1133

# PRECISIONS OF THE AGGREGATE SAMPLE SPLITTER AND TESTING METHOD

MICHIGAN DEPARTMENT OF TRANSPORTATION

TESTING AND RESEARCH DIVISION
RESEARCH LABORATORY SECTION

# PRECISIONS OF THE AGGREGATE SAMPLE SPLITTER AND TESTING METHOD

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Research Laboratory Section
Testing and Research Division
Research Projects 78 TI-483
and 79 TI-578
Research Report No. R-1133

Lansing, November 1980

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## SUMMARY

Aggregate samples obtained from sources for inspection purposes are usually greater than the capacity of the testing equipment; thus, samples are generally reduced before testing. The usual practice is to divide the sample into subsamples with a Gilson splitter. However, only one of the two subsamples is tested for inspection purposes. Of concern is whether the splitter is capable of consistently splitting a sample into two subsamples of equal gradation.

Also, the Department is currently implementing an in-place aggregate inspection procedure. The aggregate samples are to be tested using a new mechanical testing method. It is of interest to know whether or not the 'hand' and mechanical testing methods produce the same gradation results.

The following conclusions are drawn from three experiments described in this report:

1) The sample splitter is able to split a sample of aggregate into two subsamples such that their weight ratio is very nearly constant. However, this constant may not be the ratio of the number of openings on the two sides of the splitter.

2) The aggregate gradations of the two subsamples are slightly different. The differences, however, are negligible relative to in-place aggregate uniformity. Hence, either subsample can be used to represent the original sample for in-place aggregate inspection purposes.

3) The testing precision of the hand and mechanical methods are very high relative to in-place aggregate uniformity.

4) The aggregate gradation differences measured by the two testing methods are negligible based on laboratory samples, relative to the in-place aggregate uniformity. The differences, however, are significant based on field samples. After reviewing laboratory and field sample preparation procedures, it was concluded that the mechanical testing method degrades aggregate more than the hand testing method. Intuitively, the degree of degradation depends on the testing time. This suggests studying the degradation time profile of the mechanical testing method for the purpose of properly adjusting aggregate specifications.

# INTRODUCTION

Aggregate samples obtained from construction sites for inspection purposes are usually greater than the capacity of the testing equipment; thus, samples have to be reduced in size before testing. The current practice is to use a Gilson sample splitter to divide a sample into two subsamples. Only one of the two subsamples is tested using the hand or mechanical testing method. The test results are then used to accept or reject the in-place aggregate according to an acceptance sampling plan. This practice would not be meaningful unless the following questions can be answered in the affirmative.

1) Is the sample splitter capable of consistently splitting a sample into two subsamples of equal gradation?

2) Do the hand and mechanical testing methods produce the same gradation results?

3) Are splitting and testing precisions high, relative to in-place aggregate uniformity?

The major purpose of this research study is to answer the above questions in statistical terms. For this purpose, we conducted three experiments taking samples of 22A aggregate from construction projects currently inspected by a newly developed in-place aggregate sampling plan.[1] These experiments were designed so that normal inspection practice would not be interrupted. Before describing the experiments, we shall define several key terms used throughout the text.

'Testing error' is defined as the difference between the true value and the test results. 'Testing precision' is, by definition, the variance of the testing error. Similarly, 'splitting error' (on the subsample) is defined as the difference of the true values of the sample and the subsample. 'Splitting precision' is, therefore, the variance of the splitting error. By like reasoning, 'in-place aggregate uniformity' can be defined as the variance of the in-place aggregate gradation. Notice that high testing and splitting precisions as well as high in-place aggregate uniformity imply low testing, splitting, and aggregate variance.

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[1] Kuo, Wen-Hou, "Statistical Analysis of Aggregate Base Course Inspection Using an End Result Aggregate Specification," Michigan Department of Transportation, Research Report No. R-1024, February 1977.

## TABLE 1
## AGGREGATE GRAIN SIZE SPECIFICATIONS

| Pile No. | Aggregate Grain Size |
|---|---|
| 1 | Passes 1-in. sieve, and is retained on 3/4-in. sieve |
| 2 | Passes 3/4-in. sieve, and is retained on 3/8-in. sieve |
| 3 | Passes 3/8-in. sieve, and is retained on No. 4 sieve |
| 4 | Passes No. 4 sieve, and is retained on No. 8 sieve |
| 5 | Passes No. 8 sieve |

## TABLE 2
## TARGET AGGREGATE GRADATIONS FOR MAKING UP GROUP SAMPLES

| Group No. | Percent Passing Sieves | | | |
|---|---|---|---|---|
| | 3/4-in. | 3/8-in. | No. 4 | No. 8 |
| 1 | 98 | 67 | 57 | 32 |
| 2 | 98 | 69 | 59 | 34 |
| 3 | 98 | 71 | 61 | 36 |
| 4 | 98 | 73 | 63 | 38 |
| 5 | 98 | 75 | 65 | 40 |
| 6 | 98 | 77 | 67 | 42 |
| 7 | 98 | 79 | 69 | 44 |
| 8 | 98 | 81 | 71 | 46 |
| 9 | 98 | 83 | 73 | 48 |
| 10 | 98 | 85 | 75 | 50 |

# EXPERIMENTAL PROCEDURES

## Experiment A

This experiment was designed to investigate testing precision using laboratory samples. The data preparation is described below.

Aggregates obtained from Lot No. 2 of Construction Project FR 23092-10729A[2] were separated into five piles of different aggregate sizes specified in Table 1. Ten sets of four samples were then made up from these five piles according to the predetermined target gradations specified in Table 2. Each set of four consisted of two 2,000-gm and two 4,000-gm samples. One of the two samples in each weight group was tested using the hand testing method and the other was tested using the mechanical testing method, the same operator performing all tests. ASTM Procedure C136 governed the manual shaking. For the mechanical shaking, the 4,000-gm and 2,000-gm samples were shaken approximately 11 and 8 minutes, respectively. Loss-by-hand washing was determined in accordance with ASTM C117, and by the mechanical washing apparatus for the mechanical washing. The end points of the wash were determined as specified in the method. The test results of 40 samples for this experiment are presented in Table 3.

## Experiment B

This experiment was designed, using the field samples, to investigate the splitting precision of the sample splitter. Thirty-six samples obtained from Lots 4 through 6 of Construction Project M 36021-10139A[3] were processed as follows: a Gilson sample splitter was used to reduce samples to smaller size. This splitter has four openings on one side and five openings on the other side. The sides with four openings and five openings were designated Side 1 and Side 2, respectively. Each sample of 40 to 50 lb was put through the splitter. The material from Side 2 was discarded. The weight of the material from Side 1 averaged 9,870 gm. This portion of the material was put through the splitter again to produce the two final samples. Material from Side 1 (Subsample 1) was used for the inspection purpose. Material from Side 2 (Subsample 2) was used, together with Subsample 1, to study the splitting precision of the sample splitter. Both subsamples were tested using a mechanical shaker and washing machine (mechanical

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[2] This is one of the four construction projects inspected by the newly developed in-place aggregate acceptance sampling plan.

[3] Ibid.

## TABLE 3
## TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT A

| Group No. | Sample Weight, gm | Testing Method | Percent Passing Sieves | | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | 3/4-in. | 3/8-in. | No. 4 | No. 8 | |
| 1 | 2000 | H* | 98.00 | 67.45 | 56.95 | 33.55 | 4.85 |
| | 2000 | M | 98.00 | 67.50 | 57.70 | 33.25 | 6.00 |
| | 4000 | H | 97.68 | 67.93 | 56.95 | 33.38 | 5.48 |
| | 4000 | M | 98.03 | 67.83 | 57.93 | 33.70 | 6.13 |
| 2 | 2000 | H | 97.65 | 69.42 | 59.07 | 35.63 | 5.60 |
| | 2000 | M | 97.95 | 69.45 | 59.75 | 35.30 | 6.25 |
| | 4000 | H | 97.65 | 70.10 | 59.23 | 35.43 | 5.53 |
| | 4000 | M | 98.25 | 69.63 | 59.84 | 35.52 | 5.92 |
| 3 | 2000 | H | 98.00 | 71.80 | 61.00 | 37.35 | 5.55 |
| | 2000 | M | 98.10 | 71.17 | 61.76 | 37.14 | 6.56 |
| | 4000 | H | 97.85 | 71.99 | 60.94 | 37.36 | 5.68 |
| | 4000 | M | 98.00 | 71.51 | 61.61 | 37.24 | 6.45 |
| 4 | 2000 | H | 97.95 | 74.06 | 62.82 | 39.18 | 6.10 |
| | 2000 | M | 96.25 | 73.51 | 62.97 | 39.53 | 6.60 |
| | 4000 | H | 98.20 | 73.66 | 62.86 | 39.19 | 6.20 |
| | 4000 | M | 97.72 | 73.40 | 63.48 | 39.40 | 6.43 |
| 5 | 2000 | H | 97.60 | 75.38 | 65.01 | 41.14 | 6.46 |
| | 2000 | M | 98.50 | 75.35 | 65.45 | 41.10 | 7.00 |
| | 4000 | H | 97.55 | 75.34 | 64.91 | 41.27 | 6.20 |
| | 4000 | M | 98.00 | 75.53 | 65.53 | 41.20 | 6.98 |
| 6 | 2000 | H | 98.00 | 77.50 | 66.90 | 43.15 | 6.85 |
| | 2000 | M | 98.55 | 77.20 | 67.65 | 43.15 | 7.25 |
| | 4000 | H | 97.32 | 77.79 | 66.84 | 43.04 | 6.75 |
| | 4000 | M | 98.05 | 77.31 | 67.61 | 43.30 | 7.15 |
| 7 | 2000 | H | 98.05 | 80.09 | 68.88 | 45.17 | 6.70 |
| | 2000 | M | 98.00 | 79.44 | 69.24 | 45.17 | 7.20 |
| | 4000 | H | 97.77 | 79.62 | 68.71 | 45.25 | 7.13 |
| | 4000 | M | 97.77 | 79.37 | 69.29 | 45.06 | 7.25 |
| 8 | 2000 | H | 97.00 | 81.43 | 70.87 | 47.75 | 7.61 |
| | 2000 | M | 98.00 | 81.10 | 71.45 | 46.95 | 7.20 |
| | 4000 | H | 97.83 | 81.35 | 70.53 | 47.10 | 7.18 |
| | 4000 | M | 97.70 | 81.31 | 71.36 | 47.25 | 7.45 |
| 9 | 2000 | H | 97.55 | 83.94 | 72.99 | 49.63 | 7.50 |
| | 2000 | M | 98.10 | 83.19 | 73.44 | 48.92 | 7.50 |
| | 4000 | H | 97.75 | 83.45 | 72.54 | 49.11 | 6.98 |
| | 4000 | M | 98.03 | 83.42 | 72.87 | 48.99 | 7.60 |
| 10 | 2000 | H | 97.40 | 85.22 | 74.68 | 51.40 | 7.69 |
| | 2000 | M | 97.30 | 85.18 | 75.38 | 50.75 | 7.61 |
| | 4000 | H | 97.20 | 85.25 | 74.55 | 51.18 | 7.60 |
| | 4000 | M | 98.03 | 85.25 | 75.29 | 51.19 | 7.65 |

* H and M stand for the hand and mechanical testing methods.

testing method). This testing method requires about 20 minutes to wash and 15 minutes to shake. The above procedures are outlined in Figure 1, and the test results are given in Table 4. The percent passing the 1-in. sieve is 100 for every subsample and, therefore, is not included in Table 4.

## Experiment C

This experiment was designed to simultaneously study, using the field samples, the splitting and testing precisions. The sample preparation is described below. Eighty-four samples taken from Lots 4 to 10 of Construction Project FR 64015-11535A[4] were processed as follows: the average weight of these 84 samples is 6,449 gm. Each sample was split into two portions by a sample splitter. This splitter has an equal number of openings on both sides. One side of the splitter was designated as Side 1 and the other side was designated as Side 2. The material from Side 1 and Side 2 was called Subsample I and II, respectively. This is referred to as the first stage splitting. Subsample II was mechanically tested and was used for inspection purposes. Subsample I was further split into two subsamples, Subsample I-1 and Subsample I-2. This is referred to as the second stage splitting. These two subsamples were tested using the hand testing method. The above procedures are outlined in Figure 2, and test results are presented in Table 5. Again, the percent passing the 1-in. sieve is 100 for every subsample and, therefore, not included in the table.

## Remarks

We see from the above experiments that testing precisions were investigated using both laboratory and field samples, and that splitting precisions were investigated using two slightly different sample splitters. For discussion purposes, we shall identify the sample splitter used in Experiments B and C as Splitter B and Splitter C, respectively, throughout the text.

The detailed statistical techniques used to analyze the above experiments are presented in Appendices A, B, and C for readers who are interested. The findings of these experiments are presented in the next two sections. To facilitate the discussion of results, we present Table 6 which gives the in-place aggregate uniformities of construction projects known to the author.

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[4] Ibid.

## TABLE 4
## TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT B

| Sample No. | Subsample No. | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|
| | | | 3/4-in. | 3/8-in. | No. 8 | |
| 1 | 1 | 3215 | 95.89 | 70.82 | 49.27 | 5.69 |
| | 2 | 4878 | 92.62 | 63.57 | 41.78 | 6.15 |
| 2 | 1 | 3585 | 95.20 | 69.51 | 48.31 | 6.42 |
| | 2 | 5160 | 95.41 | 67.17 | 43.99 | 6.88 |
| 3 | 1 | 3090 | 91.49 | 66.34 | 46.21 | 6.54 |
| | 2 | 4563 | 92.99 | 65.64 | 42.67 | 7.12 |
| 4 | 1 | 3380 | 93.28 | 65.53 | 45.41 | 6.07 |
| | 2 | 5483 | 94.86 | 65.75 | 42.49 | 6.35 |
| 5 | 1 | 3507 | 93.36 | 68.26 | 48.73 | 6.19 |
| | 2 | 5310 | 92.98 | 65.57 | 44.26 | 6.74 |
| 6 | 1 | 3718 | 97.31 | 71.03 | 49.52 | 7.15 |
| | 2 | 5090 | 92.69 | 66.62 | 44.81 | 6.58 |
| 7 | 1 | 3873 | 94.14 | 69.20 | 48.54 | 7.64 |
| | 2 | 5398 | 94.16 | 65.73 | 44.74 | 7.87 |
| 8 | 1 | 3748 | 93.76 | 77.13 | 47.89 | 7.10 |
| | 2 | 5370 | 95.01 | 65.59 | 43.99 | 7.04 |
| 9 | 1 | 3584 | 91.63 | 64.23 | 43.81 | 7.17 |
| | 2 | 4888 | 89.81 | 62.46 | 42.04 | 7.02 |
| 10 | 1 | 3665 | 90.67 | 63.66 | 43.47 | 6.82 |
| | 2 | 4698 | 93.87 | 64.24 | 43.27 | 6.07 |
| 11 | 1 | 4234 | 94.80 | 63.16 | 40.08 | 6.05 |
| | 2 | 4728 | 89.91 | 63.68 | 40.84 | 6.20 |
| 12 | 1 | 4473 | 94.86 | 64.45 | 43.89 | 5.72 |
| | 2 | 5515 | 92.33 | 65.98 | 44.13 | 5.89 |
| 13 | 1 | 5090 | 92.99 | 66.88 | 46.74 | 6.35 |
| | 2 | 6438 | 92.79 | 65.39 | 44.80 | 6.20 |
| 14 | 1 | 4777 | 93.34 | 70.86 | 51.22 | 5.80 |
| | 2 | 6623 | 93.10 | 75.80 | 57.69 | 5.72 |
| 15 | 1 | 3952 | 93.52 | 66.24 | 46.26 | 6.00 |
| | 2 | 4835 | 93.13 | 63.91 | 43.12 | 5.73 |
| 16 | 1 | 4036 | 94.33 | 70.99 | 48.49 | 5.77 |
| | 2 | 5515 | 95.09 | 71.22 | 50.08 | 5.53 |
| 17 | 1 | 4317 | 95.39 | 70.93 | 50.06 | 5.37 |
| | 2 | 6350 | 94.69 | 69.48 | 50.39 | 5.34 |
| 18 | 1 | 3872 | 93.29 | 70.27 | 49.35 | 6.40 |
| | 2 | 6512 | 93.80 | 69.70 | 49.49 | 6.59 |

## TABLE 4 (Cont.)
## TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT B

| Sample No. | Subsample No. | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|
| | | | 3/4-in. | 3/8-in. | No. 8 | |
| 19 | 1 | 4691 | 95.89 | 71.63 | 49.31 | 6.76 |
| | 2 | 6888 | 93.92 | 72.71 | 49.40 | 7.20 |
| 20 | 1 | 4709 | 93.31 | 68.46 | 48.23 | 5.86 |
| | 2 | 7090 | 93.81 | 68.41 | 47.80 | 5.44 |
| 21 | 1 | 5268 | 93.39 | 72.49 | 52.60 | 5.90 |
| | 2 | 6570 | 95.30 | 72.50 | 49.19 | 6.10 |
| 22 | 1 | 5281 | 93.90 | 71.01 | 47.93 | 6.29 |
| | 2 | 6602 | 92.90 | 67.49 | 47.59 | 5.91 |
| 23 | 1 | 5004 | 93.39 | 70.68 | 50.48 | 7.89 |
| | 2 | 6253 | 91.91 | 68.11 | 47.42 | 7.71 |
| 24 | 1 | 4613 | 92.89 | 70.21 | 44.81 | 6.81 |
| | 2 | 5811 | 93.91 | 73.02 | 49.22 | 6.69 |
| 25 | 1 | 3947 | 93.72 | 72.18 | 50.39 | 6.06 |
| | 2 | 5065 | 95.60 | 73.39 | 49.63 | 6.08 |
| 26 | 1 | 4154 | 94.03 | 71.40 | 51.54 | 6.48 |
| | 2 | 5287 | 95.71 | 69.62 | 48.61 | 5.83 |
| 27 | 1 | 5237 | 93.45 | 69.79 | 49.74 | 6.68 |
| | 2 | 6393 | 94.40 | 68.48 | 47.43 | 6.77 |
| 28 | 1 | 4587 | 96.60 | 71.81 | 50.77 | 6.65 |
| | 2 | 6320 | 94.59 | 71.14 | 47.34 | 5.32 |
| 29 | 1 | 4378 | 96.39 | 72.45 | 50.59 | 6.99 |
| | 2 | 5818 | 94.91 | 71.52 | 47.61 | 6.77 |
| 30 | 1 | 3808 | 94.80 | 67.44 | 48.08 | 6.57 |
| | 2 | 5272 | 93.00 | 63.66 | 44.52 | 5.96 |
| 31 | 1 | 4953 | 93.30 | 68.67 | 48.68 | 6.32 |
| | 2 | 6110 | 92.75 | 66.68 | 45.43 | 5.53 |
| 32 | 1 | 3803 | 91.06 | 64.76 | 46.52 | 5.21 |
| | 2 | 5344 | 93.32 | 64.84 | 44.69 | 5.78 |
| 33 | 1 | 3907 | 92.24 | 70.62 | 50.96 | 6.53 |
| | 2 | 6000 | 96.50 | 66.37 | 45.92 | 6.67 |
| 34 | 1 | 4248 | 96.23 | 70.39 | 49.91 | 6.90 |
| | 2 | 6122 | 93.83 | 66.11 | 44.95 | 7.14 |
| 35 | 1 | 4245 | 93.83 | 70.84 | 49.33 | 6.36 |
| | 2 | 5428 | 93.90 | 69.10 | 50.99 | 6.60 |
| 36 | 1 | 3565 | 94.31 | 70.69 | 48.81 | 6.03 |
| | 2 | 5093 | 95.17 | 68.98 | 51.78 | 6.30 |

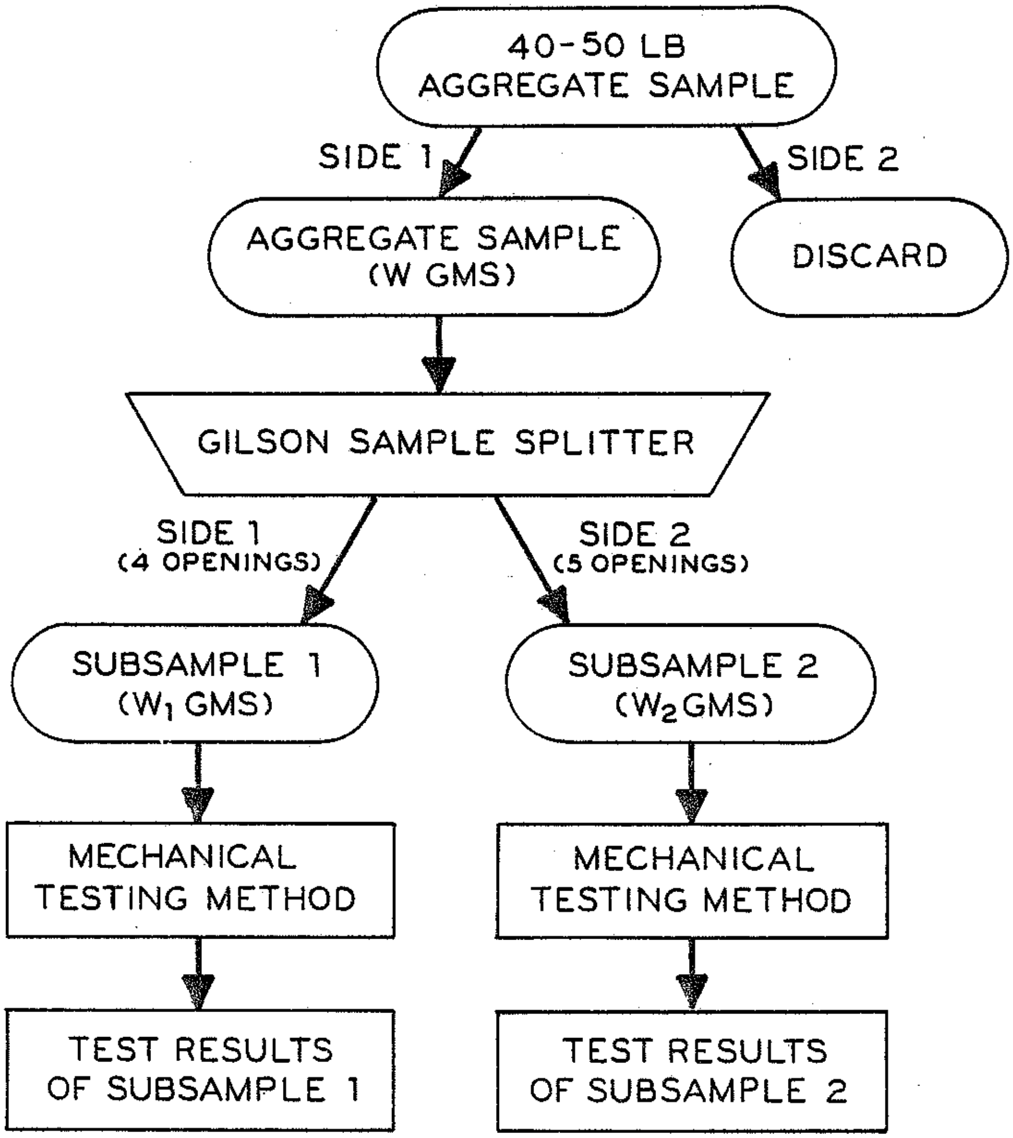

Figure 1. Sample preparation procedures of Experiment B.

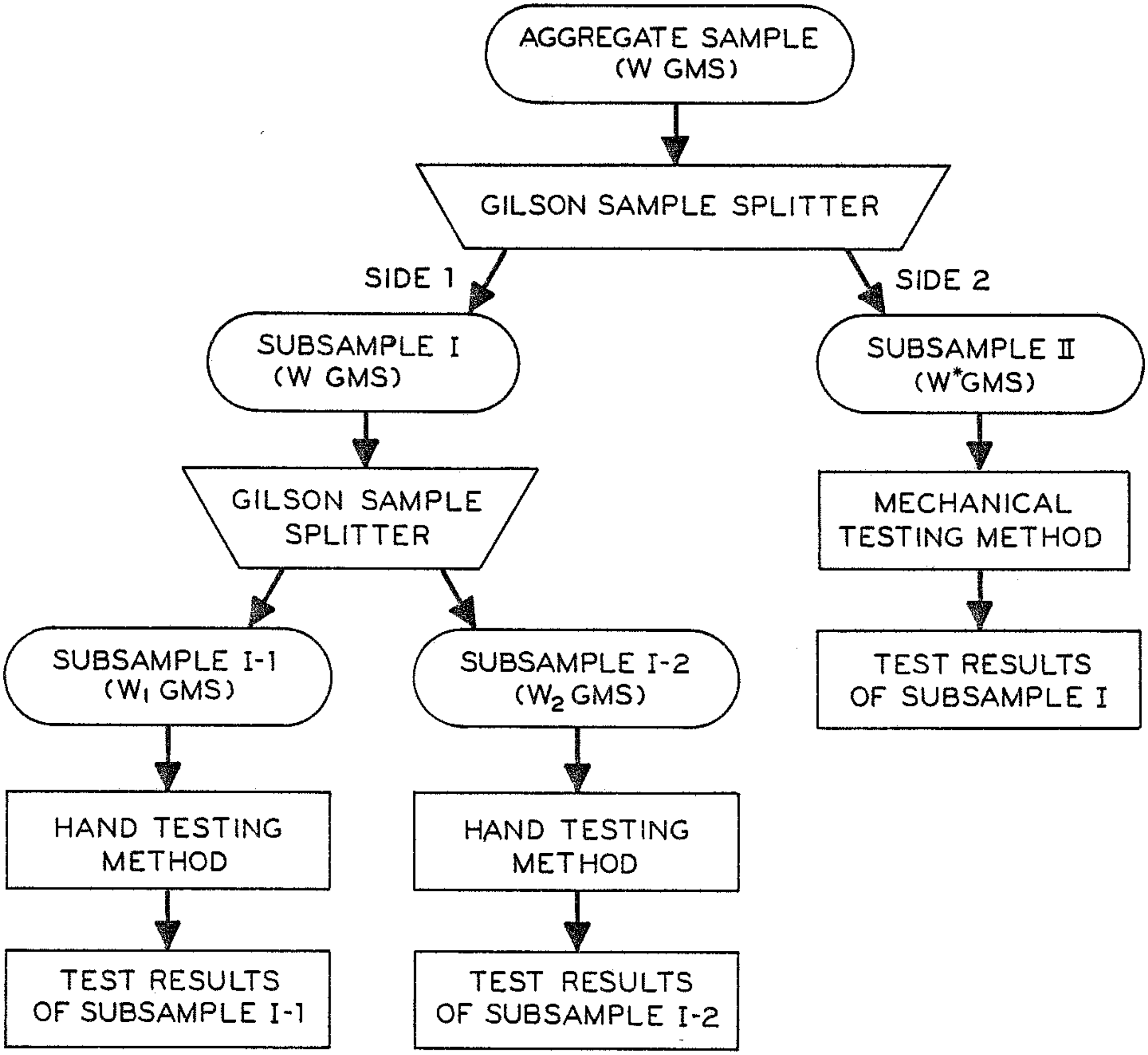

Figure 2. Sample preparation procedures of Experiment C.

## TABLE 5
## TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT C

| Sample No. | Subsample No. | Testing Method | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | | 3/4-in. | 3/8-in. | No. 8 | |
| 1 | II | M | 3628 | 95.98 | 74.31 | 46.91 | 8.27 |
| | I-1 | H | 1481 | 92.57 | 69.21 | 44.63 | 7.43 |
| | I-2 | H | 1559 | 94.10 | 71.46 | 43.94 | 7.63 |
| 2 | II | M | 2762 | 95.94 | 73.86 | 47.25 | 8.51 |
| | I-1 | H | 1265 | 97.23 | 75.65 | 45.85 | 7.51 |
| | I-2 | H | 1457 | 97.25 | 76.39 | 45.64 | 7.82 |
| 3 | II | M | 3030 | 95.58 | 72.87 | 46.34 | 8.09 |
| | I-1 | H | 1496 | 91.98 | 70.92 | 42.25 | 7.42 |
| | I-2 | H | 1274 | 93.01 | 71.59 | 44.58 | 7.46 |
| 4 | II | M | 3076 | 96.29 | 72.11 | 45.94 | 8.65 |
| | I-1 | H | 1416 | 93.64 | 66.45 | 40.25 | 8.12 |
| | I-2 | H | 1435 | 90.31 | 66.69 | 40.70 | 7.39 |
| 5 | II | M | 3157 | 95.19 | 75.55 | 47.51 | 8.46 |
| | I-1 | H | 1479 | 94.25 | 75.05 | 45.98 | 8.25 |
| | I-2 | H | 1503 | 96.81 | 72.32 | 43.71 | 8.05 |
| 6 | II | M | 2610 | 96.55 | 70.61 | 43.22 | 7.70 |
| | I-1 | H | 1557 | 92.04 | 71.10 | 43.16 | 7.90 |
| | I-2 | H | 1337 | 89.08 | 67.02 | 40.61 | 7.18 |
| 7 | II | M | 2783 | 95.33 | 72.58 | 44.16 | 7.83 |
| | I-1 | H | 1570 | 93.69 | 67.64 | 41.40 | 7.01 |
| | I-1 | H | 1445 | 97.16 | 70.80 | 41.66 | 6.71 |
| 8 | II | M | 3018 | 94.20 | 72.00 | 44.76 | 7.69 |
| | I-1 | H | 1327 | 94.80 | 68.73 | 42.43 | 7.01 |
| | I-2 | H | 1777 | 92.85 | 68.37 | 42.04 | 7.03 |
| 9 | II | M | 3461 | 94.19 | 73.94 | 47.10 | 7.37 |
| | I-1 | H | 1740 | 94.43 | 72.87 | 43.74 | 6.55 |
| | I-2 | H | 1584 | 95.08 | 72.41 | 43.43 | 6.76 |
| 10 | II | M | 3436 | 97.64 | 76.89 | 49.85 | 6.87 |
| | I-1 | H | 1602 | 94.88 | 75.84 | 45.51 | 6.18 |
| | I-2 | H | 1277 | 96.01 | 77.29 | 47.77 | 6.11 |
| 11 | II | M | 3736 | 96.33 | 73.45 | 47.78 | 7.60 |
| | I-1 | H | 1592 | 89.82 | 66.08 | 39.82 | 6.03 |
| | I-2 | H | 1396 | 94.77 | 71.92 | 45.42 | 6.73 |
| 12 | II | M | 3559 | 95.62 | 74.29 | 46.87 | 8.12 |
| | I-1 | H | 1586 | 94.45 | 71.37 | 43.44 | 7.63 |
| | I-2 | H | 1658 | 93.49 | 71.59 | 43.85 | 7.54 |

## TABLE 5 (Cont.)
## TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT C

| Sample No. | Subsample No. | Testing Method | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | | 3/4-in. | 3/8-in. | No. 8 | |
| 13 | II | M | 3525 | 94.64 | 72.09 | 46.67 | 7.38 |
| | I-1 | H | 1661 | 95.06 | 69.54 | 42.99 | 7.10 |
| | I-2 | H | 1382 | 95.88 | 74.02 | 46.53 | 7.31 |
| 14 | II | M | 4052 | 97.21 | 77.89 | 50.22 | 8.02 |
| | I-1 | H | 1668 | 96.76 | 72.78 | 43.35 | 7.43 |
| | I-2 | H | 1465 | 95.90 | 78.36 | 51.54 | 7.44 |
| 15 | II | M | 2949 | 96.13 | 77.08 | 48.42 | 7.19 |
| | I-1 | H | 1385 | 96.25 | 71.70 | 42.45 | 6.50 |
| | I-2 | H | 1595 | 93.86 | 74.86 | 44.20 | 6.83 |
| 16 | II | M | 3433 | 95.34 | 75.21 | 48.06 | 7.72 |
| | I-1 | H | 1429 | 89.78 | 63.54 | 37.51 | 6.86 |
| | I-2 | H | 1747 | 90.44 | 67.60 | 40.53 | 7.04 |
| 17 | II | M | 3088 | 94.30 | 73.09 | 47.02 | 7.58 |
| | I-1 | H | 1442 | 91.82 | 69.83 | 41.47 | 6.73 |
| | I-2 | H | 1655 | 93.60 | 69.55 | 43.08 | 7.31 |
| 18 | II | M | 3345 | 98.03 | 76.47 | 50.55 | 7.44 |
| | I-1 | H | 1237 | 90.95 | 72.92 | 45.43 | 6.79 |
| | I-2 | H | 1272 | 93.79 | 72.88 | 47.80 | 7.31 |
| 19 | II | M | 3596 | 95.75 | 76.08 | 48.47 | 6.98 |
| | I-1 | H | 1858 | 96.77 | 77.18 | 47.20 | 7.16 |
| | I-2 | H | 2060 | 94.22 | 75.00 | 45.24 | 7.23 |
| 20 | I | M | 3591 | 94.96 | 74.69 | 47.79 | 6.99 |
| | I-1 | H | 1113 | 91.64 | 69.09 | 42.14 | 6.20 |
| | I-2 | H | 1414 | 90.38 | 70.79 | 43.71 | 6.86 |
| 21 | II | M | 3289 | 96.20 | 74.10 | 47.86 | 7.02 |
| | I-1 | H | 1359 | 95.95 | 74.76 | 46.21 | 7.14 |
| | I-2 | H | 1414 | 96.96 | 70.23 | 43.49 | 6.58 |
| 22 | II | M | 3245 | 95.32 | 72.11 | 44.84 | 7.86 |
| | I-1 | H | 1339 | 90.74 | 64.45 | 39.81 | 7.02 |
| | I-2 | H | 1646 | 98.78 | 72.72 | 43.74 | 7.72 |
| 23 | II | M | 3745 | 95.41 | 75.57 | 47.93 | 7.08 |
| | I-1 | H | 1447 | 90.26 | 69.25 | 44.57 | 6.91 |
| | I-2 | H | 1905 | 92.76 | 70.92 | 42.73 | 6.93 |
| 24 | II | M | 3195 | 94.87 | 74.74 | 46.73 | 7.07 |
| | I-1 | H | 1343 | 96.28 | 73.72 | 42.81 | 7.07 |
| | I-2 | H | 1525 | 90.36 | 64.85 | 38.30 | 6.49 |

## TABLE 5 (Cont.)
## TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT C

| Sample No. | Subsample No. | Testing Method | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | | 3/4-in. | 3/8-in. | No. 8 | |
| 25 | II | M | 3220 | 98.88 | 76.43 | 48.54 | 7.92 |
| | I-1 | H | 1366 | 92.31 | 70.06 | 42.09 | 7.69 |
| | I-2 | H | 1479 | 95.74 | 74.04 | 47.19 | 8.11 |
| 26 | II | M | 3422 | 95.50 | 74.69 | 47.81 | 7.57 |
| | I-1 | H | 1562 | 94.94 | 71.06 | 42.45 | 7.17 |
| | I-2 | H | 1463 | 96.31 | 71.09 | 45.86 | 7.38 |
| 27 | II | M | 3277 | 95.33 | 74.18 | 45.50 | 7.78 |
| | I-1 | H | 1438 | 91.52 | 67.80 | 41.17 | 8.83 |
| | I-2 | H | 1653 | 90.80 | 69.21 | 43.32 | 7.44 |
| 28 | II | M | 3263 | 94.09 | 74.93 | 48.05 | 7.85 |
| | I-1 | H | 1634 | 94.74 | 73.19 | 45.23 | 7.53 |
| | I-2 | H | 1568 | 93.88 | 72.13 | 45.34 | 7.72 |
| 29 | II | M | 3063 | 98.92 | 81.42 | 51.98 | 7.61 |
| | I-1 | H | 1874 | 97.60 | 77.21 | 48.40 | 7.20 |
| | I-2 | H | 1916 | 96.71 | 76.72 | 47.70 | 7.05 |
| 30 | II | M | 3192 | 96.74 | 75.69 | 47.34 | 8.15 |
| | I-1 | H | 1604 | 92.46 | 66.58 | 42.08 | 7.36 |
| | I-2 | H | 1584 | 90.40 | 65.66 | 40.47 | 7.01 |
| 31 | II | M | 3576 | 94.71 | 72.01 | 45.69 | 6.77 |
| | I-1 | H | 1533 | 96.87 | 71.43 | 43.12 | 6.91 |
| | I-2 | H | 1671 | 91.02 | 69.24 | 44.46 | 6.40 |
| 32 | II | M | 3421 | 96.32 | 75.56 | 47.85 | 7.31 |
| | I-1 | H | 1543 | 94.49 | 68.96 | 41.87 | 7.19 |
| | I-2 | H | 1688 | 94.19 | 73.16 | 46.98 | 6.99 |
| 33 | II | M | 3805 | 95.56 | 73.40 | 46.65 | 7.39 |
| | I-1 | H | 1873 | 91.35 | 71.01 | 43.94 | 7.21 |
| | I-2 | H | 1833 | 92.47 | 70.32 | 45.61 | 6.93 |
| 34 | II | M | 3457 | 94.82 | 71.22 | 45.88 | 7.06 |
| | I-1 | H | 1634 | 94.25 | 71.42 | 45.47 | 6.73 |
| | I-2 | H | 1662 | 90.79 | 69.55 | 43.50 | 7.04 |
| 35 | II | M | 3428 | 94.19 | 72.37 | 46.12 | 7.26 |
| | I-1 | H | 1964 | 95.47 | 70.21 | 42.11 | 6.57 |
| | I-2 | H | 1958 | 91.52 | 69.71 | 43.31 | 6.69 |
| 36 | II | M | 3342 | 95.99 | 74.75 | 47.85 | 7.24 |
| | I-1 | H | 1503 | 93.68 | 73.65 | 45.11 | 7.45 |
| | I-2 | H | 1665 | 97.96 | 79.16 | 48.23 | 6.97 |

TABLE 5 (Cont.)
TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT C

| Sample No. | Subsample No. | Testing Method | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | | 3/4-in. | 3/8-in. | No. 8 | |
| 37 | II | M | 3875 | 96.98 | 74.81 | 48.46 | 7.33 |
| | I-1 | H | 1448 | 90.61 | 71.62 | 44.34 | 7.39 |
| | I-2 | H | 1932 | 94.62 | 75.21 | 46.58 | 8.02 |
| 38 | II | M | 3513 | 96.93 | 78.57 | 50.07 | 7.69 |
| | I-1 | H | 1362 | 95.89 | 73.94 | 44.86 | 7.34 |
| | I-2 | H | 1502 | 96.40 | 74.43 | 47.07 | 7.39 |
| 39 | II | M | 3416 | 95.61 | 75.26 | 47.28 | 7.58 |
| | I-1 | H | 1599 | 95.18 | 75.23 | 46.90 | 7.19 |
| | I-2 | H | 2053 | 94.93 | 70.77 | 44.18 | 7.11 |
| 40 | II | M | 2827 | 96.00 | 73.51 | 46.06 | 7.50 |
| | I-1 | H | 1306 | 94.56 | 76.26 | 44.64 | 7.96 |
| | I-2 | H | 1498 | 93.46 | 73.70 | 44.93 | 7.61 |
| 41 | II | M | 3285 | 96.99 | 79.15 | 49.92 | 8.55 |
| | I-1 | H | 1727 | 93.11 | 75.16 | 46.79 | 8.22 |
| | I-2 | H | 1406 | 92.39 | 71.05 | 44.52 | 7.54 |
| 42 | II | M | 2998 | 96.23 | 74.45 | 50.43 | 11.11 |
| | I-1 | H | 1208 | 92.80 | 72.10 | 48.76 | 9.93 |
| | I-2 | H | 1638 | 91.58 | 71.06 | 47.99 | 10.74 |
| 43 | II | M | 3262 | 95.25 | 71.46 | 44.67 | 7.48 |
| | I-1 | H | 1318 | 93.17 | 70.18 | 42.49 | 7.28 |
| | I-2 | H | 1530 | 92.94 | 68.82 | 42.35 | 7.58 |
| 44 | II | M | 2852 | 93.41 | 66.55 | 40.74 | 6.59 |
| | I-1 | H | 1316 | 93.92 | 70.82 | 42.86 | 6.99 |
| | I-2 | H | 1438 | 87.76 | 63.77 | 39.15 | 6.75 |
| 45 | II | M | 3371 | 95.67 | 70.54 | 44.26 | 7.18 |
| | I-1 | H | 1532 | 89.49 | 65.99 | 38.77 | 7.18 |
| | I-2 | H | 1559 | 93.91 | 68.95 | 42.53 | 7.44 |
| 46 | II | M | 3184 | 94.38 | 73.34 | 47.80 | 7.29 |
| | I-1 | H | 1320 | 96.67 | 76.67 | 47.05 | 7.80 |
| | I-2 | H | 1692 | 98.29 | 76.42 | 47.75 | 8.04 |
| 47 | II | M | 3252 | 96.92 | 78.38 | 48.31 | 7.35 |
| | I-1 | H | 1555 | 94.60 | 71.83 | 41.54 | 6.62 |
| | I-2 | H | 1536 | 94.34 | 73.24 | 46.16 | 7.10 |
| 48 | II | M | 3078 | 96.82 | 76.67 | 48.73 | 7.24 |
| | I-1 | H | 1249 | 87.51 | 69.26 | 42.75 | 6.57 |
| | I-2 | H | 1550 | 93.81 | 72.97 | 45.23 | 7.10 |

## TABLE 5 (Cont.)
## TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT C

| Sample No. | Subsample No. | Testing Method | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | | 3/4-in. | 3/8-in. | No. 8 | |
| 49 | II | M | 3481 | 98.65 | 76.07 | 48.78 | 7.38 |
| | I-1 | H | 1545 | 97.15 | 76.25 | 46.93 | 7.38 |
| | I-2 | H | 1439 | 96.04 | 75.75 | 45.45 | 7.02 |
| 50 | II | M | 3051 | 97.08 | 79.78 | 50.38 | 7.54 |
| | I-1 | H | 1375 | 97.02 | 75.49 | 48.87 | 7.49 |
| | I-2 | H | 1728 | 93.69 | 72.63 | 44.27 | 7.29 |
| 51 | II | M | 3343 | 97.52 | 79.30 | 51.99 | 7.90 |
| | I-1 | H | 1323 | 96.37 | 76.80 | 48.07 | 7.18 |
| | I-2 | H | 1795 | 95.43 | 76.10 | 46.85 | 7.52 |
| 52 | II | M | 3215 | 98.16 | 79.69 | 51.20 | 7.74 |
| | I-1 | H | 1363 | 92.22 | 75.79 | 48.13 | 7.34 |
| | I-2 | H | 1499 | 96.53 | 77.72 | 48.37 | 7.40 |
| 53 | II | M | 3657 | 96.64 | 75.42 | 49.11 | 7.38 |
| | I-1 | H | 1528 | 99.21 | 76.90 | 47.38 | 7.07 |
| | I-2 | H | 1587 | 97.35 | 74.86 | 47.83 | 6.81 |
| 54 | II | M | 3554 | 96.31 | 77.21 | 49.24 | 7.40 |
| | I-1 | H | 1249 | 96.08 | 75.66 | 47.96 | 7.53 |
| | I-2 | H | 1640 | 93.66 | 72.56 | 44.21 | 7.01 |
| 55 | II | M | 3860 | 96.48 | 78.11 | 49.25 | 7.10 |
| | I-1 | H | 1985 | 93.55 | 77.18 | 47.15 | 6.65 |
| | I-2 | H | 1927 | 96.78 | 77.79 | 47.90 | 6.64 |
| 56 | II | M | 3086 | 94.52 | 75.79 | 48.06 | 7.45 |
| | I-1 | H | 1359 | 96.03 | 73.14 | 45.11 | 6.70 |
| | I-2 | H | 1574 | 93.58 | 73.00 | 43.58 | 6.80 |
| 57 | II | M | 3260 | 96.84 | 78.25 | 51.26 | 6.81 |
| | I-1 | H | 1439 | 90.55 | 74.84 | 47.53 | 6.25 |
| | I-2 | H | 2043 | 95.35 | 78.32 | 49.24 | 6.66 |
| 58 | II | M | 3294 | 98.82 | 80.12 | 51.43 | 8.65 |
| | I-1 | H | 1487 | 96.30 | 75.99 | 46.00 | 7.73 |
| | I-2 | H | 1793 | 93.31 | 75.57 | 46.07 | 7.64 |
| 59 | II | M | 3270 | 96.91 | 74.19 | 46.67 | 8.13 |
| | I-1 | H | 1454 | 90.51 | 68.64 | 41.27 | 7.15 |
| | I-2 | H | 1509 | 94.23 | 71.50 | 44.40 | 8.15 |
| 60 | II | M | 3634 | 96.51 | 73.20 | 45.40 | 7.79 |
| | I-1 | H | 1371 | 96.64 | 71.55 | 41.79 | 7.08 |
| | I-2 | H | 1486 | 93.67 | 69.99 | 40.58 | 7.27 |

TABLE 5 (Cont.)
TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT C

| Sample No. | Subsample No. | Testing Method | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | | 3/4-in. | 3/8-in. | No. 8 | |
| 61 | II | M | 3612 | 94.66 | 75.08 | 47.81 | 8.14 |
| | I-1 | H | 1487 | 92.60 | 73.97 | 46.40 | 7.80 |
| | I-2 | H | 1643 | 93.67 | 73.22 | 44.00 | 7.55 |
| 62 | II | M | 3648 | 93.91 | 72.81 | 46.66 | 7.87 |
| | I-1 | H | 1729 | 92.02 | 69.46 | 42.86 | 7.63 |
| | I-2 | H | 1912 | 91.63 | 72.38 | 43.78 | 7.79 |
| 63 | II | M | 3724 | 94.33 | 73.34 | 46.62 | 8.11 |
| | I-1 | H | 1562 | 95.07 | 75.35 | 45.71 | 8.00 |
| | I-2 | H | 1536 | 93.42 | 70.83 | 42.19 | 7.36 |
| 64 | II | M | 3193 | 95.24 | 74.41 | 47.64 | 8.49 |
| | I-1 | H | 1378 | 96.59 | 78.88 | 49.49 | 8.78 |
| | I-2 | H | 1456 | 91.62 | 74.04 | 42.99 | 8.04 |
| 65 | II | M | 3371 | 94.90 | 74.28 | 46.75 | 7.86 |
| | I-1 | H | 1444 | 94.11 | 69.94 | 42.04 | 6.79 |
| | I-2 | H | 1633 | 93.39 | 71.34 | 44.89 | 7.72 |
| 66 | II | M | 3265 | 96.39 | 78.44 | 49.19 | 8.67 |
| | I-1 | H | 1393 | 95.84 | 74.30 | 47.38 | 8.18 |
| | I-2 | H | 1713 | 95.86 | 73.09 | 43.32 | 7.47 |
| 67 | II | M | 3538 | 95.34 | 72.81 | 42.85 | 6.42 |
| | I-1 | H | 1424 | 93.82 | 67.63 | 39.61 | 5.76 |
| | I-2 | H | 1484 | 92.05 | 66.24 | 38.41 | 5.86 |
| 68 | II | M | 3781 | 95.27 | 73.71 | 45.68 | 7.83 |
| | I-1 | H | 1314 | 91.02 | 72.15 | 43.15 | 7.23 |
| | I-2 | H | 1694 | 96.87 | 69.24 | 41.44 | 7.02 |
| 69 | II | M | 3396 | 97.35 | 77.56 | 49.59 | 8.60 |
| | I-1 | H | 1183 | 89.77 | 73.37 | 46.07 | 8.20 |
| | I-2 | H | 1489 | 94.83 | 69.38 | 41.64 | 7.32 |
| 70 | II | M | 3554 | 94.43 | 65.81 | 40.04 | 6.53 |
| | I-1 | H | 1570 | 93.69 | 64.52 | 38.09 | 5.86 |
| | I-2 | H | 1796 | 93.10 | 64.31 | 36.19 | 5.62 |
| 71 | II | M | 3688 | 93.28 | 72.86 | 48.07 | 7.81 |
| | I-1 | H | 1515 | 96.44 | 76.90 | 48.65 | 7.92 |
| | I-2 | H | 1935 | 94.99 | 76.12 | 46.46 | 7.60 |
| 72 | II | M | 3765 | 93.55 | 71.93 | 45.21 | 7.22 |
| | I-1 | H | 1568 | 95.92 | 71.94 | 44.96 | 7.65 |
| | I-2 | H | 1693 | 94.03 | 72.06 | 43.24 | 7.62 |

TABLE 5 (Cont.)
TEST RESULTS OF SAMPLES PREPARED FOR EXPERIMENT C

| Sample No. | Subsample No. | Testing Method | Sample Weight, gm | Percent Passing Sieves | | | Percent Loss-by-Washing |
|---|---|---|---|---|---|---|---|
| | | | | 3/4-in. | 3/8-in. | No. 8 | |
| 73 | II | M | 3429 | 93.76 | 73.20 | 46.84 | 7.29 |
| | I-1 | H | 1918 | 90.41 | 70.86 | 43.12 | 7.19 |
| | I-2 | H | 1286 | 87.25 | 70.14 | 41.99 | 6.77 |
| 74 | II | M | 3638 | 95.38 | 71.91 | 44.64 | 7.26 |
| | I-1 | H | 1694 | 89.61 | 64.64 | 39.37 | 6.85 |
| | I-2 | H | 1336 | 100.00 | 71.71 | 42.66 | 7.19 |
| 75 | II | M | 3246 | 95.93 | 74.12 | 46.58 | 7.64 |
| | I-1 | H | 1321 | 91.75 | 67.90 | 41.48 | 7.57 |
| | I-2 | H | 1685 | 92.64 | 69.91 | 43.09 | 7.66 |
| 76 | II | M | 3326 | 96.66 | 75.89 | 47.17 | 7.73 |
| | I-1 | H | 1484 | 94.41 | 75.61 | 43.35 | 7.08 |
| | I-2 | H | 1731 | 93.24 | 68.46 | 40.96 | 6.99 |
| 77 | II | M | 3681 | 93.64 | 73.95 | 46.18 | 7.61 |
| | I-1 | H | 1555 | 92.73 | 70.87 | 42.25 | 7.52 |
| | I-2 | H | 1298 | 96.30 | 75.12 | 45.45 | 7.40 |
| 78 | II | M | 3526 | 96.68 | 73.34 | 47.39 | 7.40 |
| | I-1 | H | 1403 | 96.22 | 72.42 | 47.04 | 7.27 |
| | I-2 | H | 1713 | 99.01 | 75.48 | 47.75 | 7.36 |
| 79 | II | M | 3265 | 95.34 | 71.82 | 44.26 | 7.35 |
| | I-1 | H | 1280 | 97.19 | 74.61 | 44.92 | 7.34 |
| | I-2 | H | 1205 | 95.60 | 77.18 | 46.64 | 7.55 |
| 80 | II | M | 3590 | 96.24 | 74.60 | 48.89 | 7.74 |
| | I-1 | H | 1733 | 99.13 | 74.50 | 45.76 | 8.02 |
| | I-2 | H | 1694 | 95.75 | 76.21 | 46.58 | 8.15 |
| 81 | II | M | 3273 | 95.33 | 74.18 | 48.58 | 8.49 |
| | I-1 | H | 1589 | 97.86 | 73.32 | 47.26 | 9.00 |
| | I-2 | H | 1555 | 94.47 | 66.82 | 43.34 | 8.04 |
| 82 | II | M | 2905 | 94.70 | 72.87 | 47.85 | 8.92 |
| | I-1 | H | 1649 | 93.33 | 76.41 | 50.52 | 9.95 |
| | I-2 | H | 1453 | 93.53 | 69.30 | 45.01 | 8.53 |
| 83 | II | M | 3061 | 95.98 | 73.37 | 46.19 | 8.07 |
| | I-1 | H | 1172 | 94.11 | 72.27 | 45.65 | 8.11 |
| | I-2 | H | 1637 | 94.50 | 73.37 | 45.51 | 7.94 |
| 84 | II | M | 3324 | 95.64 | 76.59 | 47.26 | 8.03 |
| | I-1 | H | 1320 | 100.00 | 74.62 | 46.21 | 8.03 |
| | I-2 | H | 1620 | 93.09 | 75.86 | 45.93 | 7.72 |

## TABLE 6
## IN-PLACE AGGREGATE UNIFORMITIES OF VARIOUS CONSTRUCTION PROJECTS

| Sources | Variances of Percent Passing Sieves | | | Variance of Percent Loss-by-Washing |
|---|---|---|---|---|
| | 3/4-in. | 3/8-in. | No. 8 | |
| Stillman Pit[1] | 4.17 | 9.88 | 10.76 | 0.59 |
| Pifke Pit[1] | 4.33 | 4.28 | 2.36 | 0.41 |
| Anderson Pit[1] | 3.02 | 4.80 | 3.49 | 0.37 |
| M 36021[2] | 2.36 | 9.52 | 6.66 | 0.27 |
| FR 23092[2] | 1.27 | 33.95 | 31.60 | 0.64 |
| FR 64015[2] | 1.77 | 7.46 | 5.15 | 0.36 |
| I 50062[2] | 0.18 | 16.17 | 26.46 | 1.35 |

[1] Information presented in Research Report No. R-1024, MDOT.

[2] The construction projects are inspected by the newly developed in-place aggregate acceptance sampling plan.

## TABLE 7
## THE ESTIMATED SPLITTING ERRORS

| Sieve Size | Sample Splitter B | | Sample Splitter C (Second Stage Splitting) | |
|---|---|---|---|---|
| | Side 1 | Side 2 | Side 1 | Side 2 |
| 3/4-in. | 0.1089 | -0.0946 | -0.0309 | 0.0291 |
| 3/8-in. | 0.8866 | -0.6279 | -0.0044 | 0.0149 |
| No. 8 | 1.0033* | -0.7131* | -0.0311 | 0.0658 |
| Loss-by-Washing | 0.0241 | -0.0232 | 0.0186 | -0.0231 |

* The figure is significantly different from zero at the 95 percent confidence level.

## TABLE 8
## THE ESTIMATED SPLITTING PRECISIONS

| Sieve Size | Sample Splitter B | | Sample Splitter C | | | |
|---|---|---|---|---|---|---|
| | | | 1st Stage Splitting | | 2nd Stage Splitting | |
| | Side 1 | Side 2 | Side 1 | Side 2 | Side 1 | Side 2 |
| 3/4-in. | 1.3289 | 0.7381 | 1.1757 | 0.9744 | 2.7516 | 2.4195 |
| 3/8-in. | 2.8082 | 1.4046 | 1.8403 | 1.5447 | 2.9029 | 2.0411 |
| No. 8 | 2.8002 | 1.4299 | 0.7458 | 0.6014 | 2.0359 | 1.8920 |
| Loss-by-Washing | 0.0639 | 0.0340 | 0.0380 | 0.0326 | 0.0592 | 0.0518 |

## TABLE 9
## ESTIMATES OF THE IN-PLACE AGGREGATE UNIFORMITIES

| Sieve Size | Experiment B | Experiment C |
|---|---|---|
| 3/4-in. | 1.1944 | 1.5422 |
| 3/8-in. | 8.0235 | 6.5195 |
| No. 8 | 8.0649 | 4.5449 |
| Loss-by-Washing | 0.3433 | 0.3908 |

# ANALYSIS AND CONCLUSIONS

## Splitting Ability

The sample splitter is able to split a sample of aggregate into two portions such that their weight ratio is very nearly constant. However, this constant may not be the ratio of the number of openings on the two sides of the splitter.

The estimated splitting errors and precisions in terms of aggregate gradation are presented in Tables 7 and 8 (see Appendices B and C for details). The symbol * in Table 7 means that the figure is significantly different from zero at the 95 percent confidence level (see Appendix B). In this case, we conclude that there is a splitting error relative to the individual splitter precision (Table 8). While we conclude that the aggregate gradations of the two portions obtained by Splitter B are slightly different, the question remains: Are these differences significant relative to the in-place aggregate uniformity? To answer this question, we compare Table 8 with Table 6 and see that the differences could remain significant if in-place aggregate uniformity is high. Since the splitting precision could positively correlate with the in-place aggregate uniformity, we should compare the splitting precision with the in-place aggregate uniformity of the job from which samples were obtained. The estimated in-place aggregate uniformities are presented in Table 9. Now, comparing Table 8 with Table 9, we see that none of the testing errors presented in Table 7 would be significant. Based on the above analysis, we conclude that the aggregate gradations of the two subsamples obtained by a sample splitter are practically the same. Thus, either subsample can be used to represent the original sample for in-place aggregate inspection purposes.

In Appendices B and C, we show that the larger subsample has less splitting error numerically than the smaller subsample. Moreover, the splitting precision on the larger subsample is higher. Thus, the larger subsample is better than the smaller subsample in representing the original sample.

In Experiment C it was shown that the larger the sample, the higher the precision of the sample splitter. The above statement can be verified by comparing the splitting precision of the first stage splitting with that of the second stage splitting (Table 8). We know that, on the average, the sample weight of Experiment B is larger than that of Experiment C. Therefore, the splitting precision of Splitter B should be higher than that of Splitter C; however, this is not the case. This phenomenon can be explained by one or both of the following reasons:

a) the splitting precision is positively correlated with the in-place aggregate uniformity, or

b) the sample splitter with an equal number of openings on two sides has superior splitting ability.

Statement (b) is given numerically in Table 7. The above arguments indicate that the sample splitter with an equal number of openings on two sides is the better tool for reducing sample size.

## Testing Ability

Experiment A is a so-called 'Two-Way Completely Randomized Block Design' with vector observations. A multivariate statistical analysis of variance program was used to analyze the data presented in Table 1. The results led us to conclude at the 95 percent confidence level that the sample weight does not affect the testing ability in measuring aggregate gradation. However, the aggregate gradations measured by the hand and mechanical testing methods are significantly different. To expand on this, we present the 95 percent simultaneous confidence intervals for mean differences of gradations measured by the two testing methods (Table 10). We also present the sample variances of the differences of gradations measured by the two testing methods (Table 11). We see from Table 10 that the differences are quite small, but significant with respect to small sample variations presented in Table 11. After comparing Table 11 with Table 6, we conclude that the small differences in Table 10 are not significant with respect to in-place aggregate uniformity. As pointed out in Appendix A, variances presented in Table 11 are the sum of variances of the two testing errors.

TABLE 10
95 PERCENT SIMULTANEOUS CONFIDENCE INTERVALS FOR MEAN DIFFERENCES OF GRADATIONS MEASURED BY THE HAND AND MECHANICAL TESTING METHODS (EXPERIMENT A)

| Sieve Size | Mean Difference | Confidence Interval | | Significance |
|---|---|---|---|---|
| | | Lower Limit | Upper Limit | |
| 3/4-in. | -0.2163 | -0.7979 | 0.3653 | No |
| 3/8-in. | 0.2549 | -0.0149 | 0.5247 | No |
| No. 4 | -0.6178 | -0.8086 | -0.4269 | Yes |
| No. 8 | 0.1067 | -0.2113 | 0.4246 | No |
| Loss-by-Washing | -0.4278 | -0.7966 | -0.0590 | Yes |

Based on the above analysis, we reach the following conclusion. The testing precisions of the hand and mechanical testing methods are very high. Consequently, the differences presented in Table 10 can be regarded as the true differences between the two testing methods in measuring the aggregate gradation. However, these slight differences are negligible relative to the in-place aggregate uniformity. That is, the hand and mechanical testing methods are practically the same in measuring aggregate gradation.

TABLE 11
SAMPLE VARIANCES OF THE DIFFERENCES
OF GRADATIONS MEASURED BY THE HAND
AND MECHANICAL TESTING METHODS

| Sieve Size | Variance |
|---|---|
| 3/4-in. | 0.3537 |
| 3/8-in. | 0.0761 |
| No. 4 | 0.0381 |
| No. 8 | 0.1057 |
| Loss-by-Washing | 0.1422 |

The above conclusion was obtained from an experiment using laboratory samples. We would like to know whether the same conclusions can be reached using field samples. Based on the data obtained in Experiment C, we present the 95 percent simultaneous confidence intervals for mean differences of gradations measured by the two testing methods in Table 12. As one can see from Table 12, the two testing methods are again significantly different, relative to sample variations, in measuring aggregate gradation. After comparing the sample variations (Appendix C) with Table 6, we conclude that the two testing methods would still differ significantly in measuring the percent passing the 3/4-in., 3/8-in., and No. 8 sieves for inspection purposes. This conclusion is contrary to the finding of Experiment A. We do not know the reason for this discrepancy; however, we speculate that aggregate might be degraded during the test (shaking process). Table 12 indicates that the percent passing each sieve measured by the mechanical method is larger than that measured by the hand sieve; that is, the mechanical test method degrades aggregate more than the hand test method. This should also have been true in Experiment A. We recall that there are two shaking processes in Experiment A: separating aggregate into five piles, and testing samples. Degradation should mostly occur on the initial shaking. That is, there is probably no significant degradation during the second shaking. This would explain the discrepancy between Experiment A and Experiment C in measuring percent passing. Since the percent loss-by-washing is measured before shaking, this observation would not apply. This is why Experiments A and C agree on loss-by-washing.

TABLE 12
95 PERCENT SIMULTANEOUS CONFIDENCE INTERVALS FOR MEAN DIFFERENCES OF GRADATIONS MEASURED BY THE HAND AND MECHANICAL TESTING METHODS (EXPERIMENT C)

| Sieve Size | Mean Difference | Confidence Interval |  | Significance |
|---|---|---|---|---|
|  |  | Lower Limit | Upper Limit |  |
| 3/4-in. | -1.75 | -2.4702 | -1.0175 | Yes |
| 3/8-in. | -2.51 | -3.4181 | -1.5953 | Yes |
| No. 8 | -3.07 | -3.6396 | -2.4939 | Yes |
| Loss-by-Washing | -0.34 | -0.4721 | -0.2088 | Yes |

If the difference between the two testing methods is aggregate degradation during the test, the Department should use the mechanical test method for the following reasons:

a) samples are obtained from the construction sites prior to compaction; the compaction process degrades aggregate, and

b) the mechanical test method would be subject to less operator variations once this method is standardized.

## Remarks

Suppose that each sample is about W grams. The aggregate gradation of this sample can be measured in the following three ways:

1) the whole sample is tested,

2) the sample is split into two subsamples by a sample splitter with equal number of openings on two sides and only one of the two subsamples is tested,

3) as in (2) the sample is split into two subsamples; however, both subsamples are tested and the test results combined as the aggregate gradation of the sample.

The sample variation for each method can be expressed as:

$$\sigma_1^2 \text{ (Method 1)} = \sigma_{P1}^2 + \sigma_t^2 \tag{1}$$

$$\sigma_2^2 \text{ (Method 2)} = \sigma_{P1}^2 + \sigma_e^2 + \sigma_t^2 \tag{2}$$

and

$$\sigma_3^2 \text{ (Method 3)} = \sigma_{P1}^2 + 1/2\, \sigma_t^2 \tag{3}$$

where $\sigma_{P1}^2$ is the in-place aggregate uniformity measured by samples with weight W grams, $\sigma_e^2$ is the splitting precision and $\sigma_t^2$ is the testing precision.

We concluded in the research study that the testing precision is high and negligible relative to the in-place aggregate uniformity. Thus, method (3) is slightly superior to methods (1) and (2) in terms of sample variation. However, this benefit is achieved by doubling the testing cost. Bearing the cost in mind, method (1) should be used in preference to method (3) unless the sample weight is beyond the capacity of the testing equipment.

When the sample weight is beyond the testing capacity, the sample would have to be split into two subsamples; that is, we must choose method (2) or method (3). If we choose method (3), we will be able to decrease the sample variation by $\sigma_e^2 + 1/2\, \sigma_t^2$. Again, this benefit is achieved by doubling the testing cost. The desirability of method (2) depends upon the magnitude of $\sigma_e^2$. In general, $\sigma_e^2$ correlates positively with $\sigma_{P1}^2$. Thus, when the in-place aggregate uniformity is high, method (2) would be suitable for measuring aggregate gradation.

Instead of taking oversize samples, we shall take samples of weight, say about W/2 grams. Generally speaking, $\sigma_{P2}^2$ would be larger than $\sigma_{P1}^2$ since the weight of this sample is within the range of the testing capacity and can be tested in entirety. Thus, the sample variation, $\sigma_4^2$, measured by this method is,

$$\sigma_4^2 = \sigma_{P2}^2 + \sigma_t^2 \tag{4}$$

and, consequently,

$$\sigma_2^2 - \sigma_4^2 = \sigma_{P1}^2 - \sigma_{P2}^2 + \sigma_e^2 \quad (5)$$

The relationship among $\sigma_{P1}^2$ , $\sigma_{P2}^2$ , and $\sigma_e^2$ determines the choice between method (2) and this alternative method. This relationship can be established in principle, but is unknown at this time. However, if the in-place aggregate uniformity is high, $\sigma_{P1}^2$ and $\sigma_{P2}^2$ would be very close and, therefore, this alternative method should be used for inspection purposes.

# APPENDIX A

## TESTING PRECISIONS OF THE HAND AND MECHANICAL TESTING METHODS

In this appendix, we present the statistical formulation of Experiment A. Experiment A is a so-called 'Two-Way Completely Randomized Block Design' with vector observations. A multivariate statistical analysis of variance program was then used to analyze the data. The results led us to conclude at the 95 percent confidence level that sample weight does not affect the testing ability in measuring aggregate gradation. However, aggregate gradations measured by the hand and mechanical testing methods are significantly different. To fully explain the above statements, we present the 95 percent simultaneous confidence interval for mean differences of gradations measured by hand and mechanical testing methods in Table 10. We also present the sample variations of the differences of gradations measured by hand and mechanical testing methods in Table 11. We see from Table 10 that the mean gradation differences between the two testing methods are quite small, but statistically significant relative to variations presented in Table 11. The question is, do these differences remain significant relative to the in-place aggregate uniformity? To answer this question, we gather and present the in-place aggregate uniformity of various construction projects in Table 6. We see that sample variations (Table 11) are negligible relative to the in-place aggregate uniformity. Thus, the slight differences between the two testing methods would not be significant relative to the in-place aggregate uniformity. This means that hand and mechanical testing methods are practically the same in measuring aggregate gradation.

Now, we would like to interpret these figures in Table 11. For this purpose, we denote $(X_{11}, X_{12}, X_{13}, X_{14}, X_{15})$ and $(X_{21}, X_{22}, X_{23}, X_{24}, X_{25})$ to be the test results (aggregate gradations) measured by the hand and mechanical testing methods, respectively. Namely, $X_{i1}$, $X_{i2}$, $X_{i3}$, and $X_{i4}$ are the percent passing the 3/4-in., 3/8-in., No. 4, and No. 8 sieves, respectively, and $X_{i5}$ is the percent loss-by-washing. We also denote $(T_{11}, T_{12}, T_{13}, T_{14}, T_{15})$ and $(T_{21}, T_{22}, T_{23}, T_{24}, T_{25})$ to be the testing errors due to the hand and mechanical testing methods, respectively. Then, $X_{ij}$ can be expressed by the following equation:

$$X_{ij} = P_j + A_{ij} + T_{ij} \qquad \text{(A-1)}$$

In Eq. (A-1), $P_j$ is the target value set for making up the sample and $A_{ij}$ is the difference between the target value and the true value of the sample. Now, we define $D_j$ to be the difference between $X_{1j}$ and $X_{2j}$. Then,

$$D_j = X_{1j} - X_{2j} = (A_{1j} - A_{2j}) + (T_{1j} - T_{2j}) \qquad \text{(A-2)}$$

If we denote $\mu(X)$ and $\sigma^2(X)$ to be the mean and variance, respectively, of the variable X, then we obtain from Eq. (A-2) the following results,

$$\mu(D_j) = \mu(A_{1j}) - \mu(A_{2j}) + \mu(T_{1j}) - \mu(T_{2j}) \tag{A-3}$$

and

$$\sigma^2(D_j) = \sigma^2(A_{1j} - A_{2j}) + \sigma^2(T_{1j}) + \sigma^2(T_{2j}) \tag{A-4}$$

Viewing our sample preparation procedures, it is reasonable to assume that $\mu(A_{1j}) = \mu(A_{2j})$. Thus, we have

$$\mu(D_j) = \mu(T_{1j}) - \mu(T_{2j}) \tag{A-5}$$

Equation (A-5) indicates that $D_j$, $j = 1, \ldots 5$, can be used to measure the differences between the two testing methods. It is obvious from Eq. (A-4) that for each i and j,

$$\sigma^2(T_{ij}) \leq \sigma^2(T_{1j}) + \sigma^2(T_{2j}) \leq \sigma^2(D_j) \tag{A-6}$$

The estimates of $\sigma^2(D_j)$, $j = 1, \ldots 5$, were presented in Table 11. We note that $\sigma^2(T_{1j})$ and $\sigma^2(T_{2j})$, $j = 1, \ldots 5$, are the testing precisions of the hand and mechanical testing methods, respectively. We see from Eq. (A-6) and Tables 6 and 11 that the testing precisions of the hand and mechanical testing methods are very high relative to in-place aggregate uniformity.

# APPENDIX B

# SPLITTING PRECISION OF THE GILSON SAMPLE SPLITTER

In this appendix, we present the statistical formulation of Experiment B. For a sample of W grams, we denote $W_1$ and $W_2$ to be the weights of Subsamples 1 and 2, respectively. Thus, $W = W_1 + W_2$. Define $R_1 = W_1/W$. If every aggregate grain acts independently, i.e., every aggregate grain has the same freedom to be received by any one of the nine openings, the expected value of $R_1$ should be 4/9. Based on the data presented in Table B-1, the sample average $\overline{R}_1$ and sample $S^2(R_1)$ are 0.423 and 0.00049, respectively. The 95 percent confidence interval for the mean value of $R_1$ is (0.4158, 0.4303). This interval does not cover the theoretical value 4/9. This means that this sample splitter does not split a sample into two portions with weight ratio 4:5. Since $S^2(R_1)$ is small, we conclude that Side 1 receives 42.3 percent of the total sample weight.

For each sample, we denote ($W_{i1}$, $W_{i2}$, $W_{i3}$, $W_{i4}$) and ($X_{i1}$, $X_{i2}$, $X_{i3}$, $X_{i4}$) to be the test results of Subsample i, i = 1, 2, in terms of weight and percentage, respectively. Namely, $W_{i1}(X_{i1})$, $W_{i2}(X_{i2})$, and $W_{i3}(X_{i3})$ are the total weight (percent) passing the 3/4-in., 3/8-in., and No. 8 sieves, respectively, and $W_{i4}(X_{i4})$ is the total weight (percent) loss-by-washing. The relationship between $W_{ij}$ and $X_{ij}$ is $X_{ij} = 100\ W_{ij}/W$. As termed in Appendix A, ($X_{i1}$, $X_{i2}$, $X_{i3}$, $X_{i4}$) is the aggregate gradation of Subsample i. We also denote ($P_1$, $P_2$, $P_3$, $P_4$) to be the true aggregate gradation of the sample. Then, viewing the sample preparation and testing procedures, $W_{ij}$ can be expressed as the sum of true value, splitting, and testing errors. That is,

$$W_{ij} = \frac{P_j}{100} W_i + E_{ij} + T_{ij} \tag{B-1}$$

In Eq. (B-1), ($E_{i1}$, $E_{i2}$, $E_{i3}$, $E_{i4}$) and ($T_{i1}$, $T_{i2}$, $T_{i3}$, $T_{i4}$) are, respectively, the splitting and testing errors on Subsample i. The units of $E_{ij}$ and $T_{ij}$ are grams. It is clear that $E_{1j} + E_{2j} = 0$ for each j. To facilitate the later analysis, we define the following variables: $X_j = (W_{1j} + W_{2j})/(W_1 + W_2)$, $e_{ij} = 100\ E_{ij}/W_i$ and $t_{ij} = 100\ T_{ij}/W_i$. It is clear that ($X_1$, $X_2$, $X_3$, $X_4$) are the test results (gradation) of the original sample. $e_{ij}$ and $t_{ij}$ are, respectively, the splitting and testing errors on Subsample i in percent. Using the above relations, we obtain from Eq. (B-1) the following basic equation,

$$X_j = P_j + R_1\ t_{1j} + (1 - R_1)\ t_{2j} \tag{B-2}$$

and

$$X_{ij} = P_j + e_{ij} + t_{ij} \tag{B-3}$$

To study the splitting ability of the sample splitter, we define the new variable $D_{ij}$ as the difference of $X_{ij}$ and $X_j$. That is,

$$D_{1j} = X_{1j} - X_j = e_{1j} + (1 - R_1)(t_{1j} - t_{2j}) \tag{B-4}$$

and

$$D_{2j} = X_{2j} - X_j = e_{2j} - R_1(t_{1j} - t_{2j}) \tag{B-5}$$

Using the fact that $E_{1j} + E_{2j} = 0$ and $W_1 + W_2 = 0$, we obtain from Eqs. (B-4) and (B-5) the relation,

$$D_{1j} = \frac{W_2}{W_1} D_{2j} \tag{B-6}$$

Let us use $\mu(Y)$ and $\sigma^2(Y)$ as the mean and variance of the random variable Y, respectively. Since both subsamples were tested by the same testing method and since (as concluded in Appendix A) sample weight does not affect the testing ability in measuring the gradation, we have $\mu(t_{1j}) = \mu(t_{2j})$. Applying this relation to Eqs. (B-4) and (B-5), we obtain the following equations:

$$\mu(D_{ij}) = \mu(e_{ij}) \tag{B-7}$$

$$\sigma^2(D_{1j}) = \sigma^2(e_{1j}) + (1 - R_1)^2 \left[\sigma^2(t_{1j}) + \sigma^2(t_{2j})\right] \tag{B-8}$$

and

$$\sigma^2(D_{2j}) = \sigma^2(e_{2j}) + R_1^2 \left[\sigma^2(t_{1j}) + \sigma^2(t_{2j})\right] \tag{B-9}$$

We also obtain from Eq. (B-6) the following two equations:

$$\mu(D_{1j}) = -(W_2/W_1)\,\mu(D_{2j}) \simeq -1.364\mu(D_{2j}) \tag{B-10}$$

and

$$\sigma^2(D_{1j}) = (W_2/W_1)^2\ \sigma^2(D_{2j}) \simeq 1.861\ \sigma^2(D_{2j}) \tag{B-11}$$

We see from Eq. (B-7) that ($D_{i1}$, $D_{i2}$, $D_{i3}$, $D_{i4}$) can be used to measure the splitting error. We present the sample mean $\overline{D}_{ij}$ of $D_{ij}$ in Table B-1 and the sample covariance matrix $S_i$ of ($D_{i1}$, $D_{i2}$, $D_{i3}$, $D_{i4}$) in Table B-2. One can see from these two tables that $\overline{D}_{1j} = -1.364\ \overline{D}_{2j}$ and $S_1 = 1.861\ S_2$, approximately. These results support Eqs. (B-10) and (B-11) and, consequently, imply that the splitting process has less effect on the larger subsample (Subsample 2) than the smaller subsample (Subsample 1). Thus, the larger subsample is a better sample in the sense of representing the original sample.

TABLE B-1

SAMPLE MEAN $\overline{D}_{ij}$ OF $D_{ij}$, $i = 1, 2$ AND $j = 1, . . 4$

| j | Sieve Size | $\overline{D}_{1j}$ | $\overline{D}_{2j}$ | $-1.364\ \overline{D}_{2j}$ |
|---|---|---|---|---|
| 1 | 3/4-in. | 0.1089 | -0.0946 | 0.1290 |
| 2 | 3/8-in. | 0.8866 | -0.6279 | 0.8565 |
| 3 | No. 8 | 1.0033 | -0.7131 | 0.9727 |
| 4 | Loss-by-Washing | 0.0241 | -0.0232 | 0.0317 |

We would like to test whether or not the estimated splitting errors presented in Table B-1 are statistically significant (relative to the estimated covariance matrix presented in Table B-2). Again, a multivariate statistical analysis of variance program was used to produce the 95 percent simultaneous confidence intervals for means of $D_{ij}$, $i = 1, 2$, and $j = 1, . . . 4$. The results are presented in Table B-3. We note that the only interval in Table B-3 that does not cover the zero is the one that measures the percent passing the No. 8 sieve. We further note that the differences in Table B-1 would not be significant at the 99 percent confidence level. The question now is, do these marginal differences remain significant relative to the in-place aggregate uniformity? To answer this question, we compare the sample variations in Table B-2 with Table 6 and conclude that these differences could remain significant if the in-place aggregate uniformity is very high (i.e., the in-place aggregate gradation does not vary significantly from spot to spot). Since the splitting errors could be correlated with the in-place aggregate uniformity, we shall compare the sample variances presented in Table B-2 with the in-place aggregate uniformity of the job from which samples were obtained. The procedures are presented below.

## TABLE B-2
## SAMPLE COVARIANCE MATRIX $S_i$ OF $D_{i1}$, $D_{i2}$, $D_{i3}$, $D_{i4}$, $i = 1, 2$

| Sieve Size Combination | $S_1$ | | $S_2$ | | $1.861\ S_2$ | |
|---|---|---|---|---|---|---|
| | Covariance | Variance | Covariance | Variance | Covariance | Variance |
| 3/4-in. and 3/4-in. | -- | 1.3289 | -- | 0.7381 | -- | 1.3730 |
| 3/4-in. and 3/8-in. | 0.2546 | -- | 0.1276 | -- | 0.2375 | -- |
| 3/4-in. and No. 8 | 0.2136 | -- | 0.1008 | -- | 0.1876 | -- |
| 3/4-in. and L.B.W.* | 0.0381 | -- | 0.0166 | -- | 0.0309 | -- |
| 3/8-in. and 3/8-in. | -- | 2.8082 | -- | 1.4046 | -- | 2.6140 |
| 3/8-in. and No. 8 | 1.9568 | -- | 0.9796 | -- | 1.8230 | -- |
| 3/8-in. and L.B.W. | -0.0113 | -- | 0.0018 | -- | 0.0033 | -- |
| No. 8 and No. 8 | -- | 2.8002 | -- | 1.4299 | -- | 2.6610 |
| No. 8 and L.B.W. | -0.0218 | -- | 0.0008 | -- | 0.0015 | -- |
| L.B.W. and L.B.W. | -- | 0.0639 | -- | 0.0340 | -- | 0.0633 |

* L.B.W. means loss-by-washing.

We obtain from Eq. (B-2) that $\sigma^2(X_j) = \sigma^2(P_j) + R_1^2\ \sigma^2(t_{1j}) + (1 - R_1)^2$ $\sigma^2(t_{2j}) \simeq \sigma^2(P_j) + 0.179\ \sigma^2(t_{1j}) + 0.333\ \sigma^2(t_{2j})$. In the Appendix A, we conclude that the testing precision is very high relative to the in-place aggregate uniformity. That is, the amount, $0.179\ \sigma^2(t_{1j}) + 0.333\ \sigma^2(t_{2j})$, is negligible relative to $\sigma^2(P_j)$. Thus, we have $\sigma^2(X_j) \simeq \sigma^2(P_j)$. The estimates of $\sigma^2(X_j)$, $j = 1, \ldots 4$, are presented in Table B-4. Similarly, we obtain from Eqs. (B-4) and (B-5) that $\sigma^2(D_{ij}) \simeq \sigma^2(e_{ij})$. The estimated ratios of $\sigma^2(P_j) + \sigma^2(e_{ij})$ to $\sigma^2(e_{ij})$, $j = 1, \ldots 4$, are also presented in Table B-4. Since the confidence interval for the No. 8 sieve in Table B-3 almost covers zero and the in-place aggregate uniformity is low relative to the precision of the sample splitter, we conclude that the aggregate gradations of two subsamples are identical relative to the in-place aggregate uniformity. That is, either subsample can be used to represent the original sample for inspection purposes.

TABLE B-3
95 PERCENT SIMULTANEOUS CONFIDENCE INTERVALS
FOR MEANS OF $D_{ij}$, $i = 1, 2$ AND $j = 1, \ldots, 4$

| Sieve Size | Side 1 | | Side 2 | | Significance |
|---|---|---|---|---|---|
| | Lower Limit | Upper Limit | Lower Limit | Upper Limit | |
| 3/4-in. | -0.5483 | 0.7660 | -0.5843 | 0.3952 | No |
| 3/8-in. | -0.0687 | 1.8419 | -1.3035 | 0.0477 | No |
| No. 8 | 0.0493 | 1.9572 | -1.3947 | -0.0314 | Yes |
| Loss-by-Washing | -0.1201 | 0.1682 | -0.1283 | 0.0819 | No |

TABLE B-4
ESTIMATES OF THE IN-PLACE AGGREGATE UNIFORMITY

| Sieve Size | In-Place Aggregate Uniformity, $\sigma^2(P_j)$ | $\dfrac{\sigma^2(P_j) + \sigma^2(e_{1j})}{\sigma^2(e_{1j})}$ |
|---|---|---|
| 3/4-in. | 1.1944 | 2.11 |
| 3/8-in. | 8.0235 | 3.86 |
| No. 8 | 8.0649 | 3.88 |
| Loss-by-Washing | 0.3433 | 6.37 |

## Summary

1) The aggregate gradations of the two subsamples are slightly different. The differences are statistically significant relative to the splitting precision; however, these differences are no longer significant relative to the in-place aggregate uniformity. Thus, either subsample can be used to represent the original sample for in-place aggregate inspection purposes.

2) The splitting error of the larger subsample is less than that of the smaller subsample. Therefore, the larger subsample is more representative of the original sample.

# APPENDIX C

# PRECISIONS OF THE TESTING METHODS AND THE SAMPLE SPLITTER

In this appendix, we present the statistical formulation of Experiment C. For each example, we denote $R_1^*$ to be the weight ratio of Subsample 1 to the original sample. Similarly, we denote $R_1$ to be the weight ratio of the Subsample I-1 to Subsample I. Since the two sides of the sample splitter have an equal number of openings, we would like to test the hypothesis that the sample splitter can split a sample into two portions of equal weight. Based on the data presented in Table C-5, the sample means, $\overline{R}_1^*$ and $\overline{R}_1$, and sample variances, $S_2(R_1^*)$ and $S_2(R_1)$, of $R_1^*$ and $R_1$ are as follows:

$$\overline{R}_1^* = 0.479999 \ , \ S^2(R_1^*) = 0.000616$$

$$\overline{R}_1 = 0.481792 \ , \ S^2(R_1) = 0.001407$$

The above sample information indicates at the 95 percent confidence level that the sample splitter does not split a sample into two portions of equal weight. However, this splitter does split a sample into two portions according to a constant weight proportion, independent of the sample weight.

TABLE C-1

SAMPLE MEAN $\overline{D}_{ij}$ OF $D_{ij}$, i = 1, 2, AND j = 1, . . . , 4

(Splitting Subsample I Into Two Subsamples Tested by the Hand Testing Method)

| j | Sieve Size | $\overline{D}_{1j}$ | $\overline{D}_{2j}$ | $-1.076\ \overline{D}_{2j}$ |
|---|---|---|---|---|
| 1 | 3/4-in. | -0.03086 | 0.02904 | -0.03125 |
| 2 | 3/8-in. | -0.00430 | 0.01485 | -0.01598 |
| 3 | No. 8 | -0.03110 | 0.06581 | -0.07081 |
| 4 | Loss-by-Washing | -0.01860 | -0.02306 | 0.02481 |

## Splitting Precision

For each sample, we denote W and ($P_1$, $P_2$, $P_3$, $P_4$) to be the weight and true gradation of Subsample I, respectively. We further denote $W_1$ and $W_2$ to be the respective weights of Subsample I-1 and Subsample I-2. As one can see, this portion of the experiment is the same as the one conducted in Appendix B except that two subsamples of Subsample I were tested using the hand testing method. Thus, Eqs. (B-1) through (B-9), Appendix B, are also the system equations for this portion of the experiment.

## TABLE C-2
## SAMPLE COVARIANCE MATRIX $S_i$ OF $D_{i1}$, $D_{i2}$, $D_{i3}$, $D_{i4}$, $i = 1, 2$
(Splitting Subsample II Into Two Subsamples Tested by the Hand Testing Method)

| Sieve Size Combination | $S_1$ | | $S_2$ | | $1.157\ S_2$ | |
|---|---|---|---|---|---|---|
| | Covariance | Variance | Covariance | Variance | Covariance | Variance |
| 3/4-in. and 3/4-in. | -- | 2.7516 | -- | 2.4195 | -- | 2.7994 |
| 3/4-in. and 3/8-in. | 1.5670 | -- | 1.4619 | -- | 1.6914 | -- |
| 3/4-in. and No. 8 | 1.0094 | -- | 0.9527 | -- | 1.1023 | -- |
| 3/4-in. and L.B.W.* | 0.1369 | -- | 0.1269 | -- | 0.1468 | -- |
| 3/8-in. and 3/8-in. | -- | 2.9029 | -- | 2.6411 | -- | 3.0558 |
| 3/8-in. and No. 8 | 2.0175 | -- | 1.8705 | -- | 2.1688 | -- |
| 3/8-in. and L.B.W. | 0.2231 | -- | 0.2095 | -- | 0.2424 | -- |
| No. 8 and No. 8 | -- | 2.0359 | -- | 1.8920 | -- | 2.1890 |
| No. 8 and L.B.W. | 0.1915 | -- | 0.1783 | -- | 0.2063 | -- |
| L.B.W. and L.B.W. | -- | 0.0592 | -- | 0.0518 | -- | 0.0599 |

* L.B.W. means loss-by-washing.

We note that $T_{ij}$ and $t_{ij}$ in Eqs. (B-1) through (B-9) should be interpreted as the testing errors of the hand testing method. Replacing $W_2/W_1$ in Eq. (B-6) with the estimated ratio obtained from this experiment, we have

$$\mu(D_{1j}) \simeq -1.076\mu(D_{2j}) \tag{C-1}$$

and

$$\sigma^2(D_{1j}) \simeq 1.157\,\sigma^2(D_{2j}) \tag{C-2}$$

The sample information regarding $D_{ij}$ is presented in Tables C-1 through C-3. Again, the results presented in Tables C-1 and C-2 support Eq. (B-6). We see from Table C-3 that every interval contains zero. This leads us to conclude at the 95 percent confidence level that the sample splitter does split a sample into two portions of equal gradation. Comparing Table C-2 with Table 6, we see that the splitting precision is high relative to the in-place aggregate uniformity and, therefore, conclude that either Subsample I-1 or Subsample I-2 can be used to represent Subsample I for in-place aggregate inspection purposes.

TABLE C-3
95 PERCENT SIMULTANEOUS CONFIDENCE INTERVALS
FOR MEANS OF $D_{ij}$, $i = 1, 2$, AND $j = 1, \ldots, 4$
(Splitting Subsample I Into Two Subsamples
Tested by the Hand Testing Method)

| Sieve Size | Side 1 | | Side 2 | |
|---|---|---|---|---|
| | Lower Limit | Upper Limit | Lower Limit | Upper Limit |
| 3/4-in. | -0.6138 | 0.5521 | -0.5176 | 0.5757 |
| 3/8-in. | -0.6031 | 0.5944 | -0.5563 | 0.5860 |
| No. 8 | -0.5326 | 0.4704 | -0.4176 | 0.5492 |
| Loss-by-Washing | -0.0669 | 0.1041 | -0.1031 | 0.0570 |

## Testing Precision

Samples used for studying testing precision in Appendix A were made up according to the predetermined target gradations. In this appendix, the actual field samples are used for this purpose.

For each sample, we denote W* to be the weight of Subsample II. That is, the weight of this sample (the original sample) is U = W + W*. We also denote ($W_1$*, $W_2$*, $W_3$*, $W_4$*) and ($X_1$*, $X_2$*, $X_3$*, $X_4$*) to be the test results of Subsample II in terms of weight and gradation, respectively, and ($Q_1$, $Q_2$, $Q_3$, $Q_4$) to be the true gradation of the sample. If we denote $F_j^*$ and $T_j^*$ to be the respective splitting and testing (mechanical testing method) errors on Subsample II and define $f_j^* = 100\ F_j/W^*$ and $t_j^* = 100\ T_j/W^*$, we have the following familiar equations:

$$W_j^* = \frac{Q_j}{100} W^* + F_j^* + T_j^* \tag{C-3}$$

and

$$X_j^* = Q_j + f_j^* + t_j^* \tag{C-4}$$

Let $F_j$ be the splitting error on Subsample I. Then, $F_j = -F_j^*$. If we define $f_j = 100\ F_j/W$, then the relation between $P_j$ and $Q_j$ can be expressed by the following equation.

$$P_j = \frac{Q_j\ W + 100\ F_j}{W} = Q_j + F_j \tag{C-5}$$

Substituting this equation into Eq. (B-2), we have

$$X_j = Q_j + f_j + R_2\ t_{1j} + (1 - R_2)\ t_{2j} \tag{C-6}$$

We note that $R_2 t_{1j} + (1 - R_2)\ t_{2j}$ is the testing error (hand testing method) on Subsample I and, for simplicity, is denoted as $t_j$. Thus, Eq. (C-6) can be rewritten as

$$X_j = Q_j + f_j + t_j \tag{C-7}$$

We now form the difference, $H_j = X_j^* - X_j$, to study the testing effects. We obtain from Eqs. (C-4) and (C-7) the following important relation.

$$H_j = f_j^* - f_j + t_j^* - t_j = (H \frac{W^*}{W})\ f_j^* + t_j^* - t_j \tag{C-8}$$

Thus, we obtain from Eq. (C-8) that

$$\sigma^2(H_j) = (H\frac{W^*}{W})\ \sigma^2\ (f_j^*) + \sigma^2(t_j^*) + \sigma^2(t_j) \tag{C-9}$$

As concluded in Appendix A, $\sigma^2(t_j^*) + \sigma^2(t_j)$ is very small, $\sigma^2(H_j)/(H \frac{W^*}{W})$ can be used to approximate $\sigma^2(f_j)$. The sample information regarding $\sigma^2(H_j)$ and $\sigma^2(f_j^*)$ is presented in Table C-4. Comparing $S_f^*$ in Table C-4 with $S_2$ in Table C-2 we see that the splitting precision is higher when the original sample is larger. This fact, together with the conclusions presented at the beginning of this section and those of Appendix B allow us to safely assume that the sample splitter is able to divide a sample into two portions of equal gradation, independently of the sample weight. That is, $\mu(f_j^*) = 0$, and, consequently, $\mu(H_j) = \mu(t_j^*) - \mu(t_j)$. This means that $(H_1, H_2, H_3, H_4)$ can be used to measure the difference between the hand and mechanical testing methods in measuring aggregate gradation. The sample information regarding $X_j^*$, $X_j$ and their difference $H_j$ is presented in Table C-5. The 95 percent simultaneous confidence intervals for $\mu(H_j)$, j = 1, 2, 3, and 4, are also presented in Table C-5. As one can see from Table C-5, no interval covers the zero. Thus, we conclude at the 95 percent confidence level that the two testing methods are significantly different on gradation measurements relative to sample variations presented in Table C-4. The question that remains to be answered is whether the differences remain significant relative to the in-place aggregate uniformity. After comparing Table C-6 with Table 10 and Table C-4 with Table 6, we believe that the hand testing method would still not agree with the mechanical testing method in measuring the percent passing the 3/4-in., 3/8-in., and No. 8 sieves relative to the average in-place aggregate uniformity.

TABLE C-4
SAMPLE COVARIANCE MATRICES $S_H$ AND $S_{f^*}$ OF
$(H_1, H_2, H_3, H_4)$ AND $(f_1^*, f_2^*, f_3^*, f_4^*)$

| Sieve Size Combination | $S_H$ | | $S_{f^*}$ | |
|---|---|---|---|---|
| | Covariance | Variance | Covariance | Variance |
| 3/4-in. and 3/4-in. | -- | 4.2717 | -- | 0.9820 |
| 3/4-in. and 3/8-in. | 3.2894 | -- | 0.7662 | -- |
| 3/4-in. and No. 8 | 1.7578 | -- | 0.4041 | -- |
| 3/4-in. and L.B.W.* | 0.1895 | -- | 0.0436 | -- |
| 3/8-in. and 3/8-in. | -- | 6.7255 | -- | 1.5461 |
| 3/8-in. and No. 8 | 3.6017 | -- | 0.8280 | -- |
| 3/8-in. and L.B.W. | 0.4799 | -- | 0.1103 | -- |
| No. 8 and No. 8 | -- | 2.6566 | -- | 0.6107 |
| No. 8 and L.B.W. | 0.3390 | -- | 0.0779 | -- |
| L.B.W. and L.B.W. | -- | 0.1403 | -- | 0.0323 |

* L.B.W. means loss-by-washing.

TABLE C-5
SAMPLE MEANS OF $X_j*$, $X_j$ AND $H_j$ AND THE 95 PERCENT SIMULTANEOUS CONFIDENCE INTERVALS FOR THE MEANS OF $H_j$, j = 1, 2, 3, AND 4

| Sieve Size | $\overline{X}_j*$ | $\overline{X}_j$ | $\overline{H}_j$ | Confidence Interval | |
|---|---|---|---|---|---|
| | | | | Lower Limit | Upper Limit |
| 3/4-in. | 95.81 | 94.06 | 1.75 | 1.0175 | 2.4702 |
| 3/8-in. | 74.61 | 72.10 | 2.51 | 1.5953 | 3.4181 |
| No. 8 | 47.37 | 44.30 | 3.07 | 2.4939 | 3.6396 |
| Loss-by-Washing | 7.67 | 7.33 | 0.34 | 0.2088 | 0.4721 |

For information purposes, we present the procedures for estimating the in-place aggregate uniformity based on the data presented in Table 5. By multiplying W/100 to Eq. (C-7), we obtain:

$$W_j = \frac{Q_j}{100} W + F_j + T_j \qquad \text{(C-10)}$$

The relation between $T_j$ and $t_j$ is that $t_j = 100\, T_j/W$. If we define $U_j = 100\,(W_j^* + W_j)/(W^* + W)$, then we obtain from Eqs. (C-3) and (C-10)

$$U_j = Q_j + R_1^* t_j^* + (1 - R_1^*)\, t_j \qquad \text{(C-11)}$$

Thus,

$$\sigma^2(U_j) = \sigma^2(Q_j) + (R_1^*)^2\, \sigma^2(t_j^*) + (1 - R_1^*)^2\, \sigma^2(t_j) \qquad \text{(C-12)}$$

Since the testing precisions are relatively high as concluded in Appendix A, $\sigma^2(U_j)$ can be used to approximate $\sigma^2(Q_j)$ which measures the in-place aggregate uniformity. We present the sample estimates of $\sigma^2(U_j)$, j = 1, 2, 3, and 4, in Table C-6.

## Summary

1) The sample splitter is able to divide a sample into two portions according to a constant weight ratio, independently of the sample weight.

2) The sample splitter is able to divide a sample into two portions of equal gradation.

3) The precision of the sample splitter correlates positively with the sample weight.

4) The two testing methods do not agree with each other in measuring the percent passing the 3/4-in., 3/8-in., and No. 8 sieves. However, these two methods agree in measuring the percent loss-by-washing.

TABLE C-6
ESTIMATES OF IN-PLACE AGGREGATE UNIFORMITY

| Sieve Size | Estimate of $\sigma^2(U_j)$ |
|---|---|
| 3/4-in. | 1.5422 |
| 3/8-in. | 6.5195 |
| No. 8 | 4.5449 |
| Loss-by-Washing | 0.3908 |