The 2nd International Conference on Sustainable Engineering Practices (IConSEP 2019)
Journal of Sustainable Engineering: Proceedings Series 1(2) 2019

Penerbit Fakultas Teknik
Universitas Sam Ratulangi
doi:10.35793/joseps.v1i2.17

Water quality and performance assessment of porous asphalt mix modified using charcoal powder

K M Thomas, N V Mathew, Rajalekshmi P R, Rajalekshmi S K and R Z Koshy

Department of Civil Engineering, SAINTGITS College of
Engineering, Pathamuttom, Kottayam, Kerala 686532, India

Abstract. Porous pavements are used to allow infiltration of water for increasing ground water storage. Bio char (Charcoal) is a low cost adsorbent used for the removal of heavy metals and other contaminants. This project examines the possibility of using bio char in porous asphalt mixes and efficiency of the asphalt layer modified with charcoal in removing contaminants from typical storm water. Bio char is added by partial replacement of fine aggregates of size less than 2.36 mm. Preliminary Marshall tests indicated that bio char content of about 1 to 2 % is not seriously affecting the properties of porous asphalt mix. Marshall test without charcoal has given the optimum binder content as 5 %. Therefore for the study, samples for Marshall tests were prepared keeping the optimum binder content as 5 % and varying the charcoal content as 1, 1.5 & 2 %. From the drain down, air void, flow and stability requirement it was seen that 1.5 % of charcoal is optimum. Subsequently for the water quality analysis of water infiltrating through the porous asphalt layer, samples are prepared using 1.5 % charcoal. Typical storm water is prepared by adding nitrate & chromium to deionized water. Water quality analysis revealed that charcoal modified asphalt layer can remove 97.2 % nitrate, 56 % of chromium from the storm water, and improve the quality of ground water.

1. Introduction

Porous asphalt pavements are specifically intended to encourage storm water infiltration through the pavement and base courses, where it is filtered through the layers. Porous pavements with 16-22 percent (or higher) of voids are specially designed. This allows adequate water percolation through it. Voids encourage aerobic bacteria development and therefore help to remove contaminants in storm water infiltrated through it. The underlying layers that constitute the pavement includes a filter course layer, stone reservoir bed and a non-woven geotextile. Each layer is designed by providing sufficient voids in it so that easy percolation is possible. Reports say porous pavements have excellent removal effectiveness in decreasing heavy metal levels, suspended solids, and faecal coliforms. Since there is always a possibility of vacuum clogging due to grits and sands, it is necessary to clean these kinds of pavements using a vacuum pump to absorb grit particles. Storm water drains are to be provided in places where the percolation rate is low.

The economic advantages include:- reducing storm water runoff, including temperature decrease, and flow rate, increasing groundwater infiltration and recharge, providing local flood control, improving the quality of local surface rivers, reducing soil erosion, reducing the need for traditional storm water facilities that can decrease general project costs, increases traction when wet, extends the life of paved area in cold climates due to less cracking and buckling from the freeze-thaw cycle, requires less snow-ploughing, reduces groundwater pollution, creates green space (grass groundcover, shade from tree canopies, etc.) and offers evaporative cooling.

2. Objective and scope of study

This research attempts to partly substitute fine aggregates in porous asphalt blend with charcoal powder of multiple percentages in order to determine its Marshall stability, flow value, air voids and drain down potential. The impact of charcoal powder in enhancing the effectiveness of porous asphalt mix removal of storm water contaminants is also scheduled to be studied. The mixes are being screened for low traffic and elevated traffic conditions. Asphalt mixes are designed as binder material using Polymer Modified Bitumen. Initially, an effective range of charcoal powder and bitumen content was acquired. Water quality tests are conducted for two cylindrical samples by simulating downpour conditions at an interval of 24 hours. Synthetic storm water was prepared using de-ionized water and by adding known quantities of chromium and nitrate as contaminants. Based on the outcomes acquired, the efficiencies of each sample were compared.

3. Literature review

Porous asphalt pavement has the ability to filter both storm water and rain water that falls on it owing to the existence of big numbers of air voids in it [7] The research was performed by preparing of two models to investigate the filtering capacity of porous asphalt pavements for both storm water and rain water. Some contaminants like Cr, Fe, Zn, Nitrite, Al, Cu and pH shows an increase in concentration after passing through both models.

A thesis on the addition of carbon-based granular activated carbon (GAC) in porous asphalt wearing course and in its sub-base filter course layer shows that adding GAC to the sub-base filter course layer is more efficient in removing volatile organic compounds and other heavy metal contaminants from storm water [2]. After passing through this layer, storm water effluent finds an undetectable concentration of Cd, toluene and dichloromethane. The size of the used GAC is about 0.42-1.68 mm. In this artificial storm water prepared using deionized water by adding known amounts of contaminants and passing through the layer using a peristaltic pump and recording the contaminants of the effluent. Thus removal efficiency of each trial is evaluated. Another research by creating a tentative mix design for porous asphalt mix [4]. The research concentrated primarily on optimum blend design binder material created as per the specification of the National Center for Asphalt Technology. Another study shows the gradation criteria for multiple layers of porous asphalt pavement [8]. The primary theories behind and requirements for the building of porous asphalt wearing course are obviously defined in the NAPA IS 131 report and design requirements of UNHSC [9, 10]

4. Methodology

The methodology adopted for the study includes the selection of gradation from a journal for the design of porous asphalt mix, the selection of aggregates and the required binder for the tests. The optimum binder content of the blend was chosen based on the Marshall stability value, sample air voids prepared and drain down value of loose asphalt blend Marshall samples were prepared with the optimum binder content by partly replacing fine aggregates of less than 2.36 mm in different percentages. Synthetic storm water was prepared with DI water. Chemical contaminants such as chromium and nitrate have been introduced to DI water, which was then passed over the samples of cylindrical specimens to determine the removal efficiencies of the samples.

4.1. Selection of aggregates

The aggregates used in the porous asphalt blend consisted of crushed angular aggregates not exceeding 19 mm in size. Strength tests of aggregates were performed to determine the quality of aggregates in road construction. The results are tabulated in Table 1.

Table 1. Test results on aggregates.

Sl. No.	Desirable Property of Aggregates	Result	Permissible value specified by IRC
1	Specific Gravity	2.85	2.5-2.9
2	Toughness	19 %	<30%
3	Strength	18 %	<30%
4	Water absorption	3.0%	0.1 %- 2 %
5	Apparent Specific gravity	3.05	

4.2. Selection of Gradation

The combined gradation is within the limit of Prof. Prithvi Singh Kandhal and Sapan Mishra's ' Design, Construction and Performance of Porous Asphalt Pavement for Rainwater Harvesting. 'The gradation selected and the weight retained on each size sieve is shown in Table 2 below.

Table 2. Aggregate gradation chosen.

Sieve Size (mm)	Percentage Passing	Standard limit as per NAPA	Weight retained(g)
19	100	100	0
12.5	82	85-100	216
9.5	60	55-75	264
4.75	18	10-25	504
2.36	9	5-10	108
0.075	1.3	2-4	108

4.3. Asphalt binder

Porous asphalt blend consists of air voids higher than 16 percent, therefore the pavement's aging resistance becomes essential. Higher air voids would promote the binder's oxidative aging even deeper in asphalt pavement. Aging makes bituminous materials harder and more fragile, increasing the danger of pavement failure, such as ravelling and cracking. The porous asphalt pavements here are more beneficial in dry and arid areas, so binder should have an anti-stripping property at elevated temperatures. The use of Polymer Modified Bitumen promotes fatigue resistance, aging resistance, durability, water resistance, and enhanced resistance to cracking and stripping. Hence for this project PMB 40 was selected as the asphalt binder. Required asphalt binder was supplied by Tiki-Tar industries, Mumbai. The rheological properties test results of PMB 40 was obtained is given below in Table 3.

Table 3. Test results on bitumen.

Name of test	Test Results	Specification
Ductility	50 cm	
Softening point	60º C	60º C
Specific gravity	1.09	<1
Penetration	48	50
Elastic recovery at 25℃ (%)	65%	75 %

Test results almost satisfy the specification available. The specific gravity value is found to be greater than 1, which shows that the bitumen contains impurities.

4.4. Characteristics of Charcoal Powder

Charcoal is usually acquired from burning wood, peat, bones, cellulose, or other carbonaceous materials with little or inadequate air. It's an amorphous carbon in the form of extremely porous microcrystalline graphite. When charcoal is used as an additive to clay, it can assist to save energy in brick manufacturing. In this study charcoal powder produced by partial combustion of *teak* and *Macaranga Peltata* wood is used for partial substitute of fine aggregates in porous asphalt blend. Charcoal powder of less than 2.36 mm was used throughout the project. Specific charcoal gravity discovered to be 1.4. Since the value is greater than one, chances of floating over the surface in presence of water can be eliminated.

Bio char has excellent adsorption capacity and its economic and environmental benefits due to its high surface area, charged surface and functional groups, influencing depth and controlled density. Bio char has excellent ability to adsorb heavy metal and organic contaminants. The addition of bio char should reduce the leaching capacity, bioavailability, toxicity, and mobility of organic and inorganic pollutants.

5. Experimental works

5.1. Marshall Test

The aggregates are first sieved, washed, and dried at a constant temperature of 110℃ as per the specification. Approximately 1200 gm. of aggregates are taken and then heated to a temperature of approximately 160-170℃. Then asphalt binder heated to a temperature of about 140℃-150℃ is blended with the heated aggregates and mixed for two minutes until a standardized blend is achieved. Marshall test involves the preparation of 4 inches (102 mm diameter) and 2.5±0.05 inches (63.5 mm) high cylindrical specimen. The temperature of the blend must be 150℃ while it is transmitted to the mould assembly. The mould assembly is placed on the compaction pedestal and compaction of 50 times is given at the top and bottom of the specimen at a temperature of 138-149℃ with a hammer of 4.535 kg sliding weight and a free fall of 18 inches. The sample is then obtained from the mould after a 24-hour time interval.

Subsequently, in order to find proportion of air voids, specimens should undergo water bath at 60℃ for 20-30 minutes. After removing the samples from the water bath, Marshall was tested at a temperature of 60℃. The stability part of the test measures the peak load backed by the test specimen at a load speed of 50.8 mm / minute. The load is supplied to the specimen until it fails and the maximum load is specified as stability. Due to the loading, a dial gauge connected measures the plastic flow of the specimen. The flow value is registered in increments of 0.25 mm when the peak load is recorded.

5.2. Drain down test

Using drain down test, the drain down properties of uncompacted bituminous mixes are determined. The experiment was primarily used to determine drainage of uncompacted bituminous mixtures when the sample is kept at high temperatures, storage, transport, and positioning of the blend. The test includes placing uncompacted bituminous porous mixes in a sieve size 6.3 mm (0.25 inch) wire basket. The wire basket depth is 165±6.5 mm and the width is 108±10.8 mm with a basket of 25±2.5 mm from the bottom of the basket. The entire test set-up is put in an oven capable of keeping temperature within a range of 120-175°C for 1 hour. The wire basket is put over a tray supplied to retrieve the drained material. After 1 hour, the wire basket and the tray are removed from the oven and weighed. Determined binder drainage loss is tabulated in Table 7 using equation (1) as shown below.

$$\%\ Drainage\ loss = (D\text{-}C/B\text{-}A)*100 \tag{1}$$

Where
A= mass of the empty wire basket, (g)
B= mass of the wire basket and sample, (g)
C= mass of the empty catch plate or container, (g) and
D= mass of the catch plate or container plus drained material (g).

6. Results and discussion

6.1. Preliminary tests

Preliminary Marshall experiments were performed to study and evaluate cognitive modifications in porous asphalt when charcoal powder is added to the blend. Initially, the tests were decided to conduct at 6 % of the asphalt content and then vary the amount of charcoal powder by replacing size aggregates of less than 2.36 mm. Charcoal powder varies by 1 %, 2 %, and 3 % by weight of aggregates One sample made without charcoal and three samples were made for each percent of charcoal added mix, giving 50 blows on each side (shown in figure 1). The experiment outcomes are shown in Table 5 below.

Table 5. Preliminary test results.

Percent of charcoal	Height of sample (mm)	Weight in air (g)	Weight in water (g)	Stability (kN)	Flow value (mm)
0	75	1077	700	6.5	5
1	76	1139	825	11.5	5.03
2	82	1207	900	9.7	6.05

(a) (b) (c)

Figure 1. (a) 1 % sample (b) 2 % sample (c) 3 % sample

It is evident that the stability value of the charcoal added samples improved relative to that of the sample without added charcoal, while the flow values show a relative rise in its value. It was discovered that an increase in the quantity of charcoal powder creates an increase in sample weight and an increase in sample height (about 7.5 cm or more). In order to attain a height of about 63.5 mm to 69.9 mm range, it was decided to raise the quantity of compaction blow from 50 to 75 blows for further Marshall trials. The mix also becomes so dry at 3 percent of the carbon content so that sufficient uniformity in the spread of asphalt cannot be achieved. Hence it was found that only 1-2% is the effective limit of charcoal that can be replaced in porous mixes.

6.2. Marshall tests for optimum binder content

The National Asphalt Pavement Association [NAPA] recommends that the optimum asphalt content for porous asphalt should be determined by the asphalt content that meets the following requirements: air voids greater than 18 percent and drain down less than 0.3 percent. Asphalt binder for optimum binder content test ranges from 4.5 %- 6 %. The test results are shown below in Table 6.

Table 6. Marshall test results for optimum binder content.

Binder Content	Weight in air (g)	Weight in water (g)	Stability (kN)	Flow value(mm)	Air Voids
4.5 %	1170	600	7.768	11.67	20.54
5 %	1177	550	14.349	6.6	25.78
5.5 %	1241	690	18.242	7.65	10.19
6 %	1236	700	11.498	6.2	9.09

6.3. Drain down tests

The drain down test results for finding the optimum binder content are given below in Table 7.

Table 7. Drain down test results.

Binder content (%)	Drain down (%)
4.5	0.079
5	0.159
5.5	0.238
6	0.238

By assessing the outcomes acquired after Marshall experiments for 4.5 %, 5 %, 5.5 %and 6 % asphalt material in porous blend, the stability value is 18.242 kN for 5.5 percent mix and 14.349 kN for 5 percent blend. The air void content for both samples is 25.78 percent and 10.19 percent respectively. Drain down proportion is also greater than 5 % sample mix for 5.5 % mix. Stability and flow values are not taken into consideration when selecting the optimum binder content for porous asphalt blend. But for this project stability and flow values are taken into consideration. Variation in air voids and drain down values are shown in figure 2. As the results of the 5 percent sample mix are closely linked to NAPA criteria for porous mixes, it was adopted as the optimum binder content for the mix.

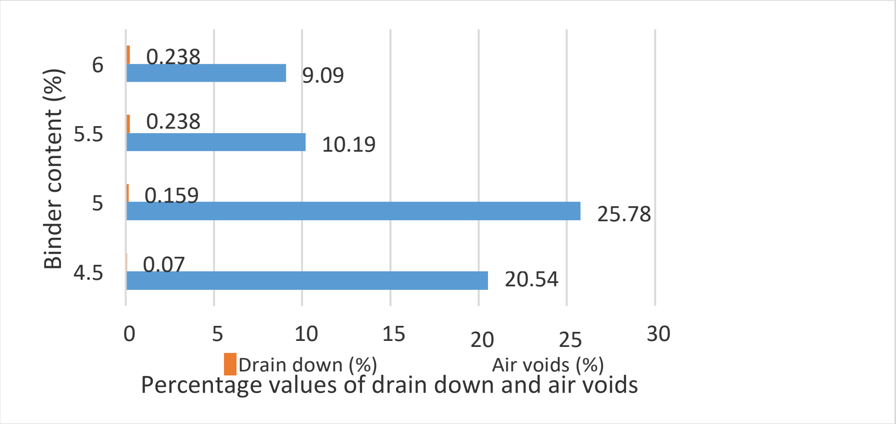

Figure 2. Variation of air voids and drain down values for Marshall test results

6.4. Marshall test for Charcoal added mixes

Based on the preliminary test outcomes from Marshall trials only up to about 2 % is selected as the maximum limit for partial replacement of fine aggregates in porous asphalt mixes. Charcoal powder of less than 2.36 mm was accepted for substitute. Marshall tests were performed for 1 %, 1.5 %and 2 % of charcoal powder by cumulative aggregate weight. The results of the Marshall tests obtained by testing three specimens for each per cent of charcoal added mixes (figure 3) are given below in Table 8.

Table 8. Marshall test results on charcoal added samples.

Charcoal Percent	1%	1.5 %	2 %
Marshall Properties			
Marshall Stability (kN)	13.7	14.8	11.35
Flow Value (mm)	4.86	5.8	5.9
Unit Weight(g/cc)	1.99	2.19	2.29
Air Voids (%)	28.21	17.13	12.47

Figure 3. Charcoal added Marshall samples

Marshall testing performed on porous asphalt mixes by partial addition of charcoal powder showed a relative rise in stability value for the 1.5 % sample. The presence of air voids in each sample is decreased by increasing the percentage of charcoal in each blend. Since permeable pavements are designed for permeability, it requires a minimum of 16% of air voids for its efficient working. Also from the drain down test for charcoal added loose mixtures, the drain down test was found to be about 0.079 % the same. Thus from the outcomes collected, for 1.5 % of the charcoal content sample includes air voids 17.13 % and drain down potential of 0.079 % which is less than 0.3 % which meets the minimum criteria for a porous asphalt blend. Therefore, 1.5 % is the optimum amount of charcoal powder that can be replaced in porous mixes. Variation in air voids and drain down values of prepared samples are shown below in figure 4.

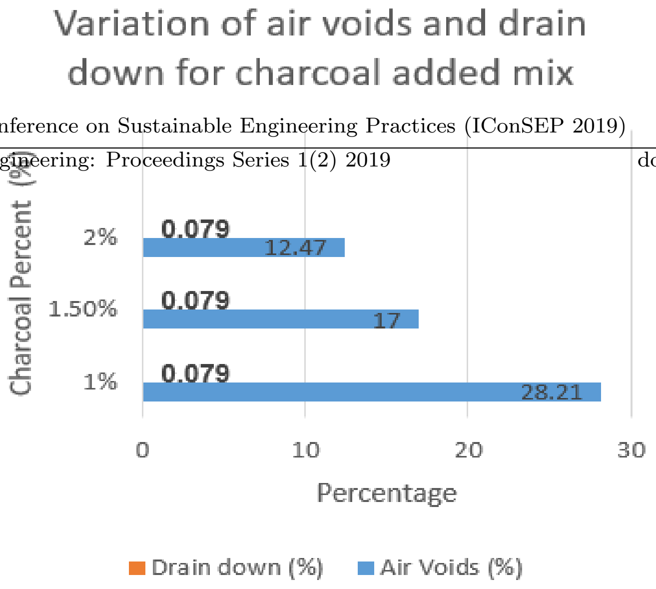

Figure 4. Variation in air voids and drain down for charcoal added samples

7. Water quality analysis

Two samples of 0 % and 1.5 % of charcoal added porous mixes were prepared to conduct water quality assessment. To simulate the flexible pavement layer, the mixes are prepared in a cylindrical mould by offering 75 compaction blows on both ends with a 4.535 kg hammer. Samples were taken from the mould after 24 hours shown in figure 5.

Figure 5. Samples prepared

Table 9. Characteristics of samples prepared.

Charcoal content	Height (mm)	Weight (g)	Air Voids (%)
0%	69	1234	26
1.5%	69.9	1264	17

Samples were then wrapped with a plastic bag and a layer of model clay was applied along the sides of the sample to avoid sidewall leakage. An experimental set-up was fully prepared as shown in figure 6 to generate a natural impact of precipitation.

Figure 6. Test set up

7.1. Synthetic roadway runoff

Based on the research on urban storm water runoff at significant locations in India, it was discovered that the existence of organic, inorganic chemicals and heavy metals was beyond the normal limit. Several study surveys discovered important concentrations of heavy metals in urban storm water, such as Cd, Cu, Pb, Ni, Cr, and Zn, which is harmful to public health and the environment. Table 10 shows the concentration of some storm water contaminants in the United States, India, and Spain.

Table 10. Storm water pollutants in the USA, India, and Spain.[1] [Padilha, 2014]

Pollutant/Parameter	India (mg/l)	USA (mg/l)	Spain (mg/l)
Ammonia	n/a	0.10-2.00	n/a
NO_3	n/a	0.10–7.40	n/a
Cadmium(Cd)	10-150	n/a	<0.01
Zinc(Zn)	40	5.0-235.0	0.52
Copper(Cu)	3-370	1.0-355.0	<0.10
Lead (Pb)	11-84	2.00–76.00	<0.20
Nickel(Ni)	5-33	1.00–14.00	<0.03
Chromium(Cr)	n/a	2.00–8.00	0.05
Iron (Fe)	21-633	n/a	n/a

1. n/a- not analysed

CPCB reports have revealed that groundwater nitrate contamination in Uttar Pradesh has a mean value of over 45 mg/l at 152 mg/l. In Orissa, groundwater chromium contamination exceeds the limits to create yellow colour presence in groundwater. The presence of these contaminants are exceed limits in ground water. Since most of the ground water are formed as a result of infiltration process, treatment need to be done at the surface layer itself. Hence for the water quality analysis, chromium and nitrate was selected as the influent contaminant in synthetic storm water. DI water of about one litre, one containing only chromium and another containing only nitrate as influent contaminants, was passed through the samples.

7.2. Nitrate removal efficiency

By adding potassium nitrate powder to one litre of DI water, stock solution was prepared. Based on influent and effluent data, removal effectiveness of two samples was found. DI water has been produced to pass through the samples and the effluent gathered from the tray and tested in Multi parameter photometer, containing distinct nitrate concentrations. Tabulated outcomes collected from two samples are in Table 11 for the test sample and Table 12 for the test sample.

Table 11. Removal efficiency for control sample

Influent (mg/l)	Effluent (mg/l)	Removal Efficiency (%)
20	0.5	98
30	1.4	95
40	2.2	95
50	1.1	98
60	1.9	97

Table 12. Removal efficiency for test sample

Influent (mg/l)	Effluent (mg/l)	Removal Efficiency (%)
20	0	100
30	1.2	96
40	1.7	96
50	1.8	96
60	1.2	98

The above two table demonstrates the two samples removal efficiencies for various influent circumstances. It is evident that both samples are consistent with the extraction effectiveness. At 20 mg/l and 60 mg/l influential concentration, the sample without charcoal powder showed peak removal effectiveness. For the charcoal added samples, the effectiveness of removal is the same for influential concentrations of 30 mg/l, 40 mg/l, and 50 mg/l. The overall average effectiveness of removal for the control sample is 96.6 % and 97.2 % for the test sample which can be inferred from figure 7.

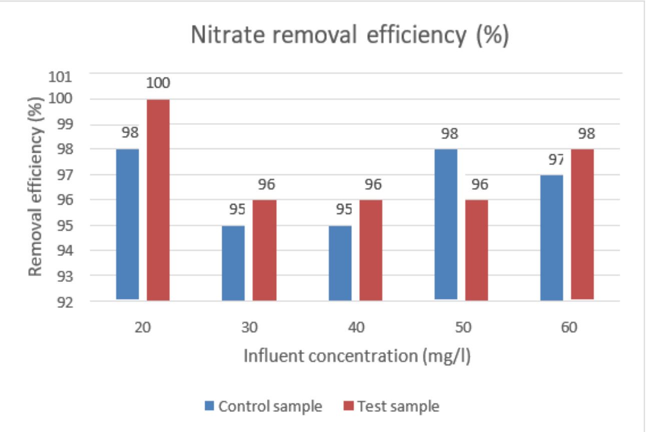

Figure 7. Nitrate removal efficiency for both samples

7.3. Chromium removal efficiency

The heavy metals in the runoff on the road are either dissolved or bound to particulate matter. Most bio char surfaces are negatively charged, which causes the positively charged heavy metal particles to attract electro-static attraction. The surface area, adsorbent speciation, and ionization relies on the solution's pH.

Researchers discovered that the removal of heavy metals from charcoal powder depends mainly on three primary variables; surface area for adsorption, contact time with contaminated water and solution pH [3]. A research was performed using *Eucalyptus globulus* bark (Choudhary B. et al) to adsorb chromium from aqueous solution. Consequently, the tests found that negligible efficiency decrease was observed for pH≥ 3. The findings in this research suggest that heavy metal adsorption on charcoal powder rises at reduced pH and thus chromium extraction effectiveness. Since a reduction in pH results in the existence of more metals in a bioavailable free ionic form, the lower pH may result in a rise in toxicity. Also the naturally occurring pH of roadway runoff is usually 6.6.But pH is not held constant in this research. The experiment was carried out by dissolving to DI water the known quantity of Potassium dichromate. The findings of the tests are presented in Table 13 and Table 14.

Table 13. Removal efficiency for control sample.

Influent (mg/l)	Effluent (mg/l)	Removal Efficiency (%)	pH
1.5	0.831	45	6.4
1.8	1.26	30	6.5
3	1.5	50	6.2
4	1.886	53	6.0

Table 14. Removal efficiency for test sample.

Influent (mg/l)	Effluent (mg/l)	Removal Efficiency (%)	pH
1.5	0.584	61	6.4
1.8	0.927	48.5	6.5
3	1.4	53	6.2
4	1.6	60	6.0

The highest effectiveness of removal is accomplished in the test sample at 1.5 mg/l influent concentration. Both the control sample and the test sample have an average effectiveness of removal of 45% and 56% respectively. Hence the effectiveness of the test sample is greater. The variations in the efficiencies of removal are influenced in each test by changing the pH of the influence. The other parameter that affected is the accessible surface area since the contact time is held constant. High efficiencies of removal are observed in both samples at lower pH, i.e. efficiencies of removal in acidic circumstances are improved. Also chromium removal efficiency is found to be increased with increase in influent concentration. Cr uptake on EBB happens as Cr (VI), facilitated by the bio char- containing carboxylic and phenolic groups. The EBB has been unsuccessful in removing aqueous Cr (VI) at pH ≥3 (Choudhary et al.). Here also bio char has been unsuccessful in attaining higher removal efficiency at higher pH. The graph in figure 8 shows that the effectiveness of chromium removal is greater for the test sample and control sample.

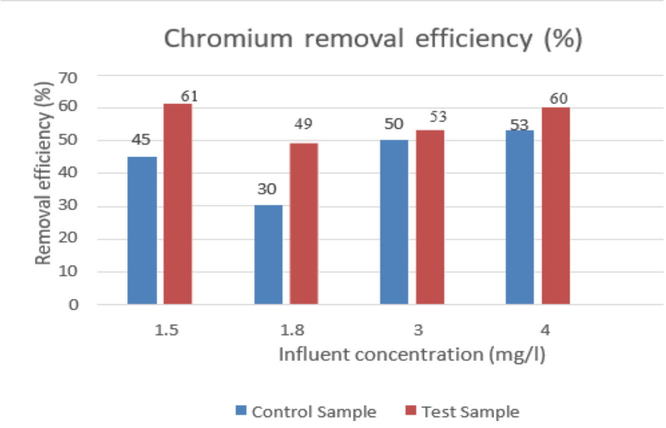

Figure 8. Chromium removal efficiencies for both samples

9. Conclusion

- From the preliminary tests conducted the optimum range to which charcoal powder can be applied in the mix is between 1 and 2 %.
- The optimum binder content for making the mix is 5 %. At 5 % the mix attains air void content of 25.78 % and drain down of 0.159 %.
- Marshall tests on porous mixes with optimum binder content 5% at various percentages of charcoal content (1 %, 1.5 % & 2 %) conducted and thus 1.5% sample mix was adopted as good for permeable pavement works.
- Water quality analysis in removing nitrate and chromium in DI water shows that the average efficiency in removing nitrate in water is higher for test sample. Average removal efficiency in removing chromium is higher for test sample.
- Chromium removal efficiency of charcoal added sample is influenced by the pH of the influent. Higher removal efficiency is observed at lower pH.

10. References

[1] Chavanpatil G N and Chokakkar S S 2018 The Study of Porous Asphalt Pavement with Emphasis in Road Construction Design *Int. Research Journal of Engineering and Technology* **5** Issue 06 pp 623- 24

[2] Choudhary. B, Paul. D, Singh. A and Gupta. T 2017 Removal of hexavalent Chromium ion interaction with bio char under acidic conditions: mechanistic insights and applications *Springer* pp 1-4

[3] Hui Chen 2014 Using Activated Carbon to enhance the Vocs and Heavy Metals Removal of a Porous Asphalt Pavement System *Open Access Dissertations pp 17-* 50

[4] Kandhal P S and Mishra S 2014 Design, Construction and Performance of Porous Asphalt Pavement for Rainwater Harvesting *Indian Highways* **42** pp 1-13

[5] Kiran Kumar B V, Manjunatha.S, Shiva Prasad.N 2014 Porous Asphalt Pavement a Tentative Mix Design Guidelines-By New Generation Open Graded Friction Course Approach *Int. Journal of Engineering Science, Invention, Research and Development* **1** Issue III, pp 106-09

[6] Patra J M, Panda S S, Dhal N K 2017, Bio char as a low cost adsorbent for heavy metal removal: A review, *Int. Journal of Research in Biosciences* **6** Issue 1 pp 1- 4

[7] Sharma A, Satyender, Sharma D K 2017 Laboratory performance of Porous Asphalt Pavement, *Research Gate* pp 1-8

[8] Thives L P, Ghisi E, Brecht D G, Pires D M 2018 Filtering Capability of Porous Asphalt Pavements *Water* **10** pp 4-11

[9] Thelen E and Howe L F 1978 *Porous Pavement* (Philadelphia: The Franklin Institute Press) *The Franklin Institute Research Laboratories* Report pp 3-17

[10] Kent Hansen 2008 *Porous Asphalt Pavement for Storm water Management Information Series 131* National Asphalt Pavement Association pp 5-17

[11] *UNHSC Design Specifications for Porous Asphalt Pavement and Infiltration Beds* 2009 (New Hampshire: The University of New Hampshire Storm water Center) pp 15-22