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Te-Hsing Chang
Department of Civil Engineering, Chung Yuan Christian University, 200, Chung-Pei Rd., 320 Chung-Li, Taiwan.

Shen-Ting Huang
Department of Civil Engineering, Chung Yuan Christian University, 200, Chung-Pei Rd., 320 Chung-Li, Taiwan., shentinghuang@hotmail.com

Shinne Chen
Agricultural Engineering Research Center, 196-1, Chung-Yuan Rd., 320 Chung-Li, Taiwan.

Jun-Cheng Lai
Department of Civil Engineering, Chung Yuan Christian University, 200, Chung-Pei Rd., 320 Chung-Li, Taiwan

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ESTIMATION OF MANNING ROUGHNESS COEFFICIENTS ON PRECAST ECOLOGICAL CONCRETE BLOCKS

Te-Hsing Chang*, Shen-Ting Huang*, Shinne Chen**, and Jun-Cheng Lai*

Key words: ecotechnology, hydraulic modeling experiment, precast ecological concrete block (PECB), Manning roughness coefficients.

ABSTRACT

Agricultural irrigation and drainage canals in Taiwan are generally constructed using concrete. Concrete is used for the safety of conveyance efficiency. It also reduced loss and is structurally safe. The irrigation ditches and soil revetments in Taiwan fitted with a strong concrete lining. The smooth non-porous concrete surface makes the biology perch difficult and causes a monotonous flow. For these reason, an artificial materials-precast ecological concrete blocks (PECBs) was developed in this research. This was done in order to modify both the traditional concrete lining and the natural field materials in canal construction.

Precast ecological concrete blocks (PECBs) were tested by hydraulic model experiments. These experiments used four kinds of height of projection under the condition of unaffecting conveyance efficiency. The experimental results show that the Manning roughness coefficients of PECBs, in a range of are greater than that of piling up cobblestone of concrete as side protection. The results also indicate that the Manning roughness coefficients are in inverse proportion to the discharges and in proportion to the bed slopes. The relationship between the roughness coefficient and surface roughness were estimated after regression analysis. The analysis of hydraulic characteristics and estimation of the Manning roughness coefficients, through this hydraulic modeling experimental study, can be used as a reference for the improvement in construction of irrigation and drainage canals.

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**Department of Civil Engineering, Chung Yuan Christian University, 200, Chung-Pei Rd., 320 Chung-Li, Taiwan.*

***Agricultural Engineering Research Center, 196-1, Chung-Yuan Rd., 320 Chung-Li, Taiwan.*

I. INTRODUCTION

In Taiwanese agricultural production canals played important roles and benefited farmers. Most of the main irrigation systems in Taiwan were established during the period of the Japanese colonization before World War II (1895-1945). During this period, the primary economic policies of the Japanese Empire was “industry for Japan” and “agriculture for Taiwan”. These policies became the footstone in an agricultural economic society in its early stages. During the 1960s and 1970s, Taiwan began to develop into a prosperous, industrialized developed country with a strong and dynamic economy, becoming one of the “Four Asian Tigers”. With a modern industrialized society, agriculture moved toward effective irrigation. Canals of the irrigation system were divided into irrigation, drainage and dual-function canals. Under considerations of the safety of conveyance efficiency, reducing losses and structure safety, canals were generally constructed by concrete material. The irrigation ditches and soil revetments were replaced by strong concrete lining. The smooth non-porous concrete surface made the biology perch difficult and caused the flow to be monotonous. During the past fifty years, the Taiwanese government has placed a strong emphasis on economic development. In turn, this has caused Taiwan’s rich and diverse ecosystem to deteriorate [15]. Presently they are 69,927 km in length that canals of the irrigation system have been framed inside of the fields in Taiwan.

During the 1990s and early 2000s, due to the economic structure changing and the concept of maintaining a sustainable ecosystem, agricultural production was gradually no more the main financial resource in the rural areas; and the agricultural policy of Taiwan’s Government had been changed. Paddy agriculture implies three functions of production, ecology and livelihood and provides multitudinous contributions to the environmental quality of living [25]. Ecological engineering or ecotechnology also provides a new strategy to restore or to maintain agricultural ecosystems, especially on the canals. Canals, inside of paddy fields, supply habitats for water fowl, fish, reptiles and amphibians. Ditches and revetment of canals are often ecotones, i.e. transition zones, between aquatic and terrestrial systems [17]. Canals can be seen as a network of agricultural systems to connect the whole ecosystem. Besides, they connect the neighboring river or stream areas to provide the nutrition to organisms at the same time.

Mitsch and Jørgensen [20] have mentioned that "we have had several energy crises during the past thirty years and we know that new crises will appear in the future. Therefore we have to rely more on solar-based ecosystems, which are the bases for ecological engineering". Ecological engineering or ecotechnology is needed to solve all of our environmental problems, especially on the interface of different ecosystems [18]. In the application of ecological engineering or ecotechnology in agriculture, twelve guidelines or commandments have been formulated [13, 19, 23]. The main point of these guidelines is that the agricultural cycle is repeated each year. Therefore the time scales that characterize the agro-ecosystems are determined to a high extent by the pattern of the human interference that makes the systems more vulnerable since they are not allowed to follow their rhythm. Then ecotones, transition zones, are as important for ecosystems as the membranes for cells. For the benefits of ecosystem, agricultural management should consider in the applications of ecotechnology and environmental management, and also provide a historical record in general to realize the right solution, therefore, it can be offered to emerging environmental problems.

In the relevant research of irrigation canals, highlighted by Uang [26], most of the concrete placing needs to be poured in the construction field of the traditional lining canals. Which caused the low efficiency and the construction influenced by the weather. Hence, the quality of construction and the safety of structure are not easy controlled. Yet precast concrete productions can improve the quality of public works including techniques and constructions enhancement. For instance, applications of precast concrete for irrigation canals can receive great benefits increasing the usage rate of paddy fields, economizing land usage, shortening construction periods, and developing land resources. Yang *et al*. [28] focused on the irrigation canals to design indoor experiments. Yang *et al*. merged two ecological concepts (1) rectangular sections changing to U-type sections and (2) stone-beam work. The first result of this experiment was that the U-type canal establishment of rectangular contributes to increase the diversified velocity of flow. Furthermore, the increased range of the Manning's coefficient was not broad. When stones were piled up on both sides of bottom to 1/4 of the canal width, the water table in the section clearly began to drop. Howere the water table on the upstream section was raised slightly. Chen *et al*. [3] provided the estimate of Manning coefficient by hydraulic model test with the considerations of convex, concave, and smooth surfaces of canal pavements. Under the normal velocity and water level, the experimental results showed that the Manning coefficients are as follows, convex > concave > smooth planes. The Manning coefficient is larger when the flux and the water depth are smaller. Under the same flux, the Manning coefficient increases as the slope rises.

Chen *et al*. [4] considered the structure and the hydraulic safety, with the ecological concept of improving construction. This study utilized the ecological concept of improving construction on the original irrigation canal. Then it used the working procedure without damaging the structure to achieve ecological purposes and create a beneficial environment for aquatic living beings. Chen *et al*. conducted this study of improving construction by making holes on the lateral sides of the canal. In order to reach a foregoing objective, the structure and the hydraulic safety needed to be considered without destroying the existing structure. As well as trying to find the size, depth, and interval of the optimum ecological hole. Research results contributed to the improvement of the ecology of irrigation canals and the reference of offering the relevant project to plan and design. Lee [16] in order to realize the ecological effects of PECB, the biological membrane adhesives experiments are conducted. The results showed that (1) the adhesive quantity of the blocks with ecological convex surface was greater than normal concrete convex surface, (2) the blocks with convex surface was greater than that of the blocks with ecological flat surface, (3) the blocks with ecological flat surface was greater than that of the blocks with flat surface.

The objective of this paper is primarily to provide a simple way to create the recovery of habitat resources in irrigation canals. This research in which this is addressed environmental goals with a slow and minimal approach and with a hydraulic stabilization design. Therefore, this study maintained ditches as corridors in the landscape or as ecotones between agricultural and other ecosystems.

II. MATERIALS AND METHODS

1. Precast Ecological Concrete Block (PECB)

Irrigation and drainage canals can be divided into eight types according to the pavement material. The types are: (1) earth ditch, (2) grassed waterway, (3) compound grassed waterway, (4) concrete lining canal, (5) stone-paved embankment, (6) brick-paved embankment, (7) precast U-type concrete canal, and (8) cast-in-site U-type concrete canal. Earth ditches, grassed waterway and stone-paved embankments are consistent with ecological functions. However with consideration to conveyance efficiency and construction convenience, most of canals were built with concrete linings. The smooth surface of the concrete canals lacks small openings for organisms to perch. This includes aquatic animals and the rooting of riparian plants. The concrete lining also causes a difficulty for the migration of amphibians. In addition, the construction of stone paved canals requires a large number of cobblestones. Therefore, if there is a lack of cobbles near the construction field, materials would need to be taken from other sites. Construction methods of excavating cobblestones from other places destroys local environments and also violates ecological principles regarding the management, the utilization and the conservation of natural resources [1].

For this reason, this paper developed artificial materials (PECB, Fig. 1) in order to modify works for both the traditional concrete lining and the natural materials used in canal

Fig. 1. Precast ecological concrete block model and its test in the flume.

constructions. The main materials of PECB are sand, cement and water. It is so-called concrete material. They were pre-cast by mouldboard. In canal field design, a 1 m × 1 m area was constructed in random shape like natural stones with rough surface. The height of projection, the width of block and gap distance in blocks are various depending on the hydraulic conditions.

Concepts of design. In the application of PECB in canal fields, a 1 m × 1 m area was constructed and laid side by side with a tiny gap between each block. In these gaps or spaces, micro organisms freely pass in and out for migration and the water infiltrates the revetment to supply local groundwater. Moreover, the interaction of environmental matrices become the nutrition materials of micro living beings. In order to diminish the disadvantages of concrete lining, PECB was firstly designed as a shape of stone-paved embankment; the diverse surfaces supplied a continuous corridor for organisms. Secondly, because of irregular block edge design, it also provided gaps for interactions.

Future missions. There were still limitations of PECB. Because of water loss, PECBs can not be applied in some areas. Therefore, e.g. drainage systems, river embankments and farm ponds would be the excellent sites for utilizing the PECB. However, for the future improvement or modification of PECB, reusing and resource cycling of the discarded materials like polypropylene fiber, rice bran or oyster shells can be added into the ecological concrete to shorten the intervals of concrete resistance for aquatic living beings.

2. Applications of Manning's Theories

This study aimed to discover at various heights of PECBs simulated by hydraulic modeling tests also to discuss the hydraulic characteristics in order to estimate the Manning roughness coefficients. From the experiment results, hydraulic engineers can use the findings as reference data for planning and designing irrigation and drainage canals. Furthermore, the Manning's n values are very important reference resources for engineering of canal construction design, especially in calculating velocity. The *slope-area method* is one accepted methods of estimations. The formula is based on known reach length L, design flow discharge Q, inflow and outflow cross-sectional flow area (A_1, A_2), hydraulic radius (R_1, R_2) and hydraulic slope S, to Manning's n by:

$$Q = \frac{1}{n_1} R_1^{2/3} S^{1/2} A_1 \quad (1)$$

$$Q = \frac{1}{n_2} R_2^{2/3} S^{1/2} A_2 \quad (2)$$

These equations can be manipulated so that the n values can be calculated, where the subscripts 1 and 2 denote the inflow and outflow respectively,

$$n = \frac{R^{2/3} A}{Q} \sqrt{S} \quad (3)$$

where $R = \sqrt{R_1 \times R_2}$ and $A = \sqrt{A_1 \times A_2}$. This shows *slope-area method*. Because the n values are easily influenced by bed slope, revetment materials and vegetations. Cowan [6] suggested river roughness should be calculated individually, with integration he developed a simple estimation formula. One relationship between discharge and cross-sectional flow area was suggested by Riggs [22]; he utilized parts of U.S. river field data measured by Barnes (1967).

$$\log Q = 0.336 + 1.33 \log A + 0.05 \log S - 0.56 (\log S)^2 \quad (4)$$

But for steep rivers lack of relevant experiment formula between n and slope, Jarrett [10] analyzed 21 steep rivers in Colorado (hydraulic conditions: bed slope S from 0.002 to 0.052 and hydraulic radius R from 0.12 m to 0.22 m, driven out huge influences by vegetations rivers) to get the relationship between n and channel slope, also between n value and hydraulic radius. He showed that the n values were in direct proportion to the bed slopes and in inverse proportion to the depths. The relationship trend among n, bed slope and depth can be showed as bellows:

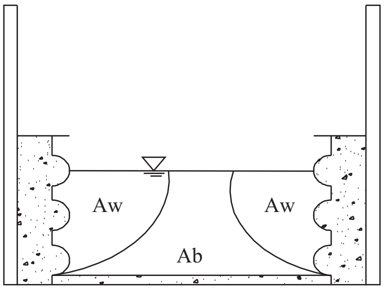


Fig. 2. Cross-section areas drawing of bed and side walls.

$$n = 0.39 S^{0.38} R^{-0.16} \tag{5}$$

The n value of the river/canal bed due to vegetation, n_b, is calculated by the following procedure suggested by Einstein [8]. Wu [27] investigated the effects of bed slope and flow depth on the n due to vegetation. His research was conducted in a laboratory flume covered with a horsehair mattress to simulate flow over vegetation. He proposed that the total flow area can be divided into areas (Fig. 2) corresponding to the bed and side walls, as follows:

$$A_T = A_b + A_w \tag{6}$$

Where as A_T, the total flow area over flume bottom, is equal to the product of the width of flume B and the water depth above the bottom y, A_b and A_w are the areas corresponding to the bed and side walls respectively.

Using Manning's equation for both the walls and the bed, namely

$$V = \frac{1}{n_w} R_w^{2/3} S_0^{1/2} \tag{7}$$

$$V = \frac{1}{n_b} R_b^{2/3} S_0^{1/2} \tag{8}$$

where V, the average velocity over channel bottom in m/s; n_w and n_b are the roughness coefficients for the side wall and bed respectively; and S_0 is the energy slope. This study rearranges (7) and (8) for the energy slope:

$$S_0 = S_w - \alpha Q^2 \frac{S_w - S_b}{g B^2 y^3} \tag{9}$$

where α = 1, S_w and S_b are the water surface and bed slope respectively; y is the water depth; B is the width of flume; and g is the acceleration of gravity. Substituting hydraulic radius of side walls as

$$R_w = \frac{A_w}{2y} \tag{10}$$

and rearranging (7) for the effective area of the walls yield

$$A_w = 2y\left(V \times n_w\right)^{3/2} S_0^{-3/4} \tag{11}$$

Once A_w was obtained from (11), the effective area of the bed, A_b, was calculated from (6), i.e. $A_b = A_T - A_w$. Substituting $R_b = \frac{A_b}{B}$ where B is the width of bottom and rearranging (8) for the bed roughness yield.

$$n_b = \frac{1}{V}\left(\frac{A_b}{B}\right)^{\frac{2}{3}} S_0^{\frac{1}{2}} \tag{12}$$

Rearranging (12) for the effective area of the bed yield

$$A_b = B\left(V \times n_b\right)^{\frac{3}{2}} S_0^{-\frac{3}{4}} \tag{13}$$

and substituting $A_w = A_T - A_b$ for the side wall roughness yield

$$n_w = \frac{1}{V}\left(\frac{A_w}{2y}\right)^{\frac{2}{3}} S_0^{\frac{1}{2}} \tag{14}$$

3. Hydraulic Modeling Experiment

In order to seek the Manning's n of PECB, this study employs systematically to install PECBs model on the straight, degraded experimental channel and to document the effects of various heights of projection. The objectives of the present study are to simulate normal canals with concrete lining the bottom, on the bottom of experimental channel is also to plaster a layer of concrete.

1) Experimental Facilities

a. *Experimental site.* Experiments are conducted at the Hydraulic Engineering Laboratory of Department of Civil Engineering at Chung Yuan Christian University (Chung-Li, Taiwan) using a tilting recirculating flume 0.5 m wide, 0.6m deep and 22 m long, with a slope varying from 0 to about 1% (Fig. 3). Both sides of the flume's material are double layer glass panes and the bottom side material is stainless steel. The flume is equipped with an upstream stainless baffle to dampen pump-related turbulence.
b. *Water supply facility.* The flume's water supply facility is equipped with two 30 *HP* water pumping motors.
c. *Measurement point gauge.* Flow depth is measured by a point gauge mounted to a movable carriage that rides along the flume rails. Precision of point gauge is 0.1 mm.
d. *Velocity Meter.* Precision of electromagnetic velocity meter is 0.001 m/s.
e. *Tank of discharge measurement.* An outflow tank, 1.25 m long, 0.8 m wide and 0.6 m deep, measures average discharges.

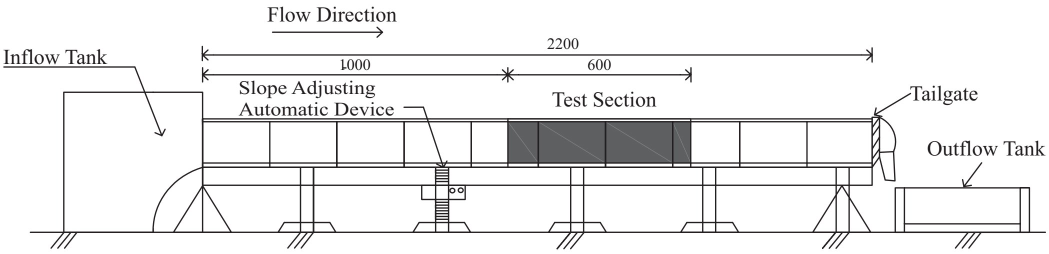


Fig. 3. Sectional drawing of experimental channel (unit: cm).

f. Tailgate. The flume is equipped with an outflow vane tailgate to facilitate establishment of uniform flow.

2) Dimensional Analysis

In order to predict the field irrigation canal from the model test, the process of dimensional analysis must be carried out between prototype and model. Similitude is the theory and art of predicting prototype performance from model observations. We shall see that the theory of similitude involves geometric similitude and dynamic similitude. In geometric similitude, the basic and perhaps the most obvious requirement of similitude is that the model be an exact geometric replica of the prototype. The focus of this research is the general irrigation canal; the width of normal canal prototype is 240 cm. The experiments were carried out in a indoor flume 50 cm wide which became 35cm wide after installing PECBs on both sides. The width of model (l_m) and prototype (l_p) are geometrically similar, the scale ratio is:

$$\lambda = \frac{l_m}{l_p} = \frac{1}{6} \tag{15}$$

In dynamic similitude, gravity force and convective acceleration influence the flow, the *Froude* number criterion can be used; following is the velocity, unit discharge, total discharge and Manning's roughness ratio of canal prototype and hydraulic model.

$$\begin{aligned}
\lambda_V &= \frac{V_m}{V_p} = \left(\frac{l_m}{l_p}\right)^{1/2} = \frac{1}{6^{1/2}} \\
\lambda_q &= \frac{q_m}{q_p} = \left(\frac{l_m}{l_p}\right)^{3/2} = \frac{1}{6^{3/2}} \\
\lambda_Q &= \frac{Q_m}{Q_p} = \left(\frac{l_m}{l_p}\right)^{5/2} = \frac{1}{6^{5/2}} \\
\lambda_n &= \frac{n_m}{n_p} = \left(\frac{l_m}{l_p}\right)^{1/6} = \frac{1}{6^{1/6}}
\end{aligned} \tag{16}$$

3) Experimental Procedure

a. *Experimental conditions.* The data of the scale-model experiments is translated from the canal field. On the assumption that the canal width is 240 cm, deep is 135 cm, normal water depth is between 40~90 cm (1/3~2/3 of canal deep) and the design velocity is 0.9~1.8 m/s. Then in experiments, flow depths and velocities were controlled between 6.67~15 cm and 0.37~0.75 m/s. Experiments were conducted in four bed slopes S = 1/500, 1/250, 1/167 and 1/125 composed with four kinds of discharges and heights of model projection.

b. *Discharge rating of pump.* The experimental pump was designed to adjust overflow and to control flume discharge by operating the valve.

c. *Reach of measurement.* The total length of the flume is 22 m, but the whole flume was not equipped with PECBs. The test section is selected by a fully developed flow site. For the four measurements of the fully developed flow are: (A) measurement point decided by flume width [7], (B) measurement point decided by water depth [9, 21], (C) measurement point decided by boundary layer [2] and (D) using velocity profile approximation to decide measurement point [24]. The velocity profile approximation was selected to make sure the test section site's appropriateness to this experimental flume size, approximating Tominaga and Nezu's [24] flume size (0.4 m width). When the velocity profile at the measurement point approximates the profile 0.5 m upstream of the measurement point, it proves that fully developed and approximated uniform flow exists.

d. *Selection of material.* The objective of this study discovers the hydraulic characteristic of PECB. Design considerations for canal restoration programs were presented with using four kinds of height of projection from the prototype blocks, the heights were 15 cm, 21 cm, 30 cm and 42 cm. After dimensional analysis, the heights of model were 2.5 cm, 3.5 cm, 5.0 cm and 7.0 cm.

e. *Flow area measurement.* Because of the irregular surface of PECB, the average projection height is calculated from the ratio between projections total volume and the model area. After reducing the two sides of average projection height in the bottom width, the flow area can easily be counted through water depth and new bottom width.

Table 1. Comparison table in various estimations of Manning's *n*.

Height of projection		Manning's *n* of Model*	Manning's *n* of Prototype	Manning's *n* of PECB (Equivalent Wetted Method)	Manning's *n* of PECB (Slope-Area Method)	Manning's *n* of PECB**
2.5 cm	Min.	0.0108	0.0146	0.0167	0.0165	0.0178
Height	Max.	0.0135	0.0182	0.0355	0.0318	0.0325
3.5 cm	Min.	0.0116	0.0156	0.0185	0.0183	0.0195
Height	Max.	0.0145	0.0195	0.0383	0.0342	0.0368
5.0 cm	Min.	0.0120	0.0162	0.0191	0.0189	0.0219
Height	Max.	0.0164	0.0221	0.0424	0.0376	0.0402
7.0 cm	Min.	0.0136	0.0183	0.0216	0.0212	0.0216
Height	Max.	0.0185	0.0250	0.0437	0.0393	0.0443

*: side walls with PECB, bottom with lining concrete; **: side walls and bottom with PECB.

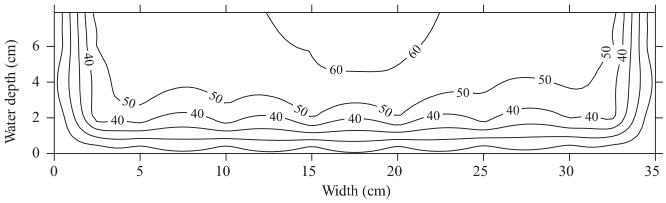


Fig. 4. Velocity contour lines at the same measurement section by the hydraulic conditions of Q = 0.0202 cms, S = 0.002 (Example 2.5 cm height).

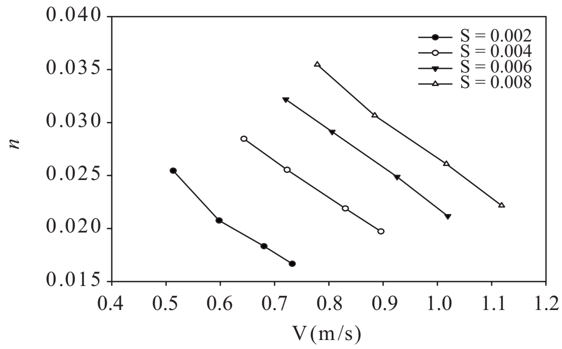


Fig. 5. The relationship between Manning's *n* and flow velocity in various bed slopes (Example 2.5 cm height).

III. RESULTS AND DISCUSSION

1. Flow Distribution

During the test section, because of the influence by equipping PECBs on the side walls, the flow produces diverse velocity distributions. These blocks make the smooth non-porous concrete surface canal produce a more different flow. Figure 4 shows the velocity distribution in section 3 (one of five measurement sections, 13 m distance from the entrance) by the hydraulic conditions of $S = 1/500$ and $Q = 0.020$ *cms*, with four kinds of height of projections, 2.5 cm, 3.5 cm, 5.0 cm and 7.0 cm. The results revealed that the cross-section area was reduced by the height of projection, and also the water level was raised. Through the placement of blocks, flow converged to the middle of the channel; high speed flow was also concentrated in the middle, thus causing the water flow on the side walls to be at a lower speed and preventing erosion.

2. Estimations of Manning Roughness Coefficient

From the data of the experiments, we utilize *slope-area method* to calculate the equivalent *n* value of PECB, because the bottom of test section lined with concrete material and it is different from the material in the side walls. The experiment revealed, from (3) that in order to gain the equivalent roughness (n_m), and then manipulate the equivalent *n* value determining the true *n* values [5]. Proving and comparing the effective area *n* by Wu [27], a summary of calculations for the *n* value with various estimations is provided in Table 1 and a *n* value for bottom concrete of 0.013 is recommended by Chow [5].

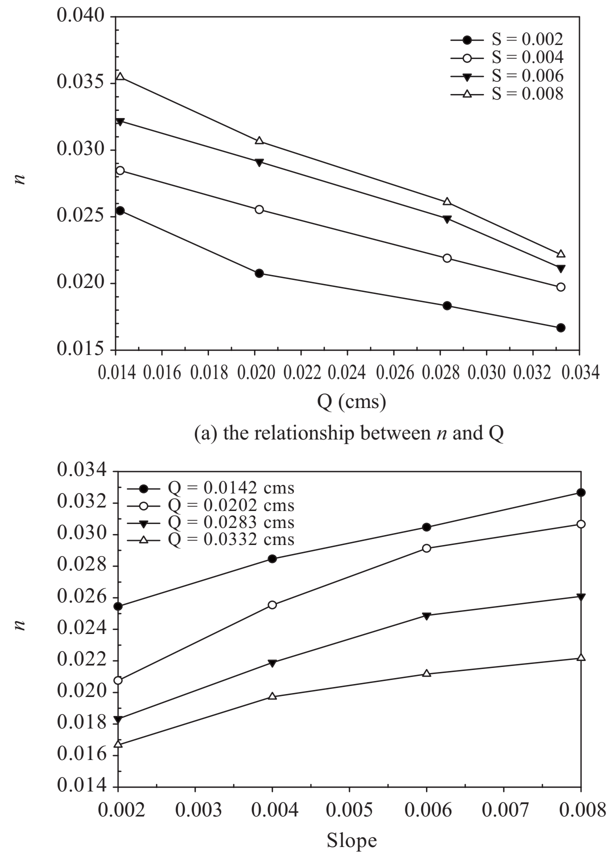
3. Manning's *n* vs. Velocity Relationship

The relationship between *n* value and flow velocity *V* is also examined, as shown in Fig. 5. With various discharges, bed slopes and heights of projection, study with 2.5 cm height and the range of flow velocity 0.51~1.12 (m/s), the *n* value of PECB is between 0.0167 and 0.0355. Results show that in low velocity because of the mild slope and rich wetted perimeter, the *n* value becomes smaller. With the increase of the slope, shallow water and slight wetted perimeter, the *n* value becomes larger. The Manning's *n* is inverse proportion to the velocity.

4. Manning's *n* vs. Flow Discharge and Bed Slope Relationship

Aiming at four discharges, heights of projection and bed slopes, the experimental results show as following (Fig. 6):

(1) *2.5 cm height*: in the same discharge condition, Fig. 6(a) shows that the *n* values increase with slope and are in proportion to the bed slope, especially at the lower discharge and mild slope. Figure 6(b) shows that Manning's *n* becomes a constant with increasing discharge and slope.
(2) *3.5 cm height*: the bed slope becomes steeper, and then the Manning's *n* reveals stable growth. Compare between 3.5 cm and 2.5 cm height of projection, the Manning's *n* increases with the height.



(a) the relationship between *n* and Q

(b) the relationship between *n* and slope

Fig. 6. The trend of Manning's *n* vs. flow discharge and bed slope (Example 2.5 cm height).

(3) *5.0 cm height*: with the increase of slope and at the same discharge condition, the Manning's *n* is 0.0323 when the slope is 0.002; the Manning's *n* increases to 0.0424 when the slope is 0.008, there is quite a difference compared to the height in 2.5 cm and 3.5 cm.

(4) *7.0 cm height*: the results show that in the same slope, the Manning's *n* decreases with the discharge. In large amounts of discharge, the *n* values are less influenced by the various slopes. The phenomenon reveals that in a large discharge the difference of *n* values remains stable.

5. Manning's *n* vs. the Height-Width Ratio Relationship

In order to calculate the relationship of *n* value and the height-width ratio, the Manning's *n* experimental data and the ratio of height *D* and channel width *B* are developed by linear regression with four flow discharges. Table 2 shows the regression and correlation index, those data could be a reference for construction.

(1) *0.0142 cms*: height-width ratio reveals the lowest correlation index, yet once the discharge increases the higher index performs in various slopes.

(2) *0.0202 cms*: there is a higher correlation index at S = 0.002 and 0.004.

Table 2. Regression of the *n* value on the data of *D/B* in various discharges and slopes.

Q (cms)	Slope	Regression of the Manning's *n*	Correlation Index
0.0142	*0.002*	$n = 0.0565x + 0.0236$	$R^2 = 0.731$
	0.004	$n = 0.0736x + 0.0257$	$R^2 = 0.810$
	0.006	$n = 0.07x + 0.0291$	$R^2 = 0.831$
	0.008	$n = 0.0735x + 0.0317$	$R^2 = 0.913$
0.0202	*0.002*	$n = 0.0488x + 0.0184$	$R^2 = 0.928$
	0.004	$n = 0.0667x + 0.0218$	$R^2 = 0.982$
	0.006	$n = 0.0601x + 0.0257$	$R^2 = 0.870$
	0.008	$n = 0.0578x + 0.028$	$R^2 = 0.871$
0.0283	*0.002*	$n = 0.025x + 0.0176$	$R^2 = 0.714$
	0.004	$n = 0.0586x + 0.0188$	$R^2 = 0.964$
	0.006	$n = 0.0515x + 0.022$	$R^2 = 0.977$
	0.008	$n =0.0548x + 0.0234$	$R^2 = 0.918$
0.0332	*0.002*	$n = 0.0406x + 0.0144$	$R^2 = 0.957$
	0.004	$n = 0.0487x + 0.017$	$R^2 = 0.983$
	0.006	$n = 0.0492x + 0.0192$	$R^2 = 0.851$
	0.008	$n = 0.0527x + 0.0204$	$R^2 = 0.763$

x: the ratio of height *D* and channel width *B*.

(3) *0.0283 cms*: there is a higher correlation index at S = 0.004 and 0.006.

(4) *0.0332 cms*: there is a higher correlation index at S = 0.002 and 0.004.

From various height-width ratio and discharges, results show that the higher correlation index is gained at mild slopes, and high discharge conditions. For example, at slope 0.008 it reveals lower correlation index.

6. Manning's *n* vs. Roughness f_r Relationship

According to the definition of roughness by Juang [14], in this experiment we calculate the roughness by the following formula:

$$f_r = \left(\frac{D}{W}\right)\left(\frac{bD}{D_m\left(b_m + W_m\right)}\right) \tag{17}$$

where f_r is the surface roughness, *D* the height of projection, *b* the width of block and *W* gap distance in blocks. For D_m, b_m and W_m are the highest height, width and gap distance in the experimental model. The size of this test are D_m = 7 cm and $B_m + W_m$ = 12 cm (see Fig. 7).

When the roughness f_r is obtained from (17) and the data of Manning's *n* is gained, the amount is around 0.446~1.17. Using the experiment results of *n* values (0.0167~0.0437) compares among height *D*, roughness f_r and *n* values, we can conclude that the higher height means the higher roughness. However, from (18) roughness f_r is in

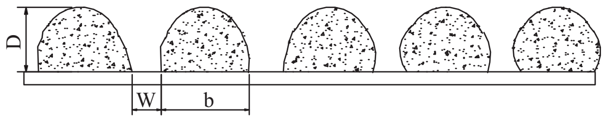


Fig. 7. Definition of model surface roughness drawing.

proportion to height D, and also when the gap distances increase, the roughness decrease. Roughness is in inverse proportion to gap distance W. From the relationship of roughness f_r and n value, there is a linear relation between height and roughness, which reveals roughness increases with increasing height. The relationship of height D and roughness f_r is analyzed by regression as following (Fig. 8):

$$f_r = 0.1723D + 0.0126 \tag{18}$$

where D is height of block, and the relationship of roughness f_r and n value yield as following (Fig. 9):

$$n = n_0 + n^* \left(1 - e^{-K \times f_r}\right) \tag{19}$$

where $n^* = (n_{max} - n_0) = 0.022$, n_0 is 0.013 by Chow [5], f_r is roughness of block and relative reference K is -1.854.

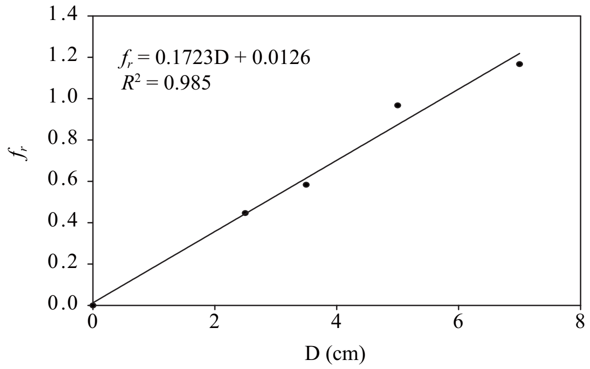


Fig. 8. Relationship between roughness f_r and height D.

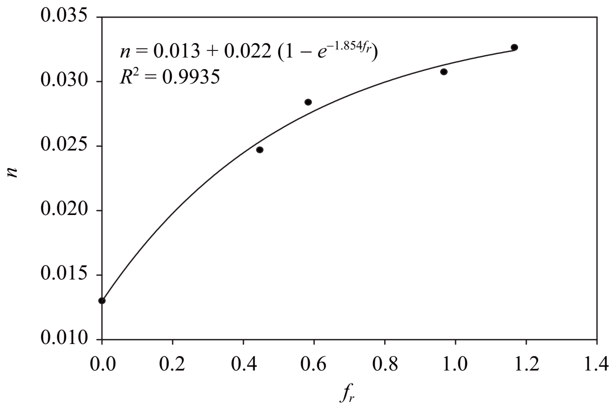


Fig. 9. Relationship between Manning's n and roughness f_r.

7. Discussion

The hydraulic characteristics of PECBs were investigated in the present study through experimental results such as the velocity distribution and the reported trend of Manning's n vs. flow velocity, flow discharge, bed slope, the height-width ratio and roughness f_r. The discussions were:

(1) The Manning's n of PECB was around 0.0167~0.0437, in various discharge conditions, the roughness coefficient decreased with increasing discharge and with depth. In the same discharge condition, the roughness coefficient increased with increasing slope, until at a certain amount the n value remained stable. That result has the same trend with Jarrett's researches in Colorado, US [10, 11, 12].

(2) In two different experiments we lined the bottom with concrete and the other we used PECB. Both n values are approximate. That proves the equivalent n method could be utilized to estimate n values of various materials at the same section.

IV. SUMMARY AND CONCLUSIONS

The hydraulic characteristics of PECBs for irrigation canals are investigated experimentally in the present study through laboratory facilities. Experimental results reveal that the reported trend of Manning's n vs. discharges and bed slopes relationship, and also reveal the relationship between heights of block and widths of canal. The conclusions of this paper are as following:

(1) The experimental results showed that for the Manning's n of PECBs is between 0.0167~0.0437 approximate to that of piling up cobblestone of concrete as side protection. Therefore, it is helpful to lower the frequency to mine stone materials for construction by developing PECB. At the same time, the research and development of repetitive mouldboard could be convenient and cost saving in construction.

(2) The curve of velocity distributions revealed that the diverse flows were created by the convex profile of side walls. In comparison with the concrete lining for canals, convex profile canals could be more available to supply habitats for organisms.

(3) The experimental results showed that the heights of projection of the model is 2.5 cm~7.0 cm, roughness of projection is 0.446~1.17 and the Manning's roughness coefficients are around 0.0167~0.047. Through regression analysis, the relationship between heights and roughness f_r is f_r = 0.1723D + 0.0126 and the relationship between roughness f_r and Manning's n is $n = n_0 + n^*(1 - e^{-1.854 f_r})$. These results could be used as a reference for the improvement in construction of irrigation and drainage canals.

We suggest that further research could focus on the vegetated effects of PECBs and also the strength of the blocks.

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