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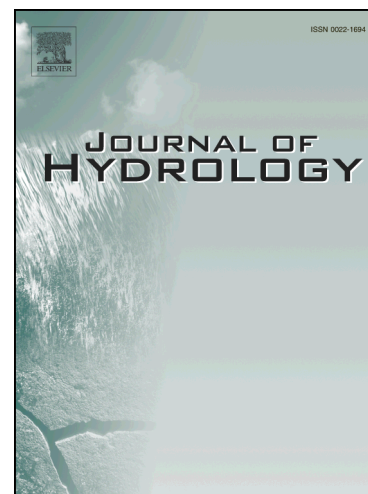
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**A method for estimating maximum static rainfall retention in pebble mulches used for soil moisture conservation**

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## Abstract

Mulching of agricultural fields and gardens with pebbles has long been practiced to conserve soil moisture in some semi-arid regions with low precipitation. Rainfall interception by the pebble mulch itself is an important part of the computation of the water balance for the pebble mulched fields and gardens. The mean equivalent diameter (MED) was used to characterize the pebble size. The maximum static rainfall retention in pebble mulch is based on the water penetrating into the pores of pebbles, the water adhering to the outside surfaces of pebbles and the water held between pebbles of the mulch. Equations describing the water penetrating into the pores of pebbles and the water adhering to the outside surface of pebbles are constructed based on the physical properties of water and the pebble characteristics. The model for the water between pebbles of the mulch is based on the basic equation to calculate the water bridge volume and the basic coordination number model. A method to calculate the maximum static rainfall retention in the pebble mulch is presented. Laboratory rain simulation experiments were performed to test the model with measured data. Paired sample t-tests showed no significant differences between the values calculated with the method and the measured data. The model is ready for testing on field mulches.

**Keywords** Pebble mulch; Rainfall interception; Moisture content; Model

## 1 Introduction

Soil surface mulching with pebbles or similar lithic materials is an agricultural strategy uniquely suited to the constraints of a dryland environment (Jury and Bellantuoni, 1976; Lightfoot and Eddy, 1994). This strategy has been used to conserve soil moisture, reduce soil erosion and increase crop yield in some low rainfall regions in the world (Lightfoot, 1993; Lightfoot, 1994; Lightfoot, 1996). For example, there is evidence that the ancient Hebrews employed gravel mulches in the Sinai Desert thousands of years ago (Corey and Kemper, 1968). Pebble-mulch gardening was employed by the Rio Grande Anasazi of northern New Mexico in the fourteenth and fifteenth centuries A.D. (Lightfoot, 1993). In this method, the sand and stones are used as mulch (known as Shatian in Chinese) to increase crop yields in areas of limited rainfall. This practice is used in the arid region of northwest China and may date back to the period of the Qing Dynasty (over 300 years ago) (Gale et al., 1993; Li, 2003; Li and Liu, 2003; Wang et al., 2003). Previous studies show that pebbles or similar lithic material mulch is a promising method for reducing evaporation and runoff, limiting soil erosion and salinization, increasing soil temperature and infiltration of precipitation and improving crop yields (Adams, 1966; Benoit and Kirkham, 1963; Corey and Kemper, 1968;

Fairbourn, 1973; Hide, 1954; Horton, 1977; Kemper et al., 1994; Li, 2002; Lu and Chen, 1955; Modaihsh et al., 1985; Unger, 1971a; Unger, 1971b; Valentin and Casenave, 1992; Xie et al., 2006; Yamanaka et al., 2004). Interception has received less attention. The rainfall interception, storage and subsequent evaporation from a pebble mulch can be considered as an interception process. A field study of rainfall interception by pebble mulches in the semi-arid loess region of China revealed that rainfall interception by a gravel mulch accounts for 11.5–17.4% of rainfall (Li et al., 2000). A further study indicated that the rainfall interception increased with increased pebble cover percentage and decreased with increased pebble size (Li et al., 2005). There are various factors that affect rainfall interception, such as pebble characteristics (particle size range and different shapes), mulch structure, antecedent pebble water content, rainfall characteristics, wind and temperature. The rainfall retention in a pebble mulch is still poorly understood and should not be ignored. The retention of moisture by the pebble mulch will be evaporated back into the atmosphere and will not be available to the vegetation. The mulch must also act to reduce evaporation from the underlying soil layers because their larger grain size means a reduced capillary rise of water through the mulch and a separation of the soil surface from the atmosphere. Because of the rainfall interception by the pebbles, the pebble mulch may not be useful in some arid areas where rainfall intensity and duration are relatively small. Quantifying the amount of rain intercepted by the pebble mulch can help to better understand the traditional farming technique. The fraction of intercepted and evaporated rainfall is variable in time. A higher fraction is intercepted from small rain events because part of the rain is stored in the mulch (Klaassen et al., 1998). When the pebble mulch is saturated, additional rain water will not be intercepted and will drain to the soils beneath the mulch. The rainfall retention in a pebble mulch when the rain stops is different from that during the rain event. The gross rainfall retention can be divided into static and dynamic parts. The static rainfall retention is defined as the rainwater held in the pebble mulch when the rain stops and does not drain to the soil surface under the pebble mulch. The maximum static rainfall retention in a pebble mulch includes the water penetrating into the pores of pebbles, the water adhering to the outside surface of pebbles and the water held between pebbles of the mulch. The dynamic rainfall retention represents the rain water held in the pebble mulch during the rain event and drained to soil surface under the pebble mulch

after the rain event. The dynamic rainfall retention is difficult to determine in the complex rainfall process. The maximum static rainfall retention in a pebble mulch is important and easy to determine for a rigorous analysis of the effects of pebble mulches on hydrological processes. The first objective in this study is to propose a rational method for estimating maximum static rainfall retention in pebble mulches. Secondly, the measured data obtained from laboratory rainfall simulation experiments are used to illustrate and validate the method and the procedures for the application of the method. This will lead to a more detailed understanding of water balances in pebble mulched fields and provide a theoretical basis for proper management strategies of such fields.

## 2 Materials and methods

### 2.1 Pebbles

Pebble samples were taken from an erosion ditch near Yachuan village, Zhonghe country, Gaolan County, Lanzhou, Gansu Province (36°10'46"N, 103°49'50"E). Fields mulched with pebbles from this erosion ditch, known locally as 'sandy fields', have been used by the farmers of Yachuan village for a long time to ensure a stable crop yield. The pebble samples were transported to the laboratory where they were washed to remove plant roots and soil particles before being air-dried.

The long ( $L$ ), intermediate ( $I$ ), and short ( $S$ ) diameters of the pebbles were measured with a Vernier caliper. It is assumed that pebbles are ellipsoidal shapes with principal axes of length  $L_i$  (mm),  $I_i$  (mm), and  $S_i$  (mm). The volume ( $V_e$ ) of the  $i$ th pebble is

$$V_e = \frac{4}{3} \pi \left( \frac{L_i}{2} \right) \left( \frac{I_i}{2} \right) \left( \frac{S_i}{2} \right) \quad (1)$$

The shape of the  $i$ th pebble also can be approximated as a sphere with diameter  $d_i$ . Its volume ( $V_s$ ) is calculated as:

$$V_s = \frac{4}{3} \pi \left( \frac{d_i}{2} \right)^3 \quad (2)$$

Combining Eqs. (1) and (2) produces:

$$d_i = \sqrt[3]{L_i I_i S_i} \quad (3)$$

The diameter  $d_i$  is the equivalent diameter (ED). The mean equivalent diameter (MED)  $\bar{d}$  of pebbles is:

$$\bar{d} = \frac{1}{n} \sum_{i=1}^n d_i = \frac{1}{n} \sum_{i=1}^n \sqrt[3]{L_i I_i S_i} \quad (4)$$

where  $n$  is the number of the pebbles,  $\bar{d}$  is expressed in mm.

In order to investigate the effects of pebble size on rainfall retention in mulch, pebbles with similar sizes were separated into 5 pebble-size grades (3 mm, 5 mm, 25 mm, 45 mm, and 65 mm). Pebbles were selected from each grade using random sampling in accordance with Chinese standard GB/T14684-2011 (in Chinese) and GB/T 14685-2001 (in Chinese). The 3 mm grade pebbles were too small to be measured conveniently with a Vernier caliper. The MED of 3 mm grade pebbles was determined by a sieving method. The 3 mm grade pebbles are defined as being finer than the 4.75-mm sieve and coarser than the 2.36-mm sieve. The mean equivalent diameter (MED)  $\bar{d}$  can be calculated using Eq. (5) (Peng et al., 2015).

$$\bar{d}_{3\text{ mm}} = \sqrt[3]{(2l_{i-1}^2 l_i^2)/(l_{i-1} + l_i)} \quad (5)$$

where  $l_{i-1}$  and  $l_i$  are the lower and upper limits of one size.

Let  $l_{i-1}$  and  $l_i$  be 2.36 and 4.75 respectively, then we have

$$\bar{d}_{3\text{ mm}} = 3.28$$

Pebbles of 4 grades (5 mm, 25 mm, 45 mm, and 65 mm) had their size characteristics determined with a Vernier caliper. Thereafter, the values of MED  $\bar{d}$  of these grades were

calculated according to Eq. (4) and are shown in Table 1.

## 2.2 Measurement of diameter of water bridge neck between pebbles

Fig. 1 shows the schematic of the experimental setup used in this study. It consists of a Mariotte bottle, 2 sprinklers, PVC container, and Chinese ink collector. The Mariotte bottle is used to control the ink supplied to the sprinklers and to simulate rainfall. This improves the stable supply of ink during the experiment. Once the PVC container was full of Chinese ink, the pebbles were soaked in the ink and the bottom of the PVC container was opened to allow the ink to drain away. Surface tension drew the ink to the places where the pebbles touched or nearly touched. After thoroughly drying the ink, black spots were left on the surfaces of pebbles.

The diameters of water bridge necks between the pebbles are approximately equal to the dried Chinese ink spot sizes on the surfaces of the pebbles.

The major diameter  $x_i$  (mm) and transverse diameter  $y_i$  (mm) of the spot sizes were measured with a Vernier caliper. The dried ink spot sizes can be similarly regarded as the measured diameters of Chinese ink bridge necks, and characterized by the scar-sectional average radius  $R_2'$  (mm).  $R_2'$  is defined as the real radius of the liquid bridge neck between two pebbles.  $R_2'$  is determined by relating to the major diameter ( $x_i$ ), and transverse diameter ( $y_i$ ) of the spot size of the  $i$ th pebble, as follows

$$R_2' = \frac{1}{2n} \sum_{i=1}^n \sqrt{x_i y_i} \quad (6)$$

where  $n$  is the number of pebbles.

## 2.3 Method for estimating maximum static rainfall retention in a pebble mulch

During a rainfall event, rock fragments at the soil surface intercept raindrops which are stored at the rock surface, penetrate the rock fragment (absorption), and evaporate from or flow on the rock fragment (Poesen and Lavee, 1994). Boushi and Davis (1969) found that water retained at contact points between adjacent coarse non-porous surface rock fragments accounts for most of the water storage within aggregates of particles with diameters smaller than about 30 mm. A pebble is a rock fragment worn smooth by the action of water. The pebbles are often smooth and rounded. As seen in Fig. 2, when a water-drop hits the pebble, water will wet the surface of a large pebble and produce numerous small splash droplets. The splash droplets fall on the pebble and the adjacent pebbles. The excess water will trickle downward, concentrate in rivulets and wet some underlying pebbles. Water bridges may be formed between adjacent pebbles. If the incoming rain flux is large enough, the mulch may not be able to intercept it all. Some of the rain will drain through the mulch, reaching and infiltrating the soil surface beneath the mulch. Water in a mulch increases with precipitation until the mulch becomes saturated. After reaching saturation and rain stoppage, the maximum static rainfall retention is defined as the water fraction contained in the mulch after it has been allowed to drain freely (i.e., field capacity of the mulch). The water stored temporarily in a mulch will be retained (1) in water filled pores within each pebble, (2) as a thin water film adhering to the outside surface of each pebble including water in small puddles on the upper side of the pebbles, and (3) in capillary-size openings at contact points between the pebbles. During and just after a rainfall event, the evaporation rate is very small and is assumed to be nil because the relative humidity of the ambient air is large.

### 2.3.1 The water penetrating into the pores of pebbles



Following a rainfall, the water penetrating into the pores of pebbles can be determined by calculating the change in mass of the mulch pebbles due to water penetration into pores of the pebbles, but not including the water adhering to the outside surface of the pebbles in this study. The water penetrating into the pores of pebbles of the mulch also can be measured as the height of an equivalent layer of water covering the pebble mulch,  $W_i$  (mm). The computational model is given as:

$$W_i = \frac{(Q_x \% - Z\%) \cdot \rho'_0 \cdot H}{\rho_w} \quad (7)$$

where  $H$  is the thickness of pebble mulch (mm),  $\rho_w$  is density of water (1000 kg/m<sup>3</sup>),  $\rho'_0$  is bulk density of the pebbles (kg/m<sup>3</sup>),  $Q_x$  is the absorption of the pebbles at a saturated surface dry state (SSD) (%),  $Z$  is the moisture content of the pebbles at the initial condition (%).

### 2.3.2 Water adhering to the outside surface of the mulch pebbles

The pebbles are coated with a thin film of water absorbed and held by their rough surfaces after rainfall. The effective water film thickness adhering to the surfaces of the pebbles can reach 0.009 mm (Wang, 2009).

The water on pebble surfaces per m<sup>2</sup> mulch  $W_s$  (mm) is given as:

$$W_s = \frac{M}{\rho_0 d^3} \cdot (6\bar{d}^2 t + 12\bar{d}t^2 + 8t^3) \times 1000 \quad (8)$$

Where  $M$  is the mass of pebble mulch (kg),  $t$  is the effective film thickness of water adhering to the pebble surfaces (mm),  $\rho_0$  is the apparent density of pebble (kg/m<sup>3</sup>).

The value of  $t$  is very small. When terms with powers of 2 and 3 in Eq. (8) are omitted, Eq. (8) becomes:

$$W_s = \frac{6tM}{\rho_0 d} \times 1000 \quad (9)$$

Letting the value of  $t$  be 0.009 mm, Eq. (9) becomes:

$$W_s = \frac{0.054H\rho_0'}{\rho_0\bar{d}} \quad (10)$$

where  $H$ ,  $\rho_0$ ,  $\rho_0'$  and  $\bar{d}$  are as defined above.

### 2.3.3 Water between the pebbles of the mulch

After a rainfall event, a water bridge is formed between two pebbles in contact with each other. It is assumed that any two pebbles are in contact, and the water contact angle is zero (Fig. 3). The basic equation to calculate the water bridge volume  $V_{\text{bridge}}$  was given by Fisher reported by Lu (1998) and Sargolzaei et al. (2009):

$$V_{\text{bridge}} = 2\pi r^3 (\sec \alpha - 1)^2 [1 - (\pi/2 - \alpha) \tan \alpha] \quad (11)$$

where  $r$  is the radius of the particle, and  $\alpha$  is the filling angle.

Let  $\bar{d}$  be equal to  $2r$ , thus,

$$R_1 = r(\sec \alpha - 1) \quad (12)$$

$$R_2 = r(\tan \alpha - \sec \alpha + 1) \quad (13)$$

$$h = r(1 - \cos \alpha) \quad (14)$$

where  $h$  is the height of the water meniscus of the water bridge.

$$V_{\text{bridge}} = 0.25\pi\bar{d}^3 (\sec \alpha - 1)^2 [1 - (\pi/2 - \alpha) \tan \alpha] \quad (15)$$

If there are  $N$  particles in the pebble mulch with a total mass of  $M$ , then the number of the pebbles  $N$  is

$$N = \frac{6M}{\rho_0\pi\bar{d}^3} \times 10^9 \quad (16)$$

The coordination number is the number of the pebbles surrounding a pebble in the mulch structure. Let  $k$  be the coordination number for a pebble in direct contact with other pebbles,

then the contact point of two adjacent pebbles  $m$  is given by Lu (1998):

$$m = \frac{kN}{2} \quad (17)$$

Following a rainfall, the amount of water bridging between a pair of pebbles per  $\text{m}^2$  mulch  $W_b$  (mm) is

$$W_b = mV_{bridge} \times 10^{-6} = \frac{3(\sec \alpha - 1)^2 kH\rho_0'}{4\rho_0} \left[ 1 - \left( \frac{\pi}{2} - \alpha \right) \tan \alpha \right] \quad (18)$$

The water-air interface of water bridge at equilibrium closely satisfies the Laplace equation (Masuda et al., 2006).

$$\Delta P = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (19)$$

where  $\sigma$  is the surface tension,  $\Delta P$  is the capillary pressure inside the water bridge,  $R_1$  and  $R_2$  are the radii of the curvature of a water bridge as shown in Fig. 3.

If the value of  $\Delta P$  is 0, the amount of water bridging between two pebbles is the largest (Lu, 1998). Eq. (19) will be:

$$|R_1| = |R_2| \quad (20)$$

Using Eq. (12) and Eq. (13), Eq. (20) can be expressed as:

$$|r(\sec \alpha - 1)| = |r(\tan \alpha - \sec \alpha + 1)| \quad (21)$$

The solution to Eq. (21) is

$$\alpha = 53^\circ 8'$$

A newly constructed pebble mulch in a field usually consists of a random loose packing structure of the pebbles. The mulch structure can be described as the repetition of a simple structural unit cell. Assuming the unit cell to be cubic, each pebble in the cell has a coordination number of 6 (Lu, 1998; Muhammed and Lambert, 1997)

Let  $\alpha=53^{\circ}8'$  and  $k=6$ , then Eq. (18) can be written as

$$W_b = \frac{0.3788H\rho_0'}{\rho_0} \quad (22)$$

Let  $\alpha=53^{\circ}8'$ , then Eq. (13) and Eq. (14) can be written as

$$R_2 = 0.3334\bar{d} \quad (23)$$

$$h = 0.6607R_2 \quad (24)$$

The theoretical diameter of a water bridge neck is  $2R_2$ . The values of  $R_2$  of different pebble-size grade samples were calculated using Eq. (23) and shown in Table 2.

The pebbles are not ideal spheres. The outline of intersection between a pebble and an imaginary plate under the presence of the water bridge is an irregular shape. A Chinese ink liquid bridge can also be formed between pebbles. In order to investigate the relationship between the theoretical diameter  $2R_2$  and the measured diameter of a water bridge neck, Chinese ink was used for marking the dotted area on the surface of a pebble left by a liquid bridge. When the ink bridges dried, ink spots were left on the surface of the pebble (Fig. 4).

The real radius of the liquid bridge neck between two pebbles  $R_2'$  was calculated using Eq. (6) and shown in Table 2.

When comparing the values of  $R_2$  and  $R_2'$  (Table 2), the differences increase with  $\bar{d}$ . Thus, the model does not fit the actual condition. Therefore, it is necessary to correct Eq. (22) by applying a correction factor  $\eta$ . Eq. (22) is rewritten as

$$W_b = \frac{0.3788\eta H\rho_0'}{\rho_0} \quad (25)$$

From Eqs. (15), (23) and (24), we have

$$V_{bridge} = v(2hR_2^2) \quad (26)$$

where  $v$  is the shape factor of the water bridge.

$R_2'$  and  $h'$  are the measured values of  $R_2$  and  $h$ , respectively. Similarly we have

$$V'_{bridge} = v'(2h'R_2'^2) \quad (27)$$

where  $v'$  is the shape factor of the water bridge.

The correction factor  $\eta$  is

$$\eta = \frac{v'(2h'R_2'^2)}{v(2hR_2^2)} = \frac{v'h'R_2'^2}{vhR_2^2} \quad (28)$$

Substituting Eq. (24) into Eq. (28) gives

$$\eta = \frac{v'h'R_2'^2}{v(0.6607R_2^3)} \quad (29)$$

$h'$  is given as

$$h' = uR_2' \quad (30)$$

where  $u$  is the shape factor of the water bridge.

$$\eta = \frac{uv'R_2'^3}{0.6607vR_2^3} \quad (31)$$

Suppose that  $uv' \approx 0.6607v$ . Then we have

$$\eta \approx \frac{R_2'^3}{R_2^3} \quad (32)$$

$\eta$  values calculated using Eq. (32) are shown in Table 2.

The regression equation between  $\eta$  and  $\bar{d}$  was established (Fig. 5) as follows:

$$\eta = 0.6141 - 5.6449\ln^{-1}(\bar{d}) + 15.4854\ln^{-2}(\bar{d}) - 9.4674\ln^{-3}(\bar{d}) \quad (33)$$

#### 2.3.4 Estimating maximum static rainfall retention in a pebble mulch

The maximum static rainfall retention in a pebble mulch is given by

$$W_t = W_i + W_s + W_b \quad (34)$$

where  $W_t$  is the maximum static rainfall retention in pebble mulch (mm),  $W_i$  is the absorption (mm) of the pebbles,  $W_s$  is the water (mm) on pebble surfaces, and  $W_b$  is water (mm) between the pebbles.

Substitution of Eqs. (7), (10) and (25) into Eq. (34) gives

$$W_t = \left[ \frac{(Q_x - Z)}{100\rho_w} + \frac{1}{\rho_0} \cdot \left( \frac{0.054}{d} + 0.3788\eta \right) \right] \cdot H\rho_0 \quad (35)$$

## 2.4 Experimental methods to verify the proposed models

### 2.4.1 Apparatus

To determine the maximum static rainfall retention in a pebble mulch, a measurement system was set up. The rainfall simulator system was comprised of eight sprinkler heads, a pump, five miniature electric valves, a control cabinet, a recording rain gauge, a main water-supply pipe, and a computer control system. The raindrops fell from a height of about 10.7 m to reach the surface of the pebble mulch. The raindrops varied from minute droplets to drops of 5 mm diameter and with a uniformity of 85% inside the plot area. The stainless steel test container for the pebbles had an inner diameter of 30 cm and a sidewall height of 15cm. The bottom and sidewall of the test container had densely spaced rows of square holes with 2 mm openings. The water could flow out of the container in two distinct directions (downward and horizontal) to reduce the effects of the container on the free flow of water. The bottom boundary condition for the system was based on the assumption that the pebble mulch allowed the rain water to infiltrate into underlying soil or flow over the surface of soil (the runoff may be generated).

### 2.4.2 Test procedure

Rainfall in the pebble mulched areas of the Loess Plateau of north-west China is in the range of 215 mm to 320 mm annually (Gale et al., 1993). The period of most intense rainfall (accounting for 60–70% of the annual precipitation) is associated with summer monsoons

(McVicar et al., 2007). Most of the rainfall events are rainstorms ( $> 8$  mm/h) (Li, 2000). Therefore, the rainfall intensity used in this study is 10 mm/h.

To determine the duration of simulated rainfall associated with the maximum static rainfall in pebble mulch, the absorption of oven-dried (at  $105\text{ }^{\circ}\text{C}$ ) pebbles was measured using experiments involving five rainfall durations (10 min, 20 min, 30 min, 40 min and 60 min) and five pebble sizes of  $\bar{d}$  (3.38 mm, 5.79 mm, 25.16 mm, 43.67 mm and 64.3 mm). Once the absorption of the pebbles after a rainfall event with one specific rainfall duration was equal to or near the absorption of the pebbles of the mulch immersed in water for  $24\pm 4$  h, the specific rainfall duration could be regarded as a critical value to determine the maximum static rainfall in a pebble mulch. Three replicates of each test were performed. If there does not appear to be a consistent relationship between the absorption and rainfall duration as the size of pebbles increases, the additional rainfall durations (65 min and 70 min) will be adopted.

The absorption of the pebbles after a rainfall event was calculated as follows:

$$A = \frac{m_1 - m_0}{S\rho_w} \times 10 \quad (36)$$

where  $A$  is the absorption of the pebbles after a rainfall event, mm;  $m_0$  is mass of oven-dry pebbles, g;  $m_1$  is mass of saturated-surface-dry pebbles after a rainfall event, g;  $S$  is the area of the container bottom,  $\text{cm}^2$ ;  $\rho_w$  is the density of water,  $\text{g}/\text{cm}^3$ .

When the inter-particle voids of the pebbles were saturated with water, the rainfall retention in a pebble mulch was almost the largest. To determine whether the pebbles after a rainfall were at or near the water-saturated condition, the pebble sample in the container was immersed in water for  $24\pm 4$  h and then removed from the water, excess water was dried from

the surface of the pebbles using a large absorbent cloth until visible films of water were removed, and the wet pebble mass was determined. Subsequently, the oven-dried pebble sample mass was determined. Using the mass values obtained in this test method, the absorption was calculated as follows:

$$A_{sat} = \frac{m_s - m_0}{S\rho_w} \times 10 \quad (37)$$

where  $A_{sat}$  is the absorption of the pebbles of the mulch immersed in water for  $24 \pm 4$  h and with water dried from the pebble surfaces, mm;  $m_0$  is mass of oven-dry pebbles, g;  $m_s$  is mass of saturated-surface-dry pebbles, g;  $S$  is the area of the container bottom,  $\text{cm}^2$ ;  $\rho_w$  is the density of water,  $\text{g}/\text{cm}^3$ .

After the rainfall duration was determined, simulated rainfall was applied, and the interceptions by pebble mulches were measured and calculated as follows:

$$A_i = \frac{m_2 - m_3}{S\rho_w} \times 10 \quad (38)$$

where  $A_i$  is the interception by the pebbles in the container;  $m_2$  is mass of a test sample after a rainfall event;  $m_3$  is mass of a test sample before a rainfall event;  $S$  is the area of the container bottom,  $\text{cm}^2$ ;  $\rho_w$  is the density of water,  $\text{g}/\text{cm}^3$ .

The characteristics of the pebble samples for estimating maximum static rainfall in pebble mulches include moisture content before the rainfall, absorption moisture content in SSD condition, bulk density, apparent density, void content, and mulch thickness.

The moisture content  $Z$  before a rainfall, absorption moisture content  $Q_x$  in SSD condition, bulk density  $\rho'_0$ , apparent density  $\rho_0$  were measured according to Chinese standard GB/T14684-2011 (in Chinese) and GB/T 14685-2001 (in Chinese), respectively, in this study.



The void content  $V_0$  was calculated as follows:

$$V_0 = \left(1 - \frac{\rho'_0}{\rho_0}\right) \times 100 \quad (39)$$

where  $V_0$  is void content, %;  $\rho'_0$  is bulk density,  $\text{kg/m}^3$ ;  $\rho_0$  is apparent density,  $\text{kg/m}^3$ .

Field pebble mulches commonly have thicknesses between 5 and 13 cm (Gale et al., 1993). In this work, the thickness of two layers of the pebbles with the 64.30 mm MED is about 12.86 cm within the range of 5 to 13 cm. In order to be under the same conditions for the comparison, all of the samples in the test container are arranged in two layers of the pebbles with different MED (3.38 mm, 5.79 mm, 25.16 mm, 43.67 mm and 64.3 mm). The thicknesses  $H$  of the mulches composed of two layers of pebbles were not exactly twice the MED of the pebbles, so the actual thicknesses were measured.

#### 2.4 .3 Statistical analysis

A paired samples two-tailed  $t$  test with an alpha level of 0.05 was used for the comparisons of the calculated and measured retention values.

### 3 Results and discussion

#### 3.1 The characteristics of the pebble samples

##### 3.1.1 The moisture content of the pebble samples before the rainfall

The initial moisture content of the samples is not one part of rainfall interception by the pebble mulch and should be determined before the simulated rainfall event. Fig. 6 shows the measured initial moisture content  $Z$  values of the samples of pebbles with different MED  $\bar{d}$  (3.38 mm, 5.79 mm, 25.16 mm, 43.67 mm and 64.3 mm). The regression relationship between the moisture content  $Z$  of the air dried samples and pebble size  $\bar{d}$  is shown in Fig. 6. The larger moisture content values are associated with the smaller pebble sizes.

##### 3.1.2 The absorption moisture content of pebble samples in SSD condition

The absorption moisture content  $Q_x$  of samples in SSD condition was measured for estimating maximum static rainfall retention in pebble mulches and shown in Fig. 6. Fig. 6 shows that the larger the moisture content value of the SSD sample, the smaller the pebble size. In general, the larger the pebble size, the smaller the surface area per unit of mass which has to be covered by water.

### 3.1.3 Bulk density of pebble samples

The bulk density  $\rho'_0$  of pebble samples was measured in order to estimate maximum static rainfall retention in pebble mulches. Values are shown in Fig. 7. The bulk density is the mass of the pebbles that would fill a unit volume (occupied by both pebbles and voids). Fig. 7 shows that the larger the bulk density value of a pebble sample, the smaller the pebble size (range 5.79-64.3 mm). However, the bulk density value of the pebble sample with 3.38 mm MED is also relatively small. It is because this size has particles with irregular shapes and relatively small particle apparent density.

### 3.1.4 Apparent density of pebble samples

The apparent density  $\rho_0$  of pebble samples was measured in order to estimate maximum static rainfall retention in pebble mulches. Values are shown in Fig. 7. The apparent density is the density of the pebble including the internal pores. Fig. 7 shows that the larger the apparent density value, the larger the pebble size. The density value of the pebble sample with particle size 3.38 mm MED is the smallest.

### 3.1.5 Void content of pebble samples

The void content of pebble samples was calculated and shown in Fig. 8. The results show that the void content of pebble samples increase as MED  $\bar{d}$  increases. The mulch composed

of the 3.38 mm MED pebbles has the smallest gaps between pebbles, and the larger pebbles have a tendency to form larger gaps between particles.

### 3.1.6 Thicknesses of pebble mulches

Pebble mulch thicknesses  $H$  were measured for estimating maximum static rainfall retention values in the pebble mulches (see Fig. 9). The regression equation between  $H$  and  $\bar{d}$  were established and shown in Fig. 9. If the value of  $H$  is not convenient to be measured in the field, it can be estimated using the regression equation.

### 3.2 The duration for the water absorption process by the oven-dry pebbles under simulated rainfall condition

The relationships between the absorption of pebble samples with five sizes of  $\bar{d}$  (3.38 mm, 5.79 mm, 25.16 mm, 43.67 mm and 64.3 mm) after a rainfall event and simulated rainfall duration are shown in Fig. 10. For the convenience of determining when the samples are at or near a saturated state during rainfall simulations, the absorptions of pebble samples immersed in water for  $24 \pm 4$  h are also shown in Fig. 10.

Fig. 10 (a) shows that the pebbles with 3.38 mm MED are saturated with water when the simulated rainfall lasts more than 30 min. Fig. 10 (b, c and d) shows that the absorption of the pebbles with 5.79 mm, 25.16 mm and 43.67 mm MED tend to be stable and close to water saturation when the simulated rainfall lasts more than 40min. Fig. 10 (e) shows that the absorption of the pebbles with 64.3 mm MED tends towards a constant value when the simulated rainfall lasts 60 min. The rainfall duration of 60 min was adopted to measure interception per rainfall event for the different pebble sizes.

Fig. 10 shows that the absorption value of the pebbles with 3.38 mm MED is the largest.

Pebbles form gradually as flowing water washes over loose rock particles. By inspecting the appearance of pebble samples, it is found that some of the pebbles with 3.38 mm MED are still loose rock particles. These loose rock particles provide stronger water absorption than that of smooth and rounded pebbles. The 5.79 mm MED pebbles are the most smooth and rounded. The absorption value of the 5.79 mm MED pebbles is the smallest. The surfaces of 64.3 mm MED pebbles are rougher than those of 25.16 mm or 43.67 mm MED pebbles. The rougher the pebble surfaces, the more strongly water is absorbed. Rougher surfaces are more conducive to the adsorption of water. Therefore, the absorption value of the pebbles with 64.3 mm MED is larger than that of the pebbles with 25.16 mm or 43.67 mm MED. The porosity in pebbles varies, and therefore, their capacities for water absorption differ. The absorption values of pebble samples measured in water for  $24\pm 4$  h are generally higher than those measured just after rainfall, because the samples in water can also be affected by water pressure for  $24\pm 4$  h. After a rainfall, some of the rain will drain through the pebble sample, and the influence of water pressure on the sample is small. The absorption values of pebbles with smaller sizes after rainfall are close to those of samples measured in water for  $24\pm 4$  h, because there are smaller voids between pebbles with smaller sizes and larger capillary forces. This leads to a sufficient number of water bridges between the smaller particles.

### **3.3 Model results and the measured interceptions**

Measured interception per rainfall event for the different pebble sizes and the model estimates are shown in Fig. 11. Fig. 11 can also shows model estimates and observations of maximum static rainfall retention. From this visual comparison, it is apparent that the model reproduces the main features of the interception variation following the pebble sizes. The

average mulch interception was 2.01 mm for the pebble size of 5.79 mm MED, followed by 1.33 mm, 1.18 mm and 1.04 mm for the pebble sizes of 25.16 mm, 43.67 mm and 64.3 mm MED, respectively. These results indicate that the mulch storage capacity decreases with increasing pebble size (MED from 5.79 mm to 64.3 mm). The smaller pebble size mulches have smaller gaps between pebbles. The smaller the gaps between mulch particles, the larger the capillary porosity. Larger capillary porosity means that the mulch can hold more water after drainage. However, the rainfall intercepted by the 3.38 mm MED pebbles was less than that for the 5.79 mm MED pebbles. The reason is that the void volume of the mulch composed of two layers of 3.38 mm MED pebbles is less than that of the 5.79 mm MED to hold water (Fig. 8).

### 3.5 Validity analyses

To further examine the validity of the model used to estimate the maximum static rainfall retention, we examined the associations between the calculated retentions and the measured retentions in the pebble mulches. A paired samples two-tailed  $t$  test with an alpha level of 0.05 was used for the comparisons. Results are shown in Table 3. A negative mean difference indicates that the calculated values are slightly larger on average than the measured values. The values calculated using the method are not significantly different from measured values (Paired-sample  $t$ -test,  $p > 0.05$ ). The results indicate that the method can be used to estimate pebble mulch maximum static rainfall retention.

### 4 Conclusions

Permeable pores of mulch pebbles can be saturated with rain water. Once the rain stops, the rain water intercepted is considered as the maximum static rainfall retention in pebble

mulch. The calculated results using the proposed method were verified by the measured data from laboratory rainfall simulation experiments. The measured/computed the maximum static rainfall retention in the mulch with two layers of the pebbles indicated that interception decreased with the increase of MED (from 5.79 mm to 64.30 mm) of the pebbles. The void content between pebbles affects the rainfall intercepted by the pebble mulch. The void content increases with MED of the pebbles. The water bridge formed between the pebbles is the contribution of the capillary force. The smaller pebble size indicates that mulch is with smaller gaps between the pebbles. More small gaps between particles of the mulch, the higher capillary porosity in the pebble much. The higher capillary porosity, more water the mulch can hold. However, the rainfall intercepted by the mulch composed of two layers of 3.28 mm MED pebbles is smaller than that for 5.79 mm MED pebbles. It is because the void content of the mulch composed of two layers of 3.28 mm MED pebbles is too small to intercept more rainfall than that of 5.79 mm MED pebbles. A regression model was constructed based on the specific test data. Further investigations are required to determine if the theoretically based model may work well for a wider range of pebble mulch conditions.

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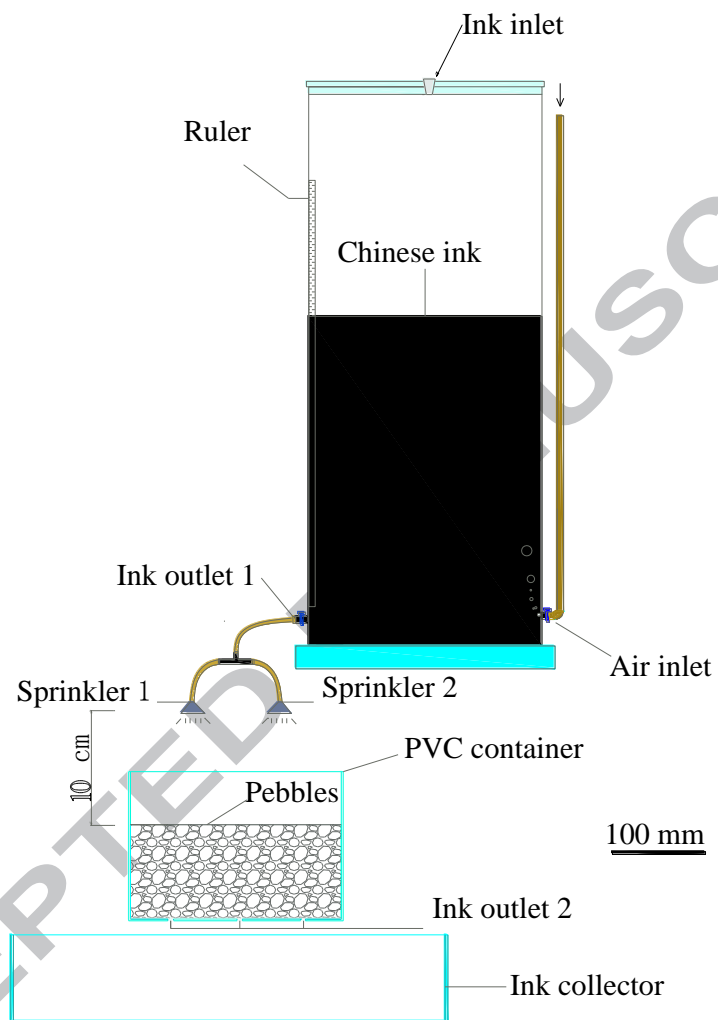


Fig. 1. Schematic diagram of experimental setup and installation.

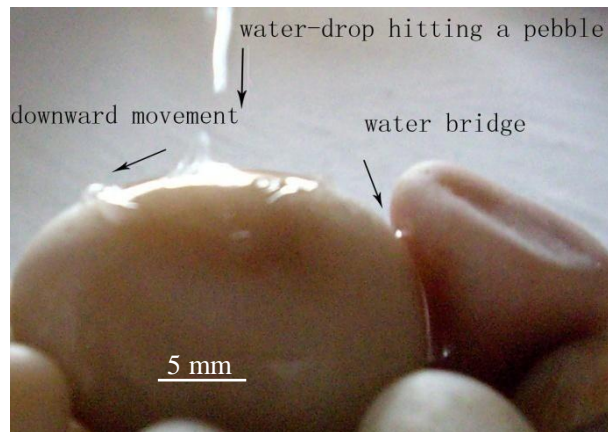


Fig. 2. Water movement after a water-drop hit the pebble.

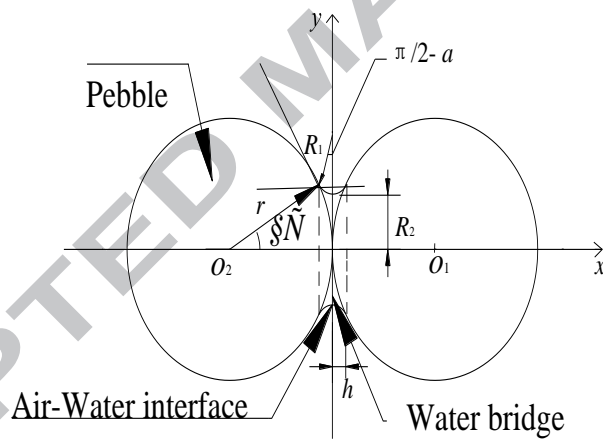


Fig. 3. Cross-section of a water bridge between two pebbles.

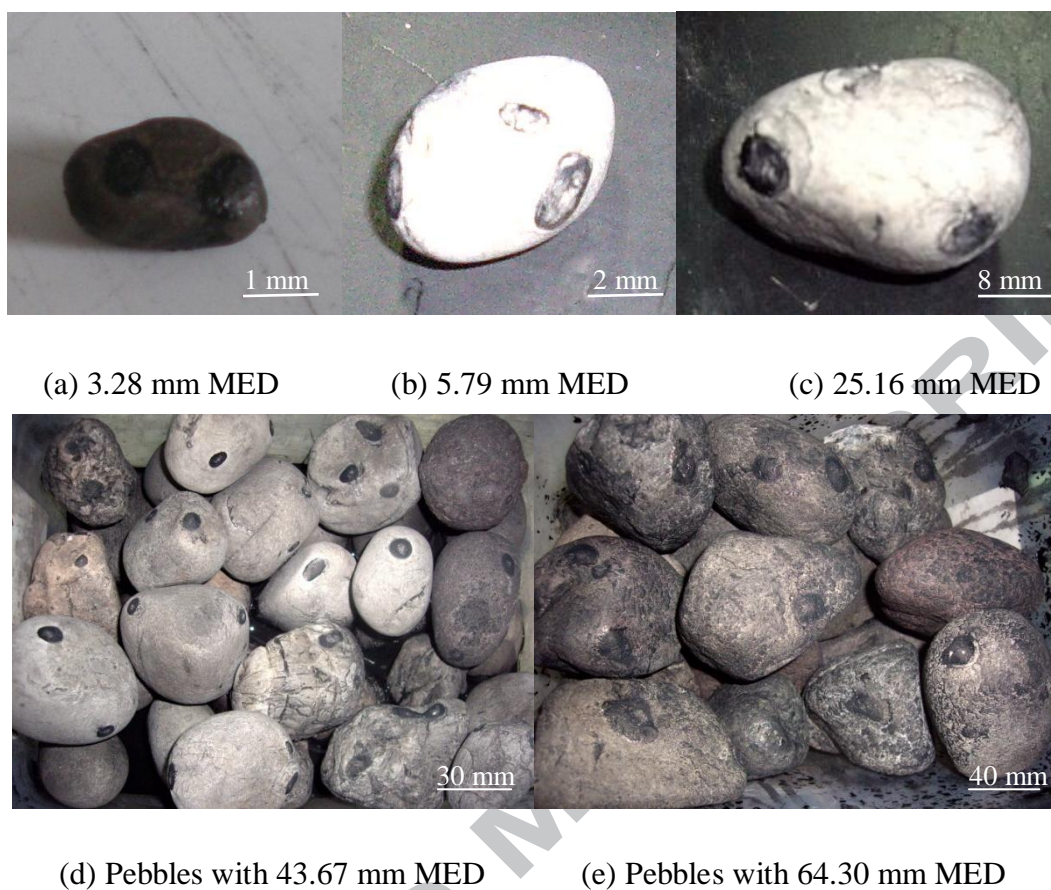


Fig. 4. The dried Chinese ink scars left on pebble surfaces.

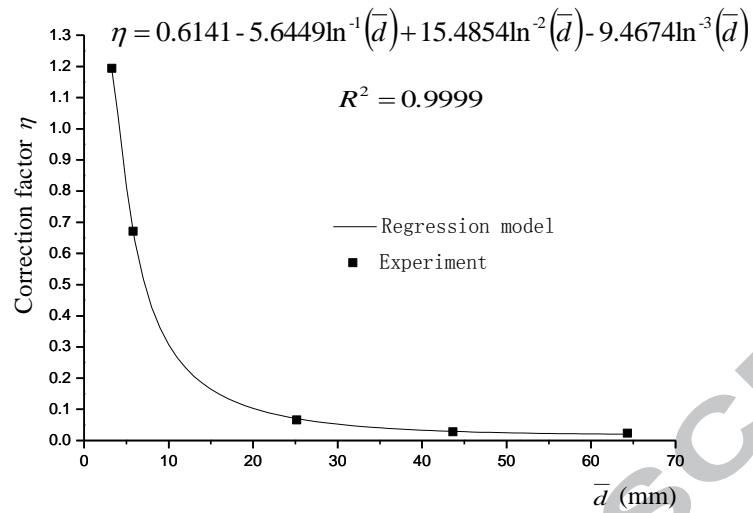


Fig. 5. Relationship between correction factor  $\eta$  and MED  $\bar{d}$

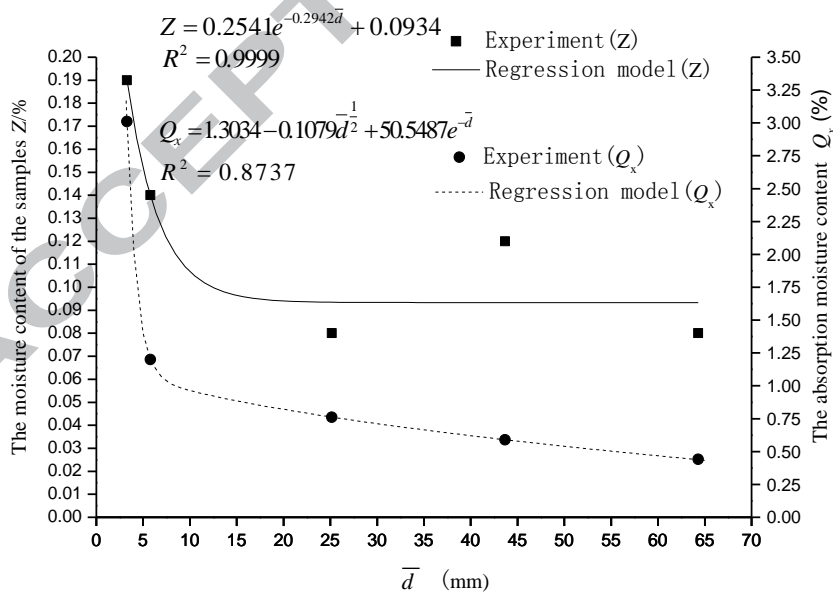


Fig. 6. The absorption moisture content values (SSD) and the moisture content values (before rainfall event) of the samples of pebbles with different MED  $\bar{d}$ .

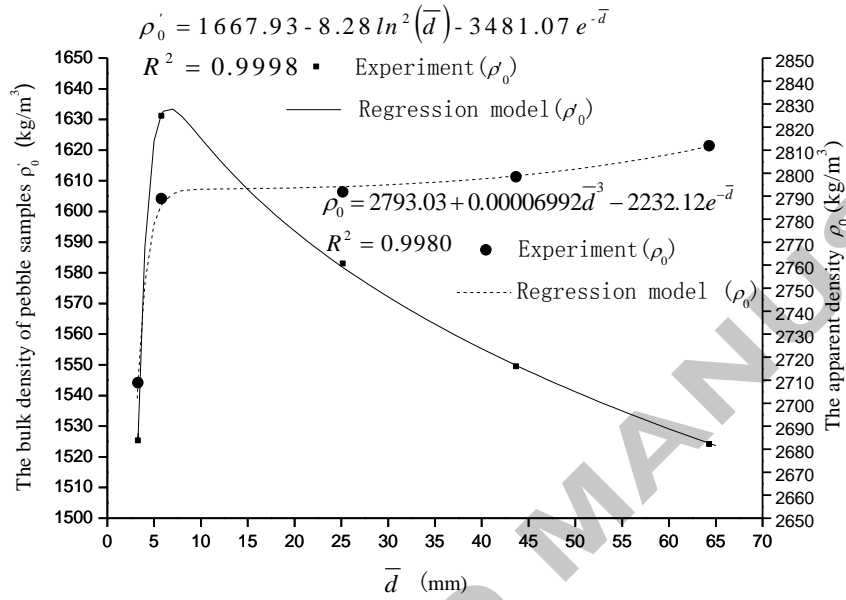


Fig. 7. The bulk density and the apparent density values of the samples of pebbles with different MED  $\bar{d}$  (3.38 mm, 5.79 mm, 25.16 mm, 43.67 mm and 64.3 mm).

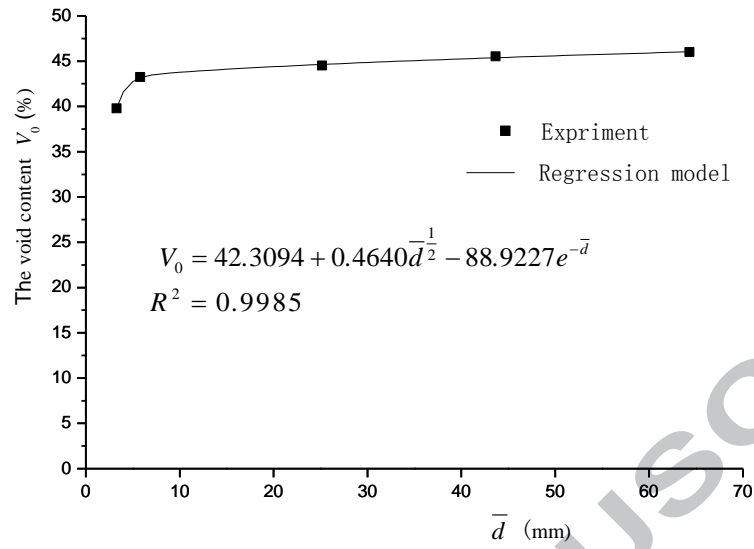


Fig. 8. The void content values of the samples of pebbles with different MED  $\bar{d}$ .

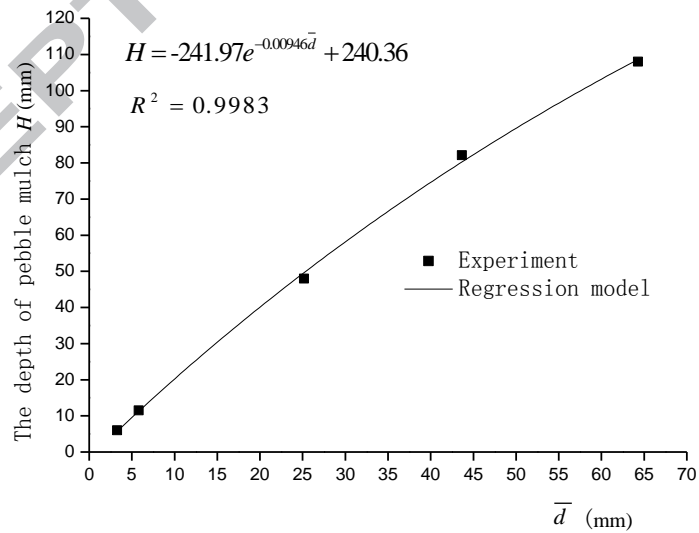
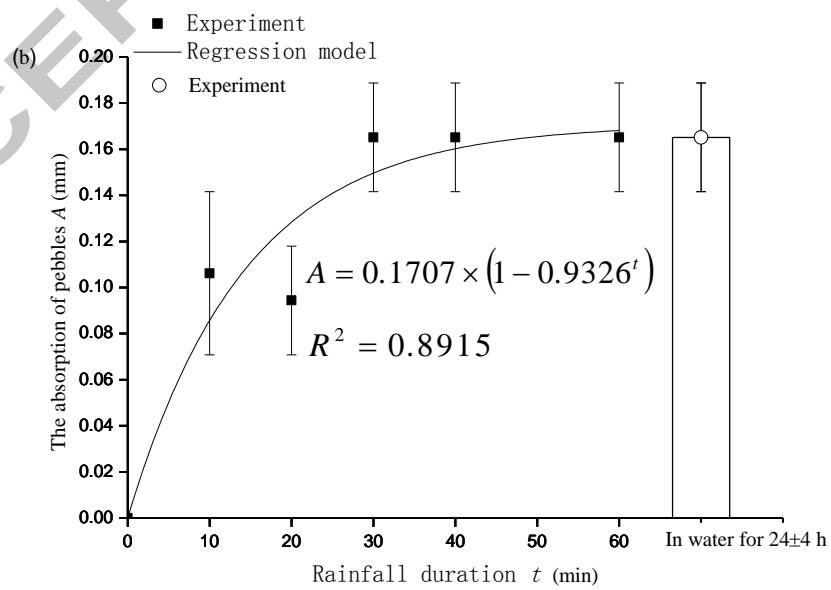
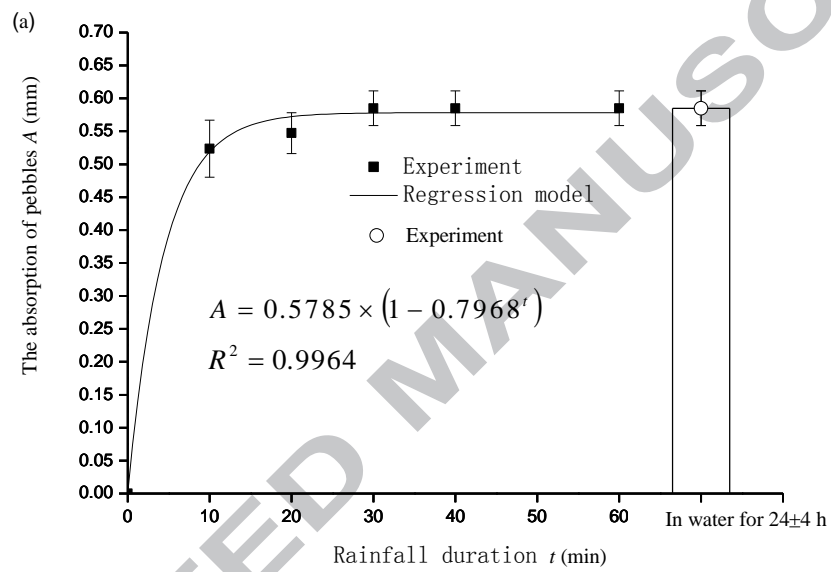
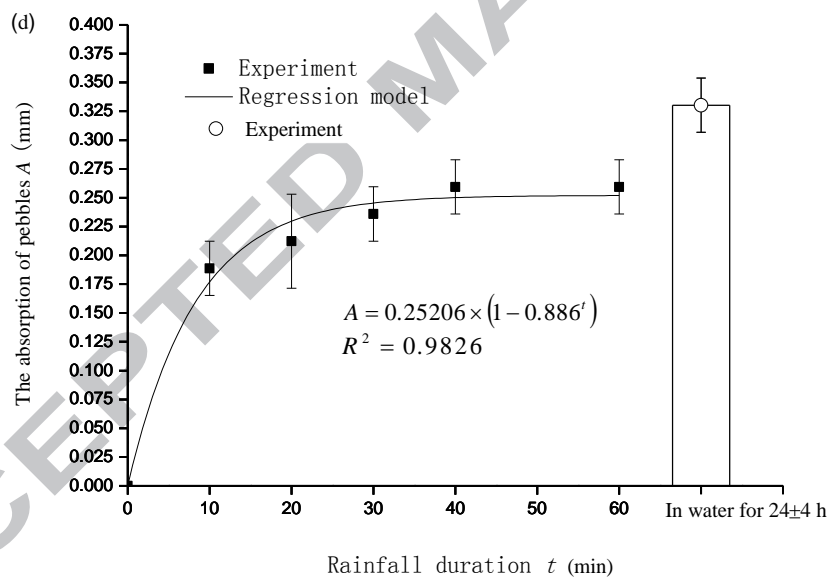
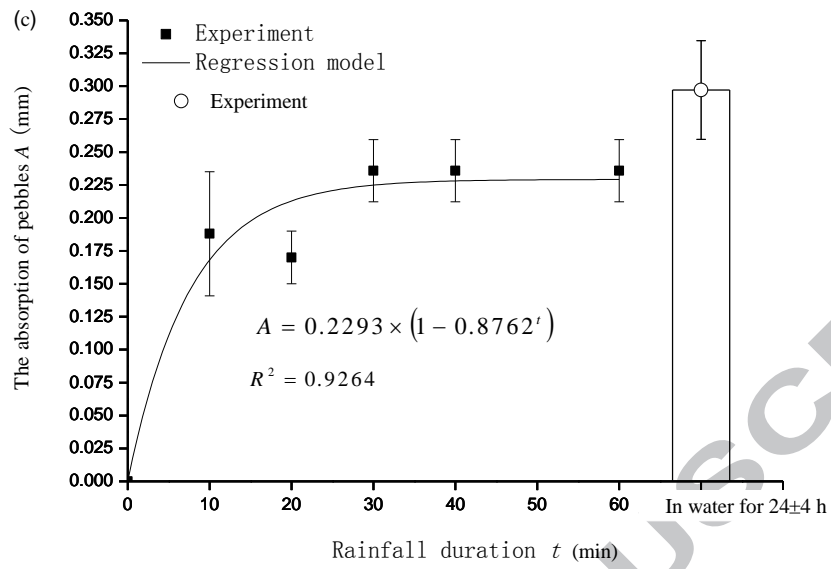


Fig. 9. The thicknesses  $H$  of the mulch composed of the samples of pebbles with different

MED  $\bar{d}$ .







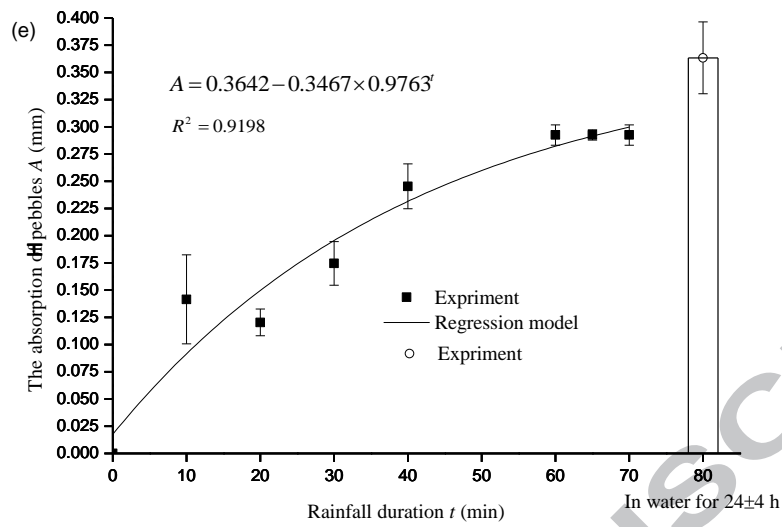


Fig. 10. Relationship of rainfall duration and the absorption of pebbles with 3.38 mm (a), 5.79 mm (b), 25.16 mm (c), 43.67 mm (d) and 64.3 mm (e) MED. ■ and ○ represent mean value. Bars indicate two standard errors.

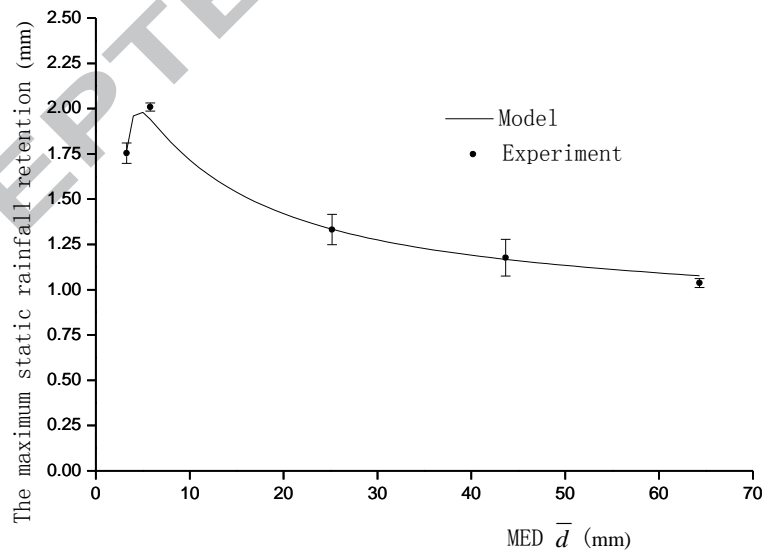


Fig. 11. The maximum static rainfall retention in the samples of pebbles with different MED

$\bar{d}$ . ● represents mean value. Bars indicate two standard errors.

Table 1

The values of  $\bar{d}$  of different pebble-size grade samples.  $\bar{d}$  values were measured and calculated using Eqs. (4) and (5).

Grade (mm)	Number of the pebbles measured	$\bar{d}$ (mm)
3	-	3.28
5	326	5.79
25	200	25.16
45	195	43.67
65	51	64.30

-: no data.

Table 2

$R_2$ ,  $R_2'$  and  $\eta$  values of different pebble size grade samples, where  $R_2$  and  $\eta$  values were calculated using Eq. (23) and Eq. (32), respectively, and  $R_2'$  was measured and calculated using Eq. (6).

No.	$\bar{d}$ (mm)	$R_2$ (mm)	$R_2'$ (mm)	$\eta$
1	3.28	1.09	1.16	1.19
2	5.79	1.93	1.69	0.67
3	25.16	8.39	3.65	0.07

4	43.67	14.56	4.90	0.03
5	64.30	21.44	6.07	0.02

Table 3

Paired samples two-tailed  $t$  test of measured and calculated retention

Methods	Paired Differences		$df$	$p$ value
	Mean	Std. Deviation		
Retention (measured-calculated)	-0.0384	0.3139	4	0.798

## Highlights

- Model of the water into the pores of pebbles based on the absorption of pebbles.
- Model of water adhering to outside surface of pebbles based on properties of water.
- Model of the water between pebbles based on the basic equation of water bridge.
- We proposed a method to estimate maximum static rainfall retention in pebble mulch.
- The model results have been validated by experimental observations.