tion after cracking. Indirect tensile tests indicate that the SAHM will provide a greater tolerance to strains before fracture than will a conventional AC mixture.

Pavement rutting is primarily related to traffic densification of surface and base courses. It has been shown that rutting of limerock base courses is less than for SAHM bases. Sixty-five to 80 percent of the rutting occurs in base-course materials. Subgrade conditions and adequacy of compaction can affect the degree of rutting. The stability selected for design of a SAHM and that achieved in construction may influence rutting. A lower-stability SAHM on the Marianna test road indicated an average 65 percent increase in rut depth over that with high-stability bases.

Pavement serviceability is comparable for pavements constructed with either limerock or SAHM bases. Surface cracking on the Lake Wales test road was more prevalent with the thinner surface. However, numerous observations indicate that cracking can be more severe in pavements that have thicker surfaces. Much of this confusion is related to different hardnesses or viscosities of the binder and the ambient temperature for that locale.

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Cement Stabilization of Degrading Aggregates

Ira J. Huddleston, Ted S. Vinson, and R. G. Hicks

The suitability of cement as a stabilizing agent for degrading aggregates has been evaluated. Specifically, wet-dry, freeze-thaw, and unconfined compressive strength tests were performed on marine basalt and three gradations of Tyee sandstone from the Siuslaw National Forest, two types of decomposed granite from the Umpqua National Forest, and a moderately weathered granite from the Colville National Forest. Tests were performed on samples at both standard and modified compactive efforts. All of the materials tested had satisfactory durability at relatively low cement contents. Variations in optimum moisture and maximum dry density associated with a change in cement content of 2 percent were insignificant. Samples compacted with a modified compactive effort generally required 1-2 percent less cement to meet durability requirements. Overall, the durability was found to be influenced more by cement content than by compactive effort. The unconfined compressive strength varied with material, cement content, and compactive effort. For a given cement content, the strengths were higher for the specimens compacted with a modified effort than for those compacted with a standard effort. The strengths increased with age for all materials and compactive efforts except the marine basalt and Calahan decomposed granite compacted at the standard effort.

The increasing demand for access to national forests for timber harvesting, recreational, and other purposes has focused attention on the need to provide roads to serve relatively low traffic volumes. These roads are generally constructed and maintained on limited budgets, but they must provide adequate service for many years. Consequently, it is desirable to use high-quality materials in the construction of these roads (i.e., materials that will provide strength and durability to withstand the anticipated environmental and traffic loads).

When high-quality materials are not locally available, three alternatives exist: (a) high-quality materials may be imported, (b) poor-quality materials may be used by lowering design standards, or (c) poor-quality materials may be improved. With respect to the third alternative, the characteristics of the locally available materials may be improved by the addition of stabilizing agents such as lime, cement, or asphalt. The stabilized materials may be used in place of the transported materials.

At the current time, in areas of several Pacific Northwest national forests, quality road-building materials are not available locally and must be transported considerable distances. However, aggregates that do not meet the degradation specifications of the U.S. Forest Service in Region 6 (herein termed degrading aggregates) are locally available in quantity. In recognition of this situation, a study was initiated to investigate the feasibility of using cement as a stabilizing agent for degrading aggregates (1).

MATERIAL CHARACTERISTICS

Five types of degrading aggregates from three national forests were selected for the study. Tyee sandstone and crushed marine basalt were obtained from the Siuslaw National Forest; two distinct types of decomposed granite (termed Goolaway and Calahan, respectively) were obtained from the Umpqua National Forest; poor-quality granite was obtained from the Colville National Forest.

Material processing and aggregate evaluation tests were performed in order to (a) prepare the materials for soil-cement testing and (b) determine their suitability as a roadway material. The material processing operations varied with the material type. For the Tyee sandstone and the Colville granite, processing included crushing, sieving, washing the coarse fraction [retained on a 4.75-mm (No. 4) sieve] and storing for further testing. The remaining materials (Calahan and Goolaway decomposed granites and the marine basalt) did not require crushing but were sieved, washed, and stored as above. Crushing was done with a Braun Chipmunk Crusher, and the materials were sieved and stored in the following sizes: 19 mm (0.75 in), 13 mm (0.5 in), 10 mm (0.375 in), 6 mm (0.25 in), 4.75 mm, and passing 4.75 mm.

Standard tests used by the U.S. Forest Service to determine aggregate quality and characteristics were conducted. The tests included sieve analysis (AASHTO T11/T27), specific gravity and percentage absorption (ASTM D854), Los Angeles (L.A.) abrasion (AASHTO T96), California durability (AASHTO T210), and sand equivalent (AASHTO T176). Results of the aggregate tests are presented in Tables 1 and 2. Also presented in Table 2 are specifications for Pacific Northwest Forest Service base course aggregates.

The data presented in Tables 1 and 2 identify a relatively wide range of material types and qualities. The completely decomposed Goolaway granite contains no material sizes greater than the 4.75-mm sieve. The Calahan decomposed granite has experienced a lower degree of weathering and chemical alteration than the Goolaway granite and contains sizes greater than the 4.75-mm sieve. The Colville granite represents a borderline degrading aggregate since it fails to meet the L. A. abrasion specifications only. The sandstone is felt to be representative of the quality of sandstones found throughout the coast range of Oregon and Washington. The sandstone is lacking in its resistance to abrasion and also in resistance to breakdown in a wet environment (indicated by the California durability test results). Finally, the marine basalt test results are probably typical of the marine basalts found in the coast range. They show good resistance to abrasion and a small amount of detrimental fines but are quite susceptible to breakdown in a wet environment.

Table 1. Grain size distribution of bedrock materials.

Sieve Size	Percentage Passing: Tyee Sandstone[a]	Marine Basalt[b]	Decomposed Granite[b]: Goolaway	Decomposed Granite[b]: Calahan	Colville Granite[b]
38 mm	88	100	100	100	100
25 mm	78		100		
19 mm	73	86	100	96	93
13 mm	61	70	100	85	64
10 mm	49	60	100	77	54
6 mm	37	47	100	69	40
4.75 mm	30	35	100	60	33
2.0 mm	24	25	83	46	23
425 µm	16	11	44	23	11
75 µm	6	6	17	9	2

Note: 1 mm = 0.04 in.

[a] After crushing with Braun Chipmunk Crusher.

[b] As received, no crushing.

TEST PROGRAM

Material Processing

The Goolaway and the Calahan decomposed granites required no crushing. Their gradations, as given in Table 1, are the result of breakdown during excavation (in situ) and transport and handling. Because of the nature of these materials, control of their gradation is very difficult, not only in the field but also in the laboratory. For the purposes of the study it was assumed that changes in the gradations of these materials due to handling, mixing, and compaction would be similar in the laboratory and field operation.

The Tyee sandstone, marine basalt, and Colville granite all required crushing to obtain material sizes smaller than 25 mm (1 in). The gradations given in Table 1 for these materials are those that resulted directly from this crushing operation and do not necessarily represent an optimum or practical gradation for stabilization with cement. For the purposes of the study, the gradations were altered so that they represent, as nearly as can be determined, an optimum gradation.

The rationale used for determining optimum gradations for these materials was based on work done by the Portland Cement Association (PCA) (2, 3). Dense-graded materials (AASHTO A-1-a) require the least amount of cement to meet durability requirements. Note that the amount of cement per unit volume of material stabilized is the product of the cement content by weight and the field dry density. For the range of dry densities and cement contents associated with this study their product is accurately reflected by the cement content alone (i.e., minimum cement contents reflect minimum amounts of cement used in the field). In addition, work by Norling and Packard (3) has shown that the addition of material that is retained on the 4.75-mm sieve to material passing the 4.75-mm sieve decreases the total cement requirement as long as the amount retained on the 4.75-mm sieve does not exceed 50 percent. Norling and Packard combined this finding with a relationship they developed that relates the maximum standard Proctor dry density and the percentage of the material

Table 2. Aggregate evaluation test results.

Test	Tyee Sandstone	Marine Basalt	Decomposed Granite: Goolaway	Decomposed Granite: Calahan	Colville Granite	Forest Service Aggregate Specs
Specific gravity (SSD)	2.32	2.55	2.64	2.56	2.61	
Absorption (%)	8.8	4.3		2.1	0.85	
L. A. abrasion	67.5	34.4		64.4	55	40 maximum
California durability[a]	9	19		60	85	35 minimum
Sand equivalent	48	46		44	82	35 minimum

[a] The results given are for the coarse or the fine fraction depending on which fraction controlled.

Figure 1. Indicated cement contents of soil-cement mixtures containing material retained on the 4.75-mm sieve.

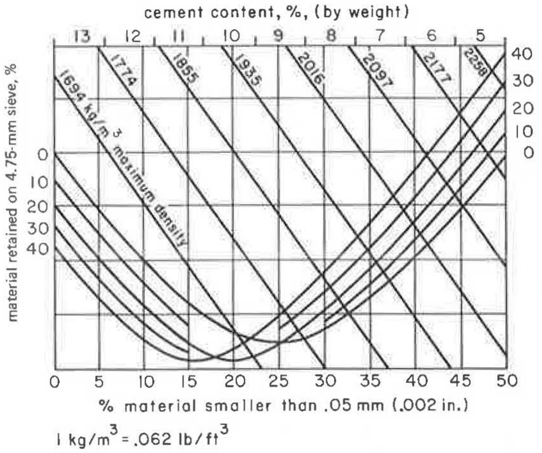

Table 3. Grain size distributions of materials used in test program.

Sieve Size	Percentage Passing: Tyee Sandstone A	B	C	Marine Basalt	Decomposed Granite: Goolaway	Calahan	Colville Granite
25 mm	100	100	100	100	100	100	100
19 mm	92	100	100	100	100	96	100
13 mm	80	93	92	100	100	85	80
10 mm	73	89	87	86	100	77	70
6 mm	65	81	81	67	100	69	58
4.75 mm	60	75	75	55	100	60	50
2.0 mm	48	60	58	40	83	46	36
425 µm	35	39	31	18	44	23	16
75 µm	19	15	6	9	17	9	4

Note: 1 mm = 0.04 in.

smaller than 0.05 mm (0.002 in) to the cement requirement for soils that contain no material retained on the 4.75-mm sieve. The results they obtained are shown in Figure 1. The relationship in Figure 1 indicates that optimum gradations (associated with minimum cement contents) may result from ratios of percentage of material retained on the 4.75-mm sieve to percentage of material smaller than 0.05 mm (0.002 in) of either 40:15 or 20:20.

The Tyee sandstone was blended to a 40:15 ratio, for two reasons:

1. This ratio was the closest to the original gradation and
2. In all likelihood, it represents the gradation most easily obtained under field conditions.

To determine the influence of variations in this gradation on the cement requirement, two additional gradations were selected. These two additional gradations define a range of gradations about the optimum that has approximately the same cement requirement as the 40:15 ratio material.

The gradations for the marine basalt and Colville granite were not obtained from Figure 1. The marine basalt came from stockpiled materials at a commercial rock quarry. It was processed through the rock crusher at the facility. Therefore, it represents a gradation that would be used in the field. Following recommended PCA test procedures, however, it was necessary to screen out material retained on the 13-mm (0.5-in) sieve so that there would not be more than 50 percent retained on the 4.75-mm sieve. The final gradation for the Colville granite was obtained by screening out the sizes retained on the 19-mm (0.75-in) sieve to get a maximum of 50 percent retained on the 4.75-mm sieve. The final adjusted gradations for each material are given in Table 3. The three gradations used for the Tyee sandstone are labeled A, B, and C, where A refers to the optimum 40:15 gradation, and B and C refer to 25:11 and 25:5 gradations, respectively.

Compactive Effort

Standard Proctor (AASHTO T 99-74) compactive effort is used when conducting wet-dry (W/D) and freeze-thaw (F/T) durability tests. Modified Proctor (AASHTO T 180-74) compaction is not normally recommended for durability testing for two reasons:

1. Maximum densities are obtained by using the modified compactive effort at significantly lower water contents than those of the standard compactive effort; this lower water content is not thought to be high enough for proper cement hydration; and
2. The high densities obtained with the modified compactive effort in the laboratory are difficult to obtain in the field in many applications.

However, results of compressive strength tests conducted by the U.S. Forest Service, Region 6 Materials Laboratory, have shown that, for the same cement content, the strengths of specimens compacted with a modified compactive effort are as much as two times greater than those of specimens compacted with a standard compactive effort. These data raise the question of whether or not it would be beneficial and feasible to design for the higher densities and strengths obtained with the modified compactive effort. In consideration of this question, all tests were conducted at both standard and modified Proctor compactive efforts.

Cement Contents

Cement contents for the materials to be tested were determined by following the procedures developed by PCA (2). The PCA method uses gradation and maximum standard Proctor dry density to estimate the required cement content. Tests are performed on samples at cement contents at an estimated optimum value and 2 percent above (high cement content) and below (low cement content) this value. Seven-day cure, unconfined compressive strength (q_u) tests were conducted at the high and low cement contents. Twenty-eight-day-cure q_u tests were conducted at the lowest cement content that satisfied all durability test requirements.

The material mixing process included three stages:

1. The cement was mixed with the material passing the 4.75-mm (No. 4) sieve,
2. The correct amount of water was mixed with the material obtained in step 1, and
3. The material sizes retained on the 4.75-mm sieve were mixed in a saturated surface dry (SSD) condition with the mixture obtained in step 2.

The materials were thoroughly mixed with a trowel at each stage until they were uniform in distribution.

Initially moisture-density tests were conducted at each of the three cement contents for the Goolaway decomposed granite and the A-gradation of the Tyee sandstone. Results from these tests indicated that the variations in optimum moisture and maximum dry density associated with a change in cement content of ± 2 percent were insignificant. Moisture-density tests

Table 4. Summary of durability tests at minimum required cement content.

	Standard Compactive Effort							Modified Compactive Effort						
	Tyee Sandstone				Decomposed Granite			Tyee Sandstone				Decomposed Granite		
Test	A	B	C	Marine Basalt	Goolaway	Calahan	Colville Granite	A	B	C	Marine Basalt	Goolaway	Calahan	Colville Granite
Cement requirement[a] (% by weight)	5	5	5	6	6	5	5	4	4	4	6	4	3	3
Controlling test	F/T	F/T	F/T	W/D	F/T	W/D	W/D	F/T	F/T	F/T	W/D	F/T	W/D	W/D
Moisture content (% by weight)	14.2	14.3	15.6	13.9	13.2	10.4	7.6	11.9	12.2	13.5	12.9	11.1	6.6	6.2
Dry density (kg/m³)	1846	1817	1793	1836	1846	2058	2115	1966	1905	1875	1952	1913	2187	2163
Soil-cement weight loss (% by weight)	7.2	6.6	9.1	13.4	4.9	12.8	5.7	8.1	3.6	8.7	12.2	10.8	9.3	8.7

Note: 1 kg/m^3 = 0.062 lb/ft^3.

[a]Minimum cement content required to pass durability test.

for the remaining materials were therefore carried out at the intermediate cement contents only.

Durability Testing

The durability testing included standard F/T (AASHTO T 136-76) and W/D (AASHTO T 135-76) tests. Duplicate samples at each cement content were compacted for F/T testing. One sample was used for brushing to determine soil-cement weight loss. The other sample was used to measure moisture and volume changes. Duplicate samples at the intermediate cement content were compacted for W/D testing, one sample each for determining weight loss and moisture and volume changes.

Strength Testing

The unconfined compressive strength of the stabilized material was measured after 7- and 28-day moist curing. On the 7th (or 28th) day of curing the samples were placed in a water bath to soak for four hours. After soaking, the samples were surface dried and the ends were capped with a sulfur-based capping compound. Unconfined compressive strength tests were conducted at a load rate of 138 kPa (20 lbf/in^2) per second. Load and deformation were continuously monitored with a load cell and linear variable differential transformer. The results represent the average of two tests for the 7-day cure specimens and one test for the 28-day cure specimens.

DISCUSSION OF TEST RESULTS

Durability

Table 4 presents a summary of the results at the minimum cement content for each material considered. Moisture and volume change results are not included because no appreciable changes could be detected during the durability testing for any of the materials tested.

Of the seven materials tested, only the marine basalt at the standard compactive effort exceeded the 14 percent weight-loss criteria established by PCA (2). The lack of failures for the remaining materials has two probable explanations.

One explanation is that the procedure used to select the cement contents for testing is an approximate one and cannot guarantee that, in each case, the minimum cement content will be determined. A possibility of error in the procedure is present when applied to the degrading aggregates that were used in this study, because of the use of maximum dry densities instead of void ratios to determine the average cement requirement. The cement requirement is a function more of particle packing, which is best described by the void ratio, than of density, which also varies with the specific gravity of the particles. The degrading aggregates used in this study typically have low specific gravities and, therefore, do not compact to high densities even though they may have relatively low void ratios.

The other explanation is that the W/D tests were conducted only at the intermediate cement content as suggested in the PCA procedure (2) because the F/T tests normally control for materials that have low silt and clay contents. However, the W/D test appeared, in some cases, to control for the materials in this study. It is believed that additional failures would have been experienced had W/D tests been conducted on the materials at the lower cement contents.

Soil-cement weight loss was generally less for the samples compacted with a modified compactive effort than for those compacted with a standard compactive effort. This was true for the sandstones, basalt, two of four cement contents of the Calahan decomposed granite, and three of four cement contents of the Colville granite. The Goolaway decomposed granite and the remaining cement contents for the Calahan decomposed granite and the Colville granite all had higher weight loss for the samples compacted with a modified effort. The differences between the values for the two compactive efforts were less than 1 percent for all cases in which the modified value exceeded the standard and varied from 1 to 7 percent for the opposite case. The minimum required cement content determined for each material was less with a modified compactive effort for all the material tested except the Goolaway decomposed granite and the marine basalt. It is likely that, had the sandstones been tested at 4 percent cement with a standard compactive effort, they would have met the durability requirements.

In general, the effect of the increased compactive effort on the durability of the materials was not great. The durability increased more with cement content than with compactive effort.

Variations in the durability between the three gradations of the Tyee sandstone were small. All three gradations required the same cement content to meet durability requirements for both compactive efforts. Calculated values of soil-cement loss varied only slightly among the three materials. The table below gives the three gradations and their total accumulated soil-cement loss for all cement contents.

Gradation	Compactive Effort	Total Accumulated Soil-Cement Weight Loss (% by weight)
A	Standard	17.8
	Modified	19.6
B	Standard	15.1
	Modified	11.4
C	Standard	21.8
	Modified	24.0

The results indicate that the B-gradation resulted in the least total soil-cement loss, followed by gradations A and C. (Refer to Table 3 for gradation characteristics.) This order is somewhat different than would be predicted. The A-gradation should be the optimum, followed in order by gradations B and C. The differences are not large, however, and a more reasonable conclusion might be that variations in gradation that were made have little effect on durability.

Strength

The strength test results are summarized in Figure 2. The strengths increased with time for all materials except the marine basalt and Calahan decomposed granite at a standard compactive effort. The density for the marine basalt was considerably higher for the 7-day-cure specimen than for the 28-day-cure specimen. This probably explains the higher strength. No explanation is available for the Calahan decomposed granite except that the two strength values are close and possibly represent the occurrence of an abnormally high strength value for the 7-day-cure test and an abnormally low strength value for the 28-day-cure test.

The strengths obtained were higher for specimens at a modified compactive effort at equal cement contents in all cases except for the marine basalt with 8 percent cement. The marine basalt had equal strengths at 8 percent for the modified and standard compaction specimens. The ratios of strengths at modified to standard compaction varied only slightly with cement content and material. The average value of the ratio was 1.45, but the Colville granite had a ratio of 1.80 and the marine basalt, as previously mentioned, had a ratio near 1.0.

The effect of variations of the gradation of the Tyee sandstone on strengths is illustrated in Figure 3. For the test specimens at the standard compactive effort the order of strengths for the three gradations is not well defined. It is apparent, however, that gradations A and B resulted in higher average strengths than the C-gradation. There is a definite order of strengths for the three gradations at the modified compactive effort. As shown, at both 4 and 7 percent cement, the B-gradation resulted in the highest average strength with gradations A and C following, in that order. This order is coincident with the order established by durability tests and suggests that the B-gradation may be the best for stabilization with cement. All three of the gradations used resulted in a satisfactory stabilized product; however, the test results cannot be extrapolated to identify situations in which gradational limits should be imposed. The C-gradation contained a low amount of silt and clay sizes and 25 percent was retained on the 4.75-mm (No. 4) sieve. The B-gradation contained 25 percent material on the 4.75-mm sieve, but it also contained three times as much material passing the 75-μm (No. 200) sieve. This indicates that the C-gradation is close to the lower limit for material sizes smaller than the 75-μm sieve.

COMPARATIVE COST ANALYSIS

To allow field engineers to determine the feasibility of using a cement-treated base (CTB) rather than a good-quality aggregate base, a comparative cost analysis was performed. Prevailing prices in 1979 for CTB and imported good-quality aggregate in the areas of the three national forests selected for the study were used in the analysis. The comparative cost analysis was further based on the following assumptions:

1. The base would be constructed over a section 8 km (5 miles) long and 6 m (20 ft) wide,
2. The CTB section is 150 mm (6 in) in depth,
3. The cement content used was 6 percent,
4. A structurally equivalent aggregate section is 250 mm (10 in) in depth,
5. A haul distance of 40 km (25 miles) is required to obtain good-quality aggregate,
6. Degrading aggregate for use in the CTB is readily available at or near the site,

Figure 2. Effect of curing time on strength.

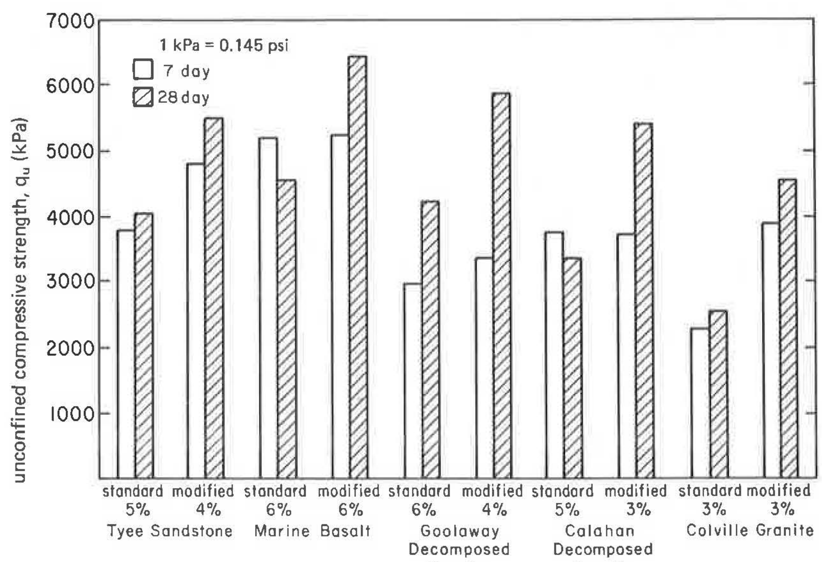

Figure 3. Cement content versus unconfined compressive strength for Tyee sandstone, A, B, and C gradations.

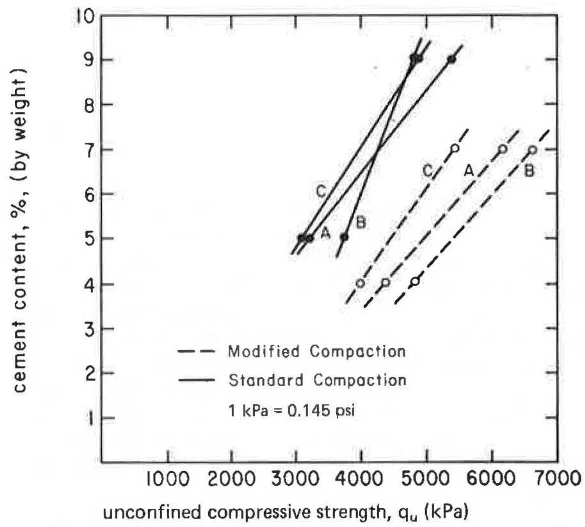

Table 5. Summary of cement-treated base costs.

Item	Unit Price ($/m³)	Total Cost ($)
Ripping, scalping, pit development, and stockpiling	2.11	15 743
Mobilization	0.60	4 498
Plant costs	0.81	6 062
Depreciation and overhead for power unit	3.22	24 054
Grading and excavation	0.71	5 280
Cement (FOB)	7.05	52 703
Haul to job site	2.01	15 058
Placement	1.82	13 591
Subtotal	18.32	136 988
15 percent profit		20 548
Total (cost and profit)[a]		157 536

Note: 1 m³ = 1.31 yd³.

[a]Total = \$3.20/m² for 150-mm depth (\$0.30/ft² for 6-in depth) and \$19 692/km for 6-m width (\$31 691/mile for 20-ft width).

7. The degrading aggregate need not be crushed to obtain the required grain size distribution, and
8. A central plant mix operation will be employed to manufacture the CTB.

A summary of the CTB costs is given in Table 5. A summary of the aggregate base costs is given in Table 6. Based on the assumptions made, the CTB is an economically feasible alternative. As the haul distance for the good-quality aggregate increases, the feasibility increases. The costs for the good-quality aggregate base would just equal those of the CTB for a haul distance of approximately 19 km (12 miles). This distance increases to 30 km (19 miles) if the poor-quality aggregate requires crushing and screening to obtain the required grain size distribution.

Table 6. Summary of aggregate base course costs.

Item	Unit Price ($/m³)	Total Cost ($)
Crushing	3.92	48 855
Blasting and ripping	1.70	21 172
Pit development	0.46	5 700
Mobilization-demobilization	0.78	9 771
Load from stockpile	0.47	5 863
Haul (40 km)	9.12	113 998
Process aggregate with grader	0.46	5 700
Rolling	0.35	4 397
Total[a]	17.30	215 456

Note: 1 m³ = 1.31 yd³.

[a]Profit is included in unit prices listed in the table. Total = \$4.45/m² for 250-mm depth (\$0.41/ft² for 10-in depth) and \$26 932/km for 6-m width (\$43 343/mile for 20-ft width).

CONCLUSIONS

For the degrading aggregates considered in this study, cement appears to be a suitable stabilizer. All of the materials tested showed satisfactory durability at relatively low cement contents. Minor variations in gradation (variations that do not change the material classification) have little effect on the strength or durability of the stabilized aggregate when compared to the effects due to a change in cement content.

Increasing the compactive effort may lead to a decreased cement requirement and associated economic savings. However, the choice of higher compactive effort requires a project-by-project evaluation and should only be applied where field conditions can ensure higher densities can be obtained. Stabilizing degrading aggregate with cement should be a standard design alternative to good-quality rock in base courses whenever haul distances for the good-quality aggregate become excessive. For the example considered in this study, when the haul distance exceeded 19 km (12 miles), cement stabilization of degrading aggregates was found to be economically justified.

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