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Performance of Sustainable Road Pavements Founded on Clay Subgrades Treated with Eco-Friendly Cementitious Materials

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Abstract: Clays encountered during road construction are mostly weak and result in major pavement failures due to their low California bearing ratio (CBR) and high swelling potential. In this study, sustainable and eco-friendly waste materials including brick dust waste (BDW), ground granulated blastfurnance slag (GGBS), recycled plastic (RP) and recycled glass (RG) at varying proportions of 11.75% and 23.5% were used as partial replacement for cement and lime in clay treatment. After determining the water content by conducting Atterberg limit and compaction test, A CBR and swell characteristics of treated and untreated clay were also conducted. A road pavement design was conducted using the Design Manual for Road and Bridges (DMRB) as a guide to determine the performance of treated clay with varying CBR values. A road pavement failure analysis was also conducted to understand the defect formation within pavement structures supported by eco-friendly treated clay. The embodied carbon of treated clay was calculated and a life cycle cost analysis (LCCA) of flexible pavement with treated clay and road with imported materials was conducted. The results show a liquid limit of 131.26 and plastic limit of 28.74 for high plasticity index (clay 1) and liquid limit of 274.07 and a plastic limit of 45.38 for extremely high plasticity index (clay 2). An increase in CBR values from 8% and 9% to 57% and 97% with a reduction in swell values from 4.11% and 5.03% to 0.38% and 0.56% were recorded. This resulted in a reduction in pavement thickness and stresses within the road pavement leading to reduced susceptibility of the pavement to fatigue, rutting and permanent deformation. Very low embodied carbon was recorded for eco-friendly treated clay and a high life cycle cost (LCC) with clay removed and replaced with imported materials compared with clay treated using eco-friendly waste materials. The study concluded that carbon and overall construction costs can be reduced using waste materials in road construction. Owners and operators can save money when clay is treated and used in road construction instead of removing clay and replacing it with imported materials.

Keywords: brick dust waste; eco-friendly solutions; pavement; clay; economic appraisal; life cycle cost analysis; fatigue; rutting; deformation

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1. Introduction

One of the vital components in the process of road projects is road pavement design. Road pavement design plays an important role in determining the layer composition, materials required and the cost of the projects based on the California bearing ratio (CBR) of clay (original ground). The California bearing ratio (CBR) is a penetration test to investigate the strength of subgrade and evaluate its bearing capacity to carry traffic load [1]. CBR plays an important role in determining the thickness and type of road pavement materials to select during the construction phase of a project [2]. In this study, the

Design Manual for Road and Bridges (DMRB) was used in the design of road pavement and road pavement failure investigation conducted using clay treated with waste and industrial by-products. Clay soils expand when wet and shrink when dry causing movement in the foundation due to the repeated expansion and shrinkage [3,4]. These movements within the road foundation cause defects in the road pavement structure leading to high cost of maintenance and sometimes a total reconstruction of the road [4]. This calls for modification and reengineering of the clay before construction. Traditional cement and lime are mostly used in clay treatment however, they are associated with high carbon dioxide (CO_2) emissions and are non-environmentally friendly [5]. This calls for the use of more sustainable and environmentally friendly binders in clay treatment.

In this study, waste materials including brick dust waste (BDW), ground granulated blastfurnance slag (GGBS), recycled plastic (RP) and recycled glass (RG) were used as binders to treat clay. Research has shown that waste materials can be used in clay treatment due to their ability to improve the engineering properties of clay through the production of calcium silicate hydrate (CSH) gel during the hydration process [6]. Materials including brick dust, synthetic fibre, thermal bituminous, rice husk, sugarcane bagasse, cow dung, geo-textiles, fabric and electrical waste have been used in soil treatment [6]. Waste materials including electric arc furnace (EAF) ladle furnace (LF) slags, coal fly (CF) ash, bottom ash, glass waste (GW) and reclaimed asphalt pavement (RAP) were used to improve the economic and environmental sustainability of road constructions [7]. Carbon reduction in pavement construction was observed when recycled plastic (RP) waste was used at varying proportions to enhance the engineering properties for eco-friendly pavement application [8]. Road pavements are superimposed layers of materials placed over the natural ground [9,10]. Development of stresses within road pavement caused by traffic load and geotechnical issues lead to damage to the road pavement [11]. According to [12], clay corrugates at the surface of the road and increases unevenness. The process of treating clay using cement and lime to improve its CBR to make them usable in road construction can lead to a high overall construction cost of road pavement [1,4]. Countries such as the United States and China have spent USD 30 billion on maintenance costs only due to road pavement defects caused by clay [2,4]. Road pavement defect that leads to permanent damage to the pavement was investigated in this study using a mixture of bentonite and kaolinite to form clay with varying plasticity index. Atterberg and compaction tests were conducted for untreated clay to determine its water content after which the clay was treated using waste materials. The CBR of treated clay was determined and the results were used in the pavement design and defect analysis conducted in this study. A life cycle cost analysis (LCCA) was conducted to determine the cost of treating clay compared with the cost of removing clay and replacing them with imported materials. LCCA serves as a tool to calculate the real cost of an asset over its useful design life [13,14]. In the 1930s the LCCA concept was introduced in highway projects and as part of federal legislation on flood control [13]. The nature and characteristics of clay (natural ground) can influence the LCC of road pavement [1].

2. Materials and Methods

Bentonite and kaolinite were mixed in varying proportions to form an Artificially Synthesised Clay (ASC): Clay 1 (25% bentonite + 75% kaolinite) of high plasticity index and Clay 2 (75% bentonite + 25% kaolinite) of extremely high plasticity index. Sustainable waste materials including brick dust waste (BDW), ground granulated blastfurnace slag (GGBS), recycled plastic (RP) and recycled glass (RG) at varying proportions of 11.75% and 23.5% were used in clay treatment. The process of water content determination (compaction and Atterberg limit tests), California bearing ratio (CBR) and swell tests, road pavement design, defect analysis and the design guidance used are as reported in the authors' previous study [3,15] using CBR values achieved in this study. Stresses within the various layers of the pavement were analysed using KENPAV software, and a detailed description of KENPAV software is as reported in the authors' previous study [3,15]. The suppliers' information for the bentonite, kaolinite, cement and lime used in this study are as reported in the authors' previous study [2]. The brick dust waste (BDW) was supplied by Celtic Sustainable Ltd., Unit 9 Parc Teifi Business Park Cardigan, Wales, SA43 1EW UK and complies with BS EN 771-1:2011+A1:2015. Ground Granulated Blastfurnace Slag (GGBS) used was in compliance with BS EN 15167-1:2006 and supplied by Francis Flower, The White House, Gurney Slade, Radstock, Somerest, England, BA3 4UU. The plastic used was supplied by Poli Plastic Pellets Ltd., Monor farmhouse, Hawarden, Flintshire, Wales, CH5 3PL, UK. The recycled glass used was supplied by Centurywise Ltd., Unit 2 Bridge House, Stuart Road Bredbury, Stockport, Greater Manchester, England, SK6 2SR. The focused on conducting road pavement design using sustainably treated clay subgrade materials in compliance with DMRB Guide to ascertain how treated clay subgrade affects road pavement design. The study also carried out pavement defect analysis to investigate the effect of varying CBR values and traffic loads on sustainably treated clay subgrade in terms of failure. Further investigations of the life cycle cost (cost effects) of road pavement designed using sustainably treated clay subgrade materials were conducted and compared with the life cycle cost of road pavement designed using imported subgrade materials. Lastly, the study investigated the embodied carbon for each sustainable binder used in stabilising clay subgrade materials. The particle size distribution, oxide and chemical composition of all materials used in this study are shown in Figures 1 and 2 and Table 1.

Figure 1. Materials used in this study.

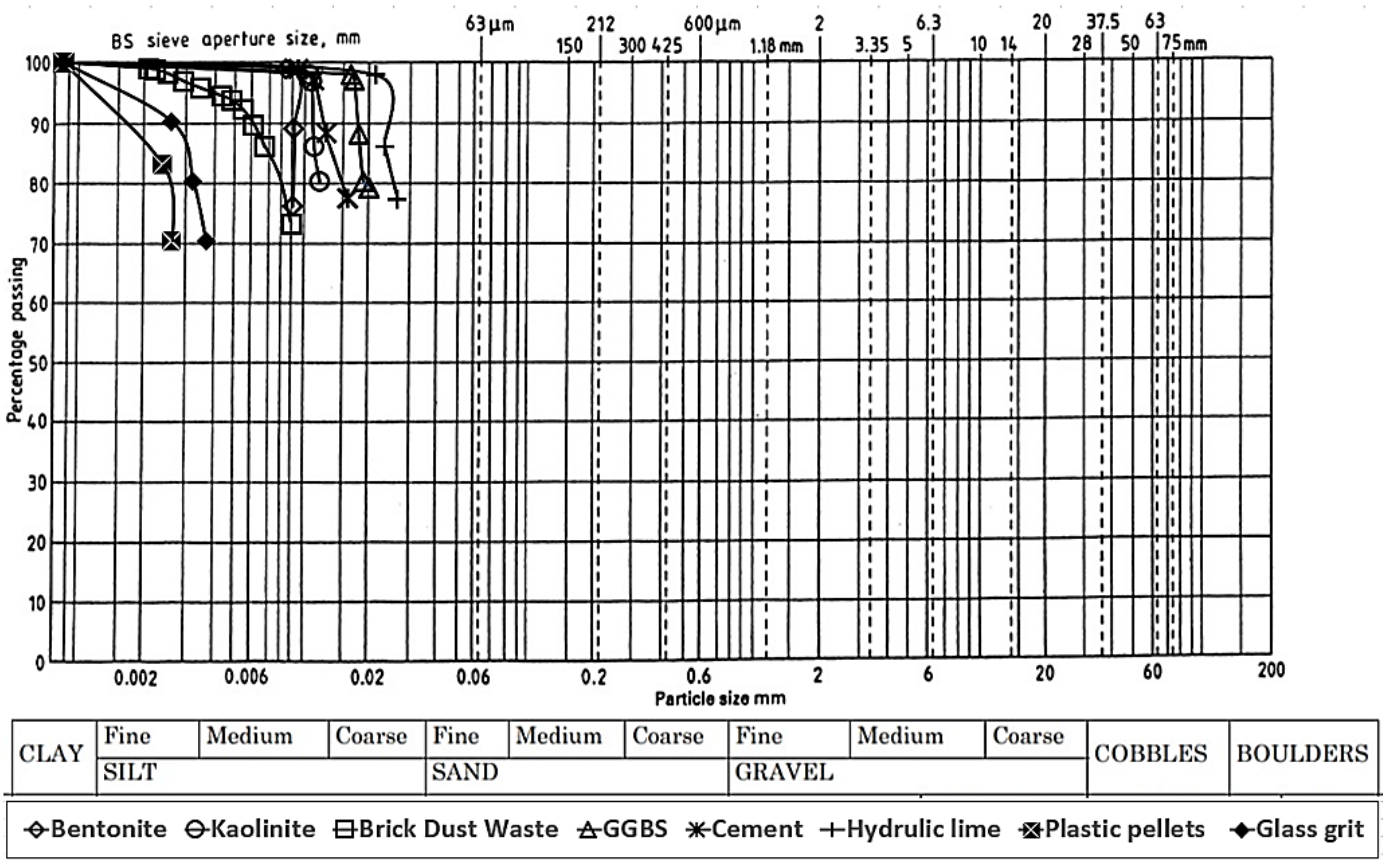


Figure 2. Particle size distribution of materials used in this study.

Table 1. Oxide and chemical composition of materials used.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	K_2O	SO_3	TiO_2	Na_2O	BaO	Cr_2O_3	Trace	L.O.I
Bentonite Clay (%)	63.02	21.08	3.25	0.35	2.67	0.65	-	-	-	2.57	-	-	0.72	5.64
Kaolinite Clay (%)	48.5	36.0	1.00	-	0.30	0.05	2.15	-	0.06	0.15	-	-	-	11.7
Cement (%)	20	6.0	3.0	-	4.21	63	-	2.30	-	-	-	-	-	0.80
GGBS (%)	35.35	11.59	0.35	-	8.04	41.99	-	0.23	-	-	-	-	-	-
Lime (%)	3.25	0.19	0.16	-	0.45	89.2	0.01	2.05	-	-	-	-	-	-
BDW (%)	52	41	0.7	-	0.12	4.32	0.53	0.33	0.65	0.05	-	-	-	2.01
Plastic (%)	45.47	12.11	1.04	-	-	38.49	0.94	0.43	-	-	-	-	-	-
Glass (%)	72.20	1.50	0.07	-	1.30	10.90	0.45	0.16	0.06	13.30	0.04	0.02	-	-

3. California Bearing Ratio (CBR) and Swell

The sample preparation, testing procedure and standards used to determine the CBR and Swell for treated and untreated clay are as reported in the authors' previous study [2]. A high-quality subgrade has a CBR value between 80% and 100% minimum [2,3]. A CBR value < 2% is unacceptable for use in road construction and would need modification or reengineering [2,3]. A subgrade swell > 2.5% is unacceptable for use in road construction and must be treated [2,3].

4. Life Cycle Cost Analysis (LCC)

Life cycle cost analysis (LCCA) was carried out in this study for the best performing mix design for a design period of 35 years in compliance with BS ISO 15686-5:2017 [16]. The LCC of clay treated using waste materials was compared with the LCC of clay removed and replaced with imported materials. The life cycle cost analysis performed in this study would help inform contractors on the choice of binders and binder proportions to adopt when they encounter clay with characteristics similar to what was used in this study. The cost of binders used was investigated using current market prices at the time of this study to calculate the total cost of binders required to stabiles a square kilometre of clay based on the percentages of binders used in a mix-design. In establishing the real cost of treating a square kilometre of clay, plant cost was estimated using the Newmarket Plant Hire (NPH) [17] Group document and ecoinvent database [18] to get product and materials data for the analysis.

5. Results and Discussion

California Bearing Ratio (CBR) and Swell

After conducting California bearing ratio (CBR) and swell test for treated and untreated clay samples soaked and unsoaked, it was observed that CBR values increased for treated soaked and unsoaked clay samples compared with untreated soaked and unsoaked samples. The highest CBR value of 97% was recorded for Clay 1 treated with ground granulated blastfurnace slag (GGBS) and brick dust waste (BDW) after 28 days of curing. This confirms that waste materials can improve the engineering properties of clay. A CBR value > 250% was achieved in a study conducted by [19] using a minimum of 20% of high calcium waste dust from asphalt concrete manufacturing to stabilise low-quality soil used as subbase course material in road structures. The study concluded that, recycled waste dust from asphalt concrete in sustainable road construction. The lowest swell value of 0.38% was recorded for Clay 1 treated with GGBS and plastic. Table 2 shows CBR and swell values for treated and untreated clay samples.

Table 2. CBR and swell values for treated and untreated clay samples.

Clay Type	Mix Design	Treated	Soaked	Curing Days	CBR Values (%)	Swell Values (%)
1	25% B + 75% K	x	x	0	8	4.11
1	25% B + 75% K	x	√	0	0.6	
2	75% B + 25% K	x	x	0	9	5.03
2	75% B + 25% K	x	√	0	1.3	
1	2L% + 2.5% C + 23.5% GL	√	x	7	14	0.52
1	2L% + 2.5% C + 23.5% GL	√	√	7	17	
1	2L% + 2.5% C + 23.5% GL	√	x	28	16	0.46
1	2L% + 2.5% C + 23.5% GL	√	√	28	11	
2	2L% + 2.5% C + 23.5% GL	√	x	7	11	0.64
2	2L% + 2.5% C + 23.5% GL	√	√	7	3	
2	2L% + 2.5% C + 23.5% GL	√	x	28	8	0.57
2	2L% + 2.5% C + 23.5% GL	√	√	28	4	
1	2L% + 2.5% C + 23.5% PL	√	x	7	13	0.56
1	2L% + 2.5% C + 23.5% PL	√	√	7	12	
1	2L% + 2.5% C + 23.5% PL	√	x	28	13	0.51
1	2L% + 2.5% C + 23.5% PL	√	√	28	8	
2	2L% + 2.5% C + 23.5% PL	√	x	7	12	0.61
2	2L% + 2.5% C + 23.5% PL	√	√	7	6	
2	2L% + 2.5% C + 23.5% PL	√	x	28	8	0.59
2	2L% + 2.5% C + 23.5% PL	√	√	28	3	
1	2L% 2.5% C + 11.75% GGBS + 11.75% PL	√	x	7	44	0.38

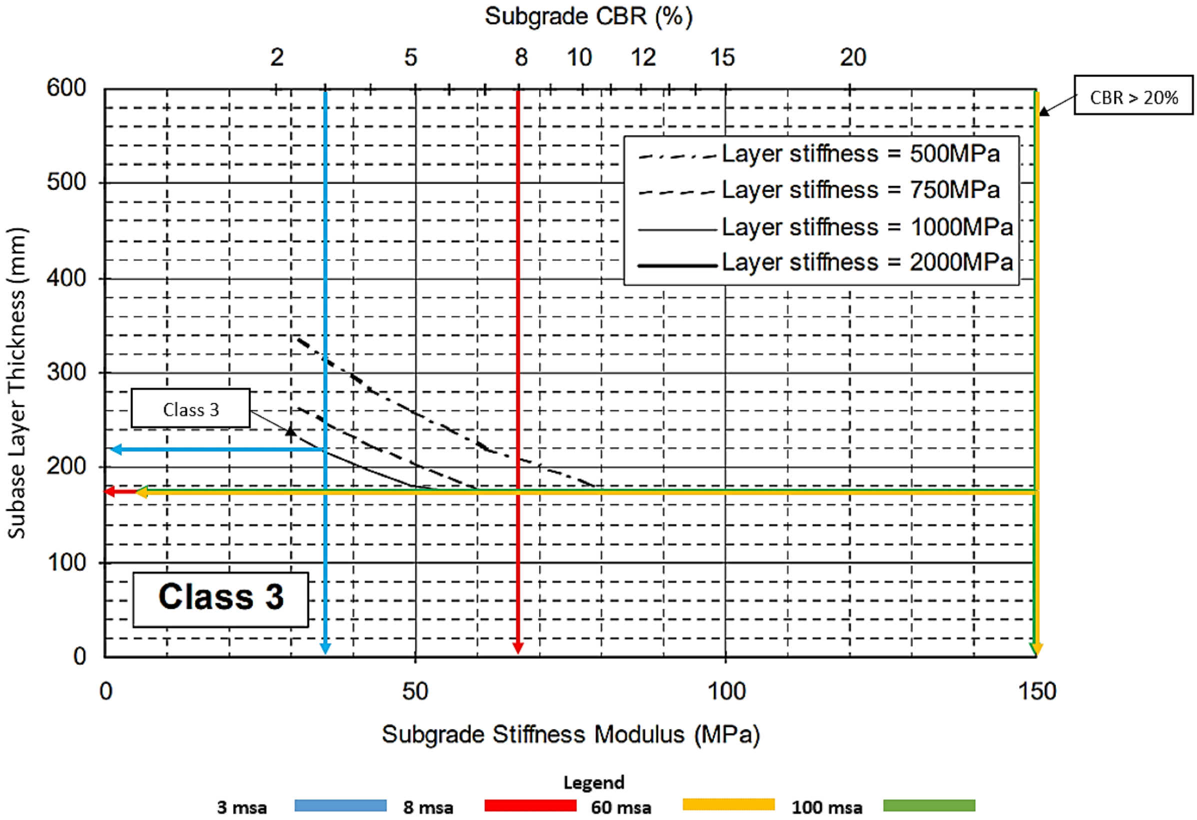
Table 2. *Cont.*

Clay Type	Mix Design	Treated	Soaked	Curing Days	CBR Values (%)	Swell Values (%)
2	2L% 2.5% C + 11.75% GGBS + 11.75% PL	√	x	7	21	0.94
1	2L% 2.5% C + 11.75% GGBS + 11.75% GL	√	√	7	59	0.39
2	2L% 2.5% C + 11.75% GGBS + 11.75% GL	√	√	7	31	0.56
1	2L% + 2.5% C + 11.75% GGBS + 11.75% BDW	√	√	28	97	0.42
2	2L% + 2.5% C + 11.75% GGBS + 11.75% BDW	√	x	7	27	0.54
2	2L% + 2.5% C + 11.75% GGBS + 11.75% BDW	√	√	7	16	
2	2L% + 2.5% C + 11.75% GGBS + 11.75% BDW	√	x	28	44	0.49
2	2L% + 2.5% C + 11.75% GGBS + 11.75% BDW	√	√	28	24	

Where B = Bentonite, K= Kaolinite, L = Lime, C = Cement, GGBS = Ground Granulated Blastfurnace Slag, PL= Plastic, GL = Glass, BDW = Brick Dust waste.

6. DMRB Road Pavement Design Using Sustainable Treated Clay

Road pavement design was conducted in this study in accordance with DMRB CD 226 [20]) using selected California bearing ratio (CBR) values achieved in this study. The procedure used and parameters adopted are as reported in the authors' previous study [13]. The design traffic load selected include 3 msa, 8 msa, 60 msa and 100 msa and the CBR values selected include 3% for Clay 2, 8% for Clay 1, 109% for Clay 1. A three-layer composite pavement was adopted for the design using class 3 design in accordance with DMRB CD 226 [20]). The results show a reduction in pavement thickness as CBR values increase for Clay 1 for all design traffic loads. A high CBR value resulted in reduced pavement thickness and the overall construction cost of a project [21]. A CBR value of 19% reflected in a reduction in the overall thickness and life cycle cost of road pavement in Uganda [4]. Ref. [22], stated in a study that pavement thickness is determined by the subgrade CBR. According to [23]. Pavements are built to a set thickness dependent on the clay quality, being dependent on anticipated traffic. After designing pavement using DMRB 226 [20], a slight change in pavement thickness was observed compared with using other standards. Changes in pavement thickness were significant for clay CBR values from 2–5% using DMRB [16]. This is so because the subbase layer forms a major part of pavement thickness and Class 3 subbase chart offers a thicker subbase layer only for CBR values between 2–10.5%, after which the sub-base thickness remains the same (180 mm). This means no significant pavement thickness was observed even with a CBR value of 100%. Using sustainable waste materials resulted in achieving very high CBR values and thinner pavement. The thickest pavement of 600 mm (100 msa) was recorded for clay with a CBR value of 3% and the thickest pavement of 418 mm (3 msa) was recorded for clay with a CBR value of 109%. Figure 3a,b shows Class 3 design–single foundation layer (IAN 73/06 [3,24]) (b) Nomograph for determining the design thickness for flexible pavement (DMRB CD 226 [3,20]). Figure 4a,b show the result of road pavement designed using DMRB for traffic 3 msa and 8 msa. (b) Result of road pavement designed using DMRB for traffic 60 msa and 100 msa.



(**a**)

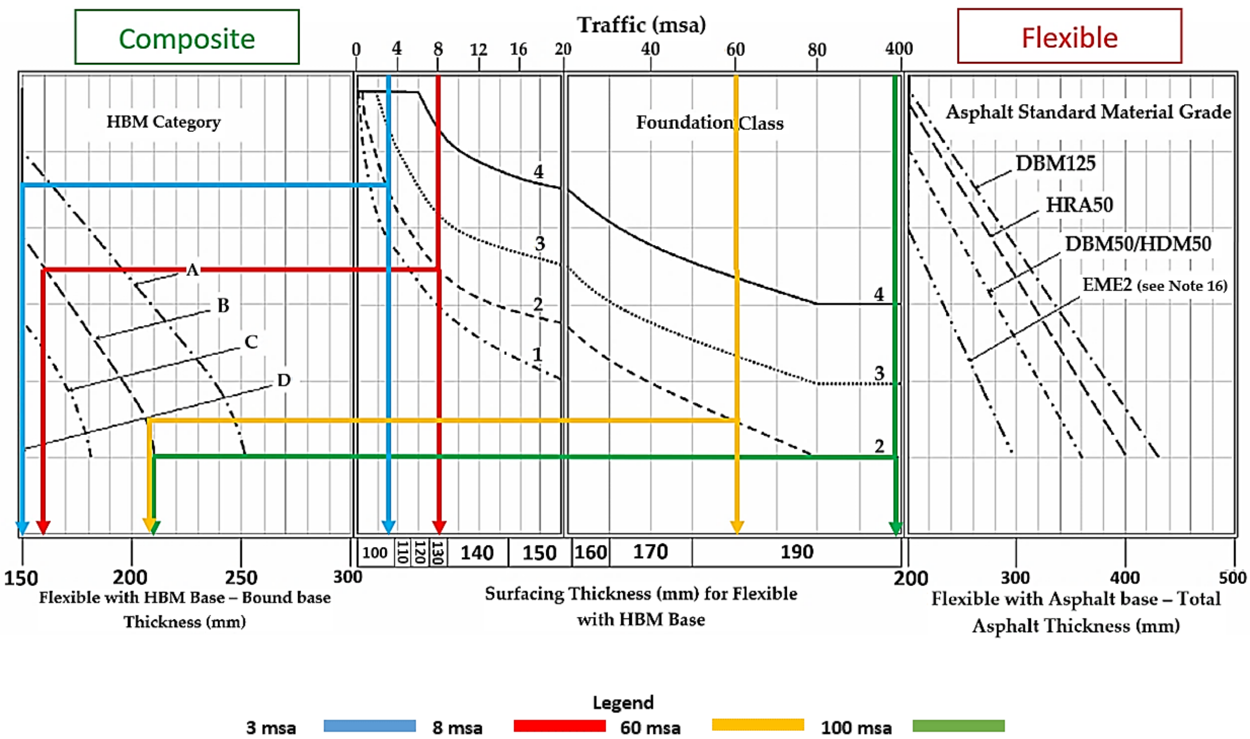


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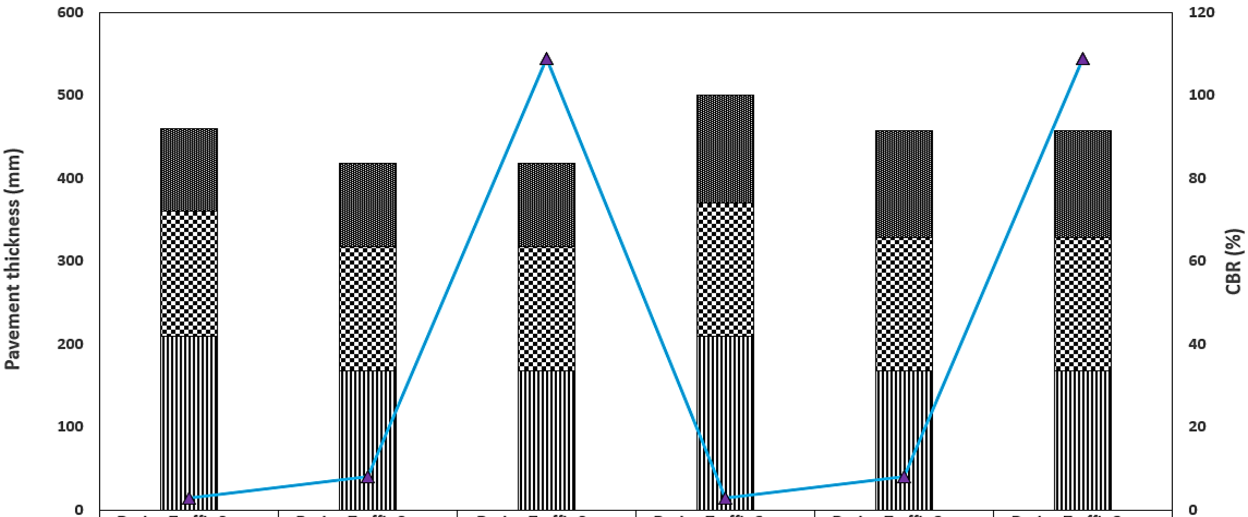
Figure 3. (**a**) Class 3 design–single foundation layer (IAN 73/06 [3,24]). (**b**) Nomograph for determining the design thickness for flexible pavement (DMRB CD 226 [3,20]).



	Design Traffic 3 msa ASS 2 +2%L+2.5%C+23.5%GLASS - soaked after 7 days curing Pavement Thickness 460mm	Design Traffic 3 msa ASS 1 +2%L+2.5%C+23.5%PLASTIC after 28 days curing Pavement Thickness 418mm	Design Traffic 3msa ASS 1 +2%L+2.5%C+11.75%GGBS+11.75%BDW after 28 days curing Pavement Thickness 418mm	Design Traffic 8 msa ASS 2 +2%L+2.5%C+23.5%GLASS - soaked after 7 days curing Pavement Thickness 500mm	Design Traffic 8 msa ASS 1 +2%L+2.5%C+23.5%PLASTIC after 28 days curing Pavement Thickness 458mm	Design Traffic 8 msa ASS 1 +2%L+2.5%C+11.75%GGBS+11.75%BDW after 28 days curing Pavement Thickness 458mm
Surface Course (mm)	100	100	100	130	130	130
Base Course (mm)	150	150	150	160	160	160
Subbase Course (mm)	210	168	168	210	168	168
Subgrade CBR(%)	3	8	109	3	8	109

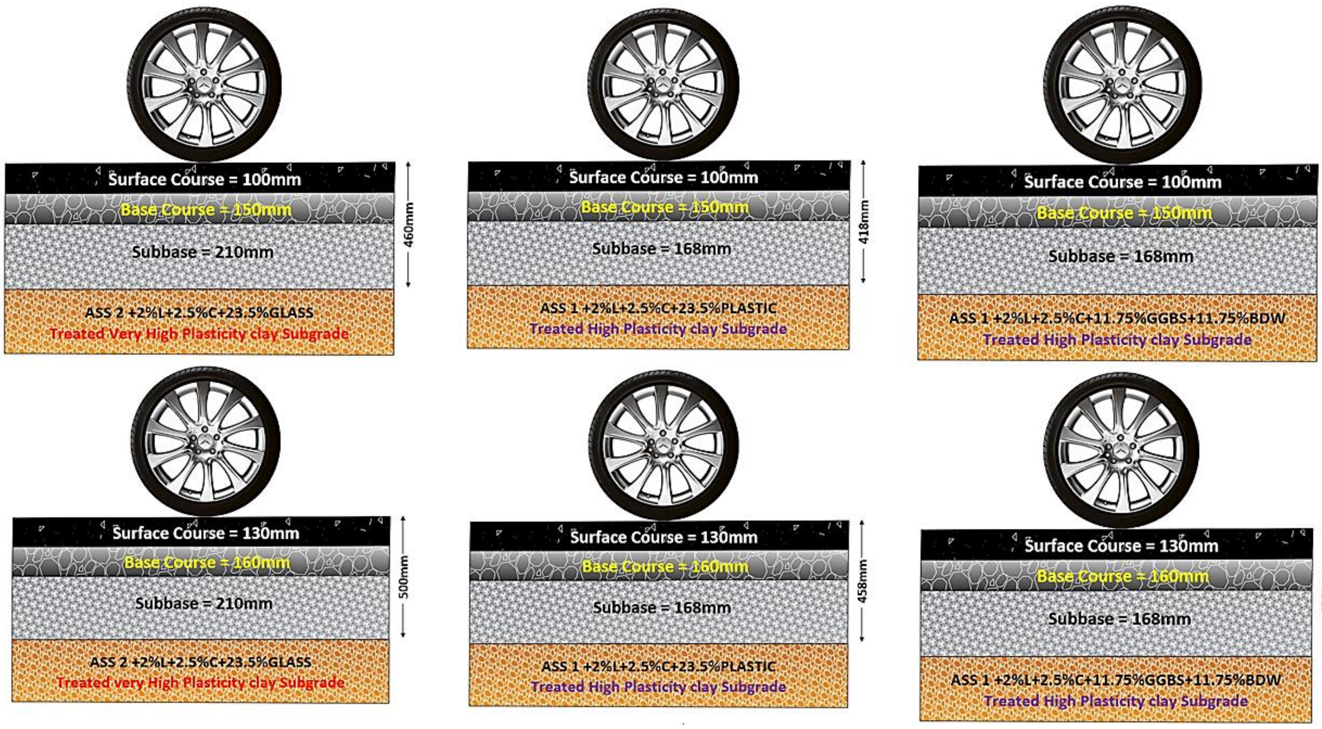


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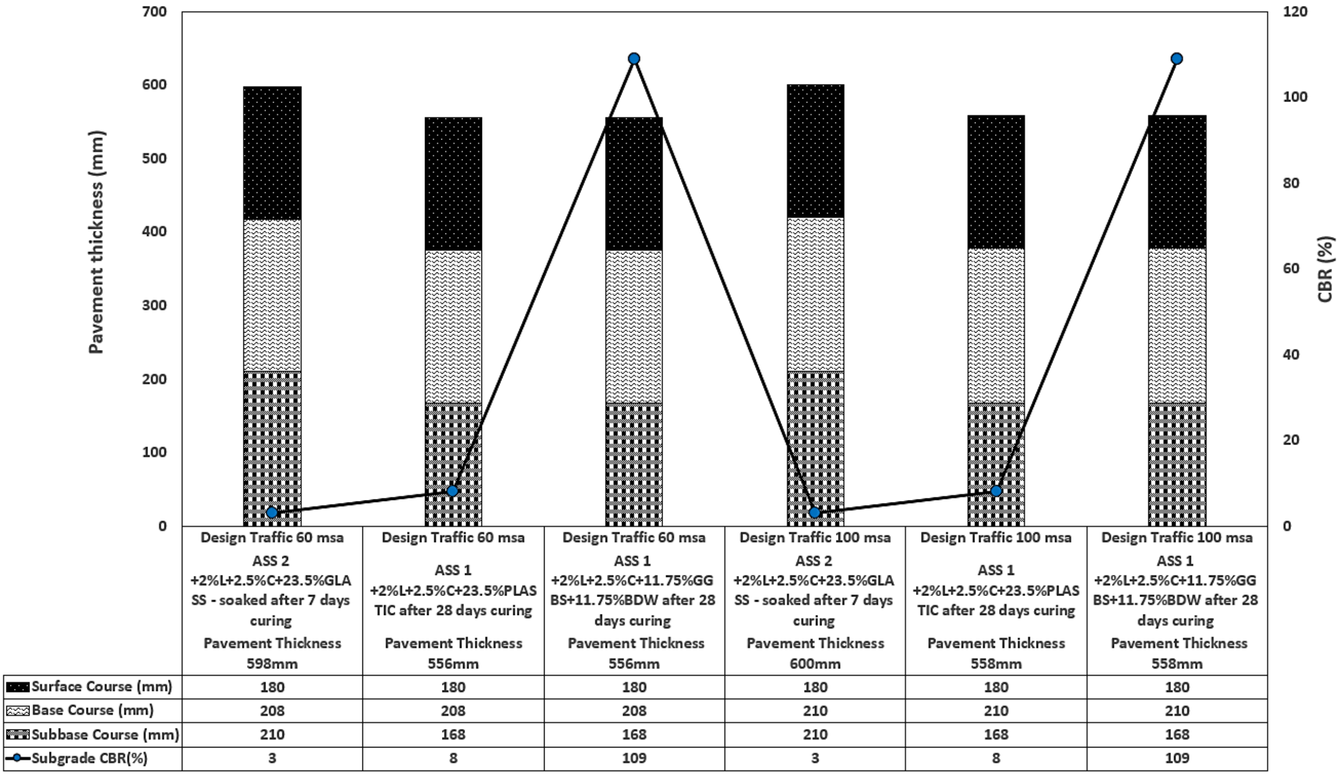
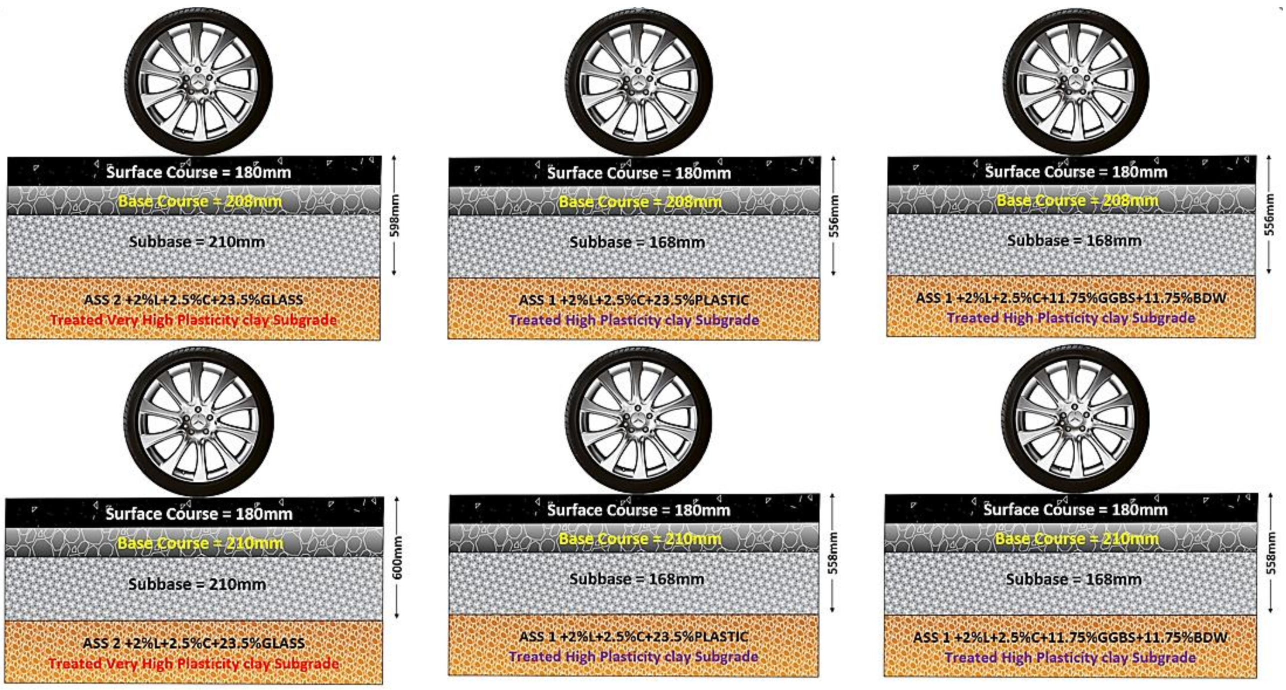
Figure 4. *Cont.*



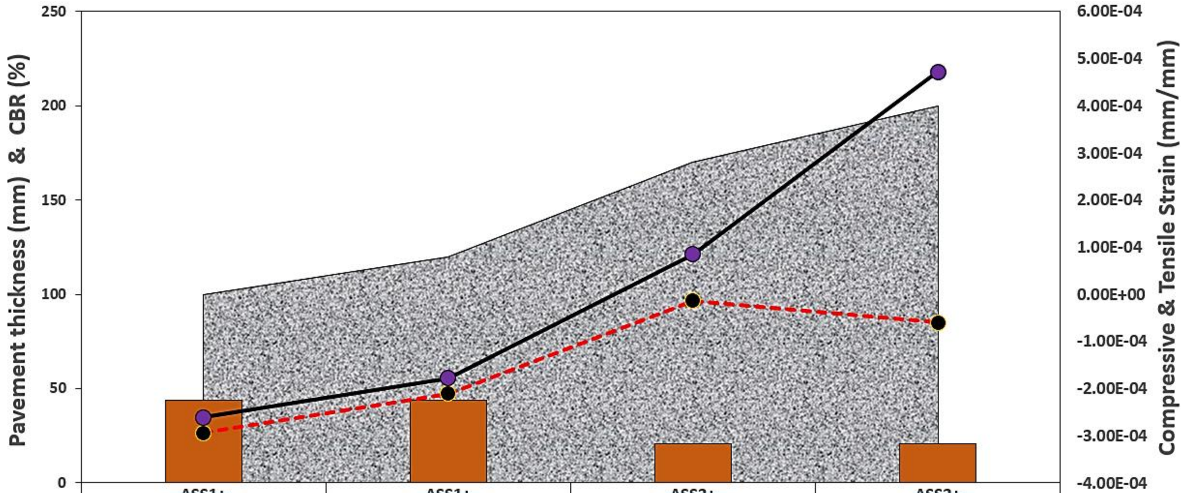


(**b**)

Figure 4. (**a**) Result of road pavement designed using DMRB for traffic 3 msa and 8 msa (**b**) Result of road pavement designed using DMRB for traffic 60 msa and 100 msa.

7. Road Pavement Failure Investigation

Road pavement defect investigations were conducted to determine the level of stresses within road pavement structures using selected CBR values achieved in this study for sustainably treated clay. The level of stress within road pavement structures is determined by the CBR values used in road construction [3,15]. For defects to occur in road pavement is dependent on the severity of the stresses within the road pavement [3]. The pavement defect analysis conducted in this study includes fatigue, rutting and deformation. The stresses within the various layers of the road pavement were analysed using KENPAV software. The procedure used, selected pavement type, design traffic adopted and other parameters used in the defect analysis are as reported in the authors' previous study [3,15]. The equations used in calculating the allowable load repetition for fatigue, permanent deformation and rutting life of the road pavement are as reported in the authors' previous study [3]. After conducting defect analysis, it was observed that clay treated with sustainable waste with low CBR values recorded very high stresses compared with clay with high CBR values. According to [3,25,26], fatigue cracks are initiated in road pavement with high stresses within its clay. Hence, clay with low CBR values achieved in this study are susceptible to defects when used in road construction. However, clay with a high CBR value has less stress making them more durable for use in road construction. Asphalt layer thickness is required to limit stresses within the pavement and reduce the severity of reflective cracking. Due to the low CBR value of 5%, a thicker pavement was required to limit the rate of pavement deterioration due to stress from traffic load [27]. Thicker pavement was observed for clay with low CBR values. The results achieved shows that sustainable waste materials can be used in road clay treatment to reduce the occurrence of defect within a pavement structure. Plastics can be used in flexible pavement to improve its performance against rutting [3,28]. To compensate for clay with low CBR values, road pavements are made thicker to help reduce the stresses within the road structure to prevent defects from occurring. However, the thicker the road pavement the high the overall cost of construction. According to [3,29], road pavement with asphalt thickness below 180 mm deforms quicker but thicker pavement deforms at a lesser rate [3,29]. High elastic modulus was recorded for pavements with high clay CBR values resulting in reduced stresses hence less chances for deformation to occur. A reduction in allowable load repetition for fatigue, rutting and permanent deformation confirms that road pavement with clay treated with sustainable waste can withstand fatigue for a longer period before they occur. A reduction in CBR values reflected in a reduction in allowable repeated loads and an increase in CBR value resulted in an increase in allowable repeated loads for fatigue, rutting and permanent deformation. Failure occurs after a large number of cycles when load repetitions are high and applied stresses are low [3]. However, low load repetitions result in high stresses hence failure occurs after a few cycles due to high stresses above the materials' yield stress [3,25]. Stresses and KENPAVE results are shown in Figures 5–7 showing stresses and KENPAVE results for treated clay and Figure 8a,b shows results for permanent deformation and fatigue and rutting for sustainably treated clay using plastic, glass and brick dust waste.



	ASS1+ 2L+2.5C+11.75GGBS+11 .75PLASTIC) 7 days curing - Light Traffic	ASS1+ 2L+2.5C+11.75GGBS+11 .75PLASTIC) 7 days curing - Heavy Traffic	ASS2+ 2L+2.5C+11.75GGBS+11 .75PLASTIC) 7 days curing - Light Traffic	ASS2+ 2L+2.5C+11.75GGBS+11 .75PLASTIC) 7 days curing - Heavy Traffic
Pavement Thickness(mm)	100	120	170	200
CBR(%)	44	44	21	21
Compressive Strain mm/mm	3.28E-05	3.28E-05	9.83E-05	5.32E-04
Tensile strain mm/mm	-2.94E-04	-2.10E-04	-1.35E-05	-6.01E-05

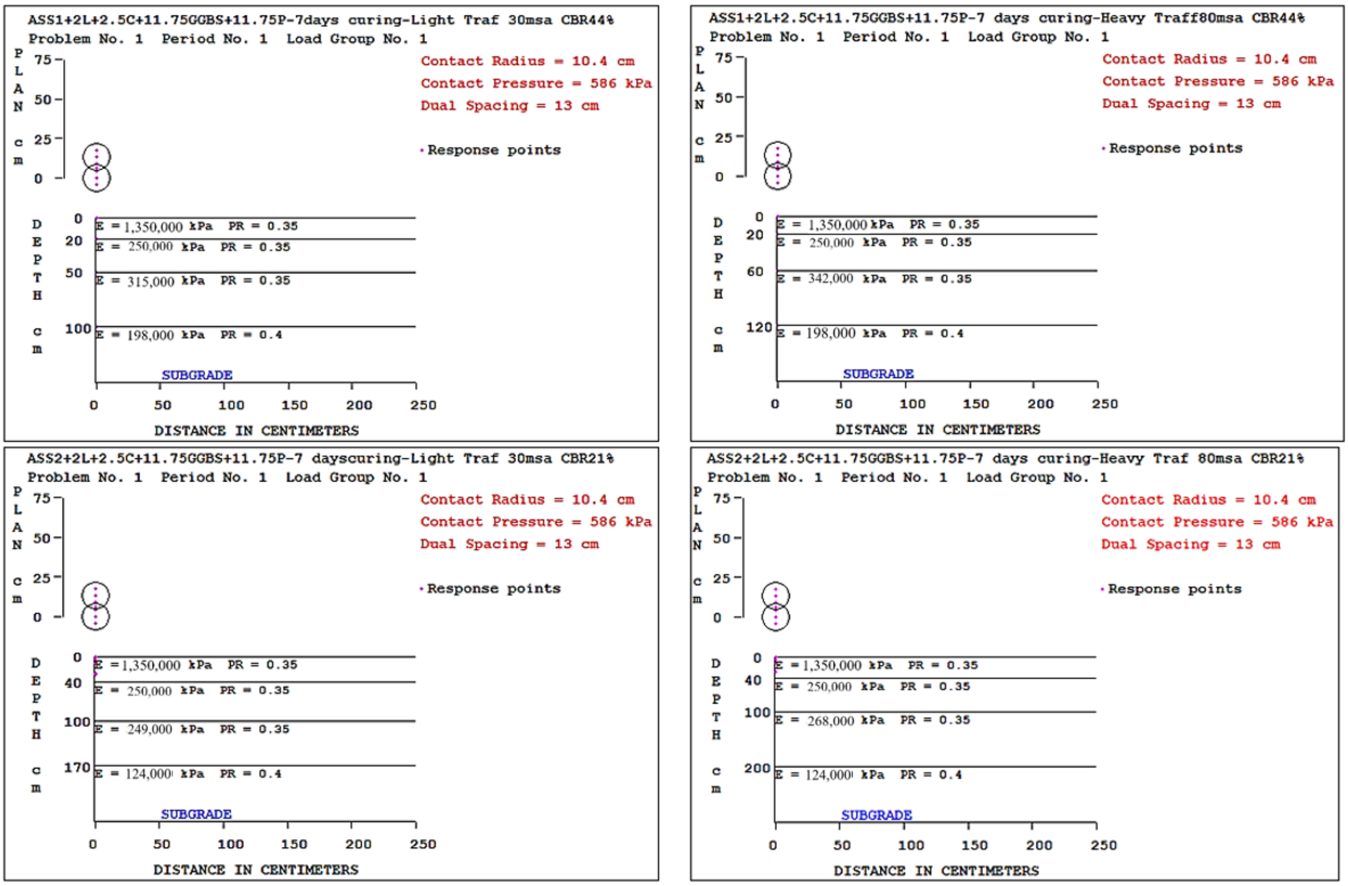
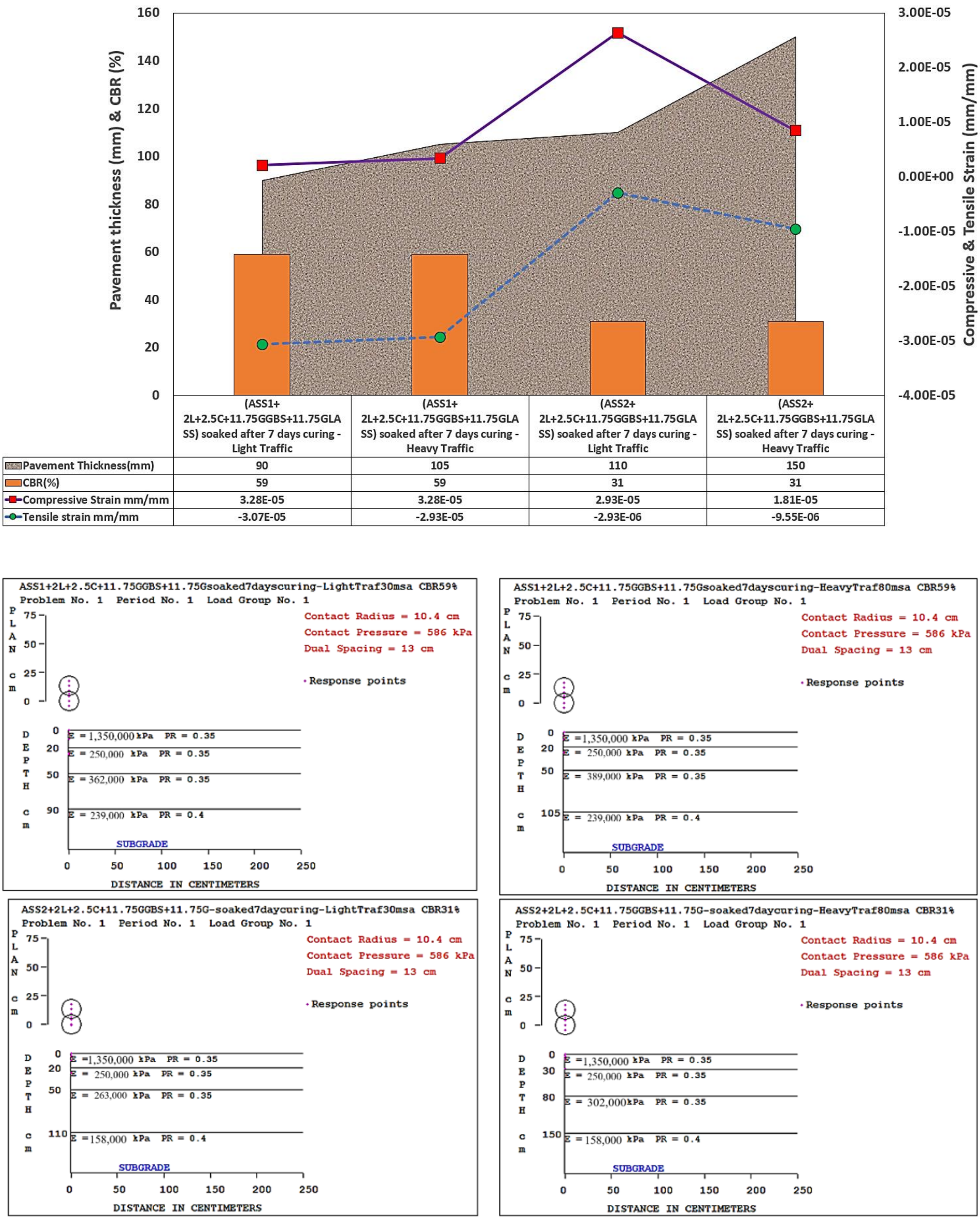
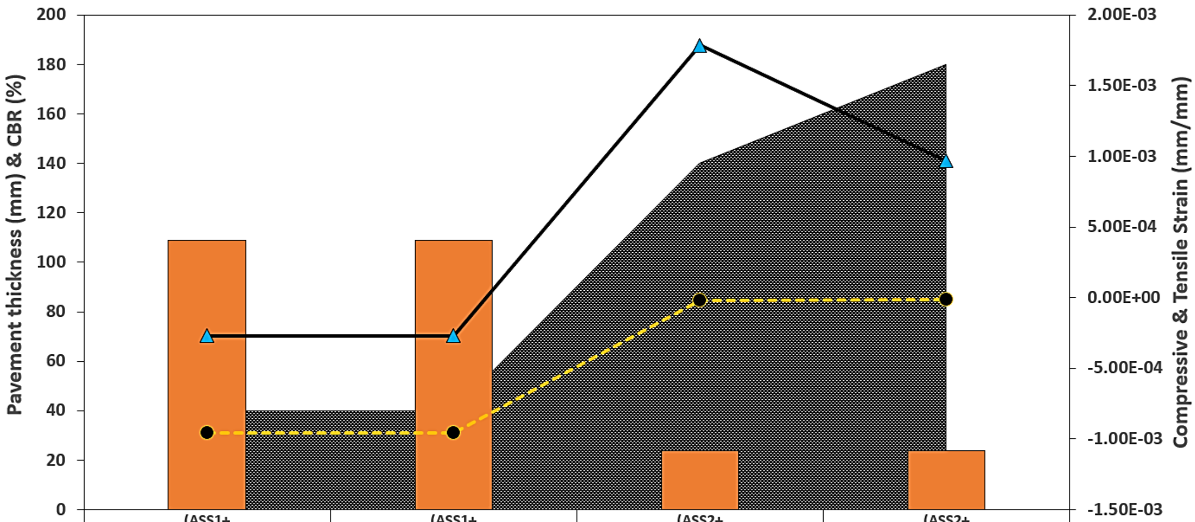


Figure 5. Stresses and KENPAVE results for clay treated using plastic waste.



	(ASS1+ 2L+2.5C+11.75GGBS+11.75GLA SS) soaked after 7 days curing - Light Traffic	(ASS1+ 2L+2.5C+11.75GGBS+11.75GLA SS) soaked after 7 days curing - Heavy Traffic	(ASS2+ 2L+2.5C+11.75GGBS+11.75GLA SS) soaked after 7 days curing - Light Traffic	(ASS2+ 2L+2.5C+11.75GGBS+11.75GLA SS) soaked after 7 days curing - Heavy Traffic
Pavement Thickness(mm)	90	105	110	150
CBR(%)	59	59	31	31
Compressive Strain mm/mm	3.28E-05	3.28E-05	2.93E-05	1.81E-05
Tensile strain mm/mm	-3.07E-05	-2.93E-05	-2.93E-06	-9.55E-06

Figure 6. Stresses and KENPAVE results for clay treated using glass waste.



	(ASS1+ 2L+2.5C+11.75GGBS+11.75BDW) 28 days curing - Light Traffic	(ASS1+ 2L+2.5C+11.75GGBS+11.75BDW) 28 days curing - Heavy Traffic	(ASS2+ 2L+2.5C+11.75GGBS+11.75BDW) 28 days curing - Light Traffic	(ASS2+ 2L+2.5C+11.75GGBS+11.75BDW) 28 days curing - Heavy Traffic
Pavement Thickness(mm)	40	40	140	180
CBR(%)	109	109	24	24
Compressive Strain mm/mm	6.86E-04	6.86E-04	1.81E-03	9.81E-04
Tensile strain mm/mm	-9.55E-04	-9.55E-04	-1.95E-05	-1.15E-05

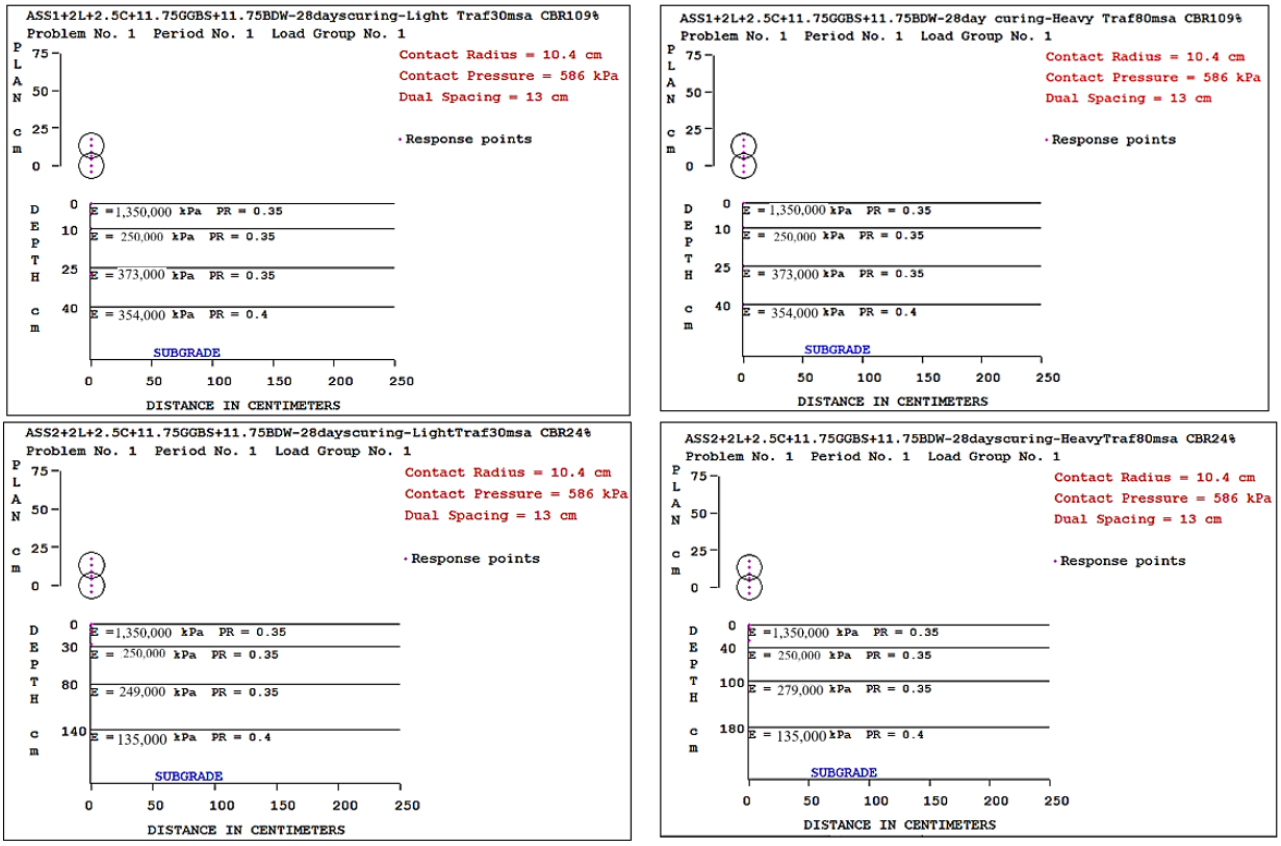
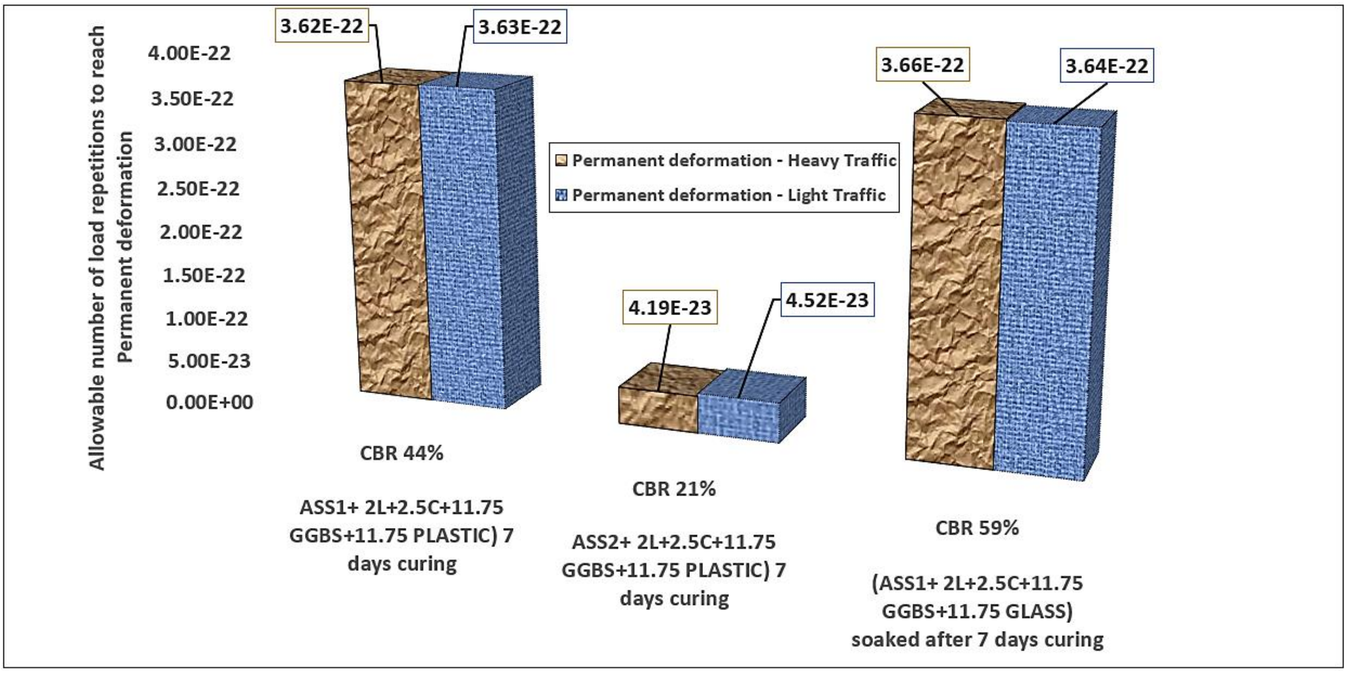
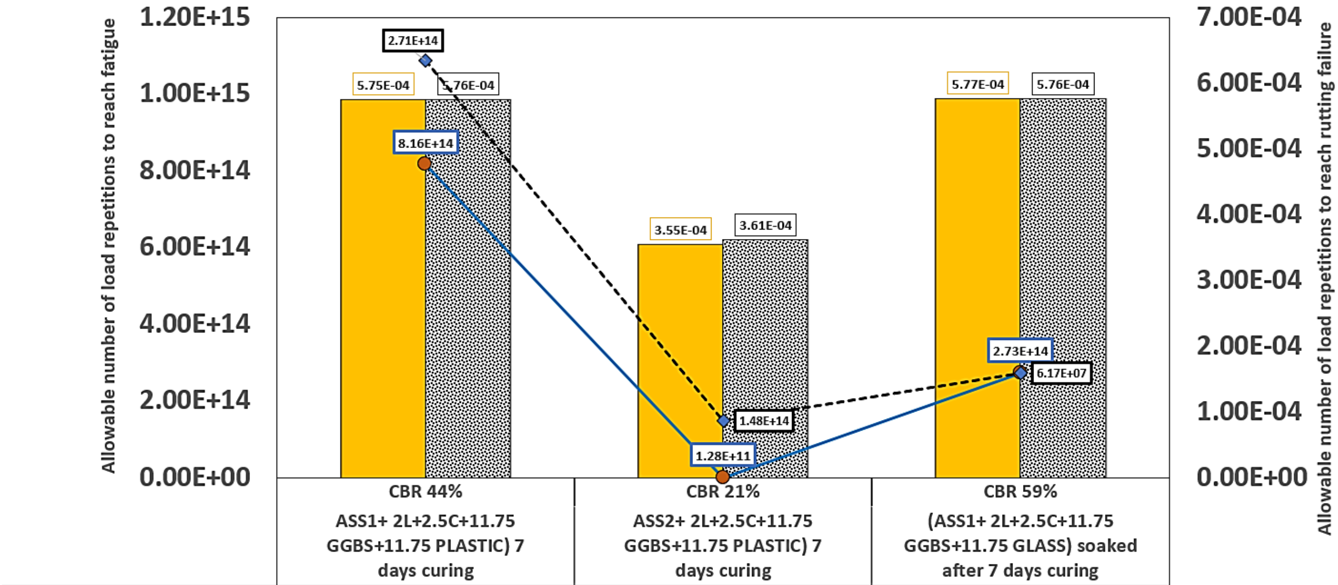


Figure 7. Stresses and KENPAVE results for clay treated using brick dust waste.



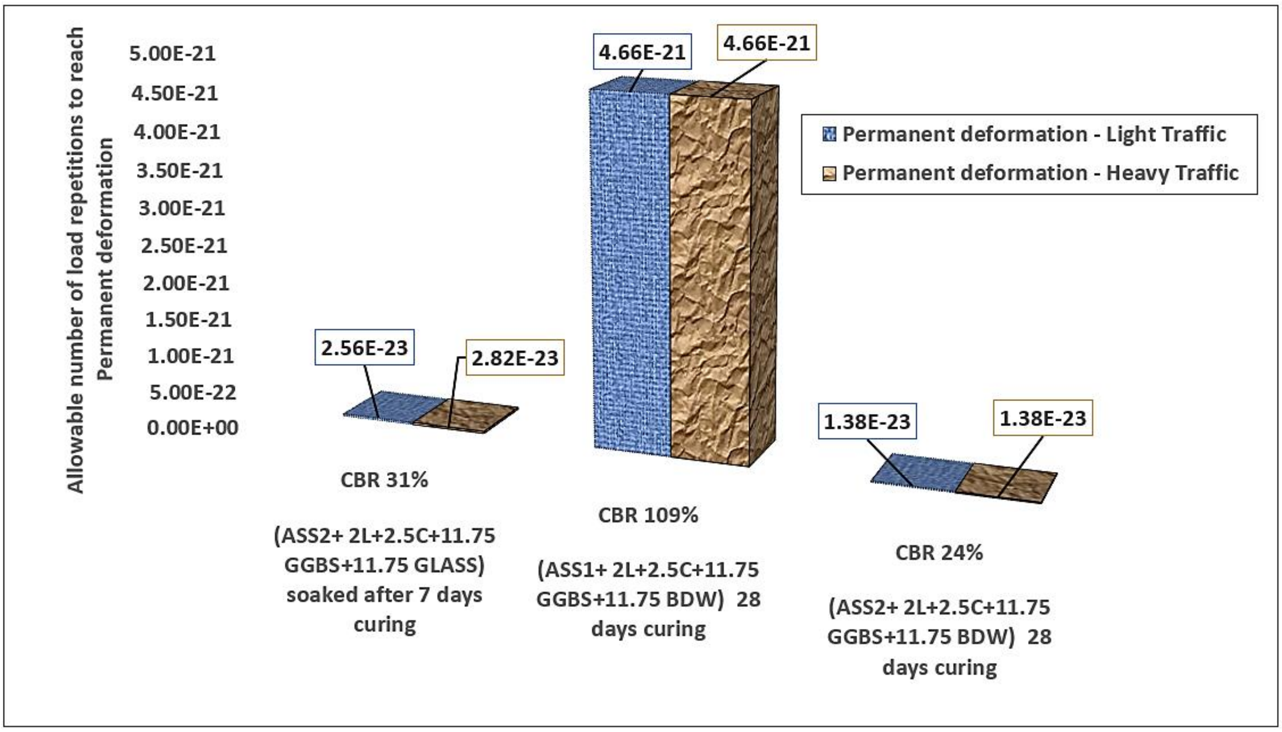
(**a**)



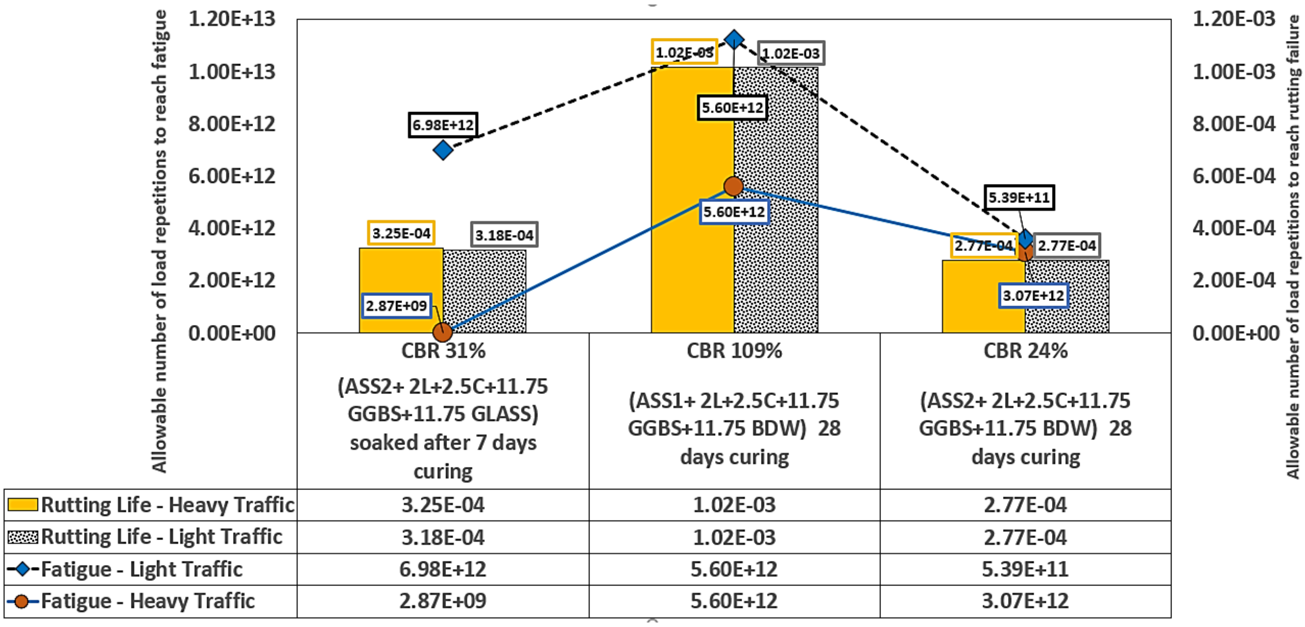
	CBR 44% ASS1+ 2L+2.5C+11.75 GGBS+11.75 PLASTIC) 7 days curing	CBR 21% ASS2+ 2L+2.5C+11.75 GGBS+11.75 PLASTIC) 7 days curing	CBR 59% (ASS1+ 2L+2.5C+11.75 GGBS+11.75 GLASS) soaked after 7 days curing
Rutting Life - Heavy Traffic	5.75E-04	3.55E-04	5.77E-04
Rutting Life - Light Traffic	5.76E-04	3.61E-04	5.76E-04
Fatigue - Light Traffic	2.71E+14	1.48E+14	6.17E+07
Fatigue - Heavy Traffic	8.16E+14	1.28E+11	2.73E+14

(**b**)

Figure 8. *Cont.*



(**c**)



(**d**)

Figure 8. (**a**) results for permanent deformation for clay treated with plastic and glass waste (**b**) results for fatigue and rutting failure for clay treated with plastic and glass waste (**c**) results for permanent deformation for clay treated with glass and brick dust waste (**d**) results for fatigue and rutting clay treated with glass and brick dust waste.

8. Life Cycle Cost Analysis

Life Cycle Cost Analysis in this study was conducted using economic principles based on a range of design traffic to ascertain the long-term cost and economic effects of roads designed using CBR values achieved in this study. Due to the effectiveness of life cycle cost analysis in determining the cost-effectiveness of road pavement, The

United States has made efforts to record life cycle cost analysis state-of-practice for all highways construction [30]. A life cycle analysis (LCA) conducted for sustainable pavement demonstrated lower environmental impacts and is suitable for eco-design in the pavement sector [31]. According to [32], a key factor in multiyear prioritisation is emphasised the use of life cycle cost information in cost calculations. LCCA has gained recognition in the road construction sector as a practice in the sustainability of its infrastructural systems [33]. Life cycle cost analysis (LCCA) is an economic analysis process used to evaluate the cost-efficiency of alternatives based on the net present value (NPV) concept [34]. The LCCA approach was used to develop an inventory of quantitative asset-level models for predicting life cycle costs associated with the preservation and replacement of highway assets [35] RealCost software was used as a tool to investigate the cost and economic effects, agency and user costs during the service life of the road. [36] used RealCost in life cycle cost analyses (LCCA) for infrastructure sustainability. RealCost software was proposed as the preferred software for use in life cycle cost analyses for road pavement [37]. The five sections of the RealCost Switchboard used for data input and results are shown in Figure 9. The initial costs, maintenance cost rehabilitation cost and salvage value of the road were projected using the net present value (NPV) indices in Equation (1). Using Equation (2), the present and future expenditure was converted into annual costs and used to calculate the equivalent uniform annual costs (EUAC) for future budget calculations while Equation (3) was used to calculate the discount rate. Table 3 shows the description of parameters used in LCCA.

$$\text{NPV} = \text{Initial Cons.Cost} + \sum_{k=1}^{N} \text{Future Cost}_K \left[\frac{1}{(1+i)^{n_k}}\right] \text{–Salvage Value} \left[\frac{1}{(1+i)^{n_e}}\right] \quad (1)$$

where:

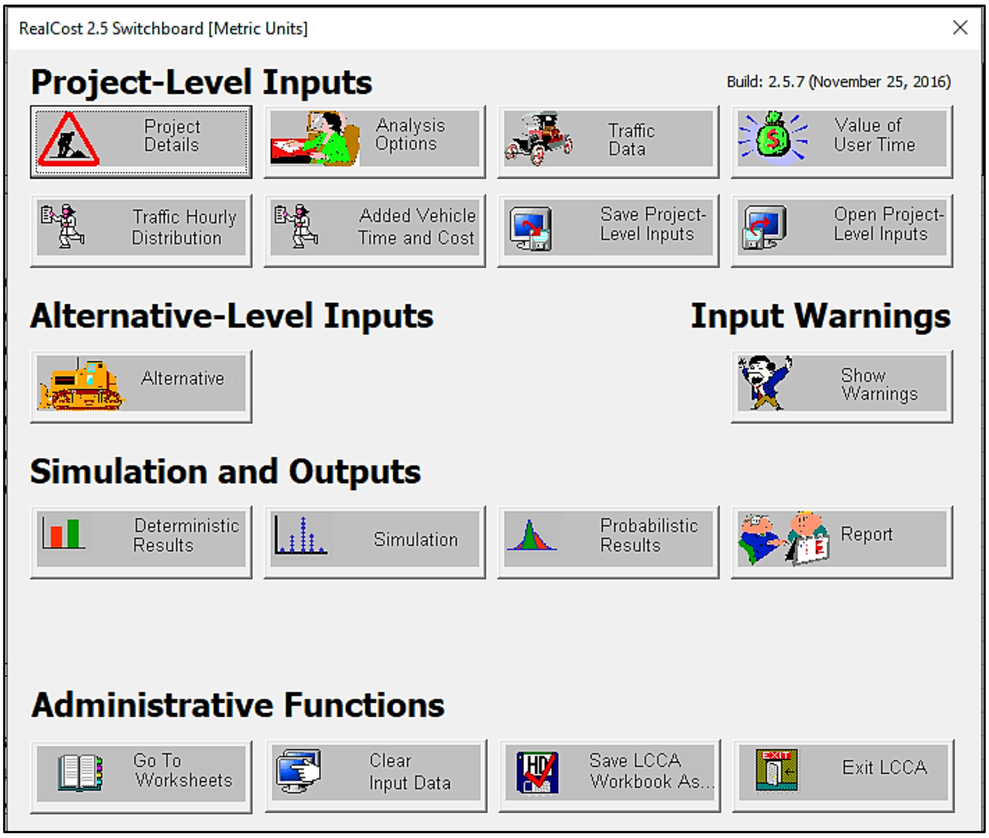


Figure 9. The five sections of the RealCost Switchboard used in this study.

Table 3. Description of parameters used in the LCCA.

Parameters	Description
Initial construction cost (ICC)	This is the cost presented in unit prices and derived from bid records of previous projects.
Maintenance and Rehabilitation cost (M&R)	This is the cost incurred to make sure the road is usable through its service life. This cost is normally M&R retrieved from previous projects.
Salvage value (SV)	Is the evaluation of the road beyond the period of analysis to ascertain the useful life of the road at the end of the analysis.
Discount rate (DR)	This is the rate used to estimate the real value of money based on the difference between inflation and interest rates.
Life Cycle Cost (LCC)	ICC + (M&R × DR)

N = number of future costs incurred over the analysis period
i = discount rate in the present
n_k = number of years from the initial construction to the K^{th} expenditure
n_e = analysis period in years.

$$\text{EUAC} = \text{NPV}\left[\frac{(1+i)^n}{(1+i)^n - 1}\right] \tag{2}$$

where:
i = discount rate
n = years of expenditure.

$$\text{Discount Rate} = \left[\frac{interest - inflation}{1 + inflation}\right] \tag{3}$$

where:
interest = Expected interest rate
inflation = Expected inflation rate.

A CBR value of 80% for clay 2 after 28 days achieved in this study was used to conduct the Life Cycle Analysis (LCCA). Two alternatives were considered during the analysis and the lowest NPV for user and agency costs derived from RealCost software was used to calculate the LCC for a period of 35 years. The initial construction cost composed of user and agency cost, cost of cement and lime treatment was calculated for a square kilometre of the road at year 0. Maintenance costs were calculated at years 6, 19 and 28 and rehabilitation costs were calculated at years 9, 21 and 30, respectively. The salvage cost of the road at year 35 in this study was based on a prorated cost of year 30 rehabilitation. The initial cost of construction was calculated based on a square kilometre of the road at year 0. Rehabilitation and maintenance costs including salvage value for clay removal and replacement were calculated for years 9, 21 and 30, respectively. This brought the Life Cycle Cost of a road with treated clay using cement and lime to GBP268,536,644.10 and Life Cycle Cost for a road with clay removed and replaced with imported materials to GBP488,754,774.64. A vast difference in life cycle cost (LCC) was observed between roads with clay treated using cement and lime and clay removed and replaced with imported materials. The LCC for the road with clay treated using cement and lime was less compared to the LCC for the road with clay removed and replaced with foreign materials. It was observed that the overall life cycle cost of the two types of roads was greatly influenced by the initial cost (user, agency cost and cost of clay treatment) at year 0. According to [38], land acquisition, renovation, modification, construction and equipment cost can increase the initial cost during Life cycle Cost Analysis (LCCA). The study proves that it is cheaper to construct roads using the existing clay compared to removing and replacing roads with clay during construction. It is more economical to design road pavement for the existing subgrade capacity than to import or raise subgrade supports by using an extra-thicker subbase [39]. A gradual increase in maintenance and rehabilitation cost was seen for road pavement with treated clay after year 0. The high maintenance cost compared with rehabilitation cost translated into a drop in salvage value at year 35. Road pavement with clay removed and replaced recorded the highest initial cost at year 0 with a gradual increase in maintenance and rehabilitation cost and a later drop in salvage value. The total cost of treating a square kilometre of road clay using cement and lime against the total cost of removing and replacing a square kilometre of clay can be seen in Figure 10. The NPV derived from RealCost software for agency and user cost for alternatives 1 and 2 can be seen in Table 4. Estimated maintenance and rehabilitation cost and the discount rates used can be seen in Figures 11 and 12. Life Cycle Cost analysis for sustainability treated clay and Life Cycle Cost analysis for road clay removed and replaced with imported materials are shown in Figures 13 and 14.

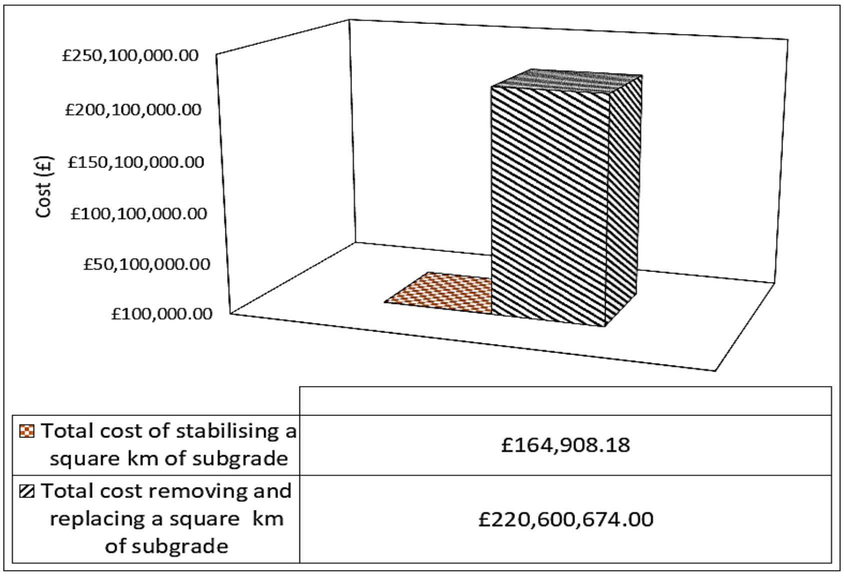


Figure 10. Cost of treating and removing clay.

Table 4. Agency and user cost for alternatives 1 and 1 derived from RealCost software.

Total Cost	**Alternative 1**		**Alternative 2**	
	Agency Cost	**User Cost**	**Agency Cost**	**User Cost**
Undiscounted Sum	GBP 6,000,000.00	GBP 80,000.06	GBP 7,200,000.00	GBP 133,000.43
Net Present Value	GBP 5,521,000.40	GBP 80,000.06	GBP 6,632,000.91	GBP 133,000.43
EUAC	GBP 295,000.82	GBP 4000.29	GBP 355,000.37	GBP 7000.15
Lowest Net Present Value Agency Cost		Alternative 1		
Lowest Net Present Value User Cost		Alternative 1		

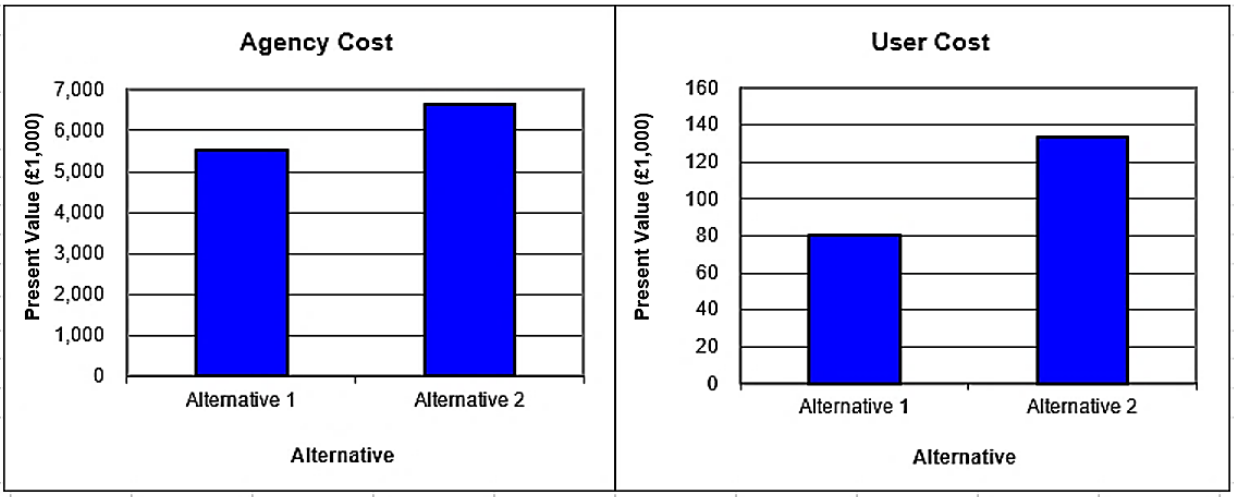


Figure 11. NPV results from RealCost software for agency and user cost for alternatives 1 and 2.

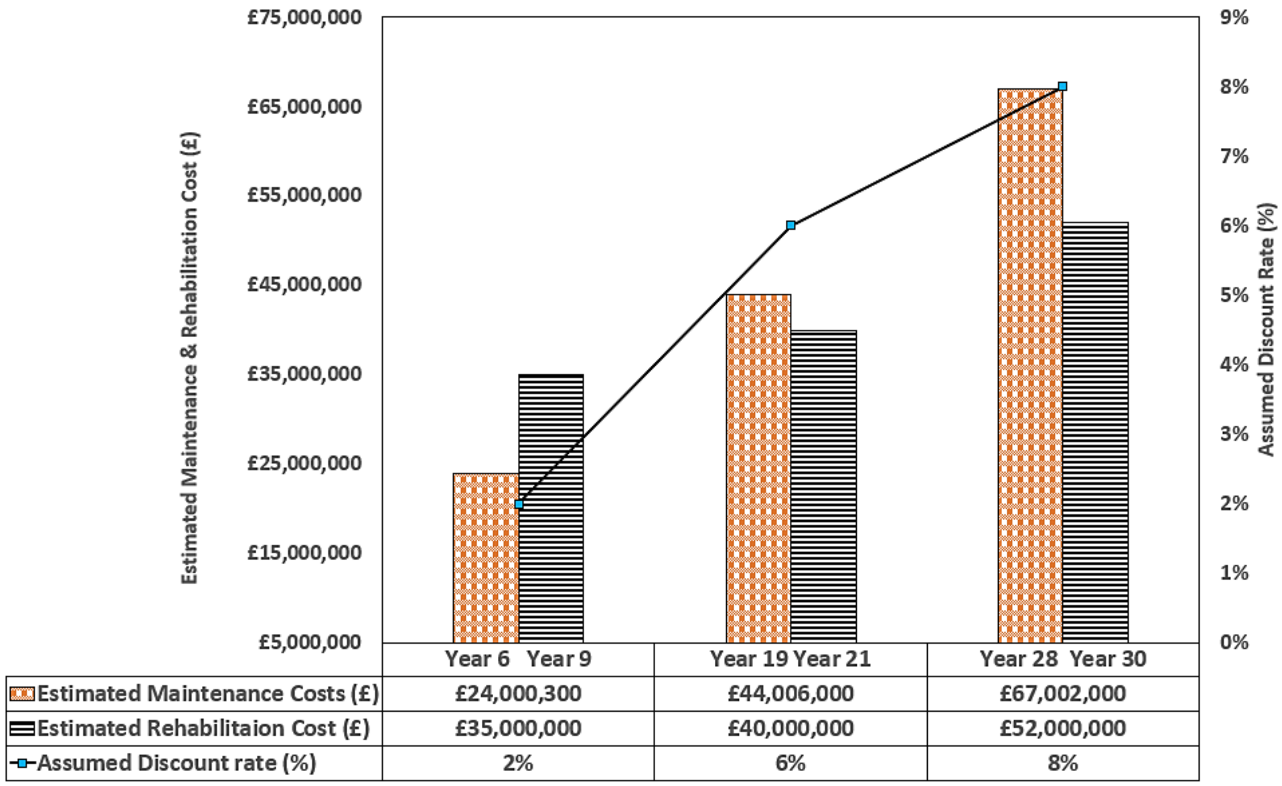


Figure 12. Discount rate, estimated maintenance and rehabilitation cost.

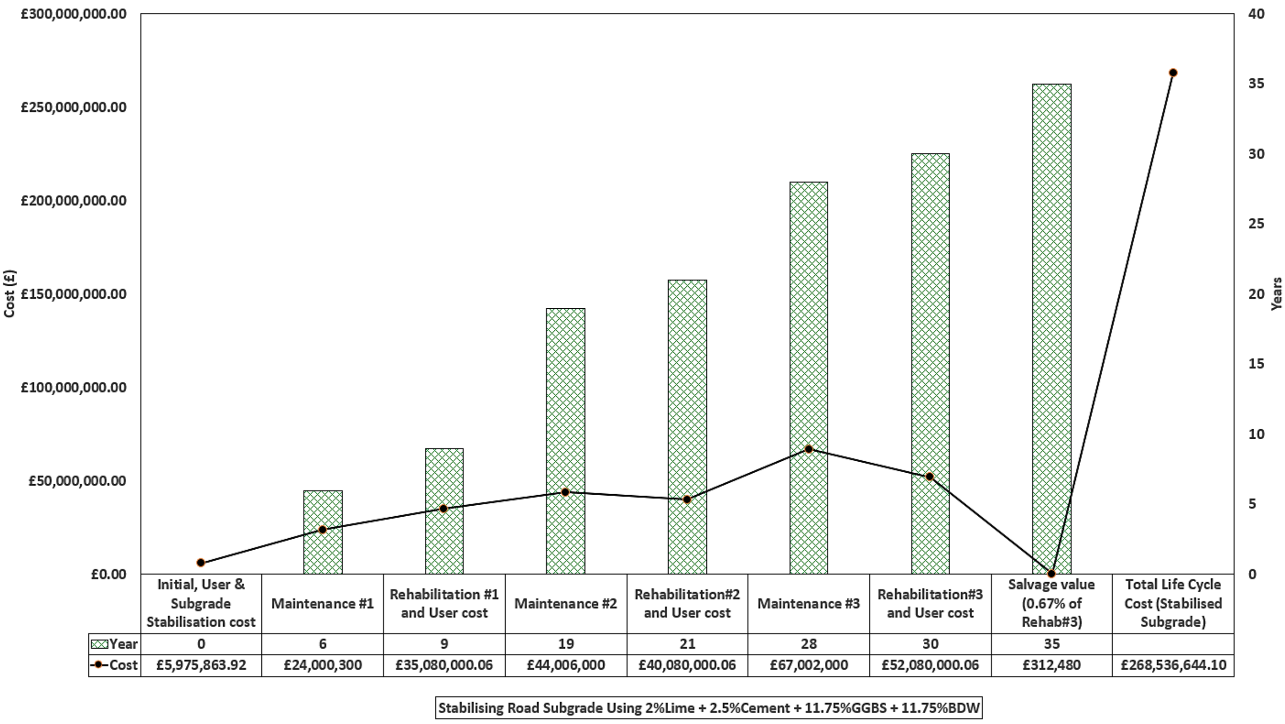


Figure 13. Life Cycle Cost analysis for sustainability treated clay.

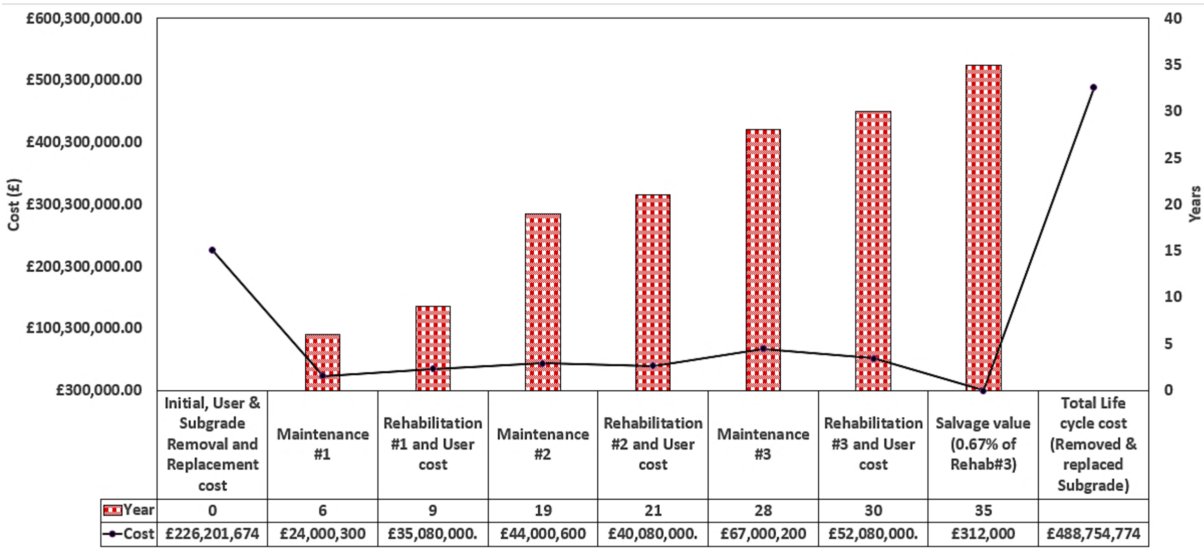


Figure 14. Life Cycle Cost analysis for road clay removed and replaced with imported materials.

9. Embodied Carbon Associated with Mix

The lowest embodied carbon was recorded for mix design 2% Lime + 2.5% Cement + 23.5% GGBS (0.0018 Co_2e/kg) compared with the control mix 8% Lime + 20% Cement of 0.0084 Co_2e/kg. However, sustainably treated mix recorded low embodied carbon except for mixed designs containing plastic. The highest embodied carbon of 0.0107 Co_2e/kg was recorded for 2% Lime +2.5% Cement +11.75% GGBS +11.75% Plastic as a result of the plastic because plastics have very high embodied carbon. [40] stated that plastics are carbon more specifically because almost all plastics are fossil carbon locked up in polymer form. Control mix 8% Lime + 20% Cement recorded the lowest Life Cycle Cost (£268,344,106.46) for treated clay followed by mix design 2% Lime + 2.5% Cement + 23.5% GGBS (£268,433,336.06). However, there was no significant difference in their LCC which makes using waste materials in clay treatment the best option for achieving more sustainable construction. Even though traditional cement and lime are cheaper compared with sustainable waste-treated clay, they are none-environmentally friendly and unsustainable due to their high embodied carbon. Table 5 shows the classification of parameters and embodied Carbon.

Table 5. Classification of Parameters and Embodied Carbon.

S/N	Binder Composition	CBR Range (%)	Embodied Carbon for Binders (Co_2e/kg) (BSRIA Guide 2022 [41])	Life Cycle Cost (LCC) 35 Years	
				Treated Clay	Clay Removal and Replacement
1	8% L + 20% C (control)	38–96	0.0084	GBP268,344,106.46	GBP488,754,774.64
2	2% L + 2.5% C + 23.5% BDW	17–23	0.0036	GBP268,447,414.50	GBP488,754,774.64
3	2% L + 2.5% C + 23.5% GGBS	46–97	0.0018	GBP268,433,336.06	GBP488,754,774.64
4	2% L + 2.5% C + 23.5% PL	3–13	0.0195	GBP268,998,357.71	GBP488,754,774.64
5	2% L + 2.5% C + 23.5% GL	3–17	0.0069	GBP268,383,764.06	GBP488,754,774.64
6	2% L + 2.5% C + 11.75% GGBS + 11.75% BDW	16–109	0.0028	GBP268,536,644.10	GBP488,754,774.64
7	2% L + 2.5% C + 11.75% GGBS + 11.75% PL	44–93	0.0107	GBP269,087,587.31	GBP488,754,774.64
8	2% L + 2.5% C + 11.75% GGBS + 11.75% GLASS	21–80	0.0072	GBP268,472,993.66	GBP488,754,774.64

Where L = Lime, C = Cement, GGBS = Ground Granulated Blastfurnace Slag, PL= Plastic, GL = Glass, BDW = Brick Dust waste.

10. Conclusions

Conducting road pavement design, defect analysis and Life Cycle Cost Analysis (LCCA) using clay treated with eco-friendly waste materials achieved good results in this study therefore the study concludes on the following:

1. Road pavement thickness reduced with an increase in CBR value however, there was no significant difference between pavement thickness.
2. CBR values from 2–5% only recorded high pavement thickness as a result thicker subbase layer influences the overall thickness of the pavement.
3. Defects are less likely to occur due to high CBR values recorded resulting in low stresses within the pavement structure.
4. High allowable repeated loads were recorded for subgrade with high CBR value resulting in the ability of road pavement to withstand several cyclic loading before failure occurs.
5. The study reveals the possibility of treating clay using waste materials which would help reduce the problem of landfill and greenhouse gas emissions and the environmental effects associated with cement and lime production while reducing our overreliance on natural resources such as clinker used in cement production.
6. Road pavement constructed using clay removed and replaced with foreign materials recorded the highest Life Cycle Cost. Compared to the Life Cycle Cost of road pavement constructed using clay treated with waste. The study confirmed that road pavement constructed using clay treated with waste is cheaper and more economical compared with road pavement with clay removed and replaced with imported materials.
7. The Life Cycle Cost (LCC) of a road is greatly influenced by the initial cost such as agency, user cost and subgrade treatment cost. Year 0 to year 19 observed a gradual increase in maintenance and rehabilitation costs as road pavement age increased. Followed by a reduction in rehabilitation cost in year 21 with an increase in maintenance cost in year 28. Both road pavements recorded the same salvage value.
8. Decision-makers, road contractors and engineers can quickly refer to this study when deciding on the Life Cycle Cost (LCC) of road projects with subgrade characteristics and parameters similar to what was used in this study.

9. To save money in road construction, this study recommends that clay or weak subgrades should be treated for use in road construction instead of removing subgrades and replacing them with imported materials. The cost of road pavement can be reduced by achieving good CBR values and thinner pavement thickness through subgrade treatment using cement and lime as binders.
10. This study would encourage the use of waste materials dumped in landfills in ground improvement and road construction. This would promote greener, sustainable and eco-friendly ways of road construction to help battle the climate change problems faced today.

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