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Laboratory and Field Studies of Oyster Larvae Settlement on Three Substrates, Oyster Shell, Tire Chips, and Expanded Shale, and the Relative Mobility of the Three Substrates

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FILE

MARINE RESOURCES REPORT NO. 89-3

LABORATORY AND FIELD STUDIES OF OYSTER LARVAE SETTLEMENT ON THREE SUBSTRATES, OYSTER SHELL, TIRE CHIPS, AND EXPANDED SHALE, AND THE RELATIVE MOBILITY OF THE THREE SUBSTRATES

By

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By

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FOREWARD

The studies reported herein arose from a request funded by the Virginia Marine Resources Commission in July 1988. During 1987 and 1988 members of the Virginia oyster industry requested permission to broadcast tire chips (shredded tire casings) on private oyster leases. In the course of discussions, questions arose regarding potential toxicity and mobility of these materials. As well, there was incomplete assessment as to whether various alternative substrate materials compared favorably with oyster shell with respect to larval settlement. In addition to oyster shell and tire chips, a commercial aggregate, SOLITE®, an expanded natural shale, was included in the studies.

Three study elements were funded by the Commission:

1. Laboratory evaluation of alternate substrates for oyster settlement.
2. Field evaluation of comparative settlement of oyster larvae on alternate substrates.
3. Mobility and hydraulic roughness of three substrate materials.

Presentation is offered as an Executive Summary followed by the three, separate reports of the principal investigators of the component studies.

ACKNOWLEDGEMENTS

The principal investigators thank Mr. Chris Kuhn of Virginia Recycling Corporation and Mr. Bruce C. Cann of Solite Corporation for contributing, respectively, tire chips and expanded shale for use in the studies. Additionally, Captain Tom Stevens of Lancaster, Virginia, contributed tire chips.

Thanks are due to Dr. Rosalie Cumbee, Kathleen Greene, Michael Hardwicke, and Joy Dameron Smith for assistance in the laboratory studies. The field work program and associated oyster spat counts were performed by James Whitcomb, Raymond Morales-Alamo, and Kenneth Walker. Frank Farmer assisted in the laboratory flume tests.

EXECUTIVE SUMMARY

A. BACKGROUND

In July 1988 the Virginia Marine Resources Commission requested and funded studies to compare the oyster larvae settlement characteristics of two commercially available substrates (tire chips and expanded shale) with oyster shell and to evaluate the relative mobility of the three substrates under waves and/or currents. Pursuant to that request, studies were designed to address three questions:

1. In the idealized laboratory situation, is there a real difference between the oyster larvae settlement characteristics for the three substrates? This question was examined using hatchery-reared oyster larvae, Crassostrea virginica.

2. Is there a real difference between oyster settlement characteristics for field conditions? This question was addressed by placing the substrate materials in mesh bags suspended in the water column at four locations in the James River during August and September 1988.

3. Are there differences in substrate mobilitiy and turbulence intensity as induced by waves and currents? This question was addressed by studies in a unidirectional flow laboratory flume and by field test plots of the respective substrate materials.

B. CONCLUSIONS

1. Comparative Settlement Characteristics.

Both the laboratory and field studies demonstrated that oyster shell was, by far, the superior substrate with respect to oyster settlement. The field tests indicated that tire chips received greater settlement than expanded shale. However, the laboratory studies did not generally disclose a statistically significant difference between settlement on tire chips and settlement on expanded shale.

2. Comparative Mobility of the Substrates.

In laboratory test beds under unidirectional flow, oyster shell was most stable, followed by tire chips and expanded shale. However, under field conditions with exposure to wave action, only tire chips dispersed away from the test plots. The oscillatory water movements associated with wave action induced shoreward movement. In marked contrast, the test plots of oyster shell and expanded shale remained intact with their surfaces exposed throughout the observation period.

It is concluded that tire chips are unsuitable for use as a substrate material in shallow estuarine environments exposed to wind waves or recurrent large boat wakes.

C. SUMMARY OF COMPONENT STUDIES

1. Laboratory Studies of Oyster Settlement.

Four experiments were conducted to examine the influence of alternate substrates:

a. Isolated chamber comparison of larval setting between expanded shale and oyster shell.

b. Isolated chamber comparison of setting between expanded shale, tire chips, and oyster shell as substrate.

c. Single chamber comparison of larval setting preference among expanded shale, tire chips, and oyster shell.

d. Effectiveness of "seasoning" expanded shale in estuarine water on oyster setting.

These experiments utilized tire chips without steel belting. All substrates were subaerially weathered. Experiments (a) through (c) were replicated ten times each. All substrates were of similar size (35 mm x 50 mm).

Results of the individual tests are:

a. Expanded Shale Versus Oyster Shell. Oyster shell, when compared independently against expanded shale, had significantly higher sets of oyster larvae. Three times as many oyster larvae set on oyster shell as on expanded shale.

b. Individual Comparisons Between Oyster Shell, Expanded Shale, and Tire Chips. Sets on oyster shell exceeded tire chips by a factor of two and exceeded expanded shale by a factor of five. There was a significant statistical difference between expanded shale and tire chips.

c. Preference Between Substrates. When oyster larvae were provided a choice in substrate, oyster shell was the preferred substrate. There were six to eight times more spat on shell relative, respectively, to tire chips and expanded shale. However, there was no statistically significant difference between setting on expanded shale versus tire chips.

d. Effect of "Seasoning" Expanded Shale. Expanded shale was immersed for two and one-half months in the York River and then cleaned and tested. Four substrates (oyster shell, tire chips, expanded shale, and seasoned expanded shale) were independently tested. The set on oyster shell was significantly larger than on the other three substrates. Among the alternate substrates there were no statistically significant differences.

Summary of Results.

In all cases oyster shell was significantly superior as a setting substrate. In two of the three tests, there was not a statistically significant difference between tire chips and expanded shale. In tests where oyster larvae were allowed a choice of substrate, oyster shell attracted six to eight times as many spat as the alternate substrates.

2. Field Studies of Oyster Settlement.

Oyster shell, expanded shale, and tire chips (without steel wires) were each packaged in duplicate plastic mesh, one-tenth bushel volume, tubes and deployed in the water column at four stations in the James River. Three, two-week deployments were made in August and September of 1988. Data were expressed as oyster spat per unit (0.1 bushel) volume of packed cultch for each station and deployment.

Summary of Results.

Oyster shell was, by far, the overall preferred substrate. In 11 of 12 replicate comparisons, oyster shell had the highest proportion of spat. The ranking of the three substrates varied statistically with time, but the general trend was consistent with settlement on shell greater than tire chips and tire chips, in turn, greater than expanded shale.

3. Laboratory and Field Studies on Substrate Mobility.

Laboratory studies and field studies were performed to examine the relative mobility of the three substrates, oyster shell, expanded shale, and steel-belted tire chips. The laboratory studies utilized a recirculating flume to examine conditions under unidirectional flow.

Field studies involved deployment of substrate plots (two meters by two meters) within light metal frames as reference. The materials were emplaced on a bed of fine sand and mud at a water depth of two meters immediately offshore of the beach at VIMS. This location is exposed to moderate tidal currents, wind waves from the easterly sector, and to boat wake waves. The observation period was 1 December 1988 to 27 January 1989 with inspections post placement and at one, two, five, seven, and nine weeks.

Summary of Results.

In the laboratory tests, loose tire chips (with or without wires) on a tire chip bed were as resistant to movement as oyster shell, but for different reasons. Loose expanded shale fragments in a similar configuration were somewhat more mobile than oyster shell. Isolated and individual tire chips are much more readily transported under unidirectional currents than are oyster shell or expanded shale.

Under field conditions with exposure to wave action, only tire chips dispersed away from the test plots. By five weeks after deployment, tire chips had migrated 30 meters seaward; after seven weeks the tire chips were scattered over a wide swath about 50 meters shoreward of the initial plots; and after nine weeks the chips were being washed ashore on the VIMS beach. Tire chips remaining in the plot were almost completely covered with mud after seven weeks. In marked contrast, the oyster shell and expanded shale plots remained intact with their surfaces exposed after seven weeks.

LABORATORY EVALUATION OF ALTERNATE SUBSTRATES FOR OYSTER SETTLEMENT

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INTRODUCTION

Oyster shell is the cultch traditionally used to collect oyster spat in nature. In addition to natural cultch materials, man-made cultch may be used as alternate cultch to collect oyster spat. The following man-made materials have been used as cultch for setting oysters: rope, tile, cement, tar, slag, old shoes, rubber boots, egg cartons, tin cans, sheet metal, automobiles, clay pipes, glass bottles, boards, cardboard, pvc pipe, and tires (Kellogg, 1910; Belding, 1912; Galtsoff, 1964, 1972). Other materials such as coal ash and shale have been used to catch oyster sets in the field (Kellogg, 1910; Belding, 1912; Haven et al., 1978; Price, 1988). Some members of the Virginia oyster industry have expressed interest in the use of various man-made products as alternate cultch for bottom culture of the American oyster, *Crassostrea virginica*. These man-made products are tire chips and expanded shale (Solite®). They would be used to prepare oyster bottoms and to collect spat. This study was performed at the request of the Virginia Marine Resources Commission to test tire chips and expanded shale as alternate cultch to oyster shell. The effectiveness of tire chips and Solite for settlement of oyster larvae of *C. virginica*, relative to oyster shell, was tested in the laboratory.

MATERIALS AND METHODS

Eyed oyster larvae, large enough to be retained on a 202 um sieve, were obtained from the VIMS oyster hatchery. Solite, tire chips, and flat oyster shells were cleaned and soaked overnight in flowing, ambient York River water prior to use in experiments. Polycarbonate animal cage bodies were used as experimental aquaria. A series of four experiments were conducted to examine the influence of Solite, tire chips, and oyster shells on the setting of oyster larva. These experiments compared: (1) Solite and oyster shell as setting substrates; (2) Solite, tire chips, and oyster shell as setting substrates; (3) larval preference among the three substrates; and (4) whether leaching increases the attractiveness of Solite as a setting substrate.

Substrate

Three substances, shredded tires (tire chips), expanded shale (Solite), and oyster shell, were tested in the laboratory. All tire chips were formed of single pieces and without steel belting. In August 1988 tire chips and Solite were placed outdoors on sheets of plywood to be weathered by the elements. Oyster shell, weathered for two years, was similarly spread on plywood sheets. Prior to laboratory experiments, the substrates were scrubbed by hand and soaked overnight in a tank of ambient, flowing York River water. Flat, whole oyster shells were chosen for experiments. Only falt Solite fragments which did not float were used in experiments (25-30% of Solite were "floaters"). All substrates were of similar size (35 mm x 50 mm).

Testing Procedure

Experiments one through three were replicated ten times each, while experiment four was performed once. Substrates were soaked overnight and placed on the bottom of aquaria filled with 1 um carbon-filtered York River water. Eyed oyster larvae were added to each aquarium at the required larval densities. All aquaria were covered with black plastic to exclude light. Experiments were run for forty-eight hours at room temperature. Minimum-maximum thermometers were used to record fluctuations of air temperature. Eyed larvae were fed daily with Isochrysis galbana Tahitian strain (T-ISO). After forty-eight hours, experiments were terminated and the aquaria were drained. The numbers of set oysters were determined from the surfaces of all substrates using a dissecting microscope. The numbers of oysters set on the bottom of aquaria were also determined.

1. Solite Versus Oyster Shell

Solite was independently tested against oyster shell as a setting substrate for eyed larvae. Five oyster shells or five pieces of Solite were used for each replicate. Aquaria were filled with 4 L of 1 um carbon-filtered York River water and three thousand eyed larvae (0.8 larva per mL).

2. Solite, Tire Chips, Versus Oyster Shell

Solite, tire chips, and oyster shell were tested independently as setting substrates for eyed larvae. Fifteen aquaria were filled with 5 L of 1 um carbon-filtered York River water. Five aquaria were used for each type of substrate. Two pieces of soaked substrate and five thousand eyed larvae (1.0 larva per mL) were placed into each aquarium.

3. Larval Choice of Setting Susbstrate

Eyed larvae were allowed to "choose" among the three substrates for settlement sites. Five pieces of each substrate type were placed in five aquaria, each holding 10 L of 1 um carbon-filtered seawater. Twenty-five thousand eyed larvae were added to each aquarium (2.5 larvae per mL).

4. Influence of Leaching on Attractiveness of Solite

The influence of leaching on the attractiveness of Solite as a setting substrate was tested. Solite was cleaned, graded for size, and placed in 13" lay-flat plastic netting bags. These bags were suspended for 2 1/2 months in the York River. The leached Solite was brought into the laboratory and cleaned. Four substrates were tested independently: (1) oyster shell; (2) tire chips; (3) Solite; and (4) leached Solite. Twenty aquaria, each of 5 L capacity, were filed with 1 um carbon-filtered York River water. Five aquaria were used to hold five pieces of each substrate type. To each aquarium, five thousand larvae were added (1.0 larvae per ml). This experiment was performed without replication due to lack of eyed oyster larvae.

Statistical Analyses

Two-way analyses of variance (ANOVA) were performed to examine the influence of replication and substrate upon numbers of larvae set. A one-way ANOVA was used to analyze data from Experiment 4. Duncan's Multiple Range test was used to compare differences between all main effect means.

RESULTS

Oyster shell, compared independently against Solite, had significantly higher sets of larvae ($p<0.0001$). Recently set oysters were readily identifiable by dissecting microscope at 10 to 30 X magnifications. Three times as many larvae set on oyster shell than Solite (36.7 spat per shell versus 12.3 spat per Solite; Figure 1). There was also a significant difference between the ten replications ($p<0.0014$); however, the substrate-replication interaction was not significant.

When tire chips and Solite were compared against oyster shell as setting substrates, the type of substrate significantly affected the number of larvae set ($p<0.0001$). Oyster shell had higher numbers of spat than tire chips or Solite ($p<0.05$). Twice as many spat had set on oyster shell than tire chips and five times as many compared to Solite (Figure 2). There were significantly ($p<0.05$) more oysters set on oyster shell >> tire chips >> Solite. There was a significant difference between the ten replications ($p<0.0001$). The substrate-replication interaction was significant ($p<0.0001$).

The setting of oyster larvae was significantly ($p<0.0001$) influenced by the substrate offered, when larvae were allowed a choice. Oyster shell was the preferred substrate. There were eight times more spat on oyster shell than Solite and six times more than on tire chips (Figure 3). There was no significant difference in the numbers of larvae setting on Solite or tire chips. There were significantly ($p<0.05$) more oysters set on oyster shell >> tire chips and Solite. There was a significant difference ($p<0.0001$) in numbers of larvae setting in the ten replications. The substrate-replication interaction was significant ($p<0.0001$).

The leaching of Solite did not improve its attractiveness to setting larvae. Oyster shell appeared to be the superior cultch, since it had the highest mean number of spat (Figure 4). There were eleven times more spat on oyster shell than Solite. Oyster shell received three times more set than tire chips or leached Solite. There was no statistical difference between the numbers of larvae set on tire chips, leached Solite, or Solite. There were significantly ($p<0.05$) more oysters set on oyster shells >> tire chips, leached Solite, and Solite. Only one run of this experiment was performed due to unavailability of eyed larvae.

```
NUMBER OF SPAT

   |       *****
   |       *****
   |       *****
30 +       *****
   |       *****
   |       *****
   |       *****
   |       *****
20 +       *****
   |       *****
   |       *****
   |       *****
   |       *****       *****
10 +       *****       *****
   |       *****       *****
   |       *****       *****
   |       *****       *****
   |       *****       *****
   -------------------------
           Oyster      Solite
           shell

               SUBSTRATE
```

FIGURE 1. MEAN NUMBER OF SPAT PER PIECE OF SUBSTRATE

```
NUMBER OF SPAT

      |        *****
      |        *****
  500 +        *****
      |        *****
      |        *****
      |        *****
  400 +        *****
      |        *****
      |        *****
      |        *****
  300 +        *****
      |        *****
      |        *****
      |        *****                   *****
  200 +        *****                   *****
      |        *****                   *****
      |        *****                   *****
      |        *****       *****       *****
  100 +        *****       *****       *****
      |        *****       *****       *****
      |        *****       *****       *****
      |        *****       *****       *****
      ------------------------------------------
               Oyster      Solite      Tire
               shell                   chip

                          SUBSTRATE
```

FIGURE 2. MEAN NUMBER OF SPAT PER SUBSTRATE

```
NUMBER OF SPAT

        |       *****
        |       *****
        |       *****
   1000 +       *****
        |       *****
        |       *****
        |       *****
    800 +       *****
        |       *****
        |       *****
        |       *****
    600 +       *****
        |       *****
        |       *****
        |       *****
    400 +       *****
        |       *****
        |       *****
        |       *****
    200 +       *****                   *****
        |       *****       *****       *****
        |       *****       *****       *****
        |       *****       *****       *****
       -------------------------------------
                Oyster      Solite      Tire
                shell                   chip

                          SUBSTRATE
```

FIGURE 3. MEAN NUMBER OF SPAT PER SUBSTRATE

```
NUMBER OF SPAT

150 +         *****
    |         *****
    |         *****
    |         *****
120 +         *****
    |         *****
    |         *****
    |         *****
 90 +         *****
    |         *****
    |         *****
    |         *****
 60 +         *****
    |         *****      *****
    |         *****      *****      *****
    |         *****      *****      *****
 30 +         *****      *****      *****
    |         *****      *****      *****
    |         *****      *****      *****      *****
    |         *****      *****      *****      *****
    -----------------------------------------------
              Oyster     Tire       Leached    Solite
              shell      chip       solite

                         SUBSTRATE
```

FIGURE 4. INFLUENCE OF LEACHING ON THE ATTRACTIVENESS OF SOLITE

DISCUSSION

Oyster shell was the preferred cultch in these laboratory experiments. More spat settled on oyster shell than on tire chips or Solite for all experiments. Tire chips have been shown in laboratory and field tests in Maryland to be a poor substrate for oyster settlement (Krantz, 1981). Tire chips on intertidal racks, however, have been successfully used in Jamaica to collect natural sets of the mangrove oyster, *Crassostrea rhizophorae* (Hanson & Alexander, 1988). Expanded shale (Solite) was a poor settlement substrate in the laboratory. Approximately 25-30% of the Solite was porous and would not sink to the bottom of aquaria. When slate fragments (0.5 to 5.0 cm in length) were used as cultch in the James River, Virginia, to collect natural spat, oyster shell was shown to be the better setting medium (Haven et al., 1987). Laboratory and field settlement tests of stabilized coal ash as a substratum for setting oysters have shown oyster shell to be superior to coal ash (Price, 1988). Oyster shell has been shown in these and other studies to be the superior setting medium when compared against artificial substrates. In addition to the setting efficiency of a cultch, the survival of spat, handling of the cultch (volume and weight), available mariculture technology, and cost effectiveness must be considered in evaluation of an artificial cultch.

SUMMARY

Oyster shell has been proven in the laboratory to be superior to expanded shale (Solite) or tire chips as a settlement substratum for eyed larvae of the American oyster, *Crassostrea virginica*.

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APPENDIX I

SOLITE VERSUS OYSTER SHELL
MEAN SET PER SUBSTRATE IN EACH REPLICATE

APPENDIX I

EXP. 1. SOLITE VERSUS OYSTER SHELL
MEAN SET PER SUBSTRATE IN EACH REPLICATE

REP	SUBSTRATE	N	COUNT
1	O	5	55.2000000
1	S	5	17.8000000
2	O	5	34.6000000
2	S	5	10.4000000
3	O	5	58.4000000
3	S	5	5.0000000
4	O	5	43.6000000
4	S	5	3.2000000
5	O	5	51.2000000
5	S	5	54.0000000
6	O	5	37.2000000
6	S	5	11.4000000
7	O	5	47.2000000
7	S	5	14.0000000
8	O	5	6.8000000
8	S	5	0.4000000
9	O	5	17.6000000
9	S	5	3.0000000
10	O	5	14.8000000
10	S	5	3.4000000

EXP. 2. SOLITE, TIRE CHIPS, VS. OYSTER SHELL
MEAN NUMBER OF SPAT PER SUBSTRATE IN EACH REPLICATE

REP	SUBSTRATE	N	COUNT
1	O	5	528.40000
1	S	5	147.60000
1	T	5	217.00000
2	O	5	371.00000
2	S	5	68.40000
2	T	5	60.60000
3	O	5	224.40000
3	S	5	68.80000
3	T	5	33.80000
4	O	5	415.40000
4	S	5	123.00000
4	T	5	71.20000
5	O	5	617.60000
5	S	5	229.40000
5	T	5	106.20000
6	O	5	805.00000
6	S	5	56.40000
6	T	5	209.60000
7	O	5	456.00000
7	S	5	50.80000
7	T	5	939.80000
8	O	5	1512.00000
8	S	5	268.80000
8	T	5	304.40000
9	O	5	168.60000
9	S	5	65.00000
9	T	5	31.80000
10	O	5	477.20000
10	S	5	108.00000
10	T	5	317.20000

EXP. 3. SOLITE, TIRE CHIPS, VS. OYSTER SHELL
MEAN NUMBER OF SET PER SUBSTRATE FOR EACH REPLICATE

REP	SUBSTRATE	N	COUNT
1	O	5	1984.00000
1	S	5	52.40000
1	T	5	165.20000
2	O	5	2593.60000
2	S	5	68.40000
2	T	5	87.40000
3	O	5	673.60000
3	S	5	44.00000
3	T	5	254.00000
4	O	5	1261.20000
4	S	5	474.00000
4	T	5	305.60000
5	O	5	692.80000
5	S	5	257.40000
5	T	5	300.80000
6	O	5	2121.20000
6	S	5	281.60000
6	T	5	272.00000
7	O	5	235.00000
7	S	5	20.60000
7	T	5	52.40000
8	O	5	332.60000
8	S	5	152.20000
8	T	5	214.80000
9	O	5	1212.80000
9	S	5	23.00000
9	T	5	68.00000
10	O	5	349.40000
10	S	5	99.40000
10	T	5	144.80000

EXP.4. INFLUENCE OF LEACHING ON ATTRACTIVENESS OF SOLITE
MEAN NUMBER OF SPAT PER SUBSTRATE FOR EACH AQUARIUM

AQUARIUM	SUBSTRATE	N	COUNT
1	L	5	84.800000
2	L	5	61.800000
3	L	5	39.000000
4	L	5	42.800000
5	L	5	3.200000
6	S	5	15.600000
7	S	5	23.800000
8	S	5	7.000000
9	S	5	5.800000
10	S	5	14.000000
11	T	5	47.000000
12	T	5	10.000000
13	T	5	5.000000
14	T	5	179.800000
15	T	5	31.400000
16	O	5	123.600000
17	O	5	319.200000
18	O	5	50.400000
19	O	5	113.800000
20	O	5	161.200000

APPENDIX II

SOLITE VERSUS OYSTER SHELL ANALYSIS OF VARIANCE PROCEDURE

APPENDIX II

EXP. 1. SOLITE VERSUS OYSTER SHELL
ANALYSIS OF VARIANCE PROCEDURE

```
SOURCE                     DF          ANOVA SS   F VALUE    PR > F

SUBSTRATE                   1    14884.00000000     23.93    0.0001
REPLICATION                 9    19035.04000000      3.40    0.0014
REPLICATION*SUBSTRATE       9     6685.80000000      1.19    0.3102


     DUNCAN'S MULTIPLE RANGE TEST
          DUNCAN GROUPING                MEAN      N  REP

                  A                      52.60    10  5
                  A
          B       A                      36.50    10  1
          B       A
          B       A   C                  31.70    10  3
          B       A   C
          B       A   C                  30.60    10  7
          B           C
          B       D   C                  24.30    10  6
          B       D   C
          B       D   C                  23.40    10  4
          B       D   C
          B       D   C                  22.50    10  2
                  D   C
                  D   C                  10.30    10  9
                  D   C
                  D   C                   9.10    10  10
                  D
                  D                       3.60    10  8


     DUNCAN'S MULTIPLE RANGE TEST
        DUNCAN GROUPING                MEAN      N  SUBSTRATE

                  A                  36.660     50  Oyster Shell

                  B                  12.260     50  Solite

  MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.
```

```
     EXP. 2.  SOLITE, TIRE CHIPS, VS. OYSTER SHELL
              ANALYSIS OF VARIANCE PROCEDURE

SOURCE                     DF           ANOVA SS  F VALUE   PR > F

REPLICATION                 9    4517816.2733331     7.64   0.0001
SUBSTRATE                   2    5212232.9199997    39.64   0.0001
REPLICATION*SUBSTRATE      18    5619226.1466659     4.75   0.0001

 DUNCAN'S MULTIPLE RANGE TEST
        DUNCAN    GROUPING             MEAN      N  REP

                       A              695.07    15  8

                       B              482.20    15  7
                       B
               C       B              357.00    15  6
               C       B
               C       B   D          317.73    15  5
               C       B   D
               C       B   D          300.80    15  10
               C       B   D
               C       B   D          297.67    15  1
               C           D
               C       E   D          203.20    15  4
               C       E   D
               C       E   D          166.67    15  2
                       E   D
                       E   D          109.00    15  3
                       E
                       E               88.47    15  9

 DUNCAN'S MULTIPLE RANGE TEST
      DUNCAN    GROUPING             MEAN      N  SUBSTRATE

                     A              557.56    50  Oyster Shell

                     B              229.16    50  Tire Chips

                     C              118.62    50  Solite

  MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.
```

```
              EXP. 3.  SOLITE, TIRE CHIPS, VS. OYSTER SHELL
                       ANALYSIS OF VARIANCE PROCEDURE

SOURCE                   DF            ANOVA SS  F VALUE   PR > F

REPLICATION               9   11640657.2599992    18.57   0.0001
SUBSTRATE                 2   31968177.2799987   229.53   0.0001
REPLICATION*SUBSTRATE    18   21368198.7199935    17.05   0.0001

 DUNCAN'S MULTIPLE RANGE TEST
         DUNCAN GROUPING              MEAN      N  REP

                       A             916.47     15   2
                       A
                       A             891.60     15   6
                       A
               B       A             733.87     15   1
               B
               B                     680.27     15   4

                       C             434.60     15   9
                       C
                       C             417.00     15   5
                       C
               D       C             323.87     15   3
               D       C
               D       C   E         233.20     15   8
               D           E
               D           E         197.87     15   10
                           E
                           E         102.67     15   7


 DUNCAN'S MULTIPLE RANGE TEST
        DUNCAN GROUPING              MEAN      N  SUBSTRATE

                     A             1145.62    50  Oyster Shell

                     B              186.50    50  Tire chips
                     B
                     B              147.30    50  Solite

      MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.
```

```
         EXP. 4.  INFLUENCE OF LEACHING ON ATTRACTIVENESS OF SOLITE
                  ANALYSIS OF VARIANCE PROCEDURE

SOURCE                    DF          ANOVA SS  F VALUE   PR > F

SUBSTRATE                  3   274426.31999998    10.41   0.0001


 DUNCAN'S MULTIPLE RANGE TEST
       DUNCAN  GROUPING               MEAN      N  SUBSTRATE

                      A             153.64     25  Oyster Shell

                      B              54.64     25  Tire Chips
                      B
                      B              46.32     25  Leached Solite
                      B
                      B              13.24     25  Solite

  MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.
```

APPENDIX III

SOLITE VERSUS OYSTER SHELL
RAW DATA

APPENDIX III

EXP. 1. SOLITE VERSUS OYSTER SHELL
RAW DATA

OBS	REP	PIECE	SUBSTRATE	COUNT
1	1	A	O	41
2	1	B	O	37
3	1	C	O	40
4	1	D	O	62
5	1	E	O	96
6	2	A	O	13
7	2	B	O	34
8	2	C	O	27
9	2	D	O	31
10	2	E	O	68
11	3	A	O	34
12	3	B	O	108
13	3	C	O	104
14	3	D	O	14
15	3	E	O	32
16	4	A	O	119
17	4	B	O	13
18	4	C	O	12
19	4	D	O	22
20	4	E	O	52
21	5	A	O	86
22	5	B	O	22
23	5	C	O	11
24	5	D	O	46
25	5	E	O	91
26	6	A	O	12
27	6	B	O	75
28	6	C	O	45
29	6	D	O	35
30	6	E	O	19
31	7	A	O	23
32	7	B	O	88
33	7	C	O	36
34	7	D	O	29
35	7	E	O	60
36	8	A	O	4
37	8	B	O	1
38	8	C	O	6
39	8	D	O	14
40	8	E	O	9
41	9	A	O	23
42	9	B	O	36
43	9	C	O	9

44	9	D	O	12
45	9	E	O	8
46	10	A	O	4
47	10	B	O	0
48	10	C	O	6
49	10	D	O	56
50	10	E	O	8
51	1	A	S	19
52	1	B	S	9
53	1	C	S	27
54	1	D	S	20
55	1	E	S	14
56	2	A	S	5
57	2	B	S	8
58	2	C	S	16
59	2	D	S	17
60	2	E	S	6
61	3	A	S	4
62	3	B	S	10
63	3	C	S	5
64	3	D	S	6
65	3	E	S	0
66	4	A	S	0
67	4	B	S	5
68	4	C	S	3
69	4	D	S	5
70	4	E	S	3
71	5	A	S	15
72	5	C	S	52
73	5	C	S	19
74	5	D	S	160
75	5	E	S	24
76	6	A	S	4
77	6	B	S	34
78	6	C	S	9
79	6	D	S	4
80	6	E	S	6
81	7	A	S	6
82	7	B	S	10
83	7	C	S	23
84	7	D	S	18
85	7	E	S	13
86	8	A	S	0
87	8	B	S	1
88	8	C	S	0
89	8	D	S	1
90	8	E	S	0
91	9	A	S	2

92	9	B	S	0
93	9	C	S	6
94	9	D	S	1
95	9	E	S	6
96	10	A	S	0
97	10	B	S	0
98	10	C	S	10
99	10	D	S	0
100	10	E	S	7

EXP. 2. SOLITE, TIRE CHIPS, VS. OYSTER SHELL
RAW DATA

OBS	REP	PIECE	SUBSTRATE	COUNT
1	1	A	O	586
2	1	B	O	416
3	1	C	O	604
4	1	D	O	604
5	1	E	O	432
6	2	A	O	492
7	2	B	O	205
8	2	C	O	461
9	2	D	O	174
10	2	E	O	523
11	3	A	O	28
12	3	B	O	214
13	3	C	O	455
14	3	D	O	221
15	3	E	O	204
16	4	A	O	728
17	4	B	O	728
18	4	C	O	126
19	4	D	O	396
20	4	E	O	99
21	5	A	O	717
22	5	B	O	192
23	5	C	O	770
24	5	D	O	394
25	5	E	O	1015
26	6	A	O	892
27	6	B	O	1046
28	6	C	O	885
29	6	D	O	566
30	6	E	O	636
31	7	A	O	394
32	7	B	O	208
33	7	C	O	367
34	7	D	O	464
35	7	E	O	847
36	8	A	O	1566
37	8	B	O	847
38	8	C	O	1076
39	8	D	O	3317
40	8	E	O	754
41	9	A	O	219
42	9	B	O	222
43	9	C	O	202

44	9	D	O	133
45	9	E	O	67
46	10	A	O	495
47	10	B	O	564
48	10	C	O	142
49	10	D	O	582
50	10	E	O	603
51	1	A	S	246
52	1	B	S	81
53	1	C	S	37
54	1	D	S	221
55	1	E	S	153
56	2	A	S	69
57	2	B	S	10
58	2	C	S	74
59	2	D	S	24
60	2	E	S	165
61	3	A	S	99
62	3	B	S	57
63	3	C	S	120
64	3	D	S	30
65	3	E	S	38
66	4	A	S	132
67	4	B	S	132
68	4	C	S	70
69	4	D	S	131
70	4	E	S	150
71	5	A	S	221
72	5	B	S	141
73	5	C	S	278
74	5	D	S	257
75	5	E	S	250
76	6	A	S	98
77	6	B	S	35
78	6	C	S	20
79	6	D	S	56
80	6	E	S	73
81	7	A	S	58
82	7	B	S	47
83	7	C	S	65
84	7	D	S	55
85	7	E	S	29
86	8	A	S	45
87	8	B	S	546
88	8	C	S	362
89	8	D	S	113
90	8	E	S	278
91	9	A	S	82

92	9	B	S	55
93	9	C	S	43
94	9	D	S	54
95	9	E	S	91
96	10	A	S	98
97	10	B	S	93
98	10	C	S	123
99	10	D	S	114
100	10	E	S	112
101	1	A	T	231
102	1	B	T	103
103	1	C	T	328
104	1	D	T	250
105	1	E	T	173
106	2	A	T	150
107	2	B	T	60
108	2	C	T	31
109	2	D	T	17
110	2	E	T	45
111	3	A	T	7
112	3	B	T	20
113	3	C	T	42
114	3	D	T	34
115	3	E	T	66
116	4	A	T	84
117	4	B	T	84
118	4	C	T	75
119	4	D	T	91
120	4	E	T	22
121	5	A	T	29
122	5	B	T	163
123	5	C	T	124
124	5	D	T	97
125	5	E	T	118
126	6	A	T	52
127	6	B	T	157
128	6	C	T	336
129	6	D	T	117
130	6	E	T	386
131	7	A	T	1032
132	7	B	T	543
133	7	C	T	573
134	7	D	T	609
135	7	E	T	1942
136	8	A	T	403
137	8	B	T	346
138	8	C	T	214
139	8	D	T	336

140	8	E	T	223
141	9	A	T	28
142	9	B	T	18
143	9	C	T	50
144	9	D	T	11
145	9	E	T	52
146	10	A	T	345
147	10	B	T	287
148	10	C	T	374
149	10	D	T	229
150	10	E	T	351

EXP. 3. SOLITE, TIRE CHIPS, VS. OYSTER SHELL
RAW DATA

OBS	REP	PIECE	SUBSTRATE	COUNT
1	1	A	0	2590
2	1	B	0	1911
3	1	C	0	2389
4	1	D	0	1617
5	1	E	0	1413
6	2	A	0	1932
7	2	B	0	2464
8	2	C	0	2860
9	2	D	0	2818
10	2	E	0	2894
11	3	A	0	948
12	3	B	0	437
13	3	C	0	744
14	3	D	0	685
15	3	E	0	554
16	4	A	0	465
17	4	B	0	2264
18	4	C	0	1798
19	4	D	0	592
20	4	E	0	1187
21	5	A	0	950
22	5	B	0	571
23	5	C	0	505
24	5	D	0	678
25	5	E	0	760
26	6	A	0	3096
27	6	B	0	1161
28	6	C	0	2042
29	6	D	0	1816
30	6	E	0	2491
31	7	A	0	261
32	7	B	0	109
33	7	C	0	212
34	7	D	0	373
35	7	E	0	220
36	8	A	0	493
37	8	B	0	337
38	8	C	0	305
39	8	D	0	272
40	8	E	0	256
41	9	A	0	1686
42	9	B	0	1225
43	9	C	0	1242

44	9	D	O	770
45	9	E	O	1141
46	10	A	O	442
47	10	B	O	279
48	10	C	O	391
49	10	D	O	331
50	10	E	O	304
51	1	A	S	128
52	1	B	S	50
53	1	C	S	43
54	1	D	S	22
55	1	E	S	19
56	2	A	S	28
57	2	B	S	57
58	2	C	S	76
59	2	D	S	138
60	2	E	S	43
61	3	A	S	98
62	3	B	S	17
63	3	C	S	18
64	3	D	S	25
65	3	E	S	62
66	4	A	S	80
67	4	B	S	247
68	4	C	S	783
69	4	D	S	610
70	4	E	S	650
71	5	A	S	166
72	5	B	S	384
73	5	C	S	127
74	5	D	S	263
75	5	E	S	347
76	6	A	S	369
77	6	B	S	39
78	6	C	S	579
79	6	D	S	314
80	6	E	S	107
81	7	A	S	17
82	7	B	S	59
83	7	C	S	13
84	7	D	S	6
85	7	E	S	8
86	8	A	S	62
87	8	B	S	220
88	8	C	S	59
89	8	D	S	236
90	8	E	S	184
91	9	A	S	1

92	9	B	S	17
93	9	C	S	6
94	9	D	S	3
95	9	E	S	88
96	10	A	S	62
97	10	B	S	61
98	10	C	S	165
99	10	D	S	130
100	10	E	S	79
101	1	A	T	70
102	1	B	T	217
103	1	C	T	297
104	1	D	T	52
105	1	E	T	190
106	2	A	T	92
107	2	B	T	148
108	2	C	T	84
109	2	D	T	65
110	2	E	T	48
111	3	A	T	548
112	3	B	T	164
113	3	C	T	183
114	3	D	T	199
115	3	E	T	176
116	4	A	T	134
117	4	B	T	666
118	4	C	T	242
119	4	D	T	105
120	4	E	T	381
121	5	A	T	370
122	5	B	T	446
123	5	C	T	222
124	5	D	T	361
125	5	E	T	105
126	6	A	T	671
127	6	B	T	140
128	6	C	T	297
129	6	D	T	75
130	6	E	T	177
131	7	A	T	26
132	7	B	T	20
133	7	C	T	30
134	7	D	T	166
135	7	E	T	20
136	8	A	T	212
137	8	B	T	287
138	8	C	T	257
139	8	D	T	128

140	8	E	T	190
141	9	A	T	28
142	9	B	T	64
143	9	C	T	11
144	9	D	T	40
145	9	E	T	197
146	10	A	T	328
147	10	B	T	105
148	10	C	T	116
149	10	D	T	111
150	10	E	T	64

EXP. 4. INFLUENCE OF LEACHING ON THE ATTRACTIVENESS OF SOLITE RAW DATA

OBS	CAGE	PIECE	SUBSTRATE	COUNT
1	W	A	L	279
2	W	B	L	78
3	W	C	L	12
4	W	D	L	8
5	W	E	L	47
6	X	A	L	36
7	X	B	L	203
8	X	C	L	29
9	X	D	L	6
10	X	E	L	35
11	Y	A	L	0
12	Y	B	L	74
13	Y	C	L	41
14	Y	D	L	66
15	Y	E	L	14
16	Z	A	L	6
17	Z	B	L	20
18	Z	C	L	165
19	Z	D	L	22
20	Z	E	L	1
21	V	A	L	0
22	V	B	L	11
23	V	C	L	2
24	V	D	L	0
25	V	E	L	3
26	W	A	O	288
27	W	B	O	402
28	W	C	O	118
29	W	D	O	171
30	W	E	O	617
31	X	A	O	23
32	X	B	O	29
33	X	C	O	44
34	X	D	O	84
35	X	E	O	72
36	Y	A	O	112
37	Y	B	O	117
38	Y	C	O	191
39	Y	D	O	61
40	Y	E	O	88
41	Z	A	O	281
42	Z	B	O	73
43	Z	C	O	119

44	Z	D	O	133
45	Z	E	O	200
46	V	A	O	111
47	V	B	O	75
48	V	C	O	120
49	V	D	O	28
50	V	E	O	284
51	W	A	S	0
52	W	B	S	0
53	W	C	S	4
54	W	D	S	29
55	W	E	S	45
56	X	A	S	17
57	X	B	S	9
58	X	C	S	79
59	X	D	S	5
60	X	E	S	9
61	Y	A	S	17
62	Y	B	S	8
63	Y	C	S	3
64	Y	D	S	1
65	Y	E	S	6
66	Z	A	S	0
67	Z	B	S	9
68	Z	C	S	2
69	Z	D	S	9
70	Z	E	S	9
71	V	A	S	38
72	V	B	S	17
73	V	C	S	3
74	V	D	S	3
75	V	E	S	9
76	W	A	T	40
77	W	B	T	38
78	W	C	T	100
79	W	D	T	25
80	W	E	T	32
81	X	A	T	1
82	X	B	T	1
83	X	C	T	36
84	X	D	T	3
85	X	E	T	9
86	Y	A	T	0
87	Y	B	T	4
88	Y	C	T	7
89	Y	D	T	12
90	Y	E	T	2
91	Z	A	T	511

92	Z	B	T	1
93	Z	C	T	155
94	Z	D	T	12
95	Z	E	T	220
96	V	A	T	32
97	V	B	T	42
98	V	C	T	33
99	V	D	T	25
100	V	E	T	25

FIELD STUDIES OF COMPARATIVE SETTLEMENT OF OYSTER LARVAE ON OYSTER SHELL, EXPANDED SHALE, AND TIRE CHIPS

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Period of Field Studies: August 5, 1988, through September 16, 1988.
Site of Field Studies: James River, Virginia.

INTRODUCTION

Following presentation of the report prepared by Dr. R. J. Byrne to the July meeting of the Virginia Marine Resources Commission, a request was made to the Virginia Institute of Marine Science (VIMS) to evaluate expanded shale (Solite) and tire chips as alternative cultch to oyster shell. This evaluation has three components: laboratory (flume) and field testing of mobility; laboratory studies of settlement using cultured oyster larvae; and field studies of settlement. This document describes the protocol and results for the field study component of the evaluation.

PROTOCOL

Present monitoring activity utilizes oyster shells threaded on metal wire. The expanded shale substrate is not suitable for drilling and threading; therefore, the materials were exposed in plastic mesh, one tenth bushel volume "tubes." Rather than attempt to quantify settlement as oysters per unit area, we compared settlement per unit packed volume of substrate. In mass "planting" of substrate, this would, effectively, be the comparative yardstick anyway, so the approach is meaningful. The tubes were 18" in circumference and had a mesh size of 1".

"Tubes" were deployed in the James River, Virginia, on the following dates: August 5, August 19, and September 2, 1988. This coincides with the period of generally high oyster settlement in the James. The sites of deployment were Naseway Shoal, Rock Wharf, Wreck Shoal, and Point of Shoals. These sites were chosen to provide good spatial coverage to include possible variability in intensity of settlement.

At each of the four stations six "tubes" were deployed, two containing each of shell, expanded shale and tire chips, in early August. At three of the stations, the "tubes" were hung from newly placed stakes. At the fourth station (Naseway), we used an old pound net pole. Stakes were placed and "tubes" deployed on August 5, 1988. Two weeks later the "tubes" were retrieved and replaced with further, previously unexposed tubes. A third deployment and retrieval followed the second as continued settlement was observed in the James on the adjacent "shellstring" monitoring station. Retrieved material was dried and subsequently examined microscopically for presence of settled and metamorphosed oyster larvae. A two-week deployment was chosen rather than a one-week deployment in order to:

(1) maximize settlement per unit cultch while still remaining sufficiently short to minimize growth of fouling organisms;

(2) allow sufficient time for spat to grow to facilitate observation; and

(3) eliminate the need to maintain the "tube" after retrieval for a "grow out" period when spat mortality or accidental further settlement (through the seawater supply) may occur.

RESULTS

Data are expressed as oyster spat per unit (0.1 bushel) volume of packed cultch for each station and deployment period in the accompanying table. The numbers are then expressed as a percentage of the total spat count for all substrates at that site for that collection date. To allow statistical comparison of settlement between the substrates within a single site and date, the percentage values were arcsin transformed. Comparisons were then made using analysis of variance (ANOVA).

Overall the shell was, by far, the preferred substrate. In 11 of 12 replicate comparisons, shell had the highest proportion of settled spat. For the entire experiment, setting on shell was significantly greater than on other substrates. The ranking of the substrates varied statistically with time even though the general trend was consistent as shell>tire>shale. For the first time period (8/5-8/19), setting on shell was significantly higher than both shale and tires. For the second time period (8/19-9/2), setting on shell was significantly greater than shale but not statistically greater than tire. For the third time period (9/2-9/16), significant differences were observed for all substrates (shell>tire>shale). Although differences were observed between stations, this was considered due to spatial variation in settlement throughout the river, something that is well documented. The relevent comparisons are at a single station within a single time period between different substrates.

In summary, shell is a better substrate than tire chips, and both are better substrates than expanded shale.

Comparative Settlement of Oyster Spat on Three Substrates in the James River, Virginia, during August - September, 1988. All spat numbers are per 0.1 bushel. Percentages are of total for all substrates at that location for that period.

Exposure Period	Station	Substrate								
		Shale			tire			Shell		
		spat	%	arcsin	spat	%	arcsin	spat	%	arcsin
8/5-8/19	Naseway Shoal	87	20.1	26.6	77	17.8	24.9	269	62.1	52.0
	Wreck Shoal	138	18.7	25.6	194	26.3	30.8	406	55.0	47.9
	Rock Wharf	92	11.6	19.9	187	23.6	29.1	514	64.8	53.6
	Point of Shoal	46	24.6	29.7	32	17.1	24.4	109	58.3	49.8
8/19-9/2	Naseway Shoal	27	27.6	31.7	23	23.5	29.0	48	48.9	44.4
	Wreck Shoal	21	26.9	31.2	34	43.6	41.3	23	29.5	32.9
	Rock Wharf	12	9.4	17.8	44	34.6	36.0	71	55.9	48.4
	Point of Shoal	14	16.3	23.8	22	25.6	30.4	50	58.1	49.7
9/2-9/16	Naseway Shoal	8	1.7	7.5	45	9.4	17.8	426	88.9	70.5
	Wreck Shoal	5	7.9	16.3	11	7.5	24.7	47	74.6	59.7
	Rock Wharf	12	2.7	9.5	47	10.4	18.8	393	86.9	68.8
	Point of Shoal	2	2.6	9.3	12	15.4	23.1	64	82.0	64.9

ANOVA Results: nsd denotes no statistically significant difference

(1) 1 way comparing substrates, all dates: $F = 45.1$, $P < 0.00001$
shell > tire, tire and shale are nsd.

(2) 1 way comparing substrates, 8/5 - 8/19: $F = 72.67$, $P < 0.00001$
shell > tire, tire and shale are nsd.

(3) 1 way comparing substrates, 8/19 - 9/2: $F = 7.03$, $P < 0.001$
shell and tire are nsd, tire and shale are nsd, but shell > shale.

(4) 1 way comparing substrates, 9/2 - 9/16: $F = 211.4$, $P < 0.00001$
shell > tire > shale.

(5) 1 way comparing dates, shell only: $F = 12.2$, $P < 0.003$
period 1 and period 2 are nsd, but both are < period 3

(6) 1 way comparing dates, tire only: $F = 9.72$, $P < 0.0056$
period 1 and period 3 are nsd, but both are < period 2

HYDRAULIC ROUGHNESS AND MOBILITY OF THREE OYSTER-BED SUBSTRATE MATERIALS

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ABSTRACT

Laboratory and field studies were conducted to examine how proposed artificial oyster bed substrate replenishment materials consisting of tire chips and heat-expanded shale (SOLITE®) compare to oyster shells in terms of hydraulic roughness and ease of transport by currents and waves. Under steady undirectional flows, beds composed of tire chips and oyster shells produce similar large roughnesses which cause appreciable form drag and reduced skin friction thereby reducing mobility. However, the oscillatory wave- and boat-wake-induced flows typical of shallow field situations, easily transport tire chips but not oyster shells and SOLITE®. It is concluded that tire chips are unsuitable for use as a substrate material in shallow estuarine environments exposed to wind waves or recurrent large boat wakes. In contrast, SOLITE® is roughly equivalent to oyster shells in terms of physical stability.

INTRODUCTION

Each year the state of Virginia and private oyster growers purchase over 2.5 million bushels of oyster shells which are used to replenish the substrates for oyster beds. With diminishing availability of oyster shells, alternative materials capable of providing artificial substrates suitable for oyster growth have been considered. Two such materials which have been proposed by industry are: (1) tire chips, produced by cutting up worn-out steel belted tires; and (2) SOLITE®, a light weight aggregate produced by heating shale to a high enough temperature to cause expansion (manufactured by SOLITE® Corporation). Figure 1 shows a side-by-side comparison of SOLITE®, tire chips and oyster shells.

In considering the suitability of the alternative materials relative to that of oyster shells, physical questions arise in addition to biological and chemical questions. The important physical questions are: (1) How would the boundary layers over substrates composed of the different materials be affected with regard to hydraulic roughness and attendant turbulent intensity and drag? (2) How readily might the materials be transported, by currents and waves, away from the intended substrate site? The first question is pertinent to assessing the likelihoods of oyster larvae setting on the artificial substrate and of siltation ultimately burying the substrate. By way of the second question we address concerns that materials might rapidly disperse and litter nearby shores. We addressed both of these physical questions through a set of laboratory experiments supplemented by a short-term field monitoring program. The purpose of this report is to present the results of our research.

SHEAR STRESS, HYDRAULIC ROUGHNESS, AND DRAG: BACKGROUND

Our analyses of the hydraulic properties of the three substrate materials are underlain by some fundamental principles which require explanation before results can be presented. The rate at which momentum is transferred from the moving water to the bed is conventionally expressed by the bed shear stress, τ_o. In fully turbulent bottom boundary layers, such as we are concerned with in this study, τ_o is related to the shear (or friction) velocity, u_*, by

$$\tau_o = \rho\, u_*^2 \tag{1}$$

where ρ is water density. In the region of the turbulent boundary layer close to the bed (within about a meter or less) the local (elevation-dependent) time-averaged current velocity $\langle u(z) \rangle$ shows a close association with the log of the elevation, z. Measurements made within this logarithmic layer can be extrapolated to estimate the <u>notional</u> elevation, z_o, at which $\langle u(z) \rangle = 0$. The "law of the wall" relates u_* and the hydraulic roughness length, z_o, by

$$\langle u(z) \rangle = \frac{u_*}{\kappa} \ln \frac{z}{z_o} \tag{2}$$

where κ is von Karman's constant = 0.408 ± 0.004 (Nowell, 1983).

A convenient, practical approach commonly employed to estimate bed shear stress from velocities measured at a single fixed elevation, z, above the bed, involves using a drag coefficient, $C_D(z)$ to which τ_o is related by

$$\tau_o = \rho\, C_D(z) \langle u^2(z) \rangle \tag{3}$$

(e.g. Sternberg, 1972). Hence

$$C_D(z) = (u_*/\langle u(z)\rangle)^2 \quad (4)$$

and the $C_D(z)$ value appropriate to any given elevation, z, is related to the hydraulic roughness length, z_o, by

$$C_D(z) = \left(\frac{\kappa}{\ln (z/z_o)}\right)^2 \quad (5)$$

In the field, z, the elevation at which u(z) is measured is usually 1 meter and the corresponding drag coefficient is designated $C_D(100)$ (z = 100 cm). In this study, we made our measurements of the threshold velocities for the entrainment of material at 0.15 m (15 cm) and have thus estimated another value, $C_D(15)$.

The total drag as interpreted from the law of the wall (eq. 2) and the associated drag coefficient as estimated from equation 5 includes both form drag and skin friction components. Strictly, the transport of sediments and other particles is a response to skin friction; however, separation of the form drag and skin friction components requires very sophisticated techniques utilizing extremely small sensors and was not attempted in our study. Nevertheless, it is worth noting that where distributed roughness elements such as tire chips, SOLITE® chips, or oyster shells collectively cause increases in z_o due to form drag, the actual skin friction over the space-averaged water-solid interface may be reduced (Chriss and Caldwell, 1982; Nowell and Church, 1979).

RESEARCH METHODS

- Laboratory methods -

Hydraulic roughness and drag of oyster shell, tire-chip, and SOLITE® substrates and threshold criteria for entrainment of the three materials were measured in the VIMS recirculating flume. This flume is 12 m long, 1 m wide, and 1 m deep, has smooth glass walls, and is capable of generating maximum free-stream flow velocities slightly greater than 1 m s^{-1}. Profiles of flow velocity within the flume were measured with a miniature Marsh-McBirney electromagnetic flow meter having a sensor sphere diameter of 1.25 cm. The flow meter was set at a time constant of 5 seconds and was interfaced to a Compaq personal computer. Independent calibration checks on the flow meter were made at the time of each experimental run by a Lagrangian technique utilizing a drifting straw, the drift rate of which was timed automatically when the straw successively intersected two laser beams located within the flume test section.

Rough, collective beds of tire chips and SOLITE® were constructed by fastening the material to plywood sheets in a random, densely packed fashion intended to simulate substrate conditions in the field. Tire chips were nailed to the plywood; SOLITE® was glued. Oyster shells were simply spread over the floor of the flume. The resulting artificial substrates were placed on the flume floor extending from the test section to 5 meters upstream of the test section in order to provide sufficient excursion lengths for vertical growth of the boundary layer. The three artificial beds are shown in Figs. 2-4.

Flow velocities over the downstream end of the rough artificial beds were profiled by measuring flows at elevations, z, of 2.5 cm, 5.0 cm and at

5.0 cm increments between $z = 5.0$ and $z = 60.0$ cm. At each level, velocities were sampled at ½ second intervals for 50 seconds by the computer and a mean and standard deviation were determined. For each substrate type, the profiles were repeated with the flume set at 10%, 20%, 30%, 40%, 50%, and 60% of capacity. Coefficient of determination, r^2, values were calculated to ascertain the degree to which local velocity mean values $\bar{u}(z)$ fit logarithmic profiles. Where high (> 0.98) r^2 values indicated log profiles, the log association was plotted to estimate z_o and the law of the wall (eq. 2) was applied to estimate friction velocities, u_*, and bed shear stress, τ_o. Drag coefficients (eq. 3) appropriate to velocities measured at elevations of 15 cm (u_{15}) and 100 cm (u_{100}) were estimated from equation 5.

At the completion of each of the three sets of profile analyses, the artificial beds were left on the flume floor upstream of the test section. In order to determine the threshold shear stress needed to transport the three material types, a bed layer of loose material was formed in the test section. The electromagnetic flow meter was set at an elevation of 15 cm and the data were recorded on the personal computer. The behavior of the loose material was viewed through the flume wall as the flow velocity was progressively increased. Different stages in the initiation of transport were recorded and the associated means and standard deviations of the flow velocities were estimated. Settling velocities of different sized particles of each type were measured in the flume by timing the descent of the particles through a 1 m column of water. Water temperature was 19°C.

- Field methods -

Flume experiments were only able to test the responses of the three materials to unidirectional flows. In order to examine the stability of the materials under natural conditions involving oscillatory flows due to wind waves and boat wakes, we conducted a small field experiment in the fetch-limited York River estuary immediately offshore from the VIMS campus. The experiment was conducted over the period 1 December 1988 - 12 January 1989 on a bed of fine sand and mud at a water depth of 2 meters. Three experimental substrate plots, one for each of the three materials, were arranged in squares 2 m x 2 m. The plots were separated from each other by horizontal distances of 2 m. Each plot was surrounded by a frame of light metal tubing for reference. For the first two weeks of the experiment, a Sea Data Model 635-9 wave/current meter was attached to the frame surrounding the middle plot to determine the heights and oscillatory flow velocities of waves and boat wakes. The plots were inspected immediately after deployment, after 1 week, after 2 weeks, after 5 weeks, and after 7 weeks.

LABORATORY RESULTS

- Material properties

Table 1 lists the means and standard deviations (σ) of the volumes, $\bar{V}$, densities, ρ_s, and settling velocities, w_s, of the three materials. Notably, tire chips are larger in size than oyster shells but are appreciably less dense and have much slower settling velocities. SOLITE® particles are the smallest of the three materials and have intermediate densities and settling velocities. Roughly 10% of the SOLITE® particles obtained from the supplier had densities less than 1.0 g cm^{-3}; these were excluded from analyses.

Table 1. Material Properties

	$\bar{V}$ (cm^3)	σ (cm^3)	$\bar{\rho}_s$ (g cm^{-3})	σ (g cm^{-3})	$\bar{w}_s$ (m s^{-1})	σ (m s^{-1})	n
Oyster Shell	25.38	14.06	2.23	0.28	0.35	0.10	26
Tire Chips	35.35	16.59	1.31	0.16	0.25	0.12	26
SOLITE®*	11.31	9.90	1.68	0.59	0.31	0.13	21

*Floating SOLITE® chunks (~ 10% of total) were removed before properties were estimated.

- Hydraulic roughness and drag -

Boundary layer velocity profiles measured over oyster shell, tire chip, and SOLITE® substrates are shown in Figs. 5-7. Profiles over all three substrates exhibited well-developed logarithmic layers within 20-25 cm above the bed. Furthermore, the profiles generated by different flume speeds converged on roughly equal z_o values indicating that the roughness estimates so obtained are reliable. The tire chips substrate produced the greatest hydraulic roughness and drag coefficient with a mean z_o value of 1.119 cm (Fig. 6) and a $\bar{C}_D(100)$ value of 8.51×10^{-3}. This latter value exceeds, by nearly three-fold, the value of 3.1×10^{-3} that is considered "typical" of sandy continental shelf environments (Sternberg, 1972). It is interesting to note, however, that the z_o and $\bar{C}_D(100)$ values associated with the tire chip substrate were only slightly larger than the z_o and $\bar{C}_D(100)$ values of 0.98 cm and 7.8×10^{-3} that characterized the oyster shell bed. Oyster shell and tire chip beds are thus hydraulically very similar, at least when they occur on a hard, mud-free foundation.

The SOLITE® bed was an order of magnitude smoother (Fig. 7) than either of the other two substrates with a $\bar{z}_o$ value of 0.142 cm. The corresponding $\bar{C}_D(100)$ value of 3.91×10^{-3} is close to the "conventional" sandy shelf value.

- Mobility and threshold criteria for entrainment of bed material -

Figures 8-10 indicate the nature of the movements experienced by the three materials as functions of the flow velocity u_{15} at $z = 15$ cm, the bed shear stress, τ_o, and u_*. In all three of the cases shown, a large range of shear stress separates the initial particle movement over the smooth bed from established motion over the rough bed.

The form drag created by the roughened bed conditions reduces the skin friction acting on individual particles, thereby increasing, appreciably, the u_{15} and τ_o values required to produce established motion. This effect is most pronounced in the case of tire chips and least for SOLITE®. Individual tire chips were readily put into sustained movement over the smooth flume floor at $u_{15} \geq 0.33$ m s^{-1}. Oyster shells, in comparison, required that $u_{15} \geq 0.49$ m s^{-1} whereas for SOLITE® the critical u_{15} value was 0.42 m s^{-1}. However, owing to high form drag over the rough tire chips bed, tire chips resting on the rough bed moved only sporadically, and often moved upstream over intermediate flow speeds. Only when u_{15} and τ_o respectively exceeded 0.65 m s^{-1} and 11.6 Pascals did chips experience sustained downstream transport over the rough bed. Well established collective downstream movement of SOLITE® chunks occurred at much lower u_{15} and τ_o values (Fig. 10).

After our initial experimental runs with tire chips, we hypothesized that the wires extruding from the rough edges of the chips might have bound chips together and reduced their tendency to move over the rough bed. We reran the mobility experiments using, in the test section, tire chips with smooth edges trimmed of wires. The results were practically identical to those obtained from untrimmed tire chips and as portrayed in Fig. 9.

FIELD RESULTS

Results from the field deployment of the three materials differed from the laboratory results in that they showed tire chips to be highly mobile whereas oyster shells and SOLITE® proved to have negligible mobility. Over the period of observation, the oyster shells and SOLITE® remained largely within the reference frames. A few SOLITE® particles scattered over the bed about 1 to 2 meters to the south of the SOLITE® reference frame apparently drifted to that location as they fell to the bed during the initial drop. No subsequent movement occurred. SOLITE® particles became embedded in the soft bottom and this undoubtedly impeded further movement. Seven weeks after deployment, the oyster shell and SOLITE® plots were still intact within their reference frames and were not covered by sediment.

During the initial two weeks of the experiment period, while the wave gauge was deployed, wave action was negligible for most of the time; however, wave height and orbital velocity maxima of 0.22 m and 0.27 m s^{-1} were recorded during the period apparently related to boat wakes. During this, tire chips were scattered over the bed to about 3 meters shoreward of the reference frame. By five weeks after deployment, chips had migrated over 30 meters shoreward; after seven weeks the chips were scattered over a wide swath that extended about 50 meters shoreward of the initial plot; and after nine weeks, tire chips were being washed ashore on the VIMS beach.

The centroid of the main plot had become diffuse and had migrated just inshore of frame by the time of the seven-week inspection. These results suggest that even though tire chips are relatively stable under unidirectional flows, they are highly mobile when subjected to oscillatory flows.

By five weeks after deployment, the tire chip plot had experienced appreciably more siltation than either of the other plots and by seven weeks the tire chips were almost completely covered with mud. The upper surfaces of oyster shells and SOLITE® chunks continued to extend above the mud. The large form drag and reduced skin friction that characterizes the rough tire chip surfaces apparently causes these substrates to act as sediment traps.

CONCLUSIONS

From the results of the flume study, one would infer that, under unidirectional steady flows, tire chips resting on a rough bed composed of other tire chips are no more mobile than are heavier oyster shells. This apparent "stability" is attributable only to the large form drag and concomitantly reduced downstream skin friction produced collectively by the many tire chip roughness elements which comprise the bed. Isolated individual tire chips are much more readily transported, even under unidirectional currents, than are oyster shells or SOLITE® chunks.

Under field conditions where oscillatory flows due to wind waves and boat wakes are the rule and where the artificial bed is underlain by mud, tire chips are by far the most easily transported of the three materials. By virtue of their flat shape and low density, tire chips become less well embedded in the muddy bottom than do either oyster shells or SOLITE®. Most importantly, wave-induced oscillatory flows tend to enhance skin friction, even over a rough bed (Grant and Madsen, 1979) while the frequently reversing flows must prevent the tire chips from imbricating or becoming interlocked.

We conclude that, of the three materials examined, oyster shells and SOLITE® can both provide hydraulically stable substrates for oyster beds in shallow estuarine environments. Oyster shells appear to be somewhat less mobile than SOLITE®, but this is only marginally so when the materials are deployed on mud. Tire chips, in contrast, are not suitable for providing artificial substrates in shallow environments subject to the action of wind waves (i.e. exposure to a relatively long fetch) or to frequent large boat wakes. Under such conditions, it is likely that many of the tire chips would be washed ashore after a few months. Tire chips should be considered for deployment only in sheltered and relatively deep environments not subject to frequent agitation by boat wakes. Because of their low settling velocities, tire chips should be dropped only at slack water and should be dropped in sufficiently dense concentrations to produce maximum bed roughness.

ACKNOWLEDGEMENTS

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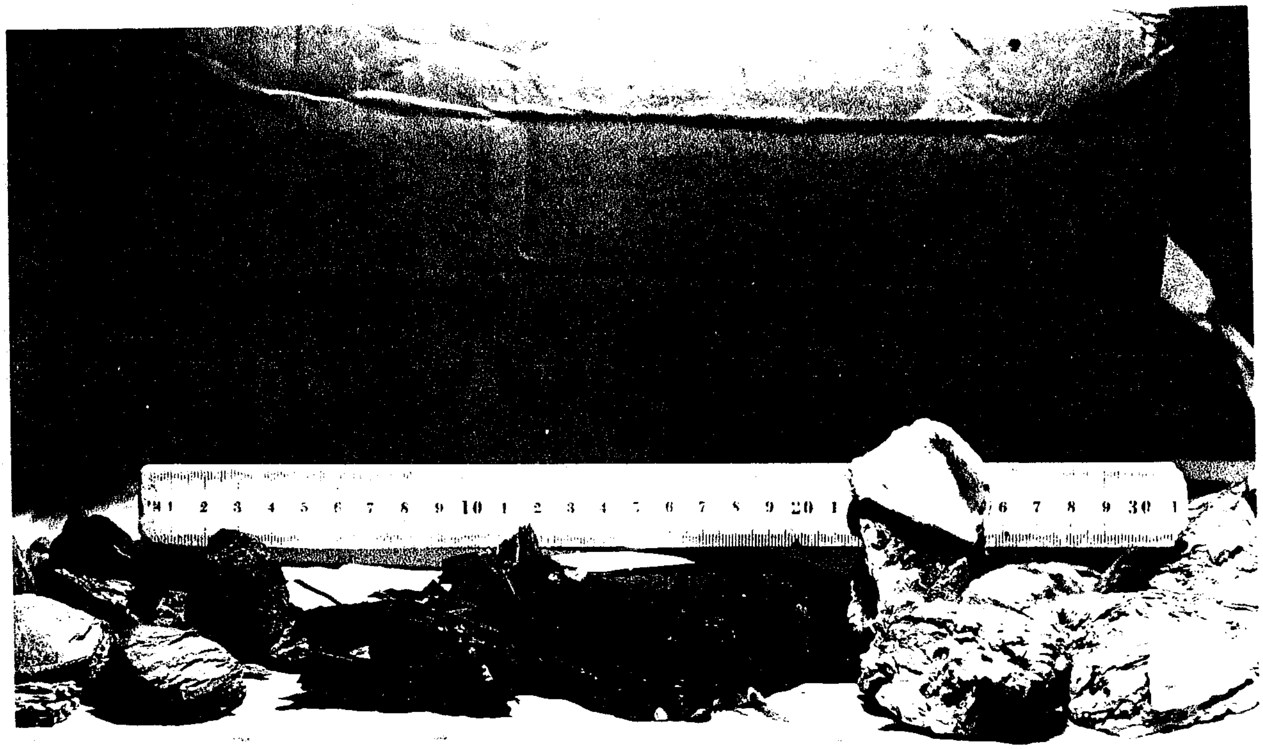

Fig. 1. Three oyster-bed substrate materials from left to right: SOLITE®, tire chips, oyster shells.

Fig. 2. Bed of artificially-placed oyster shells resting on the flume floor beneath the electromagnetic flow meter.

Fig. 3. Artificial test bed of tire chips attached to plywood.

Fig. 4. Artificial test bed of SOLITE® attached to plywood.

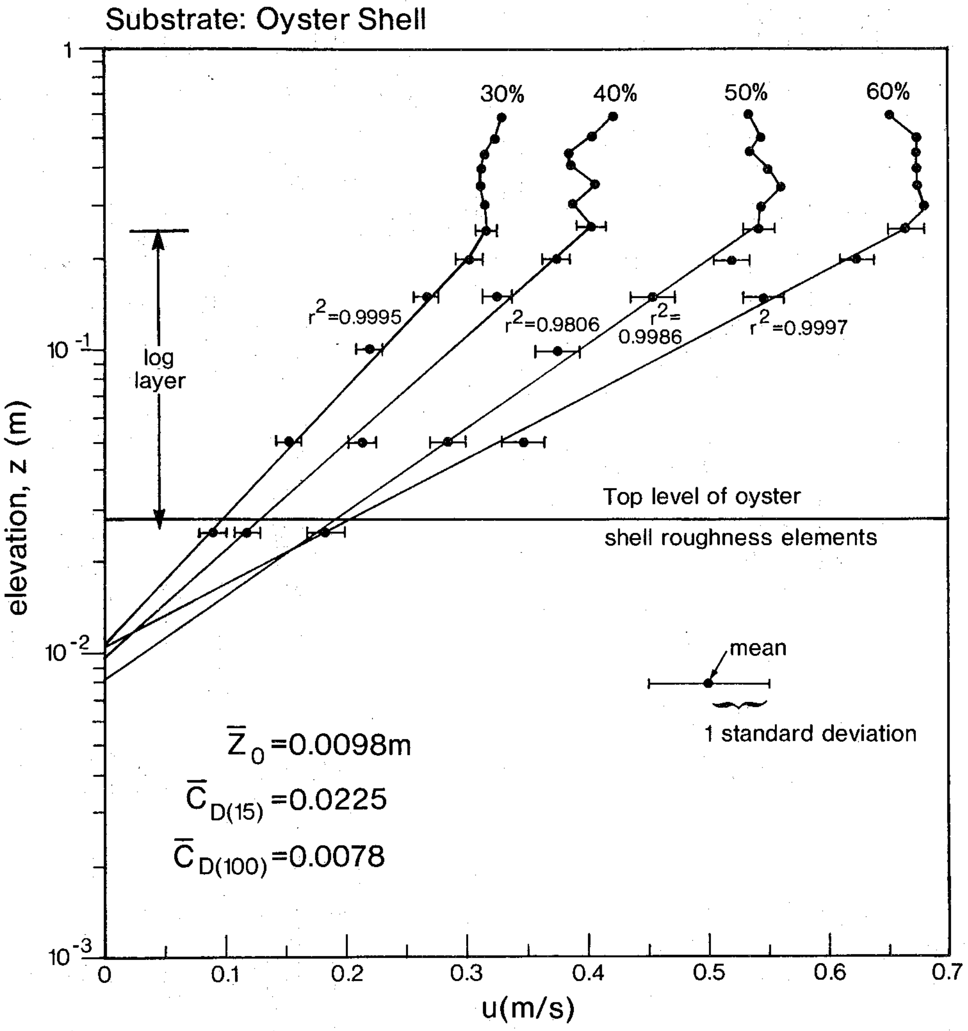

Fig. 5. Boundary-layer velocity profiles measured in the flume over an artificially-placed oyster shell substrate.

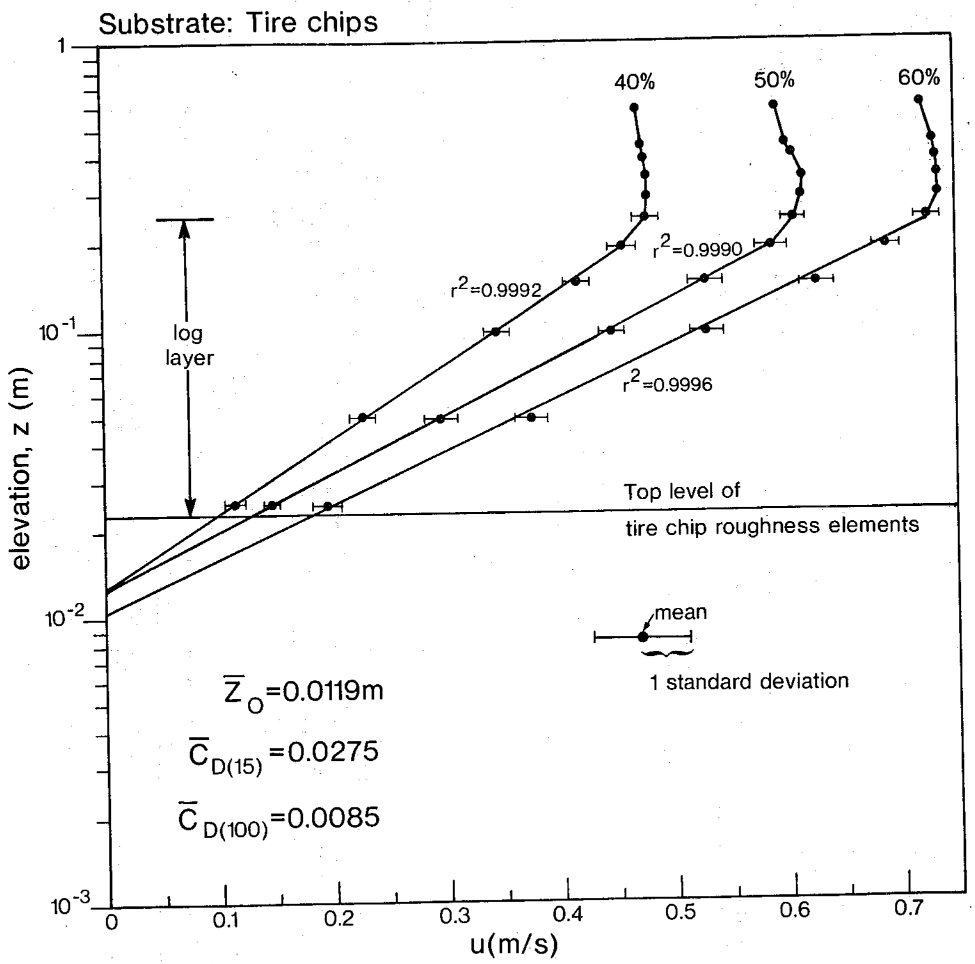

Fig. 6. Boundary-layer velocity profiles measured in the flume over an artificial bed of tire chips secured to plywood.

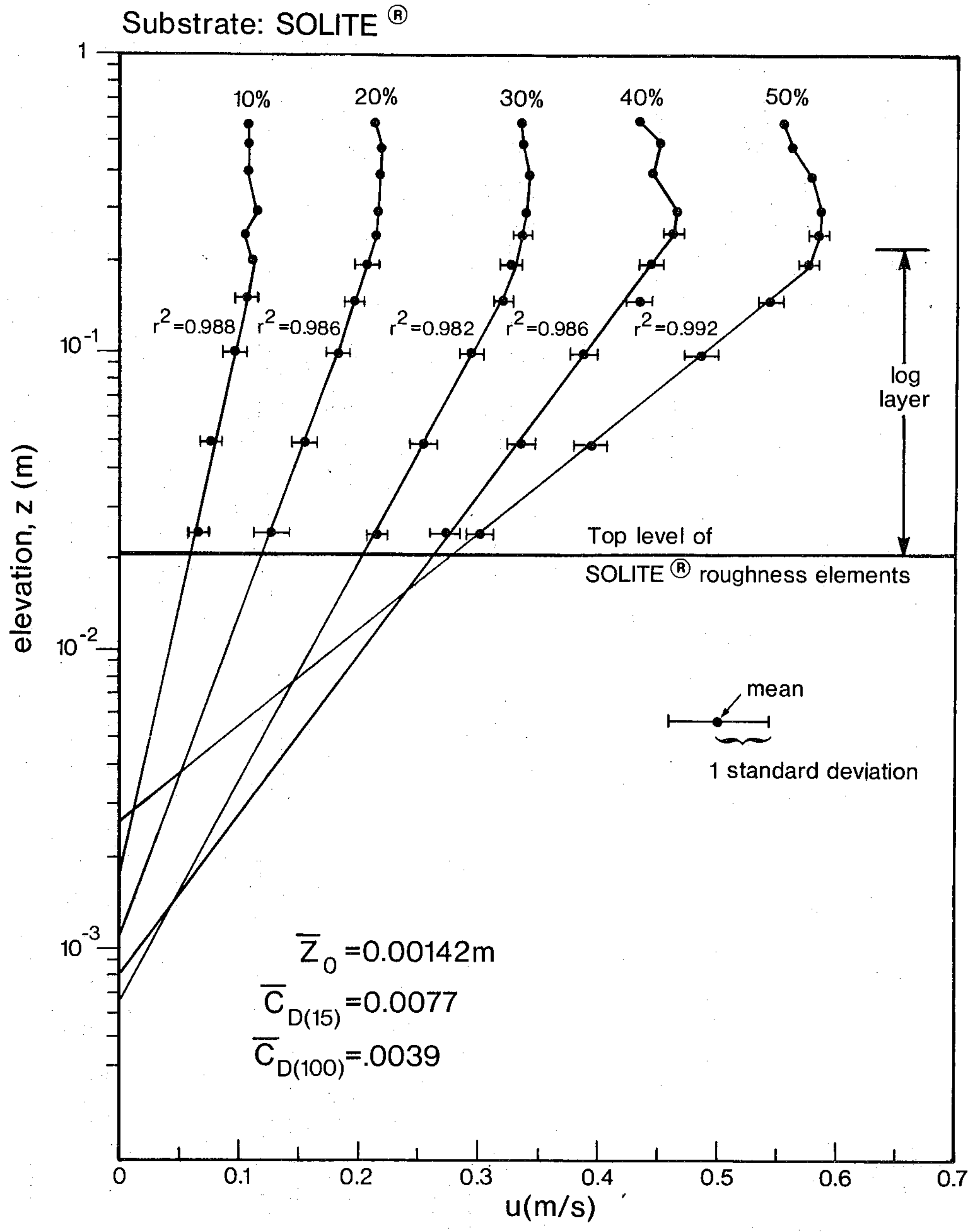

Fig. 7. Boundary-layer velocity profiles measured in the flume over an artificial bed of SOLITE® secured to plywood.

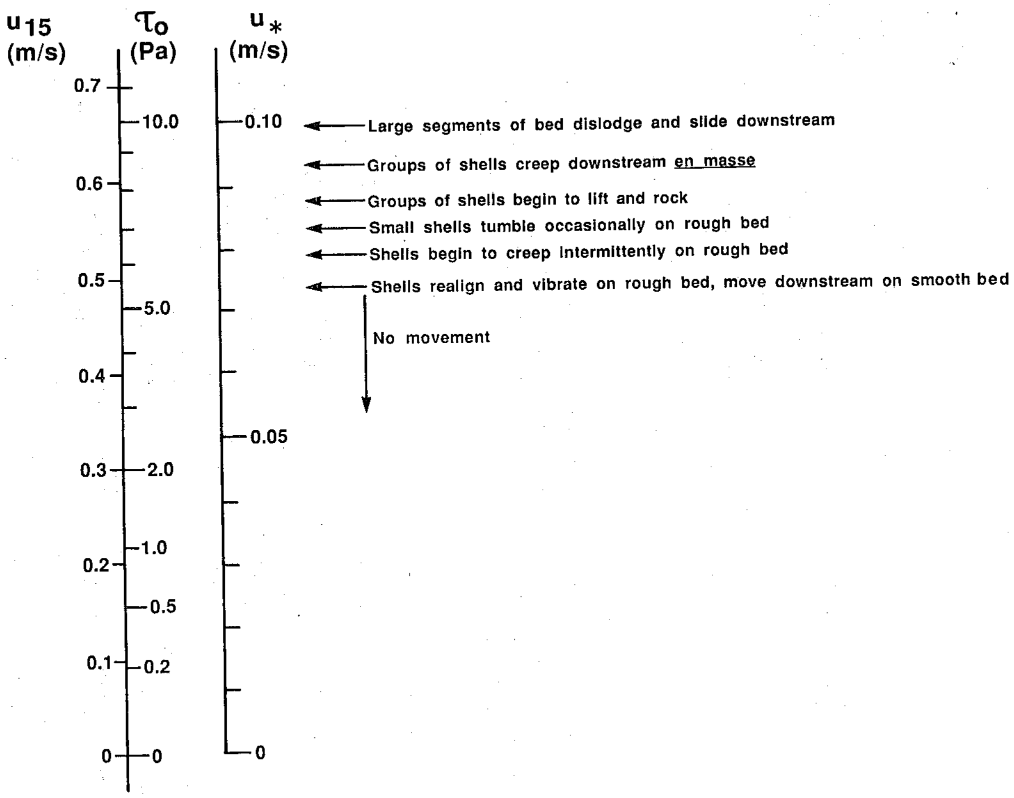

Fig. 8. Threshold criteria for movement under steady flow: Loose oyster shells on an oyster shell substrate.

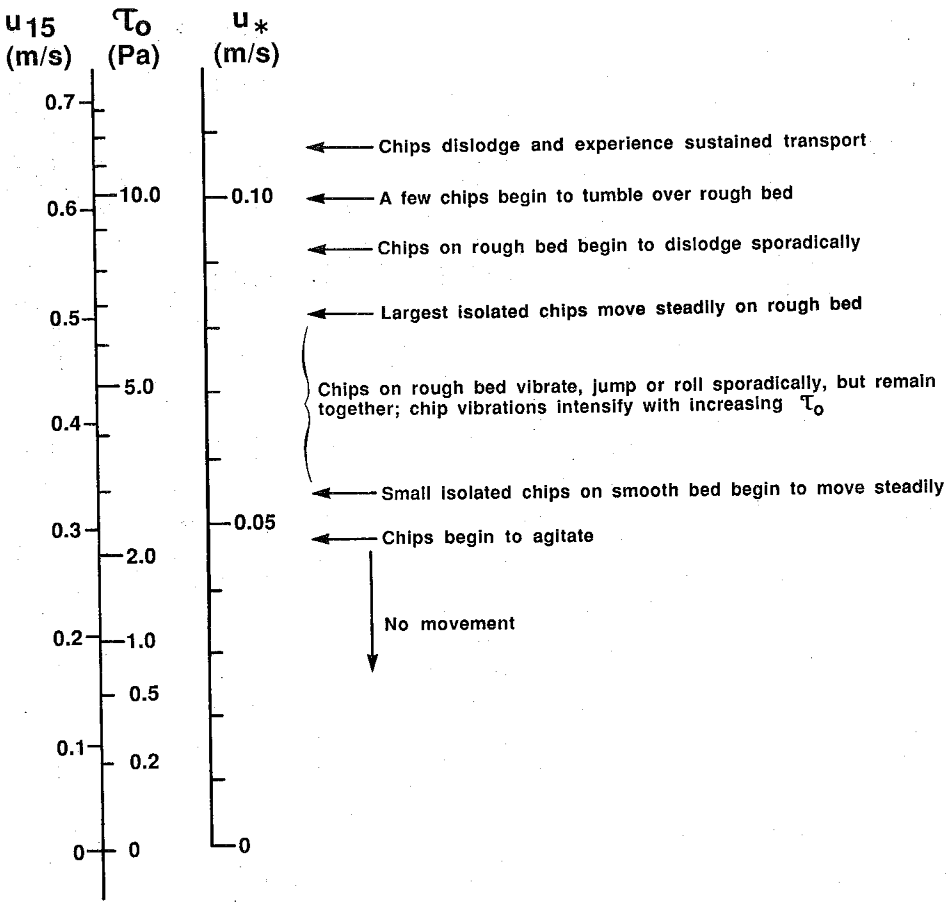

Fig. 9. Threshold criteria for movement under steady flow: Loose tire chips on a tire-chips substrate.

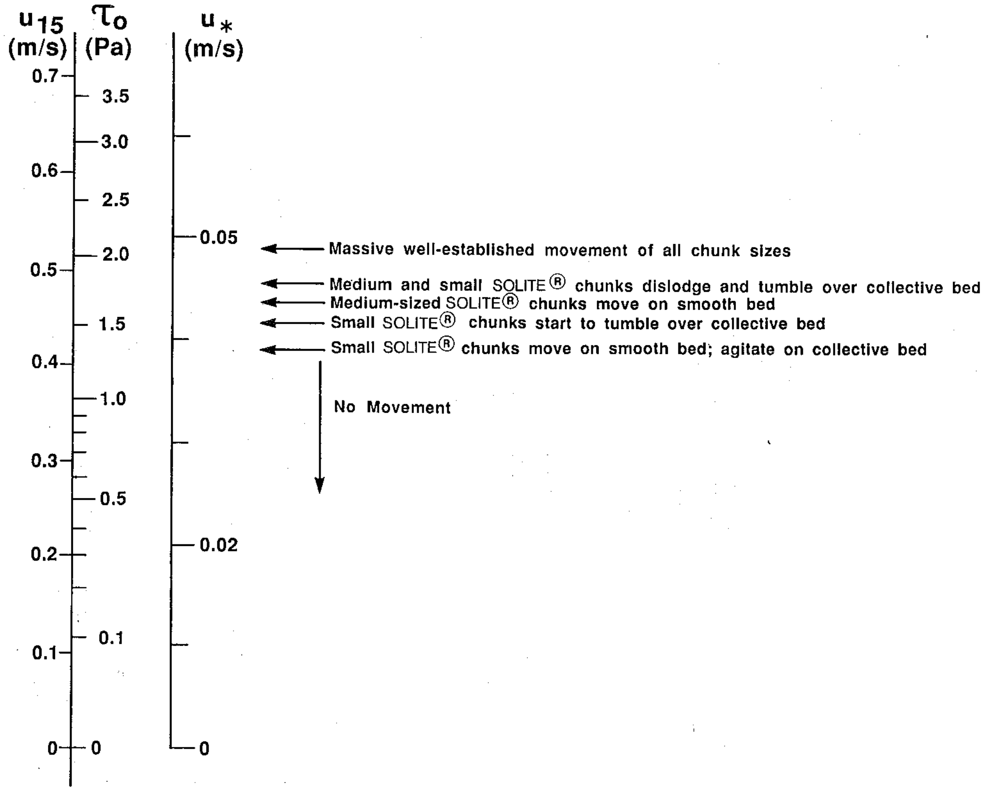

Fig. 10. Threshold criteria for movement under steady flow: Loose SOLITE® chunks on a SOLITE® substrate.