Physical Characteristics of Polish Resistance of Selected Aggregates

BARBARA J. SMITH AND GLENN A. FAGER

The British polishing wheel and the British pendulum tester were used to provide polish values similar to skid resistance information on several construction aggregates potentially usable in bituminous pavements. The aggregates included light-weight aggregates (expanded shales), industrial slags, trap rock, chert, siliceous gravel, and carbonate aggregates. Ranked from good to poor polish values, the aggregates are expanded shale; soft carbonates with high acid-insoluble residue contents, some limestones and dolomites; sandstone; boiler slag; trap rock; hard limestones with low acid-insoluble residue contents; steel slag; siliceous gravels; and chert. Petrographic studies of the aggregates demonstrate the trend of soft or surface-renewing rock providing the best results, grading to harder, or more finely crystalline, aggregates yielding the poorest results within similar lithologic types. More research is needed to determine the potential for better use of several aggregates not currently or commonly used in Kansas bituminous pavements. Future research should include field studies of aggregates that have good potential in the laboratory tests but are not now being used.

The testing of a variety of available coarse aggregates, both natural and industrially produced, could provide information for determining appropriate aggregate types for skid resistance in bituminous pavements. The researchers sought to evaluate frictional characteristics of individual aggregates rather than of the mixes. It was the first time coarse stone aggregate had been so characterized in Kansas. The methods followed were ASTM-D3319 and ASTM-E303. Eight different kinds of aggregates were tested on 21 sample sets.

BACKGROUND

Kansas researchers have evaluated aggregates for skid resistance in bituminous pavements since the 1970s (*1–3*). The design of skid-resistant pavements is a safety problem for any pavement designer. Strength and durability too often hold the primary concern of the designer, especially in bituminous construction. Even though the pavements may retain serviceable strength and durability, the frictional characteristics of some pavements deteriorate faster than others, posing a potential safety hazard. Because the previous evaluations have been field tests of pavements under traffic, some pavements being much older than others, a faster method to find skid resistance characteristics had to be found. Kansas Department of Transportation (KDOT) field data of the aggregates for evaluation are sparse or nonexistent because they had not been used or the information on projects using the limestones had been difficult to find. By polishing the several kinds of aggregates on the British polishing wheel, the time for obtaining a terminal polish on the aggregates could be cut to hours in the laboratory instead of years in the field. This saving was demonstrated by the Texas Highway Department (*4*) and was reported more recently by the New Jersey Department of Transportation (NJDOT) (*5,6*).

Kansas Department of Transportation, Topeka, Kans. 66611.

TESTING

The eight kinds of aggregates tested were steel slag; siliceous gravel consisting of quartz, feldspar and other igneous rocks, both crushed and uncrushed; carbonate-cemented sandstone; chat (crushed chert as a by-product of lead and zinc mining in southeast Kansas); boiler slag; trap rock; lightweight aggregate (expanded shale), in this report known as expanded shale, from two sources; and 12 carbonate aggregates including limestones, dolomitic limestone, and dolomite. One limestone was used as the reference stone on the polishing wheel. Altogether, 21 samples were polished and then tested with the pendulum. All are available as potential construction materials in Kansas. The procedure for polishing was ASTM-D3319 using the British polishing wheel. Each sample was run with the reference limestone. Because the methods were unfamiliar, some time was spent in checking procedures and accuracy.

Each aggregate selected for testing was supplied in a sample passing the ½ in. but retained on the ⅜ in. screen. From this sample, a set of molded samples was prepared using a polymer compound. The molded samples fit around the outer circumference of the larger wheel on the polishing machine. Each aggregate sample was run with the reference limestone. A weighted rubber-tired wheel continuously supplied with grit and water revolved in contact with the exposed aggregate surfaces of the samples. This process supplied the wear for comparative testing. At planned intervals, the wheel was stopped and the molded samples were removed for testing with the pendulum tester.

The ASTM-E303 method was used to measure the surface frictional properties with the British pendulum tester. Most of the aggregates began at an initial high polish value (PV), then quickly lost PV as the test proceeded. After several kinds of aggregates had been run for 26 and 52 hr, it was clear that the surface friction values obtained changed little after 10 hr. Thereinafter, the samples were run for times of only 10.5 hr (Figures 1–6). The wheel revolved at 320 rpm; testing was stopped at 200,000 revolutions and final PV was obtained. The higher the PV obtained at the 10.4-hr testing the better the skid resistance of the aggregate.

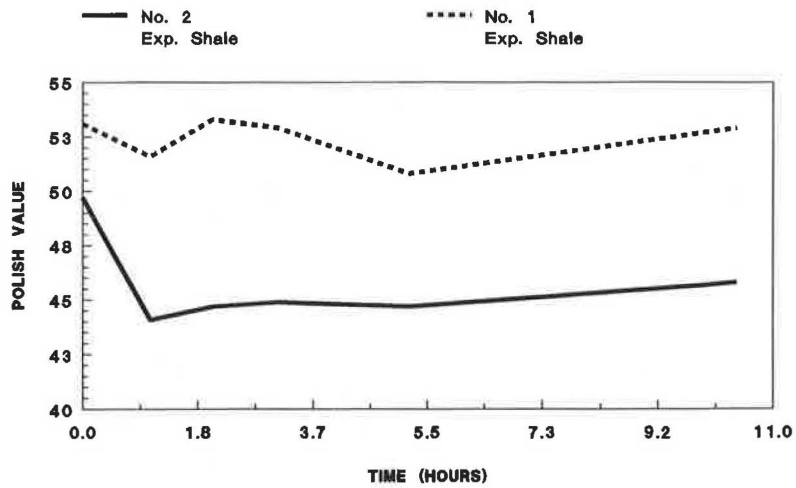

FIGURE 1 PVs of two expanded shales during more than 10 hr of testing.

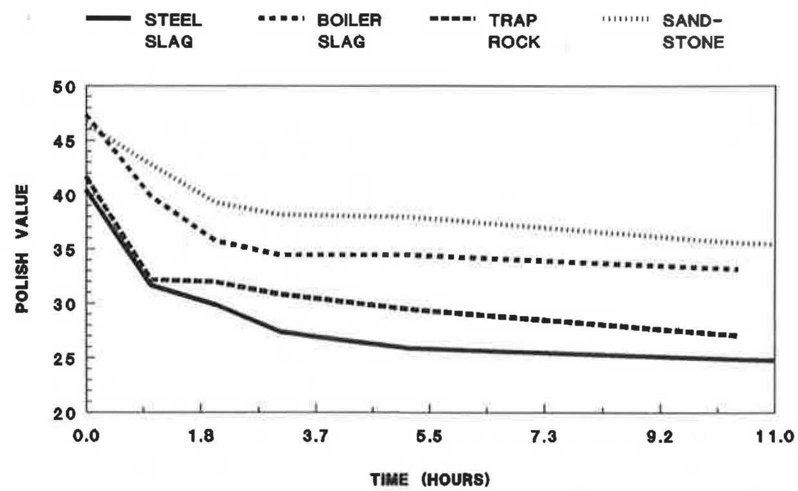

FIGURE 2 PVs of two slags, trap rock and sandstone, during more than 10 hr of testing.

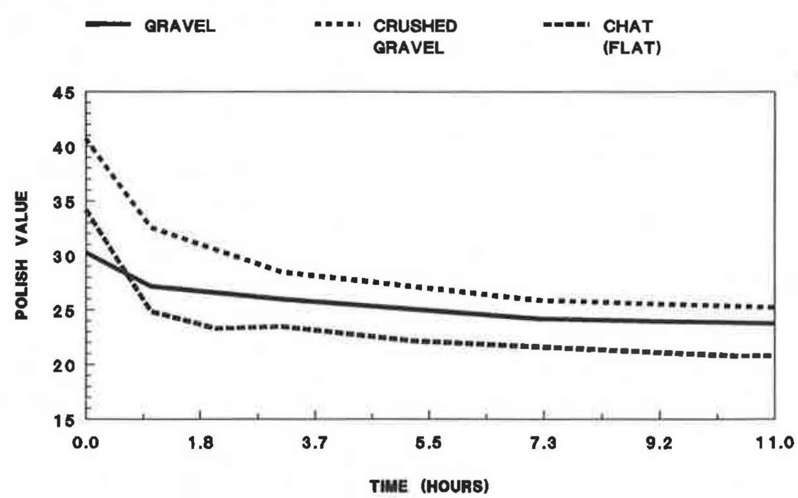

FIGURE 3 PVs of natural gravel, the same gravel crushed, and chat in a flat orientation during 11 hr of testing.

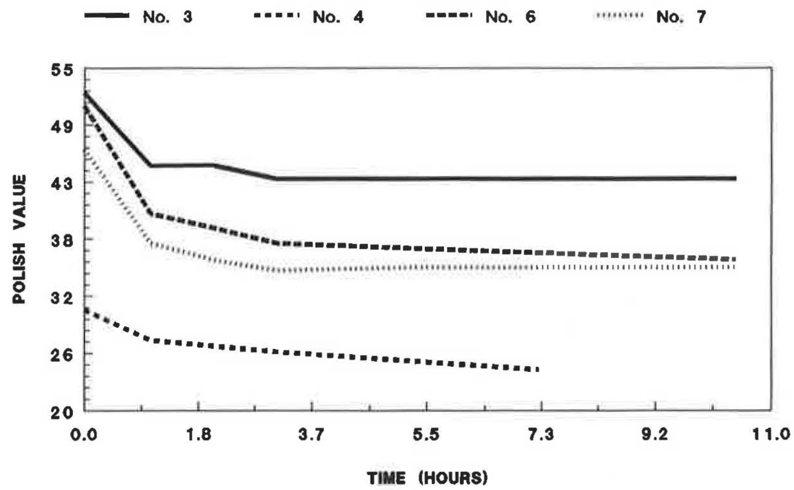

FIGURE 4 PVs of carbonate aggregates identified by rank as being in the top third of 21 aggregates tested.

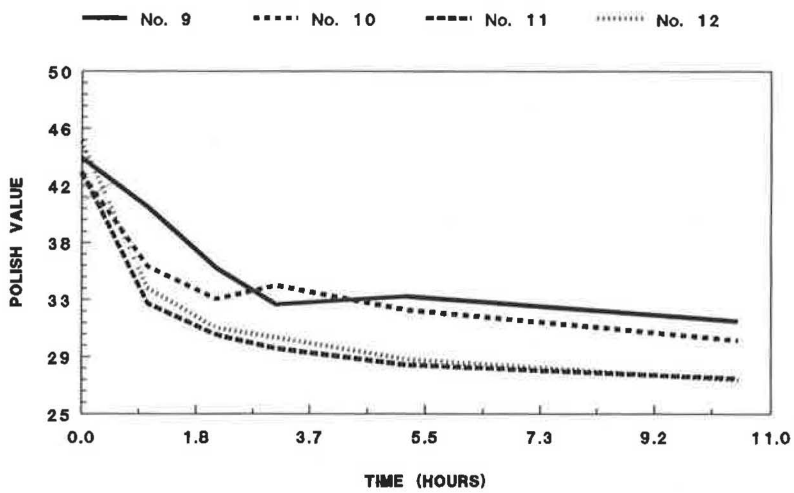

FIGURE 5 PVs of carbonate aggregates identified by rank as being in the middle portion of 21 aggregates tested.

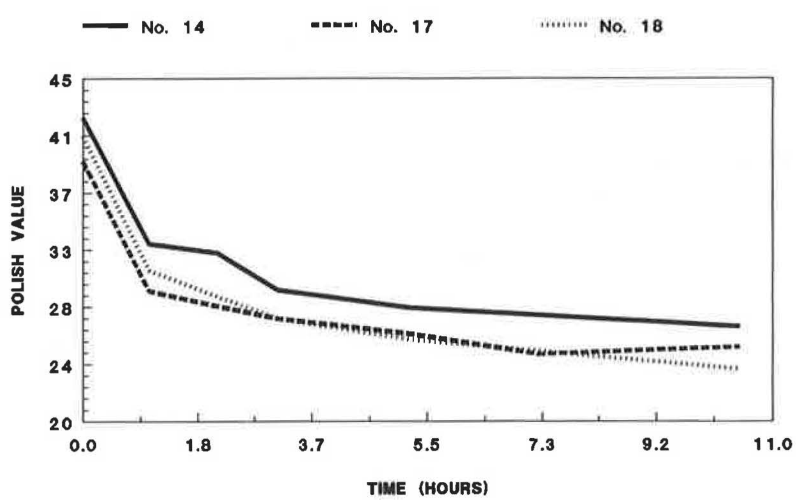

FIGURE 6 PVs of carbonate aggregates identified by rank as being in the lowest third of 21 aggregates tested.

Comparisons of some pendulum values were made with New Jersey test results (Table 1). Many of the rock samples in the comparisons are not included in the study reported here and this table has no other relevance except to demonstrate similarity of values obtained. The samples were run on different wheels for various amounts of time. Then they were tested by both KDOT and NJDOT. These comparisons were reasonable. One variable found was the age of the pad on the pendulum. Results of old pads (those used but still meeting ASTM specifications) were compared with newly conditioned pads. Changing to newly conditioned pads before testing each new aggregate sample and using them for the duration of tests on that sample resulted in better reproducibility of test numbers (Figures 7 and 8). The correlation coefficient increased from 0.62 to 0.78 for the comparison readings. For reading consistency, the swing of the pendulum had to be in the same direction as the wear of the polishing wheel tire.

A reference aggregate was established and run with each tested aggregate. This reference aggregate ensured that the tests were all comparable. Although the reference aggregate was always the same, the results of each run varied as would be expected. An average of the reference aggregate values is reported as the value for that aggregate (Figure 9).

In order to compare the aggregate test results with a bituminous mix result, several samples of KDOT BM-1 gradations were prepared using only the reference limestone. Two molded samples of each selected percent of asphalt were run. This was the first time a mix had been run on the polishing wheel and it was not known whether the molded samples would hold up. Some ran almost 10 hr; others failed earlier (Table 2). Comparisons of these values with those for the reference limestone indicated that the BM-1 had not obtained the same level of polishing as the aggregate alone, the BM-1 having higher PV than the limestone. Although no field tests could be run on the test aggregates, this finding may have relevance in trying to correlate field and test data at a later time. The test of aggregates alone may be more predictive of performance of aggregates in seal coats or friction courses than that in mixes. Because of the early failure, there has been no further attempt to correlate the mix results either with limestone results or field measurements.

DISCUSSION OF RESULTS

After the completion of the tests, the results were ranked from highest to lowest PV (Table 3). The value used for ranking was the curve-fitted final PV point at 10.4 hr of wheel wear for each sample. This value was chosen rather than the actual data point because not all samples had been tested at exactly 200,000 revolutions in the beginning of the study. More discussion of this curve fitting was given by Fager and Smith (*7*).

Of the noncarbonate aggregates tested, the expanded shales and the slags had vesicular structures consisting of tiny to larger rounded cavities throughout the resultant aggregate. The sandstone was carbonate-cemented quartz. The trap rock was generally dark igneous and metamorphic fragments with hematite and sulfides such as galena and pyrite. The gravels were igneous rocks and minerals such as granite, quartz, and feldspars with some sandstones and limestones. Chat was a cryptocrystalline quartz variety of chalcedony or chert, produced as a by-product in southeast Kansas. The trend that could be seen in this group was that the vesicular aggregates and sandstone tested better than the crystalline igneous or metamorphic rock aggregates. The cryptocrystalline variety of quartz polished easily. The vesicular aggregates possibly wore by breaking and renewing the wearing surface with a fresh edge, the more edges available the better the skid-resistant characteristics. Always having an unpolished surface best explains the lack of decrease in PV as in the other aggregates tested (Figure 1). The sandstone had a soft cement that wore faster than the harder sand particles, bringing into relief the sand and therefore always renewing at the surface. It also could renew by breaking through the cement. Of the noncarbonate aggregates tested, vesicular and sandstone aggregates produced better PV values.

The two expanded shales tested proved to have the best polish resistance characteristics of the aggregates tested. Although these were in limited use in Kansas for bituminous mixes, more use might be made especially on critical pavements, i.e., those with large traffic volumes. In early field testing of expanded shale in open-graded mixes or as sprinkle treatment (*8,9*), the surfaces retained ice and snow and were unsuitable for driving in Kansas winters. Because these results were the same for other aggregates in the field trials as well, the expanded shale should be tested in other pavement designs. One characteristic that could limit the use of expanded shale is its low resistance to freeze-thaw damage, thus possibly lowering the pavement design life. Field tests need to be run to separate assumptions from actual limits in use.

Chat has been used for many years in Kansas for bituminous design. It seems to have good skid resistance in the field that was not shown by the present tests. This limitation of the polishing tests was clearest with chat but it could also be biasing other aggregate results in less obvious ways. In order to make the small molded samples run on the wheel, individual aggregate pieces had to be selected from the sample and placed in the mold. These pieces stayed in place while the full mold set was selected. Ottawa sand was then used to fill the lower small spaces of the mold before placing the polymer over the exposed aggregate. After the polymer cured for 1 hr and the mold forms were removed, the aggregate surfaces that were on the bottom of the mold were then the exposed aggregate surfaces, having been protected from polymer penetration by the sand.

Chat is usually platy, bladed or elongated in shape, seldom compact. The pieces that best made into acceptable test molds were bladed, elongated, or compact, and the exposed surfaces were always rather smooth on the finished molded sample. This assortment was chosen as rather a random orientation of pieces in the mold. One set of samples was made with the narrow edges exposed for testing. Upon turning on the wheel to begin the test, it was apparent that the knife-like edges were wearing the test wheel excessively. Also, the wheel began to bounce rather than rolling smoothly. This test was not completed.

In the field, the chat would not have all flat surfaces or all knife-edged surfaces exposed but would be a mixture of both with pieces overlapping at angles to each other. It is probable that the narrow-edged surfaces exposed would chip off, leaving a new sharp edge under traffic, and thus would compen-

TABLE 1 NJDOT/KDOT PV COMPARISONS

No.	Description	New Jersey	KDOT[a]	KDOT[b]
1	Limestone	30	27.6	
2	Limestone	29	26.0	
3	Limestone	31	31.7	
4	Chat	20	22.6	23.3
5	Chat	19	22.3	24.4
6	Chat	22	22.9	24.0
7	Gneiss	33.4	27.0	32.0
8	Argille	28.2	23.0	27
9	Trap Rock	25.2	20.6	24.3
10	Carbonate Rock	21.0	19	22.7
11	Crushed Gravel	31.2	23	26.4
12	Steel Slag	26	19.6	22.6
13	Limestone	30	33	35.4
14	Limestone	33	27.9	32.6
15	Steel Slag	25	22.1	23.7
16	Limestone	32	28	33.0
17	Limestone	35	30	33.9
18	Limestone	30	27.3	31.7
19	Limestone	30	28.9	32.6
20	Limestone	30	23.4	27
21	Limestone	26	22.4	26.6
22	Limestone	26	23	24.7
23	Limestone	27	26.6	27.4
24	Limestone	26	27.4	31.3
25	Limestone	40	32.6	34
26	Limestone	35	25.4	32
27	Limestone	31	24.4	27.3
28	Limestone	30	23	26.0
29	Trap Rock/Fanwood	30	30	30
30	Trap Rock/Tilcon	29	28	29
31	Carb.Rock/Berks,Oley	20	24	24
32	Crush.Grav./Warner	34	34	36
33	Crush.Grav./Warner	34	33	34
34	Kingston Argillite	27	25	26
35	Carb Rock/Glasgow	21	25	24
36	Gneiss/DeVault	28	26	27
37	Trap Rock/Stavela	26	28	28
38	Gneiss/Riverdale	27	27	33
39	Gneiss/Hopatcong	27	33	26

[a] - Measured using a pad passing ASTM standards.

[b] - Measured using a newly conditioned pad.

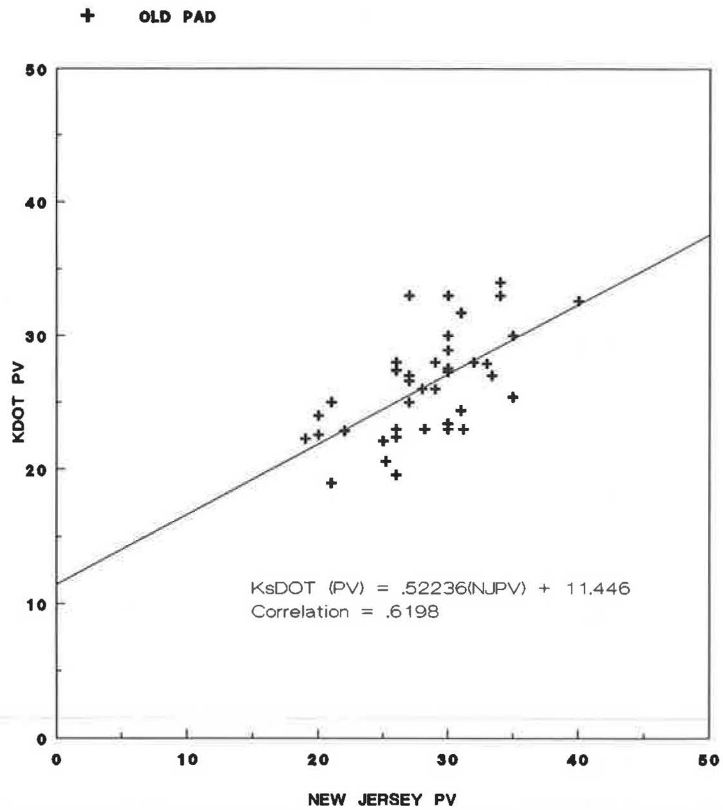

FIGURE 7 Test values recorded using the same older test pad by two agencies.

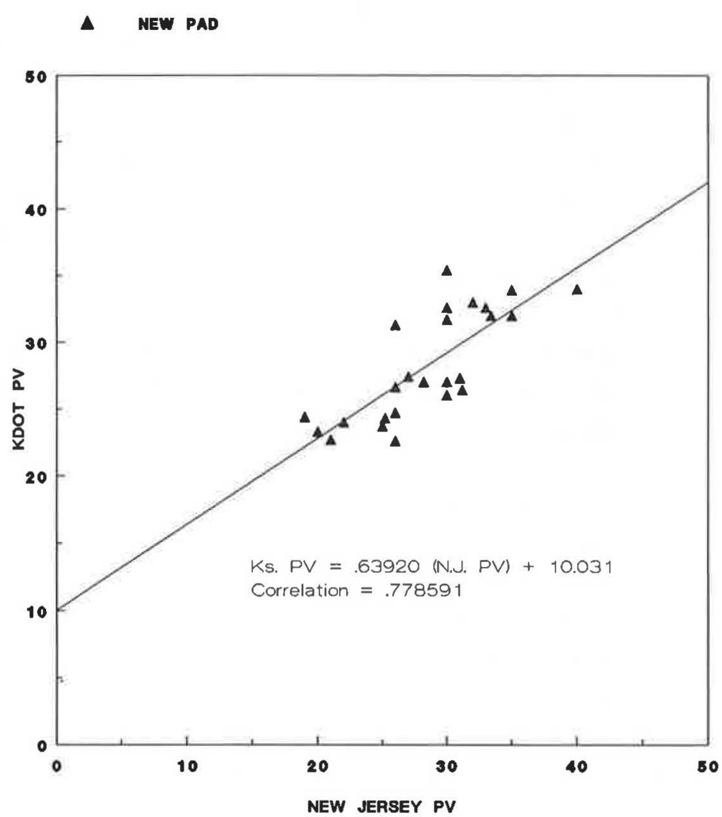

FIGURE 8 Test values recorded using a new test pad by two agencies.

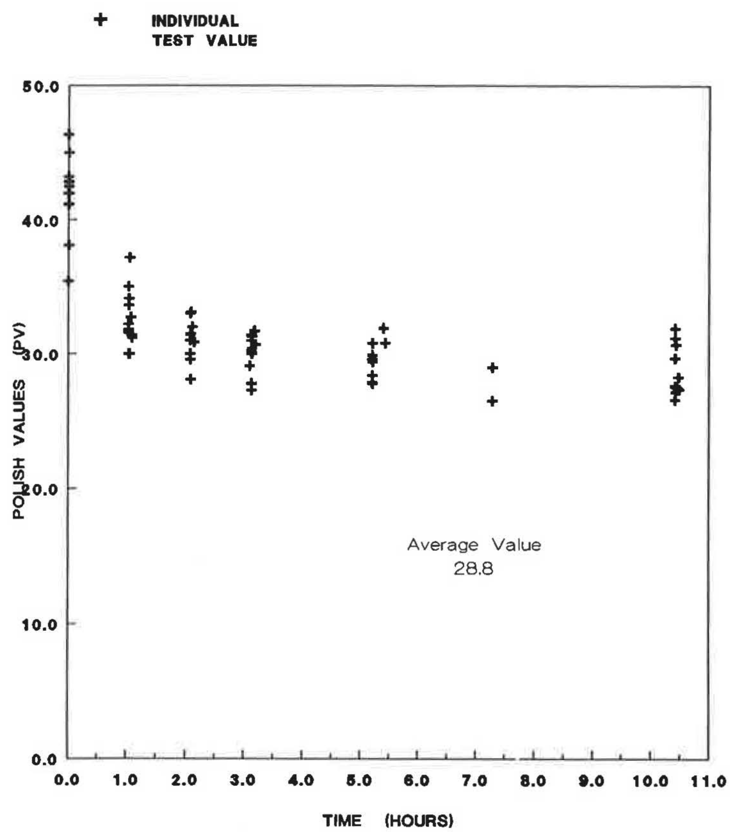

FIGURE 9 PVs of the reference aggregate during many test runs of nearly 11 hr each.

sate for those flatter, smoother surfaces that were polishing. The shapes of the aggregate in the molded samples tested were not randomly placed. This defect biased the results of the test. Other aggregates with variations in lithology that might be reflected in shape such as the carbonates (see Table 4) could be biased similarly by the process of choosing, although the results might not be as pronounced as with the chat test. They would depend on the variability within the aggregate sample.

The number of carbonate aggregates studied was limited relative to the many carbonate rock sources in the state. For 12 samples, carbonate aggregates tested included a dolomite and a dolomitic limestone as well as the usual limestone aggregates. The very light-colored limestones as well as the very dark aggregates do not usually make the best concrete for use in Kansas. Light-to-medium colors usually perform best in the concrete suitability tests and in the field. A range of colors was picked in choosing the aggregates for this study. Some of the aggregates were suitable for use in concrete and others were not. A representative sample from each aggregate was split into describable lithologies; information listed included crystallinity, luster, color using the Munsell color charts, shape, edge, and side characteristics. Tables 4 and 5 summarize some of the aggregate descriptive characteristics as well as physical test results.

While studying the characteristics of only the carbonate aggregates ranked by the research test results, several interesting relations come forth. The carbonate aggregate results overlapped the noncarbonate aggregate results. The 12 aggregates were listed by rank using the final PV results of all the aggregates tested (Tables 3–5). As an aid in generalizing the characteristics of the carbonates only, the top four, the middle four, and the bottom four by rank were grouped. The top four were ranked 3rd, 4th, 6th, and 7th, respectively, of the 21 samples. The middle four were ranked 9th, 10th, 11th, and 12th, respectively. The lowest four carbonates were ranked 13th, 15th, 16th, and 20th out of the field of 21 aggregates. These 12 aggregates have been numbered as Samples 1 through 12 for Tables 3–5, their rank in the group of 21 given in the column labeled "rank" in Table 4.

The top performers in the first group were mostly very soft limestones with dull, even chalky, luster. The softness was also evidenced by the generally rounded edges of the rock and the high Los Angeles (LA) wear numbers. Also the absorptions were high. Three had very light colors designated in Table 4 by high percentage *L*. Only one had a large acid insoluble residue (AIR), but it also had a lower absorption and wear number and darker coloration. One was a dolomite. The dolomite rock in Kansas that passed for concrete use was usually of light-to-medium color.

In the middle group, the aggregates appeared to be harder as evidenced by angular edges; straight, smooth sides; and generally lower LA wear numbers. They also were less absorptive. The luster was less dull, but the one that did exhibit a dull luster was a dolomitic limestone. This group contained the aggregates of light-to-medium color.

In the lowest grouping, all exhibited angular edges (indicating harder rock) and lower absorptive values. This group also included the aggregates having the lowest contents of acid-insoluble minerals and medium (M) to darker (D) colors.

TABLE 2 PVs OF A BM-1 ASPHALT MIX

Table 2. Polish Values (PV) of a BM-1 Asphalt Mix.

Asphalt %	Initial PV	PV Readings at Intervals 1 hr	2 hrs	3.5hrs	5.5hrs	9.75hrs	
5.75	46.8	36.7	39.1	failed			
6.25	49.3	36.0	37.5	35.7	35.9	34.7	failed
6.75	47.1	36.3	35.8	34.3	35.5	failed	
7.25	47.9	36.3	37.5	34.3	34.6	33.7	failed
7.75	42.6	33.3	33.9	34.5	35.0	failed	
8.25	31.5	33.9	34.1	34.7	33.1	failed	
8.75	32.1	32.8	33.1	32.0	34.1	32.3	failed

TABLE 3 PVs OF TESTED AGGREGATES

Rank	PV	Aggregate and Laboratory Number	
1	50.7	Expanded Shale	
2	44.0	Expanded Shale	
3	43.6	Limestone	83-1430-5
4	41.3	Limestone	83-2171-1
5	35.4	Sandstone	
6	35.3	Limestone	83-1659-1
7	34.2	Limestone	81-931-4
8	33.1	Boiler Slag	
9	31.7	Limestone	88-105-4
10	30.3	Limestone	81-749-2
11	28.7	Limestone	86-4527 Reference
12	27.5	Limestone	81-750-1
13	27.4	Limestone	81-83-13
14	27.0	Trap Rock	87-3134
15	26.8	Limestone	82-2990-2R
16	25.3	Limestone	83-2531-5
17	24.8	Steel Slag	
18	24.3	Crushed Gravel	
19	23.1	Gravel	
20	21.9	Limestone	81-945-1
21	20.7	Chat (flat)	

There was less earthy luster. From higher to lower PV, the acid-insoluble contents and absorptions tended to smaller values and the rocks tended from softer to harder. The softness of the higher-ranked carbonates probably produced higher PV by wearing away rather than by polishing, similar to the vesicular aggregates discussed.

Questions for further study center on possibilities for more research on expanded shales and dolomite or dolomitic limestones for bituminous pavements. Are there dolomites and dolomitic limestones that do not qualify for concrete aggregate but have characteristics that should be tested for bituminous pavements? If pretreated, can the softer, more absorptive carbonates be durable enough to make long-lasting, skid-resistant pavements without excessive wear ruts occurring? Are there limestones in Kansas that have reactive quartz varieties excluding them from use in concrete, but that contain enough quartz as acid-insoluble residue fraction to add abrasiveness, thereby raising the polishing value of the aggregate? How well do expanded shales weather during Kansas winters?

TABLE 4 LIMESTONE DESCRIPTIONS

Sample	Rock	Rank	Luster	Color[s]	Mineral	Shape	Edge	Sides
1	Ls[a]	3	e[d]	L^{t}_{10}[w]		b[g]	sr[k]	p[o]
2	Ls	4	e	L_7M_3[u]		c[h],p[i]	sr,r[l]	i[p]
3	Dol[b]	6	e	L_4M_6	Dol	p,c	r,a[m]	sm[q],p
4	Ls	7	e,cx[e]	L_3M_7		p,b,e[j]	a,sa[n],sr	sm,r[r]
5	Dol.Ls[c]	9	e	M_3D_7[v]	Dol	p,b,c	a	sm,r
6	Ls	10	cx,fx[f]	L_6M_4		b,p	a, sr	sm,r
7	Ls	11	e,fx	L_5M_5		c,p,e	a,sa, rd	r,sm
8	Ls	12	fx	M_{10}		c,p	a	sm,r
9	Ls	13	fx,e	L_5M_5	ch.,sh[x]	c,e,p	a,sa	sm,r
10	Ls	15	e,cx	L_7M_3		c,p	sa,a	r,i
11	Ls	16	fx	M_2D_8		c,p	a,sa	sm,r
12	Ls	20	fx	M_4D_6		c,p	a,sa	sm,r

a limestone
b dolomite
c dolomitic limestone
d earthy
e coarsely crystalline
f finely crystalline
g bladed
h compact
i platy
j elongated
k subrounded
l rounded
m angular
n subangular
o pitted, vuggy
p irregular
q smooth
r rough
s Munsell Color Charts used for obtaining value of color, lightness or darkness.
t light colored, values of 7.5 or higher.
u medium colored, values of 6 to 7.
v dark colored, values of 5.5 or darker.
w subscript times 10 gives percent of aggregate with value characteristic
x cherty, shaly

TABLE 5 LIMESTONE TEST RESULTS

Sample	Rock	A.I.R.[d]	Class	Bit	Absorption[j]	L.A.[k]
1	Ls[a]	3.94	1	NA	9.94	33
2	Ls	6.97	1	No	7.24	46
3	dol[b]	3.05	1[f]	NA	5.7	39
4	Ls	13.46	0[g]	NA	2.84	22
5	dol.Ls[c]	NA[e]	0	NA	4.72	14
6	Ls	2.29	1	Yes[h]	3.18	29
7	Ls	NA	NA	NA	2.1	29
8	Ls	7.97	0	No[i]	1.72	27
9	Ls	8.19	0	No	3.05	27
10	Ls	1.15	1	NA	2.16	35
11	Ls	1.77	0	Yes	1.49	NA
12	Ls	7.84	1	Yes	1.09	19

a - limestone
b - dolomite
c - dolomitic limestone
d - acid insoluble residue, determination of total
e - not available
f - usable in concrete
g - not usable in concrete
h - usable in bituminous pavement
i - not usable in bituminous pavement
j - Kansas Test Method KT-6
k - Los Angeles Wear Test AASHTO T96

CONCLUSIONS

Several tests of the procedure for accuracy and reproducibility were performed and comparisons with other agencies were made. The results of the study have enabled ranking of 21 different aggregates. Most of the aggregates had a rapid decrease in PV to a lower value, and then the PV leveled out. The general trend was for vesicular or softer rock to polish less than crystalline rock, and very finely crystalline rock to polish exceedingly well. The two expanded shales and the one sandstone tested gave excellent to good results. Boiler slag and trap rock performed better than similar-looking steel slag and siliceous gravel materials tested. Chat performed poorly in the flatter orientation tested. Carbonate aggregates overlapped the upper through the lower PVs. Dolomite content and the higher acid-insoluble residue contents in softer limestones of the tested aggregates characterized the better-performing aggregates. Further research should be done with these. Expanded shales warrant testing for use in critical pavements having higher traffic volumes.

ACKNOWLEDGMENTS

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