2.17E+07
Rutting Life - Light Traffic	2.79E+06	7.29E+04	6.38E+04
Rutting Life - Heavy Traffic	1.43E+06	1.40E+05	7.92E+04

Fig. 20. Load repetition for fatigue and rutting of light and heavy traffic for treated-soaked ASS materials 7 days curing.



	CBR 50% ASS 1 - Treated-Soaked - 7 days curing	CBR 40% ASS 2 - Treated-Soaked - 7 days curing	CBR 30% ASS 3 - Treated-Soaked - 7 days curing
Permanent deformation - Heavy Traffic	2.44E+03	3.20E+03	5.50E+02
Permanent deformation - Light Traffic	6.14E+04	1.68E+03	1.47E+03

Fig. 21. Load repetition for permanent deformation of light and heavy traffic for treated- soaked ASS materials 7 days curing.

4.2. Effect of the application of repeated load on treated and untreated ASS materials

An allowable number of load repetitions to reach fatigue, rutting and permeant deformation for light and heavy traffic load were recoded for untreated Artificially Synthesised Subgrade (ASS 1) with CBR 8%. These repeated loads reduced when the California Bearing Ratio (CBR) value for untreated ASS 2 reduced to 5% and later increased when the CBR value for untreated ASS 3 increased to 9%. An allowable number of load repetitions to reach fatigue for light and heavy traffic load recoded for 7 days cured treated ASS 1 with CBR 80% and ASS 2 with CBR 60% decreased when CBR value decreased to 30% for 7 days cured treated ASS 3. An allowable number of load repetitions to reach rutting failure for light and heavy traffic load recoded for 7 days cured treated ASS 1 CBR 80% and ASS 2 60% also decreased when CBR value decreased to 30% for 7 days treated ASS 3. An allowable number of load repetitions to reach permanent deformation for light and heavy traffic load recoded for 7 days treated ASS 1 CBR 80% and ASS 2 60% decreased with a decrease in CBR value to 30% for 7 days treated ASS 3. This was the case for treated 7 and 28 days CBR values, a reduction in the allowable number of load repetitions with a reduction in CBR value was observed with an increase in CBR value. This means subgrade materials with high California Bearing Ratio (CBR) could withstand fatigue, rutting and permeant deformation for a longer period of time before failure occurs compared with subgrade materials with low CBR values. High cyclic load repetition values mean the applied cyclical stresses are low and failure occurs after a very large number of cycles, typically more than 10,000 cycles [27]. Low cyclic load repetition involves higher applied cyclical stresses and failure may occur after fewer cycles because the stresses involved are above the materials yield stress both elastic and plastic deformation may occu [27]. Fig. 8 shows the types of road pavement failures. Figs. 9–11 shows the three-layer flexible composite

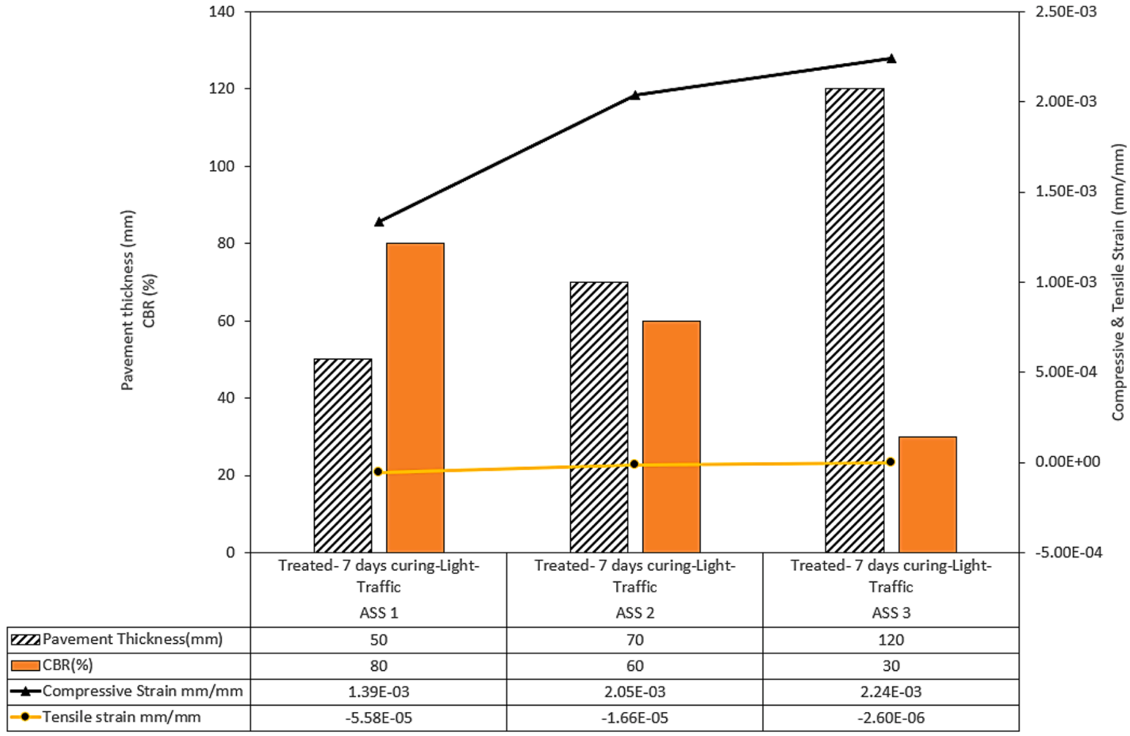


Fig. 22. Compressive and tensile strain results of light traffic for treated ASS materials 7 days curing.

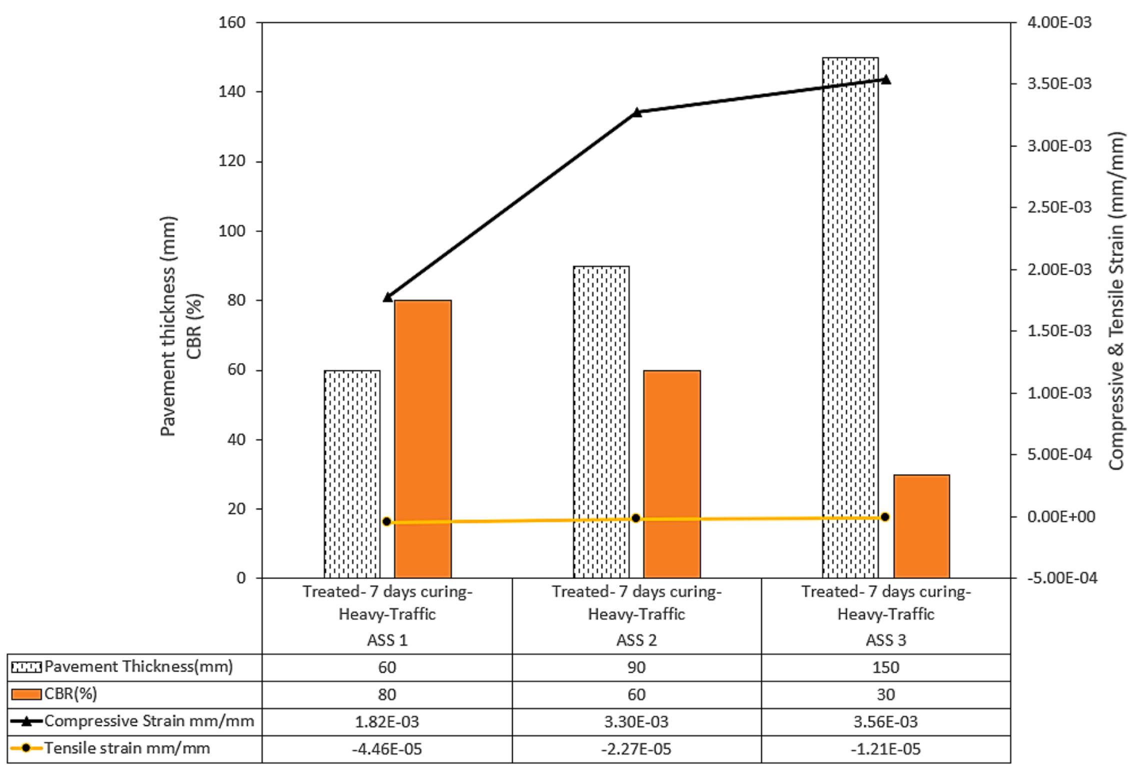
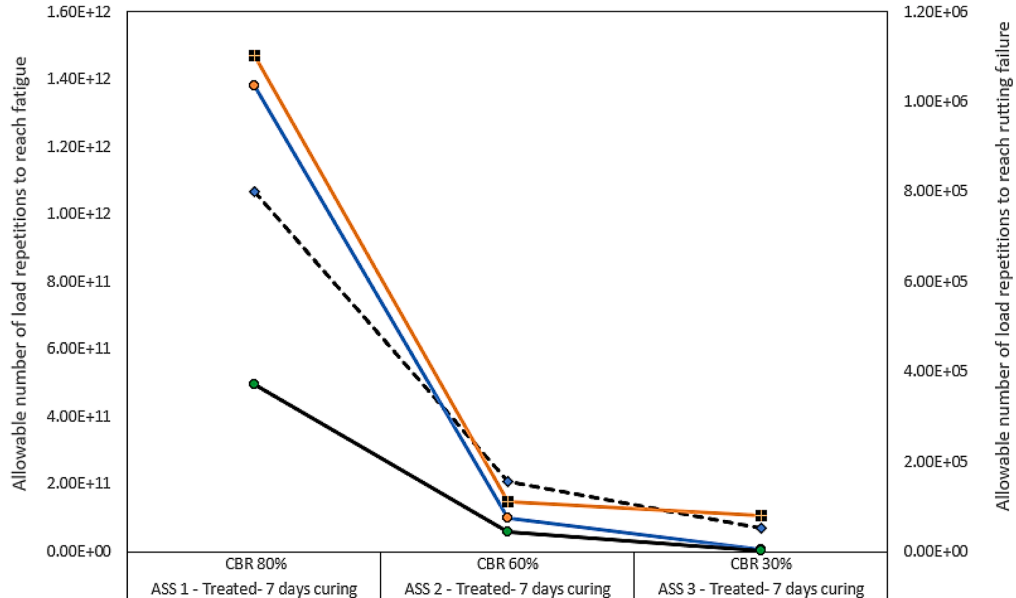


Fig. 23. compressive and tensile strain results of heavy traffic for treated ASS materials 7 days curing.

pavement structure adopted for and used in this study and the types of stress that could occur in a road pavement structure. Figs. 12 and 13 show the properties of flexible pavement layers used in this study and pavement analysis results from KENPAV for traffic load 8msa. Table 2 shows pavement details and responses for the actual tyre contact area for selected ASS materials. The results after defect analyses are shown in Figs. 14–29.

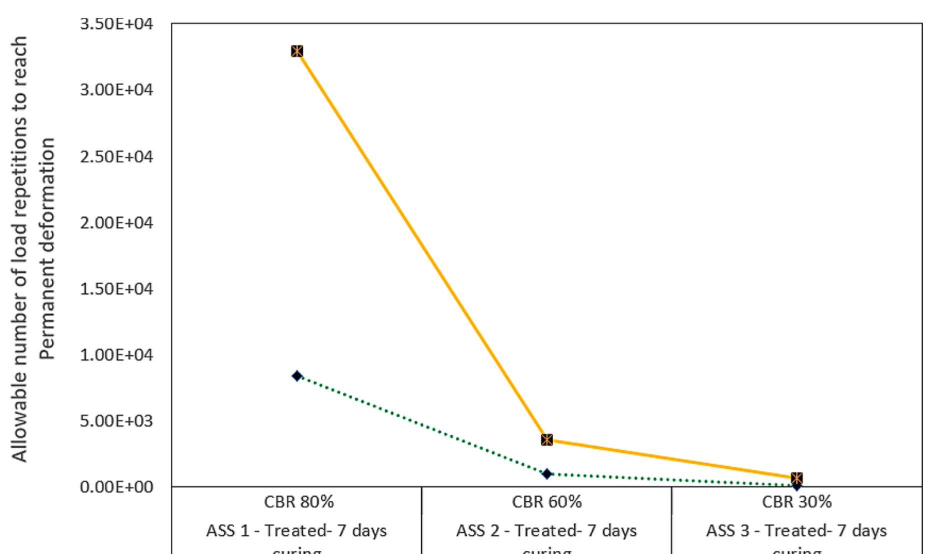
$$MR1 = 17.6 \times CBR^{0.64} \tag{1}$$

$$MR2 = E3 \times 0.2 \times h^{0.45} \tag{2}$$



	CBR 80% ASS 1 - Treated- 7 days curing	CBR 60% ASS 2 - Treated- 7 days curing	CBR 30% ASS 3 - Treated- 7 days curing
Fatigue - Light Traffic	1.07E+12	2.06E+11	6.76E+10
Fatigue - Heavy Traffic	1.38E+12	9.79E+10	4.71E+09
Rutting Life - Light Traffic	3.70E+05	4.28E+04	1.07E+03
Rutting Life - Heavy Traffic	1.10E+06	1.10E+05	7.92E+04

Fig. 24. Load repetition for fatigue and rutting of light and heavy traffic for treated ASS materials 7 days curing.



	CBR 80% ASS 1 - Treated- 7 days curing	CBR 60% ASS 2 - Treated- 7 days curing	CBR 30% ASS 3 - Treated- 7 days curing
Permanent deformation - Heavy Traffic	2.45E+04	2.52E+03	5.50E+02
Permanent deformation - Light Traffic	8.35E+03	9.92E+02	7.00E+01

Fig. 25. Load repetition for permanent deformation of light and heavy traffic for treated ASS materials 7 days curing.

$$MR3 = 17.6 \times CBR^{0.64} \quad (3)$$

Where M_R is resilient modulus of base course, M_{R2} resilient modulus of subbase course, M_{R3} resilient modulus of subgrade.

Damage Analysis

$$N_{fatigue} = f_1(\varepsilon_t)^{-f2}(E_1)^{-f3} \quad (4)$$

$$N_{permanent\ deformation} = f_4 E^{-9}(\varepsilon_c)^{-f5} \quad (5)$$

Where ε_t= is the tensile strain at the bottom of asphalt layer, and E_1= the modulus of the asphalt layer, and ε_c=compressive strain at the top of the subgrade layer, and f_{1-5} are empirical values used by Asphalt Institute for these calculations.

Rutting life Prediction

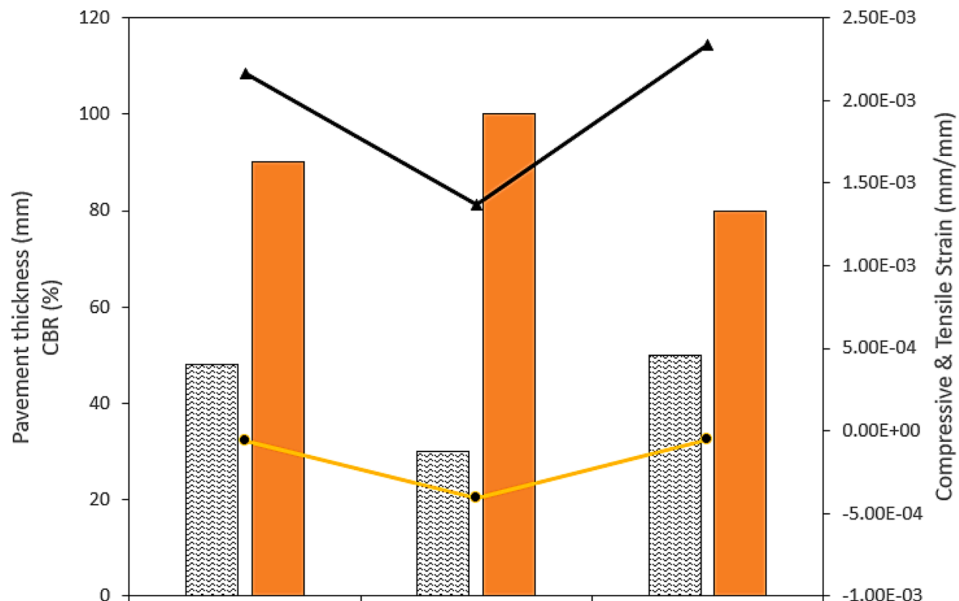
$$N = 4.1656x10^{-08}\left[\frac{1}{\varepsilon_c}\right]^{4.5337} \quad (6)$$

Where N = Number of cumulative standard axles

Ɛc = Compressive strain in the subgrade

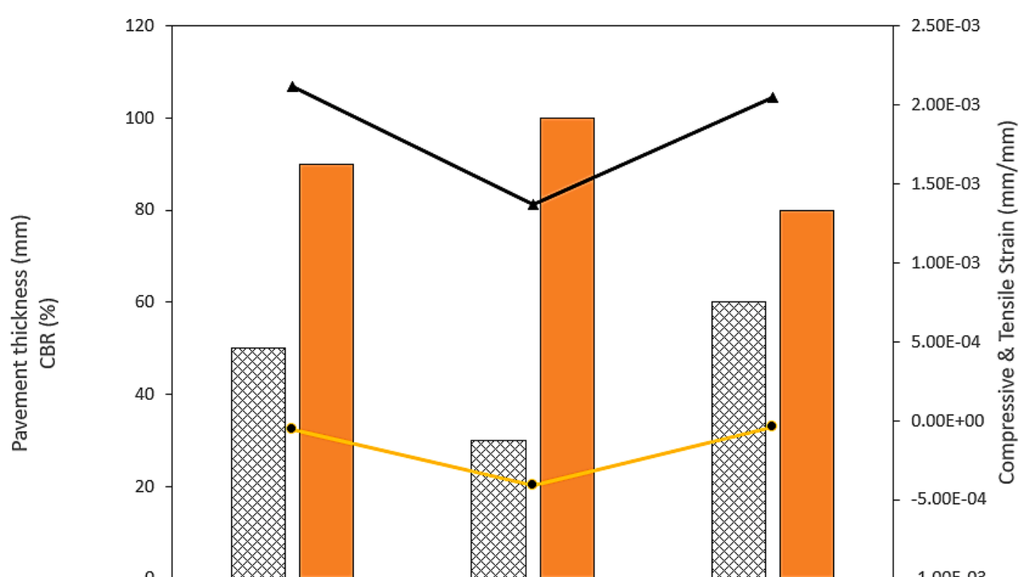
5. Conclusion

Failures in road pavement structure were analysed in this study using treated and untreated subgrade CBR values achieved in this study and



	Treated- 28 days curing-Light-Traffic ASS 1	Treated- 28 days curing-Light-Traffic ASS 2	Treated- 28 days curing-Light-Traffic ASS 3
Pavement Thickness(mm)	48	30	50
CBR(%)	90	100	80
Compressive Strain mm/mm	2.23E-03	1.78E-03	2.39E-03
Tensile strain mm/mm	-6.47E-05	-4.10E-04	-5.58E-05

Fig. 26. Compressive and tensile strain results of light traffic for treated ASS materials 28 days curing.



	Treated- 28 days curing-Heavy-Traffic ASS 1	Treated- 28 days curing-Heavy-Traffic ASS 2	Treated- 28 days curing-Heavy-Traffic ASS 3
Pavement Thickness(mm)	50	30	60
CBR(%)	90	100	80
Compressive Strain mm/mm	2.18E-03	1.78E-03	2.10E-03
Tensile strain mm/mm	-6.01E-05	-4.10E-04	-4.46E-05

Fig. 27. Compressive and tensile strain results of heavy traffic for treated ASS materials 28 days curing.

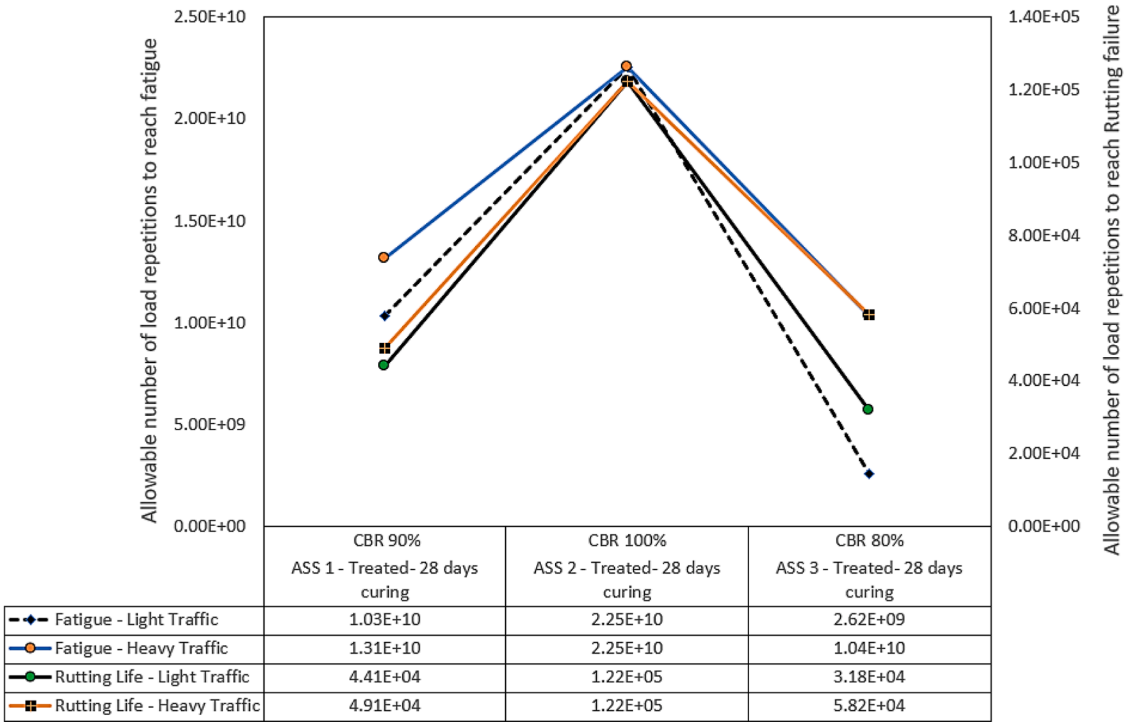


Fig. 28. Load repetition for fatigue and rutting of light and heavy traffic for treated ASS materials 28 days curing.

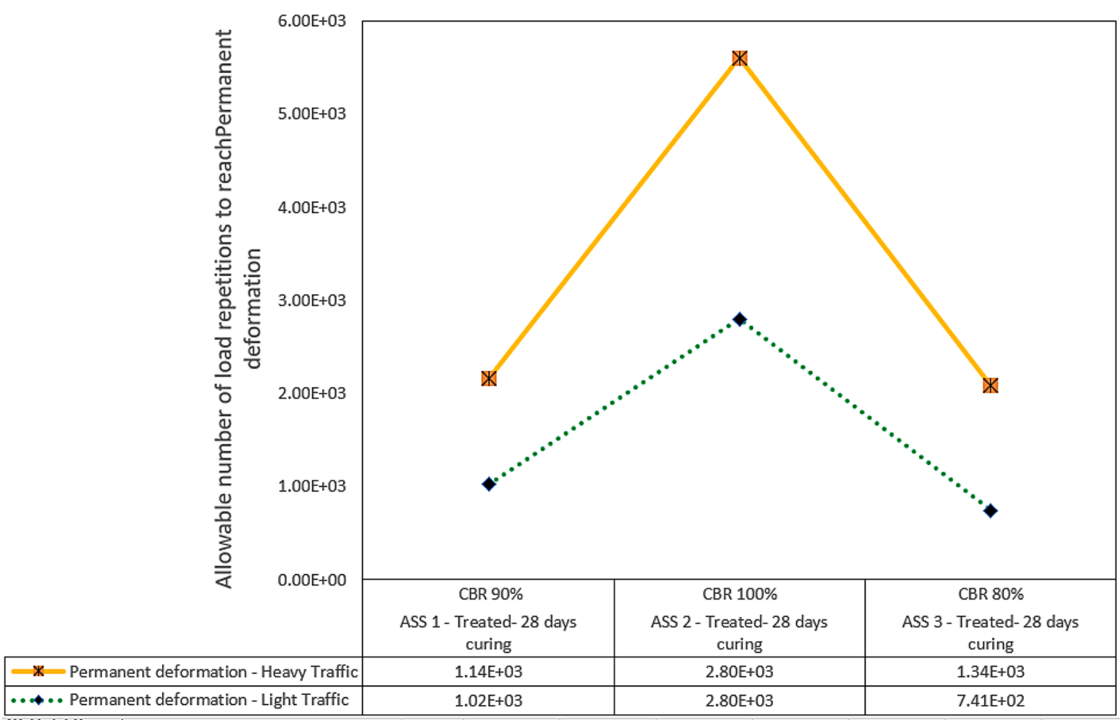


Fig. 29. Load repetition for permanent deformation of light and heavy traffic for treated ASS materials 28 days curing.

the findings are as follows;

1. A reduction in stresses responsible for failure within road pavement structure was observed. Low compressive and tensile stresses with an increasing CBR value were recorded this means it is unlikely defects may occur in the pavement with a high subgrade CBR value.
2. High allowable repeated loads were recorded for ASS materials with high CBR values and vice versa. This signifies the ability of road subgrade with high CBR values to withstand several cycles of loading (repeated traffic load) before failure occurs within the pavement.
3. A reduction and or elimination of the tendency of defects to occur with road pavement structure was observed when CBR vales increased after expansive subgrade was treated using cement and lime.
4. This study established the possibility of improving the engineering properties of expansive road subgrade using cement and lime.

5. The construction industry would benefit from this study as road contractors can refer to this study to predict the likelihood of defect occurrence within road pavement when they encounter subgrade materials with similar properties and characteristics as used in this study.
6. Overall construction costs can be reduced when weak or expansive subgrades are treated using cement and lime instead of removing and replacing subgrades with foreign materials.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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