Qualitative Assessment of the Sioux Quartzite in Asphalt Hot Mixes

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Quartzite is known to be a more expensive material than natural aggregate (natural gravel and sand) to use in asphalt hot mixes. Therefore many engineers are reluctant to use it in order to keep construction costs down, particularly during periods of difficult economic times. This point of view did no justice to quartzite, particularly when the engineering properties of quartzite are recognized by many professionals as being superior to natural aggregate. A study was conducted to determine the feasibility of using quartzite in hot mixes in lieu of natural aggregate in areas near the quartzite outcrops. Laboratory tests indicated that mixes made with quartzite yielded better air voids, flow, density, and voids in mineral aggregates (VMA). Field performances proved that quartzite surfaces possess higher Dynaflect values as well as higher skid resistance numbers. Economic analysis revealed that during a reasonable lifespan of a pavement, the total expenses incurred (initial investment, maintenance, etc.) are less for quartzite surfaces than for natural aggregate surfaces. At the break-even point between quartzite and natural aggregate, the difference in costs can be used to transport quartzite greater distances. Computer programs were developed to determine the distance quartzite can justifiably be used without adding any more expenses to the pavement.

The Sioux quartzite exists in large deposits in the southeastern part of South Dakota and the southwestern part of Minnesota. The approximate extent of the exposure is 70 mi long in an east–west direction, and 30 mi wide in a north–south direction. Most of the exposures in South Dakota are in Minnehaha County, with the largest outcrop in Dell Rapids and second largest in Sioux Falls (see Figure 1). A sizable exposure termed "natural aggregate" will be used throughout the text to describe gravel and sand found in natural deposits, which might require some crushing to improve surface textures.

The unit price of quartzite is commonly higher than that of natural aggregate because of (a) its limited exposure, which increases transportation costs to the various job sites, and (b) the way it is mined, which includes blasting, crushing, and screening. Highway engineers and contractors who have used quartzite consider it to be an excellent material for pavement construction, and their reluctance to use it is due primarily to budget constraints. A questionnaire was mailed to several midwestern state highway departments to examine the extent of quartzite usage (1).

The general belief expressed by a number of these agencies that used quartzite in their asphalt mixes and overlays was favorable, and if financial constraints were not considered a limiting factor, quartzite would have been used in more highway construction projects. Sizable amounts of the Sioux quartzite had been used in Iowa, primarily imported from either Dell Rapids or Sioux Falls, South Dakota. This quartzite, which amounted to several thousand tons over the years, had been used in several road projects in Iowa. Some of the quartzite was hauled on unit trains to locations as far as 200 mi from Dell Rapids. Quartzite used by the state of Iowa cost as much as $22.00 per ton delivered (1).

QUANTITATIVE AND QUALITATIVE ASSESSMENT OF HOT MIXES MADE WITH QUARTZITE VERSUS THOSE MADE WITH NATURAL AGGREGATES

The integrity of hot mixes relies on several factors. Some are related to the proper design of the mix as well as proper identification of the characteristics of the main components in the mix. Others deal with environmental, traffic, construction, and maintenance factors. To conduct a comparative study between two different types of aggregates, it is essential that all parameters remain unchanged except the aggregate itself.

At this stage of the research, the standard Marshall mix design method was employed to examine the quality of the mixes made with the two different types of aggregates (2). Preliminary investigations revealed that quartzite taken from various outcrops throughout the Sioux formation might vary slightly in color and specific gravity, but generally has the same basic chemical and engineering properties. Therefore, quartzite samples from the Spencer Quarry were employed in this research to be compared with the natural aggregate from Brookings. The gradation used was that of South Dakota Department of Transportation Class G-Type 2 (½ in.). An AC 85-100 was used in preparing the test specimen.

Several standard ASTM tests were conducted to identify the properties of both aggregates and asphalt. The results were documented and used in subsequent work. Computer programs were developed to perform the tedious calculations involved (1). Tables 1 and 2 and Figures 2–6 show the final outcome of the density voids and stability–flow analysis for both aggretates.

The Marshall mix design method was employed to examine the effect of asphalt content on the mix characteristics. Final interpretation of data indicated that the optimum asphalt content when natural aggregate is used in the hot mix was 6.55 percent, whereas the percentage of asphalt required when quartzite is used was only 5.70. This preliminary finding becomes significant during the economic analysis presented later in this paper.

SKID RESISTANCE, DYNAFLECT, AND FIELD PERFORMANCE OF ASPHALT SURFACES

One of the main critical elements in pavement management is to evaluate the skid resistance periodically and monitor its level

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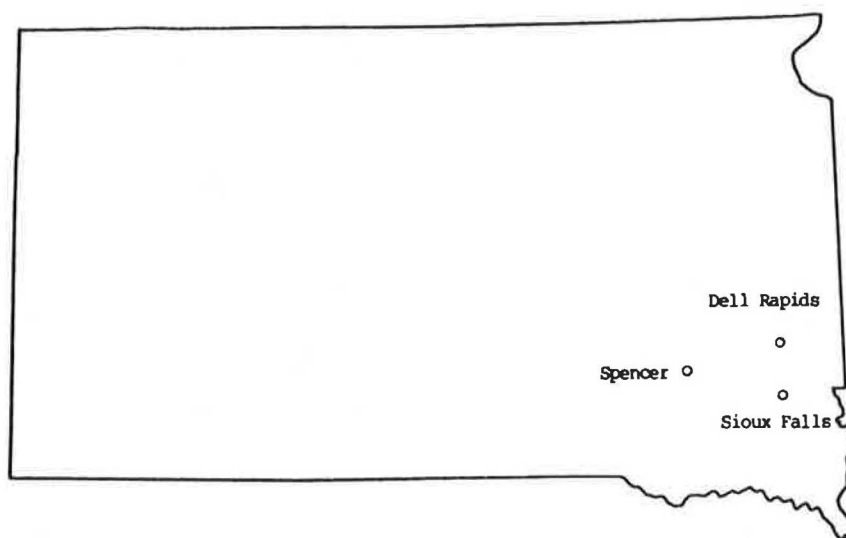South Dakota State University, Brookings, S.D. 57007-0495.

FIGURE 1   An outcrop map of Sioux quartzite in South Dakota.

of performance to ensure an adequate and safe driving surface. Several unfavorable consequences can result from the loss of proper skid resistance, ranging from higher maintenance cost to fatal accidents. It is no coincidence that accident rates have been shown to increase when pavements skid number (S.N.) drops below 40 (*3*).

Several hot-mix pavement surfaces containing quartzite were examined and compared with other hot-mix pavement surfaces containing natural aggregate having the same age. The quartzite surfaces were consistently higher in skid number as well as the Dynaflect value.

Table 3 gives results typical of those collected on skid resistance and Dynaflect from many pairs of pavement sections. The data were gathered from I-90 in South Dakota where two sizable sections were overlaid with a 2-in. hot mix. One section employed natural aggregate and the other contained quartzite. Data on skid resistance and Dynaflect were collected after approximately 18 months of service. Statistical analysis

TABLE 1   SUMMARY OF DATA—BROOKINGS NATURAL AGGREGATE

| Percent Asphalt Content | Mix Bulk Specific Gravity | Volumes (%) | | | Percent VMA | Effective Asphalt Content | Unit Weight (pcf) | Corrected Stability (lb) | Specific Flow |
		Free Asphalt	Total Aggregate	Air Voids					
3.00	2.241	2.81	80.93	16.26	19.07	1.35	139.85	1,935.4	10.00
4.00	2.309	5.07	82.53	12.40	17.47	2.37	144.10	2,300.9	10.33
6.00	2.355	9.61	82.39	8.00	17.61	4.40	146.92	2,019.6	14.00
7.00	2.353	11.82	81.46	6.72	18.54	5.42	146.82	1,513.5	19.17
8.00	2.336	13.93	80.01	6.06	19.99	6.44	145.77	1,065.2	29.17

Note: VMA = voids in mineral aggregates. Coarse aggregate: specific gravity = 2.68, absorption = 1.56 percent. Fine aggregate: specific gravity = 2.69, absorption = 1.83 percent. Mineral filler: specific gravity = 2.70. Asphalt (85–100 penetration): specific gravity = 1.079.

TABLE 2   SUMMARY OF DATA—SPENCER QUARTZITE

| Percent Asphalt Content | Mix Bulk Specific Gravity | Volumes (%) | | | Percent VMA | Effective Asphalt Content | Unit Weight (pcf) | Corrected Stability (lb) | Specific Flow |
		Free Asphalt	Total Aggregate	Air Voids					
3.00	2.253	5.22	82.05	12.73	17.95	2.50	140.57	1,962.6	9.67
5.50	2.368	11.00	84.02	4.98	15.98	5.02	147.75	2,061.9	11.83
6.00	2.385	12.19	84.19	3.62	15.81	5.52	148.84	1,913.0	13.67
6.50	2.386	13.23	83.22	3.55	16.78	6.02	148.92	1,723.2	15.50
7.50	2.356	15.34	81.84	2.82	18.16	7.03	147.03	1,250.0	23.33

Note: VMA = voids in mineral aggregates. Coarse aggregate: specific gravity = 2.64, absorption = 0.41 percent. Fine aggregate: specific gravity = 2.68, absorption = 0.61 percent. Mineral filler: specific gravity = 2.70. Asphalt (85–100 penetration): specific gravity = 1.079.
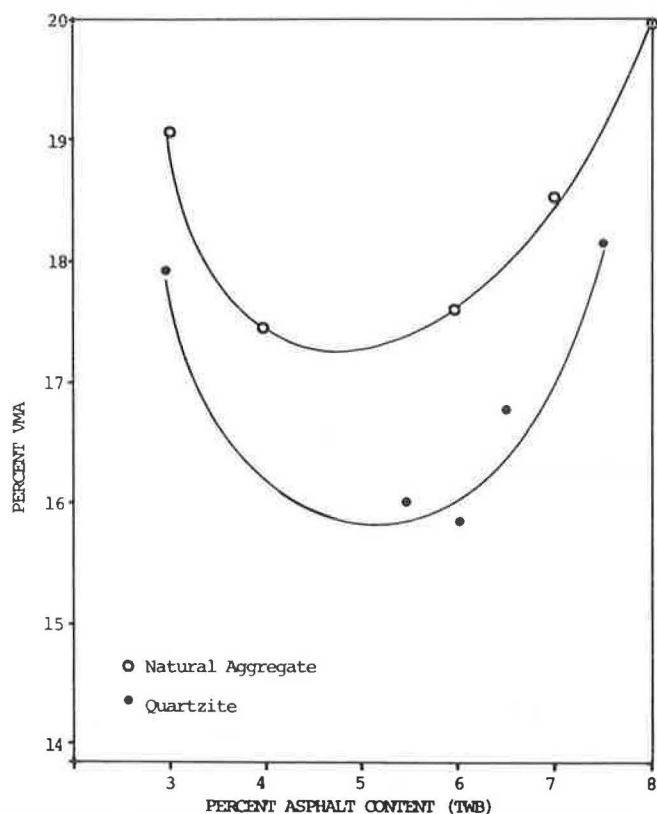
FIGURE 2 Asphalt content versus voids in mineral aggregates.

on data in Table 3 revealed that there is difference between the means of the two different treatments. The difference was significant in both skid numbers and Dynaflect values at the 5 percent level. Data provided by the Minnesota Department of Transportation on skid resistance and Dynaflect supported the same findings as did the data provided by South Dakota highways.

ECONOMIC ANALYSIS

When different items in a typical highway construction project are ranked by cost, frequently pavement appears at the top. A poor pavement can be a curse to the users as well as the owners. Maintenance costs over the life span of the pavement can be many times greater than the original cost of the pavement. Pavement maintenance is not only an expensive endeavor but also causes substantial inconvenience to the road users because of frequent closings to make the necessary repairs. When designing a hot mix, special attention should be given to the aggregate because it constitutes approximately 92 to 95 percent of the mix by weight and 80 to 85 percent by volume. It also provides the structural integrity of the pavement.

The biggest competitor of quartzite in the study area is natural aggregate. The unit price of natural aggregate is lower than that of quartzite, which makes it more attractive to use because of the lower initial investment. However, during the
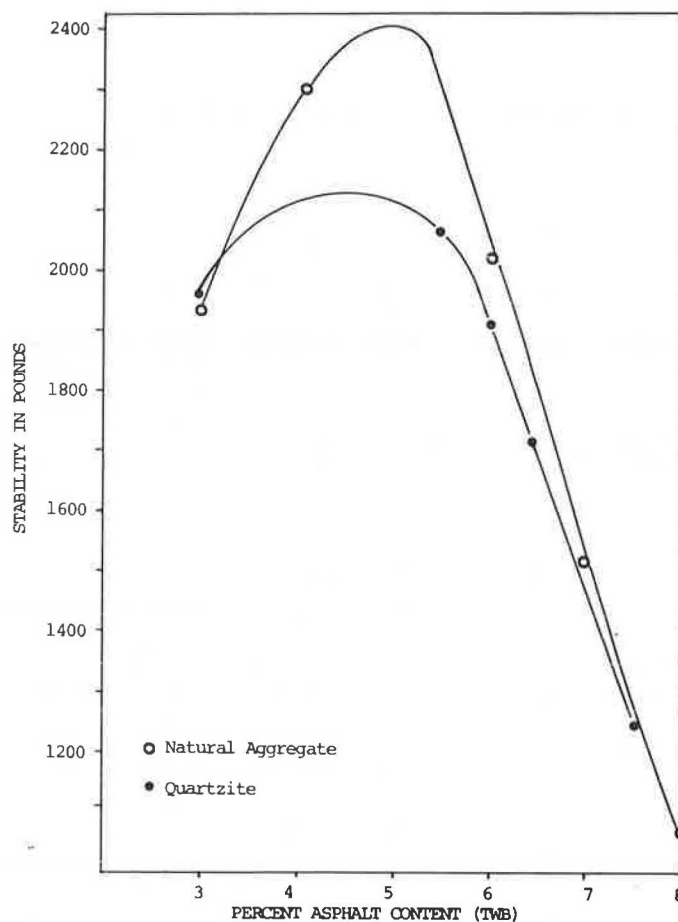

FIGURE 3 Asphalt content versus stability.
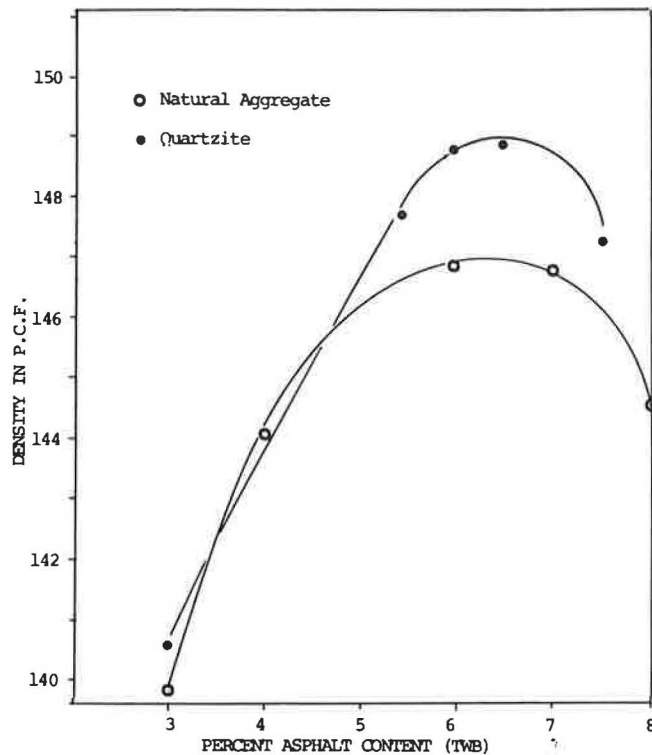
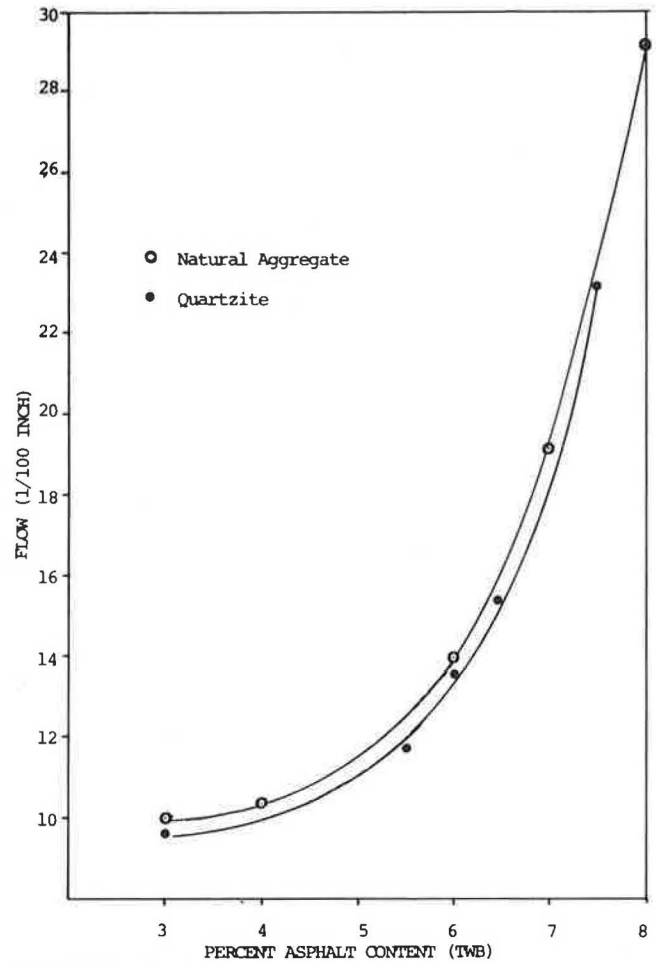FIGURE 4   Asphalt content versus density.

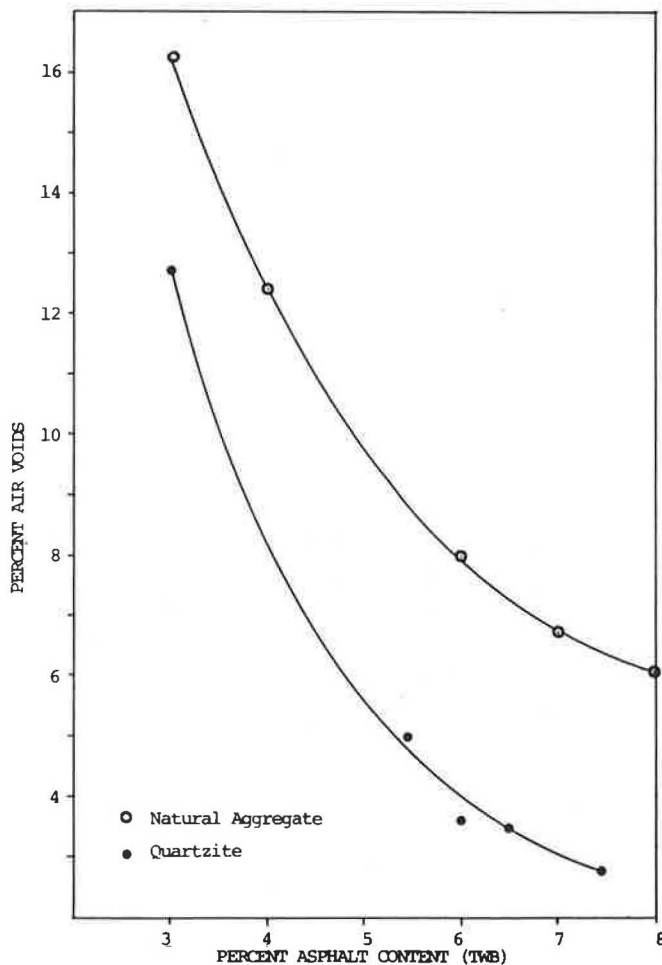FIGURE 6   Asphalt content versus flow.

FIGURE 5   Asphalt content versus air voids.

life span of the pavement, the average annual cost might be much higher when using natural aggregate instead of quartzite because of the higher maintenance cost associated with natural aggregate surfaces. In this part of the paper, the last statement will be closely examined and some light will be shed on the notion that expensive aggregate does not necessarily produce an expensive pavement.

The actual cost involved in constructing and maintaining any section of a flexible pavement during its life span depends on several items; some are associated with making the mix and others with maintaining the pavement during its life span. To conduct a nonbiased study between two alternatives, several parameters usually remain unchanged and only a few are allowed to change. In this economic study, parameters such as grading, drainage structures, base, and subbase will be considered the same for the two alternatives under study. Only the asphalt mat and the maintenance necessary during a specified period will change in the two alternatives. The following variables were considered most critical in affecting the outcome of the economic analysis.

X_1 = rate of inflation (%/yr);
X_2 = interest rate (%/yr);
X_3, X_4 = sealing cost of natural aggregate pavement and quartzite pavement, respectively ($/lane-mi);

TABLE 3 SKID AND DYNAFLECT DATA ON I-90 IN SOUTH DAKOTA

CHAMBERLAIN SECTION (QUARTZITE)			DRAPER-VIVIAN SECTION (NATURAL AGG.)		
MILE MARKER	D.F.	S.N.	MILE MARKER	D.F.	S.N.
264.39	1.20	54	200.00	1.06	47
263.53	1.19	52	201.13	1.09	48
262.29	1.21	55	202.00	1.04	42
261.10	1.18	54	205.00	1.05	49
259.52	1.17	55	206.00	1.01	46
257.00	1.21	54	207.36	1.03	51
256.00	1.18	54	208.11	1.05	51
255.00	1.20	53	209.00	1.05	50
254.00	1.22	55	210.14	1.02	49
252.99	1.18	54	211.00	1.04	49
251.01	1.19	55	212.81	1.03	45
Average corrected values	1.19	54.2		1.045	47.8

Note: D.F. = Dynaflect, S.N. = serial number.

X_5 = average distance natural aggregate is usually transported to job sites within study area (mi);

X_6, X_7 = price of natural aggregate and quartzite, respectively ($/ton-mi);

X_8, X_9 = transportation cost of natural aggregate and quartzite, respectively ($/ton-mi);

X_{10}, X_{11} = average annual maintenance cost (crack seal, potholes, etc.) of natural aggregate and quartzite surfaces, respectively ($/lane-mi/yr);

X_{12}, X_{13} = asphalt content (total weight base) in natural aggregate and quartzite hot mixes, respectively (%);

X_{14} = price of asphalt cement ($/ton);

X_{15} = fuel cost for heating the aggregate in the drum dryer ($/ton); and

Y = maximum distance that quartzite can be transported from the source to the job site (mi).

These variables were used to conduct a present-value analysis of two sections of roads that were identical as far as the dimensions are concerned, but yet different in the type of aggregate and the amount of asphalt. Each section is a hot-mix mat 1 mi long, 12 ft wide, and 3 in. thick; the first section is made out of natural aggregate and the other is made using quartzite.

These variables can be related mathematically by equating the present value of the natural aggregate pavement with that of quartzite pavement for a constant life span of 18 years.

$$PVNA = A(X_{14}) + B(X_6 + 1.9X_{15} + X_5 * X_8)$$

$$+ \sum_{n=1}^{17} C\ (1 + X_1)^n/(1 + X_2)^n \qquad (1)$$

where

$PVNA$ = present value of 1 lane-mi of asphalt mat made with natural aggregate;

A = number of tons of asphalt required;

B = number of tons of natural aggregate required;

C = X_3 for n = 3, 6, 9, 12, and 15;

 = X_{10} for other values of n;

n = period (yr); and

$$PVQZ = AA(X_{14}) + BB(X_7 + 1.1X_{15} + Y * X_9)$$

$$+ \sum_{n=1}^{17} CC\ (1 + X_1)^n/(1 + X_2)^n \qquad (2)$$

where

PVQZ = present value of 1 lane-mi of asphalt mat made with quartzite;

AA = number of tons of asphalt required;

BB = number of tons of quartzite required;

CC = X_4 for n = 6 and 12;

= X_{11} for other values of n; and

n = period (yr).

It should also be noted that a ton of quartzite needs 1.1 gal of heating fuel, whereas natural aggregate required about 1.9 gal to be dried in the drum dryer.

Preliminary calculations indicated that any reasonable set of data will yield higher values for PVNA than for PVQZ, which means that pavement employing natural aggregate is more expensive to construct and maintain during 18 years of its life than pavement constructed with quartzite. Therefore, quartzite pavement is obviously more economical to use. However, to expand the use of quartzite at locations distant from the quarries, the amount of savings between PVNA and PVQZ can be utilized to transport quartzite to various job sites. The distance (Y) to where quartzite can be transported is the maximum allowed at the break-even point, and it can be calculated by equating PVNA and PVQZ and solving for the dependent variable (Y).

Table 4 gives a summary of the variables used in the model and their values between 1979 and 1983. It should be noted that the variables X_3 and X_4 occur at different intervals. A general consensus among contractors and maintenance engineers confirmed that pavements with natural aggregates require seal coating on the average every 3 years, whereas quartzite pavements need it about every 6 years.

The model can be manipulated many different ways, and a sensitivity analysis reveals how the dependent variable Y is affected by the changes in any of the independent variables. To overcome the tedious calculations involved in determining Y, a computer program was developed to perform this task (1). Table 5 gives the values of the dependent variable Y as two independent variables X_6 and X_7 vary within a practical range.

EXAMPLE:

To explain the data in Table 5, suppose the following set of data are given:

X_1 = 7.5 percent,

X_2 = 10.0 percent,

TABLE 4 VARIABLES APPEARING IN THE MODEL AND THEIR VALUES

VARIABLE	DESCRIPTION	YEAR	NATURAL AGGREGATE	QUARTZITE
X_1	Inflation Rate in %	1983	7.50	
X_2	Interest Rate in %	1983	10.00	
X_3	Cost of Seal Coat in dollars/lane-mile	1983	$3500.00	
X_4		1983		$3500.00
X_5	distance in miles		10.0	Y
X_6	unit price of N.A. dollars/ton	1979 1981 1983	$1.20 $1.40 $1.50	-------
X_7	unit price Quartzite dollars/ton	1979 1981 1983	-------	$1.90 $2.35 $2.50
X_8, X_9	transportation cost dollars per ton-mile	1979 1981 1983	$0.065 $0.075 $0.080	
X_{10}	maintenance cost in dollars/lane-mile	1983	$500	
X_{11}				$300
X_{12}	Asphalt content		6.55	
X_{13}	(TWB) in %			5.70
X_{14}	Price of Asphalt cement in dollars/ton	1979 1981 1983	$125.0 $218.0 $185.0	
X_{15}	Fuel needed to dry agg. at ($0.70/gal)	1983	1.9 Gal/ton	1.1 Gal/ton

Note: N.A. = natural aggregate, TWB = total weight base.

TABLE 5 CRITICAL DISTANCE (Y) AS THE PRICE PER TON VARIES FOR BOTH TYPES OF AGGREGATES

	UNIT PRICE OF NAT. AGG. (DOLLARS/TON) = X_6						
	2.25	2.5	2.75	3.00	2.35	2.50	3.75
UNIT PRICE OF QUARTZITE (DOLLARS PER TON) = X_7							
3.400	138.1	141.2	144.3	147.4	150.5	153.6	156.7
3.800	133.1	136.2	139.3	142.4	145.5	148.6	151.7
4.200	128.1	131.2	134.3	137.4	140.5	143.6	146.7
4.600	123.1	126.1	129.3	132.4	135.5	138.6	141.7
5.000	118.1	121.2	124.3	127.4	130.5	133.6	136.7
5.400	113.1	116.2	119.3	122.4	125.5	128.6	131.7
5.800	108.1	111.2	114.3	117.4	120.5	123.6	126.7
6.200	103.1	106.2	109.3	112.4	115.5	118.6	121.7
6.600	98.1	101.2	104.3	107.4	110.5	113.6	116.7
7.000	93.1	96.1	99.3	102.4	105.5	108.6	111.7

X_3 = X_4 = \$3,500/lane-mi,
X_5 = 10 mi,
X_6 = \$3.50/ton,
X_7 = \$6.20/ton,
X_8 = X_9 = \$0.08/ton-mi,
X_{10} = \$500/lane-mi/year,
X_{11} = \$300/lane-mi/year,
X_{12} = 6.55 percent,
X_{13} = 5.7 percent,
X_{14} = \$200/ton,
X_{15} = \$0.7/gal.

Bulk specific gravity for both mixes was determined by laboratory tests and found to be close; therefore a value of 2.353, which yields 146.8 pounds per cubic foot, was used in the analysis.

An asphalt mat 3 in. thick, 12 ft wide, and 1 mi long needs

5,280 * (3/12) * 146.8/2,000 = 1,162.7 tons of hot mix

Case 1: Using natural aggregate

A = weight of asphalt required

= 0.655 * 1,162.7 = 76.16 tons

B = weight of natural aggregate required

= 0.9345 * 1,162.7 = 1,086.54 tons

Case 2: Using quartzite

AA = weight of asphalt required

= 0.057 * 1,162.7 = 66.27 tons

BB = weight of quartzite required

+ 0.9345 * 1,162.7 = 1,096.43 tons

PVNA = 76.16 * 200.0

+ 1,086.54 (3.50 + 1.9 * 0.7 + 0.08 * 10)

+ 3,500 $(1 + 0.075)^n/(1 + 0.10)^n$

(n = 3, 6, 9, 12, and 15)

+ 500 $(1 + 0.075)^n/(1 + 0.10)^n$

(n = 1, 2, 4, 5, 7, 8, 10, 11, 13, 14, 16, and 17)

If the PVNA is equated with the PVQZ, the value of the independent variable (Y) can be determined as follows:

40,889.57 = 66.27 * 200

+ 1,096.43 (6.2 + 1.1 * 0.7 + 0.08Y)

+ 3,500 $(1 + 0.075)^n/(1 + 0.10)^n$

(n = 6, 12)

+ 300 $(1 + 0.075)^n/(1 + 0.10)^n$

(n = 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 13, 14, 15, 16, and 17)

= 13,254.00 + 7,642.12 + 87.71Y

+ 5,705.22 + 3,882.47

Y = 10,405.76/87.7144 = 118.6 mi

This number is given in Table 5, and means that quartzite can be used in hot mixes on jobs 118.6 mi from the source and yet

yield a break-even cost with natural aggregate. Obviously if the job site is less than 118.6 mi away, a definite saving will result; the closer the job to the quartzite quarry, the more the saving will be. For the example just given, if both quartzite and natural aggregate sources were 100 mi from the mixing plant, a net savings of

$$10,405.76 - 87.7144(10) = \$9,528.62$$

will result during the 18-yr life span of the pavement for each lane-mi. Several other tables can be developed to examine the influence of other independent variables on the value of Y.

CONCLUSIONS

Sioux quartzite is available in massive quantities in eastern South Dakota. It is regarded by the majority of engineers as an excellent construction material. Its applications include building stones, paving blocks, crushed rocks, gannister, ballast, riprap, and aggregate in both portland cement and asphalt concrete mixes.

Despite several outstanding engineering properties that quartzite possesses, engineers are reluctant to use it because of its high initial cost (unit price) when compared with that of natural aggregate. Laboratory and field performances of hot asphalt mixes made with quartzite or natural aggregate were examined in this investigation. Also, economic studies were performed on the different hot mixes and the following findings were observed.

1. Asphalt mixes using quartzite aggregates required about 13 percent less asphalt than mixes employing natural aggregate because of lower absorption values. This lower absorption value also resulted in using 42 percent less fuel to dry any amount of quartzite in the drum dryer than that needed to dry the same amount of natural aggregate.
2. Field performance of a hot-mix surface course using quartzite is superior to that of a surface course using natural aggregate. The former exhibits higher skid resistance and Dynaflect over the latter, and shows fewer surface cracks and less disintegration.
3. The economic analysis revealed several interesting facts often overlooked by many individuals.
   a. Considering all expenses incurred during the life span of the pavement—such as initial cost, regular annual maintenance cost, and cost of overlays—it appears that under any reasonable set of assumptions, hot mixes with quartzite yield costs lower than those with natural aggregate.
   b. The amount of saving resulting when using quartzite instead of natural aggregate can be used to justify hauling quartzite to distant places.
   c. If the natural aggregate and quartzite are both available at the same distance from the job site, a definite saving will result by using quartzite.

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