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Publication of this paper sponsored by Committee on Frost Action.

Factors Affecting Coating of Aggregates with Portland Cement

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The Kuwaiti experience in applying the technique of cement coating the smoothly textured aggregates in the production of high-quality asphaltic mixtures has been that the success of the resulting cement treatment was not always certain. It was influenced rather by a number of material and processing variables. The effect of four such variables is investigated by preparing a number of cement-coated sand samples at different levels of treatment and under controlled laboratory conditions. Cement coats produced in these samples were then evaluated by analyzing and comparing the results from a close visual examination, a particle-size analysis, a specific-surface analysis, and a chemical analysis for cement content of the various fractions. The study indicated two extreme and identifiable states of coating within which successful treatments were attainable. At the lower levels of water and cement contents, the added cement failed to adhere permanently to the surface of particles, resulting in a poorly coated sand of a higher fines content. At the higher levels of water and cement, the finer fractions of the sand started forming weakly cemented lumps, thus effecting a coarser gradation that lacked the finer sizes. By applying certain limits on the amount of added cement to avoid arriving at these objectionable extremes, a practical relationship was developed expressing the amount of cement required for proper coating in terms of the specific surface of the sand intended for treatment.

Surface texture of aggregates is an important property influencing the behavior of asphalt pavements. It can be said in general that asphaltic mixtures made with rough-textured aggregates have better resistance to stripping (1), higher Marshall and Hveem stability values at optimum asphalt (2), and longer fatigue lives in stress-controlled tests (3,4).

In Kuwait, the technique of coating aggregates with portland cement to enhance surface texture is widely used at the present time in the production of high-quality asphaltic mixtures (5). Under the severe weather conditions of the region, these mixtures are believed to be superior in resisting such common types of failure as surface corrugations (developed particularly at traffic intersections), fatting up or bleeding, and premature distortion in the wheel tracks of heavy and channelized traffic. Experience in applying the cement-coating technique has indicated that the quality and effectiveness of the resulting treatment are not always satisfactory and depend on a number of material and processing variables. Among such variables are the type of aggregate, the amount of added cement, the quantity of water, the time of mixing, and the type of mixer used in the process.

Experience has also showed that the effect of the

above variables in coating fine aggregates is much greater than in coating coarse aggregates, where good results were readily obtainable. The large mass of individual particles in this case and consequently the higher-impact forces they produce in the mixer during the process of coating leave only a secondary role for the smaller forces due to surface tension, water viscosity, cohesion, etc., to play in distributing the added cement. With sand-size aggregates this latter role becomes more important and perhaps dominant. A knowledge of the levels at which the variables in the coating process would produce optimum results becomes highly necessary, since an arbitrary selection of these levels may produce inferior results.

A particular difficulty often encountered in the cement coating of sand is a significant and uncontrollable change in its gradation after treatment. Either an abundance of fines or severe deficiency may result, depending on the values selected for various parameters. In addition to reducing the effectiveness of the added cement, such extreme conditions often necessitate subsequent corrective measures to satisfy job-mix requirements for gradation.

The purpose of this paper is to investigate the effect of four factors on the quality of the cement coat obtained in the treatment of sand: the gradation of the sand, its initial surface characteristics, the amount of added cement, and the quantity of added water.

Guirguis, Daoud, and Hamdani (6) have dealt with the effect of coating the aggregates with cement on laboratory performance of asphaltic mixes.

METHODOLOGY

The approach adopted here was to prepare samples of cement-coated sand by several treatments and under controlled laboratory conditions. Each treatment represented a particular combination of the four variables adopted in the study. The cured samples were then analyzed by four methods, including granulometric and gravimetric measurements. Results from these analyses were compared and discussed, and the quality of the different cement treatments was appraised accordingly.

Figure 1. Program for coating sand with portland cement.

SAND TYPE		WATER / CEMENT		CEMENT CONTENT (%)		GRADATION ¹									
						6	7	8	9	10	11	12	13	14	15
NATURAL	G1	0.35	X	X	X	X	X	X	X	X	X	X	X	X	X
	G2	0.35	X	X	X	X	X	X	X	X	X	X	X	X	X
CRUSHED	G3	0.35	X	X	X	X	X	X	X	X	X	X	X	X	X
	G4	0.35	X	X	X	X	X	X	X	X	X	X	X	X	X

¹ see Figure 2.

EXPERIMENTAL PROGRAM

Figure 1 shows the levels of the variables and their combinations considered in preparing the samples. The selected levels of cement content and the water-cement ratio (W/C) were based on previous experience with the technique (5) and on results of a few pilot trials. Minimum water requirements for aggregate absorption and cement hydration were also taken into consideration (7). The optimum conditions of coating were believed to lie within these selected levels.

The aggregates procured for the investigation were natural sand and crushed sand, which had particles of distinctly different shapes. Particles of the natural sand were rounded and very smooth, whereas those of the crushed sand were angular and slightly rougher in texture. Some of their properties are given below, and more information on the characteristics of the aggregates in the Arabian peninsula can be found elsewhere (8):

Property	Natural Sand	Crushed Sand
Sand equivalent (AASHTO T176)	58	41
Sodium sulfate soundness (AASHTO T104) (%)	9	6
Mineral composition (%)		
Quartz	90	87
Albite	2	5
Microcline	8	5
Calcite	—	3

As seen in Figure 2, one gradation (G1) was selected for the natural sand and three (G2, G3, and G4) for the crushed sand. These gradations represent the range within which sand is locally supplied for the production of cement-modified asphaltic concrete. The cement used for coating is an ordinary portland-pozzolan cement conforming to ASTM C595.

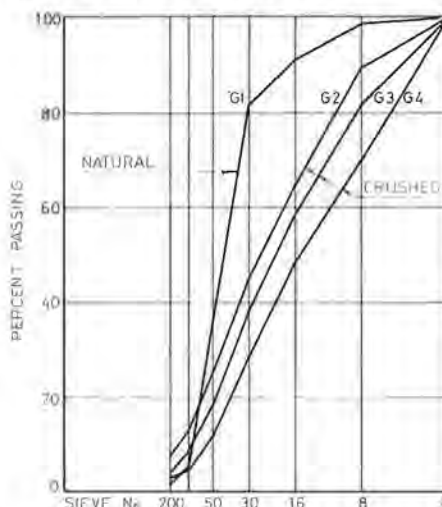
The techniques applied to evaluate the conditions of coating obtained in each sample will be described later.

SAMPLE PREPARATION

The steps followed in preparing the coated samples are summarized below:

1. The natural and the crushed sands brought to the laboratory were first separated into seven frac-

Figure 2. Gradation of sand used in study.



tions each (ASTM Sieve Nos. 4, 8, 16, 30, 50, 100, 200) by dry sieving (ASTM C136).

2. By recombining the fractions on a weight basis, samples of natural sand and of crushed sand (2 kg each) were prepared according to the gradations shown in Figure 2. A sufficient number of samples was prepared to satisfy the requirements of the experimental program adopted in Figure 1.

3. Samples were oven-dried for 24 h at 70°C. Higher drying temperatures were avoided due to the presence of unstable constituents in the natural sand.

4. Cement coating was performed for each sample independently by using a kitchen-type mixer with a 5-L bowl. The cement was added to the aggregate first, and after 30 s of dry mixing, the predetermined amount of potable water was slowly added. Wet mixing was continued for 90 s. This sequence was selected to comply with that followed on site (5).

5. The treated samples were then transferred to trays and covered with plastic sheets for a curing period of 48 h, which is the minimum period specified in the local road construction documents (5).

6. After curing, each sample was air-dried at room temperature and then separated into seven fractions by using the same set of sieves as in step 1. The fractions thus obtained were kept, after weighing, in separate containers for subsequent analyses.

TECHNIQUES OF ANALYSIS

The cement coatings obtained at different treatments were compared and judged for relative quality by applying the following methods.

Visual Examination

Separated fractions of each sample after coating were visually examined and compared with corresponding fractions of other samples and of uncoated sand. This simple method, though subjective and qualitative, allowed useful differentiation among various sand fractions regarding cement distribution. Extreme states of coating were readily discernible to the trained eye. Thicker coats obviously acquired the distinctive gray color of the cement itself and appeared darker. Thinner coats, on the other hand, appeared lighter in shade, allowing the color of aggregate minerals to be partly visible. The visual examination was aided by a magnifying lens and was performed by the same oper-

Table 1. Characteristics of sand fractions used in specific-surface determination.

Characteristic	Sieve No.							
	4	8	16	30	50	100	200	Pan
Natural sand								
Bulk specific gravity	-	2.63	2.64	2.65	2.66	2.68	2.71	2.76
Maximum voids (%)	-	43.1	45.8	42.8	44.7	47.8	55.6	66.3
Minimum voids (%)	-	36.4	37.7	34.5	35.4	39.2	46.0	55.9
Shape factor	-	1.19	1.22	1.24	1.26	1.22	1.21	1.19
Crushed sand								
Bulk specific gravity	2.48	2.71	2.67	2.60	2.67	2.71	2.75	2.79
Maximum voids (%)	42.0	49.6	49.8	50.3	51.4	56.3	59.9	66.8
Minimum voids (%)	36.9	45.3	46.4	41.6	43.0	47.3	52.4	53.2
Shape factor	1.14	1.09	1.07	1.21	1.21	1.19	1.14	1.25

Table 2. Effect of cement content on gradations of natural sand.

Sieve No.	Gradation (% passing)					
	Added Cement (%)					
	0	6	8	10	12	14
Natural Sand, W/C = 0.35						
4	100	100	100	100	100	100
8	98.2	98.3	98.5	98.6	98.9	98.3
16	93.2	93.6	94.0	94.0	94.2	93.9
30	82.5	84.5	85.2	85.0	85.7	84.6
50	36.6	45.5	45.8	44.2	42.6	34.9
100	5.4	8.7	8.7	7.5	5.9	4.7
200	1.6	4.1	4.0	3.0	2.0	1.7
Natural Sand, W/C = 0.45						
4	100	100	100	100	100	100
8	98.2	98.5	98.5	98.6	98.6	98.4
16	93.2	93.7	93.7	93.8	94.0	93.2
30	82.9	84.2	84.2	84.8	83.2	74.6
50	36.6	44.7	43.5	39.8	33.3	20.9
100	5.4	6.8	5.0	4.0	2.7	2.3
200	1.6	2.7	1.5	1.2	0.9	0.8

Table 3. Effect of cement content on gradations of crushed sand.

Sieve No.	Gradation (% passing)					
	Added Cement (%)					
	0	7	9	11	13	15
Crushed Sand, W/C = 0.35						
4	100	100	100	100	100	100
8	89.1	89.6	90.1	90.1	90.6	90.6
16	64.0	66.1	67.0	67.0	67.3	67.1
30	45.0	48.2	48.8	48.9	48.6	47.2
50	25.6	29.6	29.9	29.1	27.6	24.9
100	13.3	17.6	17.4	15.3	12.6	9.6
200	6.4	10.4	8.7	6.3	4.1	3.2
Crushed Sand, W/C = 0.45						
4	100	100	100	100	100	100
8	89.1	89.7	89.0	89.9	90.3	90.2
16	64.0	66.4	66.3	66.1	65.8	64.6
30	45.0	48.2	47.9	46.8	45.5	41.9
50	25.6	28.5	27.6	25.1	21.8	16.2
100	13.3	15.3	17.1	9.0	6.2	4.7
200	6.4	7.7	4.4	3.0	2.3	1.8

ator to enhance consistency in judgments.

Particle-Size Distribution

The particle-size distributions of the coated samples were compared with each other and with the distribution before coating. The pattern of divergence in these gradations signified whether the added cement has actually coated the particles, remained mostly as free hydrated cement powder, caused the formation of concretions by cementing smaller particles together, or any combination of these effects.

Specific Surface

The specific surface (i.e., surface area per unit weight) was used as a characterizing parameter of the sand samples and as an indicator of their state of coating after treatment with cement. Samples of finer gradations or those with increased content of fines automatically resulted in higher values of specific surface.

The surface area of each fraction A was first calculated by assuming spherical particles, as follows:

$$A = 6W/G \cdot D_m \quad (1)$$

where

W = weight of aggregate fraction retained on particular sieve,
G = density of aggregate, and

D_m = mean diameter of aggregate fraction = $(D_1 + D_2) \div 2$, D_1 and D_2 being sizes of two successive sieves within which aggregate fraction lies.

The total surface area of a particular aggregate gradation A_t , taking surface irregularity of the particles into consideration, is as follows:

$$A_t = \sum_{i=1}^n [6W_i / (G_i \cdot D_{mi})] (CF)_i \quad (2)$$

where n is the number of sieves used in the analysis and CF is a correction factor representing the effect of particle angularity.

A specific gravity and a correction factor for each fraction of the crushed and the natural sand were determined separately. Determinations of the specific gravity were made according to AASHTO T84, T85, and T100, depending on the size of the particles considered.

Since there is no simple test available to correct for the effect of surface angularity (9), an empirical shape factor was calculated as the quotient of the maximum void ratio at the loosest state and the minimum void ratio at the densest state (10). Perfectly spherical particles of equal size were considered to have the same value for the maximum and minimum voids and thus a shape factor of a unity. Void ratios at the loosest and densest states were determined experimentally according to AASHTO T20. Results of specific-gravity and shape-factor determinations are given in Table 1.

Chemical Analysis

A quick chemical test was performed to determine the weight of cement in each fraction of the treated sand. The technique is based on dissolving the hydrated cement coat in diluted hydrochloric acid and observing the resulting change in the weight of the sample. Since the acid dissolves part of the original sand particles as well, this part had to be determined before the net weight of the cement coat could be obtained. This was done by adding the acid also to a blank sample of uncoated sand. Twelve pilot tests by using aggregates coated with predetermined amounts of cement have shown that this technique produced sufficiently accurate results for the purpose of this study, provided that each case is represented by a three-test average. It was found unnecessary, therefore, to apply the more sophisticated and time-consuming titration method of cement content determination (AASHTO T211).

The chemical analysis was performed on sand samples of gradations G1 and G2 only.

RESULTS AND DISCUSSION

By applying the above methods for evaluating the coated sand samples, the following results and observations were obtained.

The visual examination was first made on the whole sample (i.e., before sieving). It was found difficult in this way to identify sample-to-sample or fraction-to-fraction variation in the quality of the cement coat produced. Accordingly, observations were subsequently made on the basis of individual fractions after sieving. The descriptions obtained indicated that the uniformity of the resulting coats among various fractions of a particular sand sample depends highly on the amount of the cement added in the process. The higher the added cement was, the better were its distribution and the coating of the particles. A critical percentage, however, was visually identified beyond which particle agglomeration seems to occur. Such an optimum cement content was found to vary slightly with the quantity of added water and the initial gradation of the sand. Cement optima for natural sand at W/C ratios of 0.35 and 0.45 were observed at approximately 14 and 12 percent, respectively. Corresponding optima for crushed sand at the same levels of W/C ratio were observed at 15 and 13 percent for G2, 14 and 13 percent for G3, and 12 and 11 percent for G4. In other words, the coarser the sand, the less cement is needed to produce an optimum distribution.

Results of the particle-size-distribution analysis for the natural sand and for one gradation, G2 (as an example), of the crushed sand are listed in Tables 2 and 3. A comparison of the figures in these tables shows that the size distributions of the coarser fractions were minimally affected by the introduction of the cement. For the finer fractions, however, the effect of coating on gradation was tangible and had a definite pattern. At the lowest cement treatments of 6 percent and 7 percent, gradations were significantly finer than before coating. As the cement content increased, the divergence progressively narrowed, and at 14 and 15 percent, respectively, the gradations became coarser than before treatment. This trend is clarified in Figure 3 by plotting the percentage of added cement versus the amount of material passing the No. 200 sieve for the treated sand. It is believed that most of the increase in this fraction is due to the fact that free hydrated cement is unable to adhere permanently to surfaces of larger particles because of the mechanical agitation they received during or after treatment. The increased fines therefore

indicate a waste of cement. The effect of increasing the W/C ratio to 0.45 was a reduction in the cement level at which this finest fraction reached its original value, as indicated by the horizontal dashed lines.

A typical set of calculations involved in surface-area analysis is given in Table 4; the following results were obtained for total surface area and specific surface:

Coating Cement (%)	Total Surface Area (cm ²)	Specific Surface (cm ² /g)
0	8 194	81.9
7	10 064	100.6
9	9 665	96.6
11	8 780	87.8
13	7 842	78.4
15	7 100	71.0

The consistently falling trend of the relationship between cement content and specific surface, shown in Figure 4, seems implausible, since by adding more cement the particles would become rougher and presumably of higher specific surface. However, this is true assuming that all the added cement would form a permanent coating on the particles of sand without changing the original number of these particles. Such an ideal coating was unobtainable because of two effects:

1. Not all the added cement contributed to the formation of a permanent coat. Under conditions of low cement and low water content, most of the cement was left free, which obviously increased the value of the specific surface of the whole sample, as seen on the left-hand side of Figure 4.

2. The actual number of individual particles of the sand is often reduced after the process of coating. While the sample was still wet, the finer particles, due to their light weight, were held together in groups or to surfaces of larger particles by the comparatively larger forces of water viscosity and surface tension. After hydration of the cement, many of these particles became inseparable; the net effect was a reduction in the total surface area of the sand sample. This behavior appeared to prevail at conditions of high cement and water contents as seen on the right-hand side of Figure 4. The final value of the specific surface of a treated sample would therefore depend on the extent to which each of the above conflicting effects takes place in the process.

Results of the chemical analysis are presented in Figures 5 and 6 for the natural sand and in Figures 7 and 8 for the finest of the three crushed-sand samples (G2). A sample of the computations involved is shown in Table 5.

At the lower level of W/C ratio, Figure 5 shows that the distribution of the added cement among the fractions of natural sand is most uniform at its highest content of 14 percent. At this level the concentration of the cement coat (grams per square centimeter) varied by 20 percent within most of the particle size range. As the amount of cement was reduced, its distribution became increasingly non-uniform. Particles between sieves No. 30 and No. 100 received the thinnest coatings, while disproportionate thicker coats were attracted by the finer material passing sieve No. 200. At the lowest treatment of 6 percent, the concentration of coating corresponding to this minus No. 200 sieve fraction is approximately 17 times that for the coarser fraction retained on sieve No. 50. Obviously this pattern is rather wasteful. It should be remembered

that the ultimate objective of the coating process is to make possible the production of better-quality asphaltic mixtures, largely by improving the surface texture of the aggregates used. A desirable pattern of cement distribution would accordingly be that producing preferential coating for those fractions of aggregate whose contribution to the frictional component of mix stability is maximum. The coarser particles of sand do contribute to this component; they are part of the load-bearing skeleton of aggregates in dense asphaltic mixtures. Consequently, the added cement should, in our view, mainly coat these coarser fractions rather than the finer particles whose function is more of filling the smaller voids within the structural matrix. Distributions similar to this were obtained generally at the higher levels of cement and water content as seen in Figures 6 and 8. Ryan (11), however, states in discussing aggregates for bituminous plant mixtures, "Particle shape and surface characteristics are just as important in the fine aggregate, even down to the minus 200 mesh or flow size as in the coarse aggregates...."

Generally the added cement produced better coatings for the crushed sand than for the natural

sand. The variation in the concentration of the cement coat for most crushed fractions is negligible at the higher cement treatments (Figure 7). Moreover, the coarser particles retained on sieve Nos. 8, 16, and 30 received heavier coatings in this case compared with corresponding sizes of natural sand (Figure 5).

The effect of increasing the W/C ratio was beneficial in almost all the cases. Cement treatment of the natural sand at 8, 10, and 12 percent levels produced more uniform coatings (Figure 6), while for crushed sand the cement produced consistently heavier coats as the size of fraction increased (Figure 8).

From the results obtained in this investigation, it was found possible to define desirable minimum and maximum cement contents for each gradation and W/C ratio. The criterion for selecting a minimum cement content was the production of a coated sand that had basically the same gradation and specific surface as before coating. The maximum cement content was defined as the minimum percentage that would produce the most uniform coating on the sur-

Figure 3. Effect of cement content on fraction passing No. 200 sieve.

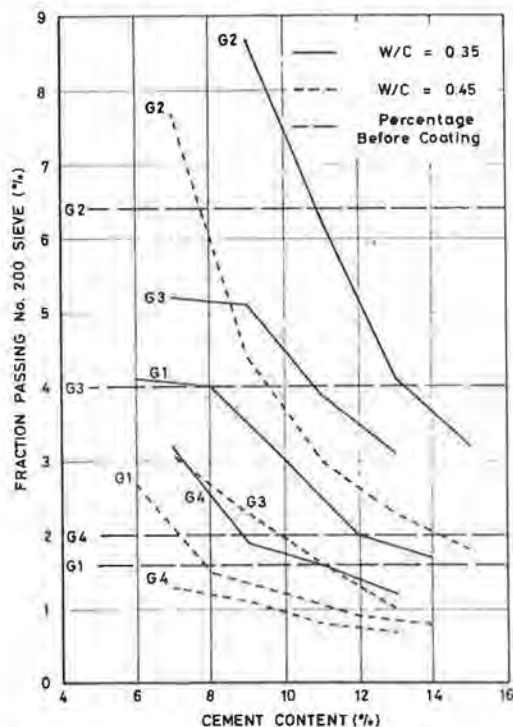
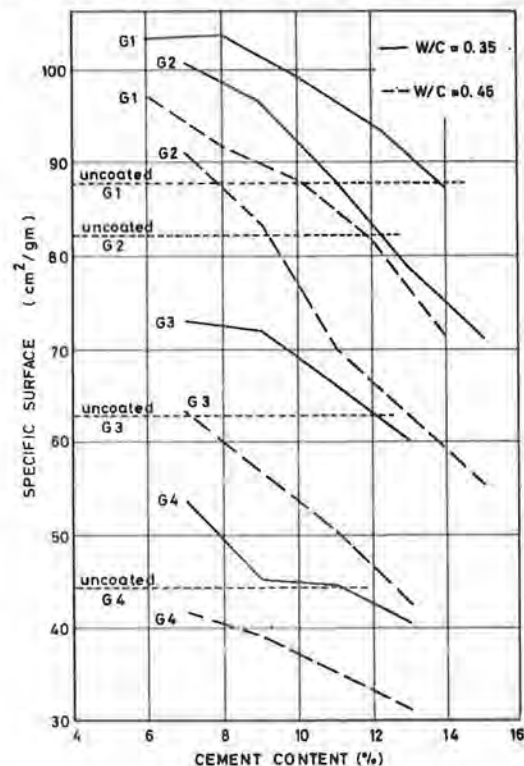


Table 4. Sample computations in determining specific surface of cement-coated sand.

Sieve No.	D_m (cm)	$[6(SF)/D_m(G)]$	Particle Surface Area ^a (cm ²)					
			Coating Cement (%)					
			0	7	9	11	13	15
4	0.3555	-	-	-	-	-	-	-
8	0.1777	6.79	75	71	67	67	64	64
16	0.0890	13.54	339	317	313	313	316	318
30	0.0450	31.36	596	564	569	568	586	624
50	0.0225	60.48	1173	1122	1147	1198	1270	1349
100	0.0112	117.14	1476	1407	1458	1617	1757	1792
200	0.0056	221.06	1459	1600	1930	1990	1879	1415
Pan	-	480.63	3076	4984	4181	3028	1970	1538

^aBased on the percentage retained on each sieve for an original sample of 2.0 kg.

Figure 4. Effect of cement content on specific surface of sand.



face of different fractions of the sand. By using such limits, a useful form of presenting the results of the study is demonstrated in Figure 9. The three gradations of crushed sand (G2, G3, and G4) provided three points for defining each of the lines in Figure 9. Obviously, a similar presentation for the natural sand was not possible since only one gradation (thus, one value of specific surface) was investigated in this case.

CONCLUSIONS

1. The direct method of visually examining the

Figure 5. Effect of cement content on its distribution among sand fractions: natural sand, W/C = 0.35.

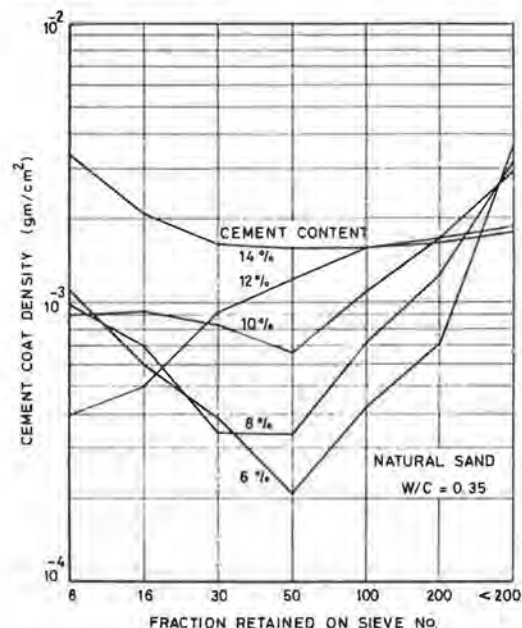
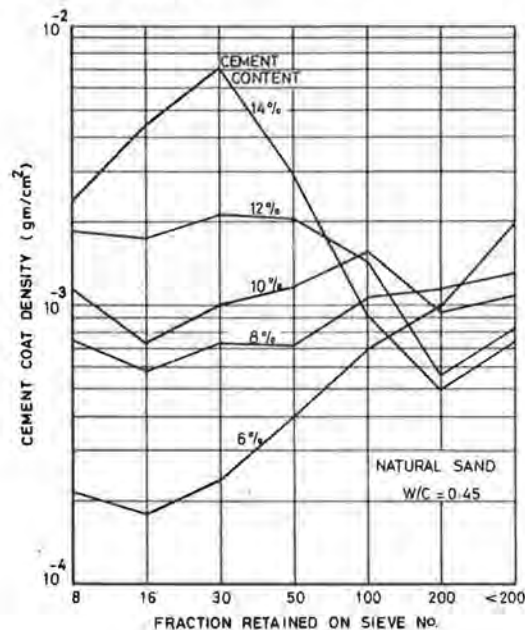


Figure 6. Effect of cement content on its distribution among sand fractions: natural sand, W/C = 0.45.



treated sand allowed a satisfactory and a rapid evaluation of the quality of the cement coat produced, provided that the samples examined were first separated into a number of fractions by sieving.

2. In the treatment of sand with portland cement, two extreme states are distinguishable within which effective coating can be found. In one, often observed at low water and/or cement content, the added cement failed to adhere permanently to the surface of particles, and thus produced a poorly coated sand with an unnecessarily high content of fines. In the other, observed at high water and/or cement content, the finer fractions of the sand

Figure 7. Effect of cement content on its distribution among sand fractions: crushed sand, W/C = 0.35.

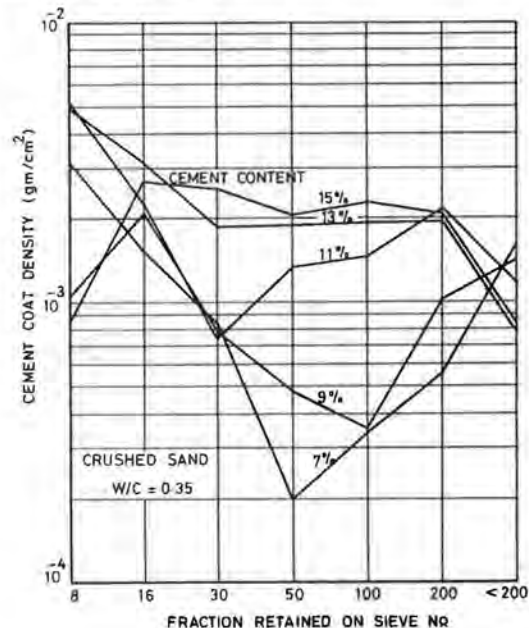


Figure 8. Effect of cement content on its distribution among sand fractions: crushed sand, W/C = 0.45.

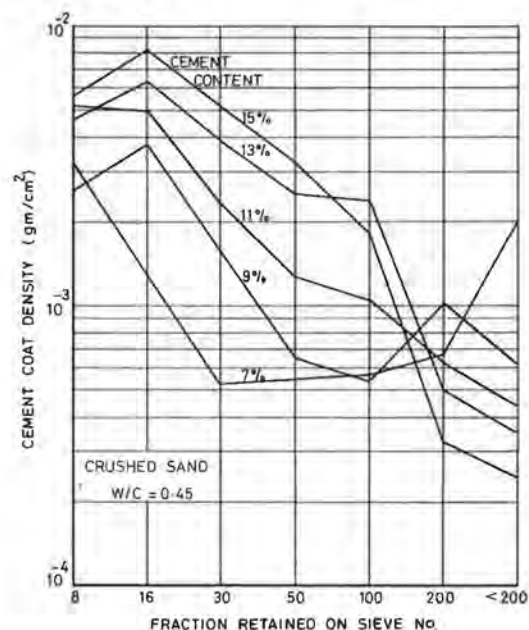


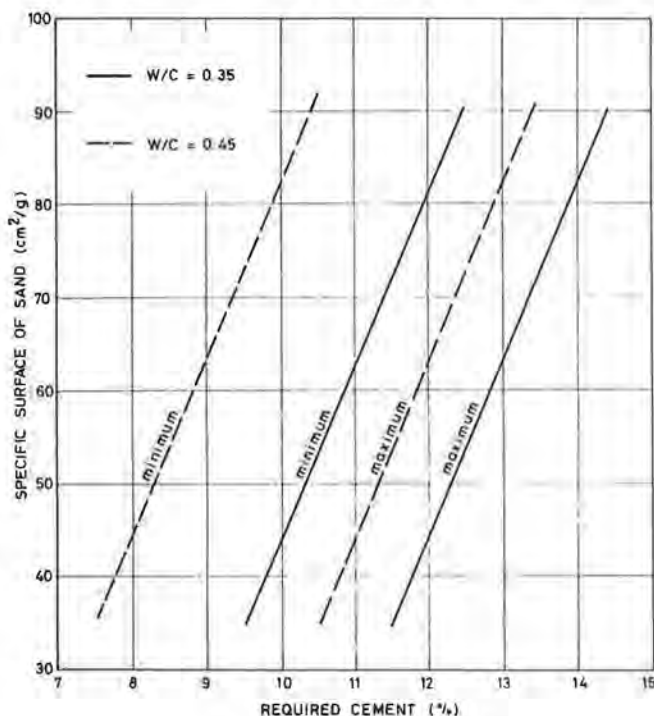
Table 5. Sample computations in determining cement distribution by chemical analysis.

Sieve No.	Coated Sample		Uncoated Sample		Cement Coat ^a (g)	Surface Area (cm ²)	Cement Coat Density ^b (g/cm ²) 10 ⁻⁴
	Weight (g)	Soluble Matter (%)	Weight (g)	Soluble Matter (%)			
8	32.3	1.83	36.0	1.71	0.04	275	1.4
16	103.2	2.84	99.4	1.44	1.44	1 548	9.3
30	201.6	3.30	206.8	0.55	5.54	6 529	8.5
50	915.8	4.91	925.8	0.59	39.56	58 566	6.7
100	822.7	11.13	625.2	0.88	84.33	75 981	11.1
200	101.3	35.13	75.7	4.14	31.40	18 028	17.4
Pan	65.6	78.70	31.5	11.13	44.32	14 573	30.4

^aColumn 3 minus column 5 multiplied by 2, all of which is divided by 100.

^bColumn 6 divided by column 7.

Figure 9. Limits of cement content for coating crushed sand.



tended to form weakly cemented agglomerations that resulted in coarser gradations lacking in fines.

3. The investigation has shown that the amount of cement required for a proper coating needs to be rationally expressed by relating it to the surface area of the sand to be coated.

4. By defining limiting criteria for the percentage of added cement in the coating process (to avoid the objectionable extremes mentioned above), such a relationship as suggested in paragraph 3 above can be developed. In this study a relationship thus developed is shown in Figure 9 for the crushed sand.

5. For a particular value of specific surface of sand, the quantity of cement required for an optimum coating is found to reduce with an increase in the W/C ratio, within the extremes mentioned above.

ACKNOWLEDGMENT

This study was conducted at the Roads Research Cen-

ter under the sponsorship of the Ministry of Public Works (Roads and Drainage Department), Kuwait.

We would like to thank S. Al-etr for her technical assistance; A. Allam, who did most of the laboratory work; and Y. Elfarra for conducting the chemical analysis.

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Publication of this paper sponsored by Committee on Mineral Aggregates.