DOI: 10.1515/jwld-2017-0030

JOURNAL OF WATER AND LAND DEVELOPMENT
2017, No. 33 (IV–VI): 149–156
PL ISSN 1429–7426

Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://www.degruyter.com/view/j/jwld

Received 16.02.2017
Reviewed 03.04.2017
Accepted 07.04.2017

A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Runoff velocity behaviour on smooth pavement and paving blocks surfaces measured by a tilted plot

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For citation: Sedyowati L., Suhardjono S., Suhartanto E., Sholichin M. 2017. Runoff velocity behaviour on smooth pavement and paving blocks surfaces measured by a tilted plot. Journal of Water and Land Development. No. 33 p. 149–156. DOI: 10.1515/jwld-2017-0030.

Abstract

Paving blocks have been widely known as an alternative technology for reducing runoff discharge due to their infiltration performance and capability of retarding the flow. Surface configuration of the different paving blocks types and the openings area play important role in decreasing the runoff velocity. In this study, we investigated the surface runoff velocity on two types of paving blocks layers, and a smooth pavement as comparison. The paving blocks type were rectangular blocks, which have 3.2% openings ratio and hexagonal blocks, which have 6.5% openings ratio. We used a tilted plot covering area of 2 × 6 m, equipped by a rainfall simulator to accommodate the variation of surface slope and rainfall intensity. We measured the velocity by using modification of dye tracer and buoyancy method. The data were then tabulated and graphed based on the paving types and the surface slopes. Generally, the velocity-slope relationship has demonstrated that the increase in surface slope leads to the increase in velocity. In this study, the result showed that slope and rainfall intensity simultaneously influenced the velocity ($F = 19.91 > F_{table} = 5.14$; $P < 0.05$). However, the findings of this study showed a weak relationship between the changes of surface slope and the changes of runoff velocity on the rectangular blocks ($R^2 = 0.38$). The greater slope did not always invariably lead to the greater runoff velocity. It was likely that there was other predictor variable that was not identified before, and need to be further investigated.

Key words: *low-impact development, overland flow, permeable pavement, urban drainage*

INTRODUCTION

In the last few decades, there has been a growing usage of permeable pavement as parking lots, driveway and road shoulders, especially in the urban area. Low impact development (LID) and sustainable urban drainage system (SUDS), both are new paradigms in infrastructure development that optimizing the use of permeable pavement. Permeable pavement is an effective way in controlling the surface runoff directly from the source [COLLINS *et al.* 2008]. The most popular permeable pavement is permeable interlocking concrete pavement (PICP) or concrete blocks pavement (CBP), which is also known as paving blocks. In recent years, there has been a development of permeable pavement technology used to increase the infiltration performance. The technology can be performed by adding specific material, such as geo-textile, PVC, or slag [ABUSTAN *et al.* 2012], or cutting the underside of blocks to make drainage slot [LUCKE 2014].

Paving blocks have ability to reduce surface runoff velocity in two ways. The first way is to utilise the joint area between individual blocks to allow penetration of water into the blocks. The second way is to consider the effects of surface configuration on the velocity of surface runoff. Water penetration leads to a decrease in runoff depth and runoff flow velocity. This is in accordance with the Boundary Layer Theory [SCHLICHTING 2017] which explained that the flow close to the bottom of channel gaining the greater influence of surface roughness and tractive force, and therefore, the flow velocity becomes lower. Saturated condition and maximum infiltration capacity is identified when water started visibly ponding on the joint area [NICHOLS *et al*. 2014]. Then, the flow will ex-filtrate from the paving blocks system [COLLINS *et al*. 2009]. The infiltrate and ex-filtrate process leads the water retained on the paving blocks surface and delays the flow toward the nearest channel. Some paving blocks have different joint shape and size that can provide different infiltration performance as well [CASTRO *et al*. 2007]. Water penetration can also be influenced by joint width, shape and size of paving blocks, thickness and slope gradient of sub-base layer [HASSANI *et al*. 2008], material of paving blocks [GOMEZ-ULLATE *et al*. 2011], filtration media of subgrade/sub-base layer [SINGHAL *et al*. 2008], clogging [LUCKE 2014], pores of paving blocks [BARRETT *et al*. 2006], and age of paving blocks construction [BORGWARDT 2006]. The infiltration performance is also affected by the frequency of vehicle wheel crossing on the paving blocks surface [ILLGEN *et al*. 2007]. However, some researches have differed in results and have arrived at different conclusions because the complexity response of the various systems of paving blocks to the changes of rainfall intensity and surface slope. Study by LUCKE and BEECHAM [2011] mentioned that there was no significant relationship between slope surface and infiltration rate. COLLINS *et al*. [2008] have investigated that paving blocks with larger opening area generated larger runoff than paving blocks with smaller opening area.

Whilst many researches have been carried out on the infiltration performance, there has been very little research directly investigating surface configuration of paving blocks and its effect on the flow velocity. For many years, this phenomenon was assumed as roughness coefficient. Previous research has examined that a decrease in the flow rate was also influenced by the time interval between the rainfall, rainfall intensity and rainfall depth [COLLINS *et al*. 2009]. However, it is necessary to observe the flow velocity on the field. The roughness values for different surfaces and flow velocities can be calibrated, and therefore, the roughness effect on surface runoff can be analysed [ZHANG *et al*. 2016]. In this research, we identified that the factors for generating the flow velocity on paving blocks surface were the combination of infiltration – ex-filtration process and surface roughness. We set up a field research in a medium plot scale to examine the infiltration – ex-filtration process and the velocity behaviour based on the different types of paving blocks, various surface slope and rainfall intensity.

MATERIALS AND METHODS

TRAVEL TIME FORMULAS

Surface runoff is closely related to the flow velocity and the time to travel along the area. Hortonian Overland Flow Theory describes that surface runoff will be generated when the rainfall intensity is greater than the infiltration rate. Therefore, the infiltration rate will significantly affect the surface runoff travel time. Saturated Overland Flow Theory explains that surface runoff occurs since the system is already saturated, and the travel time is not affected by the infiltration rate. According to LI *et al*. [2008] there are three different travel time zones and they are: 1) when rain start until the initiation of surface runoff generation, 2) runoff peak time, and 3) time of concentration. Summary of various formulas for calculating travel time at various land usage such as urban area, high drainage load area, pavement area like airport and highway is presented as follows: (1) HATHAWAY [1945] and KERBY [1959], variables: *L*, *N*, *S* (*N* = flow retardant factor), developed from drainage basin with area < 405 ha, *S* < 0.01; (2) IZZARD [1946], variables: *i*, *c*, *L*, *S* (*c* = retardant coefficient based on pavement type), values of c range from 0.007 for very smooth pavement to 0.012 for concrete pavement to 0.06 for dense turf; (3) CHEN and WONG [1993], WONG [2005], variables: *L*, *S*, *i*, *C*, *k* (for smooth pavement *C* = 3, *k* = 0,5; grass *C* = 1, *k* = 0), developed from overland flow on test plots of 1 m wide by 25 m long, slopes of 2% and 5%; (4) FAA [1970], variables: *C*, *L*, *S* (*C* = rational method runoff coefficient), developed from airfield drainage data assembled by U.S. Corps of Engineers; (5) MORGALI and LINSLEY [1965], ARON and ERBORGE [1973], variables: *L*, *n*, *S*, *i* (*n* = Manning's roughness coefficient), developed from overland flow equation from kinematic wave analysis of runoff from developed areas.

Almost all of formulas mentioned above have similarity on the main variables used, i.e. *L* is defined as length of overland flow or length of flow path, *S* is defined as surface slope or basin slope, and *i* is defined as rainfall intensity. Those formulas are distinguished by a coefficient representing the surface area condition such as surface roughness, surface configuration, surface runoff, and flow retardant factor. In this study, we used surface slope, rainfall intensity, and specific variables related to the physical properties of paving blocks, i.e. openings ratio and void ratio as research variables.

FLOW VELOCITY MEASUREMENTS

Dye method is a method for measuring the surface runoff velocity in the laboratory experiment or field observation that is commonly used by many researchers. Average velocity obtained from the dye method differs from average velocity obtained from the discharge method by an average error of only 7.07%. Therefore, dye method appears to provide a reliable method of measuring surface runoff velocity [ABRAHAMS *et al.* 1986]. There was an uncertainty result of dye method [DUNKERLEY 2001]. He suggested to avoid using this method in obtaining precision depth measurement derived from flow velocity as measured by dye method. Few years later he developed new optical tachometer to minimize the shortcoming of the dye method [DUNKERLEY 2003]. Another researcher promoted the Salt-Velocity Gauge (SVG), a new method for measuring flow velocity by applying the use of salt tracing. This method provides a high rate in measurement, short control section length, precision of the average velocity in experimental condition with turbulent and supercritical flow [PLANCHON *et al.* 2005]. This method has been modified in a miniaturized version which provides reliable velocity data over a wide range of flow speeds and with no lower limit on flow depth [TATARD *et al.* 2008]. The latest method promoted was based on the detection of buoyant fluorescent microspheres through a low-cost apparatus, which incorporates light sources to elicit fluorescence response and a digital camera to identify the particles transit [TAURO *et al.* 2012].

Measuring flow velocity at the surface of paving blocks was quite difficult. Configuration of the paving blocks potentially generated a laminar flow and turbulent, sheet flow and shallow water depth at the same time. The flow depth was very thin. Using the methods mentioned above was not easy. In this study, we used modification of the dye tracer method and the buoyant method developed by TAURO *et al.* [2012]. To obviate the effect of colour dispersion caused by the raindrop splash, we modified the material using oil as insoluble liquid and glitter powder as sparkled small buoyant object. The timing was observed visually using a stopwatch accompanied with a camera.

EXPERIMENTAL PROGRAM

Experiments were conducted on a tilted plot of 2 m by 6 m area (Photo 1). The plot was a modification of the experimental test rig developed by LUCKE and BEECHAM [2011]. In this study, the plot was placed above a platform that was laid on a 179 m^2 bare land in Malang City, Indonesia. The platform height was 1.5 m above the ground to get variation of slope up to 25% and the size was as the same as the plot. Platform had four stands on its corners. To accommodate the change in slope, the each stand was made of two hollow iron pipes. Therefore, it could be raised and lowered. The plot was also equipped by a rainfall simulator for raining the entire plot area. The simulator consisted of five sprinklers. Each sprinkler delivered rain to the area of 2.4 m^2. The

Photo 1. The tilted plot and the 5-sprinklers rainfall simulator (phot. *L. Sedyowati*)

simulator has been analysed by using distribution uniformity (DU) method and verified by using natural rainfall measurements. The DU was 78% and the root mean square error (*RMSE*) was 22%.

The paving blocks layer was laid on an impermeable layer for obtaining a saturated condition. This condition was required in order to generate a sheet flow on the paving blocks surface. There was a hole of 5 cm diameter at the bottom of the plot to drain the water that penetrates into the paving blocks. The running experiment devices and the flow measurement can be seen in Photo 2.

a)

b)

Photo 2. Running experiment (a); flow measurement (b); (phot. *L. Sedyowati*)

We designed the experiments based on three parameters, as follows: (1) the slope gradient (*S*) consisted of 5%, 10% and 15%, (2) the rainfall intensity (*I*) consisted of 50, 55 and 60 mm·h^{-1}, (3) the paving blocks type consisted of rectangular blocks and hexagonal blocks. The given variables concerning the paving blocks type comprised opening ratio (O_r), void ratio (V_r). O_r was the area of gaps among paving blocks per one square meter (m^2·m^{-2}). V_r was the ratio of the volume of water that absorbed in a single block paving and the initial volume (m^3·m^{-3}). O_r = 3.2% and 6.5%, V_r = 0.7% and 1.6%, for rectangular and hexagonal blocks respectively. Photo 3 shows the types of paving blocks.

The observed data were travel time (T_t) from upstream to downstream of the plot, and surface runoff discharge (*Q*). Experiment were performed by the following procedure: 1) setting the surface slope of the plot; 2) determining the rainfall intensity and opening the water supply valve; 3) measuring the runoff discharge at the downstream section of the plot using gutter and v-notch; 4) measuring the travel time of surface runoff after the discharge has been stable; 5) calculating the flow velocity based on the observed travel time; and 6) analysing data using MS Excel to examine the correlation and determination coefficients (R^2), multivariate analysis of variance and regression function.

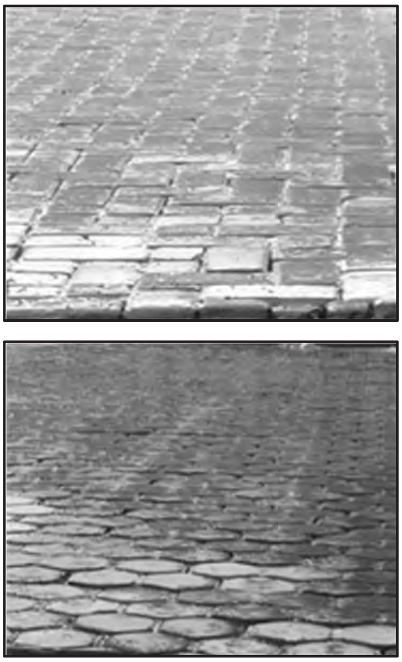
a)
b)


Photo 3. Paving blocks: a) rectangular, b) hexagonal (phot. *L. Sedyowati*)

RESULTS AND DISCUSSION

EFFECTS OF PAVEMENT TYPE, SURFACE SLOPE AND RAINFALL INTENSITY

There were three sets of observed data, i.e. smooth pavement, rectangular and hexagonal blocks data. Each set of data consisted of nine individual data. O_r and V_r were zero at smooth pavement because there was no openings area and void. The smooth pavement data were used as comparison of velocity data resulted from rectangular and hexagonal blocks. Hexagonal blocks had greater O_r and V_r compared to the rectangular blocks. The initial hypothesis was that the velocity on rectangular blocks was greater than on hexagonal blocks. Surprisingly, the results of this study showed that at some certain conditions of surface slope and rainfall intensity, the velocity on hexagonal blocks was greater than on rectangular blocks.

On the slope of 5%, there was a significant decrease in velocity between the smooth pavement and the paving blocks. On rectangular and hexagonal blocks the velocity were reduced to average 27% and 41% respectively. The velocity on rectangular blocks was higher than on hexagonal blocks. The greater openings ratio of hexagonal blocks caused the higher infiltration rate. The mild slope generated the lower velocity that also led high potential infiltration rate. Higher infiltration rate generated the lower flow depth so that the influence of surface roughness was significant in retarding the velocity. This was in accordance with the boundary layer theory developed by L. Prandtl in 1904 [SCHLICHTING, GERSTEN 2017].

Figure 1 explains the effect of rainfall intensity to the response of smooth pavement, rectangular blocks and hexagonal blocks toward surface runoff velocity at 5% slope. There was a positive correlation between rainfall intensity and the flow velocity. However, the influence of rainfall intensity was only significant on smooth pavement. In paving blocks pavement there was no dramatic change on velocity. It was caused by the smaller influence of the rainfall intensity compared with the infiltration rate as impact of the opening ratio of paving blocks and the mild slope.

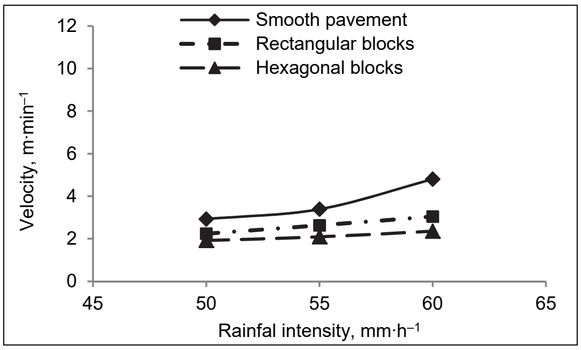


Fig. 1. Runoff velocity at slope of 5%; source: own study

On the slope of 10%, the velocity reduced maximum to 45% on the rectangular blocks and to 47% on hexagonal blocks when compared to smooth pavement. Contrastingly, there was no significant difference in velocity between rectangular and hexagonal blocks, as shown in Figure 2. On average, the flow velocity in the hexagonal blocks was slightly higher than rectangular blocks. The steeper slope speeded up the velocity so that it minimized the infiltration rate

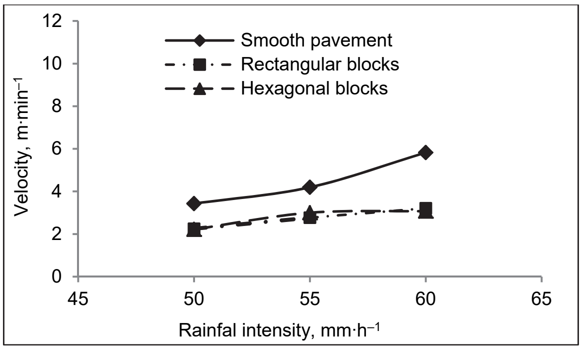


Fig. 2. Runoff velocity at slope of 10%; source: own study

and increasing the flow depth. In this condition, the surface roughness of paving was caused by the openings and gaps among paving blocks, which did not significantly influence the velocity. This correlation had similar trend to the results found by COLLINS *et al*. [2008]. It was stated that the surface runoff generated from greater void area was greater than generated from pavement surface with lower void area. Like the surface roughness, the rainfall intensity and the slope also did not significantly influence the velocity. When it was compared to 5% slope, there was a reduction in velocity up to 10% at the slope of 10% on rectangular blocks. It was predicted that there was another predictor variable influencing the velocity.

On the slope of 15%, the velocity reduced to maximum 67% on the rectangular blocks and to 61% on hexagonal blocks when compared to smooth pavement. The average velocity in hexagonal blocks was greater than the average velocity on rectangular blocks, despite of the openings and void ratio of hexagonal blocks were greater than rectangular blocks. Figure 3 shows that on rectangular blocks there was just a little change in velocity as the impact of changes in slope and rainfall intensity. These results supported the idea of former researchers. COLLINS *et al.* [2008] mentioned in his study that water flowing through the channels formed by the joint pavers was depressed and water directly penetrated into the gap.

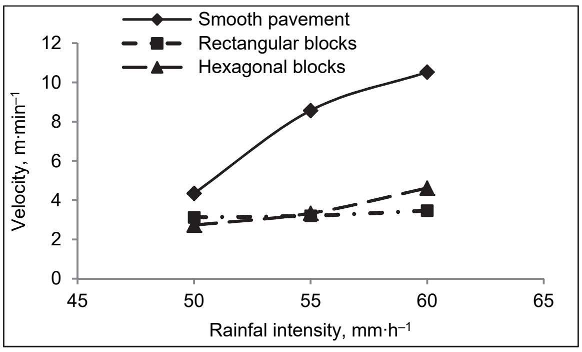


Fig. 3. Runoff velocity at slope of 15%; source: own study

At paving blocks which were not forming channels, the pavers only infiltrated water that passed over the gaps and no addition water from upper section. In this kind of paving grid, surface runoff was theoretically able to avoid open surface voids, or at least travel a distance before infiltrating. Whereas study carried out by LUCKE and BEECHAM [2011] on the new paving blocks surface found that the change in slope did not lead to any differences in infiltration rate.

This research result also indicated that the velocity was influenced more by another variable. It was possible that this unmeasured variable could account for some aspects of the results. Table 1 shows the determination coefficient of slope and rainfall intensity, and the reduce in flow velocity resulted from this research.

Table 1. Recapitulation of determination coefficient (R^2) and reduce in velocity

Pavement	R^2		Reduce in velocity, %					
			S = 5%		S = 10%		S = 15%	
	slope	rainfall intensity	average	max.	average	max.	average	max.
Smooth pavement	0.47	0.34	0	0	0	0	0	0
Rectangular blocks	0.38	0.49	27	37	38	45	53	67
Hexagonal blocks	0.56	0.31	41	51	37	47	52	61

Source: own study.

By further investigation on Collins's result, we identified that the length of straight channel on the main direction of flow formed by the joint of paving grid was probably the new variable that was not considered before. In this study, we also examined the influence of surface slope that was not studied by Collins. On the steep slope, such as the slope of 15%, the velocity was increased as the common flow characteristic. However, when the high velocity was flowing through the pavers joint and was forming a channel, the water was then penetrated into the paving blocks layer through the unpaved channel. The increase of rainfall intensity triggered more water penetrated into the channel, so that the infiltration rate became larger. The longer pathway will generate the larger infiltration rate. More water infiltrated will reduce the flow depth and the velocity.

FLOW VELOCITY BEHAVIOR ON PAVING BLOCKS SURFACES

To distinguish the runoff velocity behaviour between rectangular and hexagonal blocks, we presented the observation data in different graphs. Figure 4 describes the velocity behaviour on rectangular blocks. It was shown that the changes in surface slope and rainfall intensity did not lead significant changes in velocity, especially on the slope of 5% and 10%. On the slope of 15% the graph was almost flat. It explained that the change in rainfall intensity did not lead to the change in velocity. There was a lot of water penetration into the paving blocks led to the decrease of surface runoff.

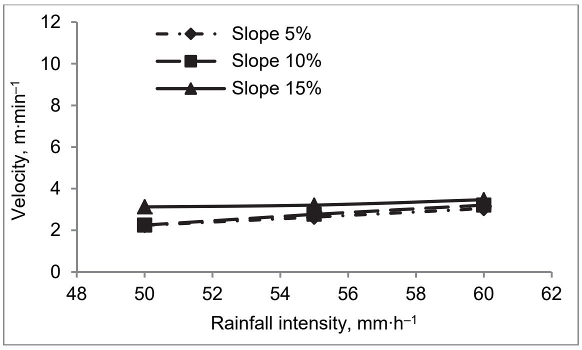


Fig. 4. Velocity behaviour on rectangular blocks; source: own study

On hexagonal blocks, there was a positive relationship between the change of velocity and the changes of surface slope and rainfall intensity (Fig. 5). It can be explained that the kind of paving blocks formed a pathway avoiding water to penetrate into the paving blocks layer [COLLINS *et al.* 2008]. The increase in surface slope and rainfall intensity led to the greater velocity flowing without any chance for water to infiltrate. Therefore, the infiltration rate decreased and there was more runoff generated from the paving blocks.

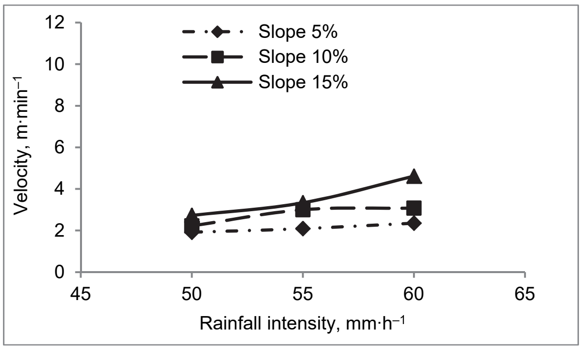


Fig. 5. Velocity behaviour on hexagonal blocks; source: own study

CONCLUSIONS

The results of experimental investigations contributed to the understanding of behaviour of surface runoff velocity on land covering by paving blocks pavement. There has been a pro-contra concerning to the paving blocks performance. The lack of flow velocity data on field led to the data that was only assumed and the result was not satisfied.

In this investigation, we concluded that paving blocks reduced the surface runoff velocity to more than 40% in average and to maximum 67%. Each type of paving blocks had different performance in reducing flow velocity. In rectangular blocks, there was a weak relationship between the changes of surface slope and the changes of flow velocity ($R^2 = 0.38$). Rainfall intensity only slightly affected the flow velocity ($R^2 = 0.49$). However, from the statistical analysis result, the slope and rainfall intensity simultaneously influenced the velocity ($F = 19.91 > F$ Table $= 5.14$; $P < 0.05$). Interestingly, during the experimental program we found a novel variable that has not been identified before, but it was probably influenced more the velocity. The variable was the length of straight channel at the main direction of flow that was formed by the joint of paving grid. It is predicted that the increase in the length of the channel will increase the infiltration rate. The surface slope and rainfall intensity also appears to influence the capacity of the channel in increasing the water penetration. This phenomenon will be very beneficial in controlling surface runoff. In order to maximize the paving blocks performance, it should be taken into account the usage of rectangular blocks.

We recommended there would be a further research to examine the best paving grid arrangement in various surface slope and rainfall intensity to get the most influence parameter so that the infiltration will be maximized and the flow velocity will be reduced as low as possible.

Acknowledgements

We would like to thank to the people who have assisted in conducting this research, especially the students of Civil Engineering Department, University of Merdeka Malang. This research is financially supported by The Ministry of Research, Technology and Higher Education, Republic of Indonesia, through research grant namely Penelitian Hibah Bersaing (PHB) 2016–2017.

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Odpływ wody z nawierzchni gładkiej oraz pokrytej kostką brukową

STRESZCZENIE

Kostka brukowa dzięki zdolności infiltracji wody i hamowania przepływu jest dobrze znanym materiałem stosowanym do utwardzania nawierzchni w celu redukowania spływu. Struktura powierzchni pokrytej kostką różnego typu i przestrzeni pomiędzy kostkami odgrywają istotną rolę w zmniejszaniu prędkości spływu. W pracy badano prędkość spływu powierzchniowego po warstwach kostki brukowej dwóch typów i porównawczo – po gładkiej powierzchni. Zastosowano kostki prostokątne z powierzchnią wolnych przestrzeni wynoszącą 3,2% całkowitej powierzchni i kostkę sześciokątną z powierzchnią wolnych przestrzeni równą 6,5%. Do badań wykorzystano pochyłe poletko o wymiarach 2 × 6 m wyposażone w symulator opadów, aby dostosować nachylenie powierzchni i intensywność opadów. Prędkość spływu mierzono, używając barwnika wskaźnikowego oraz naczynia pomiarowego. Dane przedstawiono w tabelach i na wykresach z uwzględnieniem typu i nachylenia nawierzchni. Zależność między prędkością a nachyleniem wykazała, że wzrost nachylenia powierzchni prowadzi do zwiększenia prędkości spływu. Na podstawie uzyskanych wyników stwierdzono, że nachylenie i intensywność opadu równocześnie wpływają na prędkość spływu (F = 19,91 > $F_{tab.}$ = 5,14; P < 0,05). Stwierdzono jednak słabą zależność między zmianą nachylenia powierzchni a zmianą prędkości spływu po powierzchni utwardzonej prostokątną kostką (R^2 = 0.38). Większe nachylenie nie zawsze skutkowało większą prędkością spływu. Prawdopodobnie istniał dodatkowy czynnik nieuwzględniony wcześniej, który powinien zostać poddany dalszym badaniom.

Słowa kluczowe: *drenaż miejski, nawierzchnia przepuszczalna, rozwój przyjazny środowisku, spływ powierzchniowy*