Study on Performance of Subgrade, Confinied with Geo-Tyre in Flexible Pavement

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ABSTRACT

Growth of population is necessitating constant rehabilitation and maintenance of pavements. Deterioration of roads is due to unconfinement of layers, climate change, improper execution, use of unsuitable materials, weak subgrade etc. Rehabilitation strategies that prioritize pavements, based cost-effectiveness, performance study on materials methods, sufficient case studies etc., on pavement failures can be beneficial. The disposal of waste tyres by burning is a serious problem contributing to environmental impacts. Literature survey has emphasized on the techniques used for stabilization of subgrade/subbase with 3D confinement by reinforcing layers using many geosynthetics like geocells, rubbers, and plastics. These are proven to reduce thickness of subgrade, lateral deformation, depressions enhancing the shear resistance, sustainability, and durability of pavements. The authors' objective is to use waste tyre in lieu of geocells for 3D confinement of subgrade of flexible pavement. The study is carried out by employing mathematical, finite element analysis using ANSYS software, along with laboratory experiments, and plate load tests considering well graded gravel as subgrade infill material. In the recent days, tubeless tyres are becoming more popular than tubed tyres looking to their advantages. As the tyres are manufactured in varieties using different materials combination make and method. it is not possible to test all type of tyres. Therefore, as an example some specimens of car and truck tyres are tested in laboratory to know the yield stresses from tubeless tyre of car and tubed tyre of truck. The stresses and strains obtained for both tyres from the analysis and experiments are much lower than the actual yield stresses obtained from tests on actual tyre specimens. So, the results are quite encouraging to achieve considerable economy with the reduced crust thickness i.e., equal to the section width of tyres and considerable sustainability and durability of pavement due to 3D confinement. The tyres are proved to be much stronger than the geocells. Therefore, it is recommended to use waste tyres for 3D confinement. This also addresses the problem of disposal of waste tyres as cost effective, usable, and ecofriendly solution. There is a huge scope for adoption of this innovative technique in stabilising the flexible pavement all over the world. Authors feel that the use geo-tyre technology is very useful in speedy construction of pavement like runways.

Keywords: Geo-tyre; ANSYS; Subgrade; 3D Confinement; Waste tyres; Sustainability; Flexible pavement.

INTRODUCTION

All around the world, the increase in population has led to a significant rise in traffic, which has become an indispensable aspect of human life. Particularly in urban areas, the traffic volumes on the primary highway system have seen tremendous growth over the past 20 years. Unfortunately, this increase in traffic has resulted in numerous instances of premature pavement failures. The ageing of highways and other primary systems constructed during the 1950s and 1960s has necessitated a substantial allocation of highway funds towards pavement strengthening and rehabilitation. Consequently, there is a pressing need for planned rehabilitation technology to address the problem of deterioration of roads. The structural evolution of pavement has transitioned from the ancient Roman roads “rock over rock" construction [6] to the more recent "Pavement Quality Concrete" (PQC). Common failures of pavement include the formation of cracks, ruts, depressions, unevenness, and differential settlements caused by lateral deformation of the soil beneath.

The reasons for pavement failure include

i) Poor project management ii) Unscientific upgradation of roads iii) Unscientific allotment of road funds iv) Insufficient study on local soil behaviour v) Lack of knowledge on feasible rehabilitation strategies vi) Use of unsuitable materials and methodologies vii) Climate change due to global warming viii) Poor surface and sub-surface drainage system ix) Insufficient capacity of roads x) Overlaying the pavement without strengthening the subsurface layers xi) Unconfined sub-grade, sub-base, or super layers.

To address the issues cited above, researchers have been tremendously drawn towards the development of innovations in soil stabilization technology. In this study, the authors have emphasized on 3D confinement using geo-tyre technology for stabilizing the pavement structure.

Principle of geocell confinement

The core principle behind Geocell technology is the “Cellular Confinement". The geocells are used by expanding to form a honeycomb-like structure, as shown in Fig. 1.

Fig. 1 Geocell structure [15]

The lateral deformation is a common phenomenon observed due to wheel load in unconfined subgrade/subbase leading to rutting. The use of geocells helps in enhancing the resistance to this lateral deformation. The formation of depression due to wheel load is shown in Fig. 2 and the resistance to lateral deformation using geocells is shown in Fig. 3.

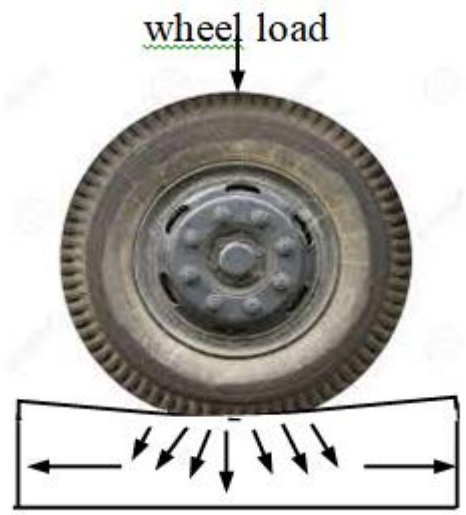

Fig. 2 Lateral deformation and rutting in subgrade.

The 3D confinement significantly reduces lateral movement of soil particles and increases shear strength through high lateral stress and high hoop strength and resistance at the cell-soil interface. Interlocking between soil particles increases the bearing capacity and reduces deformation [2]. The problem of lateral deformation can be addressed by providing confinement as shown in Fig. 3.

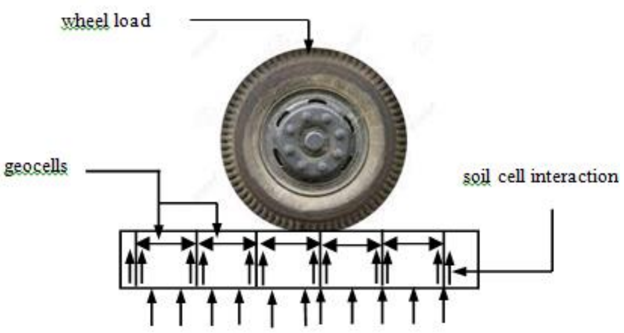

Fig. 3. No rutting in subgrade with geocell

The confinement from the adjacent geocells also provides additional resistance (passive resistance) against the loaded cell, while the high hoop strength restricts lateral expansion of the infill [5]. Compaction is maintained by confinement, ensuring long-term reinforcement Fig. 4.

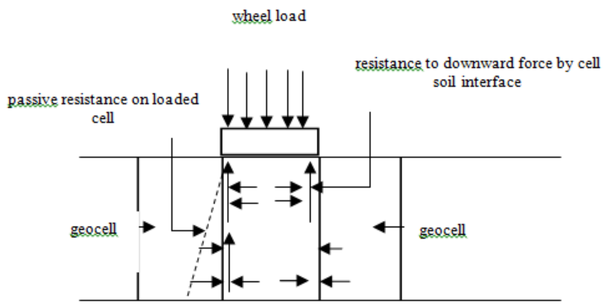

Fig. 4 Additional resistance by adjacent geocells (Passive resistance) [2 & 5].

LITERATURE REVIEW

The common geosynthetics for ground improvement in roadway construction are geotextiles, geomembranes, geogrids, geocell, geo-fibre, geonets, geofoam, geo-composites, etc.

The use of waste tyres for 3D cellular confinement in flexible pavements significantly reduces the thickness of the pavement, enhances the life span, and facilitates eco-friendly disposal of waste tyres instead of burning [16]. Geocells have proven to reduce vertical stresses by more than 50% on low-bearing capacity subgrades. The bearing capacity of subgrades increases by approximately 2.5 times with high flexural strength, stiffness, shear strength while vertical differential settlement decreases in geocell reinforced pavement compared to the unreinforced pavement [9]. Fibre reinforced subgrade soil in the flexible pavement can increase California Bearing Ratio (CBR), compressive strength, tangent moduli of soil, and reduces thickness of subgrade for an optimum quantity of fibre [13]. Geocell reinforced soil composite is proven to be stronger and stiffer than the equivalent soil without geocell reinforcement. This is due to the confinement by the geocell membrane which induces compression stress in the soil. The strength and stiffness effect of the cellular reinforcement increases with a decrease in cell sizes and with a decrease in the width to height ratio of the cells. The magnitude of the cohesive strength of soil dependents on the properties of the geosynthetics waste used to fabricate the geocell and on the thickness of the composite, which increases with the provision of geocell reinforcement [10]. Geosynthetic material in pavement construction improves its stress-strain behaviour within the range of 5 to 15%. Less stiff materials should not be placed over stiff layers reinforced with cell geosynthetic materials [7]. The use of a geocell layer in flexible pavement increases the structural stiffness of the pavement and reduces the thickness of the granular layer by 50%. It is best to provide a geocell layer as close to the surface loads as possible to achieve better results [11]. A double-layer geocell can be a feasible solution, while a thicker base layer is required when designing the pavement for heavy traffic volume [1]. Modulus improvement factors of 2.04 and 1.20 have been observed for reinforced and unreinforced pavement structures, respectively, and the traffic benefit ratio (TBR) for single and multiple geocell reinforcements has been reported as 8.0 and 12.00, respectively [12]. Non-polymer alloy (NPA) geocells improves the life of the unpaved fractional reclaimed asphalt (FRAP) sections by a factor of 1.3 and 1.8 with one layer of 75 mm and 100 mm high geocells, respectively. A thicker fill cover is required to minimize the damage to geocells [5].

Literature review indicates that the inclusion of geosynthetics as reinforcement in flexible pavement construction reduces pavement thickness, vertical stresses, vertical deformation, lateral soil movement, carbon foot prints, and subgrade bending. It also increases the flexural strength, stiffness, shear strength, cohesive strength of soil, CBR, bearing capacity of soil, modulus of soil, traffic benefit ratio, and life span of the pavement compared to unreinforced pavement.

Previous research efforts have primarily focused on using geocells and polymer materials for reinforcement. In the present work authors have attempted to use waste tyres instead of geocells. The rationale for using the waste tyres is to provide an ecofriendly disposal method for waste tyres rather than the common practice of burning them and to achieve enhancement in sustainability and durability of pavement.

Through exhaustive literature survey on the present work, it is found that no studies have been reported on the use of waste tyres for stabilization of subgrade stabilization in flexible pavement.

Objective

To utilise waste tyres for 3D confinement of the subgrade, termed as ‘Geo-tyre Technology’ in flexible pavement and to determine the stresses developed in tyres through experimental, numerical analysis and laboratory tests. The novelty of the work lies in enhancing the sustainability and durability of flexible pavement by reducing the crust thickness using waste tyres in lieu of conventional synthetic geocells thus providing 3D confinement. Additionally, to prove it as a cost-effective and eco-friendly solution for disposing waste tyres rather than conventional way of disposal by burning.

METHODOLOGY

This section discusses the principle of 3D confinement, the importance of using of waste tyres for subgrade confinement, and the procedure to be adopted in construction of flexible pavement as described below.

Principles of geo-tyre confinement

Based on the study on principle of confinement in flexible pavement using geocells, it is proposed to use waste tyres of vehicles, referred to as "Geo-tyres technology" in the similar manner. In contrast to geocells, waste tyres filled with granular subgrade material exhibit less deformation under loading due to their enhanced resistance at the interface of tyre surface and the infill subgrade material. They possess higher confinement stiffness and better elastic properties due to their composition, which includes rubber and high-tensile wire or nylon chords embedded within them. This not only improves pavement stability but also addresses the issue of waste tyre disposal in a useful, ecofriendly, and cost-effective manner. This approach to subgrade confinement, particularly on soft soils of low CBR, has the potential to increase the bearing capacity of the soil, reduce lateral deformation, enhance shear resistance, and extend the service life of flexible pavements.

Aarrangement of waste tyres and filling of subgrade material.

On one side of the tyre, the rim portion up to the edge along the periphery is cut as shown Fig. (5a and b). After removing the rims and cutting the horizontal portion of tyres they will be placed horizontally across the road and all along the road in a grid pattern. These waste tyres are joined each other by nut and bolt mechanism (Vithal Hanumantrao Jadhav. 2019). After joining the tyres on the ground in the form a grid, the subgrade material i.e., well graded gravel) is filled as shown in Fig. 5 (a, b).

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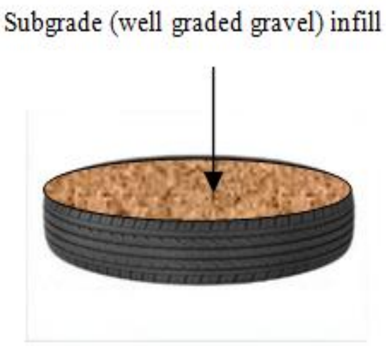

Fig. 5 (a) View from top

Fig. 5 (b) View from bottom

Xperimental Study On Tyre Specimens.

Tests are conducted as per ASTM D412 on waste tyres for i) Passenger car radial tyres with high tension (HT) wires and ii) Heavy duty truck re-treaded tyres (tubed tyres) with nylon chords. The Micro Universal Testing Machine (MUTM Tinius Olsn Model 10ST) and Universal Testing Machine are used for testing the tyre specimens. The car tyres specimens of 10 mm thick are tested in MUTM and the re-treaded truck tyres specimens with nylon chords of more than 10 mm thick are tested in UTM (Aimil Universal Testing Machine). A sample of specimen and MUTM are shown in Fig. 6.

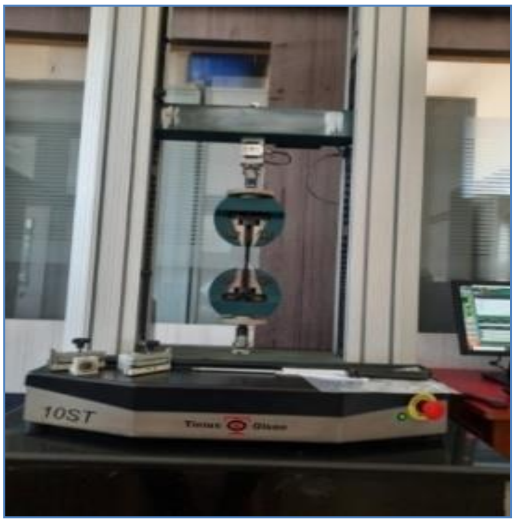

Fig. 6. Tinius Olsn Model 10ST (MUTM*)*.

Tensile test of car tyre specimen.

Three specimens are tested under Micro Universal Testing Machine (MUTM). The strength–strain relationship of the specimens is obtained. Table 1 provides the yield strength, ultimate stress, ultimate strain values.

Table 1. Test results of car tyre specimens. (Embeded with high tension wires).

Sample	Ultimate force in N	Yield strength in MPa	Ultimate stress in MPa	Ultimate strain %	Break down strain %
Avarage of 3 specimens	981.00	8.566	9.451	52.89	53.70

Tensile Test of truck tyres

Three truck tyre specimens (with Nylon chords) are tested in UTM. Table 2 shows the average yield stress.

Table2. Yield stress of truck tyre specimens

Sample No	Yield stress (MPa)
1	06.117
3	07.128
4	07.033
Average	**07.702**

RESULTS AND DISCUSSION:

The car tyre specimens embedded with high tension wires have given an average yield stress of 8.566 MPa whereas the truck tyre specimens have given an average yield stress of 7.702 MPa

Analysis by Finite element method (FEM).

The “ANSYS” software is used for the finite element method analysis to determine the ultimate stresses developed in tyres due to the confinement of the subgrade. The tyre models for both car and truck are downloaded from the web site (see http://www.GrabCAD). The models are imported in ANSYS software and the properties of tyre and infill subgrade (well graded gravel) for both dry and saturated conditions are applied. The static wheel load is applied as per the standard wheel load permitted in India (MORT&H 2018). The average car tyre dimeter is 600 mm and of truck is 1000 mm, seven car tyres and four truck tyres required to be arranged for a single lane pavement width of 3.75 m. Accordingly, the analysis is done for car and truck tyres for both dry and saturated conditions of subgrade infill. The FEA is conducted using “ANSYS” software.

For car tyre:

The analysis is conducted under static load conditions (MORT&H 2018), with the geometry model prepared without the rim and cutting the one side of tyre keeping horizontally as explained. The input data for the ANSYS software analysis for car tyre are depicted in Tables 3.

Table 3. Input data for “ANSYS” software: (**Car tyre**)

Description	Value
Model of tyre Car tyre).	Downloaded from http://www.GrabCaD.

Diameter.	600 mm.
Section width (infill height).	195 mm.
Tyre Material.	Rubber.
Iinfill material.	Gravel well graded (GW).
Density of infill material.	18 kN/m^3 = 1.8g/cc. (dry condition) 21 kN/m^{3}or 2.1 g/cc (saturated condtion)
Young's modulus of infill "E".	160 MPa. (dry condition) 120 MPa (saturated condition)
Poission's ratio "v" of infill.	0.35
Yield strength of waste tyre by laboratory test in MUTM as per ASTM D412. (least value is assigned)	7 MPa.
Force (Load) applied - Maxi. wheel load.	57,500 N As per standard (MORT&H 2018).

Case 1: Single car tyre with well graded gravel as infill subgrade material for dry condition. Results are shown in Fig. 7 a & b.

Observations: Von mises stress – 0.392 MPa & Maxi deformation- 0.269 mm

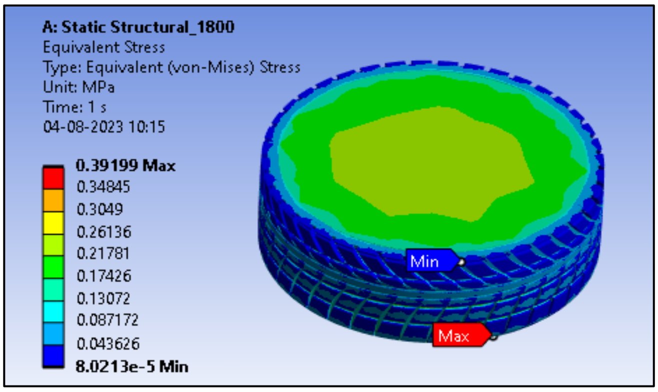

Fig. 7 a Von misses stress

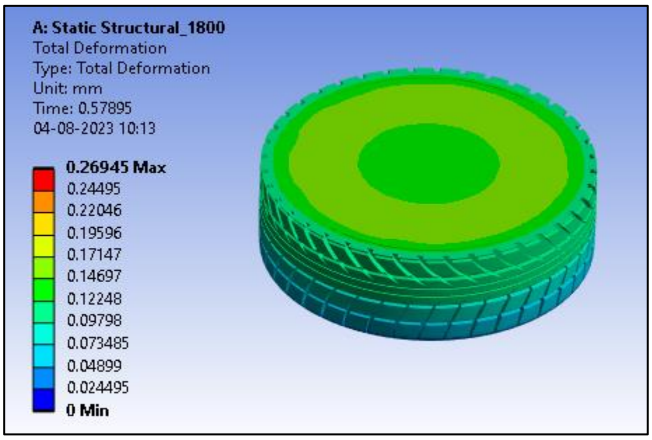

Fig. 7 b. Total deformation

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Case 2: Single car tyre with well graded gravel as infill subgrade material for saturated condition**.** Results are shown in Fig. 8 a & b.

Observations**:** Von mises stress – 0.448 MPa & Maxi deformation – 0.342 mm.

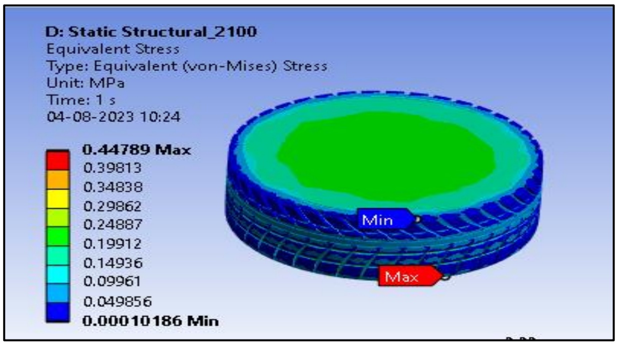

Fig. 8 a Von misses stress

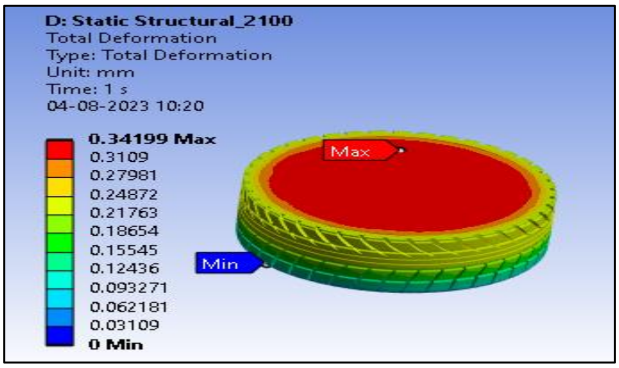

Fig. 8 b Total deformation

Case 3. Seven car tyres covering full width of single lane carriage way for dry condition for up direction. Results are shown in Fig. 9 a & b.

Observations: Von mises stress-2.533 MPa & Maxi deformation-0.461 mm

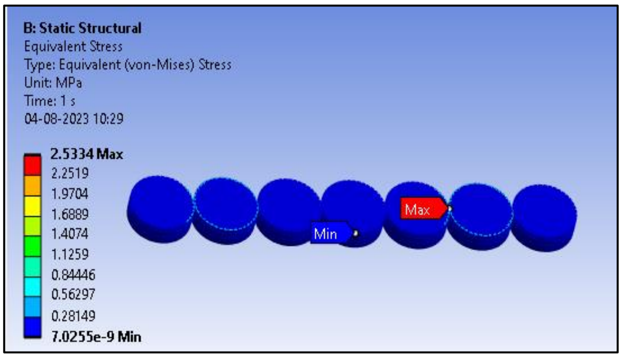

Fig. 9 a Von misses stress

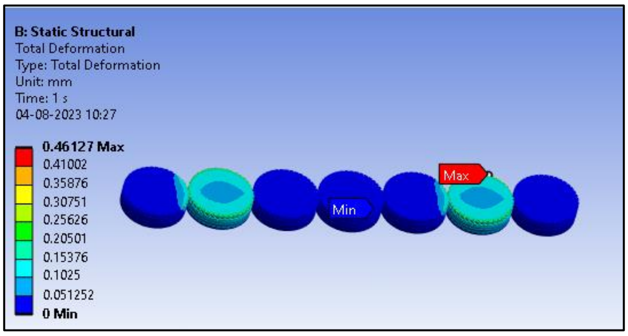

Fig. 9 b Total deformation

Case 4. Seven car tyres covering full with of single lane carriage way for dry condition for down direction. Results are shown in Fig. 10 a & b.

<u>Observations</u>: Von mises stress – 3.973 MPa & Maxi deformation-0.580mm

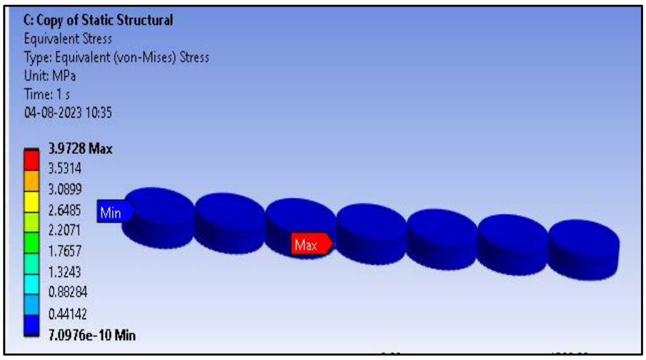

Fig. 10 a Von misses stress

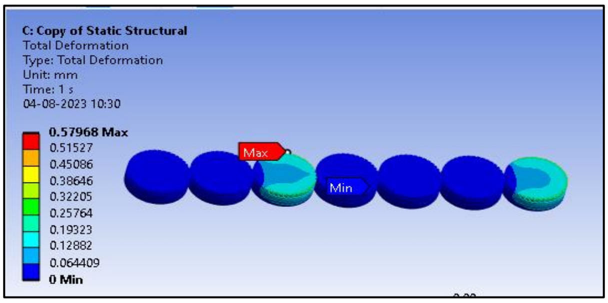

Fig. 10 b Total deformation

Case 5. Seven car tyres covering full width of single lane carriage way for saturated condition for up direction. Results are shown in Fig. 11 a & b.

<u>Observations: </u>Von mises stress-2.083 MPa & Maxi deformation – 0.172 mm

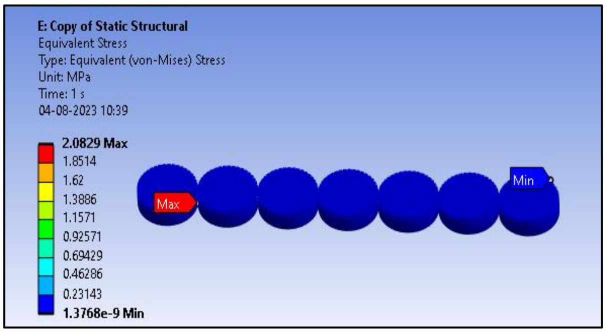

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Fig. 11 a Von misses stress

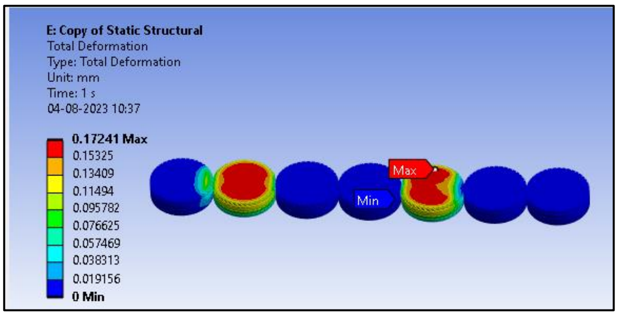

Fig. 11 b Total deformation

Case 6. Seven car tyres covering full with of single lane carriage way for saturated condition for down direction. Results are shown in Fig. 12 a & 12 b.

Observations: Von mises stress-2.009 MPa & Maxi deformation-0.172 mm

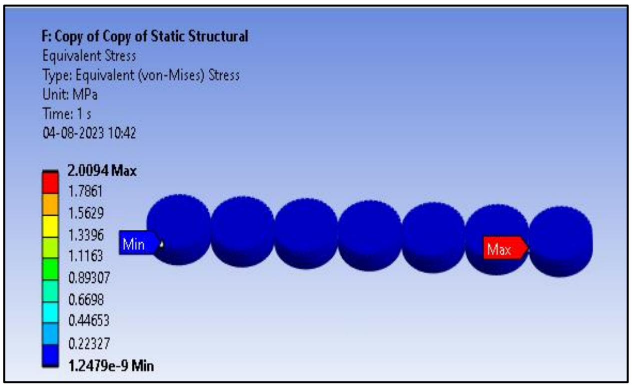

Fig. 12 a Von misses stress

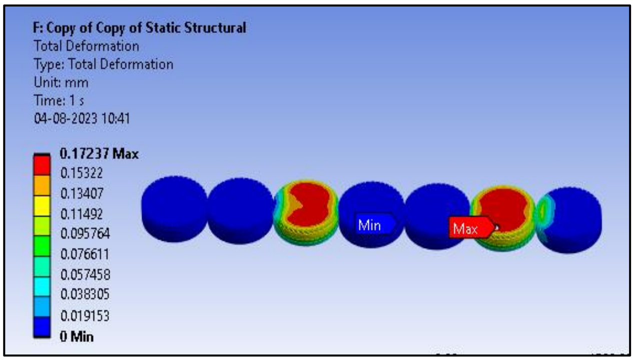

Fig. 12 b Total deformation

For truck tyre:

The analysis is conducted under static load conditions (MORT&H 2018) with the geometry model prepared without the rim and cutting one side of tyre up to the periphery keeping horizontally explained above. The input data for the ANSYS software analysis for truck tyre are depicted in Table 4.

Table 4. Input data for ANSYS software: (Truck tyre)

Description	Value
Model of tyre	Downloaded from "http://www.matweb".

Diameter	Scaled to 1000 mm
Section width (infill height)	200 mm
Tyre Material	Rubber
Iinfill material	Gravel well graded (GW)
Density of infill material	18 kN/m^3 or 1.8 g/cc (dry condition) 21 kN/m^{3}or 2.1 g/cc (saturated condtion)
Young's modulus of infill "E"	160 MPa (dry condition) 120 MPa (saturated condition)
Poission's ratio "v" of infill	0.35
Yield strength of waste tyreby laboratory test in MUTM as per ASTM D412. (least value is assigned)	7 MPa
Force (wheel load) applied	57,500 N As per standard (MORT&H 2018)

Case 7. Single truck tyre with well graded gravel as infill subgrade material for dry condition**.** The results are shown in Fig. 13 a & b.

Observations: Von mises stress-0.448 MPa & Maxi deformation-0.191 mm

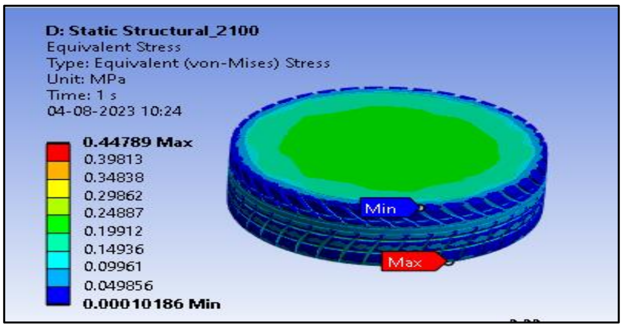

Fig. 13 a Von misses stress

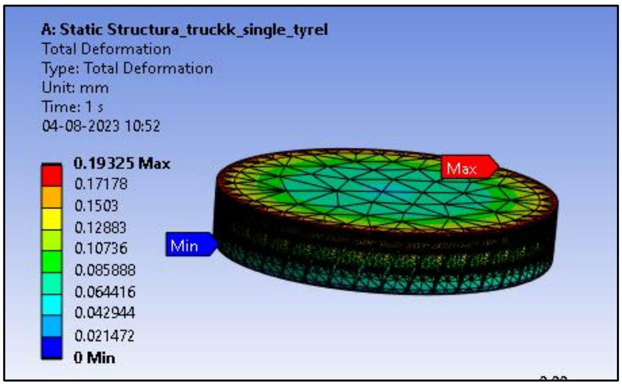

Fig. 13 b Total deformation

Case 8. Single truck tyre with well graded gravel as infill subgrade material for saturated condition. Results are shown in Fig. 14 a & b.

Observations: Von mises stress-0.242 MPa & Maxi deformation-0.210 mm

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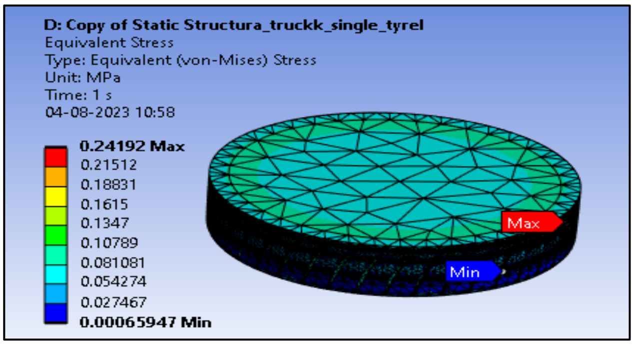

Fig. 14 a Von misses stress

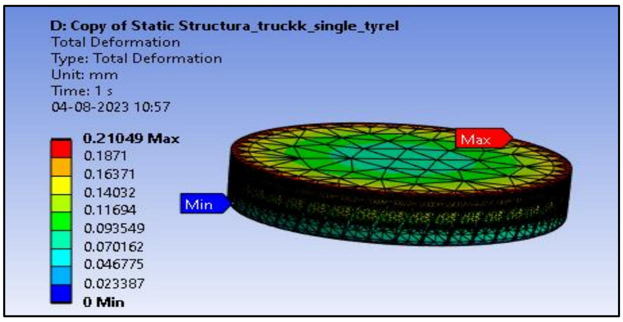

Fig. 14 b Total deformation

Case 9. Four truck tyres covering full width of single lane carriage way for dry condition for up direction. Results are shown in Fig. 15 a & b.

<u>Observations</u>**:** Von mises stress- 0.441MPa & Maxi deformation-0.096mm

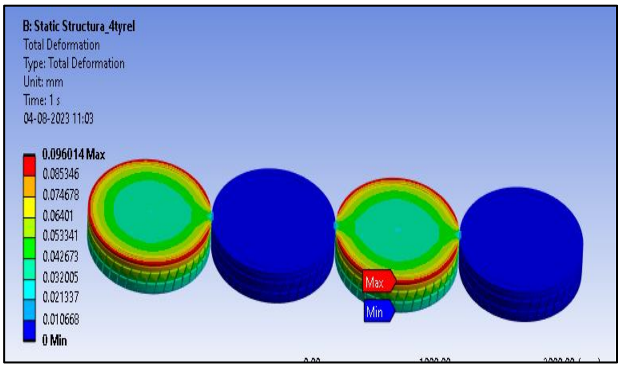

Fig. 15 a Von misses stress

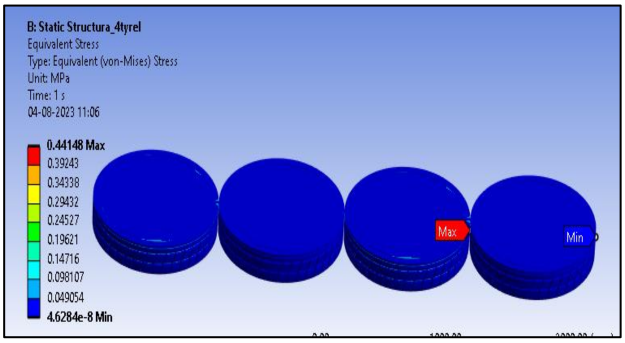

Fig. 15 b Total deformation

Case 10. Four truck tyres covering full with of single lane carriage way for dry condition for down direction. Results are shown in Fig. 16 a & b.

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Observations: Von mises stress-0.441MPa & Maxi deformation-0.096 mm

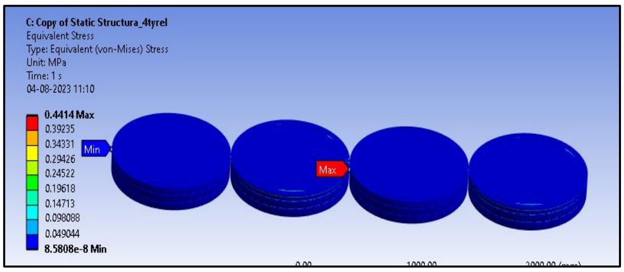

Fig. 16 a Von misses stress

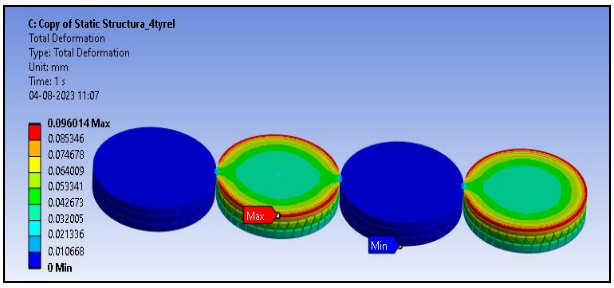

Fig. 16 b Total deformation

Case 11. Four truck tyres covering full width of single lane carriage way for saturated condition for up direction. Results are shown in Fig 17 a & b.

Observations: Von mises stress-0.494 MPa & Maxi deformation-0.104 mm

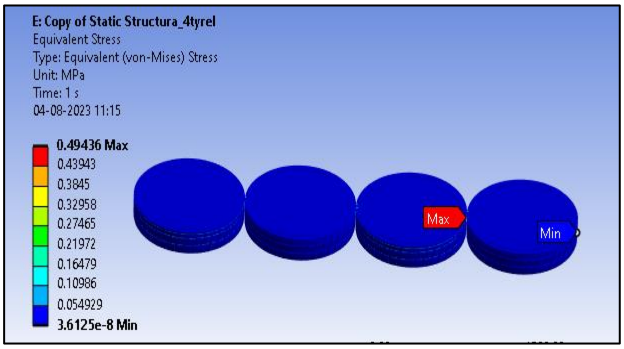

Fig. 17 a Von misses stress

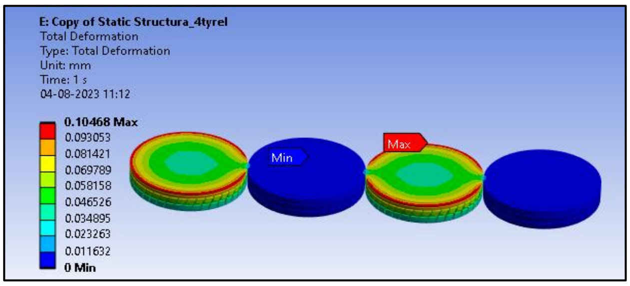

Fig. 17 b Total deformation

Case 12. Four truck tyres covering full with of single lane carriage way for saturated condition for down direction. Results are shown in Fig. 18 a & 18 b

Observations: Von mises stress-0.494MPa & Maxi deformation-0.105mm

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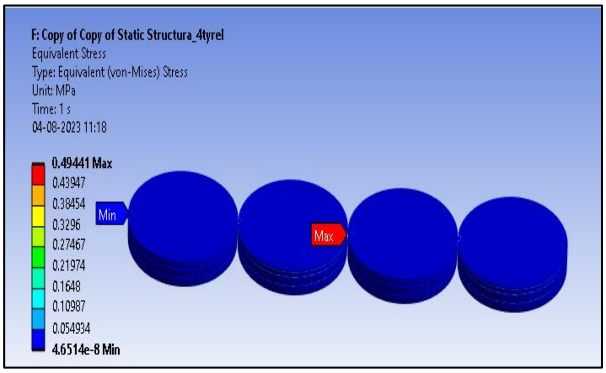

Fig. 18 a Von misses stress

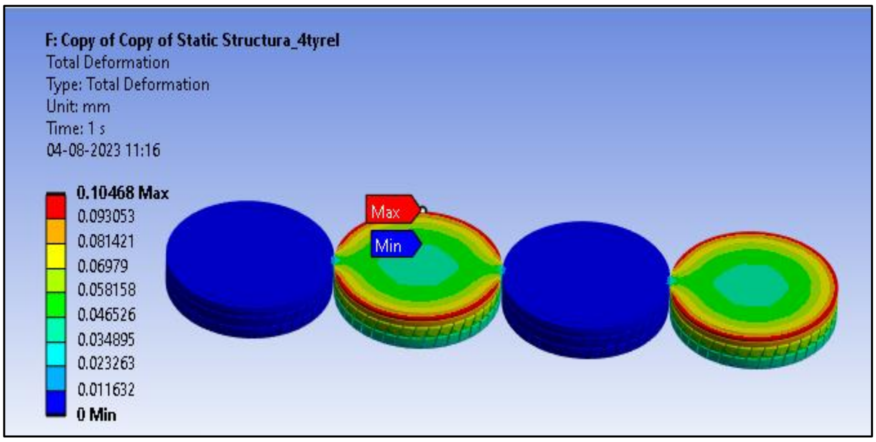

Fig. 18 b Total deformation

The abstract of results of car tyre for both dry and saturated conditions are depicted in Table 5 below.

Table 5. Abstract of FEM analysis.

Model	Condition of subgrade	Total deformationmm	Maximum Principal stress MPa	Von mises stress MPa
Single Car tyre	Dry	0.269	0.221	0.392
Single Car tyre	Saturated	0.341	0.255	0.448
Seven tyres	Dry			
	Up direction	0.461	1.806	2.533
	Down direction	0.579	1.677	**3.973**
Seven tyres	Saturated			
	Up direction	0.172	2.236	2.082
	Down direction	0.172	1.662	2.009
Single truck tyre	Dry	0.193	0.106	0.239
Single truck tyre	Saturated	0.210	0.117	0.242

Four tyres	Dry			
	Up direction	0.096	0.136	0.441
	Down direction	0.096	0.136	0.441
Four tyres	Saturated			
	Up direction	0.104	0.151	**0.494**
	Down direction	0.104	0.151	**0.494**

Figures 19 and 20 show graphical representation of deformations and von mises stresses under different conditions.

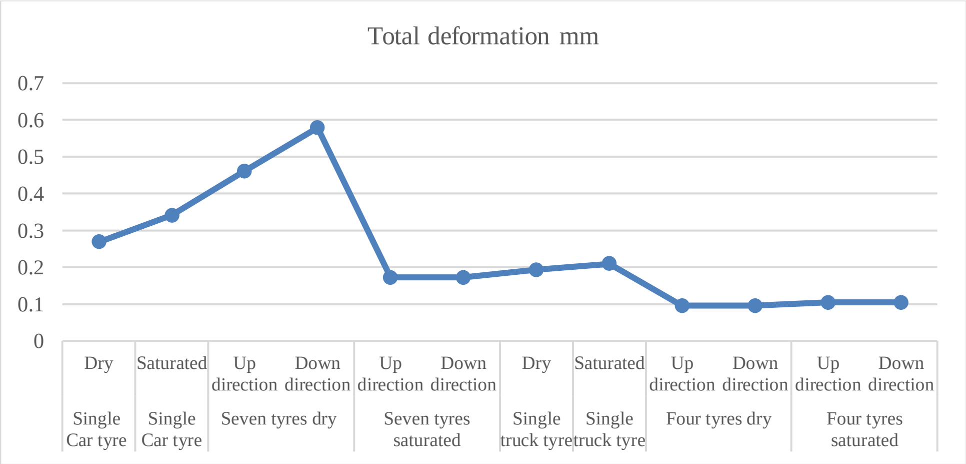

Fig. 19 Graphical representation of deformations under different conditions

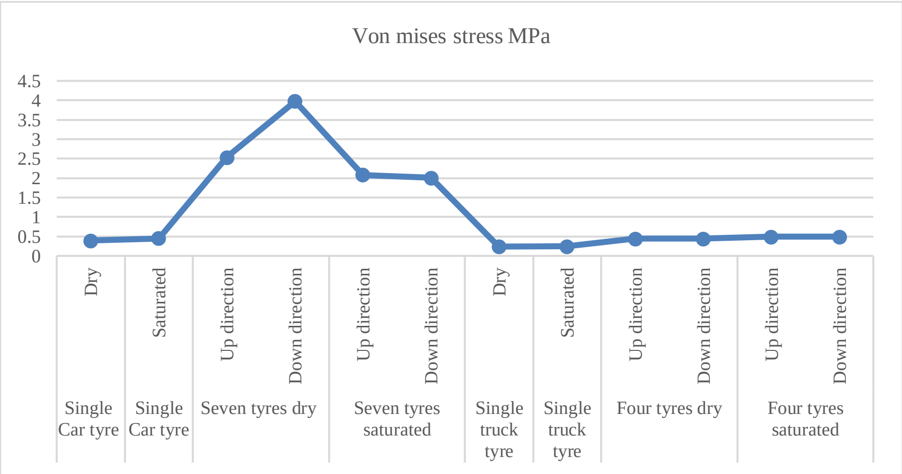

Fig. 20 Graphical representation of von mises stresses under different conditions The maximum values of the above results are shown in Table 6 below

Table 6 Maximum valuers of deformation and maximum (Von mises) stresses.

Sl. No	Tyre	Total deformation mm	Von mises stress MPa
1	Car tyre	0.579	3.973
2	Truck tyre	0.104	0.494

Comparison of the results of laboratory and ANSYS FEM

The values of both car and truck tyres as obtained by laboratory tests on tyres specimens are sufficiently high compared to the ANSYS FEM analysis results. So, it can be considered that the use of waste tyres filled with subgrade infill material as geo-tyre confinement, improves in reducing the lateral deformation and enhancing the other properties.

Plate load testing:

Plate load test has been conducted in the laboratory setup using tubeless car tyre (WR-V) having high tension wires and with 80015 km run. Tyre dimeter is 600 mm and the section with is 195 mm.

Requirements of experiment:

- Main hydraulic loading frame.
- Amil Digital Indicator
- Personal Computer (PC) or Laptop.
- Data Acquisition (DAQ) software.
- 120 Ώ sensors 4 nos.
- Connecting cables.
- Linear Variable Differential Transformer (LVDP).
- Well graded soil (GW).
- Waste tire on side cut open.
- M.S circular loading plate 600 mm Dia and 10 mm thick.
- M.S. Base Plate of 625 mm x 625 mm x 10 mm.
- Tamping load.
- Paper tape to fix the sensors to tire.
- Water.

Well graded (GW) gravel from local area has been used as subgrade infill material. The soil properties have been tested in the lab.

Experimental setup:

Fig 21 a

Fig 21 b

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Filling the GW in one side cut tyre and compacting Fig 21a & b.

Fig 22 Keeping the tye with compacted gravel in loading frame.

Fig 23 Loading position on plate

Fig 24 Fixing sensors and LVDT

Fig 25 Amil digital indicator.

Fig 26 Laptop with DAQ software connected to sensors

Procedure:

1) Installed "DAQ" software in Laptop

2) Collected GW = Qty of GW = (3.142*0.6*0.6/4) * 0.195= 0.0551 m3

Considering compaction factor of 0.25 = 0.0051*0.25 = 0.0683 m3 say 1.00m3

3) Kept rectangular M.S base plate on supporting ISMB 500 sections as shown.

4) Filled GW in the tire in three layers up to the top (195 mm thick) by tamping with tamping load for 55 blows at each layer to bring it near the field compaction.

5) Kept the GW filled tire on the base plate coinciding the center of plate with the center of the hydraulic loading piston as shown in fig.

6) Fixed the sensors on all the four sides of tire at the center with paper adhesive tape and connecting them to the Digital indicator with connecting sensor data cables.

7) Connected the Digital Indicator to Laptop with digital data cable.

8) Applied the load and noted down the results. Load v/s dispersion and Load V/s strains

Plate load test in loading frame results.

Load applied: 57.80 kN (0.3 kN more than the std load) Load v/s Displacement recorded.

Load v/s strains recorded from 4 strain gauge sensors.

Results obtained.

1) Maximum displacement = 3.75 mm
2) Maximum strain = 0.000009657

Dry condition:

Young's Modulus "E" = Stress / Strain

E = 104 MPa

Maxi Strain = 0.000009657

Stress = 0.001004 MPa

Saturated condition:

E = 104 MPa

Maxi Strain = 0.000005268

Stress = 0.000548 MPa

Maxi Displacement = 6.110 mm (Deformation) << 195 mm (section width of tire)

Tests are conducted for both dry and saturated condition of subgrade infill. Displacement for both dry and saturated conditions are shown in Fig 27 and 28

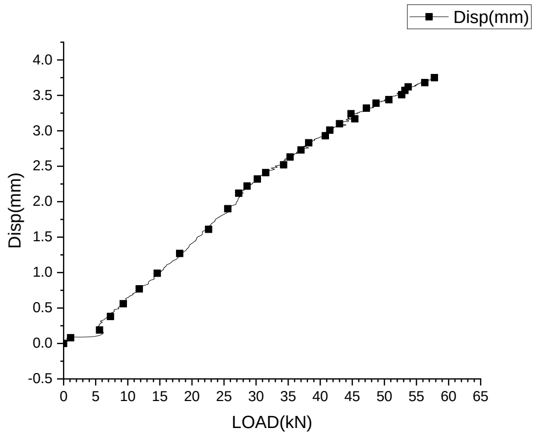

Fig 27 Plate load test graph load v/s displacement for dry condition of subgrade **3.75 mm** for 57.80 kN load

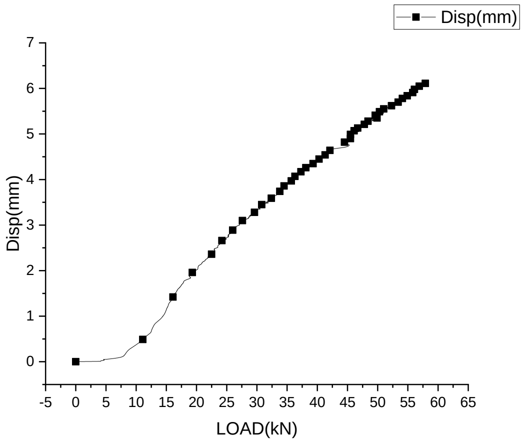

Fig 28 Plate load test graph load v/s displacement for saturated condition of subgrade. **6.11 mm** for 57.90 kN load.

CONCLUSIONS

Analytical results indicate that the tested waste tyres have a minimum of 7.702 MPa yield stress, which is much higher than the maximum stress (Von Mises stress) of 0.448 MPa obtained by “ANSYS” FEM analysis.

Stresses obtained by plate load experimental test for both dry and saturated conditions are much less than the minimum yield stress of tire specimens tested in the lab.

Based on the analytical, experimental and laboratory results, the following conclusions can be drawn.

- The waste tyres can be comfortably for 3D cellular confinement to stabilize flexible pavements, with reduced thickness. In the instant case the subgrade thickness is 195mm and 200mm for car and truck tyre (equal to their section widths) respectively, as against standard minimum thickness of 500mm subgrade. (Clause 4.3.9 - IRC:36-200)
- The tyres demonstrate sufficient safety margin in terms of stress resistance compared to geocells.
- Confinement provided by waste tyres improves the bearing capacity of the weak soil with low CBR values, reduces lateral deformation, and increases shear resistance, leading to a longer service life for flexible pavements.
- Geo-tyre technology facilitates eco-friendly disposal of waste tyres, reducing the environmental impact.
- Geo-tyre technology supports speedy pavement construction like construction of runways in airport.
- Geo-tyre technology with perforated tyres can also be used for subbase layer in case of construction of pavements on hard soil.
- This technology offers the opportunity to utilize effectively other inexpensive nonrenewable waste materials such as clay and concrete as subgrade / subbase infill materials.

Overall, the findings suggest innovative use of waste tyres for 3D confinement in pavement construction which has multiple advantages in terms of stability, disposal management, and sustainability, making it a promising approach for future infrastructure projects.

Limitations of the work done:

1. The study is limited to numerical analysis, and laboratory and experimental tests on sample tyre specimens only.
2. The structure of high-tension wire and nylon chords embedded in the tyres is very complex and the model could not be created resembling the actual tyre structure. However, the readily available model is imported from "GrabCad" website. So, the experimental results of actual tyre specimens of waste tyres collected and the tyre models adopted in the analysis differ each other.
3. The study considers test on only two types of tyres only. Since there are numerous brands, makes and compositions of tyres are available, it is a necessary to test tyres of different make, size, and compositions to understand their engineering properties and to use for the intended purpose,
4. Laboratory and numerical models may not accurately represent real-world conditions especially in terms of roadway width. Therefore, the performance of the tyres is be studied in the field by utilising them across the entire width of roadway.
5. The current study focuses on the confinement of subgrade courses using waste tyres. However, the same approach could be applied to confine subbase courses a drainage layer. This would involve perforating the tyres and covering them with a geomembrane to prevent the flow of fine soil particles as the subbase must function as a drainage layer.

Future work: Limitations mentioned in the current study can be addressed in future research. Accordingly the use of smallar tyres with lesser section width i.e, for smallaer thickness of pavement courses may be considered for 3D confinwment. The proper adhesion of bituminous binding and wearing courses with tyre surface requires propoer testing to study the properties of both bitumen and tyres to assess their suitablity.

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