COMPARATIVE INVESTIGATIONS OF INTERNATIONAL TEST METHODS FOR SMALL-SIZED COARSE AGGREGATES

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Not enough detailed knowledge exists about loads and stresses in road pavements. Consequently, based on certain models, there are many different test procedures for coarse aggregates that strain the materials by compression, impact, and abrasion or by a combination of these stresses. A comparison of test values that are obtained with the different test methods has not been possible, and experiences with various qualified aggregates cannot be transmitted from one country to another. Comparative tests were conducted by using different aggregates with the most important test methods: Los Angeles, Deval, German impact, British impact, and modified Marshall impact in standardized and modified form. The calculated linear regressions showed that, although the strains of the aggregates are very different, the tests characterize the same or at least similar properties of aggregates. In a comparison of different laboratories, we obtained a relative reproducibility of about 20 to 30 percent for the Los Angeles and the German impact tests. This means that further strict standardization of testing machinery and procedure is necessary if values obtained at different laboratories are to be compared. The calculated linear regressions that were found for the different test procedures will allow the comparison of specifications for small-sized coarse aggregates tested with different international test methods. International experiences and literature on the question of requirements for use of aggregates can now be exploited.

•NOT enough detailed knowledge exists on the loads and stresses in road surfaces resulting from traffic. Consequently, no exact values are known about the nature and the quantity of stress that highway materials are undergoing. Based on certain models, many different test procedures have been developed for coarse aggregates used in road surfaces. The specifications for their use in different countries are largely based on subjective experiences and differ greatly. The test procedures developed for testing coarse aggregates stress the materials by compression, impact, and abrasion or by a combination of these stresses. In no case, however, can a detailed analysis of stresses be performed, and thus an exact and objective evaluation of test results is not possible. A comparison of test values obtained with the different test methods has also not been possible. Because test methods are different, the experiences with various satisfactory aggregates cannot be transferred from one country to another. A meaningful comparison of national requirements for special use of aggregates has also been impossible.

In West Germany the standardized impact test is strongly questioned, especially because of the great variation in test results obtained when identical materials are tested in different laboratories. Comparative tests have shown relative deviations of ±20 percent. We believed we could find better methods that we could standardize in the future.

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INTERNATIONAL TEST METHODS FOR COARSE AGGREGATES

A detailed study of the international literature on test methods for small-sized coarse aggregates shows that special test procedures are used that stress the material by compression, impact, and abrasion or by a combination of these stresses. A procedure with compressive load for small-sized coarse aggregate is only standardized in the British Standard 812 (28) and for large-sized coarse aggregate in the German DIN 52 109 (29).

Test procedures with abrasive strain include the Deval test (22, 25, 26, 37), which is of French origin (3, 4). The most popular abrasive method is the American Los Angeles test that is used in its original or modified form in many countries around the world, for example, in the United States (23, 24), France (36), Sweden (11), Hungary (16, 20), and the Soviet Union (5). Impact crash is used for testing coarse aggregate in Norway (8), Sweden (11), Great Britain (28), Switzerland (10, 21), and Germany (29, 30, 33). The German impact test had its origin in testing methods for large-sized coarse aggregate (29) and was later modified for small-sized coarse aggregate (30, 33) in a size of 8 to 12.5 mm ($\approx$ 5/16 to 1/2 in.). This test method has long been questioned. The test machine for impact crash is very complex, and as a result only a small number of testing laboratories are equipped with it. For many years, we have tried to use equipment that is simpler and more often available such as the Marshall compaction hammer (27). The research of Pös (17) and Gragger (7) has shown that such a modified test method will bring sufficient correlation with the usual German impact test so that its use for quality control in quarries or at hot-mix plants is possible.

For testing small- and large-sized coarse aggregates, we believe that 5 testing methods are of special interest from an international point of view: the American Los Angeles test, the French Deval test, the British impact test, the German impact test, and the modified Marshall impact test.

Only a few mathematical relations among these 5 procedures can be found in the literature. Höbeda (11) reported on relations among the Swedish impact test, the German impact test, and a modified Los Angeles test. Nagel (14) found linear regressions among the German impact test, a modified Los Angeles test, and a compression test for coarse aggregate of size 5/16 to 1/2 in. and found linear correlation coefficients in the range of 0.89 to 0.96. Brand and Dinkgraeve (1) conducted comparative researches with the Los Angeles test (23, 24) and the German impact test (30, 33) for large- and small-sized coarse aggregates and found linear correlation coefficients of 0.90 and more. In Gragger's work (7), a correlation coefficient of 0.98 between results of the German impact test and the modified Marshall impact test was found.

The relations given above show that even test methods with very different loads and procedures will identify similar properties of aggregates. It was the main task of this research program to analyze experimentally such relations among the most important test methods, to point out the value of the test results, and to calculate the variations among the different methods.

TEST PROCEDURES

Initially using the 5 basic test methods in 23 standardized and modified procedures, we made 10 tests of each with 2 aggregates—limestone and basalt. The tests were only performed with methods that are used for small-sized coarse aggregates, 1 in. to No. 8, inasmuch as larger sizes usually are not used in the surface and base course in road construction. After calculating the dispersions (standard deviations), we eliminated 12 modified procedures that showed large standard deviations under identical conditions.

A full test program was then conducted with the remaining 11 test procedures. The test conditions are given in Table 1.

Test method 1 represents the German impact test (30, 33) with aggregate of size 8 to 12.5 mm ($\approx$ 5/16 to 1/2 in.) in a modified form. We took the percentage passing the 3.15-mm ($\approx$ 1/8 in.) sieve for calculating the impact value, SD_{sp8} (14, 15), instead of using the 5 sieves (8, 5, 2, 0.63, and 0.2 mm) for analyzing an impact crash value, SZ_{sp} (33). Nagel (15) found a high correlation coefficient for a linear regression between SD_{sp8} and SZ_{sp} as shown in Figure 1. The test apparatus is shown in Figure 2. The weight of the sample was 0.5 × ρ_R, where ρ_R = bulk specific gravity of aggregate in g/cm^3. The material was planed in a cylindrical steel cup and received 10 blows with a 110-lb hammer dropping from a 19.7-in. height.

For calculating the abrasion with the Los Angeles machine, the gradings B, C, and D of test samples as given in ASTM Designation C 131-69 (23) were used. In addition to these standardized methods, the gradings were varied corresponding to the German test materials of size 8 to 12.5 mm (≈$^5/_{16}$ to $^1/_2$ in.). The test value LD^*_{sp8} is obtained by using a weight of 5,000 g and analyzing the abrasion value as the percentage passing the 3.15-mm (≈$^1/_8$ in.) sieve. The test value LD_{sp8} is based on a sample with a weight of 2,500 g.

From the Deval test, the gradings D and E of ASTM Designation D 289-63 (26) were selected. Aside from these standard methods, no modified procedures were tested. We had learned from our first test program that with the Deval test procedure sufficient spreading cannot be achieved to differentiate "abrasive" from "nonabrasive" aggregates.

The modification of the British impact test had shown high dispersions in the first program so that only the standard material ($^1/_2$ to $^3/_8$ in.), according to British Standard 812 (28), was tested. The quantity of test material is determined by a "measure shell" and, depending on the bulk specific gravity of aggregate, amounts to 340 to 400 g. The test sample is subjected to 15 blows by a hammer of 30 to 31 lb falling freely from 15 in. (Fig. 3). The test value ID_{BS} is calculated as the percentage passing sieve No. 7 (BS).

For the modified Marshall impact test, the Marshall compaction hammer (27) is used. The test value MD^*_{sp8} is obtained when coarse aggregate of size $^5/_{16}$ to $^1/_2$ in. with a weight of 260 × ρ_R (in g) is compacted by 200 blows. How the material is put into the 4-in. mold cylinders between 2 metal plates is shown in Figure 4. A second Marshall value, MD_{sp8}, is obtained by the use of a sample weight of 400 g. Both values are calculated as the percentage passing a 3.15-mm (≈$^1/_8$ in.) sieve.

The method of sampling, preparing, and grading guaranteed that all samples were members of one population, thus permitting a statistical evaluation.

For all test procedures, materials of a shape with a breadth-thickness ratio of b:d ≤ 2 were prepared by a second sieve analysis with so-called slit sieves (14, 18) after narrow ranges were graded with usual sieves.

With each of these 11 procedures, 15 different aggregates that are used in road construction were tested. The program included 11 igneous rocks (granites, diabases, and basalt), a metamorphic rock (quartzite), and 3 sedimentary rocks (2 different limestones and a quartzitic sandstone).

ANALYSIS OF REGRESSION

With each of the 11 test methods and all 15 aggregates, 3 tests were made. The mean value of the 3 single values was the input for the analysis of regression (9). By the use of linear regression y = a + bx, the correlation coefficient for the relation between each two test procedures could be calculated (6, 9, 21).

The correlation coefficients r_{xy} for the linear regressions between the different test methods are given in Table 2. The calculated equations for the linear regressions are given in Table 3. The equation given in Table 3 that shows the linear regression for any correlation of 2 test methods is also given in Table 2.

A test developed by Fisher (6) can be conducted to test whether the correlations are significantly greater than 0. With the value

$$t = \left(r_{xy}/\sqrt{1 - r_{xy}^2}\right) \cdot \sqrt{n - 2}$$

or

$$r_{xy} = t/\sqrt{t^2 + n - 2}$$

the confidence belts for r_{xy} can be calculated for given reliabilities. The t-statistic is tabulated for several reliabilities and the number of degrees of freedom f. With the

Table 1. Test conditions.

Test									Spheres		
Method	Value	No.	Size Fractions	Weight of Indicated Sizes	Hammer Weight (lb)	Blows	Free Fall (in.)	Revolu- tions	Number	Weight (g)	Test Sieves
German impact	SD_{Sp8}	1	5/16 to 1/2 in.	$0.5\rho_R$[a]	110	10	19.7	—	—	—	DIN 3.15 mm
Los Angeles	$LD_{B/ASTM}$	2	3/4 to 3/8 in.	5,000 g	—	—	—	500	11	4,584	ASTM No. 12
	$LD_{C/ASTM}$	3	3/8 to No. 4	5,000 g	—	—	—	500	8	3,330	ASTM No. 12
	$LD_{D/ASTM}$	4	No. 4 to No. 8	5,000 g	—	—	—	500	6	2,500	ASTM No. 12
	LD^*_{Sp8}	5	5/16 to 1/2 in.	5,000 g	—	—	—	500	12	5,000	DIN 3.15 mm
	LD_{Sp8}	6	5/16 to 1/2 in.	2,000 g	—	—	—	500	6	2,500	DIN 3.15 mm
Deval	$VD_{D/ASTM}$	7	3/4 to No. 4	5,000 g (5,500 g)	—	—	—	10,000	6	2,500	ASTM No. 12
	$VD_{E/ASTM}$	8	1/2 to No. 4	5,000 g (5,500 g)	—	—	—	10,000	6	2,500	ASTM No. 12
British impact	ID_{BS}	9	1/2 to 3/8 in.	340 to 400 g	30 to 31	15	15	—	—	—	BS No. 7
Modified	MD^*_{Sp8}	10	5/16 to 1/2 in.	$0.26\rho_R$[a]	10	200	18	—	—	—	DIN 3.15 mm
Marshall impact	MD_{Sp8}	11	5/16 to 1/2 in.	400 g	10	200	18	—	—	—	DIN 3.15 mm

[a]Bulk specific gravity.

Figure 1. Correlation of German impact values SD_{Sp8} and SZ_{Sp}.

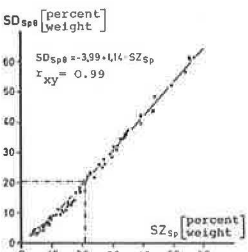


Figure 2. Apparatus for German impact test.

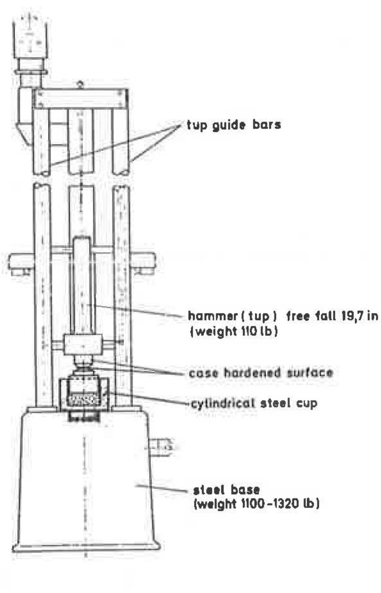
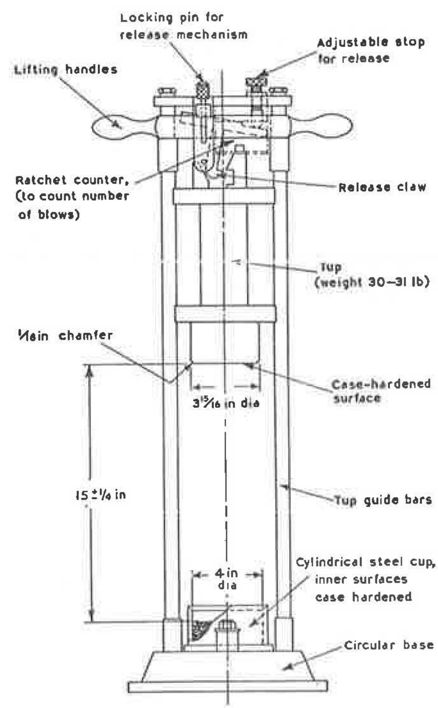


Figure 3. Apparatus for British impact test.



sample size n = 15 and f = n - 2 = 13, the confidence belts for the significance of the correlation are as follows:

Reliability (percent)	Confidence Belt for r_{xy}
95	0.51
98	0.59
99	0.64
99.9	0.75

Data given in Table 2 show that only 2 of the 55 values of the correlation coefficient r_{xy} are less than 0.75 and both are greater than 0.64. That means that in all tested cases the calculated linear regression exists with a reliability of more than 99 percent and mostly with more than 99.9 percent. It is concluded that all correlations between testing methods for coarse aggregates are significant. This would mean that with the different test methods and values the same or at least similar properties of aggregates are characterized.

With correlation coefficients close to 1, the correlations have increasing significance. Thus, we can see several special results (Table 2). Relations between procedures with similar loads show the highest correlation coefficients. This can be seen in a comparison of the German impact test, the British impact test, and the modified Marshall impact test with one another and the Los Angeles test and the Deval test with each other. As shown by the confidence belts, however, the correlations comparing the impact methods with the abrasion methods are also highly significant. Representative of that is the regression of test 1, the German impact test SD_{sp8}, and test 2, the Los Angeles test grading B, as shown in Figure 5.

An interesting phenomenon that we observed is that the correlation coefficients decrease as differences of grading size of tested aggregates increase. This is very significant with the relation of the German impact test to B, C, and D gradings of the Los Angeles Test.

Grading B ($^3/_4$ to $^3/_8$ in.) has a size similar to the grading of the German impact test ($^5/_6$ to $^1/_2$ in.) and thus r_{xy} = 0.95. The relations of the C and D (with different sized fractions of $^3/_8$ to No. 4 and No. 4 to No. 8) to the German impact test are r_{xy} = 0.87 and 0.75 respectively.

This phenomenon was also reported by Nagel (14), who showed that the behavior of smaller sized fractions with the German impact test depends on the different types of aggregate, as Figure 6 shows.

If the value for fraction size 8 to 12.5 mm ($^5/_{16}$ to $^1/_2$ in.) is set equal to 1.0, the relative value SD_{spi}/SD_{sp8} differs greatly, particularly for the smaller gradings (size i in Fig. 6). Some aggregates (C and D in Fig. 6) show relatively smaller values (<1.0); others (A and B) show relatively larger values (>1.0). That means that the smaller sizes of several aggregates have an increasing tendency to be crushed by impact. Nagel (14) called this a "selection," which means that in some aggregates one finds relatively weak particles in the smaller sizes. So it is sometimes difficult to estimate the behavior of an aggregate in all sizes if values for only one size are obtained. This different behavior of aggregates may be an explanation for the decreasing significance of correlation in relating test procedures with different sizes of test materials.

ANALYSIS OF VARIANCE

With the single values of random samples, we could calculate the variance (9) of each test procedure. With the different tested aggregates, we had k = 15 sets with n = 3 single values to conduct an analysis of variance for calculating variation within sets (9).

The variations are given in Table 4. The standard deviations calculated from n = 10 single values for a basalt and a limestone are listed for comparison. With the Los Angeles and Deval tests (No. 2 through No. 8), we generally found smaller deviations than with the German test (No. 1). In most cases we found significantly larger deviations with the British and the modified Marshall tests (No. 9, No. 10, and No. 11).

Figure 4. Mold cylinders with aggregate for modified Marshall test.

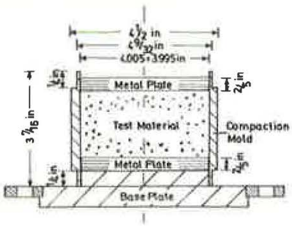


Figure 5. Linear regression $SD_{Sp8}/LD_{B/ASTM}$.

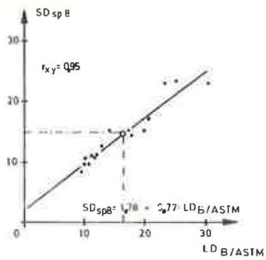


Figure 6. Relative impact value versus size of coarse aggregate.

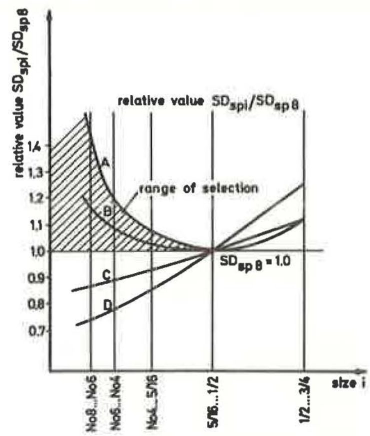


Table 2. Correlation coefficients for linear regression.

	Test										
Test	1	2	3	4	5	6	7	8	9	10	11
1		1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	1:10	1:11
2	0.95		2:3	2:4	2:5	2:6	2:7	2:8	2:9	2:10	2:11
3	0.87	0.96		3:4	3:5	3:6	3:7	3:8	3:9	3:10	3:11
4	0.75	0.87	0.96		4:5	4:6	4:7	4:8	4:9	4:10	4:11
5	0.93	0.99	0.98	0.91		5:6	5:7	5:8	5:9	5:10	5:11
6	0.95	0.99	0.96	0.88	0.99		6:7	6:8	6:9	6:10	6:11
7	0.83	0.93	0.98	0.96	0.95	0.92		7:8	7:9	7:10	7:11
8	0.81	0.92	0.98	0.94	0.94	0.90	0.98		8:9	8:10	8:11
9	0.96	0.96	0.92	0.80	0.95	0.95	0.89	0.89		9:10	9:11
10	0.94	0.92	0.82	0.68	0.88	0.91	0.76	0.75	0.92		10:11
11	0.94	0.95	0.86	0.74	0.92	0.94	0.79	0.80	0.92	0.97	

Table 3. Equations for linear regressions and correlation coefficients.

Regression	Equation	r_{xy}	Regression	Equation	r_{xy}
1:2	$SD_{sp8} = 1.78 + 0.77\ LD_{B/ASTM}$	0.95	4:6	$LD_{D/ASTM} = 7.22 + 1.00\ LD_{sp8}$	0.88
1:3	$SD_{sp8} = 2.00 + 0.65\ LD_{C/ASTM}$	0.87	4:7	$LD_{D/ASTM} = 7.79 + 1.76\ VD_{D/ASTM}$	0.96
1:4	$SD_{sp8} = 2.14 + 0.52\ LD_{D/ASTM}$	0.75	4:8	$LD_{D/ASTM} = 8.45 + 1.97\ VD_{E/ASTM}$	0.94
1:5	$SD_{sp8} = 2.43 + 0.45\ LD^{*}_{sp8}$	0.93	4:9	$LD_{D/ASTM} = 13.18 + 1.04\ ID_{BS}$	0.80
1:6	$SD_{sp8} = 2.00 + 0.75\ LD_{sp8}$	0.95	4:10	$LD_{D/ASTM} = 16.60 + 0.91\ MD^{*}_{sp8}$	0.68
1:7	$SD_{sp8} = 4.83 + 1.08\ VD_{D/ASTM}$	0.83	4:11	$LD_{D/ASTM} = 14.96 + 0.62\ MD_{sp8}$	0.74
1:8	$SD_{sp8} = 5.26 + 1.19\ VD_{E/ASTM}$	0.81	5:6	$LD^{*}_{sp8} = 0.06 + 1.60\ LD_{sp8}$	0.99
1:9	$SD_{sp8} = 5.57 + 0.87\ ID_{BS}$	0.96	5:7	$LD^{*}_{sp8} = 3.91 + 2.49\ VD_{D/ASTM}$	0.95
1:10	$SD_{sp8} = 7.48 + 0.87\ MD^{*}_{sp8}$	0.94	5:8	$LD^{*}_{sp8} = 4.52 + 2.83\ VD_{E/ASTM}$	0.94
1:11	$SD_{sp8} = 6.66 + 0.55\ MD_{sp8}$	0.94	5:9	$LD^{*}_{sp8} = 8.05 + 1.75\ ID_{BS}$	0.95
2:3	$LD_{B/ASTM} = -0.59 + 0.88\ LD_{C/ASTM}$	0.96	5:10	$LD^{*}_{sp8} = 13.16 + 1.67\ MD^{*}_{sp8}$	0.88
2:4	$LD_{B/ASTM} = -1.44 + 0.75\ LD_{D/ASTM}$	0.87	5:11	$LD^{*}_{sp8} = 10.87 + 1.09\ MD_{sp8}$	0.92
2:5	$LD_{B/ASTM} = 0.51 + 0.59\ LD^{*}_{sp8}$	0.99	6:7	$LD_{sp8} = 2.98 + 1.49\ VD_{D/ASTM}$	0.92
2:6	$LD_{B/ASTM} = 0.30 + 0.97\ LD_{sp8}$	0.99	6:8	$LD_{sp8} = 3.53 + 1.68\ VD_{E/ASTM}$	0.90
2:7	$LD_{B/ASTM} = 3.10 + 1.46\ VD_{D/ASTM}$	0.93	6:9	$LD_{sp8} = 5.49 + 1.08\ ID_{BS}$	0.95
2:8	$LD_{B/ASTM} = 3.45 + 1.67\ VD_{E/ASTM}$	0.92	6:10	$LD_{sp8} = 7.97 + 1.07\ MD^{*}_{sp8}$	0.91
2:9	$LD_{B/ASTM} = 5.43 + 1.07\ ID_{BS}$	0.96	6:11	$LD_{sp8} = 6.62 + 0.70\ MD_{sp8}$	0.94
2:10	$LD_{B/ASTM} = 7.96 + 1.05\ MD^{*}_{sp8}$	0.92	7:8	$VD_{D/ASTM} = 0.36 + 1.12\ VD_{E/ASTM}$	0.98
2:11	$LD_{B/ASTM} = 6.67 + 0.68\ MD_{sp8}$	0.95	7:9	$VD_{D/ASTM} = 2.67 + 0.63\ ID_{BS}$	0.89
3:4	$LD_{C/ASTM} = -2.15 + 0.91\ LD_{D/ASTM}$	0.96	7:10	$VD_{D/ASTM} = 4.67 + 0.55\ MD^{*}_{sp8}$	0.76
3:5	$LD_{C/ASTM} = 2.12 + 0.65\ LD^{*}_{sp8}$	0.98	7:11	$VD_{D/ASTM} = 3.95 + 0.36\ MD_{sp8}$	0.79
3:6	$LD_{C/ASTM} = 2.32 + 1.03\ LD_{sp8}$	0.96	8:9	$VD_{E/ASTM} = 2.20 + 0.55\ ID_{BS}$	0.89
3:7	$LD_{C/ASTM} = 3.88 + 1.70\ VD_{D/ASTM}$	0.98	8:10	$VD_{E/ASTM} = 3.96 + 0.48\ MD^{*}_{sp8}$	0.75
3:8	$LD_{C/ASTM} = 4.21 + 1.95\ VD_{E/ASTM}$	0.98	8:11	$VD_{E/ASTM} = 3.25 + 0.32\ MD_{sp8}$	0.80
3:9	$LD_{C/ASTM} = 7.87 + 1.13\ ID_{BS}$	0.92	9:10	$ID_{BS} = 2.60 + 0.95\ MD^{*}_{sp8}$	0.92
3:10	$LD_{C/ASTM} = 11.10 + 1.03\ MD^{*}_{sp8}$	0.82	9:11	$ID_{BS} = 1.75 + 0.59\ MD_{sp8}$	0.92
3:11	$LD_{C/ASTM} = 9.65 + 0.68\ MD_{sp8}$	0.86	10:11	$MD^{*}_{sp8} = 0.69 + 0.61\ MD_{sp8}$	0.97
4:5	$LD_{D/ASTM} = 6.74 + 0.64\ LD^{*}_{sp8}$	0.91			

Table 4. Variation and standard deviation for basalt and limestone.

Test	Variation	Standard Deviation	
		Basalt	Limestone
1	0.40	0.40	0.69
2	0.27	0.23	0.42
3	0.28	0.10	0.27
4	0.54[a]	0.16	0.46
5	0.33	0.45	0.23
6	0.42	0.41	0.19
7	0.35	0.17	0.19
8	0.21	0.09	0.24
9	0.68	1.52	1.36
10	0.75	0.86	0.33
11	0.97	0.64	0.94

[a]For 2 aggregate types, individual values were found with uncontrollable variations.

Figure 7. Mean of laboratory tests with limestone and basalt.

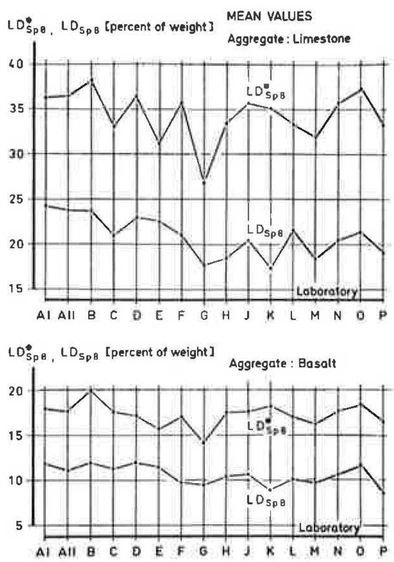


Table 5. Standard deviation and reproducibility under identical and comparative conditions.

Aggregate	Test	Standard Deviation		Reproducibility	
		Identical Conditions	Comparative Conditions	Identical Conditions	Comparative Conditions
Basalt	5	0.468	1.242	0.75	3.52
	6	0.415	1.037	0.66	2.95
Limestone	5	0.973	2.754	1.56	7.79
	6	0.454	2.180	0.73	6.08

Table 6. Requirements for small-sized coarse aggregates.

Courses	United States	France	Germany
Surface courses	40	20	19.2
Binder courses			
With high content of voids			19.2
With low content of voids			25.1
Bituminous mix base courses	45	25	29.5
Aggregate base courses	50	25(35)	25.1

The test values of the Deval test tend to be low, and the relative standard deviations are large. Therefore, no significant differentiation of abrasive and nonabrasive aggregates was achieved.

The Los Angeles test showed small standard deviations under identical conditions, and an international comparative test was performed to calculate standard deviations under comparative conditions (between laboratories).

The following 16 laboratories in 8 countries participated in this comparative test:

1. Tie-Ja Vesirakennushallitus, TVHin Laboratorio, Helsinki, Finland;
2. Valtion Teknillinen Tutkimuslaitos, Staatl. Techn. Forschungsanstalt, Helsinki, Finland;
3. Statens Vegvesen, Vegdirektoratet, Oslo, Norway;
4. Statens Väginstitut, Stockholm, Sweden;
5. Department of Civil Engineering, University of Salford, Salford, Great Britain;
6. MAPAG, Materialprüfungs-AG, Guntramsdorf, Austria;
7. Gumpoldskirchner Kalk- und Schotterwerke, Gumpoldskirchen, Austria;
8. Laboratoire Central des Ponts et Chaussées, Paris, France;
9. A branch laboratory of the preceding;
10. Evm. Szilikatipari Központi Kutato es Tervezö Intezet, Budapest, Hungary;
11. Bundesanstalt für Strassenwesen, Köln-Raderthal, West Germany;
12. Institut für bit. Baustoffe, TU München, München, West Germany;
13. Forschungsgemeinschaft Eisenhüttenschlacke, Rheinhausen, West Germany;
14. Institut für Baumaschinen, TH Aachen, Aachen, West Germany;
15. Ingenieurbüro Brand und Nies, Köln-Braunsfeld, West Germany; and
16. Institut für Strassenwesen, TH Aachen, Aachen, West Germany.

We used 2 different aggregates, basalt and limestone, and tested them with the 2 modified Los Angeles test methods, No. 5 and No. 6. The laboratories performed only the stress test with the prepared sample. The sieve analysis for calculating the test values was done in our laboratory. Thereby it was possible to find out the influence of the different Los Angeles machines on test results. Three samples were tested under the same conditions, so that every laboratory received 12 samples (3 basalt for No. 5, 3 basalt for No. 6, 3 limestone for No. 5, and 3 limestone for No. 6). The mean values of the 4 different tests obtained from the 16 laboratories are shown in Figure 7.

The values obtained at the different laboratories differ very much although their test procedures were conducted according to the standardized methods. With an analysis of variance (9) the variation within sets and between sets could be calculated (Table 5).

The standard deviations under identical conditions are within laboratories and those under comparative conditions are between laboratories. Table 5 also gives the reproducibility under identical conditions, $w = 1.96\sqrt{2}\,(s_o/\sqrt{n})$, and under comparative conditions, $v = 1.96\sqrt{2}\sqrt{s_1^2 + (s_o^2/n)}$, for a probability of 95 percent.

The reproducibility under comparative conditions was obtained in a range of about 20 to 30 percent, relative $(v/\bar{x})$, a range similar to the one we had found for the German impact test (19). This means that the Los Angeles test shows about the same variances under comparative conditions (comparing results of different laboratories) as the German impact test. To reduce this variability will require further standardization of the Los Angeles machine (length and diameter, slope, and steel) and the testing procedure. In that way we are now improving our German impact machine in order to reduce the variance of test values.

CONCLUSIONS AND APPLICATION

Linear regressions with high reliability among the Los Angeles, Deval, German impact, British impact, and modified Marshall impact tests were found. This means that, although the strains of the aggregates are very different with these test methods, they characterize the same or at least similar properties of aggregates. We learned that the magnitude of the test value is test specific but the quality of test results is aggregate specific.

In calculating the variances of the different test values, we found that the variation under identical conditions was small, especially for the Los Angeles test. However, comparing results under comparative conditions obtained in 16 different laboratories, we found that the Los Angeles test showed a reproducibility of about 20 to 30 percent relative, a range equal to or even larger than that found for the German impact test. This means that further standardization of testing machinery and of procedure is necessary if values of different laboratories are to be compared.

The calculated linear regressions found for the different test procedures will allow the comparison of specifications for small-sized coarse aggregates tested with different international test methods. It will now be possible to exploit international experiences and literature on the question of requirements for use of aggregates in road construction for different courses.

Table 6 gives a comparison of Los Angeles abrasion values that are required in the United States (34), France (35), and Germany (31). The German values that are required with the impact test, $\overline{SZ}_{sp}$ (33), are transformed into Los Angeles values grading B (23) with the regression equations given in Table 3 (2:6) and shown in Figure 2.

The comparison shows that the requirements in France and Germany are similar, whereas the requirements of the United States are extremely broad. This may show how subjective requirements are fixed in different countries.

The calculated regressions will allow further exploitation of international experiences with aggregates of different qualities.

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REFERENCES

1. Brand, W., und Dinkgraeve, D. Festigkeit als Massstab für die Eignung von Naturgestein für den Strassenbau bei Prüfung nach deutschen und amerikanischen Normen/ Testing of Aggregates Based on German and USA Standards. Berichte aus der Arbeit des Baustofflaboratoriums Brand und Nies, Müller, Köln, 1969.
2. Breyer, H. Betrachtungen zum Vorläufigen Merkblatt für Körnungen aus gebrochenem Naturstein/Considerations on Specifications for Gradings of Broken Aggregates. Strassen- und Tiefbau, Vol. 5, 1954, p. 229.
3. Dantienne, R. Confrontation des Normes d'essais des Matériaux pierreux à usages routiers adoptées dans différents pays. Mémoires du C.E.R.E.S., No. 10, May 1965.
4. Dantienne, R., and Longueville, P. Étude critique des Méthodes de qualification des pierres utilisées dans les constructions routières. Mémoires du C.E.R.E.S., No. 10, May 1965.
5. Ewers, N. Gesteinsprüfung in der UDSSR/Testing of Aggregates in the Soviet Union. Der Naturstein im Strassenbau, Vol. 40, 1965, pp. 157-167.
6. Fisher, R. A. Statistical Methods for Research Workers. Aufl., London, 1948.
7. Gragger, F., and Fey, K. Ein vereinfachtes Verfahren zur Bestimmung des Zertrümmerungswertes von Splitt/A Simple Method for Destination of Impact Crash. Strassen- und Tiefbau 24, Vol. 3, 1970, p. 177.
8. Grønhaug, A. Prüfung, Klassifizierung und Aufbereitung von Strassenbauzuschlagstoffen in Norwegen/Testing, Classification and Production of Aggregates in

Norway. Mitteilungen des Lehrstuhls f. Strassenwesen, Erd- und Tunnelbau der RWTH Aachen (Leins, W., ed.), Natürliche und künstliche Zuschlagstoffe im Strassenbau Tagung, HdT Essen, Vol. 6, April 18-19, 1968.
9. Hald, A. Statistical Theory With Engineering Applications. John Wiley and Sons, New York, 1967.
10. Haller, P. Die Prüfung der Festigkeitseigenschaften von Splitt und Schotter/ Testing and Properties of Coarse Aggregates. Strasse und Verkehr, Vol. 9, 1959, p. 401.
11. Höbeda, P. Natursteinvorkommen, Abbau, Prüfungen und Untersuchungen in Schweden/Natural Aggregates, Their Usage and Properties in Sweden. Mitteilungen des Lehrstuhls f. Strassenwesen, Erd- und Tunnelbau der RWTH Aachen (Leins, W., ed.), Natürliche und künstliche Zuschlagstoffe im Strassenbau Tagung, HdT Essen, Vol. 6, April 18-19, 1968.
12. Kohler, G. Untersuchungen über das thermische Verhalten von im Strassenbau verwertbaren Gesteinen/Researches on Thermal Behavior of Aggregates for Road Construction. Diss. TH Aachen, 1970; Forschungsbericht des Landes NRW, No. 2187, 1971.
13. Kramer, C. J. Extension of Multiple Range Tests to Group Means With Unequal Number of Replications. Biometrics, Vol. 12, 1956, p. 307.
14. Nagel, J. Beanspruchung und Prüfung von Gesteinssplitten/Strain and Testing of Aggregates. Diss. TH Aachen 1969; Schriftenreihe "Strassenbau und Strassenverkehrstechnik" des Bundesministers für Verkehr, Abteilung Strassenbau, Bonn, Vol. 93, 1969.
15. Nagel, J. Siebdurchgang oder Schlagzertrümmerungswert bei der Prüfung von Gesteinssplitten/Calculating Impact Crash by a Single Sieve or by Impact Crash Value. Die Natursteinindustrie (erscheint in Kürze).
16. Nemesdy, E. Einige ungarische Ergebnisse bei der Prüfung, Bewertung und Anwendung der natürlichen Zuschlagstoffe im Strassenbau/Some Hungarian Results for Testing and Usage of Natural Aggregates in Road Construction. Mitteilungen des Lehrstuhls f. Strassenwesen, Erd- und Tunnelbau der RWTH Aachen (Leins, W., ed.), Natürliche und künstliche Zuschlagstoffe im Strassenbau Tagung, HdT, Essen, Vol. 6, April 18-19, 1968.
17. Pös, A. Hochofenschlacke als bituminöses Mischgut für den Strassenbau/Slag for Usage in Bituminous Road Construction. Hochofenschlacke im Strassenbau, Vol. 5, 1963, pp. 5-38.
18. Pös, A. Anmerkungen zu Korngrössen-, Kornform- und Festigkeitsprüfung von Zuschlagstoffen für den Strassenbau/Considerations on Testing of Size, Form and Resistance of Aggregates for Road Construction. Der Naturstein im Strassenbau, Vol. 48, 1968, pp. 7-26.
19. Pös, A. Schlagversuche an Splitt $^8/_{12}$—Ergebnisse und Auswertung einer Ringanalyse/Impact Tests for Small Size Coarse Aggregate—Results of Comparative Tests. Forschungsgesellschaft für des Strassenwesen, 1971.
20. Rezňak, L. Gesteinsprüfungen für den Strassenbau in Ungarn/Tests for Aggregates in Hungary. Der Naturstein im Strassenbau, Vol. 40, 1965, pp. 169-183.
21. Weber, J. Anforderungen und Prüfungen von Gesteinsmaterialien für Strassenbauzwecke in der Schweiz/Requirements and Tests of Aggregates for Road Constructions in Switzerland. Mitteilungen des Lehrstuhls f. Strassenwesen, Erd- und Tunnelbau der RWTH Aachen (Leins, W., ed.), Natürliche und künstliche Zuschlagstoffe im Strassenbau Tagung, HdT, Essen, Vol. 6, April 18-19, 1968.
22. Cahier Géńeral des Chargés, Matériaux Pierreux. Ministére des Travaux Publics, France, 1966.
23. Standard Method of Test for Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles-Machine. ASTM C 131-66 and 131-69.
24. Standard Method of Test for Resistance to Abrasion of Large Size Coarse Aggregate by Use of the Los Angeles-Machine. ASTM C 535-69.
25. Standard Method of Test for Abrasion of Rock by Use of the Deval Machine. ASTM D 2-33, 1968.

26. Standard Method of Test for Abrasion of Graded Coarse Aggregate by Use of the Deval Machine. ASTM D 289-63.
27. Standard Method of Test for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus. ASTM D 1559-65.
28. Methods for Sampling and Testing of Mineral Aggregates, Sand and Fillers. British Standard 812, 1960 and 1967.
29. Widerstandsfähigkeit von Schotter gegen Schlag und Druck/Testing of Aggregates—Resistance to Impact and Compression. Prüfung von Naturstein, DIN 52 109, Oct. 1939.
30. Schlagversuch an Schotter und Splitt/Testing of Aggregates—Impact Test for Small and Large Size Coarse Aggregates. Prüfung von Naturstein, DIN 52 109, Entwurf, March 1964.
31. Merkblatt über Verwendung und Prüfung von Kies und Sand für Fahrbahndecken und Tragschichten/Specifications for Usage and Testing of Sand and Gravel for Surface and Base Courses. German Road Research Society, Dec. 1966.
32. Vorläufiges Merkblatt über Verwendung und Prüfung von Natursteinen für den Strassenbau/Specifications for Usage and Testing of Aggregates for Road Construction. Forschungsgesellschaft für das Strassenwesen, April 1963.
33. Vorläufiges Merkblatt für den Schlagversuch an Splitt $^{5}/_{12}$/Specifications for Impact Test for Small Size Coarse Aggregates. Forschungsgesellschaft für des Strassenwesen, Köln, June 1966.
34. Standard Specifications M 75-51 and M 80-51. American Association of State Highway Officials.
35. Bulletin Officiel du Ministère de l'Equipement et du Logement, Texte 125-17. 1967.
36. Essai Los Angeles. Modes Opératoires du Lāboratoire Central des Ponts et Chaussées, Ministre de l'Equipement et du Logement, Dunod, Paris, Circulaire 70-74, July 1970.
37. Essai Deval (sec et humide). Modes Opératoires du Laboratoire Central des Ponts et Chaussées, Ministre de l'Equipement et du Logement, Dunod, Paris, Circulaire 70-74, July 1970.