reports are used to construct an annual report for each plant (Figure 8). This report, which shows the yearly average and the variation of properties of each size aggregate processed at each plant, provides valuable data to the marketing, operations, and plant engineering departments as well as a comparison of the capability of each operation to maintain or upgrade the quality of its products.

As a means of continually upgrading the quality control program, all technicians and other members of the Materials Control and Research Department are required to annually attend a 2½-d seminar conducted at the central laboratory that includes sessions on new and proposed aggregate specifications, sampling and testing techniques, and basic statistics and reporting techniques. The technicians also attend seminars sponsored by state aggregate associations and qualify as registered technicians in those states that require certification.

So that the test data that result from the program are thoroughly understood, several half-day seminars that are conducted annually by personnel of the Materials Control and Research Department are held on a district basis for operating personnel and cover such areas as understanding control charts and stockpile recovery to minimize segregation. Typical training aids used in these sessions are shown in Figures 9 and 10.

In an effort to reduce sampling and testing time, we have incorporated automatic sampling and testing in our largest operation, which loads aggregate into lake vessels at 1090 Mg/h (1200 tons/h). At the touch of a button, a sample that weighs approximately 227 kg (500 lb) is sliced from a conveyor-belt transfer point, conveyed to a testing tower, split, sieved, and weighed in separate size fractions. In less than 10 min from the time the sample is taken, the technician has a printout of the gradation. In several of our district laboratories, we dry fine aggregate samples by using microwave ovens that reduce the drying time to about one-third of that required when an electric oven is used. We have recently incorporated the pycnometer method for determining the material finer than the 0.075-mm (No. 200) sieve, which eliminates the necessity for drying the aggregate and saves considerable time.

At this point, the question probably arises, What return on investment can I expect from an efficient process control program? Our experience has demonstrated that the cost of this program ranges between \$0.02 and \$0.03/Mg (\$0.018 and \$0.027/ton). After recently reviewing the program, the chairman of the board of the Standard Slag Company stated that "quality control is the most economic insurance we can purchase."

If a quantity of aggregate is rejected because of failure to comply with the specified gradation after it is incorporated in a project, the aggregate producer could at least incur the cost of production, transportation to the project, placement, and removal. These costs could well exceed the selling price of the aggregate by five or more times. On the other hand, applying process control to one of our plants that produced a large riprap order last year resulted in our technicians handling and testing samples that weighed 2727 kg (6000 lb) or more, but also resulted in shipping more than 272 700 Mg (300 000 tons) of this material without a single rejection.

Additional savings result from having process control personnel perform other services within the organization, such as the following:

1. Testing of equipment performance, which would include analyzing the input and output of crushers to determine their effectiveness in size reduction and reduction of deleterious material to provide the necessary particles with one or more fractured faces and to produce the desired particle shape;
2. Analyzing material from prospective deposits;
3. Providing technicial service for customers; and
4. Management of air and water quality.

In summary, an effective process control program in a corporation must have at least the following essential elements:

1. The total backing of top management,
2. The cooperation of plant production personnel who should immediately report malfunctions in production or loading components since it is not possible for the materials technician to be at all points of production or loading at one time, and
3. Rapid sampling, testing, and reporting procedures to provide immediate feedback of test results to the plant superintendent so that when a process adjustment is necessary the superintendent can rapidly determine whether the adjustment produced the desired effect.

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Probabilistic Model of Aggregate Plant Production Systems

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A probabilistic model that could be used to evaluate the product characteristics of an aggregate processing plant was developed by combining several theories and mathematical models. The model interest was confined to crushing and screening subsystems. The final model is in the form of a computer programming model that is ready for application to similar plant systems. The computer model will store and compile a series of subroutines; each subroutine performs a specific function, and the whole model analysis procedure is controlled by a main program. A simulator is used to generate desired data to provide for the evaluation of the statistical nature of the output products. Through the use of the high-speed computer, parameters of plant production control—such as raw material feed rate, crusher settings, screen mesh sizes, combining and splitting of certain production flow streams, and appropriate production demand schedules—can be easily evaluated. By varying the data on raw feed material, the model evaluates the tonnage and gradation of the flow streams in the production plant as well as variability.

The program analyses used in the proposed model are logical and compatible with those used in the aggregate production industry. Extensive experimental data are still required to ensure the validity of the model.

The aggregate production industry is a growing industry. Through an evaluation of the present growth rate of aggregate consumption, it has been estimated that 1.76 billion Mg (1.9 billion tons) of crushed stone will be needed by 1986 (1). The increasing demand for construction aggregates will necessitate the design and development of new aggregate processing plants and the expansion of existing plants.

The study discussed in this paper was concerned with the analysis of crushed-stone plant production systems that include the crushing, screening, transporting, and storing of the material. Although the system as a whole looks simple, the processes themselves are very complicated. Of all the subsystems in the aggregate plant production system, crushing and screening are the most important and the most complicated ones. More attention has to be paid to these two subsystems since they not only control the production capacity of the plant but also affect such characteristics of the product as size distribution and shape.

It was the purpose of this study to evaluate several theories and mathematical models so as to develop a probabilistic model that could be used to evaluate the product characteristics of an aggregate processing plant. The model interest was confined to the crushing and screening subsystems. The final model is in the form of a computer programming model that is ready for application to similar plant systems. The computer model will store and compile a series of subroutines; each subroutine performs a specific function, and the whole model analysis procedure is controlled by a main program. A simulator is used to generate desired data to provide for the evaluation of the statistical nature of the output products.

CRUSHING MODEL

Early techniques for predicting crusher performance, which used the concept of mathematical models of comminution theories, were developed by Rittinger in 1867, Kick in 1885, and Bond in 1951. These "laws" were used to predict the energy spent in crushing or grinding material from one average size to another. All of these laws do not predict the output size distribution of crushers under given conditions, which is particularly important in aggregate plant production. This is especially critical when the subsequent process—either crushing or screening—is significantly affected by changes in feed particle size. Thus, the efficiency of the whole production system is intimately linked with the efficient interaction of the various subsystems. It is necessary to develop a crushing model that is capable of predicting the size distribution of plant flow streams and that thus enables the overall system to be optimized.

Several persons have developed methods for predicting the product size distribution of rock breakage. Broadbent and Callcott's approach for evaluating the crushing process (2) has been adapted in this study where the selection function P and the breakage function B are considered.

The selection function is said to be directly proportional to the particle size. The larger the feed particle is with respect to the crusher setting, the higher is the probability of breakage (3): $P_i = 1$ for all $x_i \geq SET$ and $P_i = k_o x_i$ for all $x_i < SET$ $(0 \leq P_i \leq 1)$, where P_i is the matrix element of the selection matrix P, which describes the probability that particle size x_i will break in the crushing process; k_o is a constant suggested by Guadin and Meloy (3) for given crushing conditions, and x_i is the feed particle size.

The breakage function $B(x_i, x_j)$ usually expresses a cumulative frequency distribution function, for which $B(x_i, x_j)$ is the mass fraction of crushed material between x_j and x_{j+1} where x_j is the product particle size. The breakage function is said to be characterized by the material and is easier to evaluate for crushing machines when expressed in terms of the dimensionless parameter x_j/x_i.

It is necessary to assume a mathematical form for the breakage function to make an analytical solution possible. Schuhmann's equation (4) is used in this study because of its simplicity and because it has been verified by other authors (5, 6). The Schuhmann equation can be expressed by

$$B(x_i, x_j) = (x_j/x_i)^N \quad (1)$$

Hence,

$$dB(x_i, x_j)/dx_j = N x_j^{N-1}/x_i^N \quad (2)$$

In terms of discrete form, the fraction of mass between size x_j and x_{j+1} is equal to

$$\Delta B(x_i, x_j) = (x_j/x_i)^N - (x_{j+1}/x_i)^N \quad (3)$$

The value of the modulus of distribution (N) has been found to be unity for brittle solids (7) and in the range of 0.90 to 0.95 for quartz (5). In the evaluation of limited crushing data in connection with this study, it was found that the average value of N is equal to 0.8 for a Pioneer roll crusher and 0.9 for a Telsmith 1.2-m (4-ft) standard cone crusher under certain given conditions.

SCREENING MODEL

The proposed screening model has been constructed around the probability of a particular size of particle passing through the screen opening. The probability of a particle size x_i passing through the screen openings has been found to be a function of the size of the particle and the size of the screen opening. If S is given as a screening matrix, its matrix elements can be expressed by

$$s_i = 1 - e^{-C[1 - (x_i/k_1 CLOTH)]^R} \quad (4)$$

and, for $x_i \geq k_1^* CLOTH$, $s_i = 0$, where

- s_i = probability of particle size x_i passing through the screen opening;
- e = base of the Napierian logarithm, 2.718;
- x_i = particle size;
- CLOTH = size of the screen opening;
- k_1 = a constant usually set equal to 0.875; and
- C and R = constants that control the screening model and can be obtained through experimentation (if no data are available, values for C of 2.5 to 5.0 and values for R of 60 to 100 are reasonable assumptions).

ANALYSIS OF PLANT FLOW STREAM

The computer model evaluates the tonnage rate and gradation analysis of each stream of material in the flow diagram of the plant that is being analyzed (the model discussed in this paper is calibrated in U.S. customary

Figure 1. Flow-stream numbering system for sample aggregate plant.

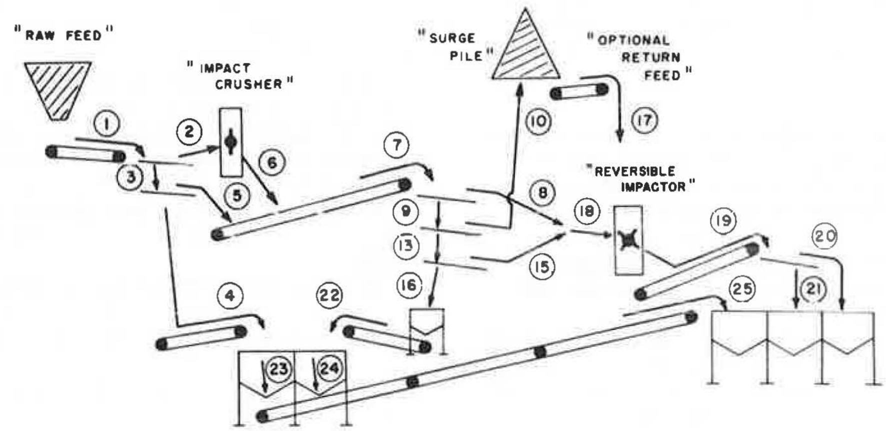
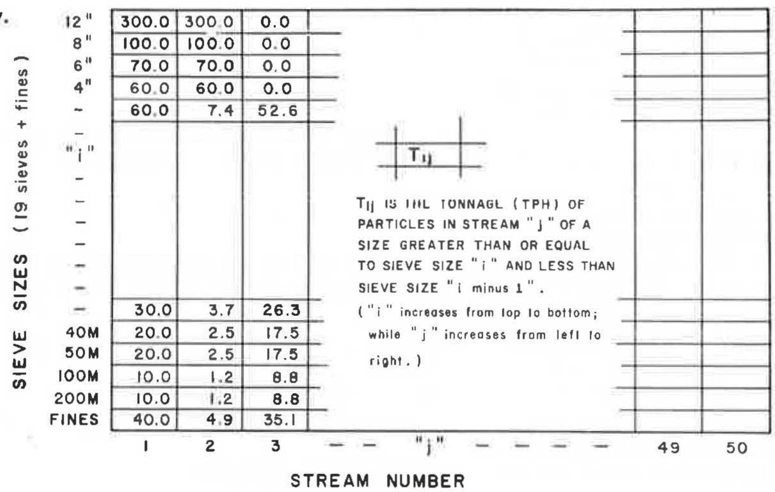


Figure 2. STREM array.



units of measurement). Therefore, the importance of carefully drawing and individually numbering the flow streams of the plant layout cannot be overemphasized. Each time the characteristics of a flow stream are changed by plant processing—for example, when the stream flows into a crusher, passes onto a screen, or combines with another stream—the old stream should be terminated and a new stream or streams, with new identification numbers, should be initiated. An example of this identification process is shown in Figure 1.

In addition to the plant flow diagram, it is necessary to identify the operating properties of each crusher and screen; these properties are essential information for the computer analysis and are identified when the crushing and screening subroutines of the program are called. The basic input data include the sieve sizes to be used to describe the product gradation, the size of the sieves in inches, the rate of raw feed flow into the plant, the gradation of the raw feed, and the estimated standard deviation of each feed size range.

Once the raw feed information has been read into the computer, the analysis of each flow stream in the plant model can be requested by calling the appropriate subroutine. As a basic rule, no stream can be called for analysis until all the streams that directly precede it have been analyzed. For instance, in Figure 1 neither stream 8 nor stream 9 can be determined unless the contents of stream 7 are known; likewise, stream 7 cannot be analyzed until streams 5 and 6 have been determined.

Flow-stream data are stored in a two-dimensional array called STREM, shown in Figure 2. Each column of the array contains the information for one stream. The array is currently set up to handle a maximum of 50 streams but could easily be expanded to handle more. Information will only be stored, of course, in the columns that correspond to the stream numbers included in the plant analysis.

Each row in the array corresponds to a different sieve size. The array is set up to handle 20 rows of information; the first 19 rows represent designated sieve sizes, and the last row represents all material finer than the nineteenth sieve. The designation of the different sieve sizes to be used for the gradation analyses is optional; however, since these sizes are used to establish the gradations of all streams in the plant, careful consideration should be given to their selection.

Each block in the STREM array represents the tonnage of material, for the stream represented by the column, that is contained between the sieve size designated by the row and the next larger sieve size. By using the information in this format, the percentage retained between sieves, the cumulative percentage retained on each sieve, plus the total stream tonnage can easily be calculated for each stream.

A similar array, ST, has been set up in the computer model to store the standard deviation of each sieve size of material for each flow stream being analyzed. This two-dimensional array is exactly the same size as the STREM array.

HONPI AGGREGATE PLANT PRODUCTION MODEL

A comprehensive aggregate plant production model developed in 1972 by Hancher (8)—set up as a computer model called HONDO—was developed to simulate the crushing and screening operations in aggregate plants. By giving certain characteristics of the feed material and the setup of plant facilities, the computer model evaluates the capacity and size distribution of any intermediate flow stream as well as the final end product in the plant flow system. However, no method was included to predict variation in plant processes.

The HONDO computer model consists of a series of subroutines, each of which simulates a certain type of operation in the plant. The total plant analysis is controlled by the main program, which dictates and directs the subroutine analyses to predict the quantities and size distributions of the required products. Regression models for both the crushing and screening models were set within the subroutines for specific types of equipment and were derived from the results of a compilation of various guidance and experimental data from machine manufacturers. The model has been deemed reasonably satisfactory for several analyses of aggregate-producing plants.

The proposed HONPI computer model has been developed by using existing theories for breakage and screening and the HONDO computer model. It has been directed toward the development of a simple and more practical method for predicting the performance of aggregate plant systems and expanded to a probabilistic prediction model. The probable prediction parameters for both crushing and screening were estimated on the basis of what was considered a reasonable extrapolation from a limited amount of available data, and a simulator function was used to generate random data for estimating the statistical nature of plant flow streams. The prob-

Figure 3. Essential subroutines of HONPI computer model.

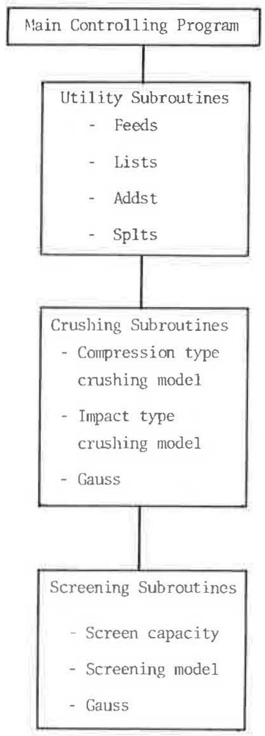


Table 1. Operating characteristics of Ward Stone Plant facilities.

Item	Operating Characteristics
Feed material	Limestone: 1613 kg/m³, dry quarried material, blocky particle shape
Primary crusher	76- by 106-cm jaw crusher (NTYPE = 1): 11.4-cm closed side setting, 227-Mg/h estimated capacity
Screen 1	1.5- by 3.6-m double-deck vibrating screen: 3.8-cm top deck of square woven wire mesh, 3.8-cm bottom deck of square woven wire mesh, 15° slope
Secondary crusher	1.2-m standard cone (NTYPE = 3): 3.8-cm closed side setting, 204-Mg/h estimated capacity
Screen 2	1.5- by 3.6-m triple-deck vibrating screen: 3-cm top deck of square woven wire mesh, 1.3-cm second deck of square woven wire mesh, 0.47-cm third deck of square woven wire mesh, 15° slope
Screen 3	1.5- by 3.6-m triple-deck vibrating screen: 5.7-cm top deck of square woven wire mesh, 3.8-cm second deck of square woven wire mesh, 1.3-cm third deck of square woven wire mesh, 15° slope
Tertiary crusher	76- by 106.6-cm roll (NTYPE = 2): 1.3-cm setting, 136-Mg/h estimated capacity
	0.9-m short head cone (NTYPE = 3): 1.9-cm closed side setting, 136-Mg/h estimated capacity

Note: 1 kg/m³ = 0.062 lb/ft³; 1 cm = 0.39 in; 1 Mg = 1.1 tons; 1 m = 3.3 ft.

Figure 4. Flow diagram of plant operation.

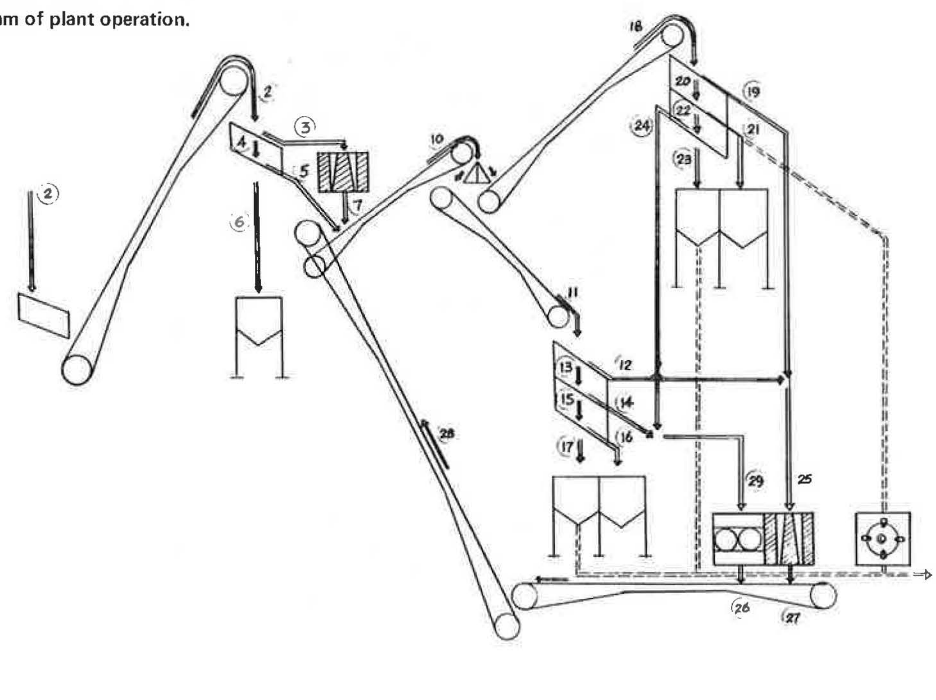


Figure 5. Basic input data for analysis of Ward Stone plant.

```
4 1/2  4  3 1/2  3  2 1/2  2  1 1/2  1 3/4  1/2  3/8  4M  8M  16M  40M  50M  80M 100 200

                    Elements of the Matrix "SIEVE" (19A4)


4.5  4.0  3.5  3.0  2.5  2.0  1.5  1.0  .75  .50  .375  .187093804690174011700700005900 29

                    Elements of the Matrix "SIZES" (19F4.4)


200.17.227.144.654.364.372.678.586.690.092.994.396.697.998.599.5100.100.100.100.

TPH              Cumulative Percent Retained on Each Sieve Size (19F4.4)
(F4.4)


6.805.984.123.945.484.471.612.082.051.190.750.740.630.240.000.000.000.000.00

          Standard Deviation of Cum. Percent Retained on Each Sieve (19F4.4)
```

Figure 6. Computer setup for plant analysis.

```
      PROGRAM HONPI(INPUT,OUTPUT,TAPE2=INPUT,TAPE3=OUTPUT)
      INTEGER CARD,PRINT
      COMMON STREM(20,60),WORK1(20),WORK2(20),SIZES(19),
     -                     SIEVE(19), CARD, PRINT
      COMMON ST(20,60)
      COMMON STEM(20,60)
      COMMON PCT(20,60)
      COMMON STMAX(20,60),STMIN(20,60)
      COMMON V(20,60),CON95(20,60)
      CARD=2
      PRINT=3
      READ(CARD,10) SIEVE
10    FORMAT(19A4)
      READ(CARD,20) SIZES
20    FORMAT(19F4.4)
      DO 35 K=1,50
      DO 34 J=1,50
      ST(J,K)=0.0
34    STREM(J,K)=0.0
35    CONTINUE
      WRITE(PRINT,40)
40    FORMAT(10X,*SIMULATION OF WARD STONE PLANT*)
      CALL FEEDS(2)
      CALL SCAPY(60,12,1.5,15,1,2,3,4,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(1,1.5,2,3,4,CAPY,70.0,4.0)
      CALL SCAPY(60,12,0.75,15,2,4,5,6,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(2,0.75,4,5,6,CAPY,70.,4.5)
      CALL CRUSH(3,1.5,7,3,225.)
      CALL ADDST(5,7,8)
      CALL LISTS(8)
      NPASS=1
      DO 25 I=1,6
      WRITE(PRINT,100) NPASS
100   FORMAT(1H1,///,*****STARTING PASS NO. *,I1,*THROUGH CLOSED-CIRCUI
     1T ANALYSES*****,///)
      CALL LISTS(8)
      CALL ADDST(8,28,10)
      CALL LISTS(28)
      CALL LISTS(10)
      CALL SPLTS(10,.50,11,18)
      CALL LISTS(11)
      CALL LISTS(18)
      CALL SCAPY(60,12,1.25,15,1,11,12,13,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(1,1.25,11,12,13,CAPY,70.,3.0)
      CALL SCAPY(60,12,0.50,15,2,13,14,15,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(2,0.50,13,14,15,CAPY,70.,3.0)
      CALL SCAPY(60,12,.187,15,3,15,16,17,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(3,0.187,15,16,17,CAPY,70.,3.0)
      CALL SCAPY(60,12,2.25,15,1,18,19,20,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(1,2.25,18,19,20,CAPY,70.,3.0)
      CALL SCAPY(60,12,1.50,15,2,20,21,22,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(2,1.5,20,21,22,CAPY,70.,3.0)
      CALL SCAPY(60,12,0.50,15,3,22,24,23,1.0,1.0,1.0,1.0,1.0,CAPY)
      CALL SCREN(3,0.50,22,24,23,CAPY,70.,3.0)
      CALL ADDST(12,19,25)
      CALL LISTS(25)
      CALL CRUSH(25,0.75,27,3,150.)
      CALL ADDST(14,24,29)
      CALL LISTS(29)
      CALL CRUSH(29,0.50,26,2,150.)
      CALL ADDST(26,27,28)
      NPASS=NPASS+1
25    CONTINUE
      CALL LISTS(28)
C     THIS IS THE END OF THE ANALYSIS
      CALL EXIT
      STOP
      END
```

abilistic approach is considered here because it coincides with real operating situations in which the feed material and the output products are almost always fluctuating.

Figure 3 shows the essential subroutines of the HONPI computer model. The individual subroutines are described below.

Subroutines

FEEDS Subroutine

The FEEDS subroutine is used to read in the information about the raw feed material where the number of the feed stream in the plant flow system is specified. The input for raw feed material must consist of

Figure 7. Computer results of plant analysis.

```
              SIMULATION OF HARD STONE PLANT

FEED STREAM - READ FROM CARD

STREAM NUMBER  2        200.0 TONS PER HOUR
 41/2    4  31/2    3  21/2    2  11/2    1   3/4   1/2   3/8    4M    8M   16M   40M   50M   80M   100   200
 34.4  19.8  35.0  19.4  20.0  16.6  12.6  15.4   6.9   5.8   2.8   4.6   2.6   1.2   2.0   1.0   0.0   0.0   0.0   0.0 TPH
 17.2   9.9  17.5   9.7  10.0   8.3   6.3   7.7   3.4   2.9   1.4   2.3   1.3    .6   1.0    .5   0.0   0.0   0.0   0.0 PCT
 17.2  27.1  44.6  54.3  64.3  72.6  78.9  86.6  90.0  92.9  94.3  96.6  97.9  98.5  99.5100.0100.0100.0100.0100.0 CUM RETN
 82.8  72.9  55.4  45.7  35.7  27.4  21.1  13.4  10.0   7.1   5.7   3.4   2.1   1.5    .5    .0    .0    .0    .0    .0 CUM PASS
 6.80  5.98  4.12  3.94  5.48  4.47  1.61  2.08  2.05  1.19   .75   .74   .63   .44   .24  0.00  0.00  0.00  0.00-0.00STD.DEV.

STREAM NO.  2 SCREENED OVER 1.50 INCH CLOTH   60 INCHES BY  12 FEET
OVERSIZE TO STREAM  3 UNDERSIZE TO STREAM  4
DECK  1 CAPACITY   358.95 TPH - CARRYING   200.00 TPH - IS   55.72 PER CENT LOADED
DECK1OPERATING AT86.9PERCENT EFFICIENCY

STREAM NUMBER  3        169.4 TONS PER HOUR
 41/2    4  31/2    3  21/2    2  11/2    1   3/4   1/2   3/8    4M    8M   16M   40M   50M   80M   100   200
 35.2  20.8  34.8  21.6  19.2  16.7  11.7   7.4    .9    .7    .4   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0 TPH
 20.8  12.3  20.5  12.7  11.3   9.9   6.9   4.4    .6    .4    .2   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0 PCT
 20.8  33.1  53.6  66.3  77.7  87.5  94.4  98.8  99.4  99.8100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0 CUM RETN
 79.2  66.9  46.4  33.7  22.3  12.5   5.6   1.2    .6    .2   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0 CUM PASS
 6.12  5.49  5.03  5.28  4.08  3.59  1.78   .42   .27   .11   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00STD.DEV.
  2.7   2.5   2.3   2.4   1.8   1.6    .8    .2    .1    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0   .00CNF95
 33.3  43.1  61.2  75.8  85.2  94.8  97.5  99.5  99.8100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MAX.PCT.RET.
  8.8  21.8  46.3  54.2  70.3  77.7  90.0  98.0  98.9  99.6100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MIN.PCT.RET.

STREAM NUMBER  4         30.6 TONS PER HOUR
 41/2    4  31/2    3  21/2    2  11/2    1   3/4   1/2   3/8    4M    8M   16M   40M   50M   80M   100   200
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   7.4   5.5   4.3   2.5   4.4   2.2   1.4   1.9   1.0   0.0   0.0   0.0   0.0 TPH
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  24.3  18.1  13.9   8.0  14.3   7.2   4.7   6.3   3.1   0.0   0.0   0.0   0.0 PCT
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  24.3  42.3  56.3  64.3  78.7  85.8  90.6  96.9100.0100.0100.0100.0100.0 CUM RETN
100.0100.0100.0100.0100.0100.0100.0  75.7  57.7  43.7  35.7  21.3  14.2   9.4   3.1    .0    .0    .0    .0    .0 CUM PASS
 0.00  0.00  0.00  0.00  0.00  0.00  0.00  5.32  7.60  7.93  8.18  5.56  4.53  2.24   .53   .00   .00   .00   .00   .00STD.DEV.
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   2.4   3.4   3.5   3.7   2.5   2.0   1.0    .2    .0    .0    .0    .0   .00CNF95
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  34.2  58.7  66.4  79.9  87.4  93.1  94.0  97.7100.0100.0100.0100.0100.0MAX.PCT.RET.
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  13.2  25.2  37.8  47.8  69.7  77.4  86.4  95.9100.0100.0100.0100.0100.0MIN.PCT.RET.

STREAM NO.  4 SCREENED OVER  .75 INCH CLOTH   60 INCHES BY  12 FEET
OVERSIZE TO STREAM  5 UNDERSIZE TO STREAM  6
DECK  2 CAPACITY   269.91 TPH - CARRYING    30.64 TPH - IS   11.35 PER CENT LOADED
DECK2OPERATING AT65.0PERCENT EFFICIENCY

STREAM NUMBER  5         17.1 TONS PER HOUR
 41/2    4  31/2    3  21/2    2  11/2    1   3/4   1/2   3/8    4M    8M   16M   40M   50M   80M   100   200
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   7.4   5.4   3.4    .9   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0 TPH
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  43.5  31.4  19.6   5.5   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0 PCT
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  43.5  74.9  94.5100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0 CUM RETN
100.0100.0100.0100.0100.0100.0100.0  56.5  25.1   5.5    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0 CUM PASS
 0.00  0.00  0.00  0.00  0.00  0.00  0.00  9.9510.04  3.64   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00STD.DEV.
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   4.5   4.5   1.6    .0    .0    .0    .0    .0    .0    .0    .0    .0   .00CNF95
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  64.4  95.7  99.4100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MAX.PCT.RET.
  0.0   0.0   0.0   0.0   0.0   0.0   0.0  30.3  57.4  88.9100.0100.0100.0100.0100.0100.0100.0100.0100.0100.0MIN.PCT.RET.

STREAM NUMBER  6         13.5 TONS PER HOUR
 41/2    4  31/2    3  21/2    2  11/2    1   3/4   1/2   3/8    4M    8M   16M   40M   50M   80M   100   200
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   1.1   1.6   4.2   2.5   1.3   1.8    .9    .0    .0    .0    .0 TPH
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   8.4  11.7  31.0  14.7   9.9  13.4   6.8    .0    .0    .0    .0 PCT
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   8.4  20.2  51.1  69.8  79.7  93.2100.0100.0100.0100.0100.0 CUM RETN
100.0100.0100.0100.0100.0100.0100.0100.0100.0  91.6  79.8  48.9  30.2  20.3   6.8    .0    .0    .0    .0   -.0 CUM PASS
 0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  3.65  9.63  7.90  5.86  3.41  1.10   .00   .00   .00   .00   .00STD.DEV.
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   1.6   4.3   3.6   2.6   1.5    .5    .0    .0    .0    .0   .00CNF95
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  15.2  41.0  63.3  80.0  85.1  95.0100.0100.0100.0100.0100.0MAX.PCT.RET.
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0    .8   7.7  37.0  58.2  73.8  91.3100.0100.0100.0100.0100.0MIN.PCT.RET.

STREAM NO. 3CRUSHED AT 1.50INCH SETTING AND   PRODUCT FED TO STREAM NO. 7

STREAM NUMBER  7        169.4 TONS PER HOUR
 41/2    4  31/2    3  21/2    2  11/2    1   3/4   1/2   3/8    4M    8M   16M   40M   50M   80M   100   200
  0.0   0.0   0.0   0.0   0.0  30.6  20.4  42.9  19.5  19.0   9.5  13.8   6.8   3.4   2.2    .4    .3    .1    .2    .1 TPH
  0.0   0.0   0.0   0.0   0.0  18.1  12.1  25.3  11.5  11.2   5.6   8.1   4.0   2.0   1.3    .2    .2    .0    .1    .1 PCT
  0.0   0.0   0.0   0.0   0.0  18.1  30.1  55.5  67.0  78.2  83.8  92.0  96.0  98.0  99.3  99.6  99.8  99.8  99.9100.0 CUM RETN
100.0100.0100.0100.0100.0  81.9  69.9  44.5  33.0  21.8  16.2   8.0   4.0   2.0    .7    .4    .2    .2    .1   -.0 CUM PASS
 0.00  0.00  0.00  0.00  0.00  1.93  3.22  1.62  1.16   .74   .58   .29   .14   .07   .02   .02   .01   .01   .00   .00STD.DEV.
 0.00  0.00  0.00  0.00  0.00   .87  1.45   .73   .52   .33   .26   .13   .06   .03   .01   .01   .00   .00   .00   .00CNF95
  0.0   0.0   0.0   0.0   0.0  22.0  36.7  59.3  69.9  80.2  85.4  92.7  96.4  98.2  99.4  99.6  99.8  99.8  99.9100.0MAX PCT RET
  0.0   0.0   0.0   0.0   0.0  15.2  25.4  53.2  65.4  77.1  83.0  91.6  95.8  97.9  99.3  99.5  99.8  99.8  99.9100.0MIN PCT RET

ADDING STREAM  5 TO STREAM  7 PUTTING RESULT IN STREAM  8

STREAM NUMBER  8        186.5 TONS PER HOUR
 41/2    4  31/2    3  21/2    2  11/2    1   3/4   1/2   3/8    4M    8M   16M   40M   50M   80M   100   200
  0.0   0.0   0.0   0.0   0.0  30.6  20.4  50.4  24.9  22.4  10.5  13.5   6.8   3.4   2.2    .4    .3    .1    .2    .1 TPH
  0.0   0.0   0.0   0.0   0.0  16.4  11.0  27.0  13.3  12.0   5.6   7.4   3.7   1.8   1.2    .2    .2    .0    .1    .1 PCT
  0.0   0.0   0.0   0.0   0.0  16.4  27.4  54.4  67.7  79.7  85.3  92.7  96.4  98.2  99.4  99.6  99.8  99.8  99.9100.0 CUM RETN
100.0100.0100.0100.0100.0  83.6  72.6  45.6  32.3  20.3  14.7   7.3   3.6   1.8    .6    .4    .2    .2    .1   0.0 CUM PASS
 0.00  0.00  0.00  0.00  0.00  1.93  3.22  3.93  4.51  1.42   .41   .29   .14   .07   .02   .02   .01   .01   .00   .00STD.DEV.
```

Table 2. Comparison between analytical results and observed results.

		Cumulative Percentage Retained					
		Observed		HONPI		HONDO	
Stream	Sieve Size[a] (mm)	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
3	115	18.6	7.23	19.7	5.71	21.4	NA
	100	27.9	7.09	34.5	5.90	33.7	NA
	90	41.8	9.38	54.1	4.52	55.5	NA
	75	52.8	8.04	65.8	3.88	67.6	NA
	64	71.4	6.14	78.7	5.79	80.8	NA
	50	83.9	4.67	88.2	5.40	90.3	NA
	37.5	92.9	3.53	96.3	1.03	98.2	NA
	25	99.6	0.30	99.9	0.03	99.4	NA
	19	99.7	0.22	100.0	0.00	100.0	NA
	12.5	99.7	0.23	100.0	0.00	100.0	NA
	9.5	99.7	0.23	100.0	0.00	100.0	NA
	4.75	99.7	0.23	100.0	0.00	100.0	NA
	0.425	99.7	0.23	100.0	0.00	100.0	NA
7	37.5	21.8	7.10	28.5	3.05	40.5	NA
	25	54.0	9.47	54.8	2.12	67.0	NA
	19	67.1	8.92	66.2	1.59	77.5	NA
	12.5	77.1	7.16	77.5	1.06	85.8	NA
	9.5	81.6	5.93	83.1	0.79	89.0	NA
	4.75	88.7	3.76	91.6	0.39	92.5	NA
	0.425	95.7	2.63	95.8	0.20	93.9	NA

Note: NA = not available.
[a]Corresponding sieve sizes: 4.5, 4, 3.5, 3, 2.5, 2, 1.5, 1, 0.75, 0.5, and 0.375 in, no. 4, no. 40.

1. The estimated flow rate of the raw feed material in tons per hour,
2. The size distribution of the raw feed material in the specified particle size ranges, and
3. The estimated standard deviation of each particle size of the raw feed material.

LISTS Subroutine

The LISTS subroutine is used to list all necessary information on the flow rate and gradation, as well as the standard deviation, of any specified flow stream in the aggregate plant production system.

ADDST Subroutine

The ADDST subroutine is used when two flow streams are merged into a single stream or a portion of one stream combines with a portion of another stream in the aggregate plant system.

SPLITS Subroutine

The SPLTS subroutine is used when any flow stream in the aggregate plant system is split into two separate streams. This subroutine can be revised in case it splits into more than two separate streams.

SCAPY Subroutine

The SCAPY subroutine is used to estimate the capacity of a vibrating screen. Many factors are known to affect screen capacity; various estimated factors proposed by manufacturers of screening equipment have been summarized. The screen capacity that was used in this subroutine is based primarily on the formula for vibrating screen capacity presented by the Iowa Manufacturing Company (9); two more variables—E and M—were added. The formula for screen capacity is

$$CAPY = AREA \times B \times E \times S \times I \times M \times D \times O \times H \times G \times A \times L \times W \quad (5)$$

where

CAPY = capacity of the vibrating screen deck, expressed as tons per hour of feed material that the screen can handle at the specified screening efficiency and under a certain set of conditions;
AREA = net effective screening area, equal to the width times length of the screen less the deck part and frames that reduce the opening of the screen;
B = basic capacity of the screen, usually expressed as tons per hour of feed material per square foot of square opening screen cloth for a material that weighs 100 lb/ft^3 with 25 percent oversize, 40 percent half size, 50 percent open area, and 90 percent efficiency;
E = efficiency factor;
S = particle shape factor;
I = screen slope or incline factor;
M = material factor;
D = deck factor;
O = oversize factor;
H = half size factor;
G = weight factor;
A = open area factor;
L = slotted opening factor; and
W = wet screening factor.

SCREN Subroutine

The SCREN subroutine analyzes by probability analysis the size separation where the feed stream to the screen is divided into two new streams; the oversize material is restrained by the screen opening and remains on the screen surface, and the amount of undersize material that passes through the screen opening is evaluated by stratification, selection, and probabilistic processes. The probability of a particular size of particle passing through the screen opening follows the formula previously proposed for the screening model. A simulator is used to generate 20 estimates of the feed stream, and these are averaged out to a final estimated stream before screening is evaluated.

CRUSH Subroutine

The CRUSH subroutine is used to predict the crushed product gradation when the feed gradation is known. This subroutine has been constructed by using the proposed crushing model described previously. The only parameter used in this subroutine is the value of N, which is the distribution modulus according to Schuhmann's equation (4). The value of N will vary according to the type of crushing machine used. The result of evaluation of the available plant data is an estimated average value of N for Telsmith's 1.2-m (4-ft) standard cone crusher of 0.9 and 0.8 for a Pioneer roll crusher. The value of N is set equal to 1.0 for any compression type of crusher if no average value of N has been preevaluated. For the impact type of crushing machine, for which speed is the controlling criterion for required product gradation, the setting equivalent used is based on tables from the Iowa Manufacturing Company. A simulator is used to generate 20 estimates of the feed stream, and these are averaged out to a final estimated stream before crushing is evaluated.

Sample Analysis of Plant Production

To demonstrate the use of the HONPI computer model to evaluate plant production, a sample analysis is done for part of the Ward Stone Plant. A flow diagram of the plant operation is shown in Figure 4. The operating characteristics of the plant facilities are given in Table 1. The computer model set up for the plant is similar to the one proposed by Hancher (8). The basic input data for the feed to the plant are shown in Figure 5. Figure 6 shows the computer statement sequence required for the partial plant analysis. The results of the computer model analysis are shown in Figure 7.

Comparison between the proposed model (HONPI) and the existing model (HONDO) predictions for test samples collected at the plant has shown a certain degree of improvement of the HONPI model for aggregate plant analysis. Table 2 gives the results of the prediction of flow stream 7—the crushed product from a Telsmith 1.2-m (4-ft) standard cone crusher—and flow stream 3—the oversize material from the second deck of the first screen unit. Considerably more testing is required to evaluate the true capabilities of the model.

SUMMARY AND CONCLUSIONS

The primary objective of this research study was to develop a probabilistic prediction model for aggregate production plants. Through the use of available crushing and screening theories, Hancher's computer model (8) has been revised, and statistical devices have been added for the development of this proposed probabilistic model. Preliminary testing of the new proposed crushing and screening models has been confirmed by the manufacturer's recommended crushed product output and available screening data.

The probabilistic model proposed in this study will be a useful tool in the design and development of new aggregate plants as well as the expansion of existing plants. Although it does not purport to be a comprehensive model of the entire aggregate processing system, it does permit the user to seek, where appropriate, proper planning and optimization of his or her own design data for the data postulated in the basic model.

The analysis techniques used in the proposed model are compatible with those used in the aggregate industry in the United States. The use of such a model greatly facilitates the evaluation of many more plant arrangements, raw-feed compositions, and equipment settings than it is now possible to evaluate. It is also much easier, by using this model, to evaluate closed-circuit plant analyses (introduction of such material was omitted from this paper because of considerations of length).

Extensive experimental data would be required to ensure the validity of this model; however, collection of such data was not feasible in this study because of a lack of funding. It is believed that, after additional study and development, satisfactory, proven probabilistic prediction models might emerge.

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Applicability of Conventional Test Methods and Material Specifications to Coal-Associated Waste Aggregates

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The applicability of standard test procedures and specifications to nonconventional, coal-associated materials such as bottom ash, boiler slag, and coal mine refuse is evaluated. Test procedures for specific gravity, Los Angeles abrasion, degradation resistance, soundness, deleterious materials, weak particles, and leachate quality were performed. Asphaltic mixtures were analyzed for Marshall stability and flow, density, voids, and degradation. It was found that, because of the unique characteristics of bottom ash, boiler slag, and coal mine refuse, application of conventional test methods and specifications is often inappropriate and that effective use of such materials requires the development of new test methods or modifications to existing methods and specifications. Application of existing test methods and specifications may result in