THE STABILITY OF STEEP CONCRETE BLOCK PAVEMENTS UNDER HIGH-VELOCITY WATER FLOW CONDITIONS

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SUMMARY

This paper deals with an actual testing of Concrete Block Pavement (CBP) under high velocity water flow on a one-to-one scale, with definition of flow and failure mechanisms in the CPB, and with the adoption of proper solutions. Five tests were performed in an experimental water flume, differing mainly in their type of bedding sand, joints sand, base course, bottom longitudinal slope and flow velocities. The use of conventional fine sand bedding under continuous water flow conditions is inappropriate, such a bedding cannot provide the necessary stability for the CBP. On the other hand, the use of fine aggregate, such as Bird's Eye Aggregate (BEA), as bedding material, ensured the stability of the CBP under continuous supercritical flow velocities and steep channel slopes, excellent performance of the CBP was observed with the underlying flow with velocities and steep channel slopes. BEA bedding, even after exposure to 5.5. hours of continuous water flow with velocities of 3.5m/sec. on a steep slope of 13%. The stability of the CBP maintained even after removal of several blocks. It is believed that the results of this study will also constitute a milestone in the future use of CBP in hydraulic structures.

INTRODUCTION

Hundreds of millions of square meters of Concrete Block Pavements are being constructed around the world each year, and this number is rising constantly. Presently, the CBP becomes an attractive engineering and economical alternative to the flexible asphaltic pavement, on the one hand, and to the rigid concrete pavement, on the other [1,2,3,4].

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In some locations the intended use of CBP involves the combination of very steep grades (up to 15 %) in a storm-sensitive region. The outcome is a risk of high-velocity water flow on the steep CBP pavements. Under these conditions, and due to the special characteristics of the CBP and its unknown response to high-velocity water flow, the following problems should be dealt with:

a. The danger of sand erosion from the bedding layer and the joints between the blocks due to the surface drainage water flow.

b. The danger of development of uplift forces due to the downward water seepage.

The accumulative effect of these two dangers may cause a gradual loss of support of the CBP up to a severe total failure. Since no technical information could be found on this subject, the solution of these problems should be treated in three ways:

a. Actual evaluation of the hydrological scope of the problem under real site condition climate.

b. Actual testing of CBP under high-velocity water flow in one-to-one scale.

c. Definition of flow and failure mechanism in the CBP, and adoption of proper solutions.

This paper deals with point "b" and "c" above. It describes an experiment which provides relevant information to the resistance of steep concrete block pavements to high velocity water flow [5].

EXPERIMENTAL PROGRAM

The Testing Flume

The laboratory study was performed in one of CAMERI's testing flumes. The dimensions of the flume are 27 m. length, 1.1m. height and 0.6 m. width. Two windows of 6 m. overall length are located at the downstream side of the flume in order to facilitate visual observations and photos. The CBP test sections were 5.0 m. length for the 5% slope tests and 2.75 m. for the 13% slope test. The experimental flume test section is described in Figs. 1 and 2. The testing flume is connected to a water supply tank by means of a recirculating pumping system with a capacity of 800 cu.m./hour.

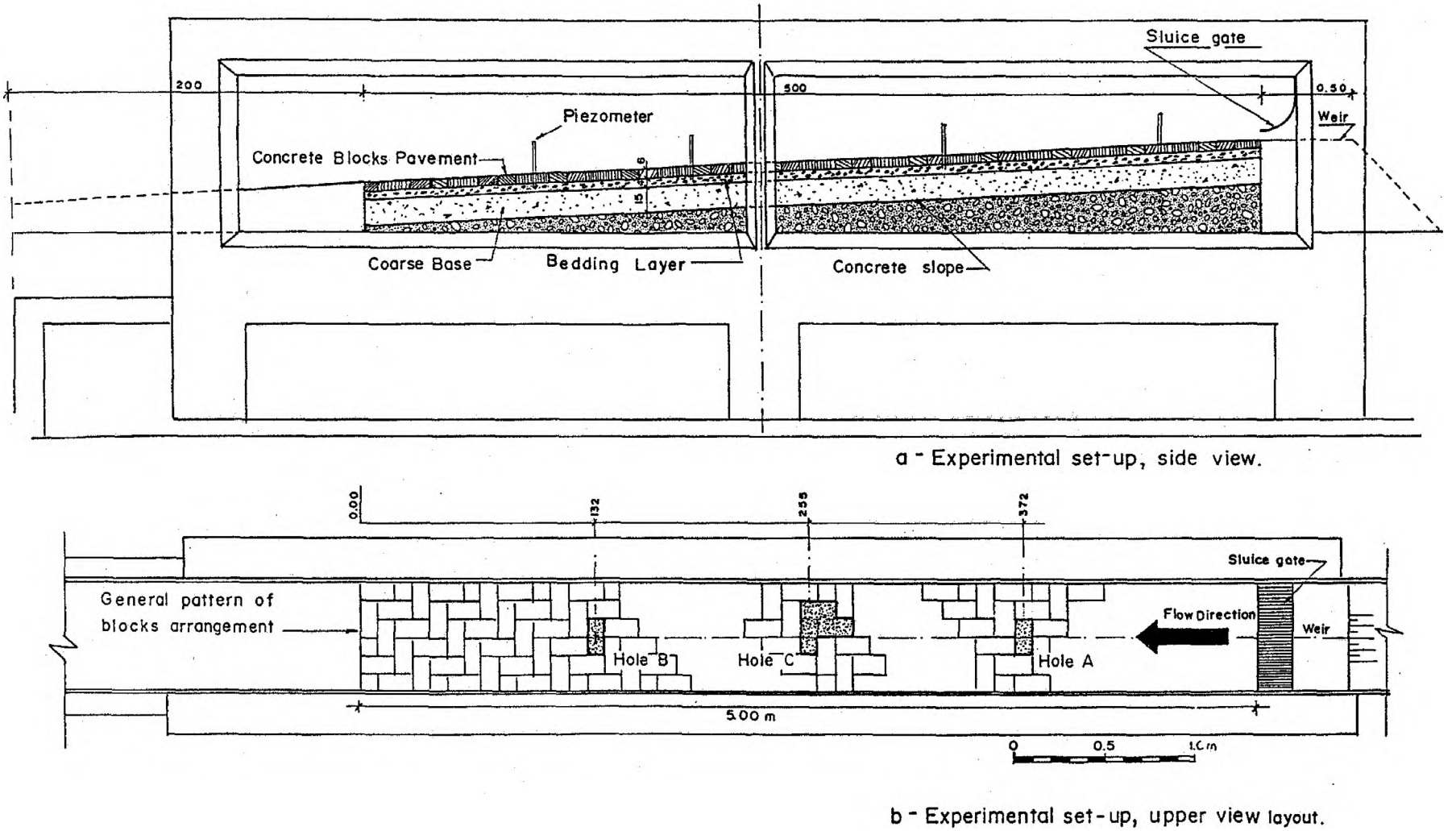


Figure 1: Description of the experimental flume test section.

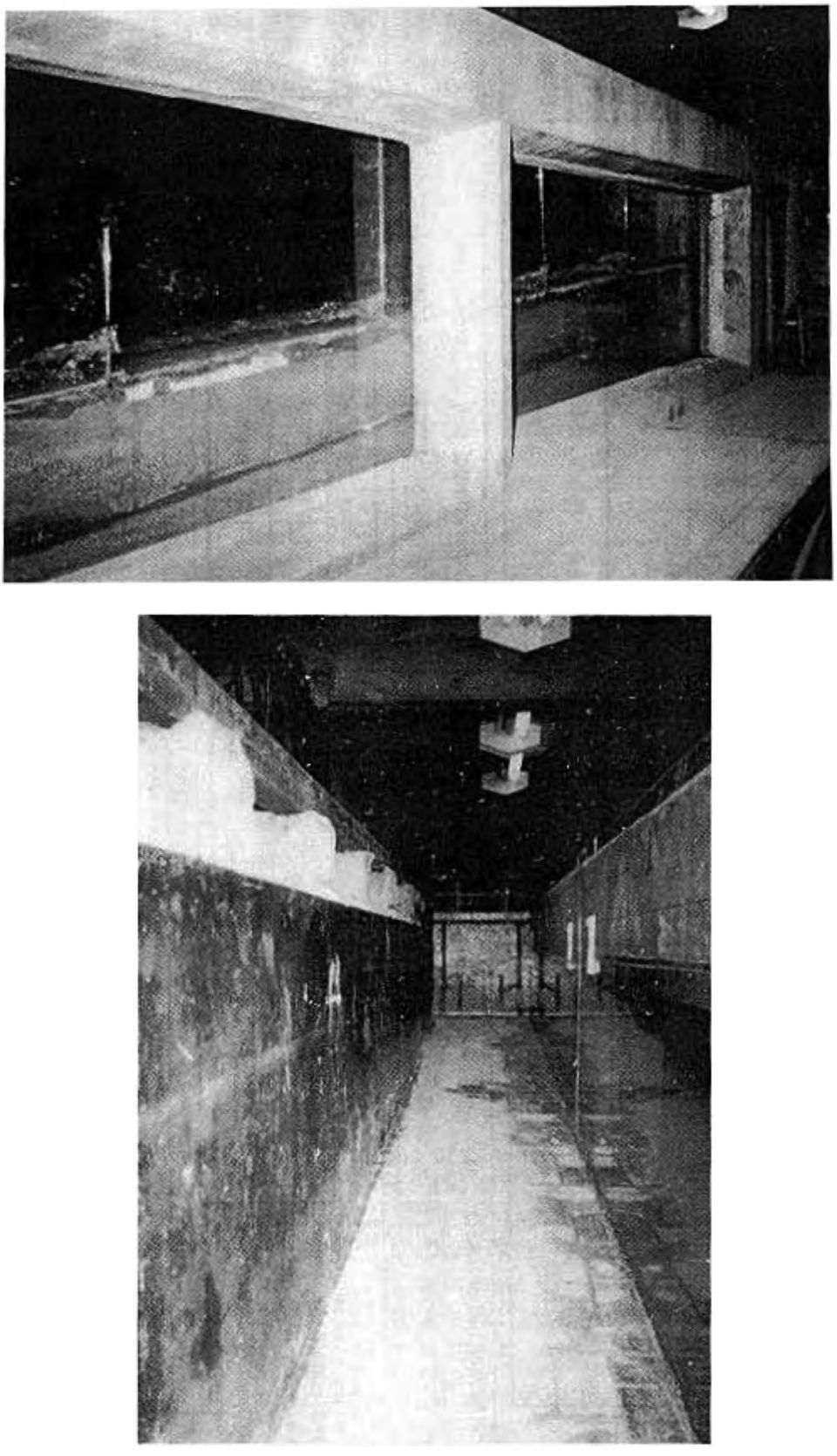


Figure 2: Photographs of the experimental flume test section.

Testing Program

Five different tests were performed. They differ mainly by the type of bedding sand, joints sand, base course, bottom longitudinal slope and flow velocities (see Table 1). During each test the water flow rate was kept constant. Flow stop intervals were helped in order to monitor the pavement structure stability and behavior. Photographic pictures were taken during each test. Tests nos. 2 and 4 were also monitored by photographic video.

In tests nos. 4 and 5, after initial common flow, single blocks were artificially bolted and afterwards some blocks were removed from the pavement surface, in order to study the resulting scour and possible instability of the CBP. Tests nos. 3, 4 and 5 were designed to be performed provided that a major failure is observed in Tests 1 and 2.

Structure of the Concrete Blocks Pavement fCPB)

For all tests the following CBP structure was utilized:

Base course	15 cm.
Bedding layer	4 cm.
Paver blocks	6 cm.
Total pavement structure	25 cm.

The paver blocks were 10x20 cm. rectangular layed in a "herringbone" pattern. The bedding layer in Tests 1 and 2 was the "Classical Fine Homogeneous Sand Bedding". In Tests 3,4, and 5, a fine, Bird Eye Aggregate (BEA) was used for the bedding layer. Gradation curves of the sand and the BEA bedding materials are presented in Fig. 3. The base course material was mostly crushed graded aggregate with maximum size of 1".

Construction of the CBP

The CBP construction was carried out in the following, common manner:

a. Laying of the base course, and compaction with a vibratory plate-tamper.

b. Spreading of the bedding sand or the BEA and leveling to the appropriate grade.

c. Laying of the paver blocks; spreading and filling the joints sand, and compaction with the vibratory plate-tamper.

TABLE NO. 1: TESTS CHARACTERISTICS

Test No.	1	2	3	4	5
Longitudinal Slope	5%	5%	5%	5%	13%
Flow Characteristics	Average velocity of 1.6 m/sec. and water depth of about 5 cm	Velocities of 1.6 to 1.9 m/sec. and water depth of 5 to 7 cm.	Velocity of 2.5 m/sec water depth of 7 to 9 cm.	Same as 3	Velocities of 3.2 to 3.5 m/sec. and water depth of 5 cm to 8 cm.
Base Course Materials	#10 - 3/8" crushed aggregates	Crushed graded base course material. 1" Max. Aggregate size.	Crushed graded bird's eye agg. 5 mm max. aggregates size	Same as 2	Same as 3
Bedding Sand Material	Uniform dune sand	Same as 1	Crushed graded bird's eye agg. 5 mm max. aggregates size	Same as 3	Same as 3
Joint Sand Material	Uniform dune sand	Same as 1	Cement stabilized (5%) dune sand mixed with bird's eye aggregates	Dune sand mixed with bird's eye aggregates	Same as 4
Special Features	—	—	—	Test involved bolted blocks and missing blocks	Same as 4

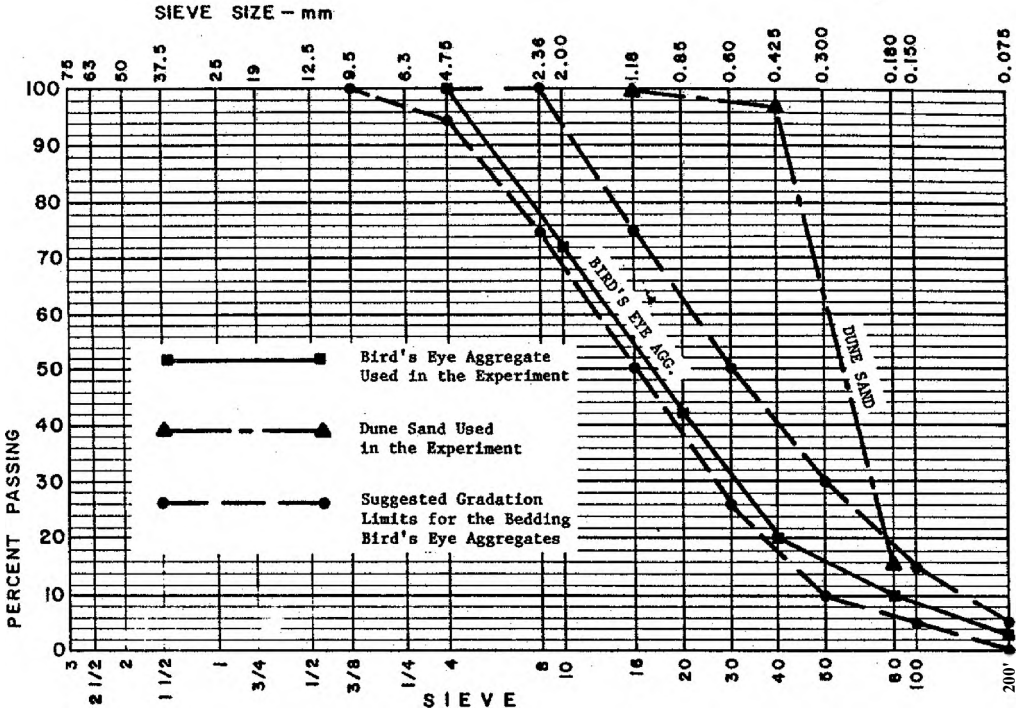


Figure 3: Gradation curves and limites of the CBP bedding and joints materials.

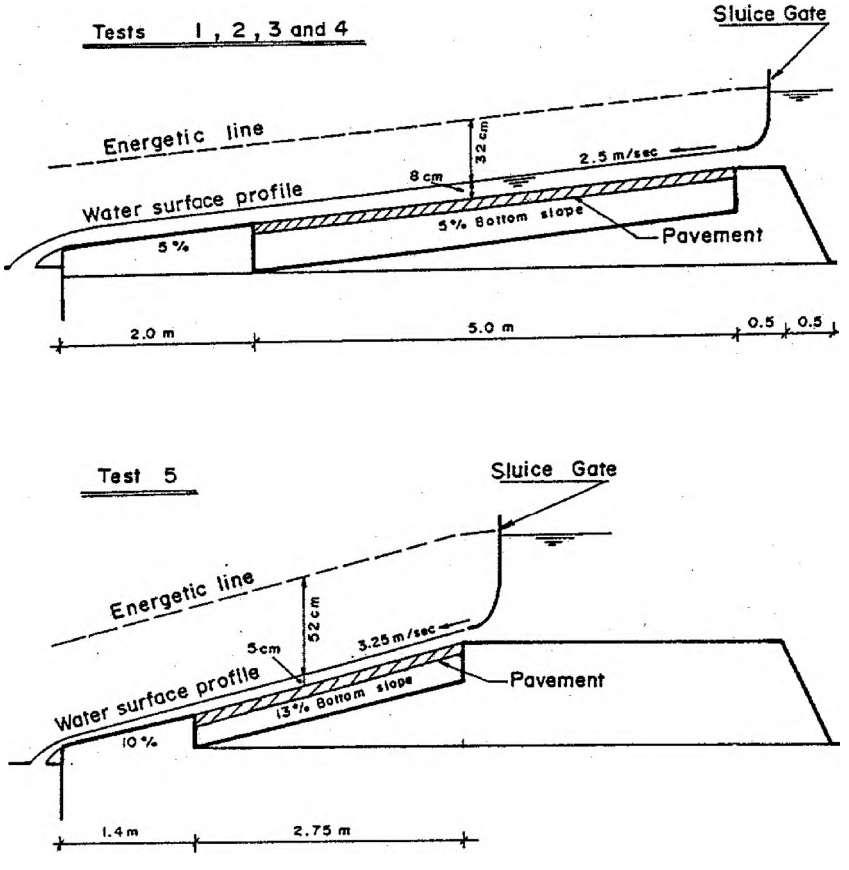


Figure 4: The water flow and channel characteristics

Other Experimental Characteristics

The flow parameters are represented in Table 1 and Fig. 4. In Tests nos. 1,2,3 and 4, the pavement was built on a flume longitudinal floor slope of 1:20 (5%) in order to obtain a mean flow velocity of 1.5 m/sec to 2.5 m/sec. Test no. 5 was performed with a pavement longitudinal slope of 1:7 (about 13%) and a mean flow velocity of 3.25 m/sec. A sluice gate was used on the upstream side in order to facilitate uniform steady flow along the entire pavement length.

The boundary conditions of the water flow were determined by a sluice gate located in the upstream one of the pavement area and by a concrete slope extension of the pavement slope, downstream of the pavement area. In Tests 1,2, and 4, four piezometers were installed along the channel floor under the CBP.

The stability of the pavement was checked during continuous supercritical water flow conditions. Continuous observations were performed during each test which was also measured and summarized. The water flow velocities were measured with a Marsh-McBimey, Model 523, Electromagnetic Water Current Meter, consisting of a transducer probe and a signal processor. The current sensor measures the water flow in a plane normal to the longitudinal axis of the probe and presents the flow by providing values of two orthogonal components.

The experimental flume is equipped with an operating Fisher and Porter Magnetic Flowmeter, Model 10D1420A, and a MAG/I, Model 50ED10000 Series, which converts the signal output produced by the Magnetic Flowmeter.

EXPERIMENTS AND EXPERIMENTAL RESULTS

Experiments with Sand Bedding

In the first set of tests, a conventional pavement structure was constructed underneath the pavers. It consisted of 15 cm. of crushed rock subbase and a layer of 4 cm. of sand bedding. The sand was a typical dune sand whose particle size ranged between 0.2and 0.4mm. The same sand was used for filling the joints which were about 2 mm. wide. This width is about 10 times the size of the average sand particle size.

The experiments were performed at average velocities of 1.6 to 1.9 m/sec and water depths of 5 to 8 cm., and test section longitudinal slope of 5%. After about 15 minutes of initial testing, the erosion of the sand from the joints was examined. Most of the joint-sand was eroded. In about the same time, the sand bedding was entirely saturated. During the second hour, the scour of the sand bedding was expanded downstream. The scour and its expansion downstream was caused by the wash-out of the sand bedding through the empty joints between the blocks at the lower part of the slope. Generally, a continuous channelling was developed underneath the blocks, while the sand bedding was gradually washed out in the downstream direction and through the joints at the lower section (see Fig.

5). As a result, the paver surface lost its support, causing significant settlement and deformation of the blocks (see Fig. 6). When the experiment was finished after 2.5 hours, the deformation of the paver surface was clearly observed. However, not even a single block was washed out or moved from its initial location due to the interlocking effect of the block pavement, as can be seen in Fig. 6.

These two experiments proved that the conventional use of fine sand bedding is unsuitable when a concrete block pavement is subject to continuous waster flow.

Experiments With Fine Aggregate Bedding of *5%* Slope

a. General Experiments

In order to overcome the wash-out of the sand bedding phenomenon, it was decided to replace the fine sand bedding layer by a coarser material whose granular size was of the magnitude of the joints' width. Bird's eye aggregate (BEA, or pea-gravel) was selected for this purpose to replace the sand bedding. The modified sub-structure was constructed underneath the paver surface, and a set of experiments was performed, at the same longitudinal slope of *5%* (test no. 4). During these experiments, high water flow velocities were applied. The velocity was about 2.5 m/sec.

Within a short period of time, the BEA layer was saturated, and its piezometric pressure was observed to be identical to the water depth. This identity could be seen in the colored water level inside the piezometers. Most of the joints sand, which was also mixed with the BEA, was washed out after a short period of flow. During more than two hours of continuous water flow, no damage was observed to the pavement surface and its sublayers, despite the high velocity of the water flow.

The experiment was stopped after about two hours and 15 minutes. The pavement surface was checked and no distortion or displacement was observed, the paver surface was found to be entirely stable.

b. Experiments with Bolted and Lowered Blocks

At this point in test no. 4, two blocks were bolted out for about 4 cm., 2/3 of their thickness from the pavement surface, and another block was lowered down for the same depth. The flow was then continued for an additional 1.5 hours. Although only 2 cm. of the bolted clocks remained to interlock with the pavement, the bolted blocks did not move, and the entire pavement still remained stable from an accumulated time of 3 hours and 45 minutes. When the bolted blocks were removed it was noticed that the bedding layer remained stable and unchanged. The experiment was then continued while leaving the two holes (created by the removal of the bolted blocks) exposed to scour.

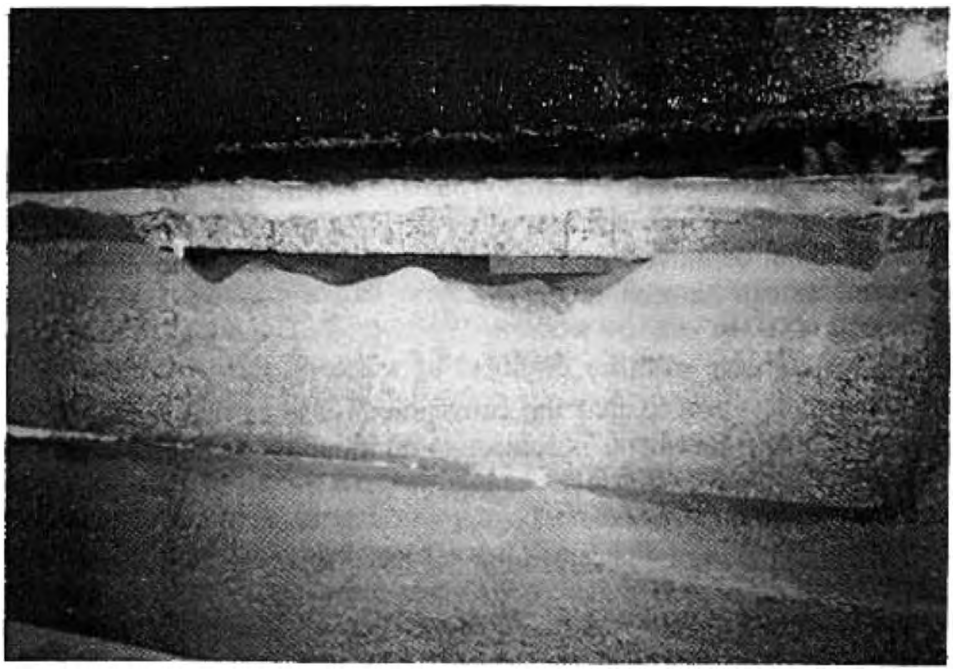


Figure 5: Continuous channeling of the bedding sand underneath the blocks in tests Nos. 1 and 2.

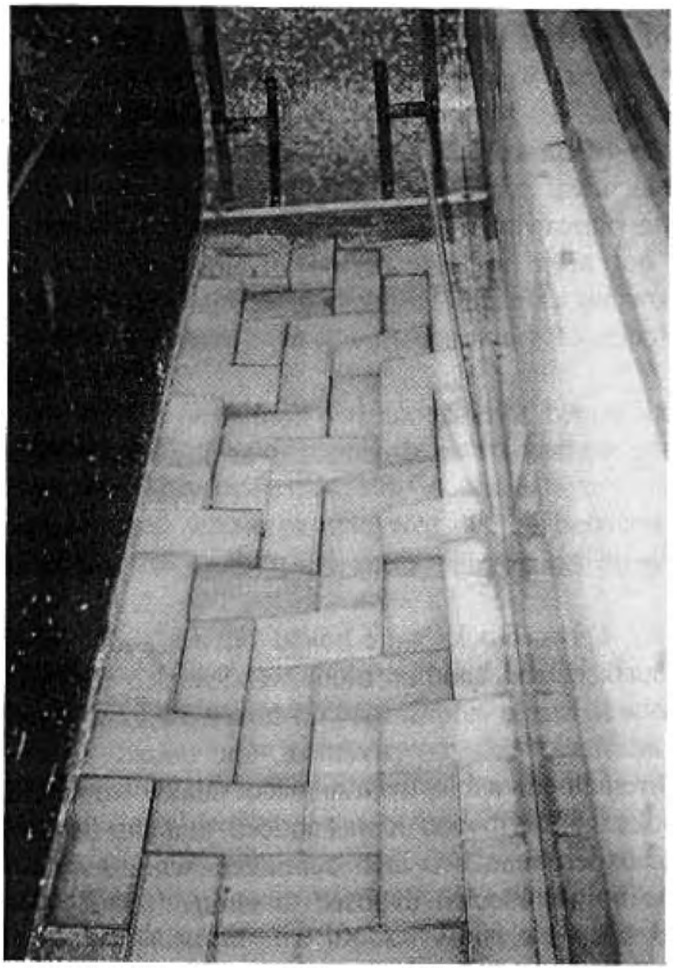


Figure 6: Significant settlement and deformation of blocks in tests Nos. 1 and 2.

c. Experiments with Removal of a Single Block

The purpose of this stage of the experiments was to investigate whether removal of a single block causes any major failure of the pavement. After 15 minutes, the flow stopped and the hole created by the scour was examined. Only limited local scour was observed. Then the experiment was continued. The downstream hole B (see Fig. 1) was exposed to supercritical flow only, while the upstream hole A was exposed to artificially created conditions of extra turbulence.

At the conclusion of the test, which lasted a total of 5.5 hours, and 1.5 hours from the removal of the blocks, no single block was displaced, and the entire pavement remained stable, intact and undistorted. The blocks adjacent to the holes were removed and the scour was examined and measured in both holes. The scour effect was found to be local and limited only to the near surroundings of the holes. The depth of the scour was limited too, and was no more than 10 cm. in both cases.

Experiments with Fine Aggregate at 13% Longitudinal Slope

Experiments, identical to those described in the preceding section, were performed with a test section whose longitudinal slope was 14%, as shown in Fig. 4. The experiments ran at similar time periods of 5.5 hours. However, the water flow velocities were much higher, of up to 3.5 m/s. (See also Fig. 7). Single blocks were removed as well as up to 4 adjacent blocks. It was observed that the paver remained stable, and only local scour effects were found in the vicinity of the removed blocks, as shown in Figs. 8 and 9.

STABILITY OF THE CBP

The CBP was found to be stable in all the experiments in which fine aggregate as BEA bedding was utilized. Even at flow velocities of 3.5 m/sec no damage of the pavement was observed. When blocks were removed and a hole was created in the pavement, only local scour occurred at the vicinity of the hole. The results related to the removal of a single block were positive from the engineering point of view, as no significant scour was observed, except for the local zone of the removed block even under severe turbulent conditions. However, more information concerning possible local or major failure had to be gathered with regard to the removal of several blocks. Tests relevant to this goal were performed as follows:

a. In Test no. 4, in which 3 adjacent blocks were removed, a section was exposed to water flow velocity of 2.5 m/sec, at a longitudinal slope of 5%.

b. In Test no. 5, in which 3 blocks were removed, a section was exposed to a water flow velocity of 3.5 m/sec, at a longitudinal slope of 13%. Results are shown in Fig. 8.

c. In Test no. 5, in which 4 blocks were removed, a section was exposed to a water flow velocity of 3.5m/sec, at a longitudinal slope of 13%. Results are shown in Fig. 9.

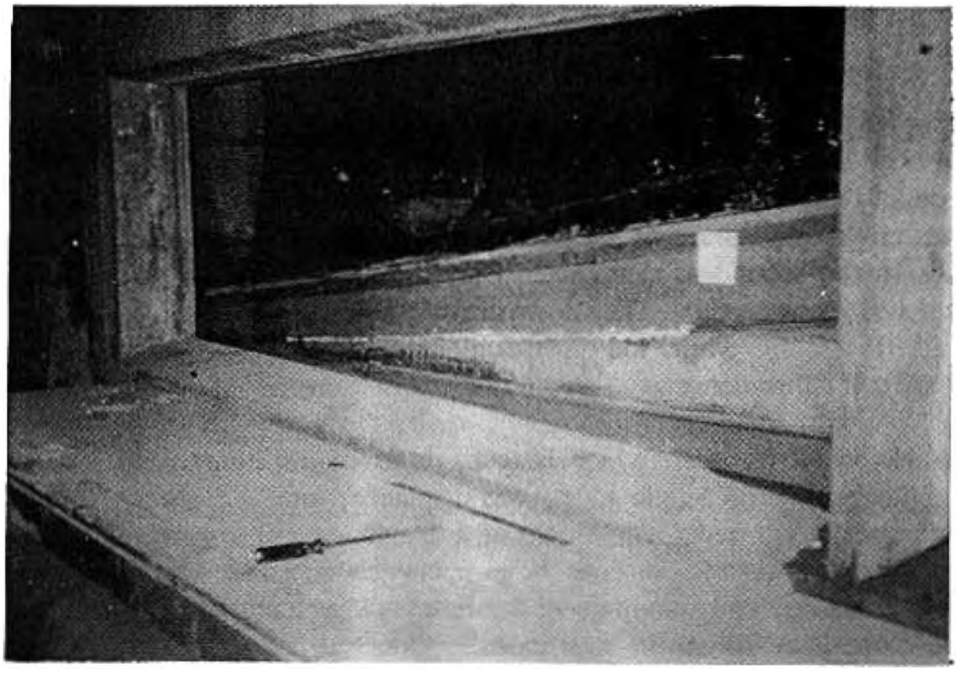


Figure 7: Experimental set up at test No. 5 with 13% slope.

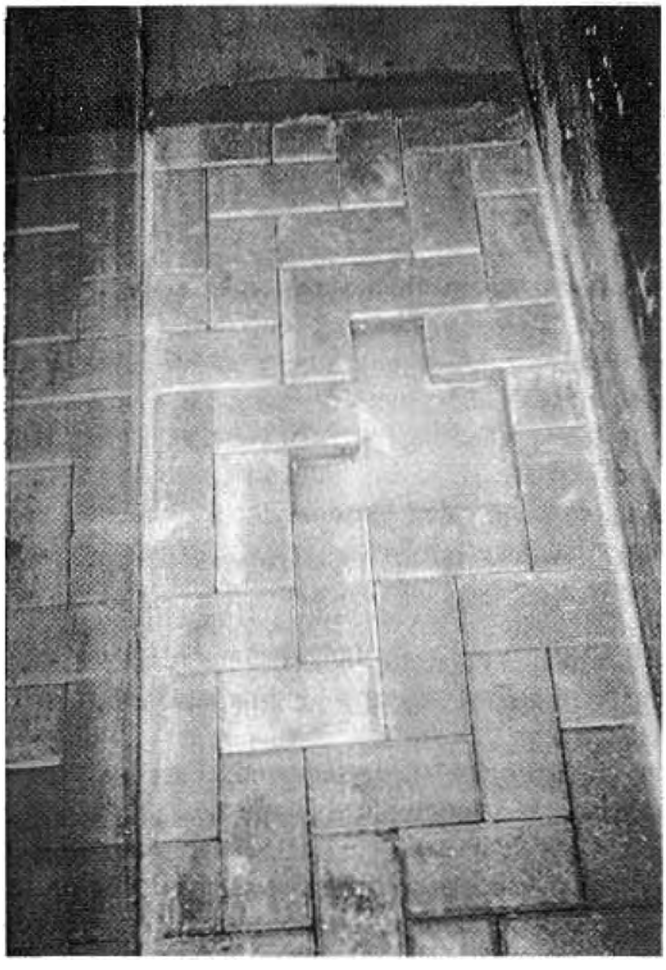


Figure 8: CBP condition after the end of test No. 5 with 13% slope.

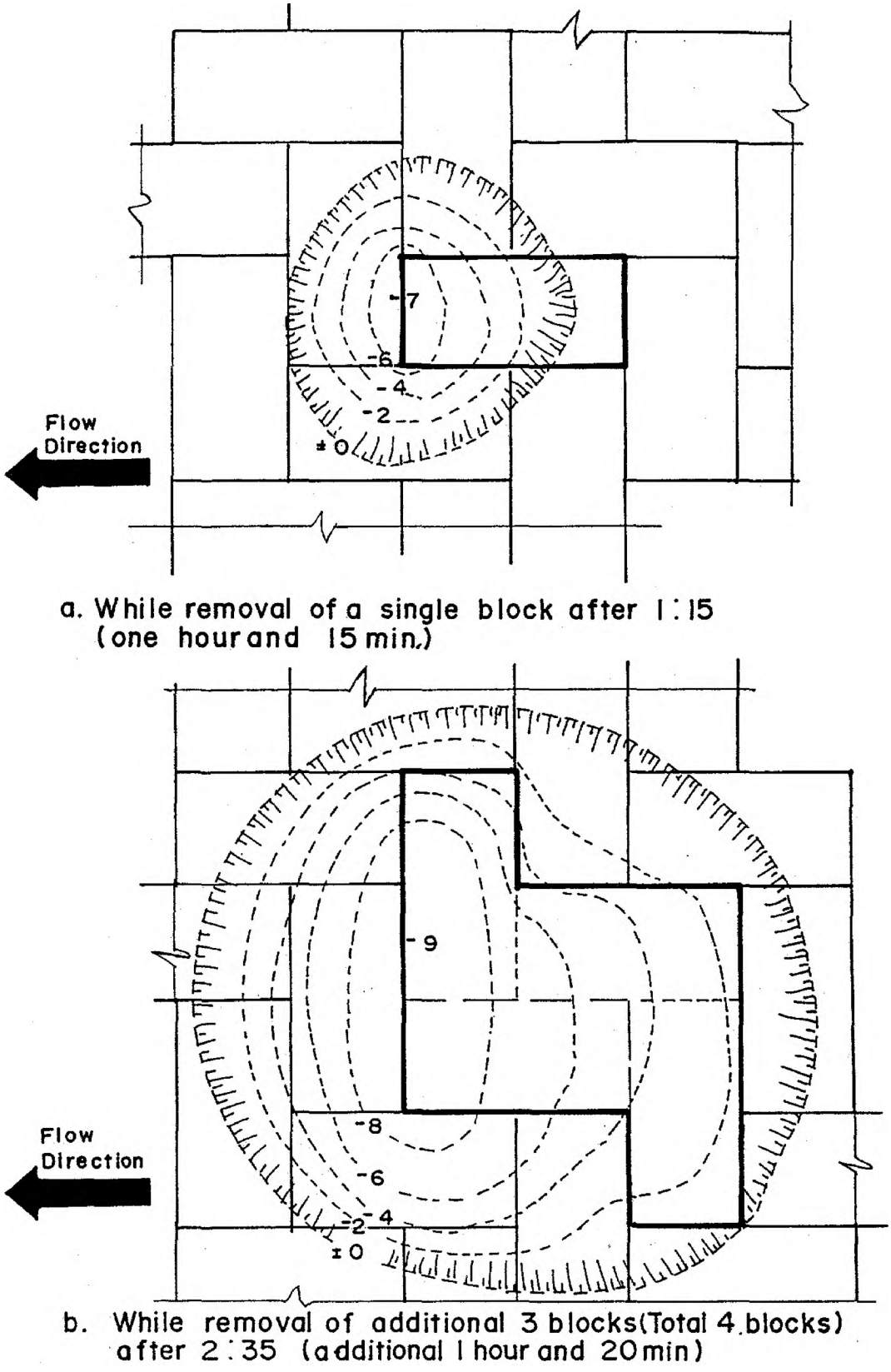


Figure 9: Test No. 5; 13% longitudinal slope: local scour occurring at supercritical flow conditions.

All experiments indicated that the scour which was developed at the vicinity of the holes remained at a limited size, and had a local nature. The interlocking effect between the pavement blocks was found to be sufficient in order to resist the flow shear forces as well as to the absence of local bedding. In all experiments, the pavement remained stable, and even a single block was not subject to a measurable displacement.

ADDITIONAL ENGINEERING PRECAUTTONAL MEANS

In a preparatory work preceding the design and performance of the above experiment, inquiry was made among CBP experts from different countries around the world [6]. The inquiry asked for any research experience, and suggestions related to the resistance of steep concrete block pavements to high velocity water flow.

Although most of the experts agreed that there is no previous research specifically performed to handle the above problem, their successful practical experience may lead to some suggestions for engineering means which may contribute to the resistance of the CBP to high-velocity water flow, the following are some of the above engineering means:

a. Improving of surface drainage to ensure that surface water runs off the pavement as quickly as possible. This can be done by close attention to the camber and transversial slopes and the provision of frequent side drain or channels.
b. Use of shaped blocks rather than rectangular ones to provide additional geometric interlocking.
c. Using thicker blocks in greater slopes in order to increase vertical block face contact.
d. Laying the blocks in "herringbone" pattern at 45° to the slope for avoiding straight lines for the water to flow.
e. Construction of the pavement in "uphill" direction in order that the pavement works “with gravity" rather than against it manly to avoid opening up of the joints.
f. Use of effective drainage layer in the pavement to help remove water penetrating into the pavement and avoid uplift erosion of bedding sand and water seepage out of pavement joints further downhill.
G. Stabilizing the jointing sand either with portland cement or Bentonite (Fullers Earth) for early sealing of the joints.
h. Design thickness should be based on soaked subgrade CBR value. High plasticity sands and crushed rock should be avoided.
i. Refilling of joints with sand after heavy rainfalls.
j. Laying a geotextile membrane between the bedding sand and the base course layer.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations summarize this study on the stability of steep CBP under high-velocity water flow conditions:

1. The use of a conventional sand bedding under continuous water flow conditions was found to be inappropriate. Such a bedding cannot provide the necessary stability of the CBP.

2. The use of fine aggregate, like the bird's eye aggregate (BEA), as a bedding material, ensured stability of the CBP under continuous supercritical flow velocities and steep channel slopes, the recommended gradation limits for the BEA are given in Fig. 3.

3. Excellent performance of the CBP was observed with the underlying BEA bedding, even when being exposed to 5.5 hours of continuous water flow of 3.5 m/sec on a steep slope of 13%.

4. The scour phenomenon occurring while removing a single or several blocks of the pavement was found to be of a very limited size, and bears only local effects.

5. Test observations indicated that, provided the CBP bedding is made of BEA or similar aggregate, the interlocking characteristics of the CBP allows only local damage to be caused by the removal of several blocks of the CBP.. No "domino Effect" is reasonable in such a structure. However, in order to provide additional safety factors to the CBP, it is recommended to use the UNI type of CBP, which provides an extra high interlocking when extreme conditions of flow velocity and pavement slope prevail.

6. The major implication of this study is that the use of sufficiently course aggregate as a bedding material is the proper engineering solution which ensures the absolute stability of the concrete clocks pavements (CBP) under high water flow velocity at supercritical conditions. Observations of this study indicated that such a bedding ensured that none of the pavement blocks may be subject to movement, and the entire pavement remains stable.

7. Additional engineering precautional means should also be considered for increasing the resistance of the CBP to high-velocity water flow.

8. It is believed that the results of this study will provide a milestone in the future user of CBP also in hydraulic structures.

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