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Influence of soil surface structure and soil amendment materials on infiltration characteristics: Establishing urban flood mitigation technology

R. Itsukushima *[1], Y. Ogahara [2], Y. Iwanaga [3]

[1] Department of Decision Science for sustainable society, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

[2] Department of Urban and Environmental Engineering, Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

[3] Japan Railway Construction, Transport and Technology Agency, 1-13-26 Nishiki, Naka-ku, Nagoya city, Aichi prefecture, 460-0003, Japan

**Corresponding Author: Tel.: +81-92-802-2071; fax: +81-92-802-3438; e-mail: itsukushima@civil.kyushu-u.ac.jp*

This study aimed to establish a runoff reduction technology to counter urban flooding using soil amendment. We conducted infiltration experiments under natural rainfall to evaluate the influence of the soil surface structure on infiltration characteristics using compacted decomposed granite, permeable soil paving material and gravel mulching. In our tests, volumetric water content when using compacted decomposed granite and permeable soil paving material was similar. However, the permeable soil paving material was judged to be a high-infiltrative surface coating because the decrease in volumetric water content after rainfall was greater than that when using compacted decomposed granite.

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Introduction

Runoff mechanisms are altered by changes in land use [1]. In particular, urbanisation decreases minimum flow rates and increases flow variability [2]. It also increases peak flooding by shortening the length of periods of high flow [3]. The concentration of storm flow associated with urbanisation is a result of the degradation of infiltration capacity by the paving of roads, shortening of flood concentration periods due to the straightening of river channels and the introduction of pipeline rainwater drainage systems [4-5-6-7]. Urban flood disaster is becoming a global issue as 233 cities and approximately 663 million people are now exposed to the danger of urban flooding [8]. In Japan, such disasters frequently occur following localised torrential rainfall. Rainfall events exceeding 30 mm/h have increased in frequency, and this is believed to be a result of global climate change. In addition, the degradation of water quality or water environment caused by combined sewer overflow is a serious problem as 200 cities in Japan use a combined system for sewerage.

In America and Europe, countermeasures against nonpoint-source urban flooding and pollution load are using approaches based on low-impact development or Green Infrastructure. Other techniques concentrate on reducing runoff, including rainwater harvesting, rain gardens, green roofs and permeable pavements. Numerous studies have confirmed the benefits of these approaches in runoff reduction and water quality improvement [9-10-11]. They play an additional role in the development of social infrastructure by enhancing the landscape, providing spaces for recreation, contributing to energy efficiency, carbon fixing and improving air quality [12-13].

BRUTSARET (2005) pointed out that the rainfall rates observed in nature rarely exceed the initial infiltration capacity of the soil. All the rainfall that reaches the surface of the ground rapidly infiltrates the soil [14]. However, surface run-off is found even when rainfall is mild. The reduction in the infiltration capacity of soil is due to the formation of crusts at the soil surface. Surface crusting has been attributed to the dispersion of aggregates, the fine particles then washing into and filing the pores in the surface of the soil [15]. European studies of crust formation date back to the 1950s, when soil conservation in dry fields was a key problem [16]. HILLEL (1969) conducted infiltration tests using three types of crust and revealed that the flux of puddle and cemented crusts was approximately one third that of sable aggregate structures [17].

The goal of this study was to establish runoff reduction by soil amendment. Significant improvements in soil infiltration capacity were achieved by the addition of bamboo charcoal or humus [18]. However, to maintain the infiltration capacity of amendment soils, it is necessary to avoid crust formation from the impact of rain drops. We therefore focused on the soil surface structure and the use of soil amendment materials to prevent decreases in the infiltration capacity. Infiltration experiments were conducted under natural rainfall to investigate the influence of the soil surface structure and different soil amendment materials on the infiltration capacity.

Materials and methods

Experiments were conducted to measure temporal changes in soil moisture under natural rainfall. The experimental site was on the Ito Campus of Kyushu University (33° 35' 57" N, 130° 13' 04"E). The experimental setup is shown in Fig 1. Polyvinyl chloride pipes with an internal diameter of 20 cm and a length of 60 cm were inserted vertically into the soil to a depth of 50 cm. The amended soil was loaded into the pipes and compacted using a 10.5 kg ram. A 5 cm layer of surface coating materials was placed on the compacted amendment. Waterproofing material was coated onto the outer bottom edge to prevent ingression of soil water.

We measured the electric permittivity of the amended soil using a profile probe (Delta-T Devices, PR 2/4) at four depths from the soil surface: 5, 15, 25 and 35 cm. Measurements were taken at intervals of one hour during rainfall and 12 hours in dry periods. Soil water content was measured using the amplitude domain reflectometry (ADR) method [19]. We calibrated the relationship between volumetric water content and electric permittivity for each experimental case because the ratio was different at different mixed ratios. A rain gauge (HOBO Data Logging) was used to measure rainfall at one minute intervals.

Twelve experiment cases were used to examine the infiltration capacity of the surface structure of each amendment soil. These comprised combinations of four kinds of amendment soil and three kinds of surface structure, as shown in Fig 2.

Surface structure: compacted decomposed granite, soil: 70% decomposed granite and 30% bamboo chips. Case 3; Surface structure: compacted decomposed granite, soil: 70% decomposed granite and 30% humus. Case 4; Surface structure: compacted decomposed granite, soil: 70% decomposed granite and 30% bamboo charcoal. Case 5; Surface structure: permeable soil paving material, soil: 100% decomposed granite. Case 6; Surface structure: permeable soil paving material, soil: 70%

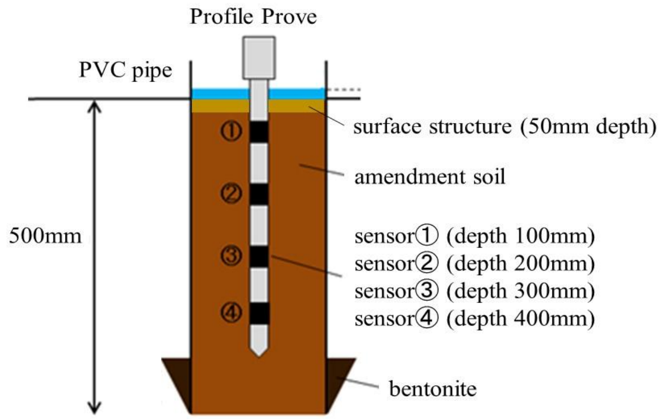

Fig. 1: Experiment setup of infiltration test

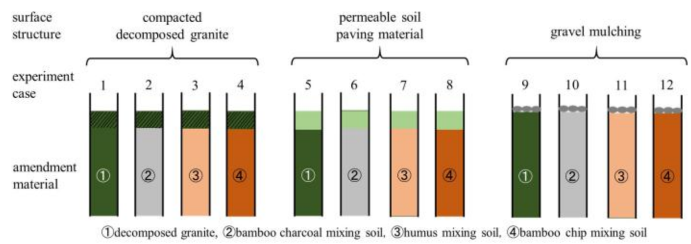

Fig. 2: Pattern diagram of experiment cases

Fig. 3: Soil amendment materials and surface coating materials

Each case was as follows. Case 1; Surface structure: compacted decomposed granite, soil: 100% decomposed granite. Case 2; Surface structure: compacted decomposed granite, soil: 70%

decomposed granite and 30% bamboo chips. Case 3; Surface structure: compacted decomposed granite, soil: 70% decomposed granite and 30% humus. Case 4; Surface structure: compacted decomposed granite, soil: 70% decomposed granite and 30% bamboo charcoal. Case 5; Surface structure: permeable soil paving material, soil: 100% decomposed granite. Case 6; Surface structure: permeable soil paving material, soil: 70% decomposed granite and 30% bamboo chips. Case 7; Surface structure: permeable soil paving material, soil: 70% decomposed granite and 30% humus. Case 8; Surface structure: permeable soil paving material, soil: 70% decomposed granite and 30% bamboo charcoal. Case 9; Surface structure: gravel mulching, soil: 100% decomposed granite. Case 10; Surface structure: gravel mulching, soil: 70% decomposed granite and 30% bamboo chips. Case 11; Surface structure: gravel mulching, soil: 70% decomposed granite and 30% humus. Case 12; Surface structure: gravel mulching, soil: 70% decomposed granite and 30% bamboo charcoal. Soil amendment materials and surface coating materials are shown in Fig 3.

Results and discussion

Fig 4 shows the total rainfall over the observation period. A detailed analysis was conducted for the period 2016 /17–1/19, during which the largest rainfall event occurred.

1. Relationship Between Improved Material and Infiltration Capacity

1.1. Infiltration capacity of compacted decomposed granite in surface structure

Fig 5 (a)–(d) show the temporal change in volumetric water content (θ) for the compacted decomposed granite in the surface structure at different depths. At 100 mm from the surface layer, the soil mixed with humus and bamboo chips showed the highest peak θ value of approximately 25%. These amendment soils also exhibited a high water retaining capacity, with the highest volumetric water content 40 hours after the rainfall peak. The decomposed granite and bamboo-charcoal-mixed soil had a low peak θ (Fig 5(a)). The temporal change in volumetric water content at a depth of 200 mm was similar to that at 100 mm, and the humus-mixed soil showed the highest peak value of θ, at approximately 45%. The highest value of θ after rainfall ended was recorded for the bamboo-chip-mixed soil, followed by humus-mixed soil (Fig 5(b)). At 300 mm depth, the bamboo-chip-mixed soil had the highest θ, similar to that at 100 mm and 200 mm. The volumetric water content of the bamboo-charcoal-mixed soil was the second highest. Temporal changes in the water content of the humus-mixed soil were comparable to those of the soil mixed with decomposed granite. Different values were recorded at 100 mm and 200 mm depths (Fig 5(c)). At 400 mm from the surface, the bamboo-charcoal-mixed soil showed the highest θ in all observation periods with a peak value of θ of almost 30%. Bamboo chips can be thought of as a high infiltration amendment material, because the bamboo-chip-mixed soil required the shortest elapsed time from the onset of rainfall to reach peak volumetric water content. Bamboo-charcoal-mixed soil had the highest volumetric water content after a long period from rainfall. However, the presence of an aquiclude directly under the experimental setting of the bamboo-charcoal-mixed soil may have affected the experimental conditions (Fig 5(d)).

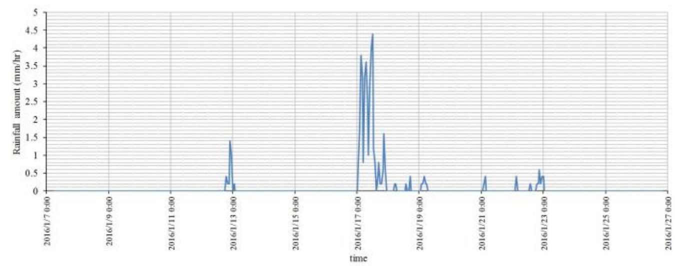

Fig. 4: Rainfall amount during observing period

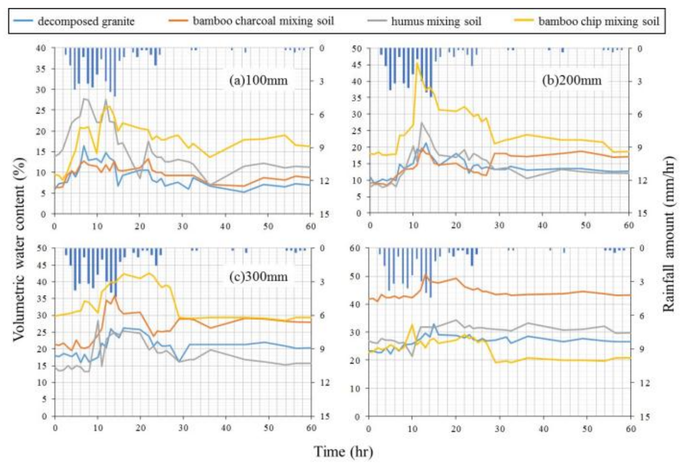

Fig. 5: Temporal change of volumetric water content in case of compacted decomposed granite in surface structure

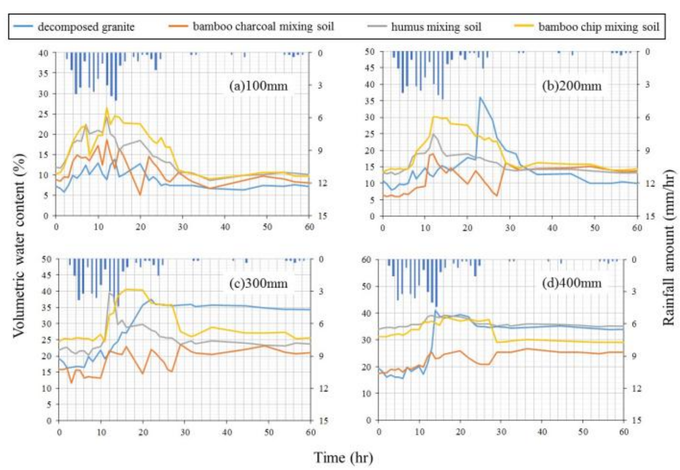

Fig. 6: Temporal change of volumetric water content in case permeable soil paving material in surface structure

1.2. Infiltration capacity of permeable soil paving material in surface structure

Fig 6 (a)–(d) show the temporal change in volumetric water content (θ) at each depth when a permeable soil paving material was applied to the surface structure. At 100 mm from the surface, the humus-mixed soil and bamboo-chip-mixed soil exhibited the highest peak values of θ after the bamboo charcoal-mixed soil and decomposed granite. This was observed when decomposed granite was used in the surface structure (Fig 5(a)), suggesting that humus and bamboo chip are improvement materials providing high infiltration.

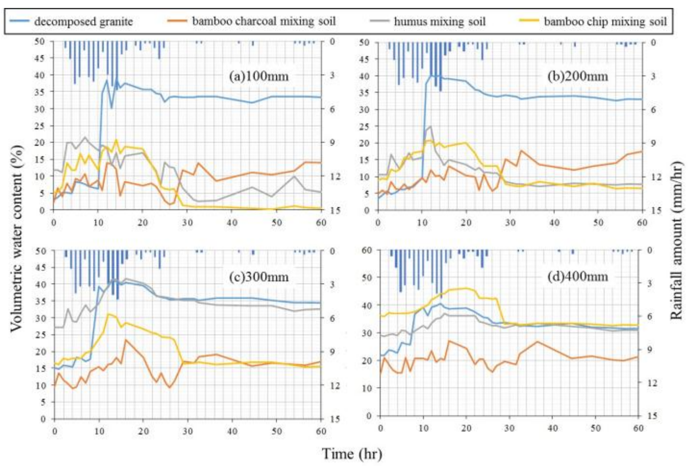

Fig. 7: Temporal change of volumetric water content in case gravel mulching in surface structure

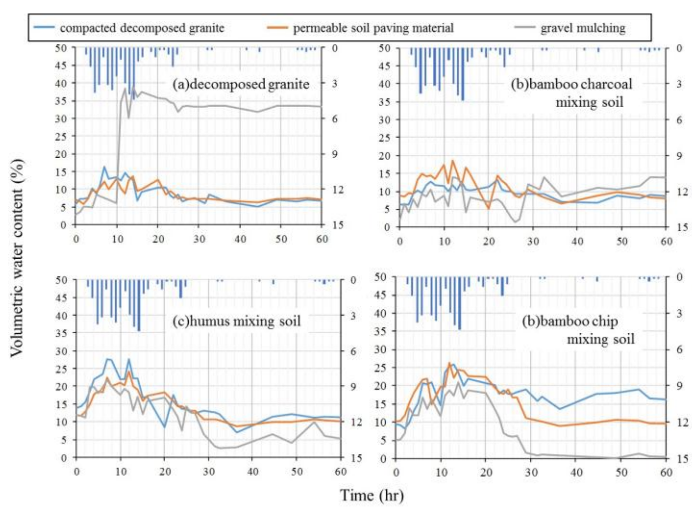

Fig. 8: Relation between volumetric water content and elapsed time for each surface structure

All amendment soils approached constant values (5-10 %) after 30 minutes from the beginning of rainfall (Fig 6(a)). At a 200 mm depth, the highest peak values of θ were, in order, bamboo-chip-mixed soil, humus-mixed soil and bamboo-charcoal-mixed soil. The bamboo-charcoal-mixed soil took the shortest time to reach the peak value of θ. Decomposed granite recorded a 35% volumetric water content at 21 hours, but this was thought to be an outlier, because much time had passed since the end of rainfall and the measured value at 100 mm was only approximately 10% (Fig 6(a)). No significant difference was found in volumetric water content at 200 mm of any amendment soil a long period from the end of rainfall (Fig 6(b)). At 300 mm, the peak volumetric water content was high in the humus-mixed soil and bamboo-chip-mixed soil, at approximately 40%, and lowest in the bamboo-charcoal-mixed soil. The decomposed granite recorded a constant volumetric water content after the peak 22 hours from the start. This was due to the aquiclude under the experimental site of the decomposed granite, with rapidly declining infiltration after the peak value of θ (Fig 6(c)). The trend in volumetric water content at a depth of 400 mm was similar to that at 300 mm. The difference in volumetric water content between the amendment soils after a long period was caused by differences in the infiltration capacity of the ground under the experimental sites (Fig 6(d)). Volumetric water content after a long period also reflected different surface structures. When the surface structure was a permeable soil paving material, the long-term volumetric water content was 5–10% in all cases (Fig 6(a)). In contrast, when the surface structure was compacted decomposed granite, the long-term volumetric water content was in the range 5–20% (Fig 5(a)). These results suggest a high infiltration capacity and homogeneity of the permeable soil paving material. Compaction of decomposed granite in the surface structure was conducted manually, possibly leading to differences in the degree of compaction between the experimental cases.

1.3. Infiltration capacity of gravel mulching in the surface structure

Fig 7 (a)–(d) show the temporal change in volumetric water content (θ) structure at each depth when gravel mulching was used in the surface structure. When decomposed granite was used as the amendment soil, a high volumetric water content after the peak value was recorded.

This suggests the presence of an aquiclude directly under the experimental site. In this section, we therefore confine our observations to the other amendment materials. At a depth 100 mm from the surface layer, bamboo-chip-mixed soil and humus-mixed soil showed the highest volumetric water content, and bamboo-charcoal-mixed soil showed the lowest. In contrast with the other surface structures, volumetric water content remained high after the peak in all cases (Fig 7(a)). This was due to trapping of water particles between the gravel and amendment soils. At the 200 mm depth, the highest peak volumetric water content was found to be, in order, humus-mixed soil, bamboo-chip-mixed soil and bamboo-charcoal-mixed soil. The volumetric water content of the humus-mixed soil and bamboo-chip-mixed soil declined after the peak, demonstrating that water retention between the gravels and amendment soils is not a barrier to infiltration (Fig 7(b)). At 300 mm from the surface, the order of volumetric water content was humus-mixed soil, bamboo-chip-mixed soil and bamboo-charcoal-mixed soil.

The volumetric water content of the humus-mixed soil remained high after the peak value. This seems to have been due to the aquiclude under the experimental site (Fig 7(c)). At 400 mm from the surface, volumetric water content was high, except for the bamboo-charcoal-mixed soil, and infiltration was disturbed by the aquiclude (Fig 7(d)). The volumetric water content of the bamboo-chip-mixed soil was stable compared to other cases at all depths. These results suggest that bamboo-chip-mixed soil has low water retention.

2. Relationship Between Surface Structure and Infiltration Capacity

To compare the infiltration characteristics of the compacted decomposed granite, permeable soil paving material and gravel mulching surface structures, we investigated the relationship between volumetric water content and elapsed time (Fig 8(a)–(c)). The 100 mm depth was selected because the influence of surface structure was clearest in the upper part of the amendment soil.

Fig 8(a) shows the temporal change in volumetric water content of the decomposed granite amendment soil. When gravel mulching was used, volumetric water content maintained a constant value after the peak, because of the aquiclude. The temporal change in volumetric water content of the compacted decomposed granite was similar to that of the permeable soil paving material.

Fig 8(b) shows the temporal change in volumetric water content of the bamboo-chip-mixed soil. The peak values were in the following order: permeable soil paving material, gravel mulching and compacted decomposed granite. Volumetric water content when using permeable soil paving material declined rapidly after the end of rainfall. It was therefore thought to have a higher infiltration capacity than the other surface coating materials. No noticeable influence of surface structure on volumetric water content was observed after a long period of time had elapsed.

Fig 8(c) shows the temporal change in volumetric water content of the humus-mixed soil 100 mm from the surface. The peak values of volumetric water content were in the following order: compacted decomposed granite, permeable soil paving material and gravel mulching. When gravel mulching was used, the fluctuations in volumetric water content were small. Water drops infiltrating the soil by running down the gravel surface smoothed the rate of infiltration.

Fig 8 (d) shows the temporal change in volumetric water content of bamboo-chip-mixed soil at 100 mm depth. The results were similar to those of humus-mixed soil (Figure 8(c)). When gravel mulching was used, volumetric water content after 30 hours was extremely low.

Although compacted decomposed granite and permeable soil paving material behaved similarly as a surface coating material, volumetric water content when a permeable soil paving material was used was larger than that of compacted decomposed granite. The permeable soil paving material had a superior infiltration performance. However, it is possible that the rainfall during the experimental period was insufficient to evaluate the different infiltration capacities of the surface materials. To properly establish the optimum surface coating technology for runoff reduction, there is a need for further studies, as follows: (1) experiments conducted in conditions that are not affected by the infiltration characteristics of the foundation soil, (2) verification of the infiltration capacity under rainfall at a scale that induces crust formation and (3) quantitative evaluation of the effect of the surface layer thickness and rainwater infiltration.

Conclusions

The objective of this study was to evaluate the influence of soil improvement material and surface structure on infiltration capacity, to establish the best approach to runoff improvement. The key knowledge acquired from the study is as follows:

(1) Soil amendment materials with high infiltration capacity;
Bamboo chip was demonstrated to be a high performance amendment material, because bamboo-chip-mixed soil had a high volumetric water content after the beginning of rainfall, regardless of the surface structure. No large fluctuations in volumetric water content were observed in the case of bamboo-charcoal-mixed soil. There is a possibility that the bamboo charcoal absorbed water by a process of infiltration. This suggests that different amendment materials have different infiltration mechanisms.

(2) Relationship between infiltration capacity and surface structure;
Although volumetric water content when using compacted decomposed granite and permeable soil paving material was similar, the decrease in volumetric water content after rainfall was larger when using permeable soil paving material than when using compacted decomposed granite. This suggests that the permeable soil paving material is a highly infiltrative surface coating. However, the rainfall amount in the test period may have been insufficient to fully evaluate the differences in infiltration capacity. Further experiments are needed to clarify the infiltration capacity of different surface coating materials.

(3) Infiltration characteristics of the foundation ground under the amendment soil;
In some of the experimental cases, it was observed that the water volumetric content remained constant after the measured peak value at depths of 300 mm and 400 mm from the surface. This suggests that the aquiclude under the amendment soil retarded infiltration. To establish the optimal runoff prevention technology, it is necessary to evaluate the influence of the infiltration capacity of the subsoil.

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