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Study on effect of porous asphalt pavements on flood mitigation for Bangalore city

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Abstract

Porous Asphalt Pavements are considered to be amongst the fastest growing technologies in pavement engineering. They are an alternative to traditional asphalt concrete that enhances society, benefits the environment and promotes economy. The prime reason for employing a porous pavement is to add hydrologic benefit to the roadway. These pavements allow the water to freely drain through the layers. In this study, the different porous asphalt gradations were studied and based on the data a relationship was developed between the void ratio and permeability. The main aim was to study the effect of porous asphalt pavements on the surface runoff reduction for Bangalore City. The hydraulic behaviour of the Porous Asphalt Pavement was analysed using HYDRUS 1-D that is a freeware Software. The pavement produced runoff at 50 cm/hr in case of free drainage condition and at 90 cm/hr in case of seepage face condition. A comparison was made by using the parameters of a single porosity model in dual porosity model which produced a runoff for free drainage at 40 cm/hr and at 90 cm/hr for seepage face condition. The modelling of Porous Pavement was done in SWMM which is a freeware software to assess the impact of pavement thickness on the runoff produced for different rainfall intensities. A relationship between the pavement thickness and runoff/rainfall ratio was developed. A comparison in SWMM was made on the pavement with and without Low impact development technique i.e a porous pavement. The results showed that there was a decrease of about 80% in runoff production after the implementation of Porous Pavement. Different LID Techniques such as the bioretention cell, infiltration trench were analysed to see the effectiveness of the Porous pavements. Assessment of the porous pavements justified its adoption for flood mitigation purpose and these pavements can be considered as a viable solution for urban areas where the water retention on the surface leads to the pavement deterioration.

Keywords: Porous Asphalt Pavement, Void ratio, Surface Runoff, HYDRUS 1-D, SWMM

Introduction

The rain water falling on the bituminous surfaces of parking lots, roads of goes to waste by its accumulation on the roads owing to the impervious surface course layers. As the water gets accumulated on the surface it is bound to cause many distresses in pavements such as deterioration of its structure, the increase in the occurrence of accidents due to loss of visibility on roads and due to slippery surface of the pavement (Ankit Sharma, 2017) [1].

To combat these effects the demand to use newer technologies has grown. Considering the rainfall and floods in the country, that have tremendously affected the road condition, regular rehabilitation is a prerequisite.

Porous Asphalt pavements can be termed as an alternative technology that is different from the traditional asphalt pavement in a way that this type of structure permits fluids to pass freely through it, controlling the amount of runoff to flow through the pavement, thus functions as an additional storm water management technique (madduri, 2014) [21].

Chen Mengjia (2016) has described the impact of the design factors namely aggregate gradation (G), gyration compaction level (GCL), Asphalt binder type (ABT) on PAM's properties. These factors have been evaluated and significantly influence PAM's air voids content, that is one of the most important volumetric parameter directly related to PAM's permeability and mixture strength. Brunetti Giuseppe *et al*. (2016) [6] in their study investigated the suitability of HYDRUS 1-D model to represent the hydraulic behaviour of permeable pavement analysing different scenarios. In the first scenario the use of single porosity model for all the layers of permeable pavement has been done and in the second scenario the dual porosity model has been used for the base and the sub base layers. The dual porosity model has reproduced accurate results in comparison to the single porosity model. Hoaran Zhu *et al*. (2019) [9] in their study used the stormwater management model (SWMM) for simulating the effect of different pavement structures i.e the drainage surface, permeable pavement and permeable road under varied rainfall conditions in order to control the surface runoff and urban stormwater. Due to the porous pavements no surface runoff was observed and consequently the runoff coefficient was zero. The permeable pavement reduced the surface runoff by 50% and had an influence on reducing flood peak. After carrying out the literature survey it was identified that long term impact of PAP on the environment is unclear. Field work and collecting more data associated with flooded pavements should be done. SWMM is widely used for runoff simulations but it needs to be applied to assess pollutant contributions. Impact of the thickness of the pavement on the runoff generation needs to be assessed.

Methodology

The first part includes Collection of gradations of Porous asphalt mix to check the various parameters affecting the properties of PAP such as void ratio, asphalt binder type and optimum binder content. A total of eight research studies were selected for extraction of Porous Asphalt gradations. Sufficient void ratio of the surface is indispensable to ensure the sufficient drainage in the pavement. One of the important factors that affects the performance of PAP is the Asphalt Binder type used. To ensure stability to the maximum level high performance binder should be employed. These binders influence asphalt mixture's properties, such as the mechanical performance, anti-ageing performance and anti-moisture performance. The various types of binders used in different studies are PG72, PG76, PG64, PG50. Modified binders improve and strengthen the properties of conventional neat asphalt binder. In the study, a conceptual model has been proposed for the hydraulic modelling of the permeable pavements using HYDRUS-1D. It correctly describes the unsaturated flow in a Permeable Pavement. HYDRUS-1D is a one-dimensional finite element model that simulates the movement of water, heat, and multiple solutes in variably saturated porous media. Different types of flow models can be implemented in the Software which are:

- Single Porosity Models which consider the layers to be homogenous.
- Dual Porosity Models.

The main objectives of the study include Implementation of the single and dual porosity models to the porous pavement with different boundary conditions to assess the surface runoff. To assess the surface runoff in dual porosity models while using the single porosity model parameters. Implementation of the dual porosity model and constant flux condition to see the water movement through the pavement. For this purpose, two different boundary conditions have been applied:

- Seepage Face Boundary Condition
- Free Drainage Boundary Condition

In order to model the pavement for the surface runoff reduction SWMM model was adopted. The main objectives of the study included to evaluate the effect of pavement thickness on the surface runoff produced in the porous pavement. To make a comparison in SWMM of pavements with and without LID Control i.e a porous pavement and make a comparative study on the different types of Best management Practices that includes porous pavement, bio retention cell and infiltration trench to see the effectiveness of the Porous Pavement. A model of the Pavement has been evaluated through SWMM Software. This model has been assigned with a permeable pavement to see its effect on the reduction of surface runoff by varying the void ratios. The pavement modelled for surface runoff reduction was assessed for water quality performance.

Results

Porous asphalt gradations with other factors affecting their properties were evaluated. For the same gradation of aggregates, the different optimum binder content percentages produced different void contents. From the literature reviewed it was observed that for 3.5%, 4%, 4.5%, 5% and 5.5% of OBC, void content of 19.2%, 17.1%, 15.7%, 13.6%, 11.1% respectively was seen. The permeability is a measure to represent the functional performance of Porous Asphalt mixture. Permeability is related to air voids from the literature reviewed.

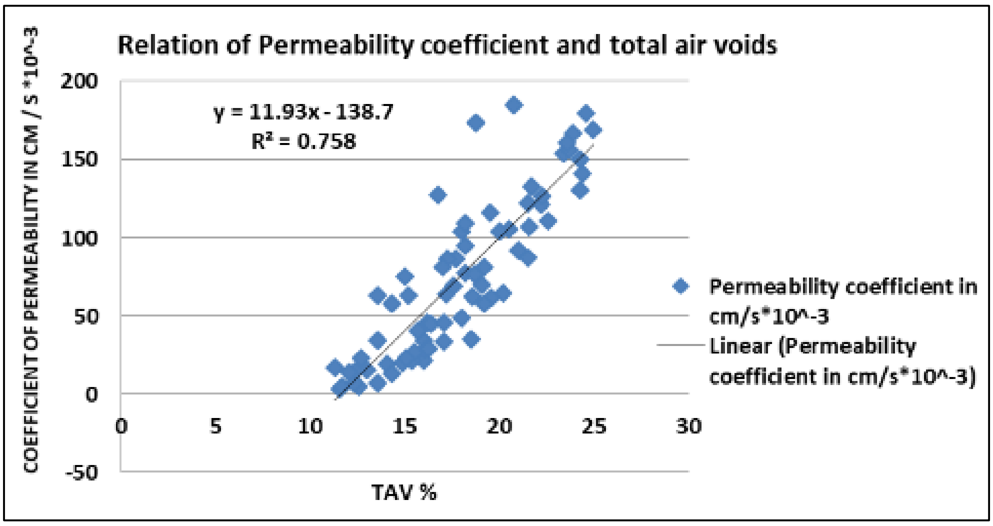

Fig 1: Relationship between void ratio on surface and permeability

Table 1: The void ratios obtained from permeability in HYDRUS 1-D Software

Model	Boundary Conditions	Runoff Start time (hours)	Runoff End time (hours)	Runoff (cm)	Permeability (cm/hr)	Void %
Single Porosity	Free Drainage	0.73	10	9.92	29.7	12.31
Single Porosity	Seepage Face	0.4	10	9	81	13.5
Dual porosity	Free Drainage	0.648	10	11.82	29.7	12.31
Dual Porosity	Seepage face	0.37	10	2.38	81	13.5

In SWMM a relationship is devised between the runoff/rainfall and pavement thickness.

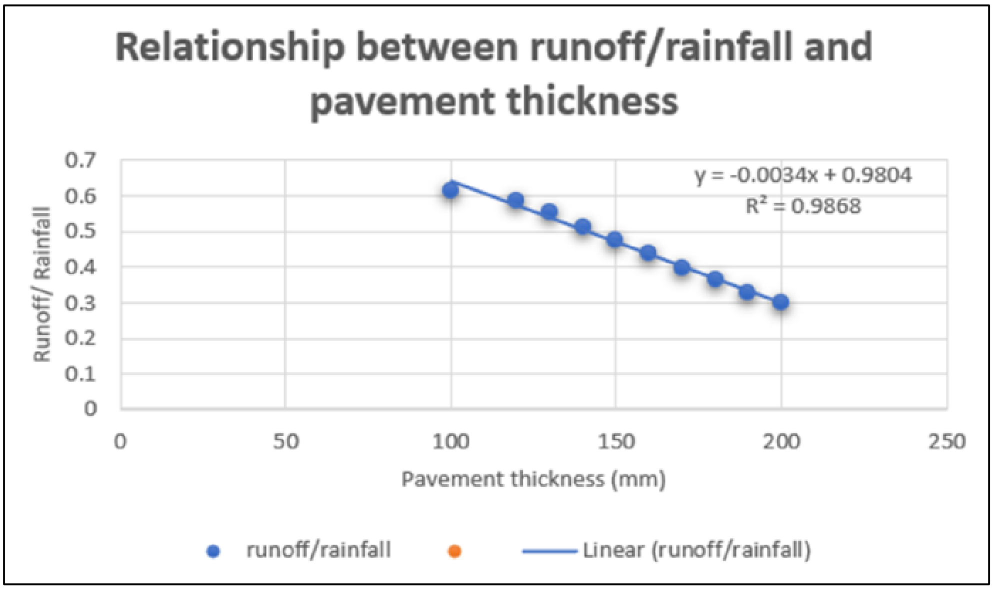

Fig 2: Relationship between runoff/rainfall and pavement thickness

Table 2: Comparison of surface runoff with and without porous pavement

Rainfall Intensity (mm/hr)	Runoff in mm with PAP	Runoff in mm without PAP	%Age Reduction of Runoff
50	5.48	48.89	86.82
60	13.62	59.34	76.2
70	17.2	68.98	74.04
80	28.70	78.99	62.93
90	33.5	89.23	62.14
100	35.8	99.20	63.4

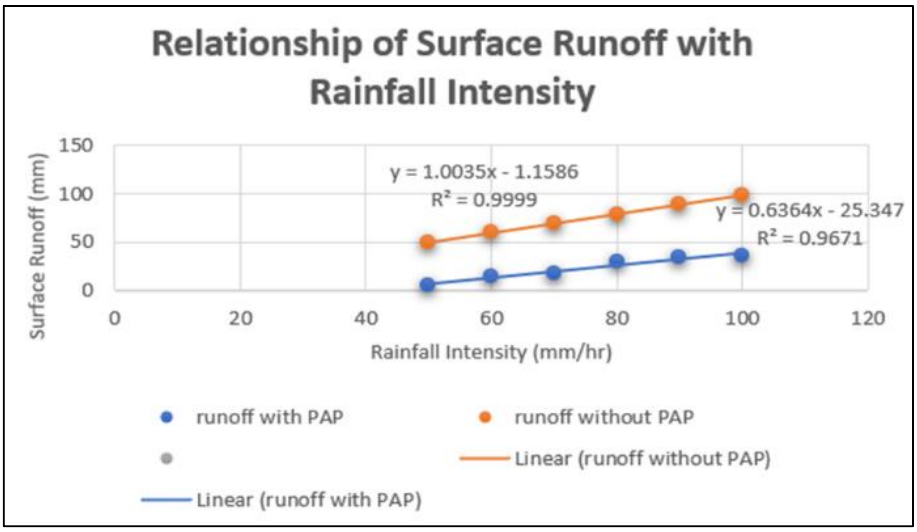

Fig 3: Relationship between rainfall and runoff with and without porous pavement

Table 3: Runoff data for different LID Techniques

Rainfall Intensity (mm/hr)	PAP Surface Runoff (mm)	Bioretention cell Surface Runoff (mm)	Infiltration trench Surface Runoff (mm)
50	20.15 (40.3)	28.61(57.22)	23.24 (46.48)
60	28.49 (47.48)	36.35 (60.58)	31.23 (52.05)
70	37.1(53)	43.28 (61.8)	39.2(56)
80	42.48 (53.1)	50.62 (63.27)	45.65 (57.06)
90	52.29 (58.1)	59.32 (65.91)	55.18 (61.31)
100	60 (60)	63.18 (63.18)	61.92 (61.92)

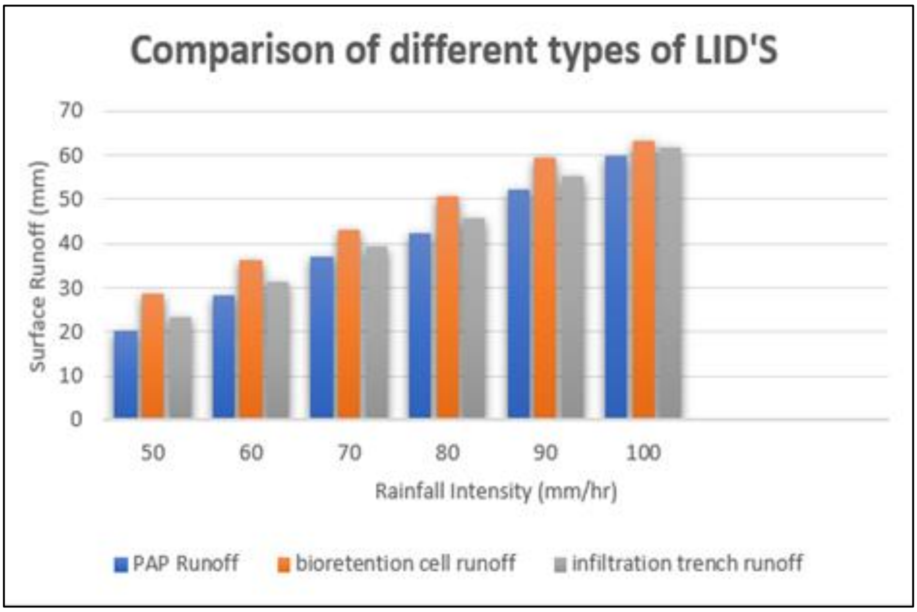

Fig 4: Runoff produced by different low impact development techniques

Table 3: Variation of Runoff with void ratios

Void ratios	Runoff (mm)
0.15	316.08
0.16	314.95
0.17	313.85
0.18	312.76
0.19	311.69
0.20	310.64
0.21	309.61
0.22	308.59
0.23	307.59
0.24	306.61
0.25	305.64

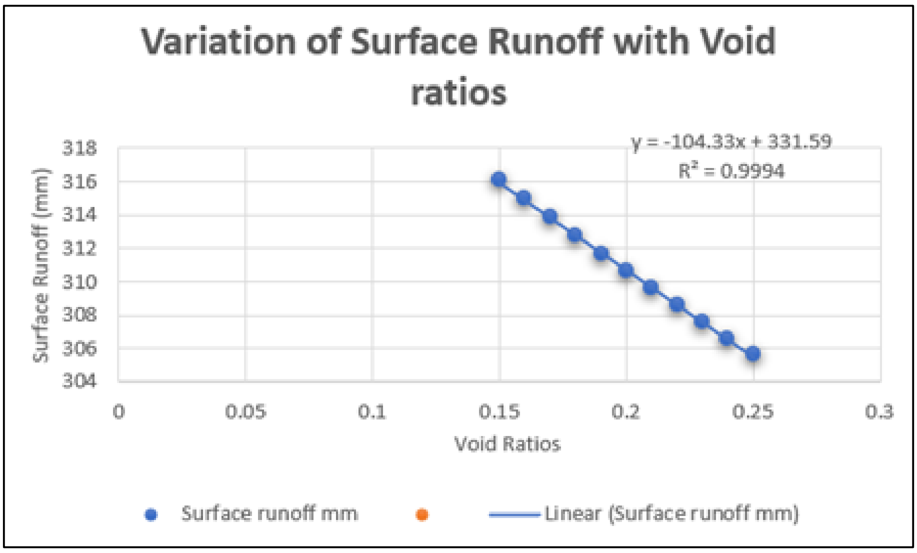

Fig 5: Representation of the variation of runoff with void ratio

Table 4: Concentration of the pollutants when no porous pavement is provided

Subcatchments	TSS (kg)	NO_3/NO_2(kg)	Phosphorus(kg)	Copper(kg)	Lead(kg)	Zinc(kg)
Sidewalk1	0.152	0.002	0.924	0.175	0.184	0.224
Driveway1	2.841	0.033	0.104	0.011	0.164	0.222
Median	0.758	0.009	0.005	0.007	0.088	0.076
Driveway2	2.836	0.033	0.104	0.011	0.164	0.222
Sidewalk2	0.152	0.002	0.924	0.175	0.184	0.224

Table 5: Concentration of the pollutants when porous pavement is provided

Subcatchments	TSS (kg)	NO_3/NO_2(kg)	Phosphorus(kg)	Copper(kg)	Lead(kg)	Zinc(kg)
Sidewalk1	0.021	0.001	0.000	0.000	0.000	0.000
Driveway1	0.403	0.023	0.002	0.001	0.001	0.000
Median	0.107	0.006	0.001	0.000	0.000	0.000
Driveway2	0.403	0.023	0.002	0.001	0.001	0.000
Sidewalk2	0.021	0.001	0.000	0.000	0.000	0.000

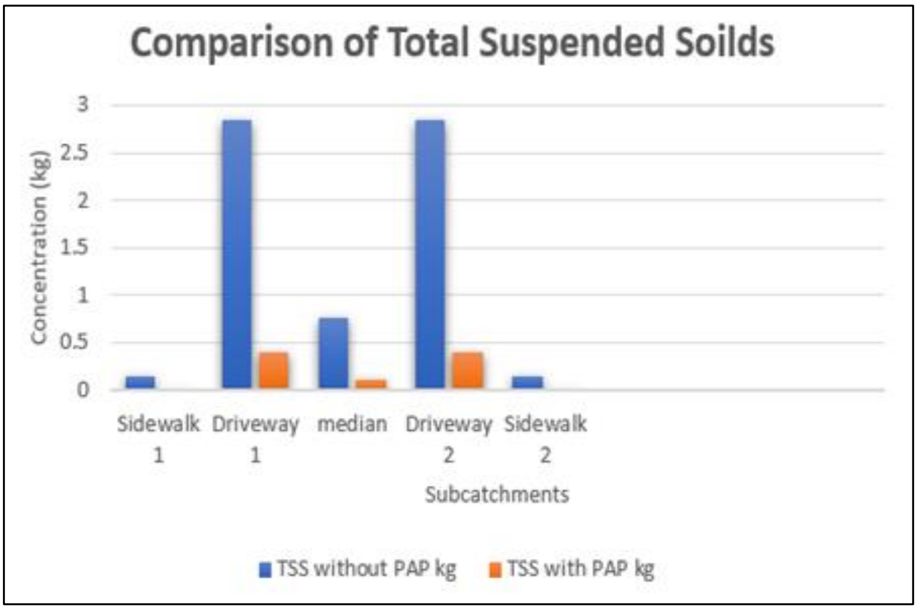

Fig 6: Comparison of the concentration of total suspended solids with and without Porous Pavement

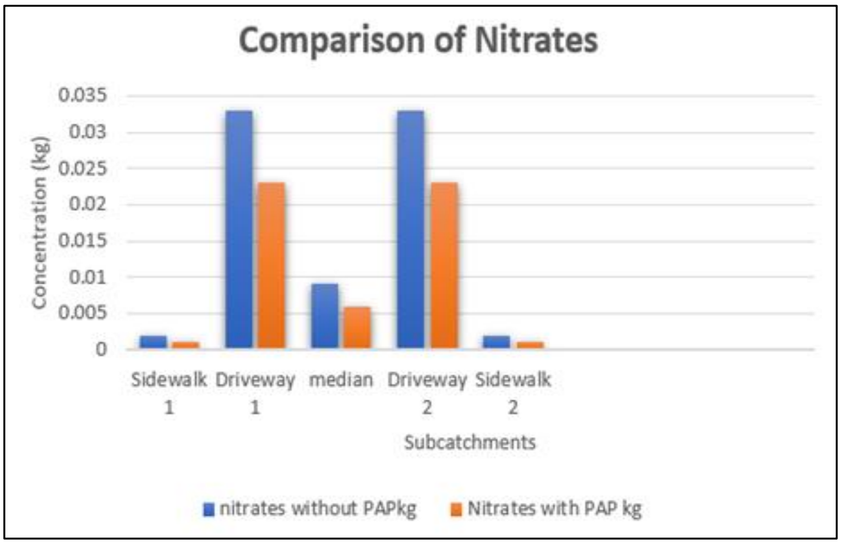

Fig 7: Comparison of the concentration of nitrates with and without Porous Pavement

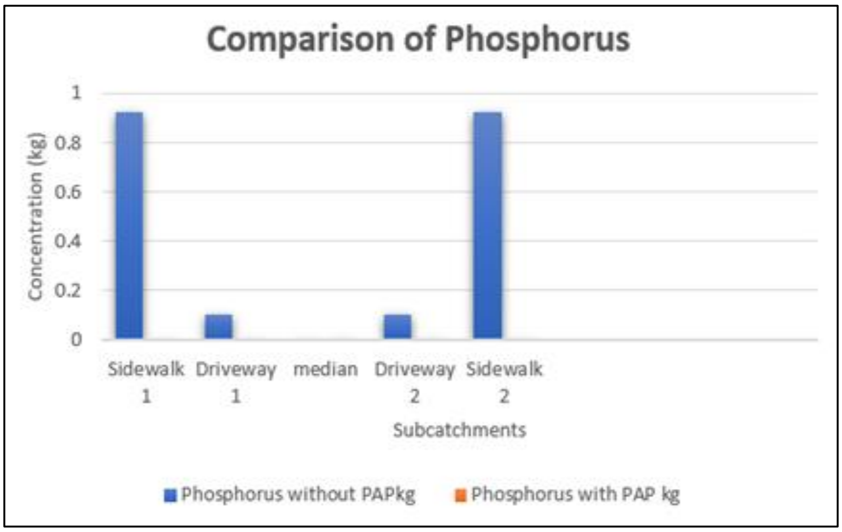

Fig 8: Comparison of the concentration of phosphorus with and without Porous Pavement

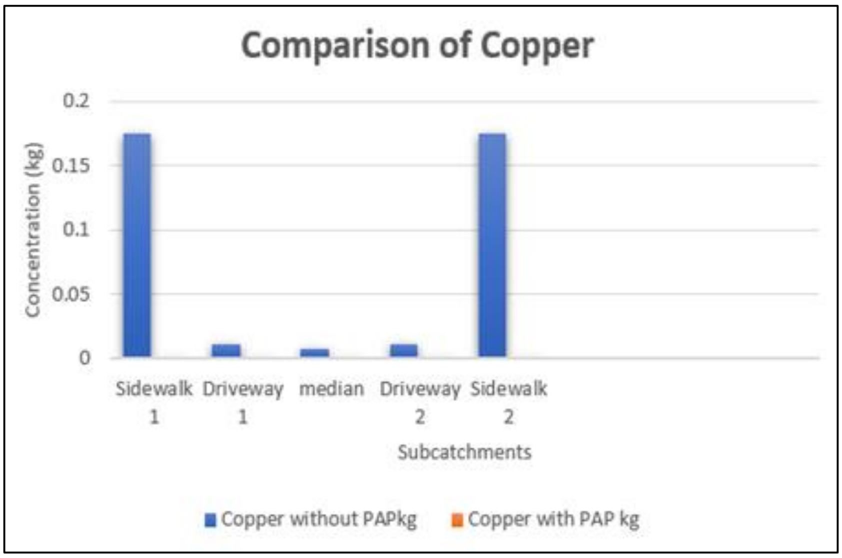

Fig 9: Comparison of the concentration of copper with and without Porous Pavement

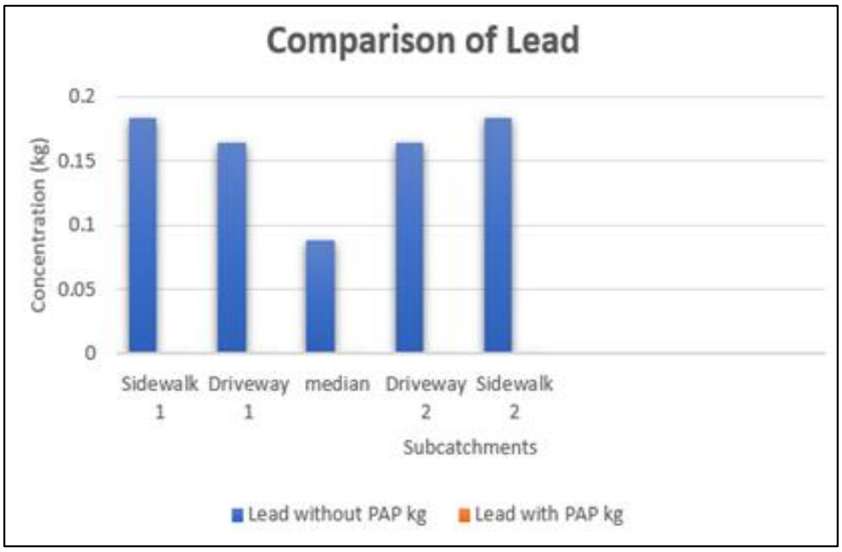

Fig 10: Comparison of the concentration of lead with and without Porous Pavements

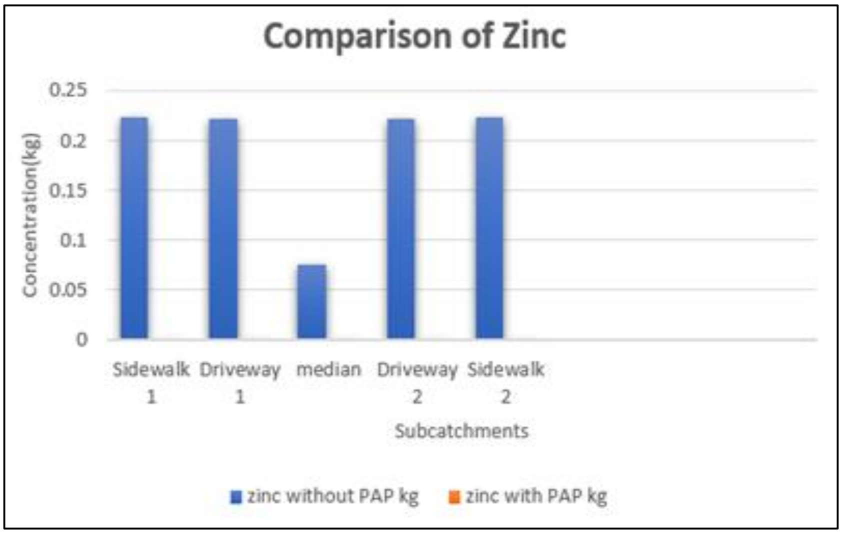

Fig 11: Comparison of the concentration of zinc with and without Porous Pavements

Discussions and Conclusions

- Permeability can be seen to have a stronger correlation with air voids mostly as the air voids on the surface layer increase, the permeability increases.
- The relation obtained between void percentage coefficient of permeability was linear with coefficient of regression as 0.7, proving it to be a close fit.
- After applying a rainfall intensity beginning from 10 cm/hr the runoff in the pavement was observed. In the case of free drainage the surface runoff was recorded at a rainfall intensity of 50 cm/hr and in case of seepage face condition the surface runoff could be attained at 90 cm/hr rainfall intensity.
- It was observed that Seepage face condition in PAP is more effective in curbing flow of runoff over the pavement surface.
- The outflow with respect to that runoff is used as the permeability. The void ratio corresponding to that permeability is attained by the equation that was developed from the relationship between permeability and void ratio.
- For the dual porosity free drainage system, when the parameters of single model were applied, the surface runoff was produced at a rainfall intensity of 40 cm/hr. For the dual porosity seepage face model, the runoff was produced at a rainfall intensity of 90 cm/hr which is the same as in the case of using the dual porosity parameters.
- When the dual porosity model is used with the hydraulic conductivities of the single porosity model, it depicted very little difference from the dual porosity parameters, but it could be inferred that dual porosity model is more effective in reducing surface runoff.
- After obtaining the permeability, the corresponding void ratio was computed by the equation obtained from the plot between permeability and void ratio.

Y = 11.93x-138.7
Where x is void ratio and
Y is the permeability.

- It was also observed that permeability in case of seepage face condition is more than free drainage condition thus yielding voider ratio. More the void ratio on the surface, better will be the movement of water through the pores thus proving that high void ratio as suitable for employment of the PAP.
- From the results it could be seen that as the thickness of the pavement increases from 100 mm to 200 mm the surface runoff shows a decreasing trend. This reduction

of surface runoff is attributed to the fact that with the increasing thickness of the pavement the infiltration increases that consequently reduces the surface runoff.

- When a porous pavement is applied the thickness of the pavement should be sufficiently large i.e about 200 mm with a void ratio of 25% which is evident in every case where the runoff is minimum at 200 mm thickness of the pavement.
- A relationship was devised between the pavement thickness and the runoff/rainfall ratio which is: y= 0.0034x+0.9804

Where y is the runoff/rainfall ratio and x is the pavement thickness.

- Two more relationship were devised for the porous and non-porous pavements between runoff and rainfall. For the porous pavements y = 0.6364x-25.347

Where x is the runoff in mm
And y is the rainfall in mm
Similarly for the non-porous pavement y = 1.0035x-1.158

- From the comparative study between the porous and non-porous pavement, it was inferred that for any rainfall intensity the surface runoff in the porous pavement gets delayed in comparison to the porous pavement. From the results it was deduced that reduction in surface runoff was about 80% which depicted the usefulness of the PAP.
- The maximum surface runoff was 316.08 mm observed for a void ratio of 15% and the minimum surface runoff observed was 305.64 mm for a void ratio of 25%.
- The relationship has been devised between the void ratios and runoff through a pavement which is found to be linear.
- The simulations to carry out the analysis was commenced for a period of 2 hours for a rainfall of 380 mm/hr. The study has aimed to simulate the urban pollutant loads with SWMM.
- Three types of stormwater management practices such as permeable pavement, infiltration trench and bioretention cell were incorporated in the study site. The performances of BMPs (in terms of runoff reduction) under different rainfall intensities was evaluated. The results depicted that the surface runoff was lowest for the porous pavement i.e 40% and maximum for the bioretention cell i.e 46.40%.
- Due to the presence of porous pavements there is a good treatment of the metals and also suspended solids. In this study the treatment appeared to be significant for metals like zinc and lead whose concentration after the implementation of porous pavement was zero.

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