PERFORMANCE EVALUATION OF FIBRE REINFORCED PERVIOUS CONCRETE PAVEMENT

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Due to Infrastructure development city streets are being covered with concrete pavements in which it makes the pavement surface impermeable. During monsoon period, the importance of counter action against the stormwater runoff develops a stress among the Central and the State Governments of India. It also attracts the attention of the Road and Transport officials mainly because of the difficulties faced with poor drainage system during heavy intensity of rainfall. The productive application of pervious concrete includes its usage for light volume transportation and it also diminishes the additional design for stormwater drainage. This concrete also holds potential to accommodate shoulders in heavy traffic roadway transportation. The behaviour of pervious pavement under various loading scenario can be well understand using Finite Element Method Analysis (FEMA). For primary assessment of pervious concrete (PC) as pavements, computer modelling software is preferable and economical comparing to ground evaluation after installation. In this paper, a EverFE (Finite Element Analysis) tool has been used to develop and determine the loading characteristics of pervious pavement based on the experimental values obtained through preliminary studies.

Keywords: *Pervious Concrete Pavement, Fibre Reinforced Pervious Concrete, Critical Loading, Finite Element analysis, Stress, Deflection*

1. Introduction

Infrastructural development and urbanization of several countries around the world results in lack of permeability in ground surface due to covering of concrete surfaces. It also encounters serious environmental effects such as global warming, reduction in ground water recharge, water pollution, and water stagnation during heavy rain falls [1]. Pervious concrete pavement is a sustainable method to manage and discharge the retaining storm water during heavy floods. Poor drainage with impermeable surface will result in difficulties in using road transport facilities and acquiring daily needs [2] and the scenario faced is represented in Figure 1. Pervious concrete is unless a conventional concrete with less or zero utilization of fine aggregates, and thus producing a high porosity making it permeable [3]. Installation of pervious concrete pavement replacing the impervious one is an efficient solution to avoid flooding frequently [4]. An additional property of noise absorption serves as a sustainable solution for reduction of noise pollution during heavy traffic [5].

The massive development of construction industry demands sustainability in it, the studies on pervious concrete will support a sustainable development in the field of transportation and highway industry. It is the key requirement of all developing country (countries with HDI 0.55 to 0.69 as per UNPD 2019 [6], Overview on Human Development Report (Figure 2) like India, to satisfy three main criteria namely sustainability, serviceability and feasibility in addition to its performance.

The ingredients of pervious concrete includes ordinary Portland cement, uniformly graded coarse aggregate (preferably of size less than 12mm or ½"), water and some special admixtures for performance enhancement [7]. The uniformity of aggregates

Fig. 1- Photos taken during heavy flooding of roadways [Chennai city, India]

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Fig. 2. Human Development Index Report (Published in 2019)

results in increasing voids content whereas while using different sized aggregates, the smaller will fill the voids between the larger one [8]. The replacement of aggregates with recycled one is also acceptable and a sustainable method to reduce construction waste [9]. These voids are interconnected to each other in the vertical direction throughout its depth [10]. This property of pervious concrete is responsible for the water percolation through it [11]. The modelling of given pervious pavement systems involves a basic vertical porosity distribution design throughout the depth of these pavements [12]. The total depth is divided into three layers (top quarter 2", middle half 4" and bottom quarter 2") with an assumption of faultless bond between the layers. The porosity of these three sections varies, and an average is finally considered as the system porosity [13]. The porosity of top quarter changes with respect to time due to the clogging effects and reduces the system porosity [14]. And the bottom quarter porosity varies with the selection of sub grade (coarser sub grade permits higher discharge rate). Whereas the porosity of middle half remains the same and is influenced by poor placement practicing which can be enhanced during pavement casting [15]. Thus, to increase the overall porosity of a given pervious pavements, each of three layers must follow different strategies such as the top quarter porosity can be recovered by practicing certain rehabilitation techniques, The bottom quarter porosity is boosted by placing the pervious pavement over a coarser sub grade and the middle half along with the top and bottom quarter porosity values can be improved by adopting pavement design with higher voids content say 20-30% [16]. The pervious concrete has some drawbacks such as high susceptibility of clogging thereby reducing its efficiency, low values of crushing strength, less durability issues due to offering of less - resistance against abrasion, high - wear & tear and low - freeze thaw resistance [17]. Adding fibre reinforcement in pervious concrete to improve durability is a proven technique. In this research, macro synthetic fibres of 47mm length and aggregate size of ½" or 12 (±2) mm is used and their test values are taken from an experimental investigation [18].

2. Analytical Evaluation

The methodologies adopted during analytical evaluation using FEMA has been discussed elaborately:

i) A three-layer pervious model (top quarter 2", middle half 4" and bottom quarter 2") 3D slab of dimension 6.5' x 6.5' (2m x 2m) and thickness 8" (0.2m) is developed using a FEM software, the above said slab model is taken as an array of 2 rows and 3 columns as shown in Figure 3. Varying stiffness for each layer with respect to its porosity is provided. Other solid properties such as Young's modulus, Poisson's ratio, crushing and flexural strength obtained from the laboratory testing were taken.

ii) To record the absolute 3-Dimentional effect of the pervious slab, real time parameters such as sub base with thickness of 10" (0.25m) and a sub grade (underneath soil stratum) thickness of 39" (1m), are also considered to have some effects on stress and deflection as shown in Figure 4.

iii) The stress and deflection of pervious pavement along with the sub base and sub grade are calculated for a vehicle point load at various critical loading conditions by considering wheel location such as (i) at near center, (ii) at one side edge and (iii) at corner locations of the model.

This approach of FEM evaluation is used to design and develop a large-scale model. The elementary steps involved in FEA comprises three-dimensional model generation, assigning material and model properties (such as elasticity modulus, Poisson's ratio, compressive strength and flexural strength) from the derived experimental values, meshing, applying wheel loading and boundary conditions, analysis and reading the results.

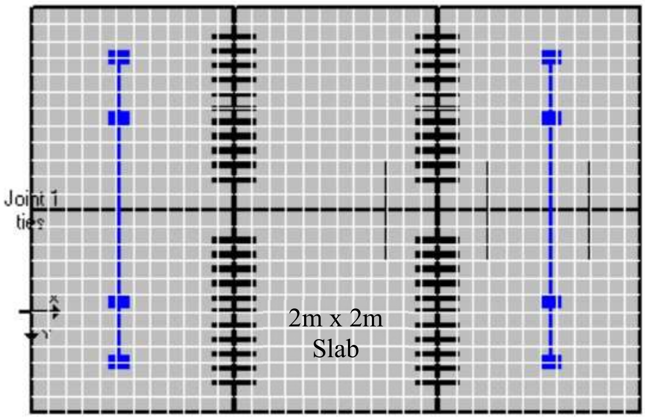


Fig. 3 – Ever stress FE model of pervious slab

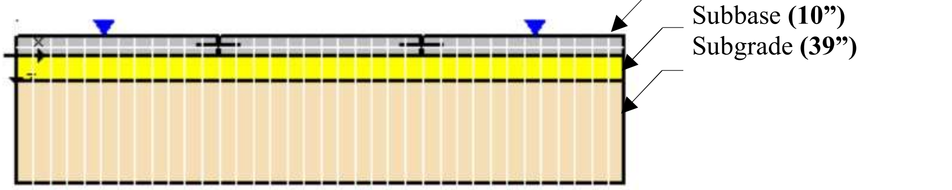


Fig. 4 – Cross section of slab showing sub base and subgrade

3. Pavement Design

High water permeability is the desired property of pervious concrete pavement (PCP) and the similarity in aggregate size enhance the interconnected voids percentage [19]. The fibre reinforcement in PCP does not affects the strength or hydraulic properties, but it does have a measurable outcome on durability of the pavement [20]. In addition to this the structural performance of the pavement depends on several factors such as mix design, placement and curing of concrete, clogging along with surface durability [21]. Image scanning technology can be used to assess clogging on pervious concrete pavements [22].

3.1 Loading Characteristics

The concept for introducing tie bars in slabs is to provide an interface to endure load from the wheel. The wheel load for invading truck has been considered as per AASHTO standard specifications are represented in Table 1 and schematically represented in Figure 5.

The wheel configuration adopted in the modeling is Dual wheel tandem axle. From the Table 1, the rear wheel tandem loading was considered as the maximum design loading, and this value is taken for the testing of pavement model. The wheel configuration and pressure were kept as constant for all the four types of truck

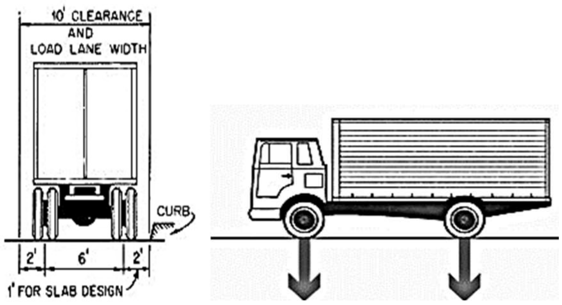


Fig.5 - Wheel load - Schematic representation

Table 1

AASHTO standard Specification for H-type truck wheel load

Designation	**Approved Wheel Live Load lbs. (kN)**	
H5	2000 (8.89)	8000 (35.58)
H10	4000 (17.79)	16000 (71.17)
H15	6000 (26.68)	24000 (106.76)
H20	8000 (35.58)	32000 (142.34)

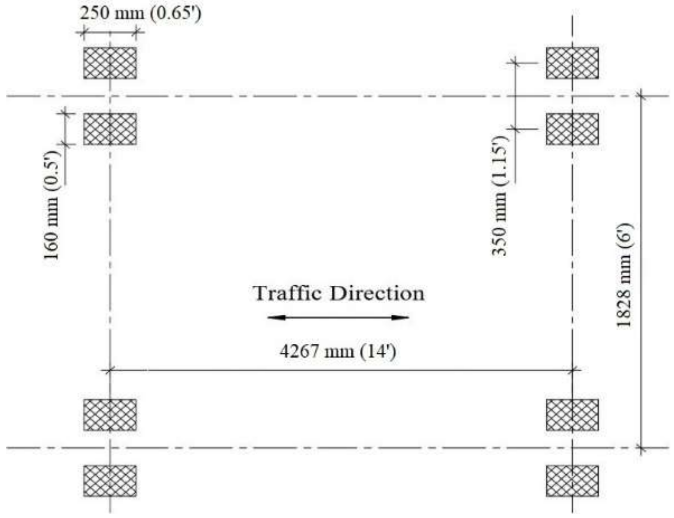
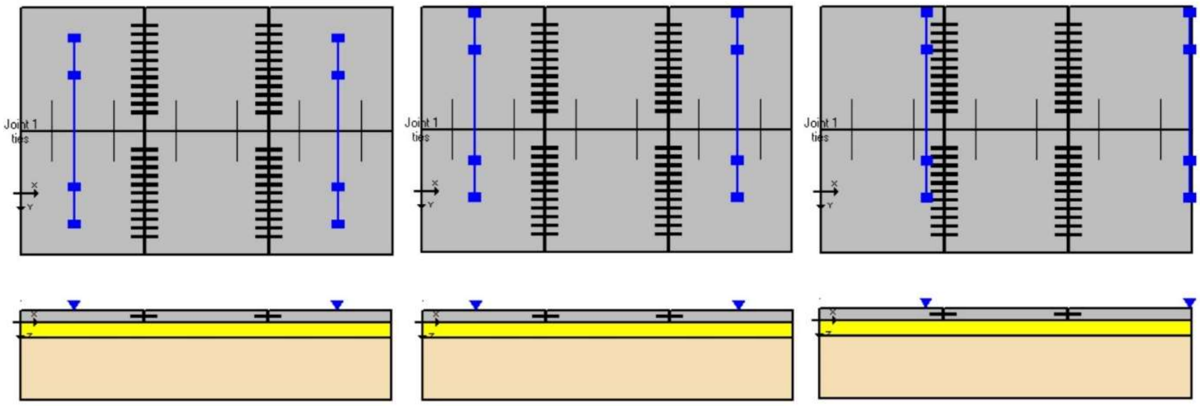


Fig. 6 - Wheel Configuration



(a) (b) (c)

Fig. 7 – Wheel location
(a) at near center, (b) at one side edge (c) at corner locations of the model.

designation in its three boundary conditions of this analysis. The wheel configurations of the trucks in the direction of traffic, taken for modelling along with its footmark on the FRNFC pavement, are shown in Figure 6

The solution for the above four kind of wheel loads (H5, H10, H15 and H20) for three boundary conditions (at near center, at one side edge and at a corner) as shown in the Figure 7 are discussed briefly and the corresponding stresses and deflections are derived using EverFE V2.24. The symmetrical identification of the model, choosing of appropriate boundary conditions, proper meshing details of the model and selection of element type are the essential parameters for accuracy in model detailing. Other external factors including computer capacity (like RAM and ROM) can optimize the computing time.

3.2. Material Properties

The difference between the traditional concrete and Fibre Reinforced Pervious Concrete (FRPC) are observed in the values of their stiffness, crushing strength and flexural behaviour. Whereas the stiffness of subbase and subgrade are taken into consideration which is kept to be constant for both the concretes. Along with this Young's modulus and Poisson's ratio of different kinds of soil is taken from the textbook Foundation Analysis and Design [23]. The material properties required for analysis and the composition of the Fibre Reinforced Pervious Concrete were taken from references and experimental investigation as tabulated in Table 2a and 2b.

The composition of the Fibre Reinforced Pervious Concrete includes OPC 53 grade cement, single graded aggregates of size S1 (9.5 to 12.5 mm) and S2 (12.5 to 16 mm). Macro synthetic fibres of varying length L1, L2 and L3 (i.e. 36, 47 and 60 mm), specific gravity ranging from 0.90 to 0.92, whose tensile strength ranging from 550 – 640 Mpa, Youngs modulus of about 6-10 Gpa and melting point ranging from 159 - 179 ^{o}C. The fibres were received free of cost from Bajaj Reinforcement LLP,

Table 2a

Material Properties Obtained from reference and laboratory testing

Layer	Youngs Modulus E (Mpa)	Poisson's ratio nu (-)	Density ρ (kg/m^3)
Test Methods	Cube Compression Test	Gauge method	Weighing method
Pervious Slab	18533	0.2	1866
Subbase	5000	0.2	1542
Subgrade	200	0.4	1430

Table 2b

Composition of the Fibre Reinforced Pervious Concrete

Mix ID	Cement (kg/m3)	Aggregate (kg/m3)	Water (kg/m3)	Fibre (kg/m3)	WRA (g/m3)	VMA (g/m3)
CN_1	258	1129	46.4	-	645	-
FN_{11}	244	1071	44.0	4.27	611	733
FN_{12}	244	1071	44.0	4.27	611	733
FN_{13}	244	1071	44.0	4.27	611	733
CN_2	258	1151	46.4	-	645	-
FN_{21}	244	1091	44.0	4.27	611	733
FN_{22}	244	1091	44.0	4.27	611	733
FN_{23}	244	1091	44.0	4.27	611	733

Maharashtra. To stabilize and enhance the desire mechanical characteristics of fibre reinforced pervious concrete such as workability of the mixtures, bond strength between aggregates and cement paste, some chemical admixtures like, a Viscosity modifying agent (VMA): Eucoplacant-721, and a Water reducing agent (WRA): Auramix-400, conforming to the requirement of IS-9103:1979 sponsored by FORSAC Chemicals Pvt. Ltd., Chennai were used for the entire study. Locally available portable water from Nandha Engineering College, Erode campus conforming to IS-456:2000 and aggregates from Blue Metals Pvt. Ltd., Perundurai region were used.

An aggregate to binder ratio was kept as 4.5:1 with a fibre proportion of 0.30% throughout the study, and the water to binder ratio was maintained as 0.28. The water reducing agent WRA: Auramix-400 was added to both conventional and Fibre Reinforced Pervious Concrete taken in an optimal dosage of 0.25%. The Conventional and FRPC mixes with varying aggregate size (9.5 to 12.5 mm, 12.5 to 16 mm) and fibre length (36, 47 and 60 mm), arrived are given in Table 2b. The Mixes identified with 'CN_{xy}' refers to Conventional NFC mix and 'FN_{xy}' refers to Fibre-reinforced NFC mix. The suffix xy indicates the aggregate size and fibre length used in that particular mix, for example, FN_{11} represents FRNFC mix with S1 size of aggregate and L1 length of fibre.

3.3. Slab Joints

The properties of fibre reinforced pervious slab near its joints are difficult to predict, and generally steel reinforcement shall not be suggested in this case. Slabs are modeled to be join each other using dowels (direction parallel to traffic) and ties (direction perpendicular to the traffic) of standard specifications (Figure 8).

4. Finite Element Analysis

Comparing to other modeling methods, Finite Element Analysis (FEA) has the ability to handle any structures even with arbitrarily complex geometry and recreate the actual model. It also consumes less amount of time with respect to experimental study [24]. There are numerous

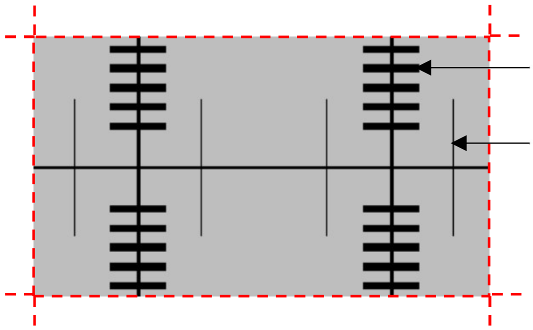


Fig. 8 - Specifications for slab joints

Fig. 9 - Stress indication on Slab (in MPa)

platforms available to do finite element analysis such as ANSYS, ABAQUS, ADINA, PLAXIS, etc., Ever stress FE (or) EverFE is one of the free and effective software specially used to design and analyze jointed plain three-dimensional concrete pavements [8]. This software employs a simple tool to generate up to 9 slabs along with up to 3 base layers below the specific slab. The solution to four kind of maximum wheel load (H5, H10, H15 and H20) for three conditions (at near center, at one side edge and at corner) are discussed briefly in this section. The modeling of pervious pavement using any FEA software includes the below step procedures.

(i) Illustration of geometrical specifications,
(ii) Designation of material properties of the pavement along with subbase,
(iii) Application of the wheel loading and dowel specification, and finally
(iv) Meshing details of elements which are to be analyzed.

A typical stress indication against the corresponding wheel loading on the pavement is shown in Figure 9. The stress value in the figure varies for different load combinations, the principal maximum stress (σ_{max}) refers the tensile stress and the principal minimum stress (σ_{min}) refers the compressive stress on the slab. However, the results obtained from this analysis were validated with experimental results to design and develop a physical prototype model with all said practical applications for real time study. The application of FEA for Pervious Concrete Pavements is a new approach, and it can be used for study the transportation, percolation and clogging properties in comparison with a prototype model [26].

4.1. Wheel load at near center

It is vibrant from the observations that the increase in the wheel load produces compressive stress up to 9.6 MPa and tensile stress up to 0.91 MPa for wheel load at the near centre. Figure 10 shows the stress distribution pattern on the pavement with near centre wheel load for four different kinds of truck loads. The results certify that the stresses from trucks H5, H10 and H15 are within the permissible limit. For truck H20, the stresses value increases at the second column of the slab pavement but considering the subbase and subgrade stiffness, the wheel loading can be distributed evenly to the subbase and has negligible stress (in both compressive and tensile). So, this condition shall not be taken for further comparison.

4.2. Wheel load at one side edge

The wheel load at one side edge creates maximum tensile stress comparing to other types of loading as shown in Figure 11, and the increase in the load produces compressive stress up to 14.43 MPa and tensile stress up to 2.42 MPa. Similarly, the results show that trucks H5, H10 and H15 develop stress values within allowable limits. The truck H20 develops maximum stress over the width of the pavement where the wheel loads are heavily concentrated. This condition results in the settlement of the pavement with the subbase and subgrade over its service period along the one side edge where the wheel load is acting for a given period. This condition is a critical one for the tensile stress and magnitude of settlement.

4.3. Wheel load at corner

The wheel load at the corner of the pavement for different trucks shows the stress distribution pattern as shown in Figure 12. Similarly,

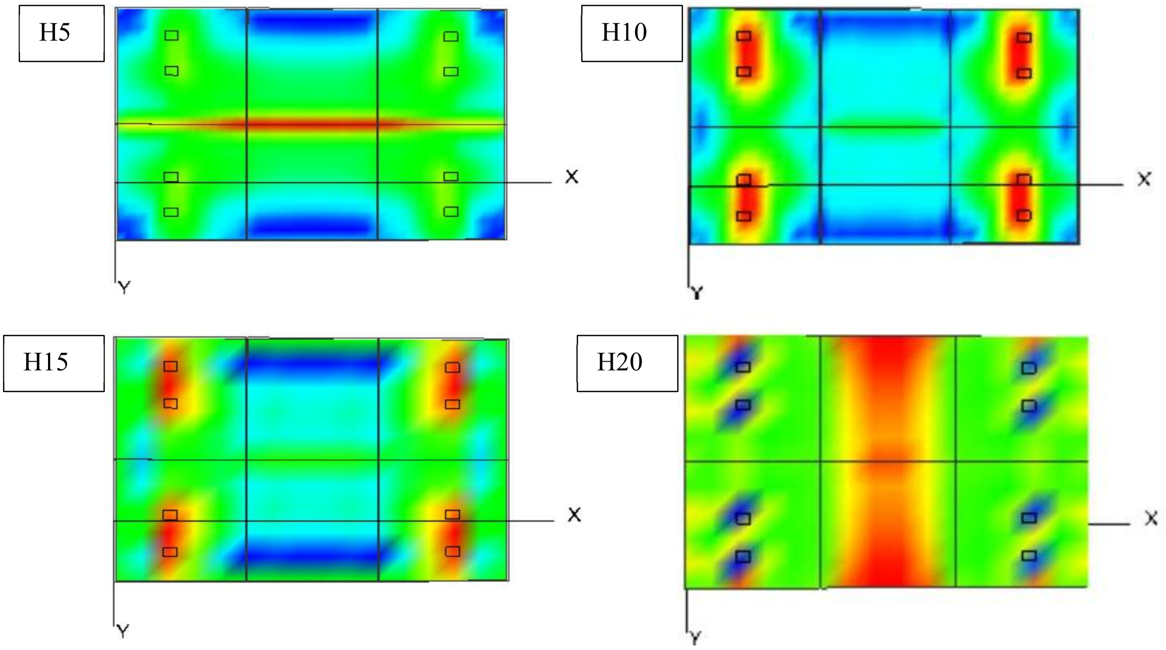


Fig.10- Stress distribution pattern on the pavement with near centre wheel

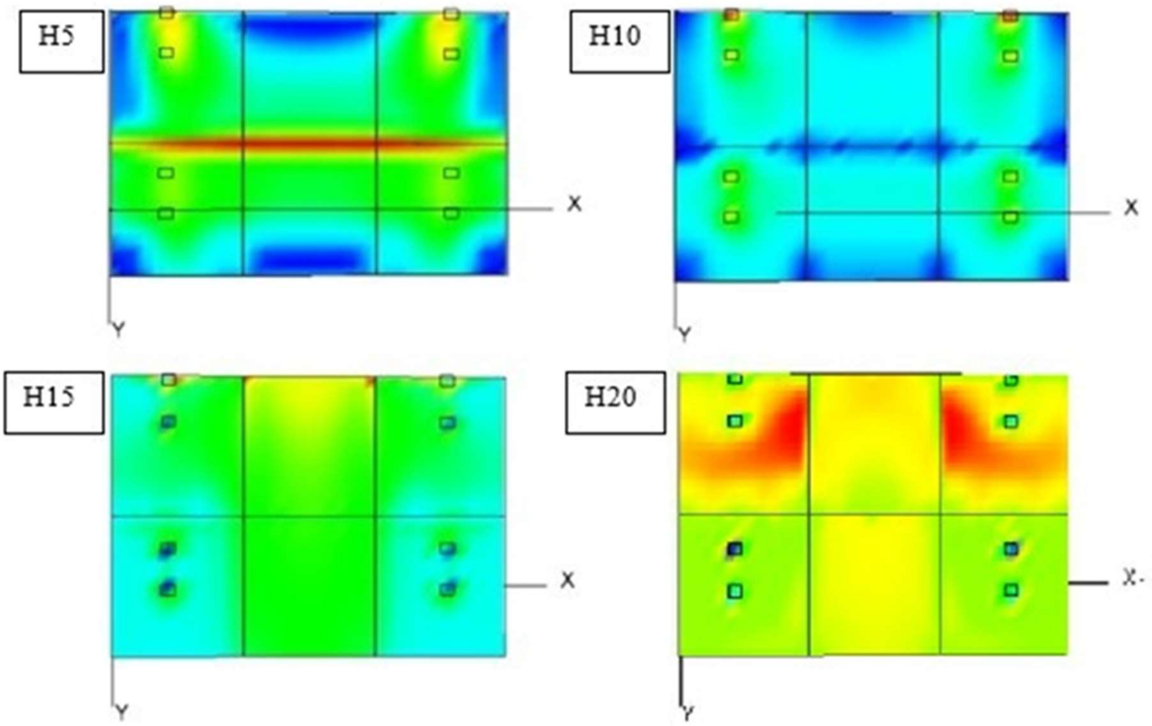


Fig. 11 - Stresses for wheel load at one side edge

the analytical results show that trucks H5, H10 and H15 develops stress values again within the allowable limits. The truck H20 develops maximum compressive stress of 18.86 MPa over the corner of the pavement where the wheel loads are heavily concentrated. The critical displacement of 2.53 mm recorded for the truck H20, which is the maximum deflection among all load combinations.

5. Maximum Deflection

The maximum deflection of FRNFC pavement was observed in the maximum loading condition, for the wheel load at the corner and recorded as 2.53 mm. The pavement stiffness and self-weight are considered for calculating the displacement. Figure 13 shows the maximum deflection for various loading conditions. The displacements are visualized with a deformation scale factor of 1000, for magnifying the deflections.

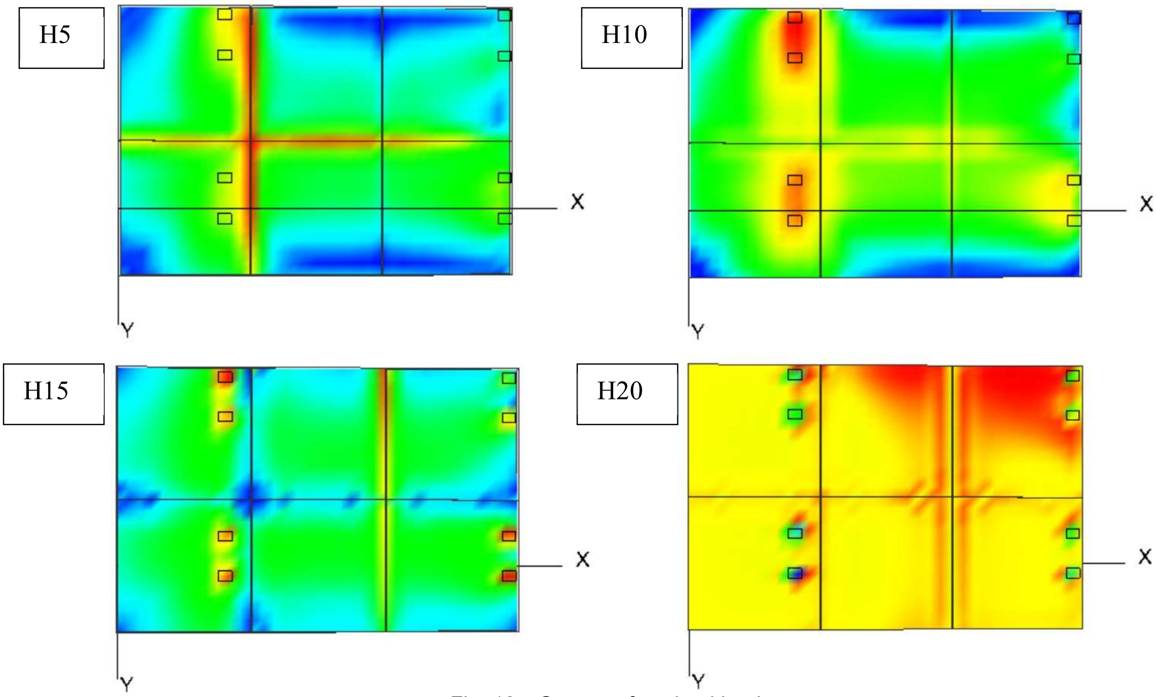
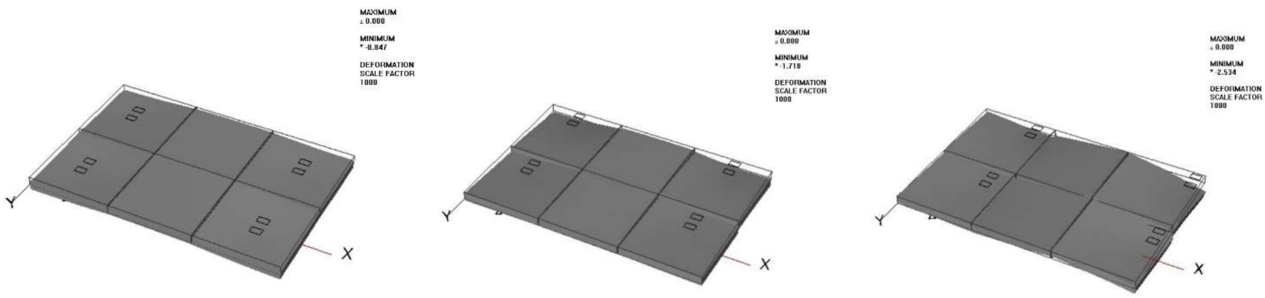


Fig. 12 – Stresses for wheel load at corner



a)Wheel load at near center corner b)Wheel load at one side edge c)Wheel load at corner

Fig.13- Maximum deflection

Table 3

Summary of Stresses and Deflection

Boundary Condition	**Truck Type**	**Maximum Stress (MPa)**		**Deflection (mm)**
		Compression	**Tensile**	
Wheel load at near center	H5	2.999	0.202	0.225
	H10	5.147	0.384	0.404
	H15	7.401	0.653	0.628
	H20	9.630	0.915	0.847
Wheel load at one side edge	H5	4.266	0.491	0.426
	H10	7.560	1.125	0.851
	H15	11.011	1.779	1.290
	H20	14.431	2.416	1.718

table continues on next page

Wheel load at corner	H5	5.514	0.451	0.640
	H10	9.915	1.010	1.256
	H15	14.443	1.593	1.902
	H20	18.864	2.158	2.534

The thickness of the pavement and subbase increases the overall stiffness of the pavement and thereby creates a negative impact on the system displacement. Table 3 gives the maximum deflections for various load combinations.

These stresses and deflections are calculated considering the overall stiffness of the system (i.e., including the stiffness of subbase.) For high loaded trucks like H20 (142 kN), the deflections are comparatively very high, and this can be reduced by increasing the thickness of the pavement or subbase, thereby increasing the overall system stiffness.

6 Comparative analysis of mechanical properties

6.1 Comparison of Compressive Strength

The maximum compressive stress of the pavement is higher for the trucks with maximum wheel load H20, (142 kN) compared to that with minimum wheel load H5, (36 kN). The maximum compressive stress is observed for the condition with wheel load at the corner for all four types of truck loads. Comparing the values of the maximum compressive stress (18.86 N/mm^2) obtained from the analytical evaluation with the experimental values of compressive strength of the selected mixture (15.55 N/mm^2) showed that the designed pavement is not suitable for the H20 truck type. By increasing the thickness of the FRNFC pavement (or) subbase the maximum compressive stress recorded can be reduced. Figure 14 shows the maximum compressive stress obtained for different loading conditions.

6.2 Comparison of Tensile Strength

The values of the maximum tensile stress (2.41 N/mm^2), obtained from the analytical evaluation are within the limit of experimental values of splitting tensile strength (3.33 N/mm^2) of the selected FRNFC mixture. Figure 15 shows the maximum tensile stress obtained for different loading conditions.

The maximum tensile stress is observed for the condition with wheel load at one side edge for H20 truck. The maximum tensile stress can also reduce by increasing the thickness of the FRNFC pavement (or) sub base thereby increasing the stiffness of the system.

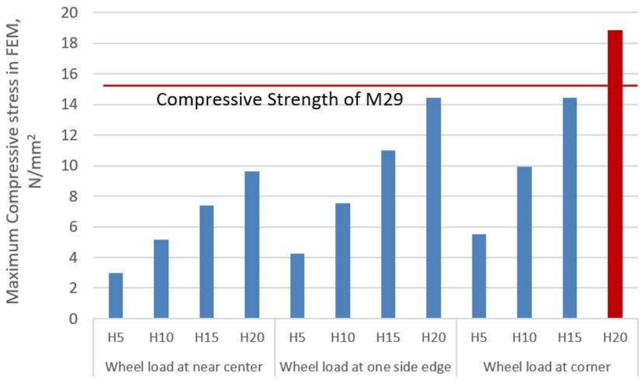


Fig. 14 – Comparison of Comptressive Strength

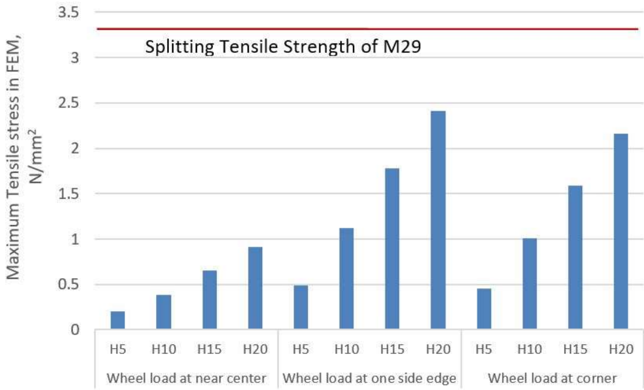


Fig. 15 – Comparison of Tensile Strength

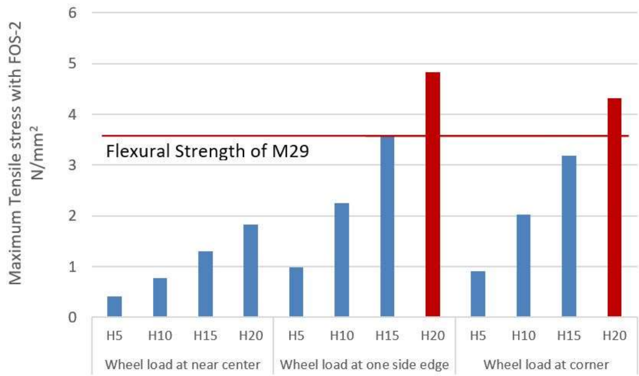


Fig. 16 – Comparison of Flexural Strength

6.3 Comparison of Flexural Strength

Since the modelling software can only give the maximum compressive and tensile stresses, to compare the flexural strength of the FRNFC pavements, a cutoff line was plotted in the tensile stress plot stating the flexural strength of the selected mixture (3.5 N/mm^2). The maximum tensile stress with a factor of safety (FOS) 2 were also plotted to represent the stress requirements crossing the limits as shown in Figure 16.

This graph clearly shows that the wheel loading characteristics at the various critical locations in the pavement model for the flexural strength of the concrete. The maximum tensile stress with FOS 2, for the H20 type of truck, crosses the cutoff line (i.e., limiting value of the flexural strength of the mixture), and thus not recommended to use the FRNFC highway shoulder. This can be revised by increasing the thickness of the pavement or sub base.

7. Conclusion

The effect of different types of wheel loading at various critical locations in the pavement was discussed. From the analytical evaluation of 12 sets of load combinations, and the comparison of analytical stress results with the experimental strength values, it is proved that the FRNFC pavement can be used as a highway shoulder. Also, it is advisable to license maximum truck loading up to H15 (i.e., ≤ 107 kN) for the given specification of FRNFC and sub base. Still, the load-bearing capacity of the pavement can be readily increased by increasing the thickness of either pavement or sub base.

i) Finite Element analysis is accepted as a suitable method to explore additional performance of the pervious pavement, which can be further validate with classical theories before the field placement.

ii) The principal design functions taken here in the Finite Element analysis are stress (tensile) and deflection, whereas the crushing strength for pervious concrete is very low and shall be taken for low loading cases.

iii) While analyzing the wheel loading characteristics at various critical location in the pavement model and after getting the stress diagrams, it is advisable to license maximum truck loading up to H15 (i.e., ≤ 107 kN) for the given specification of FRPC and sub base.

iv) The load bearing capacity of the pervious pavement for all loading conditions can be readily increased by increasing the thickness of either pavement or sub base.

v) From the above static linear analysis, it is concluded that FRPC pavements can replace the existing impervious pavements for moderate volume of traffic conditions.

vi) Within the selected boundary of properties, FRPC can also be used for highways of high volume of traffic conditions with some safety factors. And further extensive research is must to improve the performance and efficiency of this kind of pervious pavement.

8. Future Research

The approach of finite element for no-fines concrete has some limitations, such as the complex characteristics of FRNFC cannot be accurately modelled. However, this concrete also has some practical drawbacks such as high susceptibility of clogging thereby reduction in its efficiency, low values of crushing strength, fewer durability issues due to offering less - resistance against abrasion, high - wear & tear and low - freeze-thaw resistance. But still, it can produce an appropriate result of stress and deflection with sensible efficiency. The application of FEA for FRNFC Pavements is a new approach, and it can also be used to study the percolation, clogging properties in comparison with the physical prototype model. With this analytical result, field placement is planned to be constructed inside our campus, in the minimal level of slope to collect the rainwater received throughout the year.

The composite structure of pervious concrete and distribution of vertical porosity can be better understood with micro structural study. The bond established between various layers of FRPC are assumed to be flawless, and it is practically not possible. Further a complete study considering the friction between the layers of pervious concrete should be targeted for more accuracy. A small amount of water always remains in the pavement or subbase after a discharge, and the effects of this water molecules in the structural and durability characteristics of FRPC pavements should be examined in future. The same model can be subjected to a nonlinear analysis, and a diverse result should be projected. At last in addition to structural failure at maximum stress, failure due to durability point of view should be focused; from this, a concept of fibre reinforcement in pervious pavement was introduced. Their effects on their efficiency shall be comprehensively studied, which further helps in expanding their applications.

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