COMPARATIVE ANALYSIS OF WATER INFILTRATION POTENTIAL: A STUDY OF PRECAST PERMEABLE BLOCKS, PRECAST IMPERMEABLE BLOCKS, AND TRADITIONAL BRICKS

Gaurav Bhusal[1 *] **, Badal Koirala**[1]**, Sunita Kharbuja**[1]**, Rajan Duwal**[2]

[1]Department of Civil Engineering, Khwopa College of Engineering, Tribhuvan University
[2] Gorkha Precast and Windor Pvt. Ltd., Bhaktapur, Nepal

Abstract

Groundwater depletion is a global issue leading to shrinking aquifers and sinking lands. The increase in the rate of usage of groundwater and the decrease in recharge rate is its main cause. Conversion of natural lands to concrete and bituminous roads, urbanization, and industrialization are blocking groundwater infiltration. In such an intricate scenario, the use of permeable blocks in the pavement could be a viable solution. With the use of permeable blocks in areas like low-traffic roads, parking lots and pedestrian walkways, the groundwater table will get recharged to some extent. Permeable blocks could be an eco-friendly paving material reducing surface runoff, ponding of water and flood risk too. This study has experimentally determined and compared the two major characteristics contributing to groundwater infiltration- porosity and infiltration rate of permeable blocks, impermeable blocks, and bricks used generally in pavement design. We found that permeable concrete blocks are 6.89 and 2.19 times more porous than impermeable concrete blocks and burnt clay bricks respectively. Moreover, the permeable concrete blocks infiltrate 816.96 and 171.89 times more water in an hour than impermeable concrete blocks and burnt clay bricks respectively through the center of the blocks and 320.96 and 38.26 times more water in an hour than impermeable concrete blocks and burnt clay bricks respectively at the joints.

Keywords: Porosity, Infiltration Rate, Groundwater, Permeable Block (PB), Impermeable Block (IB)

1. Introduction

The rising need for water worldwide stems from the increasing population, the expansion of irrigated agriculture, and ongoing economic development. In areas where water is often scarce and there are vast underground water systems, people often rely on groundwater as an extra source of water. Globally, ground water accounts for almost half of the drinking water, approximately 40% of irrigation water and one-third of industrial water (IGRAC, 2018). But if we extract more groundwater than what naturally gets replenished over large areas and for long periods, it leads to overuse or long-term depletion of the groundwater (Wada et al., 2010). The utilization of groundwater in Kathmandu Valley, characterized by a high population density, has led to over-exploitation of this vital resource. A comprehensive study reveals that the natural recharge rate of the valley is estimated at 5.5 million cubic meters per year, while the water table is declining at an alarming rate of 2 meters per year (Shrestha et al., 2018). Apart from the reduction of the water sources, groundwater depletion also induces land subsidence ultimately damaging the structures above it (Kadiyan et al., 2021). In light of this challenging scenario, it becomes imperative to explore effective and sustainable solutions to recharge the groundwater table. In this regard, the incorporation of Permeable Blocks (PB) within pavement systems emerges as a promising approach worthy of investigation and implementation.

Conventional road pavement is generally impervious and accumulates a huge amount of runoff water during a storm, which contains pollutants from transportation and related activities (Imran et al., 2013). Permeable blocks are porous

*Corresponding author: Gaurav Bhusal
Department of Civil Engineering, Khwopa College of Engineering
Email: bhusal.gaurav@khwopa.edu.np
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in nature allowing certain portion of runoff to pass through it to the ground. The captured runoff is stored in the voids until it either percolates into the underlying subgrade, or is routed through a perforated under-drain system to a conventional stormwater conveyance. There are various reasons behind use of such blocks like infiltration of groundwater, reduction in traffic noise, increase in driving safety during rainy weather and alleviation of the heat island phenomena in urban city centers (Abd Halim et al., 2018). Similarly, it improves rain water quality, works as bio-filter (Bratieres et al., 2008) and reduces thermal pollution.

Permeable blocks can be used in different areas including but not limited to mentioned below:

- Parking areas
- Roadway shoulders
- Pedestrian walkways cycle path
- Low-traffic roads
- Badminton and tennis courts
- Agriculture facilities like horse washing pads
- Driveways
- Greenways (Shinde et al., 2021)

Unlike traditional installation of concrete, porous concrete usually contains a void content of 15 to 25 percent, which allows water to infiltrate directly through the pavement surface to the subsurface (Shinde et al., 2021). Most of the blocks used nowadays in walkways are impermeable and do not contribute in groundwater recharge. Hence, their replacement by permeable blocks becomes important.

There have been various study on permeable concrete blocks. Beecham et al. (2009) evaluated the performance of permeable paving blocks in Australia considering the age of the laid blocks. A study in USA (Alam et al., 2019) compared various types of permeable pavement systems in semi-arid southern Texas. Khanal et al. (2020) examined the technical suitability of autoclaved aerated concrete blocks as alternative building wall construction material. Moreover, a study on the characteristic study of use of plastic waste as binding material in pervious pavement blocks has also been carried out (Ghimire et al., 2021). But there is a significant research gap in comparative study of permeable, impermeable concrete blocks, and brick pavements.

The main objective of this study is to determine and compare two major characteristics contributing to groundwater infiltration - porosity and infiltration rate of permeable blocks, impermeable blocks, and burnt clay bricks generally used in pavement design. The permeable concrete blocks were expected to be more porous and capable of infiltrating more water than the impermeable blocks and burnt clay bricks. Nevertheless, the analysis of the structural properties of the blocks which should be considered carefully to ensure their cost effectiveness over their design life (Hein, 2014) is not the scope of this study.

We try to answer how effective permeable block is compared to impermeable block and bricks with a comparative analysis of the porosity and infiltration capacity of these three pavement materials.

2. Methodology

For this study, an experimental research design was employed to determine and compare the porosity and infiltration capacity of permeable blocks (PB), impermeable blocks (IB), and burnt clay bricks (BCB). It involved measuring the total volume and solid volume of the three types of blocks to determine the porosity. Each type of block was then subjected to uniform static water pressure measuring the rate of water infiltration. A comparative analysis was then conducted to ascertain variations in permeability among the material. Steps like randomized sampling, controlled variables, and repetitions were taken to ensure the validation of the data acquired. The methodology of the experiment can be described by the flowchart shown in Figure 1.

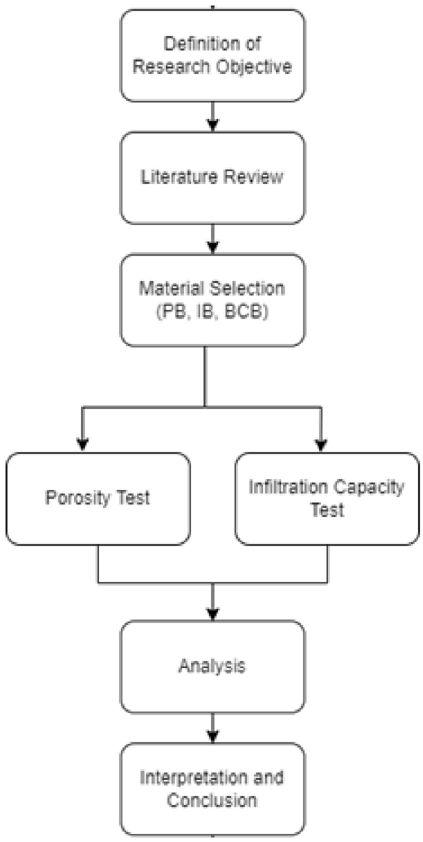

Figure 1. Methodology flowchart

2.1. Materials used

Although the Kathmandu Valley was not the focus area of the study, the widespread usage of permeable block, impermeable block, and brunt clay bricks on pavements across the Kathmandu Valley was the reason they were selected for this study.

1. Permeable block with height of 70 mm (PB70)

Figure 2. Permeable blocks of 70 mm height

This precast permeable block is a new concept and is widely used in low-density road pavements and parking lots nowadays. Cement and aggregates (size less than 5 mm) are used for the manufacturing process of permeable block. No sand is used during the process. Firstly, cement and aggregate were mixed in proportion of 1:5 by volume maintaining the water content around optimum moisture content. The blocks were machine made in room temperature (20–22°C) and left air dried for 24 hours. Then, curing was done for at least 7 days after that. Samples of precast permeable block of 70 mm height (Figure 2) are used for this study and are designated as S1, S2, and S3.

2. Impermeable block of 60 mm height (IB60)

Figure 3. Impermeable blocks of 60 mm height

The materials used during the manufacturing process of impermeable block were cement, sand, and aggregates (size less than 12 mm). Initially, cement, sand, and aggregate were mixed in proportion of 1:3.1:2.2 by volume maintaining the water content around optimum moisture content. The blocks were machine made in room temperature (20–22°C) and then air dried for 24 hours. Furthermore, curing was done for at least 7 days. The samples of precast impermeable block of 60 mm height used in this study is shown in Figure 3. For this study, the samples of impermeable 60 mm blocks are designated as N6-S1, N6-S2, and N6-S3.

3. Impermeable block of 70 mm height (IB70)

The manufacturing process and composition of 70 mm impermeable blocks (Figure 4) is similar to that of the 60 mm impermeable blocks. The 60 mm and 70 mm blocks are used according to need, suitability, and load to be handled by the pavement. The samples of 70 mm high impermeable blocks are designated as N7-S1, N7-S2, and N7-S3.

Figure 4. Impermeable blocks of 70 mm height

4. Clay bricks used in pavements

Burnt clay bricks with L x B x H dimensions of 205 x 140 x 45 mm (Figure 5) manufactured in local kilns of Bhaktapur were used in this study. The manufacturing process of these bricks involves selection of suitable clay, preparation of clay, maintaining consistency of the clay, molding in proper shape, drying in air, firing in local coal kilns, and finally cooling. The samples of clay bricks used for the experiment are designated as B1, B2, and B3.

Figure 5. Sample of burnt clay brick used in study

Three samples from each of permeable blocks, impermeable blocks, and bricks were used in the experiment. Volume of permeable and impermeable blocks hexagonal in shape (Table 1) was calculated geometrically using Equation 1.

$$V = \frac{3\sqrt{3}}{2}a^2h \tag{1}$$

Table 1. Volume of hexagonal blocks

Sample	Side Length-a (mm)	Height-h (mm)	Volume-V (mm^3)
	Permeable Blocks		
S1, S2, S3	112	70	2281318.76
	Impermeable Blocks		
N7-S1, N7-S2, N7-S3	115	70	2405169.05
N6-S1, N6-S2, N6-S3	115	60	2061573.47

where,
V = volume
a = side length and
h = height of the blocks.

Similarly, volume of burnt clay bricks (Table 2) which are rectangular in shape was calculated as the product of length, breadth, and height.

Table 2. Volume of rectangular burnt clay brick

Sample	L(mm)	B(mm)	H(mm)	(mm^3)
B1, B2, B3	205	140	45	1291500

2.2. Tests performed

Following two tests were performed in the study:

1. Porosity test
   Porosity, as a fundamental property, quantifies the extent of empty spaces or void areas present within a material or substance. It serves as a valuable metric, expressing the proportion or percentage of the overall volume occupied by voids or pores. By assessing porosity, one gains insight into the internal structure and potential permeability of the material.

   For permeable block, porosity was determined using water displacement method. First, its solid volume was determined by placing each sample in a container with water and measuring the height of water displaced, then the volume (V) was obtained as the product of area of container (Ac) and the height of water (Ht) displaced by the sample. The porosity was then calculated as the ratio of difference in total volume and volume of solid (volume of void) to total volume expressed in percentage.

   For impermeable block and brick, initially the dry weight was measured and the blocks were placed in water for 24 hours and then wet weight was measured. Similarly, porosity was calculated as the ratio of volume of voids to total volume of specimen.

   There two different methods were employed because the water displacement method for impermeable blocks and brick require significant amount of time to remove trapped air, and measuring the wet weight of permeable blocks is challenging due to water oozing out of the voids immediately when removed from water.

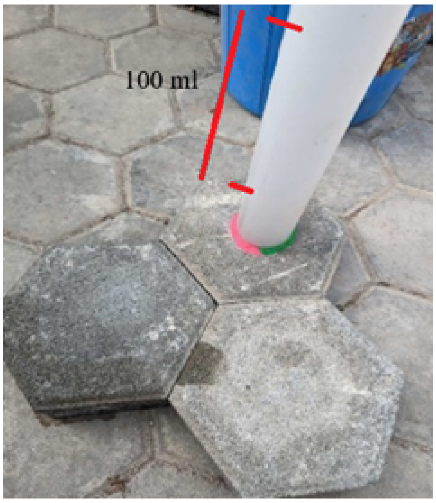

Figure 6. Experimental setup for infiltration capacity test

2. Infiltration capacity test
   Infiltration tests play crucial role in assessing the permeability and water absorption characteristics of pavement blocks or bricks by quantifying the rate at which runoff is able to infiltrate or permeate through them. These tests provide valuable information about the drainage efficiency and potential water retention capacity of the pavement system, aiding in the design and maintenance of effective and sustainable drainage solutions. This test modified some of the procedures of ASTM D3385-18 (ASTM, 2018) for testing on pavement blocks instead of soil as described by the code. The joints between the blocks were open and no filler or mortar were added in the joints.

   The time taken by water to fall between fixed points

(100 ml) in a measuring cylinder was recorded to determine the infiltration rate at two locations: the center of the block and the joint of two blocks, as illustrated in the Figure 6 and Figure 7.

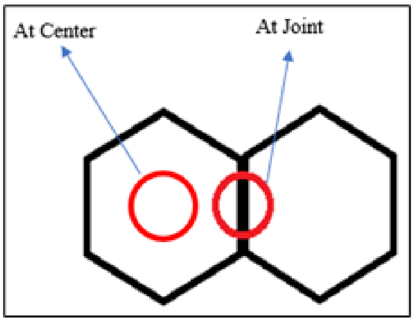

Figure 7. Locations for infiltration capacity measurement

3. Results and Discussion

The results from experiments on porosity and infiltration capacity are discussed separately in this section.

3.1. Porosity test

The solid volume of the permeable blocks obtained from water displacement method (Table 3) was used to calculate the porosity of the blocks and expressed as percentage, as shown in Table 4. With three permeable blocks, we calculated the mean porosity of permeable block as 27.06%.

Table 3. Determination of solid volume (SV) of permeable blocks by water displacement method

Sample	Ac(mm^2)	Ht(mm)	SV(mm^3)
S1	72344.79	23.1	1671164.69
S2	72344.79	23.0	1663930.21
S3	72344.79	22.9	1656695.74

Table 4. Determination of porosity (ϕ) of permeable blocks

Sample	Total Vol.(mm^3)	SV(mm^3)	ϕ(%)
S1	2281318.76	1671164.69	26.74
S2	2281318.76	1663930.21	27.06
S3	2281318.76	1656695.74	27.38
Mean			27.06

In case of impermeable block and burnt clay bricks, amount of void was obtained as difference in dry weight and wet weight of block and porosity was calculated. The mean porosity for 60 mm impermeable blocks was 3.93%, for 70 mm impermeable blocks it was 4.03%, and for bricks it was 12.34%. (Table 5).

The graphical comparison of the porosity of the different blocks is illustrated in Figure 8. The permeable blocks were the most porous with porosity of 27.06% which is 6.89 times greater than that of the impermeable 60 mm blocks (3.93%), 6.71 times greater than that of impermeable 70 mm blocks (4.03%) and 2.19 times greater than that of clay bricks (12.34%). It can be observed that the porosity of impermeable blocks of 60 mm and 70 mm height have porosity of similar values. This can be attributed to the fact that porosity of the blocks is independent of the dimensions but depends upon the composition of the blocks. Furthermore, we found the porosity of the burnt clay bricks was higher than that of the impermeable concrete blocks. The probable cause for this phenomenon is that the moisture content in the clay evaporates during the firing process of brick manufacturing.

Table 5. Determination of porosity (ϕ) of impermeable blocks

Sample	Dry wt(kg)	Wet wt(kg)	Total volume(mm^3)	ϕ(%)
N6-S1	4.284	4.36	2061573.47	3.88
N6-S2	4.482	4.57	2061573.47	4.07
N6-S3	4.362	4.44	2061573.47	3.83
Mean				3.93
N7-S1	4.694	4.79	2281318.76	4.08
N7-S2	5.000	5.10	2281318.76	4.52
N7-S3	4.944	5.02	2281318.76	3.50
Mean				4.03
B1	1.902	2.06	1291500.00	12.25
B2	1.910	2.07	1291500.00	12.65
B3	1.898	2.05	1291500.00	12.14
Mean				12.34

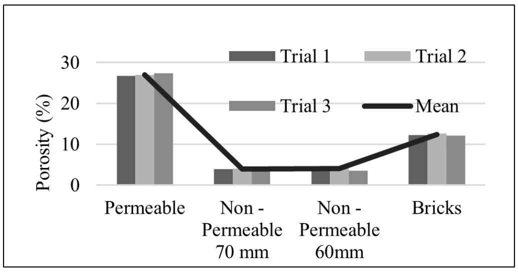

Figure 8. Comparison of porosity of blocks

3.2. Infiltration capacity test

Infiltration capacity was calculated as the ratio of height of water displaced to time taken to displace that height. It is expressed in mm/hr. Infiltration capacity for permeable block at center and at joints with three trails each is shown in Table 6.

It was observed that the mean infiltration capacity at joints of permeable blocks was 22296.83 mm/hr and 16927.43 mm/hr at the center. It was observed that the average water infiltration rate through the joint of a permeable block is 1.32 times higher than that in the center (Figure 9), as the joint consists of more voids than the center solid surface.

Table 6. Infiltration capacity of permeable blocks

Trials	Displaced water height(mm)	Time (s)	Infiltration capacity(mm/hr)
	At the center		
Trial 1	33	7.05	16851.06
Trial 2	33	7.14	16638.66
Trial 3	33	6.87	17292.58
Mean			16927.43
	At the joints		
Trial 1	33	5.57	21328.55
Trial 2	33	5.24	22671.76
Trial 3	33	5.19	22890.17
Mean			22296.83

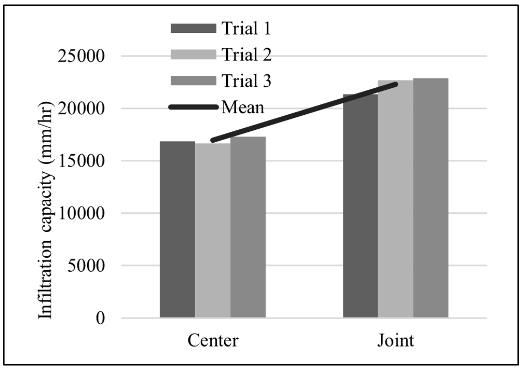

Figure 9. Infiltration capacity of permeable blocks at center and at joints

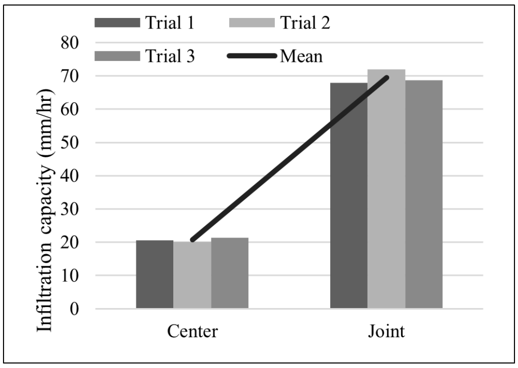

Figure 10. Infiltration capacity of impermeable blocks at center and at joints

Similarly, the infiltration capacity for impermeable block at center and at joints is shown in Table 7. It was observed that the mean infiltration capacity of impermeable block at center was 20.72 mm/hr and 69.47 mm/hr at joints (Figure 10).

Table 7. Infiltration capacity of impermeable blocks

Trials	Displaced water height(mm)	Time (s)	Infiltration capacity(mm/hr)
	At the center		
Trial 1	3.5	612.45	20.57
Trial 2	3.5	624.12	20.19
Trial 3	3.5	589.12	21.39
Mean			20.72
	At the joints		
Trial 1	3.5	185.71	67.85
Trial 2	3.5	175.21	71.91
Trial 3	3.5	183.56	68.64
Mean			69.47

The average water infiltration rate through joints was 3.35 times higher than through the center in the case of impermeable blocks.

Likewise, the mean infiltration capacity of burnt clay bricks at center was observed as 94.10 mm/hr and at joints as 582.73 mm/hr (Table 8 and Figure 11). It can be observed that the average water infiltration rate through joints is 6.19 times higher than the center in case of burnt clay bricks.

Table 8. Infiltration capacity of burnt clay bricks

Trials	Displaced water height(mm)	Time (s)	Infiltration capacity(mm/hr)
	At the center		
Trial 1	3.5	133.79	94.18
Trial 2	3.5	131.56	95.77
Trial 3	3.5	136.45	92.34
Mean			94.10
	At the joints		
Trial 1	3.5	21.61	583.06
Trial 2	3.5	21.14	596.03
Trial 3	3.5	22.14	569.11
Mean			582.73

The relative comparison of infiltration capacity at centers of different blocks is shown in Figure 12 and at joints of different blocks is shown in Figure 13. The average infiltration rate of water in the center of permeable block was 816.96 times greater than that of impermeable block and 179.89 times greater than that of brick, clearly indicating that more water percolates through permeable block compared to other two materials.

The average infiltration rate of water at joints in permeable block was 320.96 times greater than that of the impermeable block and 38.26 times greater than that in bricks, indicating the highest water infiltration in the permeable blocks, followed by impermeable blocks and finally, the bricks with the lowest infiltration. This might be due to the difference in adhesion of filler materials in joints with the surface of these blocks, resulting in a change in void spaces. In real-world scenario, the materials used at the joints while laying these blocks and bricks will have significant effect in the infiltration at joints.

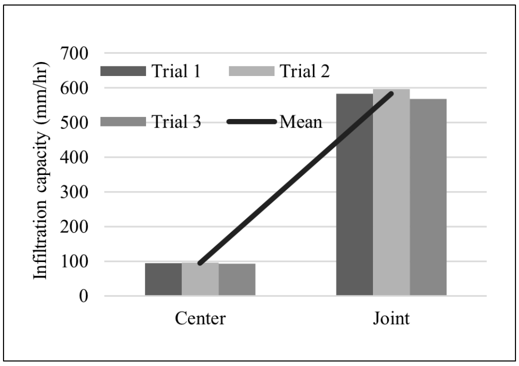

Figure 11. Infiltration capacity of bricks at center and at joints

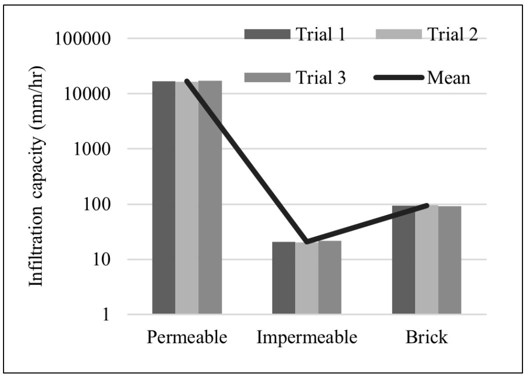

Figure 12. Comparison of infiltration capacity of different materials at center

As expected, the permeable blocks were found to be more porous than other types. Moreover, the average infiltration rate of water at both joints and the center in permeable blocks was much higher than in impermeable blocks and burnt clay bricks. The lack of fine aggregates (sand) in the manufacturing process of the permeable blocks creates voids in the concrete blocks resulting in better percolation of water through it than in the impermeable and burnt clay bricks. The utilization of permeable blocks offers distinct advantages over impermeable blocks and bricks due to their increased volume of voids, facilitating enhanced water infiltration capacity and water flow dynamics. The findings of this study is similar to previous study carried in Nepal (Khanal et al., 2020, Ghimire et al., 2021).

These permeable blocks can be used in low traffic areas like parking lots, sub-urban streets, walkways, and cycle lanes. This helps in reducing surface runoff and mitigating urban flooding by allowing water to infiltrate into the ground and reducing the burden to drainage systems. Furthermore, it enhances ground water recharge which is important in areas where aquifers have been depleted making it a sustainable urban development idea. By reducing runoff, it can also reduce erosion which is beneficial for both urban and rural areas. These permeable blocks can also improve the safety of the sidewalks or areas where they are built as it prevents puddling or even ice formation making it safer for pedestrians and traffic.

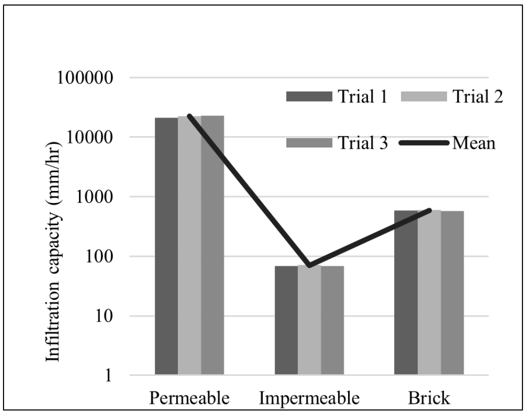

Figure 13. Comparison of infiltration capacity of different materials at joints

If we consider a unit hectare of area paved by the permeable blocks, then the average water infiltration through center and joints will be 54.47 m^3/sec, which is significantly higher compared to impermeable block being 0.13 m^3/sec and that of brick being 0.94 m^3/sec.

4. Conclusions

From this study, we can conclude that permeable blocks can be an effective tool against increased surface-runoff that causes flash flood and ground water depletion in an urban and sub-urban setting. The structural and hydrological concerns are to be considered in their design and construction to ensure that they provide cost-effective solutions over their design life. The use of permeable block is suitable in terms of infiltration and porosity characteristics but further research is needed in terms of strength and cost.

5. Acknowledgment

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6. Authors' Contribution

SK and RD conceptualized and designed the study. GB and BK carried out the experiments, analyzed the data, and drafted the manuscript. All authors read and endorsed the final version of the manuscript.

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