Int. J. of GEOMATE , Oct. 2011, Vol. 1, No.1 (Sl. No. 1), pp. 50-55
Geotec., Const. Mat. and Env., ISSN:2186-2982(P), 2186-2990(O), Japan

Alternative Employment of Crushed Shell Particles in Capillary Barrier of Soil

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ABSTRACT: Capillary barrier is a tilting soil layer system which is composed of a finer soil layer underlain by a coarser soil layer. Water which infiltrates into the soil is suspended just above an interface between the soil layers and diverted downward along the interface, with the result that a vertical movement of water into deeper soil layers below the interface stops within some length along the interface. As the water diversion in the capillary barrier is caused by a sharp contrast in water retention capacity between the finer and coarser soils, any material which can provide the sharp contrast in water retention capacity can be alternatively employed in the capillary barrier system. In the study a coarse-grained material of crushed shell particles is selected as an alternative candidate for the lower layer soil of the capillary barrier, and its water retention capacity is measured to examine a practical effectiveness of the crushed shell particles in the capillary barrier system.

Keywords: Capillary barrier, Water retention capacity, Crushed shell particles, Fishery byproduct waste

1. INTRODUCTION

Capillary barrier is a tilting soil layer system which is composed of a finer soil layer underlain by a coarser soil layer. Water which infiltrates into the soil is suspended just above an interface between the soil layers and diverted downward along the interface, with the result that a vertical movement of water into deeper soil layers below the interface stops within some length along the interface [1]-[5]. Because of this excellent diversion of infiltration water, the capillary barrier of soil has been successfully employed in a top cover of waste landfill. The capillary barrier of soil has been also adopted as effective measures for slope protection of natural soil or earth embankment [4]- [6]. As the water diversion in the capillary barrier is caused by a sharp contrast in water retention capacity between the finer and coarser soils, any material which can provide the sharp contrast can be alternatively employed in the capillary barrier system.

In the study, a coarse-grained material of crushed shell particles is selected as an alternative candidate for the lower layer soil of the capillary barrier, and its water retention capacity is measured to investigate a practical effectiveness of the crushed shell particle. There are two reasons for selecting the crushed shell particles: the coarse-grained material of crushed shell particles is environmentally friendly one such as gravel which has been employed in the capillary barrier of soil; a better employment of shell will offer some possible solution to a recycling of fishery byproduct waste.

Firstly geotechnical features of the capillary barrier of soil are briefly introduced, and some study conducted to determine the length of water diversion of the capillary barrier of soil is summarized in the paper. Then the crushed shell particles are sieved into three groups, 9.5-4.75 mm, 4.75-2.0 mm and ones smaller than 2.0 mm in particle diameter, and their soil-water characteristic curves (SWCC) are measured by a pressure membrane method using a SWCC apparatus. An effect of mass densification of the crushed shell particles caused by effective confining pressure on the SWCC is also investigated. In constructing the capillary barrier system, an inclusion of the finer soil particles in the upper layer into the coarser soil in the lower layer should be avoided in order to keep the sharp contrast in water retention capacity between the finer and coarser soils. To find a solution to this problem in constructing the capillary barrier system, lastly, a degree of the inclusion of sand particles into the crushed shell particles is investigated by tapping a soil column in the laboratory.

2. WATER DIVERGENCE BY CAPILLARY BARRIER

2.1 Soil Water Movement in Capillary Barrier System

In the capillary barrier system, water which infiltrates into the soil is suspended just above the interface between the soil layers due to a physical difference in the water retention characteristics of the finer and coarser soils. When the interface between soils has an inclination as shown schematically in Fig. 1, the suspended water flows downward along the interface. This water flow downward along the interface between soil layers gradually accumulates its mass of flow due to continuous infiltration from the soil surface, and, at some length along the interface, water percolates vertically into the coarser soil layer. A horizontal distance from the beginning of water flow to this percolation or breakthrough into the coarser soil layer is called a divergence

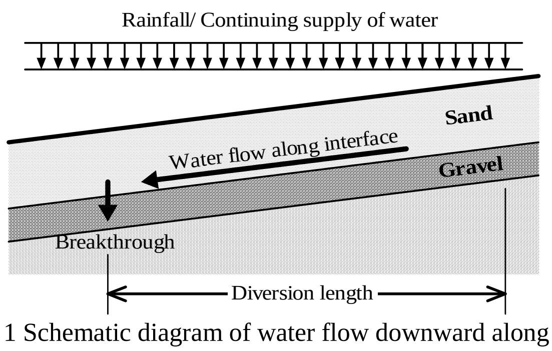


Fig. 1 Schematic diagram of water flow downward along an interface between soil layers in capillary barrier system.

length, and is one of important design parameters to determine a structural configuration of capillary barrier and to select a suitable combination of the finer and coarser soils [1], [2]. In this chapter the divergence length of capillary barrier is investigated based on a field measurement of soil moisture in slope soil [6] and a series of laboratory soil box test.

2.2 Field Experiment to Determine Water Divergence

The capillary barrier of soil was constructed in the natural sand slope as shown in Fig. 2, and volumetric moisture content in the soil layers was measured together with rainfall intensity for about four months. Dry densities of the sand layer and the gravel layer were 1.38 and 1.67 Mg/m^3, respectively. A completely-permeable polypropylene net was placed over the compacted gravel layer so that the sand particles did not fall into the gravel layer or clog void formed in the gravel layer. Inclination of the interface between the sand and gravel layers was 19.7 degrees in average. Fig. 3 shows grain size distribution curves of sand and gravel. The sand is classified into "Sand" with less-5 % fine and coarse fractions; the gravel, commercially available, is siliceous and its mean particle size is 5 to 6 mm. Relationships of negative pore pressure h with the volumetric moisture content of the sand and gravel were measured by a laboratory soil column test, and are plotted in Fig. 4. The SWCC's in Fig.4 are determined using van Genuchten equation [8]. It is found in Fig. 4 that an air-entry pressure head of the sand determined from a drainage curve, h_a, is about 16 cm, and a water-entry pressure head of gravel, h_w, about 1 cm.

The volumetric moisture contents measured in the sand and gravel layers are given in Fig. 5. The upper, central and lower

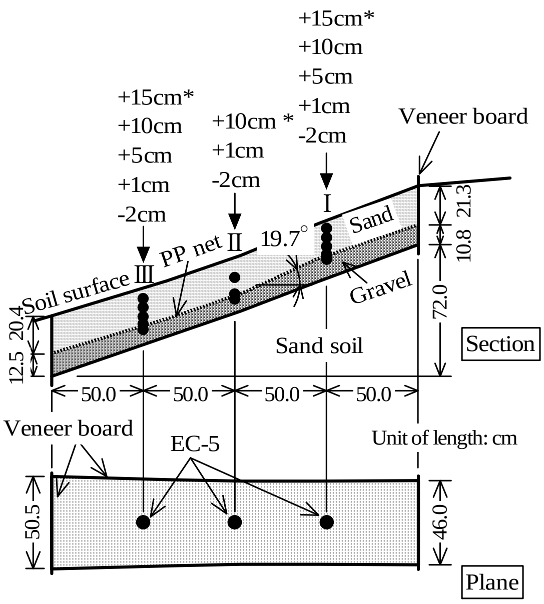


Fig. 2 Configuration of capillary barrier soil constructed in the natural sand slope. Numerals show vertical distances (cm) of the moisture sensor, EC-5, embedded below (-)/ above (+) the interface between sand and gravel.

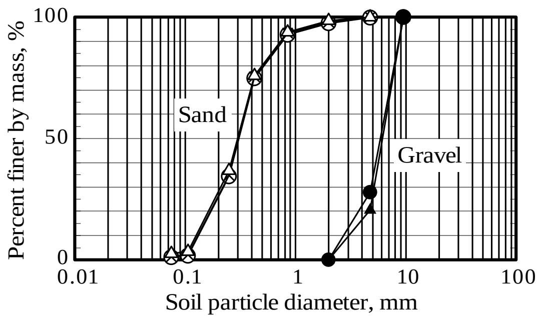


Fig. 3 Grain size distributions of sand and gravel employed in the capillary barrier soil slope.

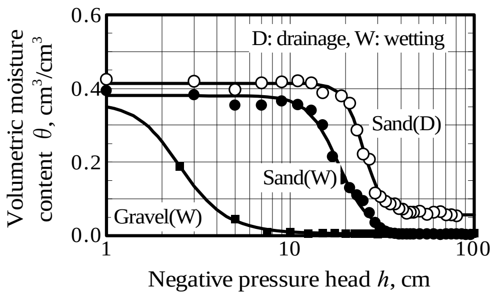


Fig. 4 Soil-water characteristic curves of sand and gravel measured by laboratory soil column tests and estimated by using the van Genuchten equation.

figures in Fig. 5 show the measurement at the position Ⅰ, Ⅱ and Ⅲ in the slope shown in Fig. 2, respectively. The precipitation is given by an inverse bar with the right vertical axis of each figure. It's found in Fig. 5 that the volumetric moisture content measured in the sand layer increases rapidly after rainfall and then decreases slowly, in a successive way from shallow to deep depth in the soil. But in the gravel layer, as opposed to the sand layer, there can be seen only very small or negligible change after rainfall event. It may be understood that this is exactly due to the water diversion by the capillary barrier for long time duration.

2.3 Estimation of Length of Water Divergence

Comparing the upper figure with the central and lower ones in Fig. 5, there can be notified some difference in the soil moisture changes measured in the gravel layer (denoted by "-2" in Fig. 5 which indicates the depth of the moisture sensor embedded as shown in Fig. 2). That is, although the low moisture content of soil is maintained in the upper position of the slope during four-month measurement, the soil moisture contents measured at the central and lower positions of the slope increase with a small amount immediately after rainfall. It may be thought that this difference in the soil moisture changes indicates the percolation or breakthrough of the water flow along the interface into the gravel layers. Based on this observation and taking account of the location of measurement points shown in Fig. 2, the divergence length of the capillary barrier is estimated to be around 100 cm.

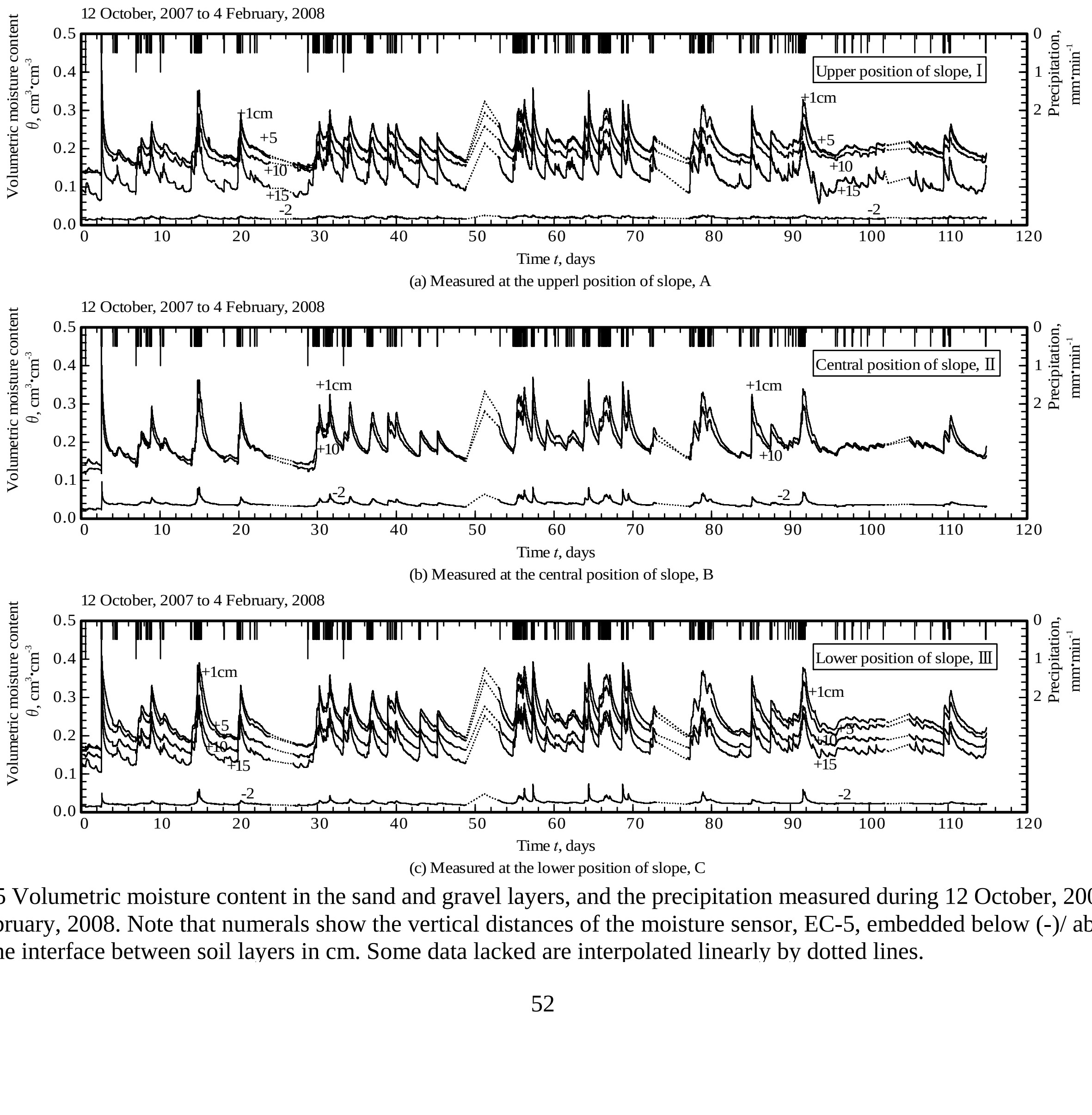
Some equations have been proposed to estimate the divergence length of capillary barrier by several researchers such as Ross [1], Kung [9], and Steenhuis, Parlange and Kung [7]. Among these, the equation by Steenhuis, Parlange and Kung is effectively adaptable [2], [3]. In the case where an infiltration rate, q, is much smaller than a saturated hydraulic conductivity of sand (the upper finer soil), K_s, the equation of the divergence length, L, is given by

$$L \leq \frac{K_s}{q} \tan\varphi\left[\alpha^{-1} + \left(h_a - h_w\right)\right] \qquad (1)$$

where φ is the slope angle of the interface, h_a and h_w are the air-entry pressure head of sand and the water-entry pressure head of gravel, respectively, as explained in 2.2. α is an exponential constant describing a relationship between h and an unsaturated hydraulic conductivity, K, of sand near saturation.

Estimating K from the SWCC of sand in Fig. 4 by the van Genuchten equation and plotting K with h, α near saturation can be estimated to be 0.084 cm^{-1} [6]. Introducing K_s=8.2×10^{-3} cm/s which was determined by a laboratory permeability test, φ=19.7 degrees given in Fig. 2, h_a=16 cm and h_w=1 cm determined in Fig. 4 into (1) and assuming that q is approximately equal to an average value of precipitation, 0.5 mm/min, then about 99 cm is calculated as a value of L. This L corresponds fairly well to the observation, 100 cm, as explained in the preceding paragraph. Fig. 6 shows this good comparison of the diversion length observed in the field with one estimated by (1) by using a double circle.

In order to observe directly the breakthrough of water flow along the interface and to measure the diversion length, a series of the laboratory soil box test was carried out. The soil box with an acrylic front panel 100 cm in length, 50 cm in height and 5 cm in depth was placed on a horizontal floor, and gravel was compacted into the layer of 10 cm thickness, then the sand into 10 cm thickness above the gravel layer in the soil box. The same polypropylene net that was used in Fig. 2 was placed over the compacted gravel layer. After a gauze sheet was spread over the soil surface to protect soil erosion by rainfall droplet, one side of the soil box was lifted so that the interface between the sand and gravel layers had the inclination, then rainfall was supplied onto the soil surface. Rainfall was simulated by emitting needles attached to the base plate of water reservoir with constant head of water. The emitting needles were placed so that the rainfall droplet did not fall along the front panel. Intensity of rainfall was



(a) Measured at the upperl position of slope, A

(b) Measured at the central position of slope, B

(c) Measured at the lower position of slope, C

Fig. 5 Volumetric moisture content in the sand and gravel layers, and the precipitation measured during 12 October, 2007 to 4 February, 2008. Note that numerals show the vertical distances of the moisture sensor, EC-5, embedded below (-)/ above (+) the interface between soil layers in cm. Some data lacked are interpolated linearly by dotted lines.

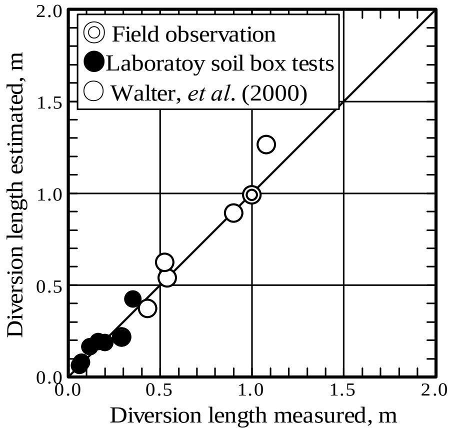


Fig. 6 Comparison of the diversion length measure in the field and the laboratory with one estimated by Steenhuis, Parlange and Kung [7].

regulated by adjusting the head of water in the water reservoir.

The divergence lengths which were observed under different condition of the inclination and the rainfall intensity are compared with ones estimated by (1) in Fig. 6 by using painted circles. Laboratory results published by Walter, et al. [2] are also plotted by single circles. It may be found in Fig. 6 that (1) can be well employed to estimate the diversion length of capillary barrier. Because it is known that the diversion length reaches theoretically as long as 5 to 50 m under a proper combination of soil particle size [1], a continuing investigation in the range of larger diversion length will be required.

3 ALTERNATIVE EMPLOYMENT OF CRUSHED SHELL PARTICLES

3.1 Water Retention Characteristics of Crushed Shell Particles

As the water diversion in the capillary barrier is caused by sharp contrast in water retention capacity between the finer and coarser soils, any material which can provide the sharp contrast in water retention capacity may be alternatively employed in the capillary barrier system. In this chapter, a coarse-grained material of the crushed shell particles is selected as an alternative candidate for the lower layer soil of the capillary barrier, and its water retention capacity is measured to examine a practical effectiveness of the crushed shell particles in the capillary barrier system.

Being washed and oven-dried, the shells of clams, *Meretrix lusoria* and *Ruditapes philippinarum*, were crushed and sieved into three groups, that is A: 9.5-4.75 mm, B: 4.75-2.0 mm and C: ones smaller than 2.0 mm in particle diameter, as shown in Fig. 7. The SWCC's of three groups of the crushed shell particles were measured by the pressure membrane method using a thin porous membrane [10] in the SWCC apparatus. The crushed shell particles were compacted into a steel mold and saturated with de-aired water. Then a specimen of the crushed shell particles compacted in the steel mold was loaded with matric suction from 0 to 200 cmH_2O step by step. After this drying process, the matric suction was inversely decreased to 0 cmH_2O to wet the specimen along a wetting process. During the drying and wetting processes, water mass drained from and absorbed into the specimen, respectively, was successively measured by using a burette of the SWCC apparatus. The SWCC's of the crushed shell particles A, B and C are given in Fig. 8. Dry densities of the specimen of crushed shell particles A, B and C were 1.00, 1.19 and 1.27 Mg/m^3, respectively. It's found in Fig. 8 that the water-entry pressure head of the crushed shell particles determined from the wetting curve is well similar to that of

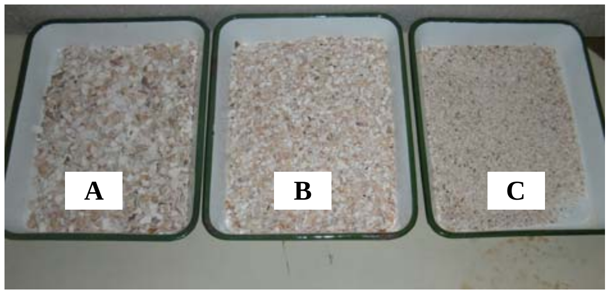


Fig. 7 Crushed shell particles sieved into A: 9.5-4.75 mm, B: 4.75-2.0 mm and C: ones smaller than 2.0 mm in particle diameter.

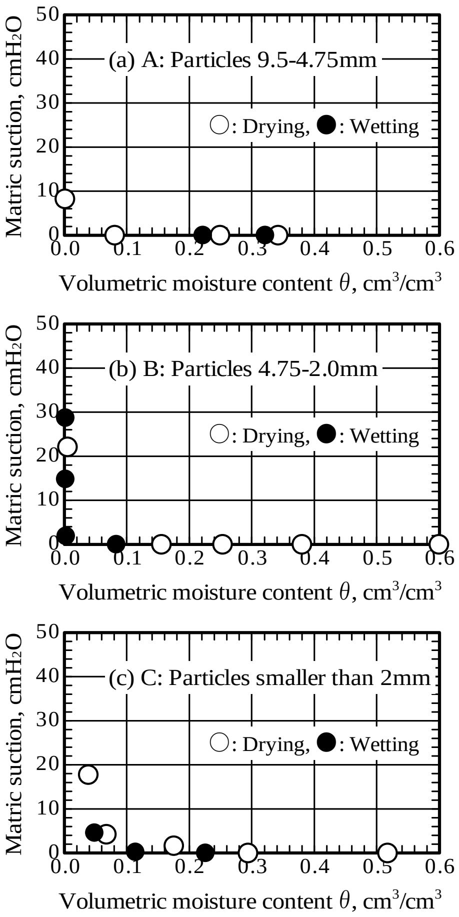


Fig. 8 Water retention characteristics of the crushed shell particles measured by the pressure membrane method.

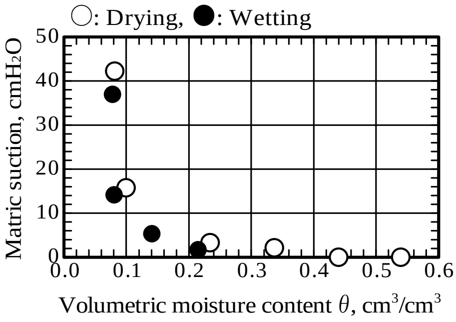


Fig. 9 Water retention characteristics of the crushed shell particles smaller than 2 mm in particle diameter under the confining pressure of 50 kPa. Dry density of the specimen was 1.37 Mg/m^3.

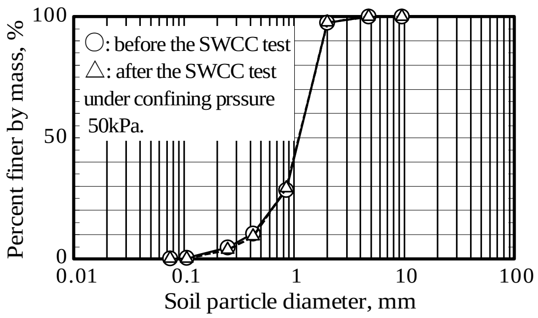


Fig. 10 Grain size distributions of the crushed shell particles smaller than 2 mm in particle diameter, the group C, measured before and after the SWCC test under the confining pressure of 50 kPa.

gravel in Fig. 4 even in the group C, the crushed shell particles smaller than 2 mm in particle diameter. As shown in (1), the smaller the water-entry pressure head is, the larger the divergence length becomes. This leads to a practical adopted evaluation that the crushed shell particles can be preferably as the alternative of gravel usually employed in the capillary barrier system.

Because the coarser material is overlain by the finer material in the capillary barrier system, a possible increase of dry density of the coarser layer may cause a change of its water retention characteristics. Fig. 9 shows the SWCC of the crushed shell particles C measured under the confining pressure of 50 kPa which corresponds to about 3 to 4 m thickness of the upper sand layer. There can be seen, in Fig. 9, some small increase of the water-entry pressure head. As there is not any change in the grain size distribution of the crushed shell particle before and after the measurement of the SWCC as shown in Fig. 10, it may be thought that the small increases in the water-entry pressure head of the crushed shell particles under the confining pressure were caused by mass densification of the specimens. However a small value of the water-entry pressure head observed in Fig. 9 will recommend a practical adoption of the crushed shell particles as the alternative of gravel usually used in the capillary barrier system.

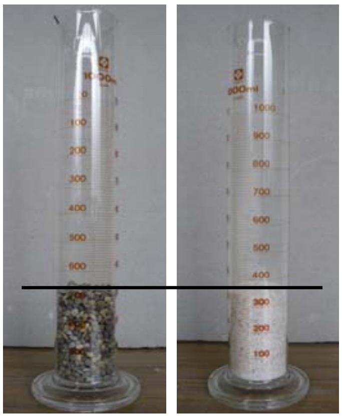
3.2 Sand Particle Inclusion into Crushed Shell Particles

In constructing the capillary barrier system, inclusion of the finer soil particles in the upper layer into the lower coarser soil layer should be avoided to keep the sharp contrast in water retention characteristic between both the layer soils. Although a chemical sheet was employed for a technical convenience in the field experiment described in the preceding chapter, its use should be avoided in constructing the capillary barrier system from an environmentally-conscious point of view as well as a long-term durability. To investigate the effectiveness of the crushed shell particles as the effective alternatives of gravel, the degree of inclusion of sand particles into the crushed shell particles were measured by a tapping soil column test in the laboratory. Two combinations of gravel overlain by the sand and the crushed shell particles overlain by the sand were tested. The grain size distributions of the sand and gravel are given in Fig. 3. The group C of the crushed shell particles was selected in the test because of the preferable reason mentioned in 3.1.

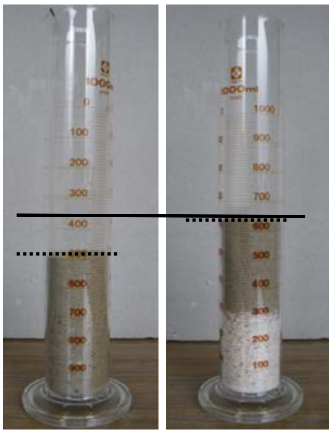
Firstly gravel and the crushed shell particles were poured and lightly compacted into two 1,000cc-graduated glass cylinders 35cm in height and 6.8cm in inner diameter to form the same height of cylindrical volume as shown in Fig. 11(a). Then the sand was poured above the cylindrical volumes of gravel and the crushed shell particles in the graduated glass cylinders so that both the heights of the cylindrical volume reach the same. After being placed on a horizontal desk, the graduated glass cylinder was tapped around its base plate cyclically, continuously and lightly by a wood hammer with an horizontal amplitude of 5 cm. Fig. 11(b) shows the cylindrical volumes in the graduated glass cylinders after the cyclic tap 100 times. A higher line given in Fig. 11(b) shows the initial height of the cylindrical volume measured in Fig. 11(a) before the cyclic tap. In the case of gravel overlain by the sand, the left-hand side in Fig. 11(b), a large amount of the sand particles fell down into the lower volume of gravel, and the initial height of the cylindrical volume lowered to a position denoted by a dotted line. Contrary to this, the cylindrical volume of the crushed shell particles overlain by the sand, the right-hand side in Fig. 11(b), keeps its initial height almost the same after the cyclic tap 100 times, and the interface between the sand and the crushed shell particles was clearly observed. Both of these observations suggest less inclusion of the sand particles into the crushed shell particles than gravel. Although the grain size of the crushed shell particles C is smaller than gravel as shown in Fig. 3 and Fig. 10, the water-entry pressure head of the crushed shell particles is very small similar to gravel as shown in Fig. 8 and Fig. 9 and, furthermore, small inclusion of the finer soil particles from the upper layer in constructing the capillary barrier system will be well expected as observed above.

4 CONCLUSIONS

Geotechnical features of the capillary barrier of soil were briefly introduced, and the study conducted to determine the length of water diversion of the capillary barrier was summarized. Soil moisture changes in the gravel layer were well compared those in the sand layer to confirm a practically excellent divergence of infiltration water along the tilting interface between the sand and gravel layers. The divergence length of the water flow along the interface was estimated using the soil properties determined by the laboratory tests and the structural configuration of the capillary barrier of soil. Fairly good correspondence of the divergence length between the observation and the estimation proved a practical effectiveness of the equation proposed by Steenhuis, Parlange and Kung [7].



(a) Gravel (left) and the crushed shell particles (right) poured and lightly compacted in the glass cylinder. A solid line shows the height of both the cylindrical volumes.



(b) Cylindrical volumes in the glass cylinders after the cyclic tap 100 times. The left-hand side is gravel overlain by sand, and the right-hand side the crushed shell particles overlain by sand. A solid line shows an initial height, and dotted lines show the height after the cyclic tap.

Fig. 11 Inclusion of the sand particles in the upper layer into gravel and the crushed shell particles in the lower layer observed in the tapping soil column test.

Because the coarse-grained material of the crushed shell particles is an environmentally-conscious one and a better employment of shells will offer some possible solution to the recycling of fishery byproduct waste, the effectiveness of the crushed shell particles as the alternative of gravel was investigated by a series of the pressure membrane test and the tapping soil column test in the laboratory. It was found that the water-entry pressure head of the crushed shell particles smaller than 2.0 mm in particle diameter was extremely small even under the confining pressure. It's also found in a series of the tapping soil column test that the inclusion of the sand particles in the upper layer into the lower coarser layer could be well eliminated by using the crushed shell particles. As the inclusion of the sand particles into the lower coarse-grained layer is one of important problems to be solved in constructing the capillary barrier system, the result of the tapping soil column test will support attractive employment of the crushed shell particles in the capillary barrier system.

5 ACKNOWLEDGMENT

The present study is supported by the Grant-in-Aids for Scientific Research (B), No. 22380127, and Scientific Research (C), No. 22560507, made by the Ministry of Education, Science, Sports and Culture of Japan.

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International Journal of GEOMATE , Oct. 2011, Vol. 1, No.1 (Sl. No. 1) MS No. 1g received September 9, 2011, and reviewed under GEOMATE publication policies.

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