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THE USE OF PLASTIC WASTES AS REINFORCEMENT IN RIGID ROAD PAVEMENTS

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Abstract —*Low tensile strength and high temperature shrinkage cracking reduce the future load carrying capacity (performance) of Jointed Plain Concrete rigid road Pavements (JPCP) under fatigue loading. The fatigue failure in JPCP is much higher compared to Continuously Reinforced Concrete Pavement (CRCP) thus the higher fatigue failure in JPCP structures and durability issues associated with the steel reinforcement corrosion in CRCP structures seek a solution. This research study implements an improved technique of using PET plastic as a reinforcement in slab of rigid road pavement in a grid pattern because the PET plastic possesses better resistance to environmental temperature, moisture and aggressive chemicals degradation. The effectiveness of PET-grid reinforcement in two mix designs M1 and PAVTAL was studied. Significant improvement in compressive, tensile, and flexural strength was determined. The Compressive strength of PET-grid reinforced concrete was found 23% higher compared to plain cement concrete of M1 while for PAVTAL this increase was 20% compared to plain cement slag concrete (CSC). Splitting tensile strength of PET-grid reinforced concrete was found 11% higher compared to plain cement concrete of M1, while for PAVTAL this increase was observed 12% compared to plain cement slag concrete. Flexural strength of sawed beams of PET-grid reinforced concrete was found 91% higher compared to plain cement concrete of M1 while for PAVTAL this increase was 64% compared to plain cement slag concrete. An improved tensile behavior of PET-grid reinforced concrete was observed. It was experimentally evaluated that PET-grid reinforcement is effective in enhancement of compressive, tensile and flexural strength and in lowering the growth and propagation of tensile cracking under loading in rigid road pavement slab. It was also experimentally concluded that 6 in. x 6 in. multiple layered PET-grid of 345.00mm gauge length possessed 78% higher ultimate strength and experienced 41.9% lower tensile strain compared to 4 in. x 4 in multiple layered PET-grid of 177.80mm gauge length. Similarly, the Break stress of 6 in. x 6 in. PET-grid was evaluated as 22.8% higher than 4 in. x 4 in. PET-grid.*

Keywords*-Reinforcement in rigid road pavements, PET wastes, compressive strength, Tensile strength, Flexural strength*

I. INTRODUCTION

A rigid road pavement is generally comprised of a prepared subgrade underlying a subbase layer and a Portland cement concrete surface slab. Rigid road pavement has specific advantage over asphalt pavement when subgrade strength is low and unusual heavy point loads are foreseen. Rigid road pavements are commonly found in three different types such as [1];

(a) Unreinforced Concrete Pavement (URCP) also known as Jointed Plain Concrete Pavement (JPCP)
(b) Jointed Reinforced Concrete Pavement (JRCP)
(c) Continuously Reinforced Concrete Pavement (CRCP)

In rigid road pavement major part of structural capacity is delivered by the concrete slab due to its high modulus of elasticity and rigidity hence, minor alterations in subgrade strength imparts little influence on the structural capacity of the rigid road pavement. Base course contribution to load carrying capacity may be comparatively minor. In Rigid road pavements stress inducing factors can be broadly classified as, (1) externally applied vehicular loads, (2) moisture and restrained temperature deformations (warping, and expansion or shrinkage), (3) continuity of subgrade support as affected by loss of support through pumping or plastic deformation of the subgrade [2]. The structural deterioration or distresses in JPCP are much higher than the CRCP. The distress criteria for fatigue cracking in rigid pavement is based on maximum tensile stress in pavement slab [3]. Flexural strength and Tensile behaviour under cyclic loading are important parameters that affect the performance of a concrete pavement [4]. Therefore, shrinkage cracks and lower tensile behaviour of JPCP and the durability issues associated with the steel reinforcement corrosion in JRCP and CRCP seek a solution.

To enhance the performance of concrete various studies have been performed on concrete reinforcement using Plastic fibers [5].

This research study will demonstrate a new approach of Continuously Plastic-Reinforced Concrete Pavement (CPRCP) by utilizing PET plastic in a grid pattern as a reinforcing material.

II. SIGNIFICANCE OF RESERCH STUDY

In previous studies, Kim et al., 2009 [5] evaluated 1 to 9% lower compressive strength compared to non-reinforced concrete by using 0.2 x 1.3 mm and 50mm long straight imprinted PET fibers for concrete specimens reinforced with 0.5, 0.75 and 1% fibers volume fractions. Malagavelli & Rao.P.N, 2010 [6] evaluated 9.11% increase in ultimate load carrying capacity and 5.63% increase in compressive strength for 1% PET fibers' mixed concrete. Foti, 2013 [7] observed enhanced ductile behaviour, with an adverse effect of reduction in workability by using 5mm wide circular fibers and long strips (half bottle) of PET. Taherkhani, 2014 [8] evaluated a decrease in elastic modulus, compressive strength, tensile strength and flexural strength and this decrease was more for increasing fiber contents. Ochi, Okubo, & Fukui, 2007 [9] found favourable adhesion properties and increased toughness for PET fibers reinforced concrete. Chowdhury, Maniar, & Suganya, 2013 [10] derived that due to weak bond between fibers and concrete constituents a reduction occurs in flexural, tensile and compressive strength.

The main objective of this study is to evaluate the effectiveness of an improved technique of using PET-grid reinforcement as a substitution of steel reinforcement in rigid road pavements.

III. EXPERIMENTAL METHODOLOGY AND TESTS RESULTS

A. Materials

Mix-designs in this research study included Ordinary Portland Cement (OPC), crushed coarse aggregates with max size of 19mm (3/4 in.), river sand, water, reinforcement (PET-grid and steel) and supplementary cementitious materials (e.g. Ground Granulated Blast Furnace slag (GGBFS), gypsum and lime). Two different types of sand were mixed in the ratio of 1:4 to achieve the sand of desired fineness modulus. Determined physical characteristics of fine and coarse aggregates are reported in Table 1;

Table 1. Physical Characteristics of coarse and fine aggregate

Physical Characteristics	Value	Standard test procedure
Coarse aggregate		
Bulk density by rodding (lb/ft^3)	91.67	AASHTO T 19M/T 19-14
Specific Gravity		AASHTO T 85-14
Bulk (Oven Dry)	2.66	
Bulk S.S.D	2.69	
Apparent	2.73	
Fine aggregate		
Specific Gravity		AASHTO T 84-13
Bulk (Oven Dry)	2.37	
Bulk S.S.D	2.41	
Apparent	2.46	
Absorption (%)	1.47	
Fineness Modulus (FM)	2.84	AASHTO T 27-14

B. Preparation of concrete mix designs

Two mix designs, designated as M1 and PAVTAL were prepared to proportion concrete mixes as specified by ACI committee 211 [11]. "PAVTAL" is the name given to the design mix adopted for Indus Highway, Pakistan.

Proportion of concrete mix, adopted for the mix design-M1, was 39% coarse and 38% fine aggregate by weight of fresh concrete (3960 lb/yr3) with water content 340 lb/yr3, fixing a water/cement ratio of 0.57. Table 2 summarizes the proportion of M1.

Table 2. M1 concrete mix-design composition (lb/yrd3)

Mix Design	Cementitious material (CM)	Aggregate		Water	W/CM
	OPC	Coarse	Fine		
M1	596.49	1527.60	1497.26	374.30	0.57

Proportion of concrete mix, adopted for the mix design PAVTAL, was 44% coarse and 41% fine aggregate, and 15% cementing material (OPC plus GGBFS) by volume. Water content adopted was 12.59 lb/ft3 (340 lb/yr3) keeping a water/cement ratio of 0.43. Total cementitious material (CM) was comprised of OPC and 14% of GGBFS by weight of total CM. GGBFS was used as a partial replacement of OPC in the mix design. The contents of lime and Gypsum were 7% and 3% respectively by weight of OPC. Table 3 summarizes the proportion of PAVTAL.

Table 3. PAVTAL concrete mix design composition (lb/ft3)

Mix design	Cementitious material				Water	Aggregate		W/CM
	OPC	GGBFS	Gypsum	Lime		Coarse	Fine	
PAVTAL	25.36	4.13	0.76	1.77	15.17	73.17	60.80	0.43

C. Fabrication of PET reinforcement grid

- PET bottles with imprinted surface were chosen with aim to achieve the superior bonding characteristics (Figure 1a).
- The imprinted middle portions were cut off from PET bottles and thoroughly rinsed with detergent (Figure 1b).
- Strips of uniform width of 12mm were extracted from PET bottles using a cutting tool (Figure 1c).
- PET grid was fabricated manually using 12mm wide PET strips (Figure 1d).

Figure 1. Fabrication of PET Grid: (a) Collection of PET beverages bottles; (b) Rinsing of cut imprinted bottles with detergent; (c) strips extraction; (d) fabrication of PET grid

D. Compressive and tensile strength test specimens

With the aim to evaluate the compressive and tensile strength of drilled cores, slabs of two mix designs M1 and PAVTAL were casted in steel molds as under;

(a) 1 m x 1 m x 100 mm (39.37in. x 39.37in x 4in.) plain concrete slab without reinforcement (Figure 2).

(b) 1 m x 1 m x 100 mm (39.37in. x 39.37in x 4in.) concrete slab with a layer of continuous reinforcing grid (6 in. x 6 in. grid) of PET strips embedded at mid-depth in the slab (Figure 3).

Placement of reinforcement at the mid-depth of slab keeps shrinkage cracks firmly closed [12].

A distinct attractive feature of fixing reinforcement at the center of a pavement slab is that the positive and negative moments are balanced equally allowing the slab to bend equally prior to cracking and failing [1].

Figure 2. 1m x1m x100mm Plain cement concrete slab

Figure 3. 1m x1m x100mm PET-grid reinforced cement concrete slab

E. Flexural strength test specimens

To determine the flexural strength of sawed beams from rigid pavement slab, various slabs were casted in steel mold of two mix designs, M1 and PAVTAL as under;

(a) 1 m x 1 m x 50 mm (39.37in. x 39.37in x 2in.) plain concrete slab without reinforcement (Figure 4).
(b) 1 m x 1 m x 50 mm (39.37in. x 39.37in x 2in.) concrete slab with a layer of continuous reinforcing grid (6 in. x 6 in. c/c) grid of PET strips embedded at mid-depth in the slab (Figure 5).
(c) 1 m x 1 m x 50 mm (39.37in. x 39.37in x 2in.) concrete slab with a layer of reinforcing mesh (6 in. x 6 in. c/c) of #2 steel rebars embedded at mid-depth in the slab (Figure 5).

Figure 4. 1 m x 1 m x 50 mm plain concrete slab

Figure 5. 1 m x 1 m x 50 mm PET-grid reinforced and steel reinforced concrete slab

Similarly, beam specimens as shown in Figure 6 and 7 were casted in molds of the concrete mix design M1 as under;

(a) 150 mm x 150 mm x 700 mm (6 in. x 6 in. x 28 in.) beams of plain cement concrete (PCC) without reinforcement.
(b) 150 mm x 150 mm x 700 mm (6 in. x 6 in. x 28 in.) PET-grid reinforced cement concrete (PET-CC) beams with a layer of continuous reinforcing 4 in. x 4 in. grid of PET strips embedded at mid-depth in beams.
(c) 150 mm x 150 mm x 700 mm (6 in. x 6 in. x 28 in.) steel reinforced cement concrete (RCC) beams with a layer of continuous 4 in. x 4 in. steel mesh of #2 steel rebars embedded at mid-depth in beams.

Figure 6. (150 x 150 x 700)mm PCC, PET-CC, RCC beams

Figure 7. Concrete slabs and molded beams after casting

F. Drilling cores for compressive and splitting tensile strength tests

Cores were drilled from 1m x 1m x 100mm slabs of plain concrete and PET-grid reinforced concrete of the two Mix designs M1 and PAVTAL adopting the procedure as below;

Gridlines were drawn on hardened concrete slabs prior to removal of mold by transferring the marks on molds, representing the actual center line of PET-grid, to the slab. Circles were drawn on slab for drilling cores. Cylindrical core specimens were obtained using Core cutter (Figure 8). Core specimens in length of 4in. and in diameter of 1.75in. were drilled from slabs at the age of 14 days.

The length-diameter (L/D) ratio was adjusted to 2.0 by reducing the length of core from 100 mm (4 in.) to 75 mm (3.5 in.) because the small diameter drilled core is more sensitive to the effect of L/D ratio.

G. Sawing beams for flexural strength tests

Beams specimens in square cross section of 50mm x 50mm (2 in. x 2 in.) and 400mm (16 in.) in length were sawed from 1m x 1m x 50mm slabs of plain concrete, PET-grid reinforced concrete and steel reinforced concrete of the two concrete Mix designs M1 and PAVTAL to determine the flexural strength adopting the following procedure;

Gridlines were drawn on hardened concrete slabs prior to removal of mold by transferring the marks on molds to the slab, representing actual center lines of PET-grid embedded in slabs. Beams were sawed using grinder (Figure 9). Sawed beams were 8 in. longer than 4 times the depth. Sawed beams form PET-grid reinforced concrete slab contained a 12mm wide strip with three (03) nods of PET-grid at its mid-depth.

Figure 8. drilling cores from slabs

Figure 9. Sawing beams from slabs

H. Compressive strength of drilled cores

Table 4 shows that the compressive strength of drilled cores PET-CC, drilled from slabs of PET-grid reinforced concrete, was found 23% higher than the compressive strength of cylindrical cores PCC, drilled form slabs of plain concrete, of the mix design M1. Similarly, the compressive strength of drilled cores PET-CSC, drilled from slabs of PET-grid reinforced concrete, was found 20% higher than the compressive strength of cylindrical cores CSC, drilled form slabs of plain concrete, of the mix design PAVTAL.

Table 4. Compressive strength of drilled cores

Mix design	Length (in.)	Dia (in.)	Average compressive strength (psi)	Average compressive strength (MPa)
M1				
PCC	3.5	1.75	2229	15.38
PET-CC	3.5	1.75	2738	18.88
PAVTAL				
CSC	3.5	1.75	2110	14.55
PET-CSC	3.5	1.75	2521	17.39

I. Compressive strength of molded cylinders

Tests results as reported in Table 5 show that the compressive strength of concrete molded cylindrical specimens CSC, of size 6 in. in diameter and 12 in. in length, of the mix design PAVTAL was found 37% higher than a mix CC similar to PAVTAL in constituent materials but in absence of supplementary cementitious materials (e.g., GGBFS, gypsum and lime). Thus 14% GGBFS as a direct partial replacement of ordinary Portland cement increased the compressive strength by 37%.

Table 5. Compressive strength of molded cylinders

Mix design	Length (in.)	Dia (in.)	Average compressive strength (psi)	Average compressive strength (MPa)
CC	12	6	3441	23.73
CSC	12	6	4706	32.45

J. Splitting tensile strength of drilled cores

Tests results as reported in Table 6 show that the splitting tensile strength of drilled cores PET-CC, drilled from slabs of PET-grid reinforced concrete, was found 11% higher than the splitting tensile strength of drilled cores PCC, drilled form slabs of plain concrete, of the mix design M1. Similarly, the splitting tensile strength of drilled cores PET-CSC, drilled from slabs of PET-grid reinforced concrete, was found 12% higher than the splitting tensile strength of drilled cores CSC, drilled form slabs of plain concrete, of the mix design PAVTAL.

The splitting tensile strength of concrete cylindrical specimens CSC, of size 6 in. in diameter and 12 in. in length, of the mix design PAVTAL was found 30% higher than splitting tensile strength of a mix design CC similar to PAVTAL in constituent materials but in absence of supplementary cementitious materials (e.g. GGBFS, gypsum and lime). Thus 14% GGBFS as a direct partial replacement of ordinary Portland cement can improve the tensile strength by 30%.

Table 6. Splitting tensile strength of drilled cores

Mix design	Length (in.)	Dia (in.)	Average Splitting tensile strength (psi)	Average Splitting tensile strength (MPa)
M1				
PCC	3.5	1.75	251.67	1.74
PET-CC	3.5	1.75	281	1.94
PAVTAL				
CSC	3.5	1.75	305.34	2.11
PET-CSC	3.5	1.75	342	2.36

K. Splitting tensile strength of molded cylinders

Tests results as reported in Table 7 show that the splitting tensile strength of concrete cylindrical specimens CSC, of size 6 in. in diameter and 12 in. in length, of the mix design PAVTAL was found 30% higher than the splitting tensile strength of a mix design CC similar to PAVTAL in constituent materials but in absence of supplementary cementitious materials (e.g. GGBFS, gypsum and lime). Thus 14% GGBFS as a direct partial replacement of ordinary Portland cement can improve the tensile strength by 30%.

Table 7. Splitting tensile strength of molded cylinders

Mix design	Length (in.)	Dia (in.)	Average Splitting tensile strength (psi)	Average Splitting tensile strength (MPa)
CS	12	6	254.5	1.76
CSC	12	6	329	2.27

L. Flexural strength of molded concrete beams

Tests results as reported in Table 8 show that for molded concrete beams PET-CC, of PET-grid reinforced concrete, 17% increase in flexural strength was observed compared to molded concrete beams PCC, of plain concrete, of the mix design M1. For molded concrete beams RCC, of steel mesh reinforced concrete, 37% increase in flexural strength was observed compared to molded concrete beams PET-CC, of PET-grid reinforced concrete, of the mix design M1. Likewise, for molded concrete beams RCC, of steel mesh reinforced concrete, 59% increase in flexural strength was evaluated compared to molded concrete beams PCC, of plain concrete, of the mix design M1.

Table 8. Flexural Strength of molded beams

Mix design	Length (in.)	Breadth (in.)	Depth (in.)	Average Modulus of rupture (psi)	Average Modulus of rupture (MPa)
M1					
PCC	24	6	6	717	4.95
PET-CC	24	6	6	837	5.77
RCC	24	6	6	1145	7.89

M. Flexure strength of sawed beams

Tests results as reported in Table 9 show that for sawed concrete beams PET-CC, of PET-grid reinforced concrete, 91% increase in flexural strength was observed compared to sawed concrete beams PCC, of plain concrete, of the mix design M1. For sawed concrete beams RCC, of steel mesh reinforced concrete, 418% increase in flexural strength was observed compared to sawed concrete beams PET-CC of the mix design M1. In 1 m x 1 m x 50 mm slab reinforcement as a PET-grid was 0.2% and steel mesh was 0.8 % by volume of hardened concrete. Thus, the evaluated flexural strength of sawed concrete beams RCC was 891% higher than that of sawed concrete beams PCC of the same mix design M1. Similarly, for sawed concrete beams PET-CSC, of PET-grid reinforced concrete, of the mix design PAVTAL 64% increase in flexural strength was observed compared to sawed concrete beams CSC, of plain slag concrete of the same mix design.

Table 9. Flexural Strength of sawed beams

Mix design	Length (in.)	Breadth (in.)	Depth (in.)	Average Modulus of rupture (psi)	Average Modulus of rupture (MPa)
M1					
PCC	8	2	2	265	1.83
PET-CC	8	2	2	507	3.5
RCC	8	2	2	2630	18.14
PAVTAL					
CSC	8	2	2	184	1.27
PET-CSC	8	2	2	301	2.08

Figure 9. Sawed beams of CSC for flexure strength test after rupture

Figure 10. Sawed beams of PET-CSC for flexure strength test after rupture

N. Tensile Strength of 6 in. x 6 in. and 4 in. x 4 in. PET Reinforcing-Grids

The UTM generated results for tensile strength of 6 in. x 6 in. PET Reinforcing-Grid are presented in Table 10, Figure 12 and Figure 13. Similarly, tensile strength results of 4 in. x 4 in. PET Reinforcing-Grid are presented in Table 11, Figure 14 and Figure 15. The Force-stroke and Stress-Stroke strain results describe that 6 in. x 6 in multiple layered PET-grid, five ribs wide by four junctions long having 345.00mm gauge length, possess 78% higher ultimate strength and undergoes 41.9% lower tensile strain compared to 4 in. x 4 in multiple layered PET-grid, five ribs wide by four junctions long, having 177.80mm gauge length. Similarly, the Break stress of 6 in. x 6 in. PET-grid is 22.8% higher than 4 in. x 4 in. PET-grid.

Table 10. Force-Stroke and Stress-Stroke strain result of 6 in. x 6 in. PET-grid

Shape: Plate

	Thickness	Width	Gauge Length
Units	mm	mm	mm
PET	0.3100	12.0000	345.0000

Name	Max_Force	Max_Disp	Max_Stress	Max_Strain	Break_Force
Units	kN	mm	N/mm2	%	kN
PET	1.44594	170.270	388.693	49.3536	0.67219

Name	Break_Disp	Break_Stress	Break_Strain	YP_Force	YP_Disp
Parameter				0.1 %/FS	0.1 %/FS
Units	mm	N/mm2	%	kN	mm
PET	230.460	180.696	66.8000	-.-	-.-

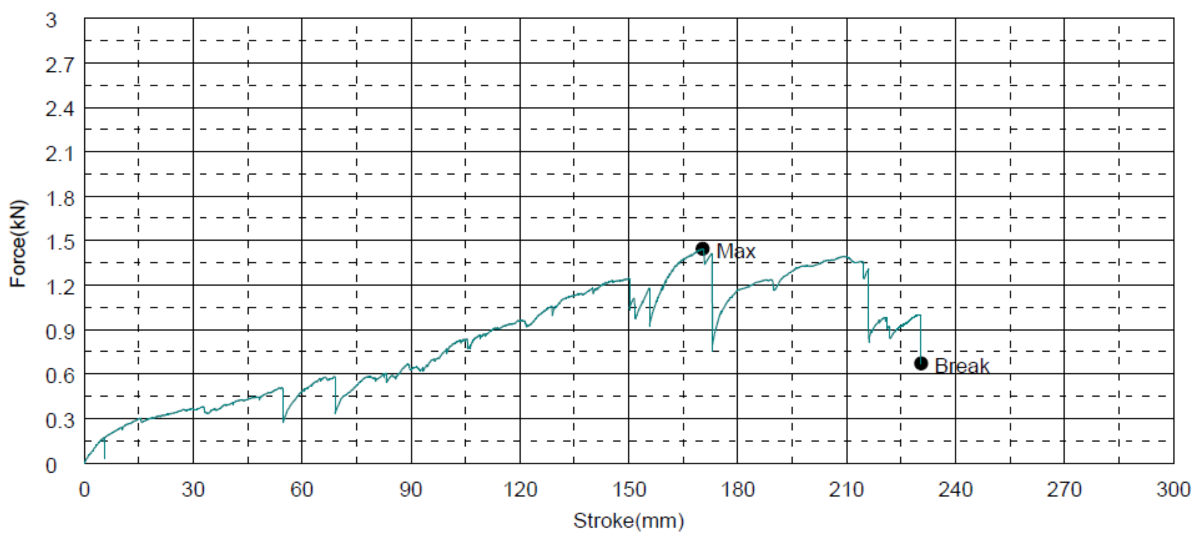

Figure 12. Force-Stroke relationship of 6 in. x 6 in. PET-grid

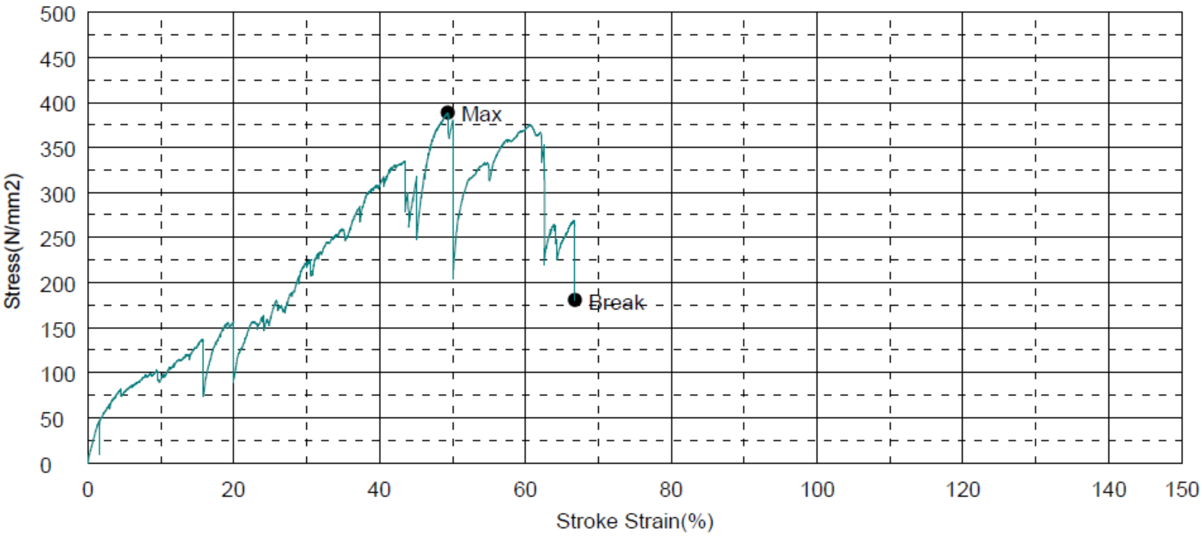

Figure 13. Stree-Stroke strain relationship of 6 in. x 6 in. PET-grid

Table 11. Force-Stroke and Stress-Stroke strain result of 4 in. x 4 in. PET-grid

Shape: Plate

	Thickness	Width	Gauge Length
Units	mm	mm	mm
PET	0.3100	12.0000	177.8000

Name	Max_Force	Max_Disp	Max_Stress	Max_Strain	Break_Force
Units	kN	mm	N/mm2	%	kN
PET	0.81219	167.966	218.330	94.4691	0.54750

Name	Break_Disp	Break_Stress	Break_Strain	YP_Force	YP_Disp
Parameter				0.1 %/FS	0.1 %/FS
Units	mm	N/mm2	%	kN	mm
PET	168.574	147.177	94.8110	-.-	-.-

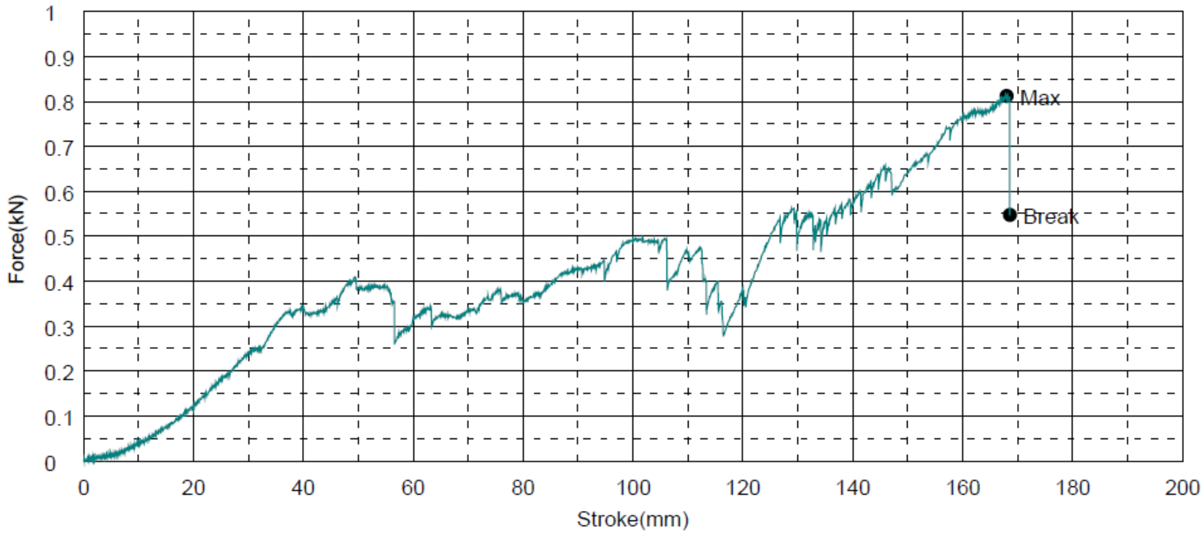

Figure 14. Force-Stroke relationship of 4 in. x 4 in. PET-grid

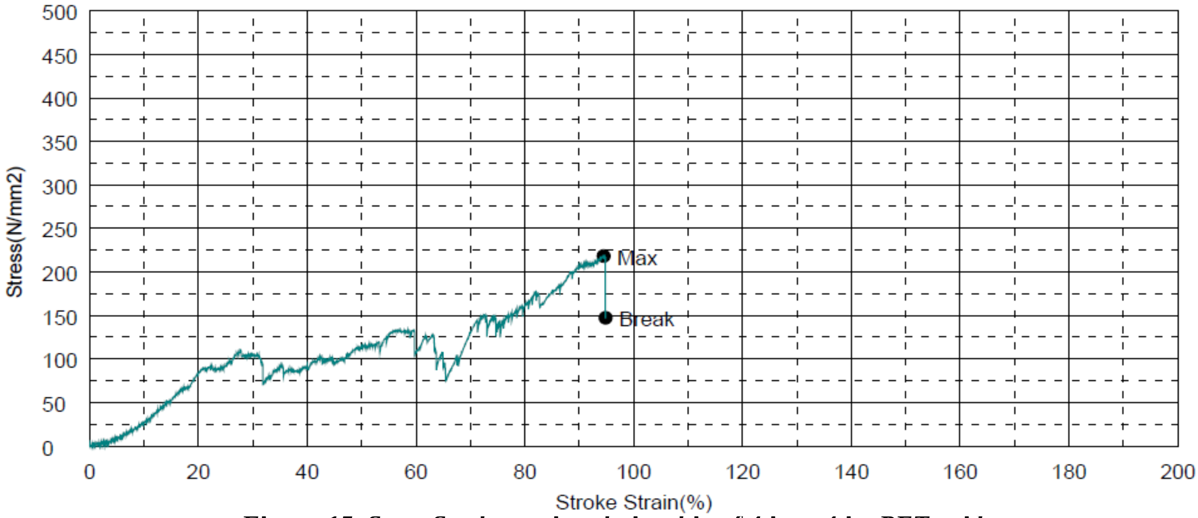

Figure 15. Stree-Stroke strain relationship of 4 in. x 4 in. PET-grid

O. CONCLUSION

1. It was experimentally evaluated that PET-grid reinforcement is effective in enhancement of compressive, tensile and flexural strength and in lowering the growth and propagation of tensile cracking under loading. Hence, PET-grid reinforcement can be effectively used to enhance the performance of rigid road pavement slab.
2. The compressive, splitting tensile and flexural strengths of PET-grid reinforced concrete are higher than plain concrete for both Mix designs M1 and PAVTAL.
3. 14% GGBFS, as a direct partial replacement of ordinary Portland cement, can improve the compressive strength by 37% and the tensile strength by 30%.
4. The behavior of crack propagation and growth of PET-grid reinforced beams is similar to RCC beams. The abrupt failure as observed in beams of plain concrete is prevented by reinforcing PET-grid and steel mesh.
5. 6 in. x 6 in multiple layered PET-grid of 345.00mm gauge length possess higher ultimate strength and undergoes lower tensile strain compared to 4 in. x 4 in multiple layered PET-grid of 177.80mm gauge length.

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