Evaluation of Infiltration Capacity and Water Retention Potential of Amended Soil Using Bamboo Charcoal and Humus for Urban Flood Prevention

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Abstract: In Japan, floods occur frequently in urban areas because non-infiltrating areas are seeing increased urbanization. To prevent floods, urban basins must improve the infiltration capacity and water retention of the whole basin. There are several basic technologies for river basin management, such as infiltration trenches or rainwater storage. However, a method of soil amendment that prevents flood disasters has not been established. This study aims to evaluate the infiltration capacity of soil amendments using bamboo charcoal and humus. A constant-head infiltration test and rainfall simulation were conducted to evaluate the properties of the soil amendments. The constant-head infiltration test’s results showed that soils mixed with 30% humus had the greatest potential for influencing initial and final infiltration rates, and the more the mixing rates of bamboo charcoal and humus were increased, the higher the water retention capacity. The results of the rainfall simulation showed that soils mixed with 30% humus had the highest final infiltration rates and lowest multiplication spillage. To reduce the runoff volume using soil amendment technology, it is important to delay overland flow, and the hydraulic properties of the soils mixed with bamboo charcoal and humus were as effective as those of granite soils.

Key words: Soil amendment, infiltration capacity, urban flood prevention, constant-head infiltration test, watering experiment.

1. Introduction

Urbanization changes the runoff mechanism and causes various problems related to flood-control, water utilization, and river environment, such as increasing the flow discharge rate, decreasing the flow discharge in the normal state [1], or causing water quality deterioration by CSO (combined sewer overflow) [2]. Recently, flood disasters caused by localized torrential rain in urban areas have occurred frequently in Japan [3]. This phenomenon is considered to have become more serious because of global warming. The Intergovernmental Panel on Climate Change predicted that localized torrential rain will occur more frequently in the mid-latitude region [4]. In addition, CSO causes the serious problem of water quality deterioration by heavy rain in cities where combined sewers have been adopted.

The concept of “integrated watershed management” has strengthened the infiltration, retention, and storage capacities of the whole basin, which is effective for reducing the impact of urbanization on flood control, water utilization, and river environment [5]. Legal systems or policies were established to mitigate flooding in urban areas, such as the Integrated Urban Flood Prevention Plan for Severe Rainfall, or the Act...
on Countermeasures against Flood Damage of Specified Rivers Running Across Cities in Japan. However, damage by urban flooding has not been reduced owing to the lack of element technology development for mitigating urban flooding and a quantitative rating of these technologies.

A green infrastructure approach to manage storm water was first adopted in New York City [6]. For instance, storm water is infiltrated or impounded by rain gardens [7], green roofs [8], permeable pavement [9], or rain storage tanks [10, 11] to avoid flooding or effluence of untreated sewage into the river. Runoff reduction by these green infrastructure element technologies has been verified and implemented for practical use. In addition, the water retention capacity and infiltration of agricultural land was noticed in the EU [12], and a conservation policy was established to mitigate flooding.

It is obvious that most soils have high infiltration and retention capacities. In the agricultural sector, there are advanced studies on enhancing infiltration and water retention capacities using Shirasu soil and seashells, respectively [13]. However, there are few studies on improving the infiltration capacity of soil for flood mitigation.

In this study, we focused on bamboo charcoal and humus as the materials for improving the water infiltration capacity of soil. We also conducted a constant-head infiltration test and rainfall simulation to evaluate the properties of soil amendments.

2. Methodology

2.1 Concept of Runoff Prevention Using Soil Amendments

This study aims to establish outflow prevention technology by enhancing the infiltration and retention capacities of soil using bamboo charcoal and humus. In this section, we describe the concept of strengthening infiltration capacity by soil amendment and its physical mechanism.

Infiltration is a phenomenon in which water on the ground surface penetrates into the soil. At the beginning of rainfall, effective rain is spent in moistening the ground, and surface runoff does not occur. Surface runoff occurs when the effective rain exceeds subsurface percolation. This subsurface percolation is described by the Horton infiltration equation (Eq. (1)):

\[ f = f_c + (f_0 - f_c) e^{-kt} \]  

where \( f \) is the infiltration amount, \( f_0 \) is the initial infiltration amount, \( f_c \) is the final infiltration ratio, \( t \) is time, and \( k \) is a constant.

Fig. 1 presents a conceptual diagram of soil moisture fluctuation and surface runoff emergence. When rainfall (\( r \)) occurs, rainwater reaches the ground surface, and the amount of soil water (\( \theta \)) increases. In the case of \( r < f_c \), all rainwater infiltrates into the soil, and surface runoff does not occur. In the case of \( f_c < r \), surface runoff occurs at the time when rainfall (\( r \)) exceeds the infiltration amount (\( f \)) and the amount of soil water reaches \( \theta_0 \). From this point forward, surface runoff occurs, which is indicated by the colored area.
It is essential to strengthen the infiltration capacity of the soil in order to achieve urban flood mitigation. The following two methods are considered to reduce the runoff amount:

1. Delay the time to reach critical saturation and the occurrence of saturation ($t_p \rightarrow t'_p$);
2. Enhance the final infiltration ratio ($f_c \rightarrow f'_c$).

2.2 Experimental Setup for the Constant-Head Infiltration Test

We measured the infiltration characteristics of amended soil by measuring the soil water content using a profile probe. We implanted a cylinder, which was filled with amended soil, into the soil and supplied water to the cylinder. Cylinder intake rate tests were used as a reference for constructing the experimental setup [14].

Fig. 2 shows the configuration of the experimental system. A cylinder (PVC pipe VU, inside diameter: 20 cm, length: 60 cm) was vertically introduced into the soil to a depth of 50 cm and filled with amended soil. Waterproofing material (bentonite) was coated onto the outer bottom edge to prevent soil water entering from outside. Amended soil was added at 10-cm intervals and tamped using a ram (weight: 10.5 kg).

We used seven types of soil in this experiment. The mixing ratios of the improved soil by volume ratio were: (1) 100% decomposed granite; (2) 90% decomposed granite and 10% bamboo charcoal; (3) 80% decomposed granite and 20% bamboo charcoal; (4) 70% decomposed granite and 30% bamboo charcoal; (5) 90% decomposed granite and 10% humus; (6) 80% decomposed granite and 20% humus; (7) 70% decomposed granite and 30% humus. The mixed bamboo charcoal was 2-4 mm granular charcoal. Bamboo charcoal and humus were sufficiently mixed with the surface-dried decomposed granite so as to be equitable.
We measured the decrement of water in a Mariotte’s bottle and electric permittivity in the amended soil using a profile probe (Delta-T Devices, PR2/4) at one-minute intervals. The sensors of the profile probe were installed at four depths from the soil surface: 5, 15, 25, and 35 cm. Soil water content was measured on the basis of the ADR (amplitude domain reflectometry) method [15]. We calibrated the relationship between the volumetric water content and electric permittivity for each experimental case because this relationship was different between mixing ratios.

The water supply to the cylinder was stopped when the electric permittivity of the lowest censor (35 cm from the soil surface) became a constant value: at this point, it was considered that the amended soil was saturated. After the soil was saturated, we tracked the drainage process by measuring electric permittivity. The electric permittivity measurements were completed when the value of the lowest sensor became constant.

2.3 Experimental Setup for the Watering Experiment by Rainfall Simulation

In the watering experiment, the method was to apply a coarse water spray from above to imitate actual rainfall. A characteristic of this method is that hydraulic pressure at submerged depths cannot be provided, but a water supply close to the actual precipitation is possible. In an actual rainfall, water droplets with radii greater than 0.1 mm, called raindrops, fall in a state in which the downward force of gravity and upward force of air resistance are balanced. However, a large space and artificial rainfall equipment with a height greater than 20 m are necessary to reproduce the actual rain conditions of a particle diameter, dropping velocity, and rainfall amount. In this study, we established an artificial rainfall device to reproduce only the rainfall amount. Fig. 3 illustrates the configuration of the experimental system. The artificial rainfall device could reproduce rainfall rates from 48 to 200 mm/h using a centrifugal humidifying device (NAKATOMI...
A diffusion filter was installed to spread and up-size the droplets. The acrylic cylindrical tube (inside diameter: 30 cm; length: 70 cm) was filled with amended soil and supplied with water from an atomizer placed above it. We measured the amount of supply water and surface runoff volume. In addition, the volumetric water content was measured using a soil moisture meter (Campbell Ltd., CS616 TDR) at ten-second intervals. The sensors of the soil moisture meter were installed at four depths measured from the soil surface: 5, 15, 25, and 35 cm. We examined seven types of amended soil ((1) 100% decomposed granite; (2) 90% decomposed granite and 10% bamboo charcoal; (3) 80% decomposed granite and 20% bamboo charcoal; (4) 70% decomposed granite and 30% bamboo charcoal; (5) 90% decomposed granite and 10% humus; (6) 80% decomposed granite and 20% humus; and (7) 70% decomposed granite and 30% humus), which were identical to those used in the constant-head infiltration test. The rainfall rate was set in two patterns at 50 and 100 mm/h.

3. Results

3.1 Results of the Constant-Head Infiltration Test

As the result of the constant-head infiltration test, the volumetric water content increased soon after the starting the water supply, became stable at the saturation point, and gradually decreased in all cases. In this section, we describe the time change of the volumetric water content of the amended soil at each depth, using three cases ((1) 100% decomposed granite; (4) 70% decomposed granite and 30% bamboo charcoal; and (7) 70% decomposed granite and 30% humus) as examples.

In the experimental case of (1) 100% decomposed granite (Fig. 4), the maximum volumetric water content was 41.8% at a depth of 15 cm and became constant 230 minutes after starting the water supply. About seven hours after the water supply stopped, no significant change in volumetric water content was observed. Subsequently, the volumetric water content declined drastically and became stable 20 hours after stopping the water supply. The volumetric water content at each depth was reduced to 21.8% (5 cm), 30.4% (15 cm), 28.9% (25 cm), and 27.2% (35 cm) 49 hours after stopping the water supply.

In the experimental case of (4) 70% decomposed granite and 30% bamboo charcoal (Fig. 5), the maximum volumetric water content was 45.3% at a depth of 5 cm. We determined that the amended soil was saturated 210 minutes after starting the water supply because the volumetric water content at the deepest point became constant. The volumetric water content at a depth of 5 cm began to decrease one hour after stopping the water supply and became stable at 40%. Subsequently, it declined rapidly and then gradually decreased. Similar behavior in the time change of volumetric water content was also observed at other depths. The volumetric water content at each depth was reduced to 26.4% (5 cm), 38.2% (15 cm), 38.2% (25 cm), and 37.0% (35 cm) 73 hours after stopping the water supply.

In the experimental case of (7) 70% decomposed granite and 30% humus (Fig. 6), the maximum volumetric water content was 40.0% at a depth of 5 cm. We determined that the amended soil was saturated 200 minutes after starting the water supply because the volumetric water content at the deepest point became constant. The volumetric water content at a depth of 5 cm began to decrease rapidly seven hours after stopping the water supply and returned to a moderate decrease 17 hours after stopping the water supply. Similar behavior in the time change of volumetric water content was also observed at depths of 15 and 25 cm. The volumetric water content at the deepest point (35 cm) increased after stopping the water supply. After the volumetric water content increased to 41%, it began decreasing 17 hours after stopping the water supply. The volumetric water content at each depth was reduced to 22.6% (5 cm), 30.2% (15 cm), 32.2% (25 cm), and 31.8 % (35 cm) 105 hours after stopping the water supply.
Fig. 7 shows the relationship between infiltration capacity and elapsed time in each of the experimental cases. The infiltration capacity (mm/h) was calculated from the decrement of water in the Mariotte’s bottle using the Horton infiltration equation (Eq. (1)). We defined the first measured infiltration ratio as the initial infiltration amount ($f_0$) and the last measured infiltration ratio, at the end of water supply, as the final infiltration ratio ($f_c$). The damping constant ($k$) was calculated by the least-square method as the actual measured value. The initial infiltration amount ($f_0$) for 100% decomposed granite was the lowest, and the infiltration capacity increased with increasing mixing ratios of bamboo charcoal and humus.

### 3.2 Results of the Watering Experiment

As an overall trend, we identified the increasing volumetric water content as time proceeded in common...
with the constant-head infiltration test. In this section, we describe the time change of the volumetric water content in amended soil at each depth, using three cases at 50 mm/h as examples: (1) 100% decomposed granite; (4) 70% decomposed granite and 30% bamboo charcoal; (7) 70% decomposed granite and 30% humus.

In the case of 100% decomposed granite (Fig. 8), the maximum volumetric water content was 0.29 at a depth of 5 cm, and the experiment time was 150 minutes.
Both curves were S-shaped, and the volumetric water content values were comparable except for the depth of 35 cm. In the case of decomposed 70% granite and 30% bamboo charcoal (Fig. 9), the maximum volumetric water content was 0.34 at a depth of 35 cm, and the experiment time was 150 minutes. The behavior of volumetric water content gradually settled down to a stable declining value after rising was observed at depths of 5, 15, and 25 cm. In the case of 70% decomposed granite and 30% humus (Fig. 10), the maximum volumetric water content was 0.36 at a depth of 5 cm, and the experiment time was 149 minutes. The volumetric water content settled down to a stable value except for the depth of 5 cm.

We calculated the infiltration amounts as the difference between the watering amount and surface runoff. The amount of infiltration and runoff for each of the experimental cases are indicated in Fig. 11 (50 mm/h) and Fig. 12 (100 mm/h), respectively. In the 50 mm/h case, surface runoff occurred earliest in the 100% decomposed granite, approximately 20 minutes after the start of the experiment. As for the bamboo charcoal amendment soil, surface runoff occurred earliest in the 30% mixing ratio, approximately 60 minutes after the start of the experiment. In contrast, surface runoff did not occur in the cases of (6) 80% decomposed granite and 20% humus and (7) 70% decomposed granite and 30%
humus. In the 100 mm/h case, surface runoff occurred in all of the amended soils. It occurred earliest in the (2) 90% decomposed granite and 10% bamboo charcoal at about 10 minutes after the start of the experiment. The occurrence of surface runoff was delayed in the cases of: (4) 70% decomposed granite and 30% bamboo charcoal; (6) 80% decomposed granite and 20% humus; and (7) 70% decomposed granite and 30% humus.

4. Discussion

4.1 Influence of Void Structures between Bamboo Charcoal and Humus on Infiltration and Water Retention Capacity

Table 1 indicates the initial infiltration capacity and final infiltration ratio obtained from the constant-head infiltration test. Initial infiltration capacity is defined as the infiltration amount per unit of area from the
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Fig. 12  Amount of runoff and infiltration (100 mm/h).

Table 1  Infiltration capacity obtained from constant head experiment.

<table>
<thead>
<tr>
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<th>decomposed granite soil</th>
<th>bamboo charcoal mixing soil</th>
<th>humus mixing soil</th>
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<tbody>
<tr>
<td></td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
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<tr>
<td></td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
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<tr>
<td>initial infiltration capacity (mm)</td>
<td>106.1</td>
<td>228.7</td>
<td>182.8</td>
</tr>
<tr>
<td>final infiltration rate (mm/hr)</td>
<td>8.5</td>
<td>9.8</td>
<td>12.5</td>
</tr>
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solid line: runoff amount
dash line: infiltration amount

start of the experiment to the inflection point of the penetration curve. We defined final infiltration ratio as the infiltration capacity per unit area and the time at the end of water supply. The initial infiltration ratio was 1.7 times larger when mixing 20% bamboo charcoal, 2.9 times when mixing 30% bamboo charcoal, 1.8 times when mixing 20% humus, and 2.3 times when mixing 30% humus, than it was for 100% decomposed granite. Initial infiltration capacity increases with increasing mixing ratios of bamboo charcoal and humus. The final infiltration ratio was 1.5 times larger when mixing 20% bamboo charcoal, 2.3 times when mixing 30% bamboo charcoal, 2.4 times when mixing 20% humus, and 4.3 times when mixing 30% humus than it was for 100% decomposed granite. Focusing on the increasing characteristics of infiltration capacity of bamboo charcoal and humus, the initial infiltration capacity of bamboo charcoal is greater than that of humus, whereas the final infiltration ratio of humus is greater than that of bamboo charcoal. We consider the cause of these differences as follows: In the case of bamboo charcoal, the initial infiltration capacity increases due to large gaps in the surrounding soil. However, the degree of increase of the final infiltration ratio is smaller than that of humus mixing soil because the large gaps are filled by fine soil particles carried with the water from above (Fig. 13). In contrast, in the case of humus, fine soil grains are attached to the aggregate structure of the humus. Its infiltration capacity is increased by a void structure included in the aggregate structure (Fig. 14). This void structure is smaller than that generated by bamboo charcoal. Therefore, the initial infiltration capacity of humus mixing soil is smaller than that of bamboo charcoal.
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**Fig. 13** Pattern diagram of void structure of bamboo charcoal mixing soil.

**Fig. 14** Pattern diagram of void structure of humus mixing soil.

**Fig. 15** Initial infiltration capacity of each case.
mixing soil. However, in the humus mixing soil, washing out of fine soil particles is prevented by the aggregate structure, and the final infiltration ratio is greater than that of bamboo charcoal mixing soil. To determine the ideal void structure for improving infiltration capacity and water retention capacity, further verification is required.

4.2 Comparison of Experiment Results of Constant-Head Infiltration Test and Watering Experiment by Rainfall Simulation

Fig. 15 shows the initial infiltration capacity obtained from the constant-head infiltration test and watering experiment. The initial infiltration capacity in the constant-head infiltration test is greater than that obtained via the watering experiment in all experimental cases. Fig. 16 shows the conceptual diagram of initial infiltration capacity obtained from the constant-head infiltration test and watering experiment. In the constant-head infiltration test, water submergence occurs, and water infiltration is promoted by the pressure of the filling water. Therefore, the initial infiltration capacity of the constant-head infiltration test is likely to be overestimated. In contrast, in the watering experiment, the initial infiltration capacity is considered to be greater when accompanied by an increasing rainfall rate. Therefore, to reveal an extremely accurate value of initial infiltration capacity, the experiment should be done with a precisely set rainfall rate. However, the rainfall rate in Japan is up to approximately 100 mm/h in reality; therefore, it does not make sense to assume a high degree of rainfall to examine flood prevention. Therefore, we decided that an initial infiltration capacity of 100 mm/h for the watering experiment would be an appropriate value.

Fig. 17 shows the comparison of final infiltration ratio in the constant-head infiltration test and watering experiment. The final infiltration ratio in the constant-head infiltration test is smaller because the boundary of amendment soil is in contact with the ground line, and it is difficult for air in the amendment soil to escape. Therefore, the boundary surface condition influences the final infiltration ratio, and there is a need to consider the boundary surface at locations where soil improvements are being conducted.

![Fig. 16 Conceptual diagram of initial infiltration.](image-url)
5. Conclusions

This study aimed to reveal the infiltration characteristics of amendment soil comprising bamboo charcoal and humus by means of a constant-head infiltration test and watering experiment for flood prevention technology. The acquired knowledge from the results is summarized as follows:

1. From the results of the constant-head infiltration test and watering experiment, it is revealed that the initial infiltration capacity and final infiltration ratio became larger along with an increase in the mixing ratio of bamboo charcoal or humus.

2. The infiltration characteristics of amendment soil using bamboo charcoal or humus are dependent on its void structure. Bamboo charcoal improved the initial infiltration capacity, whereas humus was better at improving the final infiltration ratio.

3. Our experimental results suggest that an amendment soil using bamboo charcoal or humus is an effective element technology for comprehensive integrated watershed management.

References


