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Performance Prediction and Validation of Railway Ballasted Trackbed and Crumb Rubber Modified Asphalt-Ballast Trackbed in the Tropics

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Abstract

The granular sub-ballast in ballasted trackbed, though cheap and easy to construct, requires frequent maintenance, and cannot protect the subgrade against water infiltration. However, asphaltic sub-ballast in asphalt-ballast trackbed can reduce stresses on the subgrade and provides a waterproofing layer against water infiltration. The aim of this research, therefore, is to replace the granular sub-ballast with asphaltic sub-ballast, and compare the performance of the two track types. The study used the finite element package, KENTRACK software to calculate the tensile strains and compressive stresses, in five different layer thicknesses of granular sub-ballast and asphaltic sub-ballast. The calculated tensile strains and compressive stresses were used to predict the service lives of the two track types, using multiple regression analysis. The numerical simulation results showed that the asphalt-ballast trackbed has a much longer predicted service life than the ballasted trackbed. The inclusion of asphaltic sub-ballast in the trackbed reduced deformations and stresses on the subgrade. One significant finding was that the service life of asphalt-ballast trackbed due to 100 mm thick asphaltic sub-ballast was 33.28 years, while the service life of ballasted trackbed due to 200 mm thick granular sub-ballast was 28.56 years, under the same loading conditions. KENTRACK software results were validated by using measuring devices. Results showed no significant difference between the KENTRACK predicted and the validation values. The study concludes that asphaltic sub-ballast, offers higher ability to transmit stresses down to the subgrade, resulting in increased service life. It reduces maintenance costs and ensures passenger's comfort and safety.

1.0 Introduction

Although asphaltic mixtures, which are frequently used in flexible pavement, are intended to endure for 20 years, but they break down sooner than expected because of the emergence of heavier vehicles with higher axial loads [1]
There are several environmental implications associated with the construction of a new flexible pavement, as it requires a significant amount of energy and resources. Additionally, the primary source of bituminous binder, being

crude oil, has seen a significant increase in price in recent years. As a result, bituminous mixtures are now more expensive. The bituminous pavement industries may become more sustainable and cost-efficient by creating new materials and technologies that integrate waste, recycled resources, and greener components into the bituminous mix manufacturing cycle. Because people are more worried about the effects that pavement construction will have on the environment, sustainable materials are being used more and more in pavement construction. In order to conserve the natural resource base and mitigate the ecological issues associated with the disposal of solid wastes, sustainable pavements are planned and built. The primary goal of sustainable infrastructure development is violated by the widespread use of natural aggregates in pavement construction and maintenance [2]. All types of pavement need to implement sustainability goals, but this research is particularly interested in flexible pavement since it is more commonly used in tropical regions like Nigeria and other parts of the world.

Sustainable and environmentally safe materials are used in the construction of a green flexible pavement [3]. In Europe and around the world, conventional ballasted track structures with granular trackbed is very common and popular, because it is cheap and easy to construct [Figure 2]. This kind of trackbed presents good results but, in most cases, require frequent maintenance to ensure adequate operating conditions. Whereas one of the main aims of railway companies is to limit track maintenance costs, therefore, the all-granular trackbed needs to be replaced with a solution that gives better performance as well as lower costs of maintenance and operation. It is important to find alternative solutions that are cheaper to construct, and yet offer satisfactory performance.

In this study, to achieve this objective asphaltic sub-ballast was used to replace the granular sub-ballast in various configurations, on Abuja to Kaduna railway line, in order to enhance the performance of railway infrastructure and contribute to the reduction of track maintenance needs [Figure 3].

The study was carried on a high-speed railway line in Nigeria. Nigeria is situated between latitudes 40N and 140N and longitudes 20E and 150E, respectively. It is 923, 768 square kilometers in total area, and it is situated between the Tropic of Cancer and the Equator. Nigeria's latitude is in the tropical zone, yet the country's climate is not entirely tropical. The northern and southern regions of Nigeria have different climates. The northern region experiences an arid environment, whereas the southern region experiences an equatorial climate.

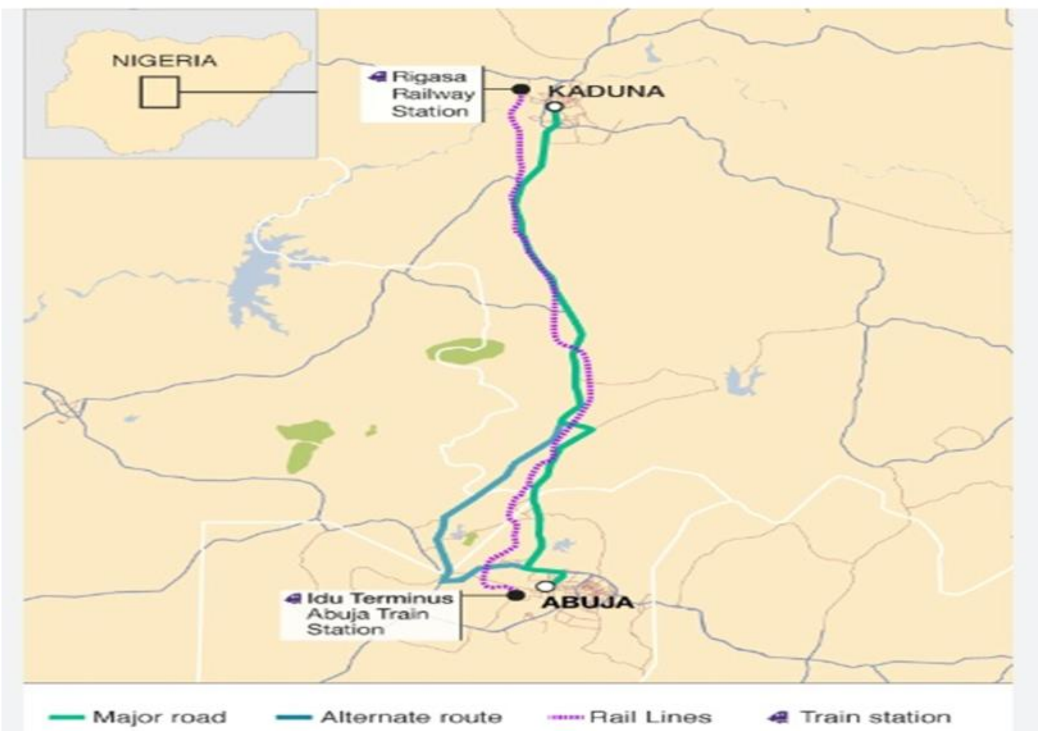

Figure 1. Map showing the Abuja to Kaduna high-speed railway line

The trains depart Idu in the Federal Capital Territory and travel to Rigasa in the Northwest Nigerian state of Kaduna. Abuja to Kaduna railway line has nine stations, namely Idu, Abuja. with Latitude 9^0 04’ 07.9’’ N, Longitude 7^0 21’ 10.7’’ E, Kubwa, Abuja, with Latitude 9^0 8’ 28’’ N, Longitude 7^0 21’ 9’’ E, Asham, Kaduna state, with Latitude 10^0 20’ 60.0’’ N, Longitude 8^0 16’ 60.0’’ E, Jere, Kaduna state, with Latitude 9^0 34’ 8’’ N, Longitude 7^0 26’ 6’’ E, Gidam, Kaduna state, with Latitude 10^0 42' 14'' N, Longitude 7^0 44' 54'' E, Rijana, Kaduna state, with Latitude 10^0 8' 35'' N, Longitude 7^0 47' 41'' E, Dutse, Kaduna state with Latitude 10^0 28' 06'' N, Longitude 7^0 27' 44'' E, Kakau, Kaduna state, with Latitude 10^0 22' 45'' N, Longitude 7^0 23' 29'' E, and Rigasa, Kaduna state with Latitude 10^0 31' 47'' N, Longitude 7^0 22' 45'' E.

Like other parts of Nigeria, the climate of Abuja and Kaduna, in Northern Nigeria are primarily influenced by temperature, wind, pressure, atmospheric humidity, and precipitation.

Abuja has a tropical climate, with two main types of tropical climates occurring there: wet and dry. There are three distinct weather patterns in Abuja each year; the warm season, the humid rainy season, and the dry season. The temperature can reach as high as 40 ^{0}C during the day and as low as 15 ^{0}C at night during the dry season. Abuja's weather is influenced by its medium height and undulating terrain. The city has higher daily temperature fluctuations than coastal towns like Lagos because of its inland location.

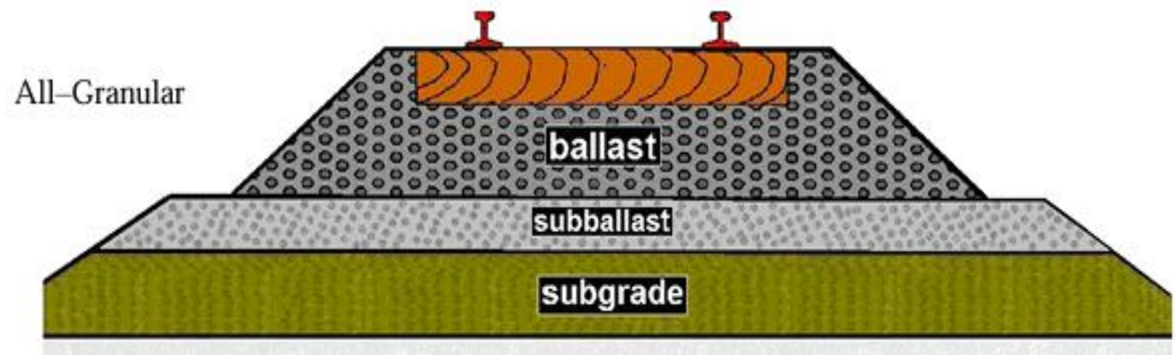

Figure 2. Layout of the components of ballasted (All-granular) trackbed sample [4]

The components of ballasted track structure (Figure 2), in this study are :

- Ballast
- Granular sub-ballast, and
- Subgrade

However, the asphaltic layer is normally used together with granular materials, as an intermediate solution. It is laid between the ballast and subgrade [Figure 3]. This solution was employed in the first Italian high-speed line and also in Japan, for example. The experience obtained in Italy after 20 years showed a good long-term structural behaviour [4].

This study is justified, in that, it will assist in the resolution of some of the world's most difficult problems, as well as making significant contributions to sustainable living and the United Nations Development Goals, which aim to "Ensure a Sustainable Future for All."

The study's findings will have impact on Nigeria and the entire world by making life more equitable and sustainable for all people and protecting the environment through applied research.

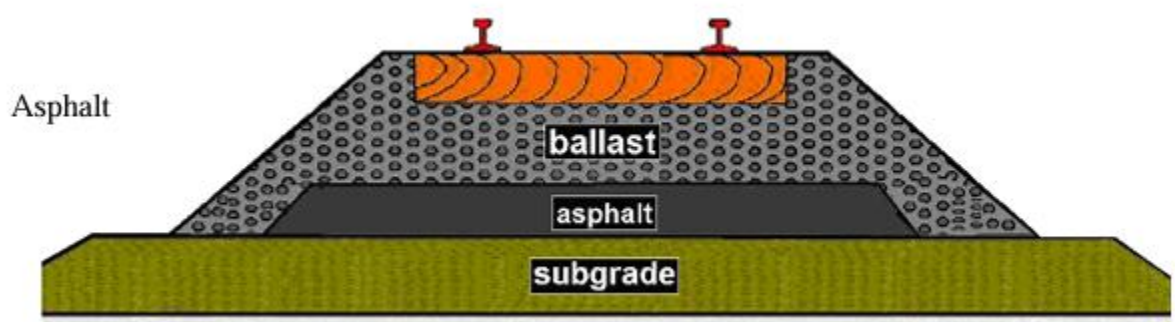

Figure 3. Layout of the components of asphalt-ballast trackbed sample [4]

The components of asphalt-ballast track structure (Figure 3), in this study are:

- Ballast
- Crumb rubber modified asphaltic sub-ballast, and
- Subgrade

1.1 The environment and health - Tyre wastes or end-of-life tyres are burned in the open space on a daily basis across Africa, causing environmental pollution. Carbon monoxide (C_O) levels in tyre fires can reach 50,000 parts per million (ppm). Meanwhile, carbon monoxide has an allowable exposure limit of 50 parts per million (ppm). The quantity of polycyclic aromatic hydrocarbons (PAHs) discharged into the environment is one of the issues surrounding tyre waste disposal [5]. Numerous PAHs are commonly known as teratogens, mutagens, and carcinogens, and as such, they represent a serious risk to human health and welfare [6].

When carbon monoxide is discharged into the atmosphere without being purified, it can replace oxygen in the blood, reducing the amount of oxygen available to the heart, brain, and other critical organs. Anoxemia, a condition that can cause permanent harm or even death, may arise from this [7]. When tyres are burned at low temperatures, dioxins and furans are created. As these dioxins move up the food chain, their concentrations are continually amplified, a phenomenon known as bio-magnification.

Skin rashes, liver damage, cancer, and issues with development and reproduction have all been linked to high dioxin levels in the body. In addition, children are far more vulnerable than adults.

1.2 Sustainability - Maintenance of the conventional ballasted trackbed used on Nigerian rail lines necessitates regular replacement of new ballast. This requires more quarrying, which harms the environment, depletes scarce natural resources, and consumes a lot of energy. Presently, in Nigeria, this energy is not enough to meet our needs. Nigerian railway lines are made up mostly of granular-only materials and have ballasted platforms (sand and gravel). One issue with this solution is that it requires high thicknesses in some cases to fulfill the minimal strength requirements for high-speed railway operations.

The ballast used in Nigeria is 300 mm thick, while the sub-ballast has a thickness of 200 mm, meaning that a lot of aggregate is being consumed in the process, while the asphaltic sub-ballast, when used to replace the granular sub-ballast, will offer more adequate bearing capacity, and with a thickness of about 120-150 mm or even less, as opposed to the ballasted track currently in operation. Furthermore, it does not involve regular maintenance, has strong long-term systemic conduct, and lower overall life-cycle costs.

1.3 Whole-life cycle costs - Nigeria is actively investing in the construction of high-speed railway lines, after discovering that, among the various forms of transportation, railways are well suited for transporting vast quantities of heavy goods and bulk goods, as well as passengers, over long distances in a clean, comfortable, and convenient manner.

The ballasted trackbed being used in Nigeria is increasingly degrading due to increased traffic intensity and axle load. Meanwhile, since Nigeria's economy is over 90% reliant on oil and gas, and the country's budgetary provision for transportation infrastructure growth is decreasing. The Nigerian government is finding it difficult to fund capital projects owing to the uncertainty in the oil and gas prices, as well as the vagaries of market forces. Crumb rubber modified asphalt-ballast trackbed is required in Nigeria to reduce the rapid degradation of the ballasted trackbed, and frequent and costly maintenance, particularly now that all indices show that Nigerian economy is not strong. As a result, using crumb rubber from end-of life tyres reduces the costs of construction, it also has a lower environmental footprint, making sure that the air we breathe is safe and the natural resources are preserved for the next generation.

1.4 The effects of burning waste tyres on Environment

The importation of all types of motor vehicles into Nigeria, has increased in tandem with her rapid population growth and wealth expansion. The quantity of end-of life tyres produced on a regular basis has increased as a result of this shift in consumption patterns. Consequently, there is a significant concentration of this solid waste in an amount that is detrimental to the environment.

Approximately 800 million tyres are discarded globally each year [8]. About 260 million tyres were generated as end-of life tyres in the US in 2019 [9]. By the 2030s, it is predicted that 1.2 billion tons of end-of life tyres will be produced annually worldwide [10]. According to some estimates, there are currently 1.5 billion tyres discarded annually worldwide, and by 2030, that number is predicted to rise to 5 billion tyres [11].

In order to address these issues, residents frequently end up burning these discarded tyres, a practice that has become very popular in third world countries. In addition to other industrial chemicals, tyres are made of natural and synthetic rubber, sulfur, filler, accelerators, antioxidants, textiles, and optional steel wires.

End-of life tyre is frequently recycled into a variety of products, such as outdoor items that have a high risk of releasing chemicals or tyre fragments into the surrounding environment [12].

For instance, the majority of end-of life tyres utilized in California, USA, involve its incorporation into construction projects, burning for fuel, and producing crumb rubber out of it. Tyres have a similar use around the world, with the majority being recycled or used to produce electricity. Tyres are frequently recycled into items like tyre buffings and tyre crumb that include microplastic [13].

The majority of these substances originate from hydrocarbons, and when they are heated to extremely high temperatures during combustion, air pollutants are most likely to be present in the emissions [14, 15]. Additionally, tyres contain a variety of heavy metals, including silicon, tin, titanium, zinc, aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, magnesium, manganese, mercury, nickel, selenium, and zinc [16, 17].

End-of life tyres have been linked to environmental issues due to the disposal procedure and air pollutants from open burning. Thick black toxic smoke that comes from burning end-of life tyres outside produces large toxic residues and dangerous gaseous emissions [18].

Burning tyres can release gaseous pollutants and toxic residues that can seriously endanger public health and safety as well as damage the environment. Another significant contaminant from the open burning of discarded tyres has been discovered to be black carbon.

The majority of these pollutants, particularly dioxins, travel great distances from the places where they are released, and remain in the atmosphere for decades without decomposing into less dangerous forms, and eventually end up in food, water, and soil, posing a risk of poisoning for future generations [19, 20].The length and intensity of exposure to the emissions from open burning of end-of life tyres have been associated with a number of health issues, including respiratory problems, skin and eye irritations, and nervous system challenges [21].

1.5 Modified Bituminous Binders

Recently, hot bituminous mixtures have gained popularity in the construction of railway tracks, particularly in the sub-ballast layer. This is because, in contrast to the traditional granular sub-ballast layer, these materials can provide the subgrade with more protection and higher bearing capacity. If bituminous binders are not modified, they face the following problems:

The process of choosing which asphalt binder and aggregate to employ, as well as the best possible combination of these two components, is known as hot mix asphalt (HMA) mix design. A well-designed HMA mix should have the following qualities: workability, fatigue resistance, resistance to low-temperature cracking, resistance to deformation, durability, resistance to moisture susceptibility, and skid resistance. The qualities of the asphalt mixture and the asphalt binder, or bitumen, are generally connected to its ability to resist pavement distresses. In general, pavement distresses are related to asphalt binder (bitumen) and asphalt mixture properties.

Among the main distresses that cause the pavement surface to permanently fail are rutting and fatigue cracking. And, typical asphalt lacks the resilience and dynamic qualities necessary to withstand pavement distresses. Therefore, it is now the responsibility of asphalt engineers and researchers to find various types of polymer-modified asphalt, including crumb rubber.

This research used crumb rubber to modify the bituminous mixtures to further enhance the quality of hot mix asphalt produced. The use of crumb rubber in asphalt binder has become an alternative to minimize the environmental impact, and simultaneously improve the mechanical properties of the asphalt mixture.

In addition, Pavement is affected by temperature; at high temperatures, it becomes soft, and at cold temperatures, it hardens and cracks. Consequently, bitumen has to be modified with materials that can contribute to its increased elasticity, decreased temperature responsiveness, aging resistance, and higher softening point in order to improve its quality.

Both mechanical and viscoelastic property tests were conducted, and the study found that the addition of diatomite and crumb rubber particles to asphalt can improve its viscoelasticity, high and low temperature properties, and stability [22]. The results of laboratory tests indicate that asphaltic mixtures containing crumb rubber improve their mechanical qualities. The modified asphaltic mixture has good stability, excellent resilience, resistance to abrasion, cracking deformation, and waterproofing qualities [23].

[24] Employed crumb rubber in their investigation. They examined the mixture's mechanical characteristics, including thermal cracking and fatigue. The results of the study revealed that employing asphalt-rubber combinations provides benefits for the environment, economy, and sustainability. Additionally, it greatly increased the resistance to cracking. Crumb rubber is thus, confirmed as a modifier in asphalt, to protect the environment, promote eco-friendly construction methods, and reduce asphalt's susceptibility to temperature changes.

2.0 Materials and Methods

2.1. Materials

Materials used for this research and their descriptions are as follows:

2.1.1. Bitumen 60/70 Penetration Grade was collected from Zeberced asphalt plant, Abuja, Nigeria

2.1.2. Fine aggregate sample used was collected from river Kaduna, Kaduna state, Nigeria. The fine aggregates have aggregate particles larger than the filler, a material passing through sieve 4.75 mm (#8) sieve but retained on sieve 0.075 mm.

2.1.3. Coarse aggregates: The coarse aggregate samples used were angular, with 100% crushed faces, containing relatively little deleterious material. The crushed aggregate samples of sizes 19mm, 12.5mm, 9.6mm, 6.3mm, and 4.75mm respectively were collected from Zeberced quarry at Bwari, Abuja, Nigeria. Coarse aggregate in this study is a material that is retained on sieve 4.75 mm,

2.1.4. Ordinary Portland cement produced by Dangote Cement Company at Obajana, Kogi state, in Nigeria was used as a filler material. For this material, more than 75% of the material passed through sieve 0.075 mm. The cement was bought at a building materials shop located in Kuje, Abuja, Nigeria.

2.1.5. Crumb rubber was obtained from end-of life tyres, that were collected from a tyre dump at Kuje in Abuja, Nigeria. After being washed with water, these tyres were dried and the steel breeds were removed, the clean tyres were shredded into sections, and the sections were then chopped into small pieces using a hacksaw and knives. Additionally, the shredded tyres were ground into rubber fragments and a blend of synthetic fibers using an electric grinding machine. Rubber particles that were retained on 0.3 mm sieve were then collected for use, after the mixture was sieved.

2.2 Research Method

In this research, the resilient modulus of the ballast and sub-ballast were computed by using bulk stress mathematical model, also known as the K-θ model, the dynamic modulus of asphaltic concrete layer was determined by using Asphalt Institute mathematical modeling equation, and the California bearing ratio (CBR) value of the subgrade [25] was converted to resilient modulus using a mathematical conversion equation.

To assess the performance of the conventional ballasted trackbed, the resilient modulus of the ballast, sub-ballast, subgrade (Table 7), and the materials properties of the superstructure; the rail (Table 1), sleeper (Table 2), and fastening system (Table 3) were inputted into the KENTRACK software to estimate the vertical compressive stress at the top of the subgrade.

Also, to assess the performance of the asphalt-ballast trackbed, the resilient modulus of the ballast, dynamic modulus of the asphaltic layer, the resilient modulus of the subgrade (Table 8) and the material properties of the superstructure; the rail (Table 1), sleeper (Table 2), and fastening system (Table 3) were also inputted into the KENTRACK software to estimate the horizontal tensile strain under the asphaltic concrete layer and the compressive stress at the top of the subgrade.

The prediction of the service life of the ballasted trackbed, due to the calculated compressive stress at the top of the subgrade, while considering the various thicknesses of the granular sub-ballast was achieved using multiple regression modeling equations (Table 10).

The prediction of the service life of the asphalt-ballast trackbed, due to the calculated tensile strain at the bottom of the asphaltic sub-ballast, while considering the various thicknesses of the asphaltic sub-ballast was achieved using the multiple regression modeling equations (Tables 11 and 12).

The validation of the predictions of the two trackbed types was conducted in the laboratory, using an earth pressure cell and a vertical strain gauge to measure the compressive stresses at the top of the subgrade of both the ballasted trackbed, the asphalt-ballast trackbed and tensile strain at the bottom of the asphaltic layer, in the asphalt-ballast trackbed (Table 13).

To assess the effect of an asphaltic concrete layer in the railway trackbed structure, two tests setups were considered:
(i) A ballasted trackbed (Figure 2)
(ii) An asphalt-ballast trackbed (Figure 3).

The setups consisted of one sleeper, 200mm deep, 250mm wide, and 357mm long, fully embedded in 300mm thick ballast layer. In the case of ballasted trackbed, the ballast was supported by 200mm thick granular sub-ballast. And in the case of the asphalt-ballast trackbed, 100mm thick asphalt layer supported the 300mm thick ballast layer.

The three components of the ballasted trackbed were prepared and compacted inside a rectangular steel box, measuring 1100mm high, 500mm wide, and 600mm long (Figure 4) starting with the subgrade layer, followed by the granular sub-ballast layer and the ballast layer. In the conventional ballasted track, settlement of the track structure is expected

at the top of the subgrade soil due to the impact of vertical compressive stress. Thus, a soil pressure cell was inserted 50mm into the subgrade from the top to measure the vertical compressive stress.
And as for the asphalt-ballast trackbed, its three components, being the subgrade, crumb rubber modified asphaltic sub-ballast, and the ballast layer were prepared inside a rectangular steel box, measuring 1100mm high, 500mm wide and 600mm long. In this type of trackbed, cracking is expected to appear first under the asphaltic concrete sub-ballast, due to the impact of horizontal tensile strain. Thus, to measure the horizontal tensile strain, a strain gauge was inserted 20 mm into the asphaltic concrete sub-ballast, from the bottom.

Figure 4. The steel box

Preparation of subgrade layer in the rectangular steel box (Figure 4): The first layer that was constructed inside a rectangular steel box in the laboratory was the subgrade to the height of 600mm, and this was compacted in four layers of 150mm each. To measure the vertical compressive stress, a soil pressure cell was inserted the subgrade soil at a depth of 50 mm, from the top.

Preparation of crumb rubber modified asphaltic concrete in a rectangular steel box (Figure 4): 50mm thick asphaltic concrete was poured and compacted, to 3% air voids content. While the asphalt was still hot, another 50mm thick was poured and compacted, and a strain gauge was inserted 20 mm into the asphaltic concrete from the bottom to measure the horizontal tensile strain. Increasing asphalt thickness from 50mm to 100mm could extend its fatigue life and decrease the subgrade stress.

Preparation of ballast in a rectangular steel box (Figure 4): The first step in creating the compaction and slope profile involved hand-packing the ballast aggregate of 150 mm thick and vibrating it. Next, an electrical vibro-tamper was used to apply the same amount of vibration to the ballast, with a field unit weight of 15.5 kN/m^3 and a typical field density of 1560 kg/m^3.
In order to achieve uniform weight distribution to the ballast layer, which improved uniformity, the same amount of compaction (1 minute on each side slope) was applied to the ballast surface prior to the sleeper's placement. After setting one concrete sleeper on the ballast surface, 150mm of additional ballast was poured around it and vibrated as well.
Then, a cyclic loading was applied to the sleeper, using a hydraulic UTM 30 loading frame, which is capable of working in temperatures ranging from -25 to +60^0 C, in an environmental chamber. A vertical load equivalent to a 23-ton, being the train axle load on Abuja to Kaduna railway line was applied to excite the sleeper for the normal test duration of 14,600 cycles, simulating a succession of moving axle loads. 70 to 80 km/hour is the train operating speed on Abuja to Kaduna railway line, thus a frequency of 10 Hz was applied using a servo-hydraulic actuator. A servo valve in the hydraulic actuator allowed exact shaft response to an electrical command signal by directing oil through the actuator. A channel controller was linked to the servo valve, load cell and measurement devices. A computer that stored functions, and collects data for processing was linked to this stand-alone controller.

A nine-inch-diameter cylindrical disk, made of stainless steel, inside the strain gauge was filled with de-aired hydraulic fluid and sealed at the periphery. The fluid was driven out of the connected tube as pressure was applied to the cell. The pressure transducer in this tube transformed the hydraulic fluid's pressure into an electrical signal for the computer to read.

2.1 Rail

Table 1. The properties of the rail used in KENTRACK simulation

Type of rail	UIC 60
Young's modulus	192, 000 MPa
Poisson's ratio	0.3 MPa
Unit weight	60 kg/m
Unit of proportionality	500 MPa
Limit of elasticity	600 A

2.2 Concrete sleeper

Table 2. The properties of the concrete sleeper used in KENTRACK simulation

Young's modulus	30,000 MPa
Poisson's ratio	0.25 MPa
Unit weight	51.8 kg/m
Sleeper thickness	21 cm
Sleeper width	16.9 cm
Sleeper length	259 cm
Sleeper spacing	60 cm

2.3 Fastening system

Table 3. The specifications of the fastening system used in KENTRACK simulation

Fastening system type	Pandrol fast clip
Static stiffness pad rubber	>150 kN
Clamping force	>16 kN
Creep resistance	>9 kN

2.4 Ballast

Table 4. Ballast specifications

Parameter	Specifications
Size	25 – 60 mm
Porosity	≤3%
Specific gravity	≥2.65
Organic and mud content	≤0.4%
Abrasion – Los Angeles	≤25%
Absorption	≤2%
Mass density	≥1500

2.5 Sub-ballast

Table 5. Sub-ballast specifications

ASTM sieve standard	% Passing
2 ½''	100
¾''	50 - 100
No. 4	32 - 95
No. 40	10 - 35
No. 200	0 - 10

2.6 Non-Linear elastic behaviour of granular materials

The elastic modulus of non-linear materials was calculated by using Eq. 1 below:

$E = K_1\theta^{k2}$……………………………………………………… (1)

E = Resilient modulus

K_1, K_2 are regression constants

θ = Bulk stress

The results of aggregate gradation, volumetric design values, asphalt layer temperature through seasons, and the viscosity of the modified asphalt were substituted in the Asphalt Institute modeling equation to calculate the dynamic modulus of asphaltic sub-ballast in the asphalt-ballast trackbed (Table 6).

2.7 Dynamic modulus of the asphaltic layer

The material properties in (Table 6) were substituted into the empirical Asphalt Institute predictive equation to compute the dynamic modulus of the asphaltic layer.

The Asphalt Institute Predictive Model:

$E^* = 100{,}000\ (10^{\beta 1})$…………………………………………. (2)

Equations used to calculate the five constants (β_1, β_2, β_3, β_4, and β_5) so as to determine the dynamic modulus of hot mix asphalt are (Table 6):

$\beta_1 = \beta_3 + 0.000005\beta_2 - 0.00189\beta_2\ f^{-1.1}$……………………………………. (3)

$\beta_2 = \beta_4^{\ 0.5}\ (Tmin)^{\ \beta 5}$………………………………………… (4)

$\beta_3 = 0.553833 + 0.028829\ (P_{200}f^{-0.1703}) - 0.03476Vv + 0.07037\lambda + 0.0931757f^{-0.02774}$ ……………………………………......... (5)

$\beta_4 = 0.483Vb$……………………………………………….. (6)

$\beta_5 = 1.3 + 0.49825\ \log f$……………………………………... (7)

β_1 is a constant as well as the other four. To calculate β1, the above four constants were first calculated . Then β1 was substituted into equation.
where,
E* = Dynamic modulus (psi)
F = Loading frequency (Hz)
T = Temperature of asphalt pavement (^{0}C)
Vv = Volume of voids (%)
λ = Asphalt viscosity at 77 ^{0}F (25 ^{0}C) (10^6 poises)
P_{200} = Percentage by weight of aggregates passing No. 200 sieve (%)
Vb = Volume of bitumen (%)
P_{77} ^{0}F = Penetration at 77 ^{0}F or 25 ^{0}C

Table 6. Material properties used in Asphalt Institute modeling equations

Binder grade	% passing 200 (0.075 mm)	% passing 4 (4.75 mm)	% passing 3/8 (9.5 mm)	% passing ¾ (19 mm)	Air voids (Vv)	Volume of bitumen % (Vb)
60/70 P	5	51	38	6	3	5.45

Binder grade	Asphalt pavement temperature 1 (^{0}C)	Asphalt pavement temperature 2 (^{0}C)
60/70 penetration grade	15.44	24.53

Binder grade	Viscosity (ƛ) at 77 ^{0}F (25 ^{0}C)
60/70 penetration grade	3.51

2.8 Mathematical model to calculate the resilient modulus of subgrade

A total of 39 samples from 13 sampling points were collected by disturbed sampling, along the Abuja to Kaduna railway line. The samples were prepared in accordance with [25]. Before testing, the soil materials were soaked for 4 days. And the tests were carried out in accordance with [25]. Samples were subjected to a compaction test to find their Maximum Dry Density and Optimal Moisture Content. After soaking for 96 hours, the OMC and MDD, were used to produce a specimen for the CBR test. After that, a seated load of roughly 4.5 kg was added to the CBR specimen, which was then weighed and put under the CBR machine. At 2.5 kg and 5.0 kg of penetration, the load was observed. Finally, the following equation was used to convert the CBR to subgrade resilient modulus:

$$\mathbf{M_R = 1500 \times CBR} \quad (8)$$

2.9 Poisson's ratio used in this study

Poisson's ratios of pavement components are typically assumed rather than calculated in mechanistic-empirical design. By default, all constituent materials' Poisson's ratio is included in the KENTRACK software (Tables 7 and 8).

3.0 Results and Discussions

3.1 Results

Table 7. Mechanical properties of ballasted trackbed used in KENTRACK simulation

Layer	Thickness (m)	Coefficient K2	Resilient Modulus (MPa)	Poisson's Ratio	Unit Weight (kg/m^3)
Ballast	0.3	0.5	81.00	0.35	1800
Sub-ballast	0.1 – 0.5	0.5	76.32	0.35	1600
Subgrade	0.6	0	72.60	0.40	2150

Table 8. Mechanical properties of asphalt-ballast trackbed used in KENTRACK simulation

Layer	Thickness (m)	Coefficient K2	Resilient Modulus (MPa)	Poisson's Ratio	Unit Weight (kg/m^3)
Ballast	0.3	0.5	81.00	0.35	1800
Asphaltic layer	0.05 – 0.25	0	3456.64	0.45	2400
Subgrade	0.6	0	72.60	0.40	2150

Table 9. Summary of the predicted subgrade compressive stress and asphaltic tensile strain using KENTRACK software

Track type	Sub-ballast layer thickness (m)	Subgrade compressive stress (kPa)	Subgrade service life (years)	Asphaltic layer tensile strain	Asphaltic layer service life (years)
Conventional Ballasted Track	0.10	111.99		Not applicable	Not applicable
	0.20	79.51		Not applicable	Not applicable
	0.30	64.40		Not applicable	Not applicable
	0.40	54.77		Not applicable	Not applicable
	0.50	48.30		Not applicable	Not applicable
Track type	Sub-ballast layer thickness (m)	Subgrade compressive stress (KPa)	Subgrade service life (years)	Asphaltic layer tensile strain	Asphaltic layer service life (years)
Asphaltic Underlayment Track	0.05	80.86	-	9.650 x 10 -5	-
	0.10	56.02	-	5.655 x 10 -5	-
	0.15	44.80	-	3.566 x 10 -5	-
	0.20	40.49	-	2.566 x 10 -5	-
	0.25	38.00	-	1.968 x 10 -5	-

Table 10. Predicted Compressive Stress and Subgrade Service Life in ballasted trackbed L_1 (years)

Thickness of sub-ballast layer (m0	Subgrade compressive stress, C (kPa)	Regression equation	Predicted subgrade service life (years)
0.10	111.99	L_1 = 21.8761 + 111.4229 (T) – 0.15696 (C)	16.32
0.20	79.51		28.56
0.30	64.40		46.32
0.40	54.77		61.44
0.50	48.30		67.53

Table 11. Predicted Compressive Stress and Subgrade Service Life in asphalt-ballast trackbed L_2 (years)

Thickness of sub-ballast layer (m0	Subgrade compressive stress, C (kPa)	Regression equation	Predicted subgrade service life (years)
0.05	80.86	L_2 = 17.84824 + 264.959(T) - 0.15675(C)	19.16
0.10	56.02		33.28
0.15	44.80		50.46
0.20	40.49		68.61
0.25	38.00		75.67

Table 12. Predicted Tensile Strain and Asphaltic Layer Service Life in asphalt-ballast trackbed L_3 (years)

Thickness of sub-ballast layer (m0	Asphalt tensile strain, C (kPa)	Regression equation	Predicted asphalt layer service life (years)
0.05	9.650×10^{-5}	L_3 = 39.54058 + 177.5969(T) – 70457.6(S)	41.23
0.10	5.655×10^{-5}		54.67
0.15	3.566×10^{-5}		62.44
0.20	2.566×10^{-5}		73.21
0.25	1.968×10^{-5}		82.86

Table 13. Predicted and measured subgrade compressive stresses, asphaltic tensile strain and their service lives in the ballasted trackbed and asphalt-ballast trackbed.

Ballasted Trackbed	Predicted subgrade compressive stress (kPa)	Service life of subgrade due to predicted compressive stress (years)	Measured subgrade compressive stress (kPa)	Service Life of subgrade due to measured compressive stress (years)	Predicted Asphaltic Tensile Strain	Service life of asphaltic layer due to predicted tensile strain (years)	Measured Asphaltic Tensile Strain	Service life of asphaltic layer due to measured tensile strain (years)
Granular Sub-ballast Thickness (0.20 m)	79.51	28.56	77.46	32.01	N/A	N/A	N/A	N/A
Asphalt-ballast trackbed	Predicted subgrade compressive stress (m)	Service life of subgrade due to predicted compressive stress (years)	Measured subgrade compressive stress (kPa)	Service life of subgrade due to measured compressive stress (years)	Predicted asphaltic tensile strain	Service life asphaltic layer due to predicted tensile strain (years)	Measured asphaltic tensile strain	Service life of asphaltic layer due to measured tensile strain (years)
Asphaltic Subballast Thickness (0.10 m)	56.02	33.28	54.76	35.76	5.655×10^{-5}	54.67	3.96×10^{-5}	55.86

3.2 Discussion

The results of this study are hereby discussed:

(i) The results shown in Tables 10, 11 and 12, indicate that when the sub-ballast thickness in ballasted trackbed was increased 5 times higher than 0.10m, the subgrade compressive stress was reduced from 111.99 kPa to 48.30 kPa, representing **52.06%** reduction, and enhancement of subgrade service life of about **4.14 times**. Also, when the asphaltic concrete thickness in asphalt-ballast trackbed was increased 5 times higher than 0.05 m, the subgrade compressive stress was reduced from 80.86 kPa to 38.00 kPa, representing **41.85%** reduction, and enhancement of subgrade service life by **3.95 times**. As the thickness of granular sub-ballast and the thickness of asphaltic sub-ballast were increased, the vertical compressive stress and horizontal tensile strain exerted on the subgrade and asphaltic sub-ballast were reduced.

(ii) Further analysis showed that the predicted subgrade compressive stress due to 0.20 m thick granular sub-ballast, on Abuja to Kaduna railway line was 79.51 kPa and a service life of 28.56 years, while the predicted subgrade compressive stress due to 0.10m thick asphaltic sub-ballast was 56.02 kPa and a service life of 33.28 years. There was a subgrade compressive stress reduction of 27.49 kPa in the asphalt-ballast trackbed, representing **34.57%,** and the service life due to asphaltic sub-ballast in the asphalt-ballast trackbed was enhanced by about **1.16 times.**

(iii) Over thirty three (33.28 years) of subgrade service life can be said to be long enough, for a trackbed with 0.10 m thick asphaltic layer. This was made possible due to the fact that asphaltic sub-ballast is a viscoelastic material, and it is located between the ballast and the subgrade, this maintains the layer in a protected environment, thus shielding it from sunlight exposure, and consequently making it to undergo minimum variation in temperature extremes throughout the year. The stiffness modulus is reasonably uniform throughout the year and weathering or oxidation of the hot mix asphalt is minimal compared to what is obtainable in highway applications.

(iv) Result shown in Table 13 contains the values used in the validation of the conventional ballasted track.

(v) The predicted value of vertical compressive stress on the subgrade was 79.51 kpa, while the measured value was 77.46 kpa. The difference is 2.05 kPa representing a reduction of 2.58%.

(vi) And on validation of the asphalt-ballast trackbed, the predicted value of vertical compressive stress was 56.02 kpa, while the measured value was 54.76kpa. The difference is 1.26 kPa representing a reduction of 2.25%.

(vii) And the predicted tensile strain on asphaltic layer was 5.655 x 10 -5, the measured value was 3.96 x 10 -5, a difference of 1.695, representing a reduction of 29.97% (Results are shown in Table 13).

(viii) The validated results were close to the KENTRACK predictive values, thus, giving the predicted values a measure of credibility. The potential reason for the slight difference between the validation results and predicted results could be due to errors in measurement.

4.0 Conclusion

Based on the analysis and results of this study, the following conclusions can be drawn:

(i) The asphalt-ballast trackbed outperformed the traditional ballasted track in terms of structural performance, with less deformation as shown in Tables 10, 11 and 12. Increasing the thickness of the ballast and sub-ballast layers to more than 30 cm, in an effort to improve the performance of the ballasted trackbed, could worsen its condition, because it could lead to more deformations, increased construction costs, increased environmental pollution, and above all, it would use up more scarce natural resources.

(ii) Results on the two rail track types showed that a thicker granular sub-ballast, and asphaltic sub-ballast generated lower compressive stress and tensile strain. Consequently, the service life of the granular sub-ballast layer was increased, as expected, with lower subgrade compressive stress on the subgrade and the service life of asphaltic sub-ballast was also increased with lower tensile strain under the asphaltic sub-ballast.

(iii) The asphaltic sub-ballast of 100 mm thick performed better than the granular sub-ballast of 200 mm thick, because the service life of the asphaltic sub-ballast was 33.28 years, while the service life of the granular sub-ballast was 28.56 years. It is obvious that asphalt-ballast trackbed has higher ability to transmit loads and stresses and reduced subgrade compressive stresses.

(iv) The addition of crumb rubber improved its resistance to fatigue, and moisture-related failures. Using crumb rubber in the asphaltic sub-ballast also enhanced its functionality.

(v) The asphalt-ballast trackbed, where, asphaltic sub-ballast was used to replace the traditional granular sub-ballast can be applied in tropical regions, including Nigeria. This is because this research showed that the sensitivity of bitumen to temperature changes, one of the main limitations of bituminous mixtures, could be reduced by using crumb rubber as a modifier, and consequently increasing the viscosity of the binder, thereby extending the temperature range of viscoelasticity.

(vi) This study demonstrated that asphalt-ballast trackbed could offer a better standard of railway track and a reliable transportation system for the functioning of passenger trains in general.

(vii) According to the findings, using secondary materials reduces the need for traditional materials, lowers the overall cost of construction, and provides an efficient method of disposing of end-of life tyres.

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[1] Nandal, M, Mor, N, and Sood, H. [2021]. An Overview of Use of Artificial Neural Network in Sustainable Transport System Eng, Springer, Singapore, pp. 83-91. DOI: 10.1007/978-981-168 76-3-7
[2] Li W, Han, S, Han, X, and Yao, Y. [2021]. Experimental and numerical analysis of mechanical properties of geocell reinforced reclaimed construction waste composite base layer. Constr. Build. Mater., vol. 304, 124587. https://doi.org.10.1016/j.conbuildmat..2021.124587.
[3] Li-Ping, G, Miao, W, Cong,D, and Li-Juan, C. [2020]. Effect of incorporating reclaimed asphalt pavement on macroscopic and microstructural properties of high ductility cementitious composites. Constr. Build. Mater., 260. DOI: 10.1016/j.conbuildmat.2020.119956
[4] Rose, J.G, Agarwal, N.K, Brown, J.D, and Ilavala, N. [2010]. KENTRACK, a performance-based layered elastic railway trackbed structural design and analysis procedure – A tutorial. JCR2010 – 36067.
[5] Carmo-Calado, L; Hermoso-Orzaez, M.J; Mota-Panizio, R; Guilherme-Garcia, B; and Brito, P. [2020]. Co-Combustion of waste tires and plastic-rubber waste with biomass technical and environmental analysis. Sustainability, 12(3). 1036; https://doi.org/10.3390/su12031036
[6] Mallah, M.A; Changxing, M.A; Noreen, S; Liu, Y; Saaed, M; Xi, H.E; Ahmed, B; Feng, F; Mirjat, A.A; Wang, W; Jabar, A; Naveed, M; Li, J.H; and Zhang, Q. [2022]. Polycyclic aromatic hydrocarbon and its effects on human health: An overview. Chemosphere, 296, p. 133948. https://doi.org.10.1016/j.chemosphere.2022.133948.
[7] Cieslik, E; and Fabianska, M.J. [2021]. Preservation of geochemical markers during co-combustion of hard coal and various domestic materials. Sci. Total Environ., 768(1), p. 14438. DOI: 10.1016/j.scitotenv.2020.144638
[8] Tsang. H.H. [2019]. Uses of scrap rubber tires Rubber: Types, Properties and Uses, Nova Science Publishers, Inc., New York, New York, US.
[9] U.S. Tire Manufacturers Association. [2020]. U.S. Scrap Tire Markets 2020 Management. https://www.ustires.org/sites/default/Management.
[10] Liu, L; Cai, G; Zhang, J; Liu, X; and Liu, K. [2020]. Evaluation of engineering properties and environmental effect of recycled waste tire-sand/soil in geotechnical engineering: a compressive review. Sust. Energ. Rev., 126 (2020), https://doi.org. 10.1016/j.rser.2020.109831
[11] Grammelis, P; Margaritis, N; Dallas, P; Rakopoulos, D; and Mavrias, G. [2021]. A review on management of end of life tires (elts) and alternative uses of textile fibers Energies, 14(3), p. 571, https://doi.org/10.3390/en14030571
[12] Dabic-Miletic, S. Dabic-Miletic, V. and Simic, S. K.[2021]. End-of-life tire management: a critical review Environ. Sci. Pollut. Res., 28 (2021), pp. 68053-680 10.1007/s11356-021-16263-6.
[13] Valente, M; and Sibai; A. [2019]. Rubber/Crete: mechanical properties of scrap to reuse tire-derived rubber in concrete; a review. Journal of Applied Biomaterials & Functional Materials, 2280800019835486 17, https://doi.org. 10.1177/2280800019835486.
[14] Peter, K.T; Hou, F; Tian,Z; Wu, C; Goehring, M; Liu, F; and Kolodziej, E.P. [2020]. More than a first flush: Urban Creek storm hydrographs demonstrate broad contaminant Pollutographs. Environ. Sci. Technol., 54 (10), pp. 6152-6165, 10.1021/acs.est.0c00872.
[15] Tian, Z; Zhao,H; K.T. Peter, M. Gonzalez, Wetzel,J; Wu,C; Hu, J; Prat, E; Mudrock, R; Hettinger, A.E; Cortina, R; Biswas, F.V.C; Kock, R; Soong, A; Jenne, ; Du, F; Hou, H; He, R; Lundeen, A; Gilbreath, R; Sutton, N.L; and Scholz, J.W. [2021b]. A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmonScience [2021], https://doi.org.10.1126/science.abd6951
[16] Tian, Z; Wark, D.A; Bogue, K; and James. C.A. [2021a]. Suspect and non-target screening of contaminants of emerging concern in streams in agricultural watershed. Sci. Total Envi., 795, 148826. https://doi.org.10.1016/j.scitotenv.2021.148826
[17] Siddiqui, S; Dickens, J.M; Cunningham, B.E; Hutton, S.J; Pedersen, E.I; Harper, B; Harper, S; and Brander, S.M. [2022]. Internalization, reduced growth, and behavioral effects following exposure to micro and nano tire particles in two estuarine indicator species Chemosphere, 296, 13393. https://doi.org. 10.1016/j.chemosphere.2022.133934.
[18] Du, B. Du, B. Liang, Y. Li, M. Shen, L.-Y. and Liu, L. Z.. [2022]. First Report on the occurrence of N-(1,3-Dimethylbutyl)-N′-phenyl-p-phenylenediamine (6PPD) and 6PPD-Quinone as pervasive pollutants in Human urine from South China Environ. Sci. Technol. Lett., 9(12), pp. 1056-1062, 10.1021/acs.estlett.2c00821
[19] Skoczyńska, E; Leonards, P.E.G; Llompart, M; and de Boer, J. [2021]. Analysis of recycled rubber: development of an analytical method and determination of polycyclic aromatic hydrocarbons and heterocyclic aromatic compounds in rubber matrices Chemosphere, 276, 130076, https://doi.org.10.1016/j.chemosphere.2021.130076.

[20] Consoni, D, Sindaco, R, and Alberto, P. [2012]. Blood levels of dioxins, furans, dioxin-like PCBs, and TEQs in general populations: A review, 1989-2010. Environ. Int., 44, 151-162. [Cossref][PubMed].

[21] Behnood A. [2019]. Application of crumb rubber to improve the rheological and mechanical properties of asphalt binders and mixtures: a review. J. Clean. Prod., 231, pp. 171-182.
[22] Picado-Santos, L.G, Capitão,S.D, and Neves J.M.C. [2020]. Crumb rubber asphalt mixtures: a literature review Constr. Build. Mater., vol. 247, PP. 247. https://doi.org. 10.1016/j.conbuildmat.2020.118577
[23] Liu, H, Luo, G, Wang, X, and Jiao, Y. [2020]. Laboratory Evaluation of the Pavement Performance of a rubber-modified
Asphalt Mixture. Emerg. Mater Res. 9, 99-103. [Google scholar][Crossref].
[24] Liang, C, Zhang, H, Gu, Z, Xu, X, and Hao J. [2020]. Study on mechanical and viscoelastic properties of asphalt mixture modified by diatomite and crumb rubber particles. Appl. Sci., 10(23) 8748, pp. 1-17. **https://doi.org/10.3390/app10238748**.
[25] BS 1377 – 2. [2022]. The Standard for Methods of Test for Soils for Civil Engineering Purposes: Part 2: classification tests and determination of geotechnical properties.