



# The Effect of Land Slopes Covered with Paving Blocks on Rainwater Infiltration

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**Abstract:** Rapid urban development has increased impervious surface coverage, causing higher surface runoff and reduced rainwater infiltration that contribute to flooding and groundwater depletion. Permeable pavement systems, such as paving blocks, are widely applied to support sustainable urban water management. This study analyzes the effect of land slope covered with hexagonal paving blocks on rainwater infiltration performance. Laboratory experiments were conducted using a rainfall simulator with a constant intensity of 50 mm/h. Three slope variations were evaluated, namely 0%, 2%, and 4%. The paving blocks had a compressive strength of 25 MPa (Class B) and were installed on a compacted sandy bedding layer. Infiltration and surface runoff volumes were measured at five-minute intervals until stable conditions were achieved. Results indicate that land slope significantly influences infiltration behavior. The highest infiltration performance occurred at a 2% slope, with a maximum infiltration volume of approximately 570 mL recorded between the 40th and 45th minutes. Conversely, the 0% slope showed decreased infiltration due to soil saturation, while the 4% slope exhibited lower efficiency because the increased slope accelerated surface runoff. These findings demonstrate that hexagonal paving blocks installed on a moderate slope enhance infiltration, reduce runoff, and support urban flood mitigation and groundwater recharge.

**Keywords:** Infiltration; Paving blocks; Runoff; Slope

## Introduction

Global urban development and road infrastructure have increased the coverage of impervious surfaces, causing significant changes in the local hydrological cycle. Impervious surfaces, including conventional pavements such as concrete and asphalt, inhibit stormwater infiltration, triggering larger runoff volumes, accelerating peak flow rates, and increasing the risk of inundation and flooding downstream (Franco et al., 2025). Furthermore, increased surface runoff contributes to soil erosion, particularly on slopes, and causes water quality degradation by transporting sediment and pollutants to natural water bodies (Ghisi et al., 2020).

In response to these issues, permeable pavement systems have been proposed as a Low Impact Development (LID) strategy to manage stormwater

runoff and enhance water infiltration into the ground (Zhu et al., 2021). Pavement blocks with gaps are designed to allow rainwater to infiltrate into the subsoil, thereby reducing the rate and volume of runoff and aiding groundwater recovery. Recent studies have shown that permeable pavements can enhance infiltration and reduce surface runoff compared to conventional impervious pavements in urban stormwater management scenarios (Liu et al., 2020).

Research on rainwater infiltration on paving blocks has covered various configurations of permeable interlocking concrete pavement (PICP), including variations in block geometry, rainfall intensity, and base course conditions (Abduljaleel et al., 2025). For example, experimental studies on permeable pavement systems have shown that infiltration capacity and runoff volume are significantly influenced by rainfall intensity, pore structure, and slope conditions of the test area (Zhu et

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al., 2021). However, comprehensive studies of infiltration and runoff behavior on slopes covered with hexagonal paving blocks are relatively limited (Hashim et al., 2023).

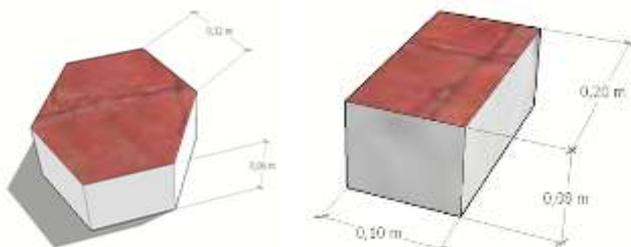
Hexagonal paving blocks have different interlocking geometric characteristics than regular square or rectangular paving blocks, potentially resulting in different flow patterns and infiltration rates on sloped surfaces (Rangkang et al., 2020). Furthermore, the influence of land slope on the interaction between rainwater infiltration and runoff dynamics in hexagonal paving blocks has not been clearly defined in the context of geotechnical and urban hydrology research.

Based on this scientific framework, this study was designed to answer the following questions: (1) How does slope gradient affect surface runoff volume in this permeable pavement system? (2) How effective are hexagonal paving blocks in increasing infiltration while reducing runoff compared to other block shapes? This identification is important for developing environmentally friendly infrastructure design recommendations and enriching the literature in the fields of civil engineering and water resources that focus on flood mitigation and groundwater conservation. The analysis and findings of this study are expected to support the development of sustainable drainage system planning practices and soil conservation in slope areas.

**Method**

The paving block material used in this research was obtained from paving craftsmen located in Balikpapan City. This paving block has sufficient compressive resistance to support the weight of vehicles without experiencing significant structural damage. The paving blocks used in this study are hexagonal and block shaped.

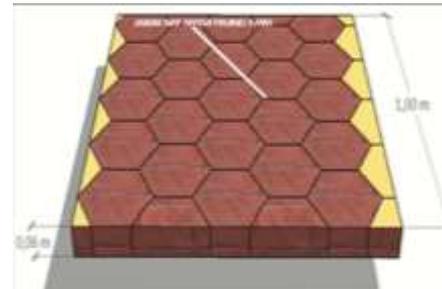
Hexagonal paving blocks measure 12 centimeters on each side as illustrated in Figure 1, and they are organized in a square arrangement as depicted in Figure 2.



**Figure 1.** Paving block type hexagon and block shapes

Paving stones are placed on a 7 cm thick layer of packed sandy soil known as the Bedding Layer. This layer is compacted by tamping to reach the desired

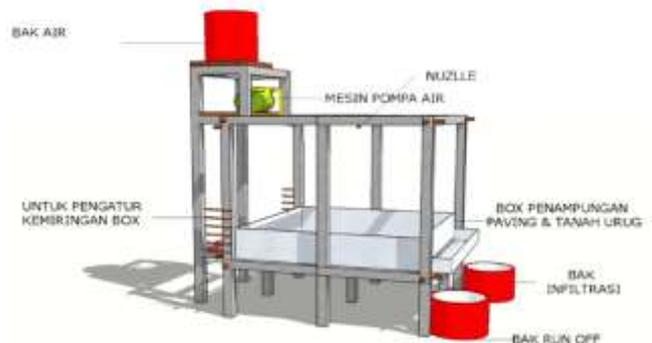
density. The stones are laid out with a 5 mm space between them, as illustrated in Figure 2. The spaces between the stones are filled with sand called Jointing Sand, which is similar in grade to the sand used for the bedding layer. This method is based on experiments done by other scientists regarding the effectiveness of both fine and coarse sand for filling gaps (Rangkang et al., 2019).



**Figure 2.** Arrangement of hexagonal paving blocks on boxes

*Rainfall Simulator Modification*

The created tool has three key components, which are: a rainfall simulator, a testing tool framework, and a testing box as illustrated in Figure 3.



**Figure 3.** Sketch of rainfall simulator tools

The altered rainfall simulator measures 100 cm by 100 cm and is constructed from 3 mm thick elbow iron, as noted. The reservoir's support stands 30 cm above ground. At the top, there is a holder for the sprayer or nozzle, which is positioned 85 cm above the reservoir's base. This rainfall simulator is built to create simulated raindrops using a simple pipe outfitted with a sprayer that hangs right above the area being tested. It is linked to a water pump that has a valve allowing for adjustments in the flow rate, so it can achieve a certain level of rainfall intensity. For this research, the selected intensity is 50 mm/h. A five-minute interval has been set to gather and measure the amount of water that infiltrates and the amount that runs off until the infiltration rate stabilizes.

At the bottom, there is a reservoir that collects the water that has infiltrated, as well as an additional

reservoir to hold any overflow, which allows for the determination of QI and QR values. The diagram of the artificial rainfall setup is displayed in Figure 4.

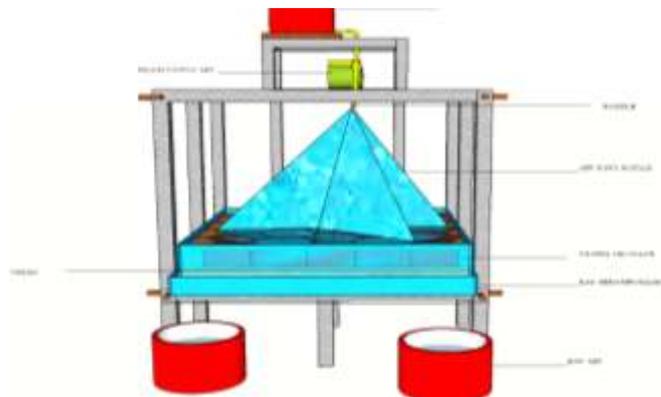


Figure 4. Infiltration test sketch

*Test Box*

The test box was created with dimensions of 100 cm x 100 cm x 15 cm. It has a drain funnel to gather water that seeps in and a 20 mm wide gutter to collect water that runs off, directing it to a reservoir. These features are positioned on opposite sides of where the screw is located to allow for adjusting the angle. It is believed that rainwater passes through the pavement and reaches the bottom, where it then goes into the water catchment funnel situated directly below the runoff gutter. Figure 5 displays a drawing of the test box.

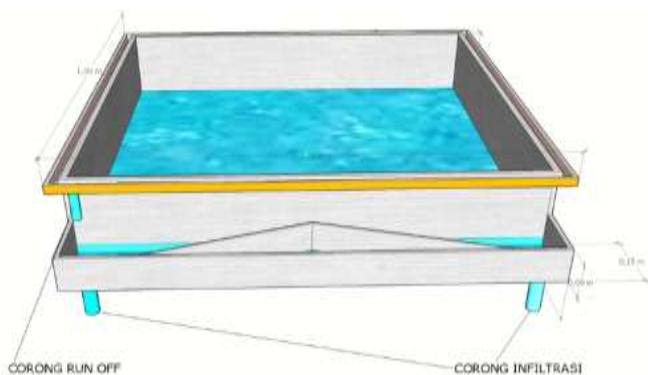


Figure 5. Infiltration test sketch

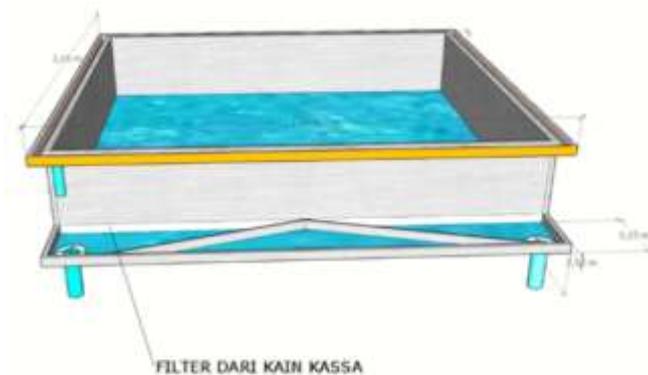


Figure 6. Infiltration test sketch

In the front part of the bathtub, there is a filter set up to stop the bedding material from breaking down when the water seeps out. The installation of the filter can be seen in Figure 6.

*Sand Material*

The sand layer's thickness in this research was set at 70 mm, which was compressed and smoothed out by hand. This layer is set inside a testing box, following the gradation standards of ASTM C 33 (Interlocking Concrete Pavement Institute, 2015). The sand used was collected from a quarry in Samboja, East Kalimantan, commonly referred to as Samboja Sand. Various tests must be conducted to assess the physical and mechanical characteristics of the sand, which are listed in Table 1.

Table 1. Sand Testing Materials

Types of Testing	Testing Standards
Moisture Content	SNI 03-1965-1990
Specific Gravity	SNI 03-1964-1990
Sieve Analysis	SNI 03-1968-1990
Permeability	SNI 03-2435-1991
Proctor Standards	SNI 03-1742-1989

*Rainfall Test Method*

In this research, different levels of rain strength, types of pavements, and the angle of the test box were applied so that it would be simpler to grasp the experiment and the kind of infiltration test conducted. This can be observed in Table 2.

Table 2. Rainfall Simulator Test Scheme

Rainfall Intensity (mm/hour)	Box Slope (%)	Types of Paving Blocks
50	0	
	2	hexagonal and block shapes
	4	

*Bedding Layer*

Based on the findings from the sieve analysis test shown in Figure 8, it indicates that just 16.04% of the soil went through filter No. 200. This suggests that the soil is classified as coarse-grained. Additionally, 98.42% of the soil managed to pass through filter No. 40, indicating that the soil used for the bedding layer is fine sand, mainly consisting of grains that range from 0.425 to 0.234 mm in size. This will have an impact on how much soil can absorb water and how quickly the water moves through it.

Research Flowchart and So On

To help with carrying out research and creating reports, a diagram is created as displayed in Figure 7.

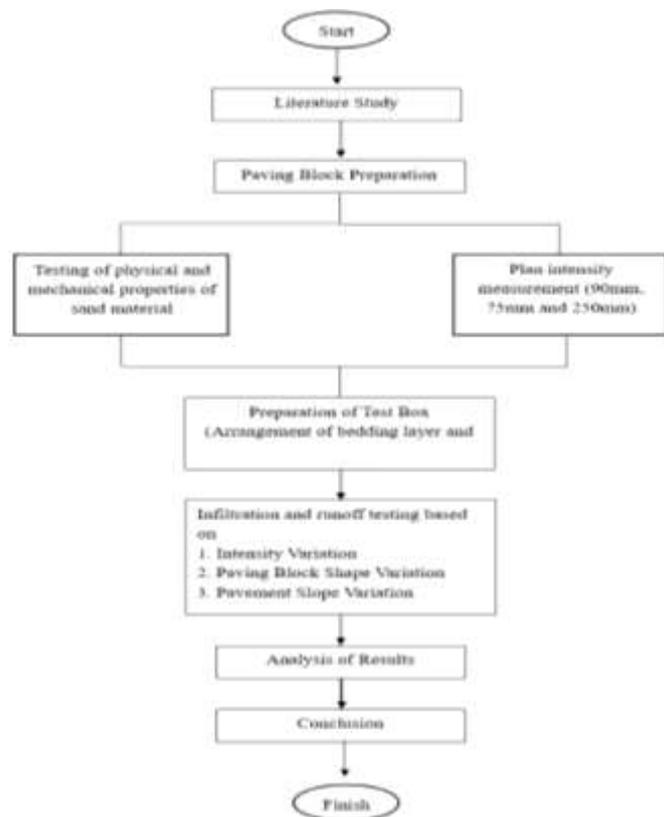


Figure 7. Flow chart

Result and Discussion

Rainwater infiltration analysis in this study was conducted to evaluate the ability of a hexagonal paving

block-covered slope to absorb rainwater and its effect on surface runoff formation. Infiltration data were obtained from experimental tests that recorded the volume of water infiltrating the soil as a function of time during artificial rainfall events with controlled intensity.



Figure 8. Screening analysis test results

The Effect of Slope Gradient on Infiltration and Runoff Infiltration Data Results with a 0% Slope

Based on Table 3, the test results for hexagonal paving blocks on a flat surface with a rainfall intensity of 50 mm/hour show that no infiltration volume was observed for the first 5 minutes. After 10 minutes, the measured infiltration volume reached 170 mL. At 20 minutes, the volume increased to 340 mL. The highest recorded infiltration volume was 360 mL at 30 minutes, but by 35 minutes, the water volume had dropped to 350 mL. The volume continued to decrease over time, and at the end of 50 minutes, the measured volume was 310 mL as shown in Table 3. The total amount of runoff collected from the test of hexagonal paving blocks on a flat surface was 240 mL.

Table 3. Infiltration Data of Hexagon Type Paving Block with 0% Slope and Intensity of 50 mm/hour

Time Interval (minutes)	Initial Infiltration (mL)	Final Infiltration (mL)	$\Delta I$ (mL)	$\Delta t$ (minutes)	Infiltration Rate (mL/min)
0 - 5	0	0	0	5	0
5 - 10	0	170	170	5	34
10 - 15	170	290	120	5	24
15 - 20	290	340	50	5	10
20 - 25	340	350	10	5	2
25 - 30	350	360	10	5	2
30 - 35	360	360	0	5	0
35 - 40	360	360	0	5	0
40 - 45	360	360	0	5	0
45 - 50	360	360	0	5	0
50-60	360	360	0	5	0

Figure 9 shows how the infiltration volume (mL) changes with respect to the dwell time (minutes). During the early minutes of a rainfall event, measured infiltration volume may be zero because incoming rain is initially abstracted by surface processes rather than contributing immediately to downward flow. This

‘initial abstraction’ encompasses wetting of surface materials, filling of macropores and void spaces in pavement surfaces, and accumulation in micro-depressions before water reaches the subgrade. These processes must be satisfied before measurable vertical infiltration is observed, as conceptualized in

hydrological infiltration models and demonstrated experimentally in permeable pavement systems (Wu et al., 2024).

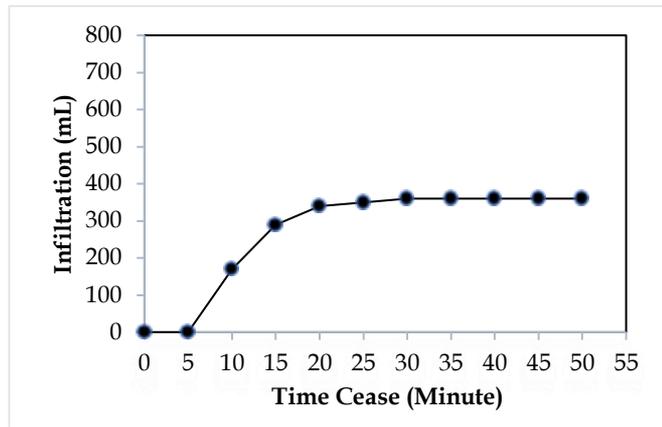


Figure 9. Infiltration data graph

In the early stages of a rainfall event, soil infiltration rates are initially very high because the soil is unsaturated, exhibiting large matric suction and a significant water potential gradient that drives rapid downward flow into pore spaces (S. Wang et al., 2025). In this test, at the 5th minute, the infiltration rate was 34 mL/minute and continued to decrease in the following minutes. As rainfall continues, these driving gradients diminish as pore spaces fill and soil moisture increases, causing the infiltration rate to decline toward a lower steady state in accordance with classical infiltration behavior described in Horton’s model (Sharghi S. et al., 2025). Experimental studies on unsaturated soil infiltration confirm that the initial wetting front and matric suction dynamics control this early high infiltration followed by a decrease over time (Zhong et al., 2023).

On a flat surface, rainwater does not immediately flow laterally; all rainwater is available for the infiltration process. As long as the initial infiltration capacity ( $f_0$ ) is greater than the rainfall intensity, almost all rainwater will be infiltrated, so the measured infiltration rate is very large in the first few minutes (Morbidelli et al., 2018). This is why the runoff volume is also small, only 240 mL.

*Infiltration Data Results with a 2% Slope*

Unlike flat surfaces, infiltration on gentle slopes is initially slow and only reaches its maximum rate after a few minutes. This is because on sloping surfaces, the gravitational force is split into a component perpendicular to the slope, which drives infiltration, and a component parallel to the slope, which drives lateral flow (initial surface flow) (Q. Yang et al., 2024). In the initial minutes of rainfall, the component parallel to the slope dominates, with some rainwater flowing laterally

before infiltration. As a result, the volume of water actually available for infiltration is still limited, resulting in a relatively low measured infiltration rate (Zhan et al., 2023). The infiltration volume at the surface at 5-10 minutes was 170 mL, while on gentle slopes (2%), the infiltration volume was only 100 mL. On gentle slopes, although rainwater does not linger in one place for long, the surface residence time is still low at the start of the test. Over time, water begins to be retained in surface cracks, micro-dips, or between paving blocks, increasing the residence time and allowing infiltration to develop show on Table 4 and Figure 10 (Quintero et al., 2023).

In block paving systems, including hexagonal configurations, the voids between the paving blocks and the underlying base layer are initially dry, allowing rainwater to initially fill these pore spaces (Morillyn et al., 2024). On sloped surfaces, infiltrating water is partly retained within the voids and partly transported laterally downslope. Maximum infiltration is only achieved when the base layer approaches saturation, at which point vertical flow becomes the dominant transport mechanism (Madrazo-uribeetxebarria et al., 2023; Moretti et al., 2025).

**Table 4.** Infiltration Data of Hexagon Type Paving Block with 2% Slope

Time Interval (minutes)	Initial Infiltration (mL)	Final Infiltration (mL)
0 - 5	0	0
5 - 10	0	100
10 - 15	100	230
15 - 20	230	260
20 - 25	260	270
25 - 30	270	370
30 - 35	370	560
35 - 40	560	570
40 - 45	570	570
45 - 50	570	570
50-60	570	570

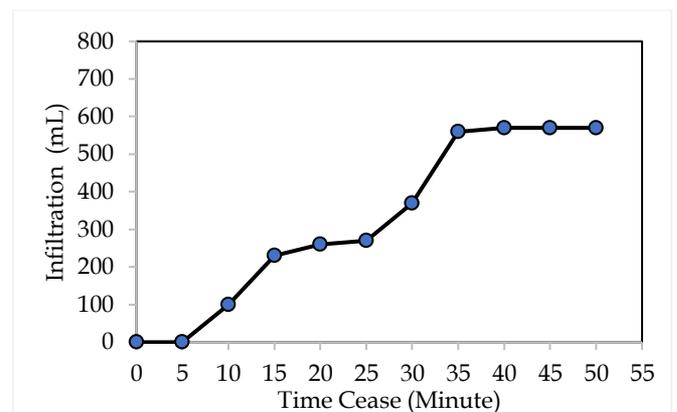


Figure 10. Infiltration data graph

Hydraulic conditions evolve over time. During the initial phase, the vertical hydraulic gradient is relatively

low, reducing effective hydraulic conductivity. As infiltration progresses, the soil moisture content increases, vertical flow paths form, and the downward hydraulic gradient intensifies. This temporal evolution explains the delay in peak infiltration rates (F. Wang et al., 2022). This is why, on a 2% slope, the infiltration rate reaches its maximum approximately 30 minutes after the onset of rainfall. The resulting runoff increases significantly, reaching 15,423 mL compared to only 240 mL on a flat surface.

Test results show that the infiltration volume on gentle slopes (2%) is higher than on flat surfaces. This occurs because flat surfaces saturate more quickly. On flat surfaces, rainwater is retained in one area, and infiltration occurs very rapidly initially, causing the soil to quickly reach saturation. After saturation, the infiltration rate decreases drastically, and additional infiltration becomes very small, and excess water immediately becomes ponding or runoff. This means that the infiltration volume is quickly "used up" prematurely (Shen et al., 2025).

On gentle slopes, some water flows slowly downward, and infiltration does not occur simultaneously; a wetting front develops gradually along the slope. As a result, the soil is not immediately saturated, and infiltration takes longer, and the cumulative infiltration volume can exceed that of a flat surface after just a few minutes of rainfall (Chen et al., 2006). Although the residence time at one point is shorter, water moves along the slope, with each slope segment receiving an opportunity for infiltration, increasing the total effective infiltration area (Xue et al., 2025). This creates a distributed infiltration effect rather than the localized infiltration effect found on flat surfaces. On flat surfaces, the soil saturates within 25-30 minutes, while on gentle slopes, saturation occurs within 35-40 minutes. The comparison graph is shown in Figure 11.

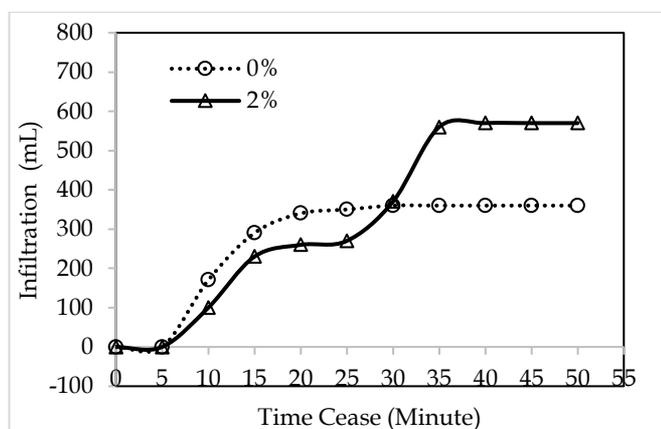


Figure 11. Infiltration data graph Comparison 0% vs 2%

### Infiltration Data Results with a 4% Slope

On steeper slopes (4%), the total infiltration volume tends to be smaller than on gentler slopes (2%). The primary reason is that rainwater moves quickly laterally along the slope, resulting in a very short surface residence time, with only a small portion of the water infiltrating the soil. As a result, even though the soil has a high infiltration capacity, this potential is not optimally utilized (Shen et al., 2025). Conceptually: high infiltration capacity, low infiltration opportunity.

The infiltration rate on steep slopes is relatively low in the early minutes. Infiltration is limited by the low availability of surface water, and the parallel-slope component of gravity dominates (Jia et al., 2024). In the middle minutes, the infiltration rate does not increase significantly, and it struggles to reach its maximum value as on flat surfaces, resulting in a slow and uneven wetting front development (Shen et al., 2025). In the later minutes, the infiltration rate tends to quickly reach a low, constant state, often lower than the saturated infiltration rate of the same soil on a flat surface (S. R. Yang et al., 2023). The infiltration graph is shown in Figure 12.

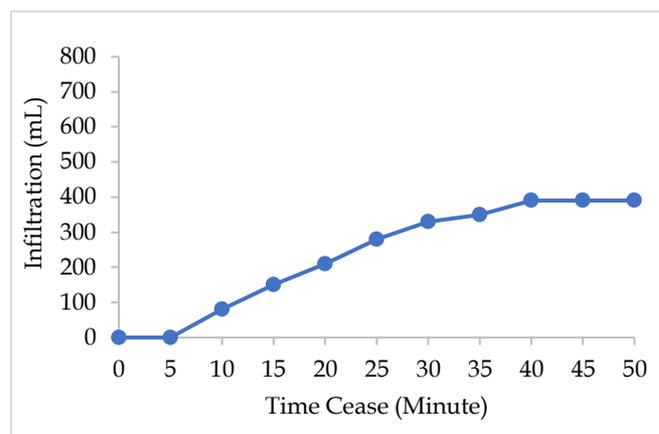


Figure 12. Infiltration data graph

Steeper slopes (4%) generate the highest runoff compared to other slope conditions. The primary characteristics of this runoff include a very rapid onset, high runoff volume, elevated flow velocity, increased erosion potential, and enhanced sediment transport. Even on surfaces paved with blocks, the gaps between the blocks are unable to retain water for a sufficient duration, causing water to move through the system predominantly as surface runoff (Huang et al., 2025).

Relationship with Hexagonal Paving Blocks. On steep slopes, the influence of the hexagonal paving block arrangement is predominantly structural rather than hydrological. Infiltration is reduced, while the role of the paving system in controlling surface flow velocity becomes more pronounced. This is clearly reflected in the observed runoff volume of 24,999 mL, which is

approximately 1.6 times greater than that measured on a 2% slope, as shown in Figure 13.

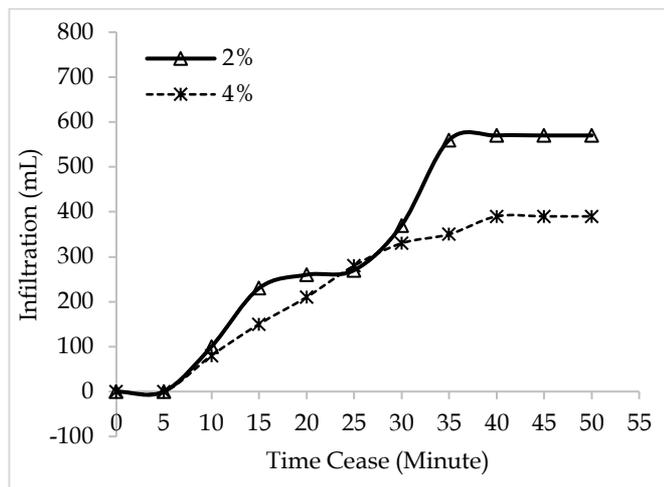


Figure 13. Infiltration data graph comparison 2% vs 4%

Differences in slope gradient, although relatively small, significantly impact rainwater infiltration. A 2% slope exhibits a higher initial infiltration rate because water has a longer residence time on the surface, allowing for more effective infiltration before runoff forms. Conversely, at a 4% slope, the parallel-slope gravity component is more dominant, causing water to move more quickly as surface flow, resulting in a lower initial infiltration rate and a delayed peak. The impact of these differences is evident in the cumulative infiltration volume: a 2% slope absorbs more water, while a 4% slope produces faster runoff and a smaller infiltration volume, as shown in Figure 13. These findings emphasize the importance of slope gradient in regulating the balance between infiltration and runoff, as well as the effectiveness of hexagonal paving blocks in supporting infiltration on gentle slopes (S. R. Yang et al., 2023).

*The Effect of Paving Shape and Slope Gradient on Infiltration and Surface Flow*

The shape of paving blocks significantly influences surface hydrological behavior, particularly infiltration, flow velocity, and stormwater runoff. Hexagonal paving blocks tend to have a higher degree of interlocking than block paving blocks, resulting in more even load distribution and improved surface stability (Moretti et al., 2025). From a hydrological perspective, the hexagonal configuration generally creates a more uniform and interconnected network of gaps, allowing rainwater to be distributed more evenly across the surface and increasing the opportunity for infiltration (Huang et al., 2025).

Conversely, block paving blocks have a more linear joint pattern, which can facilitate the formation of

preferential flow paths. This allows rainwater to flow more easily along the joints, especially on sloped surfaces, resulting in higher surface flow velocities and shorter water retention times. As a result, infiltration opportunities are more limited, and surface runoff can form more quickly than hexagonal paving blocks (Hashim et al., 2023).

In terms of stormwater runoff, hexagonal paving blocks tend to produce smaller runoff volumes due to their ability to slow surface flow and increase infiltration through the gaps between blocks. Meanwhile, block paving, while still allowing infiltration, is generally less effective at retaining and distributing rainwater, resulting in relatively greater surface runoff, especially during high rainfall intensities or with increasing slope gradients (Al-Fatlawi et al., 2025).

Overall, hexagonal paving is superior in supporting infiltration and controlling rainwater flow velocity and runoff compared to block paving, particularly when applied to sloped surfaces. These findings confirm that the choice of paving geometry is a critical factor in designing permeable pavements focused on runoff management and water conservation (Rangkang et al., 2020). The comparison graph is shown in Table 5 and Figure 14.

Table 5. Infiltration data Comparison Hexagonal and Block Shape

Time Interval (minutes)	HEXAGON	BLOCK
	Infiltration Volume (mL)	
0 - 5	0	0
5 - 10	0	0
10 - 15	100	0
15 - 20	230	430
20 - 25	260	450
25 - 30	270	470
30 - 35	370	490
35 - 40	560	480
40 - 45	570	470
45 - 50	570	470
50-60	570	450

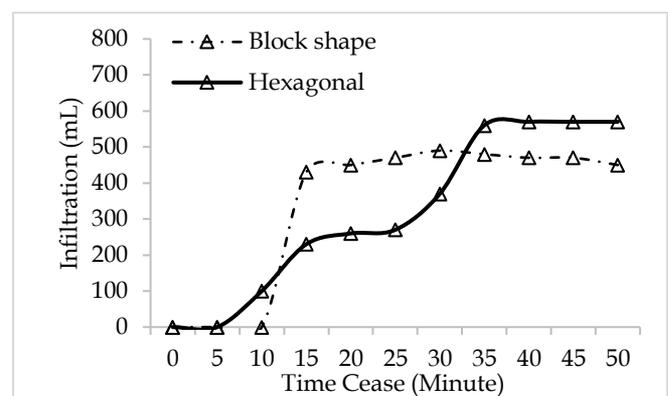


Figure 14. Infiltration data graph comparison hexagonal and block shape

## Conclusion

This study demonstrates that land slope significantly influences rainwater infiltration performance on surfaces covered with hexagonal paving blocks. Experimental results using a rainfall simulator with an intensity of 50 mm/h indicate that a 2% slope provides the most optimal infiltration condition, achieving a maximum infiltration volume of approximately 570 mL between the 40th and 45th minutes before reaching a stable state. In contrast, the 0% slope experienced a decrease in infiltration rate after prolonged rainfall due to soil saturation, while the 4% slope showed reduced infiltration efficiency caused by increased surface runoff. These findings confirm that hexagonal paving blocks installed on a moderate slope are effective in enhancing rainwater infiltration, reducing surface runoff, and supporting urban flood mitigation and groundwater recharge efforts. Nevertheless, differences between laboratory conditions and actual field environments—such as soil type, soil compaction, and rainfall variability—may affect system performance. Therefore, further studies involving field-scale experiments and a wider range of environmental conditions are recommended to validate and expand upon these results.

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## Author Contributions

Conceptualization, A.M. Indriani. and G. Utomo; methodology, A.M. Indriani. and G. Utomo.; formal analysis, A.M. Indriani.; investigation, G. Utomo.

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## Conflicts of Interest

No conflict interest.

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