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BENEFICIATING SHALE CONTAMINATED LIMESTONE BY HEAVY MEDIA SEPARATION

Division of Materials and Research
Missouri State Highway Department

MO. S H. D.
RESEARCH
SECTION

A STUDY OF THE FEASIBILITY OF BENEFICIATING A SHALE CONTAMINATED LIMESTONE BY HEAVY MEDIA SEPARATION

A Progress Report on

COARSE AGGREGATE STUDY

Investigation 59-1
HPR 1(4)-28
Area B, Phase I, Test 1.

MISSOURI STATE HIGHWAY DEPARTMENT
DIVISION OF MATERIALS AND RESEARCH
RESEARCH SECTION

in
Cooperation
With

BUREAU OF PUBLIC ROADS

Jefferson City, Missouri

October 1965

FOREWORD

In performing the experiment reported herein, we gratefully acknowledge the cooperation of two Missouri coarse aggregate producers for their help in obtaining and crushing the aggregate, and of the Conco-Western Stone Company of North Aurora, Illinois for the use of their HMS separation equipment. We also wish to thank the representatives of the Eagle Iron Works of Des Moines, Iowa (manufacturers of the equipment used by the Conco-Western Stone Company) for their guidance and help in the heavy media separation process.

It should be stated that any doubt expressed in this report, concerning the benefit to be derived from subjecting the shale contaminated stone to heavy media separation, should not be construed as a reflection on the value of heavy media benefication of all aggregates. Most obviously the Conco-Western Stone Company was very successfully removing a low gravity chert from a higher gravity stone. In this successful operation the material being processed had a gap gravity gradation, whereas the material used in this test had a continuous gravity gradation. In addition the specific gravity of the contaminant (chert) in the material being processed by the Conco-Western Stone Company was consistently lower than that of the stone, whereas the specific gravity of the shale contaminated material (in the product used in these tests) had a range in specific gravity approaching that of the clean stone.

The above differences between the material used in this experiment and that being successfully processed by the Conco-Western Stone Company were obvious. The question, and reason for this experiment, was whether this obvious successful method with some aggregates would benefit the shale contaminated stone used in this experiment. As no one appeared to know how benefical heavy media separation of this type of material would be, this rather extensive experiment was initiated. Consequently, any implied deficiences of heavy media separation are applicable only to the material used in this experiment, and most definitely should not be construed as a reflection upon a method which has been very successfully used with other aggregates.

SYNOPSIS

This is a report of the results obtained when a shale contaminated Missouri limestone was subjected to heavy media separation in an operating plant. This stone was processed through a heavy media of 2.54 gravity and the sink product of this separation was reprocessed through a heavy media of 2.60 gravity.

Results of laboratory tests on samples of the various products of separation, and of the initial feed, are presented and discussed.

Several methods of evaluating the effectiveness of the beneficiation (of the separation) are presented and applied to the data.

The results indicate that the heavy media separation is beneficial in reducing the amount of contaminative shale in the material treated, but the reduction was not sufficient to insure that a product of unquestionably improved quality was obtained. In addition, the possible improvement in quality was accompanied by the loss of a considerable amount of the highest gravity stone. The loss of good stone plus the cost of heavy media separation casts considerable doubt upon the economic feasibility of improving the quality of this stone by heavy media separation. This fact, concerning the economic feasibility, was so evident that it presently appears unwarranted to undertake expensive freezing and thawing tests on concrete containing these separation products.

Phase B. PHASE I, Test 1
OF
COARSE AGGREGATE STUDY

A STUDY OF THE FEASIBILITY OF BENEFICIATING A SHALE CONTAMINATED LIMESTONE BY HEAVY MEDIA SEPARATION

A. Introduction

1. Scope: This phase of the coarse aggregate study, made in cooperation with the Bureau of Public Roads, was designed to determine the feasibility of beneficiating a shale contaminated limestone by heavy media separation under operating plant conditions. This stone is one widely used in approximately one quarter of the state, but the quality ranges from medium to unsatisfactory as a concrete aggregate depending upon shale content.

2. Procedure: Following preliminary laboratory tests, approximately eight tons of stone,[1] containing approximately 12.5 percent of material classified as "Deleterious" (slightly more than double the permissible maximum of 6 percent), was thoroughly blended at the quarry. From this blend, three samples or portions of approximately 5, 1, and 0.6 tons were obtained. The smallest portion (0.6 ton) was trucked to the laboratory in Jefferson City, Missouri, for test purposes, and the 5 and 1 ton portions were trucked to the heavy media plant. The one-ton portion was used to adjust the specific gravity of the media so that the desired separations could be obtained on the five-ton portion. The final products of

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[1] Concrete coarse aggregate of nominal maximum size of 1.5 in.

the one-ton portion were wasted, and those of the five-ton portion were returned to the laboratory for test purposes. The final products of the five-ton portion consisted of: (a) 0.82 tons of material which floated when the specific gravity of the separation media was near 2.54; (b) 0.89 tons of material which sank when the specific gravity of the separation media was near 2.54 but floated when the specific gravity of the separation media was near 2.60; and (c) 3.16 tons of material which sank when the specific gravity of the separation media was near 2.60.[2]

The three separated products of the stone subjected to heavy media separation, plus the 0.6 ton sample of the original feed were subjected to the following laboratory tests:

a. Each product was separated into three size groups: +1 in., 1 in. to 1/2 in., and -1/2 in.

b. The gradation of each size group of each product was determined.

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[2] The sum of the weights of these three products is 4.87 tons, whereas the original weights indicated that 5.12 tons of material were processed. The loss of 0.25 ton can be attributed to loss of material during heavy media separation, errors in moisture tests and sampling, difference in scales, material used in tests, and removal of minus 1/4" material at time of separation into size groups in the laboratory. As it is impossible to account for all of this lost material or to correctly distribute it among the three final products, it was assumed that the probable distribution of the stone after separation would be obtained by using the weights of 0.82, 0.89, and 3.16 tons for the three products. This procedure undoubtedly introduces a slight error in the computations, since it is extremely doubtful that the composition of the material in the lost 1/4 ton was exactly the same as that obtained by combining these three fractions. However, this investigation, by requiring tests on an untreated sample of the "Feed", insures that this error cannot be significantly large without being detected.

c. The weight of material in each size group of each product was determined.

d. Three samples from each size group of each product were vacuum saturated, then separated in laboratory heavy liquid media having specific gravities of 2.47, 2.51, 2.55, 2.59, and 2.63. (Specific details of the laboratory procedure for this heavy liquid media separation are shown in Appendix A.)

e. The bulk specific gravities (Vacuum Saturated Surface Dry and Dry) and percent absorption (vacuum saturated) of the material obtained by laboratory heavy liquid media separations were determined. In this operation, the proportion of the sample retained in each specific gravity fraction was also determined.

f. The material in each specific gravity fraction was separated visually into "Clean", "Objectionable", and "Deleterious" material.

The results of the above tests were used to determine the physical characteristics and define the properties of the following classifications of material:

a. "Feed" (material in the 0.6 ton of blended untreated stone),

b. "Combined" (combined results obtained on the three products obtained by heavy media separation),

c. "Low Gravity" (float at 2.54 specific gravity heavy media separation under plant conditions),

d. "Total Float" (float at 2.60 specific gravity heavy media separation under plant conditions),

e. "Medium Gravity" (float at 2.60 specific gravity and sink at 2.54 specific gravity heavy media),

f. "First Sink" (sink at 2.54 specific gravity heavy media separation under plant conditions), and

g. "High Gravity" (sink at 2.60 specific gravity heavy media separation under plant conditions).

3. Description of Shale Contaminated Limestone

This stone is composed of massive, nodular, and mottled stone plus shale. The shale portion can occur as pure shale particles or as a mixture with the stone.

The "Clean" fraction of this stone is that portion remaining after removal of all the contaminative materials. The contaminative materials in this limestone, which have been designated as "Deleterious" or "Objectionable", are made up of several sub-classes as follows:

"Deleterious" Material

Shale
Soft Stone
Pure Shaly Stone
Cap Shale (+20%)

"Objectionable" Material

Cap Shale (-20%)
Shale Seams
Skin Shale
Mud-Coated Stone

A detailed description of these various types of contaminants is given in Appendix B. Essentially, with the exception of the soft stone, the descriptions tend to classify the materials on the basis of a visual estimate of the quantity or percent of shale or mud within or on the aggregate particle.

Previous gravity analyses of this stone indicated that beneficiation might be possible by heavy media separation, pro-

viding a fairly efficient separation could be made under plant conditions.

B. Results

1. The quantity of material in each size group of each of four (Feed, Low Gravity, Medium Gravity, and High Gravity) classifications of the stone, from the heavy media separation, was as follows:

Classification of Stone	Size Group +1" Wt., Lbs.	+1" %	1" to 1/2" Wt., Lbs.	1" to 1/2" %	-1/2" Wt., Lbs.	-1/2" %
Feed(0.6 ton)	172.5	14.26	719.5	59.49	317.5	26.25
Low Gravity (Float at 2.54)	273.0	16.61	840.5	51.16	529.5	32.23
Med. Gravity (Sink at 2.54, Float at 2.60)	199.5	11.21	969.5	54.48	610.5	34.31
High Gravity (Sink at 2.60)	943.5	14.95	3853.5	61.04	1516.0	24.01
Combined Low, Medium, and High Gravity	1416.0	14.55	5663.5	58.17	2656.0	27.28

Note that the percentages of material in the three size groups of the three (Low, Medium, and High Gravity) classifications of separated material differed from that of the Feed. However, by combining these three classifications of material, the percentage of material in each of the three size groups was near that of the Feed, as expected.

2. The gradation of the material in each size group and each classification of stone is shown in Table 1.

TABLE 1. Tabulation of Sieve Analysis of Each Size Group of Six Classifications of Stone

Sieve Size	Percent Passing: "Low Gr." (Float at 2.54) +1"*	1" to ½"	-½"	All	"Med. Gr." (Float at 2.60) (Sink at 2.54) +1"*	1" to ½"	-½"	All	"High Gr." (Sink at 2.60) +1"*	1" to ½"	-½"	All
2"	100.0			100.0				100.0	100.0			100.0
1½"	99.15			99.86	100.0			100.0	99.16			99.88
1¼"	71.55	100.0		95.27	85.08	100.0		98.33	81.59	100.0		97.25
1"	27.84	99.40		87.70	45.34	99.37		93.53	41.81	99.62		91.07
3/4"	1.04	71.23	100.0	68.84	2.46	74.58	100.0	75.21	2.16	64.94	100.0	63.97
1/2"	0.19	5.62	97.20	34.24	0.20	6.23	97.93	37.01	0.15	5.47	96.05	26.42
3/8"	0.19	0.39	48.93	16.00	0.16	0.23	42.92	14.87	0.13	0.30	39.97	9.80
#4	0.17	0.24	0.45	0.30	0.14	0.17	0.22	0.19	0.12	0.23	0.29	0.23

Sieve Size	Percent Passing: "Feed" +1"*	1" to ½"	-½"	All	Combined "Low", "Medium", and "High" Gravity +1"*	1" to ½"	-½"	All	"First Sink" or Combined "Medium" and "High" Gravity (Sink at 2.54) +1"*	1" to ½"	-½"	All
2"	100.0			100.0	100.0			100.0	100.0			100.0
1½"	95.21			99.32	99.27			99.90	99.31			99.91
1¼"	86.00			98.00	80.14	100.0		97.11	82.20	100.0		97.49
1"	42.30	100.0		91.77	39.61	99.54		90.96	42.43	99.57		91.61
3/4"	2.04	65.86	100.0	65.72	1.98	67.54	100.0	66.87	2.21	66.88	100.0	66.44
1/2"	0.16	4.86	94.51	27.72	0.16	5.64	96.72	29.70	0.16	5.62	96.59	28.75
3/8"	0.10	0.20	42.91	11.39	0.14	0.31	42.44	11.79	0.14	0.29	40.82	10.91
#4	0.09	0.13	0.23	0.15	0.13	0.23	0.31	0.23	0.12	0.22	0.27	0.22

*Note that the so-called +1 inch material contains an appreciable amount of -1 inch material. Most of this -1 inch material was retained on the 3/4 sieve.

The gradations of these materials further confirm the previously indicated variation in percentage of material in each of the three sizes of the various classifications of stone. The indication is that the size of the aggregate particles affected the separation obtained. This could be due to either of two conditions observed from the data; namely, the gravity gradation of the treated stone varied with particle size, or the efficiency of the separation varied with particle size.

Although the above indication was obtained, the gradation of the two sink products (High Gravity and First Sink) was not radically different from that of the Feed. This would indicate that treatment of this stone by heavy media separation would not create a problem in control of gradation.

3. The gravity gradation (laboratory heavy liquid media), the bulk specific gravities (Vacuum Saturated Surface Dry and Dry), and the absorptions (vacuum saturated); (for each laboratory heavy liquid gravity fraction of the three size groups and the combined sample of each of the seven classifications of stone) are shown in Table 2. The results in Table 2 are the average results of tests made on three vacuum saturated samples taken from each of the three size groups of each of the four (Feed, Low Gravity, Medium Gravity, and High Gravity) classifications of stone. The results of the remaining three (Combined Low, Medium, and High Gravity; Total Float at 2.60 specific gravity separation media; and the First Sink at 2.54 specific gravity separation media)

ity Fraction for each of Three Size Groups for each of the Seven Classifications of Stone

e Gravity (Dry)				Percent Absorption by Weight							Percent Absorption by Volume						
2.55 to 2.51	2.51 to 2.47	-2.47	Avg.	+2.63	2.63 to 2.59	2.59 to 2.55	2.55 to 2.51	2.51 to 2.47	-2.47	Avg.	+2.63	2.63 to 2.59	2.59 to 2.55	2.55 to 2.51	2.51 to 2.47	-2.47	Avg.
ch Size Group																	
.4217	2.3486	-	2.5726	1.33	2.87	3.82	4.86	6.19	-	2.25	3.49	7.29	9.48	11.78	14.54	-	5.78
.4242	2.3563	2.2571	2.5714	1.30	2.72	3.77	4.79	6.07	7.59	2.29	3.42	6.94	9.35	11.62	14.31	17.14	5.90
.4240	2.3582	2.2571	2.4556	1.52	3.09	3.86	4.81	6.01	7.59	4.25	3.98	7.82	9.57	11.65	14.18	17.14	10.44
.4237	2.3569	2.2571	2.4889	1.57	2.88	3.81	4.81	6.05	7.59	3.67	4.09	7.31	9.45	11.66	14.27	17.14	9.15
.4211	2.1852	-	2.5359	1.58	2.81	3.72	4.83	11.86	-	2.87	4.12	7.15	9.24	11.70	25.93	-	7.28
.4258	2.1852	-	2.6007	1.30	2.69	3.66	4.71	11.86	-	1.81	3.42	6.85	9.10	11.43	25.93	-	4.71
.4396	-	-	2.6148	1.28	2.63	3.54	4.35	-	-	1.58	3.36	6.70	8.83	10.62	-	-	4.14
Inch Size Group																	
.4210	2.3500	1.9733	2.5811	1.27	2.68	3.78	4.86	6.09	12.16	2.11	3.34	6.84	9.39	11.77	14.32	24.00	5.44
.4190	2.3554	2.2212	2.5849	1.33	2.72	3.78	4.92	6.17	8.35	2.09	3.49	6.92	9.39	11.89	14.53	18.55	5.41
.4187	2.3588	2.2177	2.4826	1.51	2.77	3.87	4.93	6.09	8.56	3.79	3.94	7.05	9.59	11.93	14.36	18.97	9.41
.4206	2.3583	2.2211	2.5237	1.39	2.76	3.80	4.88	6.08	8.36	3.07	3.65	7.03	9.43	11.82	14.33	18.56	7.76
.4259	2.3556	2.2414	2.5604	1.35	2.76	3.71	4.75	6.00	7.18	2.45	3.55	7.03	9.23	11.52	14.13	16.09	6.26
.4196	2.3396	2.2414	2.6036	1.31	2.70	3.71	4.88	6.52	7.18	1.79	3.46	6.89	9.25	11.81	15.26	16.09	4.66
.4065	2.1429	-	2.6147	1.31	2.69	3.72	5.16	13.33	-	1.62	3.45	6.85	9.27	12.41	28.57	-	4.24
/4 Inch Size Group																	
.4206	2.3634	2.2344	2.5760	1.26	2.67	3.73	4.88	5.87	8.39	2.18	3.32	6.80	9.28	11.81	13.87	18.75	5.62
.4354	2.3766	2.2606	2.5809	1.27	2.60	3.70	4.70	5.68	7.70	2.14	3.34	6.64	9.20	11.45	13.49	17.41	5.52
.4369	2.3808	2.2935	2.5303	1.31	2.48	3.64	4.64	5.69	7.59	2.99	3.45	6.34	9.08	11.30	13.54	17.42	7.57
.4339	2.3746	2.2761	2.5503	1.31	2.54	3.72	4.70	5.74	7.60	2.64	3.44	6.49	9.27	11.44	13.63	17.30	6.74
.4292	2.3585	2.1655	2.5679	1.31	2.58	3.80	4.80	5.88	7.64	2.33	3.44	6.60	9.45	11.66	13.86	16.55	5.99
.4342	2.3711	2.1300	2.5938	1.26	2.63	3.72	4.75	5.66	8.14	1.92	3.33	6.72	9.25	11.57	13.41	17.33	4.99
.4398	2.3839	2.0625	2.6044	1.25	2.66	3.67	4.70	5.44	9.09	1.76	3.29	6.79	9.12	11.47	12.96	18.75	4.59
Groups Combined																	
.4210	2.3551	2.1530	2.5786	1.28	2.71	3.77	4.87	6.01	9.54	2.14	3.36	6.90	9.37	11.78	14.16	20.54	5.53
.4246	2.3653	2.2437	2.5818	1.31	2.68	3.75	4.83	5.93	7.95	2.14	3.44	6.84	9.33	11.71	14.03	17.84	5.52
.4237	2.3667	2.2651	2.4932	1.40	2.69	3.83	4.84	5.94	7.94	3.61	3.68	6.87	9.50	11.73	14.05	17.98	9.01
.4245	2.3649	2.2557	2.5276	1.37	2.71	3.79	4.82	5.94	7.87	3.01	3.59	6.90	9.41	11.69	14.04	17.75	7.62
.4267	2.3573	2.1946	2.5602	1.35	2.72	3.73	4.77	5.93	7.46	2.45	3.55	6.92	9.28	11.58	13.98	16.37	6.28
.4262	2.3615	2.1552	2.6006	1.30	2.68	3.71	4.81	5.92	7.94	1.83	3.43	6.84	9.23	11.68	13.99	17.11	4.75
.4254	2.3682	2.0625	2.6122	1.29	2.67	3.68	4.88	5.92	9.09	1.65	3.40	6.81	9.17	11.84	14.01	18.75	4.31

are calculated from the results obtained with the Low, Medium, and High Gravity classifications.

These results will be discussed in Section C.

4. The amount of Clean, Objectionable, and Deleterious material, as determined by visually separating the material in each laboratory heavy media gravity fraction of each size group of the seven classifications of stone, are shown in Table 3.

These results in Table 3 will be discussed in the following section.

C. Discussion of Results in Tables 2 and 3

In analyzing the results of the laboratory tests, shown in Tables 2 and 3, the following points will be discussed:

1. Physical characteristics of the stone as determined by tests on the Feed and the three (High, Medium, and Low Gravity) products of heavy media separation, and relationship between particle size and the physical characteristics of the stone.
2. Effectiveness of the heavy media separation in removal of contaminative materials, and relationship between particle size and effectiveness or efficiency of the heavy media separation in removal of contaminative materials.

Physical Characteristics of the Stone

Under the method of sampling and testing used, the physical characteristics of the stone were determined:

1. By tests on the Feed which was a sample of the untreated stone.
2. By combining results obtained in testing the three separation products from the heavy media treatment plant.

isually) in Each of the Seven Classifications of Stone, and in Each of Three Size Groups and Six Gravity Groups for Each Classification

ied as Clean, Objectionable, and Deleterious in Each Classification and in Each Gravity Group

2.59 to 2.55				2.55 to 2.51				2.51 to 2.47				-2.47			
Total	Clean	Obj.	Del.	Total	Clean	Obj.	Del.	Total	Clean	Obj.	Del.	Total	Clean	Obj.	Del.
Plus 1 Inch Size Group															
12.91	1.59	4.90	6.42	9.30	-	1.28	8.02	1.27	-	-	1.27	-	-	-	-
13.75	1.64	5.58	6.53	10.05	0.34	1.69	8.02	1.00	-	0.11	0.89	0.06	-	-	0.06
37.24	3.77	12.89	20.59	45.52	1.46	7.28	36.78	5.11	-	0.55	4.56	0.29	-	-	0.29
34.32	3.91	13.54	16.87	29.16	0.84	4.79	23.53	2.97	-	0.32	2.65	0.17	-	-	0.17
30.32	4.09	14.43	11.80	6.77	-	1.38	5.39	0.04	-	-	0.04	-	-	-	-
8.14	1.12	3.84	3.18	1.58	0.07	0.36	1.15	0.01	-	-	0.01	-	-	-	-
3.45	0.49	1.60	1.36	0.48	0.09	0.14	0.25	-	-	-	-	-	-	-	-
1 Inch to 1/2 Inch Size Group															
10.59	3.41	3.79	3.39	7.70	1.27	1.28	5.15	1.74	-	0.57	1.17	0.13	-	-	0.13
9.77	3.44	3.01	3.32	6.61	0.53	1.49	4.59	1.64	0.03	0.21	1.40	0.20	-	-	0.20
26.54	7.14	8.75	10.64	28.71	1.72	6.48	20.52	9.35	0.21	1.20	7.94	1.15	-	-	1.15
22.54	6.76	7.90	7.88	18.29	1.37	4.55	12.37	5.07	0.10	0.65	4.32	0.62	-	-	0.62
19.07	6.43	7.16	5.48	9.26	1.09	2.87	5.30	1.36	-	0.18	1.18	0.17	-	-	0.17
6.85	2.80	2.02	2.03	2.75	0.32	0.63	1.80	0.30	-	0.04	0.26	0.03	-	-	0.03
3.78	1.89	0.72	1.17	1.11	0.12	0.06	0.93	0.03	-	-	0.03	-	-	-	-
1/2 Inch to 1/4 Inch Size Group															
10.62	5.65	2.11	2.86	7.67	2.05	1.33	4.29	2.93	0.32	1.07	1.54	0.73	0.10	0.11	0.52
9.19	4.82	1.93	2.44	7.59	2.03	1.32	4.24	3.49	0.45	0.56	2.48	0.78	0.11	0.01	0.66
13.36	7.78	2.99	2.59	17.08	4.61	3.21	9.26	9.97	1.24	1.61	7.12	3.19	0.47	-	2.72
12.52	6.68	3.09	2.75	13.01	3.48	2.46	7.07	6.39	0.74	0.96	4.69	1.70	0.22	0.02	1.46
11.79	5.72	3.17	2.90	9.48	2.50	1.81	5.17	3.28	0.31	0.40	2.57	0.41	-	0.03	0.38
8.15	4.08	1.66	2.41	5.22	1.40	0.84	2.98	1.88	0.25	0.30	1.33	0.18	0.01	0.01	0.16
6.69	3.43	1.05	2.21	3.50	0.95	0.45	2.10	1.32	0.22	0.27	0.83	0.09	0.01	-	0.08
Three Size Groups Combined															
10.93	3.74	3.51	3.69	7.92	1.29	1.29	5.33	1.99	0.08	0.62	1.27	0.27	0.03	0.03	0.22
10.21	3.57	3.10	3.54	7.37	0.90	1.48	4.99	2.05	0.14	0.29	1.62	0.33	0.02	0.00	0.31
24.08	6.79	7.58	9.70	27.76	2.61	5.55	19.60	8.84	0.51	1.22	7.11	1.67	0.15	0.00	1.52
20.84	6.34	7.08	7.42	18.03	2.00	3.88	12.15	5.21	0.29	0.72	4.20	0.92	0.07	0.01	0.84
17.84	5.92	6.61	5.31	9.05	1.45	2.33	5.27	1.86	0.10	0.24	1.52	0.23	-	0.01	0.22
7.38	2.91	2.18	2.29	3.23	0.56	0.64	2.03	0.68	0.06	0.11	0.51	0.07	-	-	0.07
4.44	2.06	0.94	1.44	1.59	0.31	0.17	1.11	0.34	0.05	0.07	0.22	0.02	-	-	0.02

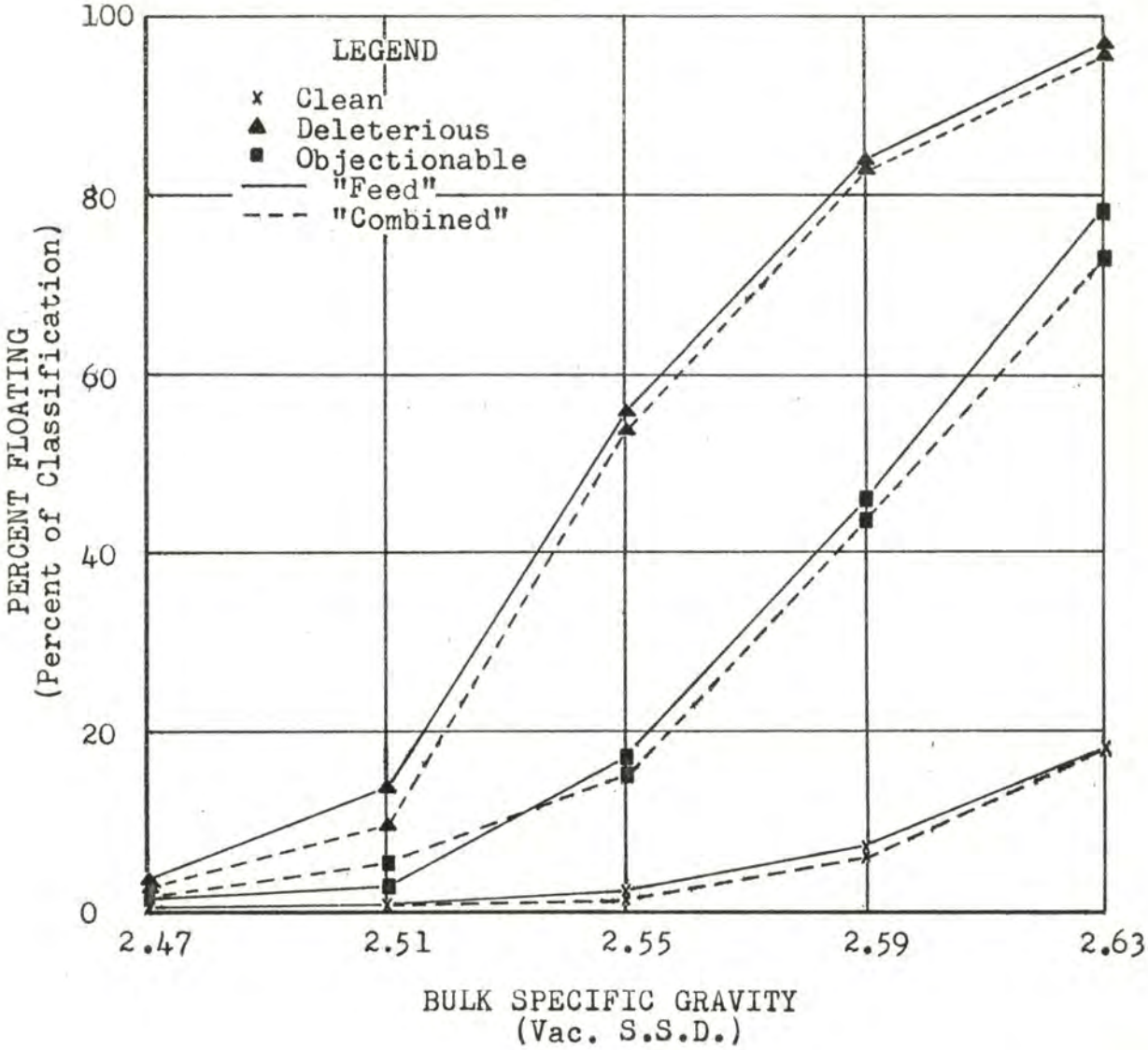
Providing the sampling procedure was adequate, both determinations should show identical or nearly identical results; unless the physical character of the stone was altered by the heavy media separation. The following results from Tables 2 and 3 indicate that the physical properties of the Feed and the Combined products (Low, Medium, and High Gravity fractions) are essentially the same:

Property	Feed	Combined Products of Separation
Table 1 - Bulk Sp.Gr. (V.S.S.D.)	2.6339	2.6370
Table 1 - Bulk Sp.Gr. (Dry)	2.5786	2.5818
Table 1 - % Absorption by Wt. (Vacuum Saturated)	2.14	2.14
Table 1 - % Absorption by Vol. (Vacuum Saturated)	5.53	5.52
Table 2 - % Clean Material	74.70	76.78
Table 2 - % Objectionable Mat'l.	12.56	10.77
Table 2 - % Deleterious Material	12.74	12.45

In addition to the above evidence, the curves in Fig. 1, which show the gravity gradation (laboratory media separation) of each of the three (Clean, Objectionable, and Deleterious) visual classifications, indicate essentially the same results for these two methods of determining the physical character of the Feed. To facilitate analysis, the properties of the Feed will, henceforth, be considered as that obtained by combining the results of tests on the three (Low, Medium, and High Gravity) products of separation.

Fig. 1

GRAVITY ANALYSES OF "CLEAN", "OBJECTIONABLE", AND "DELETERIOUS" FRACTIONS OF THE "FEED" AND "COMBINED" AGGREGATE



Data from Tables 2 and 3 have been retabulated in Table 4. The results of tests on the combined Feed are shown in column 1, and the results of tests on the three (+1 in., 1 in. to 1/2 in., and 1/2 in. to 1/4 in.) size groups are shown in columns 2, 3, and 4. The variation in the visual composition of this stone with particle size is evident from a study of these data (Table 4, item 8, columns 2, 3, and 4), where: the percent of Clean stone varied from 60.6 in the +1 in. size to 83.6 in the 1/2 in. to 1/4 in. size. Conversely the amount of Deleterious material (Item 9) varied from 20.1 percent in the +1 in. to 10.9 percent in the 1/2 in. to 1/4 in. size. These variations in percents would lead one to expect a greater variation in the bulk specific gravities (V.S.S.D. and Dry) and absorption (vacuum saturated) than those shown in Table 4 (Items 3, 4, 5, and 6 and columns 2, 3, and 4). These variations in percents did not cause a great variation in the specific gravities (V.S.S.D. and Dry) and absorption (vacuum saturated) because the laboratory heavy liquid gravity gradation varied with particle size. Therefore, the variation in the laboratory gravity gradation had an effect on the specific gravities (V.S.S.D. and Dry) and absorptions (vacuum saturated) inversely to that of the variation in percents of the visual classifications; thus resulting in a small combined variation in the specific gravities and absorptions.

From the preceding it should be obvious that discussion of variations in the laboratory gravity analysis is at best difficult and can be most confusing. To partially overcome this difficulty it appeared desirable to express the laboratory gravity

TABLE 4. Characteristics of Stone Before and After Heavy Media Separation

Gravity Classifications of Stone

"Sink" in Heavy Media of 2.54 Gr.				"Float" in Heavy Media of 2.54 Gr.				"Sink" in Heavy Media of 2.60 Gr.				"Float" in Heavy Media of 2.60 Gr.			
All Sizes	+1"	1" to 1/2"	1/2" to 1/4"	All Sizes	+1"	1" to 1/2"	1/2" to 1/4"	All Sizes	+1"	1" to 1/2"	1/2" to 1/4"	All Sizes	+1"	1" to 1/2"	1/2" to 1/4"
5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3.12	11.74	49.54	21.84	16.88	2.81	8.63	5.44	64.84	9.69	39.58	15.57	35.16	4.86	18.59	11.71
6006	2.6007	2.6036	2.5938	2.4932	2.4556	2.4826	2.5303	2.6122	2.6148	2.6147	2.6044	2.5276	2.4889	2.5237	2.5503
6481	2.6478	2.6502	2.6437	2.5833	2.5601	2.5767	2.6061	2.6553	2.6562	2.6571	2.6502	2.6038	2.5804	2.6013	2.6177
.83	1.81	1.79	1.92	3.61	4.25	3.79	2.99	1.65	1.58	1.62	1.76	3.01	3.68	3.07	2.64
.75	4.71	4.66	4.99	9.01	10.44	9.41	7.57	4.31	4.14	4.24	4.59	7.62	9.15	7.76	6.74
0.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
4.19	71.25	76.22	71.14	24.97	4.36	20.96	41.99	80.63	80.18	82.34	76.55	38.68	14.76	37.53	50.41
5.81	28.75	23.78	28.86	75.03	95.64	79.04	58.01	19.37	19.82	17.66	23.45	61.32	85.24	62.47	49.59
1.36	9.73	9.93	15.43	62.35	88.16	65.75	43.60	6.39	3.93	4.92	11.60	45.00	66.62	46.52	33.62
3.98	1.59	3.08	7.28	38.27	50.92	39.21	20.24	1.95	0.48	1.14	4.91	24.16	32.30	23.98	21.10
0.75	0.01	0.33	2.06	10.51	5.40	10.50	13.16	0.36	0.00	0.03	1.41	6.13	3.14	5.69	8.09
0.07	0.00	0.03	0.18	1.67	0.29	1.15	3.19	0.02	0.00	0.00	0.09	0.92	0.17	0.62	1.70
3.65	72.02	84.76	87.38	42.92	12.92	36.68	68.27	87.73	78.53	88.99	90.26	56.57	24.86	53.44	74.66
1.04	63.79	72.96	70.59	23.87	4.23	19.26	41.34	77.30	72.27	79.01	76.08	36.85	12.42	35.13	49.70
2.61	8.23	11.80	16.79	19.05	8.69	17.42	26.93	10.43	6.26	9.98	14.18	19.72	12.44	18.31	24.96
3.53	1.19	3.12	5.74	10.06	5.23	9.07	14.10	2.42	0.58	2.01	4.61	8.71	4.75	8.23	11.12
0.62	0.07	0.32	1.66	3.27	1.46	1.93	6.32	0.36	0.09	0.12	1.18	2.36	0.84	1.47	4.44
0.06	0.00	0.00	0.26	0.66	0.00	0.21	1.71	0.05	0.00	0.00	0.23	0.36	0.00	0.10	0.96
0.00	0.00	0.00	0.01	0.15	0.00	0.00	0.47	0.00	0.00	0.00	0.01	0.07	0.00	0.00	0.22
6.98	9.46	5.91	8.08	39.42	64.37	42.08	22.35	4.86	6.57	3.85	6.39	26.46	46.97	27.09	16.97
0.51	1.32	0.45	0.18	0.17	0.00	0.34	0.00	0.52	1.46	0.42	0.17	0.31	0.27	0.46	0.11
6.47	8.14	5.46	7.90	39.25	64.37	41.74	22.35	4.34	5.11	3.43	6.22	26.15	46.70	26.63	16.86
4.90	4.34	4.12	6.88	37.93	62.22	40.25	21.69	2.79	1.61	2.13	5.22	24.61	43.22	25.19	15.97
2.61	1.16	2.09	4.47	28.23	41.63	29.61	19.10	1.35	0.25	0.96	3.01	17.19	26.35	17.31	13.22
0.58	0.01	0.29	1.49	8.63	4.85	9.09	9.84	0.24	0.00	0.03	0.91	5.04	2.82	4.94	6.15
0.07	0.00	0.03	0.16	1.52	0.29	1.15	2.72	0.02	0.00	0.00	0.08	0.84	0.17	0.62	1.46
9.37	18.52	9.33	4.54	17.66	22.72	21.24	9.38	7.41	14.90	7.16	3.35	16.97	28.17	19.47	8.37
2.64	6.14	2.81	0.37	0.93	0.13	1.36	0.65	2.81	6.45	2.91	0.30	1.52	2.07	1.94	0.60
6.73	12.38	6.52	4.17	16.73	22.59	19.88	8.73	4.60	8.45	4.25	3.05	15.45	26.10	17.53	7.77
2.93	4.20	2.69	2.81	14.35	20.72	16.43	7.81	1.18	1.74	0.78	1.77	11.69	18.65	13.10	6.53
0.75	0.36	0.67	1.15	6.77	7.83	7.68	4.82	0.24	0.14	0.06	0.72	4.61	5.11	5.20	3.44
0.11	0.00	0.04	0.31	1.22	0.55	1.20	1.61	0.07	0.00	0.00	0.27	0.73	0.32	0.65	0.98
0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02

of separation.

rption by volume = 100 [Bulk Sp. Gr. (Vac. S.S.D.) - Bulk Sp. Gr. (Dry)]

gradation of each product by a single parameter, which has been designated as "Gravity Modulus". (See Appendix C for discussion of Gravity Modulus) The formula for the Gravity Modulus, which appeared to be best for the available data, is:

$$\text{Gravity Modulus} = 1.00A + 0.80B + 0.64C + 0.51D + 0.41E + 0.33F$$

Where: A = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is greater than 2.63.

B = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.63 and greater than 2.59.

C = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.59 and greater than 2.55.

D = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.55 and greater than 2.51.

E = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.51 and greater than 2.47.

F = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.47.

The Gravity Moduli for the Feed and the various fractions of the Feed for the stone are shown in column 2b of Table 5.

To show the relationship between the Gravity Modulus and the bulk specific gravity (V.S.S.D. and Dry) and the percent absorption (vacuum saturated) for this stone, data from Tables 4 and 5 have been plotted in Figures 2 and 3. These graphs show that the bulk specific gravity varies directly and the percent absorption varies indirectly with the Gravity Modulus.

Using the values of the Gravity Modulus to study the physical character of the Feed it will be noted, in Table 5, column 2b, that:

1. The Gravity Modulus for the Feed is 88.5.
2. The Gravity Moduli for the Clean, Objectionable, and Deleterious fractions of the Feed are 95.3, 74.7, and 58.3 respectively.
3. The Gravity Moduli of the three sizes of the three (Clean, Objectionable, and Deleterious) visual classifications are highest for the +1" size and lowest for the 1/2" to 1/4" size.
4. For the entire Feed the Gravity Moduli is highest (89.4) for the 1" to 1/2" size and lowest (86.1) for the +1" size. However, the difference (3.3) is relatively small.[3]

The preceding data clearly show a difference between the Gravity Modulus of the Clean, Objectionable, and Deleterious fractions of the stone. This indicates that heavy media separation of this stone might be effective in reducing the amount of contaminative material. The effectiveness of a plant scale heavy media separation in removal of the contaminative materials is discussed in the following section.

Effectiveness of Heavy Media Separations in Removal of Contaminative Materials from Crushed Stone

The effectiveness of heavy media separations in removal of the contaminative materials from crushed stone may be shown by many methods; such as:

1. Comparison of the amounts of Objectionable and Deleterious materials in the Feed and the Sink portions of the plant separation.

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[3] Statement 4 appears to disagree with statement 3. However, the disagreement is due to the variation in the percentages of the three visual classifications in the three size groups.

Material and the "Gravity Modulus" for Various Sizes, and Visual Classifications of the Products of Heavy Media Separation

Columns																	
4a	4b	4c	4d	4e	4f	5a	5b	5c	5d	5e	5f	6a	6b	6c	6d	6e	6f
"Float" at 2.54 Sp. Gr. Media						"Sink" at 2.60 Sp. Gr. Media						"Float" at 2.60 Sp. Gr. Media					
Actual		Theor.(3)		Theor.(4)		Actual		Theor.(3)		Theor.(4)		Actual		Theor.(3)		Theor.(4)	
%(2)	Gr.Mod.	%(2)	Gr.Mod.	%(2)	Gr.Mod.	%(2)	Gr.Mod.	%(2)	Gr.Mod.	%(2)	Gr.Mod.	%(2)	Gr.Mod.	%(2)	Gr.Mod.	%(2)	Gr.Mod.
16.9	68.9	13.0	52.3	13.2	53.2	64.8	94.8	74.4	97.7	73.6	97.5	35.2	76.7	25.6	61.6	26.4	63.1
2.8	59.5	2.3	54.0	2.3	54.7	9.6	95.4	9.9	97.0	9.8	96.9	4.9	67.7	4.6	62.4	4.7	63.5
8.6	67.5	6.7	52.9	6.9	53.7	39.6	95.6	44.4	97.8	43.9	97.7	18.6	76.4	13.8	62.3	14.3	63.9
5.5	75.9	4.1	50.3	4.1	50.9	15.6	92.7	20.1	97.8	19.8	97.7	11.7	81.0	7.2	59.6	7.5	61.0
7.3	86.2	2.2	57.0	2.5	58.6	56.9	97.1	68.6	98.4	67.7	98.4	19.9	90.0	8.2	69.1	9.1	72.2
0.4	78.6	0.1	59.4	0.1	61.0	7.6	98.3	8.1	98.6	8.0	98.6	1.2	86.5	0.7	72.2	0.8	75.8
3.2	85.8	1.0	58.8	1.2	60.3	35.3	97.4	40.9	98.5	40.3	98.5	9.9	90.3	4.3	70.1	4.9	73.4
3.8	87.3	1.1	54.7	1.2	55.8	14.0	95.9	19.5	98.1	19.3	98.0	8.8	90.0	3.3	66.9	3.5	69.3
3.0	62.4	2.8	54.7	2.9	55.6	4.8	84.5	4.5	90.5	4.5	89.9	6.0	66.8	6.3	63.5	6.3	64.0
0.6	60.8	0.5	57.2	0.6	58.2	1.4	86.7	1.3	90.9	1.3	90.4	1.4	68.4	1.5	66.0	1.5	66.5
1.8	63.6	1.6	55.0	1.6	55.9	2.8	86.3	2.9	90.7	2.8	90.2	3.7	67.4	3.6	64.0	3.7	64.5
0.5	59.7	0.7	51.9	0.7	52.5	0.6	69.7	0.3	87.3	0.3	85.8	0.9	62.4	1.2	58.8	1.2	58.9
6.6	52.9	8.0	50.2	7.9	50.5	3.1	68.8	1.4	86.5	1.5	84.3	9.3	54.7	11.0	54.8	10.9	54.8
1.8	55.3	1.6	52.6	1.6	53.1	0.6	80.0	0.5	86.8	0.5	84.8	2.3	57.5	2.4	57.8	2.4	57.9
3.6	53.3	4.2	50.5	4.1	50.9	1.5	70.0	0.7	87.0	0.8	84.7	5.0	55.1	5.8	55.1	5.7	55.1
1.2	48.0	2.3	47.8	2.2	48.0	1.0	59.8	0.2	84.0	0.2	81.4	2.0	50.7	2.8	51.6	2.8	51.6

Fig. 2

RELATIONSHIP BETWEEN

"GRAVITY MODULUS" AND BULK SPECIFIC GRAVITY

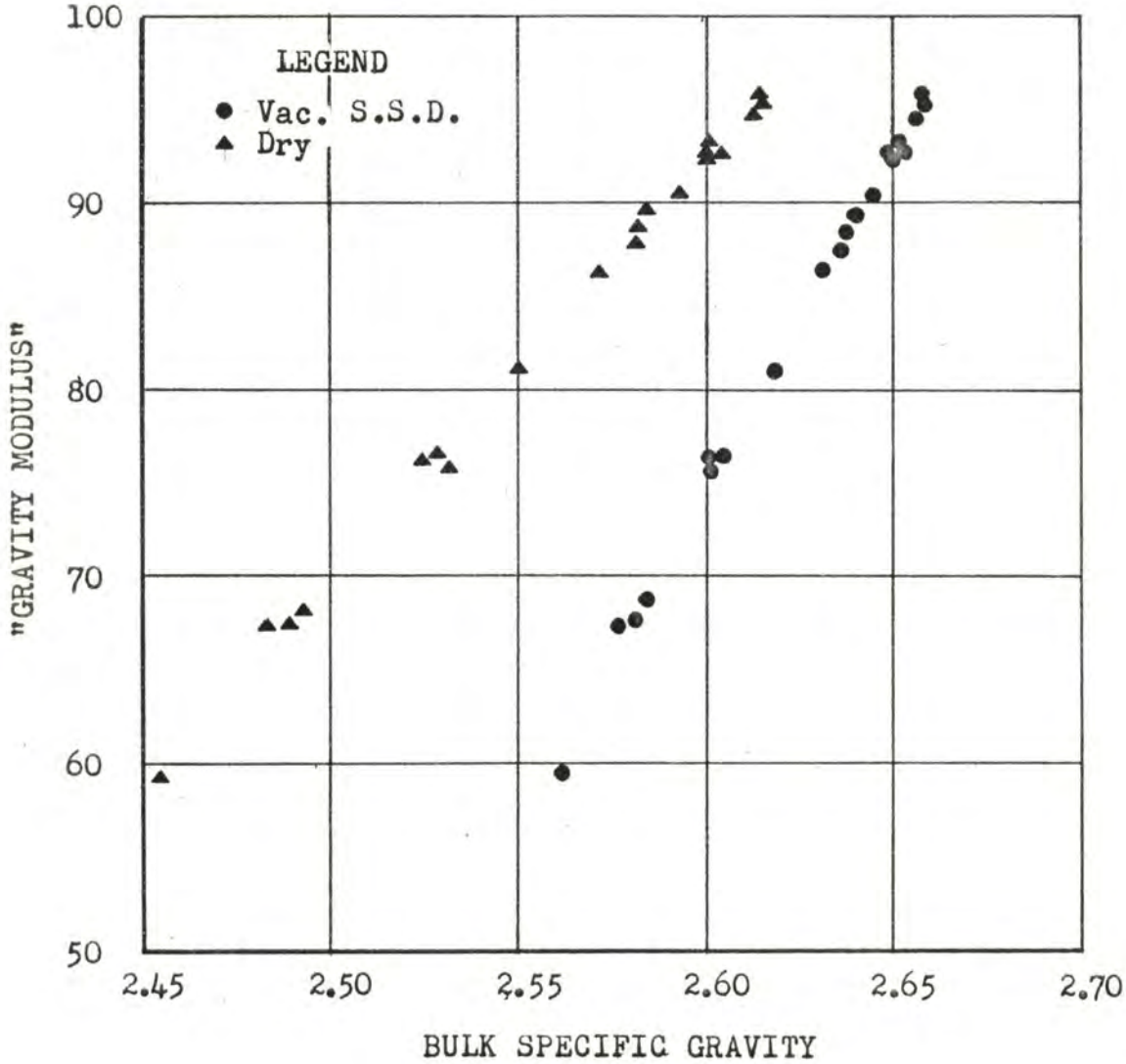
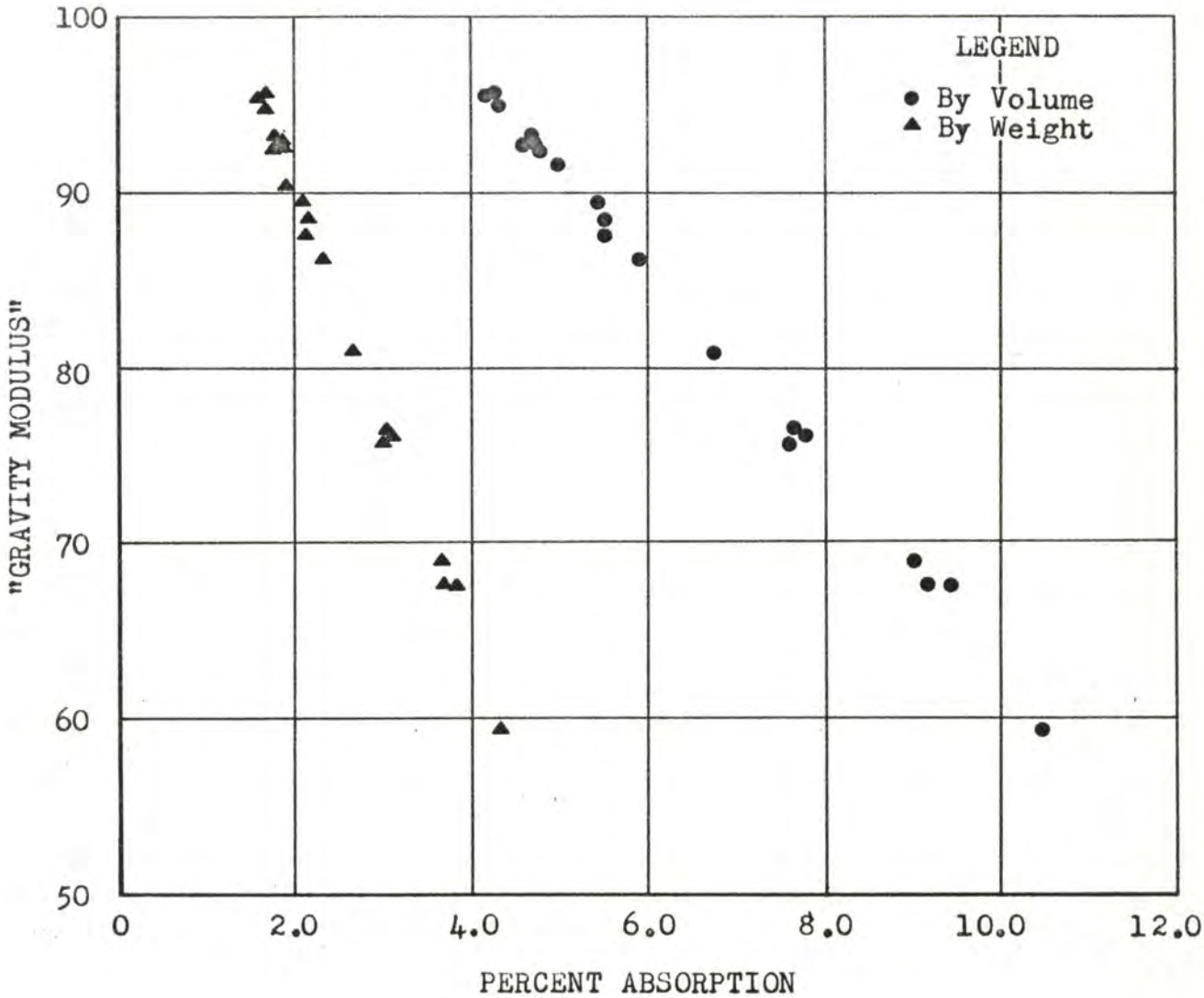


Fig. 3

RELATIONSHIP BETWEEN

"GRAVITY MODULUS" AND PERCENT ABSORPTION



2. Comparison of the amounts of material, having a Bulk Sp.Gr. (V.S.S.D.) less than certain specified values (as 2.47, 2.51, 2.55, 2.59, ...), in the Feed and the Sink portions of the plant separation.
3. Comparison of the bulk specific gravities (V.S.S.D. and Dry), the absorptions (vacuum saturated), and the Gravity Moduli of the Feed and the Sink portions of the plant separation.

By making these comparisons, for the total combined samples and each of the three size groups of the Feed and the Sink products, some idea of the actual effectiveness of these heavy media separations in removal of Objectionable, Deleterious and/or low gravity materials is obtained.

However, to make only these observations is to ignore the ideal comparison of actual vs theoretical reduction in contaminative material. This latter comparison may be the most practical method of evaluating the effectiveness of the separation.

The first three comparisons are those most easily made and are as follows:

Comparison 1

The following results from Table 4 show the relationship between the amount of Objectionable and Deleterious materials in the Feed and Sink portions of this stone.

Size of Stone	Feed % Obj.	Feed % Del.	Sink at 2.54* % Obj.	Sink at 2.54* % Del.	Sink at 2.60* % Obj.	Sink at 2.60* % Del.
All Sizes	10.77	12.45	9.37	6.98	7.41	4.86
+1"	19.33	20.05	18.52	9.46	14.90	6.57
1" to 1/2"	11.09	11.28	9.33	5.91	7.16	3.85
1/2" to 1/4"	5.50	10.94	4.54	8.08	3.35	6.39

*Approximate effective gravities of separation for the degree of saturation of the stone at time of separation.

These results can be used to calculate the reduction in Objectionable and Deleterious material. The percent reduction in these materials was:

Size of Stone	Sink at 2.54 Percent Reduction in Obj.	Sink at 2.54 Percent Reduction in Del.	Sink at 2.60 Percent Reduction in Obj.	Sink at 2.60 Percent Reduction in Del.
All Sizes	13.0	43.9	31.2	61.0
+1"	4.2	52.8	22.9	67.2
1" to 1/2"	15.9	47.6	35.4	65.9
1/2" to 1/4"	17.5	26.1	39.1	41.6

These results show:

1. The reductions in Objectionable and Deleterious materials tend to conform to expectations because:
   a. The reductions were greatest for the higher gravity media of separation.
   b. The reduction in Deleterious material was always greater than the reduction in Objectionable material.
2. The reduction in Objectionable material varied inversely with the size of the stone; whereas the reduction in Deleterious material varied directly with the size of the stone.
3. The reduction in Objectionable material was only 13 and 31 percent, respectively, at heavy media gravities of separation of 2.54 and 2.60.

4. The reduction in Deleterious material was 44 and 61 percent, respectively, at heavy media gravities of separation of 2.54 and 2.60.

Comparison 2

From the data in Table 4, the reduction in the percent of material (in the two sink products vs. the Feed), having a bulk specific gravity (V.S.S.D.) less than certain specified values may be calculated. These reductions were:

Bulk Sp.Gr. of Mat'l. Less Than*	Size of Material	Percent Reduction at Heavy Media Gravity of Separation of 2.54				2.60			
		All Classes	Clean	Obj.	Del.	All Classes	Clean	Obj.	Del.
2.63	All Sizes	24	8	20	46	43	24	45	64
2.63	+1"	31	1	14	57	52	25	41	73
2.63	1" to 1/2"	26	7	23	50	45	21	50	68
2.63	1/2" to 1/4"	17	11	18	27	32	25	40	42
2.59	All Sizes	43	24	40	53	68	48	76	73
2.59	+1"	61	40	43	72	84	71	76	90
2.59	1" to 1/2"	46	22	43	57	73	50	83	78
2.59	1/2" to 1/4"	27	22	26	30	45	38	54	47
2.55	All Sizes	59	42	58	62	80	66	86	81
2.55	+1"	86	79	80	87	96	74	92	97
2.55	1" to 1/2"	64	43	61	66	86	79	96	85
2.55	1/2" to 1/4"	39	36	39	39	59	54	62	59
2.51	All Sizes	69	63	62	70	85	69	76	88
2.51	+1"	99	-	100	99	100	-	100	100
2.51	1" to 1/2"	82	100	81	82	98	100	100	98
2.51	1/2" to 1/4"	52	54	46	53	67	59	53	71
2.47	All Sizes	79	100	-	77	94	100	-	94
2.47	+1"	100	-	-	100	100	-	-	100
2.47	1" to 1/2"	85	-	-	85	100	-	-	100
2.47	1/2" to 1/4"	77	91	-	76	88	91	100	88

*The data for each specified Bulk Specific Gravity (V.S.S.D.) shown here, represents all material below that gravity, not just that material between the specified gravities.

These results show:

1. The reduction in the percent of material having a Bulk Sp.Gr. (V.S.S.D.) less than certain specified values increased as the Bulk Sp.Gr. (V.S.S.D.) of the total sample decreased.
2. The percent reduction also varied with:
   a. Size of material (the maximum and minimum reductions were obtained respectively with the +1" and the 1/2" to 1/4" sizes),
   b. Visual classification (in general, the maximum and minimum reductions were obtained respectively with the Deleterious and Clean fractions),
   c. Gravity of separation media (maximum reduction being obtained at the highest gravity media of separation).
3. Complete reduction of the material of lowest Bulk Sp. Gr. (V.S.S.D.) was never attained.
4. At the heavy media gravity separation of 2.54, only 59 percent of material having a Bulk Sp. Gr. (V.S.S.D.) less than 2.55 was removed.
5. At the heavy media gravity separation of 2.60, only 68 percent of material having a Bulk Sp. Gr. (V.S.S.D.) less than 2.59 was removed.

In the preceding tabulation, it is impossible to determine, except for the -2.47 gravity group, the percent reduction in the material in the various gravity groups (+2.63, 2.59 to 2.63, 2.55 to 2.59, 2.51 to 2.55, 2.47 to 2.51 and -2.47). Therefore, the following tabulation has been prepared to show the percent change in the amount of material in the various laboratory gravity groups of the two Sink products vs. the Feed.

Bulk Sp. Gr. (V.S.S.D.) of Material	Size of Material	Percent Change at Gravity of Separation of 2.54				Percent Change at Gravity of Separation of 2.60			
		All Classes	Clean	Obj.	Del.	All Classes	Clean	Obj.	Del.
+2.63	All Sizes	+13	+13	+12	+13	+22	+23	+20	+16
+2.63	+1"	+22	+22	+23	+24	+37	+38	+29	+38
+2.63	1" to 1/2"	+12	+12	+ 8	+ 5	+21	+22	+12	- 2
+2.63	1/2" to 1/4"	+ 9	+11	-14	+28	+16	+18	-30	+21
2.59 - 2.63	All Sizes	+ 2	0	+ 7	+ 3	- 8	-12	- 4	0
2.59 - 2.63	+1"	+13	+11	+18	+ 9	- 5	-11	- 4	0
2.59 - 2.63	1" to 1/2"	+ 1	+ 1	+ 2	- 2	- 7	- 8	- 8	- 4
2.59 - 2.63	1/2" to 1/4"	- 1	- 3	+ 7	+ 9	-13	-16	+ 2	+ 5
2.55 - 2.59	All Sizes	-28	-19	-30	-35	-57	-42	-70	-59
2.55 - 2.59	+1"	-41	-32	-31	-51	-75	-70	-71	-79
2.55 - 2.59	1" to 1/2"	-30	-19	-33	-39	-61	-45	-76	-65
2.55 - 2.59	1/2" to 1/4"	-11	-15	-14	- 1	-27	-29	-66	- 9
2.51 - 2.55	All Sizes	-56	-38	-57	-60	-78	-66	-89	-78
2.51 - 2.55	+1"	-85	-79	-79	-86	-95	-74	-92	-97
2.51 - 2.55	1" to 1/2"	-58	-40	-58	-61	-83	-77	-96	-80
2.51 - 2.55	1/2" to 1/4"	-31	-31	-36	-30	-54	-53	-66	-51
2.47 - 2.51	All Sizes	-67	-57	-62	-69	-83	-64	-76	-86
2.47 - 2.51	+1"	-99	-	-100	-99	-100	-	-100	-100
2.47 - 2.51	1" to 1/2"	-82	-100	-81	-81	-98	-100	-100	-98
2.47 - 2.51	1/2" to 1/4"	-46	-44	-46	-46	-62	-51	-52	-67
-2.47	All Sizes	-79	-100	-	-77	-94	-100	-	-94
-2.47	+1"	-100	-	-	-100	-100	-	-	-100
-2.47	1" to 1/2"	-85	-	-	-85	-100	-	-	-100
-2.47	1/2" to 1/4"	-77	-91	-	-76	-88	-91	-100	-88

The principal difference between these and the preceding results is that, in the higher gravity groups, an increase rather than a reduction in the amount of material (of the two sinks vs. the Feed) is shown. Also, the correlation between visual classification and percent reductions in the lower gravity fractions is less pronounced.

Comparison 3

The following results, from Tables 2 and 5, show a comparison of the bulk specific gravities (Dry), the absorptions (vacuum saturated), and the Gravity Moduli of the Feed and Sink portions of this stone.

	Feed			Sink at 2.54			Sink at 2.60		
Size of Stone	Bulk Sp.Gr. (Dry)	% Abs. by Wt.	Gr. Mod.	Bulk Sp.Gr. (Dry)	% Abs. by Wt.	Gr. Mod.	Bulk Sp.Gr. (Dry)	% Abs. by Wt.	Gr. Mod.
All Sizes	2.582	2.14	88.5	2.601	1.83	92.4	2.612	1.65	94.8
+1"	2.571	2.29	86.1	2.601	1.81	92.5	2.615	1.58	95.4
1" to 1/2"	2.585	2.09	89.4	2.604	1.79	93.2	2.615	1.62	95.6
1/2" to 1/4"	2.581	2.14	87.6	2.594	1.92	90.6	2.604	1.76	92.7

The above results indicate an improvement in the quality of the stone by heavy media separation, because the bulk specific gravity (Dry) and Gravity Moduli are higher, for the sink products, and the absorptions have been reduced.

From the three comparisons made thus far, it is indicated that this stone is improved by beneficiation, but as previously stated these comparisons ignore another more practical means of determining the effectiveness of the heavy media separation, namely: comparison of the actual and theoretical reductions

in contaminative material. The data for this comparison are tabulated in Table 5. The amount of material in each of the four (two sink and two float) products of separation, the three size groups, and the three visual classifications is expressed as percent of the Feed (combined products of separation). Also the Gravity Moduli for the Feed and each of the many size groups of the Feed material are shown. For each of these four products of separation, three sets of values for Percent of Feed and Gravity Modulus are shown. These three sets of values are:

1. For the actual products of separation.
2. Approximate[4] values assuming an absolutely clean separation of a completely saturated material, at heavy media gravities of 2.563 and 2.606. (As this stone was only partially saturated when subjected to plant heavy media separations at 2.54 and 2.60 specific gravity media, the specific gravities of the heavy media must be increased to approximately 2.563 and 2.606, respectively, to obtain separation products similar to those obtained (as shown in this report) if completely saturated stone were used. The values of 2.563 and 2.606 were obtained by using the laboratory gravity gradations of the separated products, and calculating the gravity at which there was a 50-50 probability of the material sinking or floating).

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[4] Approximate for several reasons, two of which are:

a. A constant gravity media of separation was used in making the calculations, although it is indicated that the gravities of the separation products varied with the size and visual classification of the stone.
b. It was assumed that, within a specific gravity range such as 2.55 to 2.59, there was a uniform relationship between quantity and gravity.

3. Approximate[5] values assuming:

   a. A clean separation at gravities of the saturated material of 2.563 ± 0.03 and 2.606 ± 0.03.

   b. That the probability of a particle of stone floating was 0.0 at specific gravity 0.03 above the gravity of the separation media (2.563 and 2.606) and increased uniformly to 1.0 as the specific gravity of the particle decreased to 0.03 below the gravity of the separation media.

From the results in Table 5 many facts are evident, and are discussed in the following:

1. In columns 2a and 2b the Gravity Modulus of the Feed (100%) is 88.5; whereas the Gravity Moduli of the Clean (76.8%), Objectionable (10.8%), and Deleterious (12.4%) fractions are 95.3, 74.7, and 58.3 respectively. This indicates that the value of the Gravity Modulus of this stone would vary indirectly with the amount of contaminative materials (visual rating), and that heavy media separation should be beneficial in removal of the so-called Objectionable and Deleterious materials.

2. In columns 3a, b, c, d, e, f, and 4a, b, c, d, e, f, the results of the heavy media separation at a gravity of 2.54 are shown. These results indicate:

   a. Theoretically, the Gravity Modulus of the Sink or the beneficiated portion of the Feed should have been near 93.9 instead of the actual value of 92.4.

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[5] See footnote No. 4 on Page 26.

b. Theoretically, the amount of Float material should have been near 13.0 percent of the Feed instead of the actual 16.9 percent.

c. Theoretically, the 3.9 percent of excessive Float material was divided between the Clean, Objectionable, and Deleterious fractions, respectively, as follows: +5.1, +0.2, and -1.4 percent. This indicates that an excessive amount of Clean stone, and an insufficient amount of Deleterious material floated.

d. The effect of statement "c" upon improvement in the Gravity Modulus of the Clean, Objectionable, and Deleterious fractions of the Sink portion is clearly evident by comparing the actual (column 3b) with the theoretical (columns 3d and 3f) values. The values for the Clean (96.2 vs. 96.4 and 96.5) are very good as compared with the values for the Objectionable (79.5 vs. 81.7) and the Deleterious (64.5 vs. 73.3 and 72.1) fractions.

e. Even theoretically it would be impossible, at this gravity of separation, to obtain a Sink product having a Gravity Modulus greater than 93.9 or 1.4 points less than the Gravity Modulus of 95.3 for the Clean fraction of the Feed.

f. The Gravity Moduli indicate that there was a tendency for the Float portion of the Clean fraction to contain an excessive amount of high gravity material, and the Sink portion of the Deleterious fraction to contain an excessive amount of low gravity material. Although this tendency was true for all three sizes of material, it became progressively greater as the size of the stone decreased.

3. In columns 5a, b, c, d, e, f, and 6a, b, c, d, e, f, the results of the heavy media separation at a gravity of 2.60 are shown. These results indicate:

   a. Theoretically, the Gravity Modulus of the Sink or the beneficiated portion of the Feed should have been near 97.7 instead of the actual value of 94.8.

   b. Theoretically, the amount of Float material should have been near 25.6 percent of the Feed instead of the actual 35.2 percent.

   c. Theoretically, the 9.6 percent of excessive Float material was divided between the Clean, Objectionable, and Deleterious fractions, respectively, as follows: +11.7, -0.3, and -1.7 percent. This indicates that an excessive amount of Clean stone, and an insufficient amount of Objectionable and Deleterious material floated.

   d. The effect of statement "c" upon improvement of the Gravity Modulus for the Clean, Objectionable, and Deleterious fractions of the Sink portion is clearly evident by comparing the actual (column 5b) with the theoretical (columns 5d and 5f) values. The values (97.1 vs. 98.4) for the Clean fraction are very good as compared with the values for the Objectionable (84.5 vs. 90.5 and 89.9) and the Deleterious (68.8 vs. 86.5 and 84.3) fractions.

   e. Theoretically, it is possible, at this gravity of separation, to obtain a Sink product having a Gravity Modulus of 97.7 or 2.4 points above the Gravity Modulus of 95.3 for the Clean fraction of the Feed.

f. The Gravity Moduli indicate that there was a tendency for the Float portion of the Clean fraction to contain an excessive amount of high gravity material, and for the Sink portion of the Deleterious fraction to contain an excessive amount of low gravity material. Although this tendency was true for all three size groups of material, it became progressively greater as the size of the stone decreased.

These results are both confusing and discouraging. They are confusing because of the inconsistent and unexplainable variations in the separations obtained with the three visual classifications of this stone. They are discouraging because it appears that removal of a high percentage of the so-called contaminative materials can only be accomplished by removal of a high percentage of the Feed. Furthermore, it appears that this waste product, or Float, would contain from 24 to 37 percent (See Table 3, +2.63 gravity fraction for the three size groups combined for the two float classifications) of the best stone available in this formation. Obviously, from the indicated effect of particle size, in Table 5, the loss of high gravity material in the float should be reduced by making the heavy media separation on the stone between the primary and secondary crusher, or at a time when the minimum amount of minus 1/2 inch material would be processed.

Summary

The result of this work (refer to the following tabulation) indicates heavy media separation would be effective in

reducing the content of Deleterious and Objectionable material, of this stone, only to be accompanied with a high loss in Clean material. As much as 20 percent of Clean material was sacrificed to reduce the Deleterious material by 9 percent. If the cost of this operation is determined by adding the cost of separation to the cost of the discarded Clean material, the economics of this method of beneficiation would probably exceed the benefit gained.

COMPARISON OF SINK AND FLOAT PRODUCTS
OF BOTH GRAVITY SEPARATIONS

Classification	Total Product (Percent)	Visual Classification of Stone (Percent)*		
		Clean	Obj.	Del.
Feed	100	76.78	10.77	12.45
Separation at 2.54 gravity media				
Float	16.88	7.25	2.98	6.65
Sink	83.12	69.53	7.79	5.80
Separation at 2.60 gravity media				
Float	35.13	19.87	5.96	9.30
Sink	64.87	56.91	4.81	3.15

*Percents are expressed as part of the total product.

From the comparisons and the discussions presented throughout this report, it is apparent that an adequate evaluation of the relative quality of these various products cannot be determined entirely in this manner. These comparisons do, however, show that heavy media separation of this Feed material did not result in beneficiated (Sink) products of unquestionable

superiority in quality to that of presently accepted material. Even though the quantity of low gravity material could be reduced, it was never eliminated.

In addition, it must be remembered that the Deleterious fraction of this stone is primarily shale, which usually occurs intermingled with or attached to the good or high gravity stone. Thus, if the combined gravity of some of this material is sufficiently high it will not be removed by heavy media separation. This of course means that, regardless of the efficiency of the separation, some percentage of contaminative material will be found in the beneficiated product, thereby giving a product of questionable superiority to that presently obtained. Also, to obtain this product, as much as 35.13 percent of the Feed went into the Float with as much as 56.57 percent of this Float classified as Clean stone, and 36.85 percent of this Clean stone was of the highest specific gravity (+2.63, V.S.S.D.) produced. This again indicates that the cost of heavy media beneficiation of this stone could be excessive when the increased production cost, resulting from wastage of good stone, is added to the treatment costs.

Proof of the increase in quality of the treated aggregate could only be determined by exhaustive testing of these products of separation in concretes subjected to detailed durability studies. Furthermore, there is considerable doubt that a sufficient amount of information would be obtained if the durability tests were confined entirely to concretes containing these products of separation. If the tests were enlarged in a

well designed experiment, they could become quite costly and time consuming. In view of the indicated high cost and questionable benefit obtained in subjecting this stone to heavy media separation, there is considerable doubt regarding the justification of a costly and time consuming durability study of these products.

APPENDIX A

DESCRIPTION OF THE LABORATORY HEAVY LIQUID SEPARATION PROCEDURE

For the laboratory gravity classification, two liquids were combined by different ratios (by volume), to yield the desired gravity of separation media. The liquids used were:

1. Acetylene Tetrabromide (Specific Gravity = 2.93)

2. Carbon Tetrachloride (Specific Gravity = 1.58), and combined by the following relationship:

$$A = \left[Bx + (100 - x)C\right] \div 100$$

Where: A = Desired specific gravity of separation media

B = Specific gravity of acetylene tetrabromide

C = Specific gravity of carbon tetrachloride

x = Percent by volume

Thus the percent by volume of each of the liquids may be calculated.

Example: Desired specific gravity of separation media is 2.40. Assuming Liquid B has a specific gravity of 2.93 and Liquid C has a specific gravity of 1.58,

Then:

$$2.40 = \frac{(2.93\ x) + (100 - x)\ 1.58}{100}$$

$$240 = 2.93\ x + 158 - 1.58x$$

or $$x = \frac{82}{1.35} = 60.74\%$$

$$100 - x = 39.26\%$$

Check: $$\frac{2.93(60.74) + (100 - 60.74)\ 1.58}{100} = 2.40$$

$$\frac{177.97 + 62.03}{100} = 2.40$$

$$2.40 = 2.40$$

This means the two liquids should be combined volumetrically by 60.74 percent Acetylene Tetrabromide and 39.26 percent Carbon Tetrachloride.

Operating Procedure:

During the laboratory heavy liquid separation, approximately two gallons of each of the desired gravity liquids (2.47, 2.51, 2.55, 2.59, and 2.63) were made up and placed in 16 quart stainless steel pails. The vacuum saturated sample to be separated was surface dried and placed in a 13 quart stainless steel pail, the bottom of which had been perforated with 1/8 inch holes. The pail containing the sample was lowered into the pail containing the 2.47 gravity liquid, thoroughly stirred and all floating particles removed with a small screen. The pail containing the sink fraction of the sample was then removed from the 2.47 gravity liquid, shaken to remove the excess of 2.47 gravity liquid on the stone particles and placed in the pail containing the next higher gravity liquid. This operational procedure was repeated until the sample had been separated in all five liquids.

Due to the more rapid evaporation of the Carbon Tetrachloride, the gravities of the liquids tended to increase during the test. Therefore, by starting the separation in the lowest gravity liquid, the carry over of lighter gravity liquid from pail to pail tends to offset the evaporation of the Carbon Tetrachloride and maintain the desired accuracy in gravity of the liquids. Between samples, the gravity of each liquid was checked with hydrometers or a Westphal Balance and the necessary adjustments made.

As each portion of stone was removed from the heavy liquid it was washed in Carbon Tetrachloride, a commercial alcohol (Solox) and tap water, respectively, and stored under tap water in suitable closed containers for further testing.

APPENDIX B

DESCRIPTION OF THE CONSTITUENT MATERIALS COMPOSING THE TWO CLASSIFICATIONS, "DELETERIOUS" AND "OBJECTIONABLE"

The contaminative materials in this limestone which have been designated as "Deleterious" or "Objectionable" are made up of several sub-classes as follows:

"Deleterious" Material

Shale
Soft Stone
Pure Shaly Stone
Cap Shale (+20%)

"Objectionable" Material

Cap Shale (-20%)
Shaly Seams
Skin Shale
Mud-Coated Stone

The following description of the various types of "Deleterious" and "Objectionable" materials was furnished by the Testing Laboratory:

1. Shale

   Lumps or particles of shale, substantially free of stone or stone fragments. Breaks down readily on wetting or immersing in water. Generally of a laminated structure. Essentially pure shale. Black in color, when wet.

2. Shaly Stone

   (Sometimes referred to as "Pure Shaly Stone" or "Heavily Contaminated Shaly Stone").

A. Occurs as stone that is generally intermingled with or "shot through" with shale to a high degree. Has gray, reasonably uniform appearance, somewhat similar to some soft, absorptive stones. When particle is wet, slight rubbing removes sufficient shale from surface to cause surface water on particle to become muddy, or dirty.

B. Also occurs in the form of shale lines, or seams, in large number and closely spaced throughout stone particle. Has a laminated or streaked appearance. (Distinguishable from "Shaly Seams", listed as No. 5, below, because of contamination to a higher degree as evidenced by greater number of shale lines or seams.)

C. Also occurs as stone with shale coating on two faces, somewhat similar to "Skin Shale", listed as No. 4 below, except that shale coatings are much thicker than in case of skin shale.

D. Also may occur as combination of "B" and "C", described above.

3. Cap Shale

Occurs as a layer with a line of demarcation of the layer, or "Cap" of shale or shaly stone which generally occurs on one face of stone particle. Usually little or no other contamination on stone particle, except shale cap. Where cap exceeds 20 percent of depth, or volume, of stone particle, it is classified "Cap Shale (+20%)", and is considered deleterious

material. In those cases where caps amount to 20 percent and under, the particle is classified as "Cap Shale (-20%)" and is considered objectionable material.

4. Skin Shale

Occurs as comparatively thin, continuous coating of shale, usually on two opposite faces of stone particle. Total coverage of shale coating equivalent to 50 percent or more of surface area of particle.

5. Shaly Seams

Occurs as comparatively thin lines or seams of shale extending through particle. Number of lines depends somewhat on particle size. Lines are generally parallel, or approximately so.

6. Soft Stone

Usually classified and reported as "Soft and Porous Stone". Some types can be readily broken in two with fingers. In some cases, because of larger particle size, or more rounded spherical shape, the stone cannot be broken with fingers, however small areas can be spalled, or chipped off with fingers. Particles can be cut or broken in half, by mechanical means, after which edges of cut face can be spalled with fingers. Porosity, or high absorption, detected by rapid disappearance of surface water on particle, and by breaking or cutting particle in half and observing depth of moisture penetration. Also includes some stone which may not be soft but is highly porous and absorptive. Soft stone in this formation usually tends toward brown or buff color.

7. Mud-Coated Stone

Stone particles which, on becoming wet, show a partial or complete coating of mud (soil, or clay, as differentiated from shale). Stone particle itself may be sound and uncontaminated except for mud coating or covering.

APPENDIX C

GRAVITY MODULUS

The formula for Gravity Modulus, as presented on page 15, is:

$$G.M. = A + 0.8B + 0.64C + 0.51D + 0.41E + 0.33F$$

Where: A = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is greater than 2.63.

B = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.63 and greater than 2.59.

C = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.59 and greater than 2.55.

D = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.55 and greater than 2.51.

E = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.51 and greater than 2.47.

F = Percent by weight of material for which the Bulk Sp. Gr. (V.S.S.D.) is less than 2.47.

Actually this equation can be written:

$$G.M. = A + (0.8)^1B + (0.8)^2C + (0.8)^3D + (0.8)^4E + (0.8)^5F$$

The objective of the Gravity Modulus is to obtain a single parameter for each gravity gradation to simplify comparison or evaluation of various gravity gradations. The most suitable equation for a Gravity Modulus would depend upon the size and number of the gravity groups being analyzed. In this

report the gravity gradation was separated into six gravity groups and in the middle four groups the range in bulk specific gravity (Vac. Sat. Surf. Dry) was only 0.04.

In setting up the Gravity Modulus it was thought desirable to have the Gravity Modulus equal 100 for material in the highest gravity group. In addition it was deemed desirable to obtain a successively reduced Gravity Modulus for material in the lower gravity groups. The use of powers of 0.8 appeared to provide a suitable spread in the Gravity Modulus. This procedure may at first glance appear wrong as the reduction in Gravity Modulus does not remain constant between successively lower gravity groups, but becomes decreasingly smaller. Although this may appear to be, it is not necessarily inconsistent. For example let us look at the following percents of absorption (by vol.) for the various gravity groups:

Ident.	Gravity Group	Percent Abs., by Vol.	Percent Increase in Abs. from Preceeding Group
A	+2.63	3.44	-
B	2.59 to 2.63	6.84	99
C	2.55 to 2.59	9.33	36
D	2.51 to 2.55	11.71	26
E	2.47 to 2.51	14.03	20
F	-2.47	17.84	27

In the preceeding table the percent increase in the percent absorption (by vol.), from that of the preceeding group, becomes successively smaller with decreasing gravity groups. The only exception to this being group F which includes all material having a bulk specific gravity (V.S.S.D.) less than 2.47.

Consequently use of powers of 0.8 (or of some other number) is not inconsistent with the properties of the material in the gravity groups. It might also be expected that use of powers of 0.8 would result in obtaining a relative consistent relationship with the effect of the material in the various gravity groups upon the frost resistance of concrete, providing the only variation in the material was the porosity. When, as was the case for the material used in this experiment, the variation in gravity was partially due to a contaminative material, no consistent relationship between Gravity Modulus and resistance to frost action should be expected.

Consequently the Gravity Modulus should only be considered a means of condensing the data, and of providing another method of evaluating the effectiveness of the Heavy Media Separation of this material.