

Chapter 12

Comparison of Abrasion Tests

12.1 Introduction

One of the stated objectives of this thesis is to recommend an abrasion test to ensure that standards are maintained in the industry, with the eventual inclusion of this test into the present SABS specification for cbp. To this end an extensive testing programme was undertaken and three abrasion tests have been analysed in some detail in chapters 9, 10, and 11.

The focus in this chapter will therefore be to critically compare the three tests with a view to finding the most suitable one. This will entail recalling a number of the findings of the preceding chapters, especially chapters 9, 10, and 11 with the aim of creating a degree of clarity and perspective. The tests are then critically assessed relative to their respective performances with regard to 24 desirable attributes.

12.2 Critical Comparison of the Three Abrasion Tests

Table 12.1 sets out 24 attributes that are considered desirable for an abrasion test.

The ability of the abrasion tests to measure and assess these attributes is recorded under the heading 'performance of test'. A scale of one (poor) to five (very good) is used. These values are multiplied by a 'weight' factor, which indicates the relative importance of the various attributes. A few weights are judged to be crucial and are afforded the status of 'cardinal' = 10 points, but generally the weights are restricted to a scale of one ('minor, not important') to five ('very important').

The sum of the 'weighted performances' of each test forms the basis for deciding on an abrasion test.

Deciding on the 'performance of test' and 'weight' is clearly a matter of judgement. Inevitably a subjective element is present in the interpretation and assessment of many of the attributes. In making these assessments the writer has relied on 16 years of experience in the manufacture of cbp, and 14 years of investigation into abrasion resistance.

The remainder of this chapter will be devoted to a systematic evaluation of the abrasion tests in the light of the 24 attributes. In each case an explanation is given on how the 'performance of test' and 'weight' given in table 12.1 was derived.

TABLE 12.1 CRITICAL COMPARISON OF 3 ABRASION TESTS

ATTRIBUTES	PERFORMANCE OF TEST			WEIGHT	WEIGHTED PERFORMANCE		
	MA20	WIRE	C418		MA20	WIRE	C418
1 AGE OF TEST	3	2	4	1	3	2	4
2 INTERNATIONAL STATURE	3	1	4	3	9	3	12
3 COST - INITIAL CAPITAL	4	2	4	4	16	8	16
4 COST - ABRASIVE	4	1	3	10	40	10	30
5 COST - LABOUR	4	2	1	3	12	6	3
6 SIMPLICITY	3	3	3	4	12	12	12
7 INDICES - LIMITING CRITERIA	2	4	1	10	20	40	10
8 SURFACE INFORMATION	5	2	1	4	20	8	4
9 SIMULATION OF APPEARANCE	2	5	3	2	4	10	6
10 SIMULATION OF "CRUSHING"	5	2	4	5	25	10	20
11 SIMULATION OF "SHEARING"	3	5	4	3	9	15	12
12 WEAR WRT VOLUME	5	4	3	3	15	12	9
13 SENSITIVITY - MIX DESIGN	5	2	1	5	25	10	5
14 CORRELATION WITH COMPRESSION	4	3	3	4	16	12	12
15 WEAR WRT DEPTH	5	3	3	3	15	9	9
16 SEVERITY	4	3	5	5	20	15	25
17 SURFACE MEASUREMENT	5	5	1	10	50	50	10
18 COMPATIBILITY - LAB	5	5	5	5	25	25	25
19 COMPATIBILITY - INSITU	3	5	1	1	3	5	1
20 REPEATABILITY	1	3	5	5	5	15	25
21 REPRODUCIBILITY	3	3	3	5	15	15	15
22 AGGREGATE HARDNESS	5	1	1	10	50	10	10
23 ABRASIVE OBTAINABILITY	5	5	2	4	20	20	8
24 RELATIONSHIP WITH IN-SITU WEAR	4	3	5	10	40	30	50
				TOTAL	469	352	333

PERFORMANCE OF TEST

1 = POOR

2 = FAIR

3 = ACCEPTABLE

4 = GOOD

5 = VERY GOOD

WEIGHTS - RELATIVE IMPORTANCE
OF ATTRIBUTES

1 = MINOR, NOT IMPORTANT

2 = SECONDARY

3 = INTERMEDIATE

4 = IMPORTANT

5 = VERY IMPORTANT

10 = CARDINAL

12.2.1 Age of test

Importance of attribute

There is always a possibility that a new test may be devised, which may prove more suitable than older more established tests. A test should therefore be judged primarily on the basis of its ability to accurately assess a defined characteristic in the specimen. However, that a test should remain in use while other tests fall into disuse, does say something for the test and thus the duration that a test has been in existence should not entirely be overlooked. A weight of (1) has been assigned to this attribute to indicate the 'minor' importance of the age of a test.

Performance of test

ASTM C418: This test has been in existence since 1958 as an abrasion resistance test, and was specified in 1982 as the means of testing the abrasion resistance of cbp (see ASTM C936 - 82 'Solid Concrete Interlocking Units').

MA20: This test is a derivative of another American abrasion resistance test, ASTM C779 - 82 (proc. C), that in turn appears to have its origins in the form of the Davis ball test, [Smith(1958)], a test that appears to have first been used in the 1940s. In Australia the MA20 version of this test was first used by the Perth City Council, and after careful investigation and some modifications was adopted as a national standard in 1986.

Wirebrush: This test, used in South Africa only, was developed by the PCI from 1986. In 1990 it was adopted as one of their official test methods (PCI.TM.7.11). However, unlike the MA20 and ASTM C418, this test has not as yet been adopted as a national standard.

The performance of the three tests relative to the attribute of 'age of test' reflect the duration that these tests have been in operation as follows:

ASTM C418	'good'	(4)
MA20	'acceptable'	(3)
Wirebrush	'fair'	(2)

12.2.2 International stature

Alexander(1984) listed numerous abrasion resistance tests, many of them national standards. At about the same time the CMAA investigated 32 standard test procedures for measuring abrasion resistance. From this it is obvious that one world standard test for abrasion resistance of cbp would be a lot less confusing. Certainly what the world does not need is yet another test, unless it can be shown that the test is superior.

Therefore in deciding on an abrasion resistance test for South Africa, it would be preferable to use an existing test that already has international acceptance. Hence the inclusions of ASTM C418 (USA) and MA20 (Australia) in this programme.

Performance of test

ASTM C418: This test is recommended by the cbp industry in the USA. The performance of the test relative to the attribute 'international stature' is therefore assessed as 'good' (4).

MA20: The claim to international stature lies in its similarity to ASTM C779 - 82 (proc. C), from which it was derived. It was also used nationally in Australia and New Zealand from 1986 through 1996 as a means of quality control, and in South Africa to a small degree. However, it is no longer in use, having been 'upstaged' by a tumbler test in Australia and New Zealand, AS/NZS 4456.9.

The generic equivalent of this test continues to be used in America, in the form of ASTM C779 Proc. It has held its own against other ASTM tests such as ASTM C944 and ASTM C418. More recently this test has been used in Japan. On the other hand 'MA20', specifically, is no longer in use. These mixed fortunes are therefore assessed with an 'acceptable' (3) international stature.

Wirebrush test: This is a purely local test that therefore has 'poor' (1) international status.

Importance of attribute

The attribute of international status is judged to be of 'intermediate' importance, i.e. a weight of (3).

12.2.3 Capital expenditure

The cost of purchasing the necessary equipment for testing the abrasion resistance of blocks is an important consideration for small manufacturers with limited resources, and of lesser concern to established manufactures. However, since poor quality will reflect negatively on the industry as a whole irrespective of which manufacturer actually produced the blocks, it is advisable to select a test that is affordable to as many producers as possible. The costs quoted hereafter all reflect prices as they stood in 1994, but this is nevertheless sufficient for comparisons.

Importance of attribute

Given the importance of ensuring that all cbp manufacturers produce a quality paver with respect to abrasion resistance the 'important' weight of (4) has been selected for this attribute.

Performance of test

MA20: The initial cost for the MA20 test equipment including the 1000-watt drill, drill stand, optical rev counter, special chuck etc. was approximately R 6000 (in 1994).

Wirebrush: The cost of building the PCI.TM.7.11 apparatus was estimated at R 12000.

ASTM C418: The cost of assembling this equipment, assuming the availability of compressed air, is R 3000. This would include the cost of a small enclosure, a clamp, a nozzle assembly, a funnel, a pressure gauge etc. A suitable compressor if required may add another R 6000 to this cost. Thus the capital outlay is either

R 3000 or R 9000. An average between the two of R 6000 is therefore used for comparing this test with the other two.

Based on the above figures the relative performances of the respective tests are:

MA20, 'good' (4), Wirebrush, 'fair' (2), ASTM, 'good' (4).

The higher numbers reflect the cheaper apparatuses.

12.2.4 Cost of abrasive

If the cost of the initial purchase is a significant consideration, then so would be the ongoing costs of purchasing the abrasive mediums. As for 12.2.3, all costs apply to 1994 prices.

Performance of test

MA20: Shackel(1992) concluded that bearings should not be used beyond 65000 revolutions. He found that the test need only run for 2000 revolutions (see 9.10.7), which significantly extends the life of the bearing.

Cost per block = R 180 per bearing / 65000 revolutions per bearing x 2000 revolutions per block = R 5,54 per block

Wirebrush: PCI.TM.7.11 states that the wirebrush should be changed after every test on a block

Cost per block = R 25,00 per brush = R 25,00 per block

ASTM C418: The specification states that 0,6 kg of silica sand shall be used to make each crater, and that there shall be eight craters in a block. It is assumed that the sand will be replaced after every hole, for the reasons given in 11.7.5. In addition the nozzle must be replaced after every hour of operation.

Cost per test = cost of sand + cost of nozzle
 = (R 4300 per 3000 kg sand in a container ex Philippi, Cape x 0,6 kg per hole x 8 holes per block) + (R10,00 per nozzle / 60 minutes per nozzle x one minute per hole x 8 holes per block) = R 6,88 + R 1,33 = R 8,21 per block

In the following exercise it will be assumed that 11 blocks per days production are tested, (one at 24 hours, as an early indicator, and ten at 14 days prior to despatch). This would be a typical control requirement for conformity to SABS standards. If an average production month of 22 working days is also assumed, and 11 production months in the year, the annual cost of abrasive would amount to:

MA20: R 5,54 per block x 11 blocks per day x 22 days per month x 11 months per year = R 14 747,48 / year

Wirebrush: R 25,00 per block x 11 blocks per day x 22 days per month x 11 months per year = R 66 550,00 / year

ASTM C418 R 8,21 per block x 11 blocks per day x 22 days per month x 11 months per year = R 21 855,02 / year

Based on the totals given above, ratios may be calculated, which can be used to indicate the relative performance of the three tests:

MA20: 4 ('good')
 ASTM C418: 3 ('acceptable')
 Wirebrush: 1 ('poor')

Importance of attribute

These not inconsiderable costs are ongoing year after year. It must also be born in mind that some factories have up to four production lines running concurrently, all producing paving blocks. In this case these costs would increase fourfold. Thus the ongoing month-by-month cost of the abrasive is considered of 'cardinal' importance, and a weight of (10) is therefore assigned to this attribute.

12.2.5 Cost of Labour

The duration of the respective tests also plays a part in the cost. If the abrasion tests done on say 11 blocks every day take a considerable time, it may be necessary to employ a second laboratory operator, an unwanted additional expense.

Performance of test

MA20: The test takes about 7 minutes including the time to clamp and afterwards remove the block.

Wirebrush: Like MA20, the actual duration of testing is 5 minutes, but additional time is required to change the brush after each block. A cycle time of 8 minutes is realistic. At a later stage, modelling clay is pressed into the crater, levelled, weighed, and the volume of the crater can then be determined. This operation takes about six minutes, and the total time is thus 14 minutes per block.

ASTM C418: The sandblast test is the slowest. Four minutes are required to weigh the sand into eight lots of 600 grams. Twelve minutes are required to re-position the block eight times and sandblast for one minute at each location. A further 12 minutes are required to fill the holes with modelling clay, level and re-weigh. The total time to test one block is thus 28 minutes.

(It is possible to speed up this operation by using an apparatus that can blast two blocks simultaneously, but the same could be done for the other tests e.g. two drilling rigs for the MA20 could run at the same time. Therefore this option is not considered here).

If it is assumed that semi-skilled laboratory operators typically cost in the region of R 10,00 per hour, and that once again 11 blocks will be tested per machine per day, then for a typical month manpower costs would be:

MA20	R 282,33 per month	$(11 \times 22 \times R10,00 \times 7 / 60)$
Wirebrush	R 564,67 per month	$(11 \times 22 \times R10,00 \times 14 / 60)$
ASTM C418	R 1129,33 per month	$(11 \times 22 \times R10,00 \times 28 / 60)$

The equivalent number of days in the month that the operator will be employed doing these tests is:

MA20	3 days
Wirebrush	6 days
ASTM C418	12 days (this may require an additional operator)

The corresponding ratios may be calculated, and the relative performance of the three tests will be in inverse proportion:

MA20:	4 ('good')
Wirebrush:	2 ('fair')
ASTM C418:	1 ('poor')

Importance of attribute

The costs given here are not beyond the reach of a typical manufacturer and a weight of (3) 'acceptable' is thus applied. (In the case of the MA20 and the wirebrush tests the existing laboratory staff will probably be able to cope with the additional testing).

12.2.6 Simplicity

All three tests require a certain level of technical skill on the part of the operator. Gauges need to be read or adjusted. Orifice diameters must be checked. Nozzles, plates, bearings need to be changed. Sand must be weighed, blocks must be carefully fastened and aligned etc. A semi-skilled operator will be able to master these functions, but it is essential for thorough training and ongoing quality auditing to take place.

Performance of test

The level of simplicity can be described as 'acceptable' (3) for all three tests.

Importance of attribute

It is 'important' (i.e. a weight of 4) that any test which is going to be used as a means of quality control in a manufacturing environment be reasonably simple (particularly in South Africa).

12.2.7 Limiting criteria

Performance of test

The limiting criteria of the three tests vary in sophistication.

ASTM C418: ASTM C936 states that the average depth of the holes should not exceed 3 mm (see 11.3.3). The 'performance' of this criterion can be considered as 'poor' (1), since it does not allow for different traffic categories. It is designed for freeze-thaw conditions that do not apply in this country. Only two of the 48 mixes in this investigation met this requirement (see fig 11.3).

MA20: This specification had three limiting criteria for the abrasion index, corresponding to heavily trafficked, intermediate, and lightly trafficked areas. Some examples are given as to what traffic loadings constitute these three classifications (see 9.3). These limits however never went beyond the status of interim, and no longer apply with the introduction of the AS/NZS 4456.9 tumbler test. The improved scope of the limits (compared to ASTM C936/ASTM C418) is thus tempered by the discontinuity of the test in Australia/New Zealand. Nonetheless they may still be useful if the ASTM C779 form of the test is to be used. Their 'performance' can therefore be considered to be 'fair' (2).

Wirebrush: PCI.TM.7.11 has the most sophisticated limiting criteria, with four categories, each with a clearly defined application. The results of work in this thesis confirm a reasonably good correlation (see figure 10.10) of wear depth with equivalent MPa results. Their 'performance' may therefore be said to be 'good', (4).

Importance of attribute

In any manufacturing environment meaningful limiting criteria are of 'cardinal' 'importance', if the manufacturer is to produce a product that will meet the end users requirements. Accordingly a weight of (10) is given.

In chapter 14 the three abrasion tests are correlated in terms of the measured degrees of abrasion at Westgate. The limits of the three abrasion tests are reviewed. This may lead to new limits being proposed, particularly in the case of the over designed ASTM limit.

12.2.8 Surface information from wear-duration curves

Importance of attribute

In both the MA20 test and the wirebrush test, penetration readings are taken every minute making it possible to construct a wear-duration curve, i.e. P vs R. Such information is useful to the eye of the trained technician. For example an unusually steep rise in the initial 1000 revolutions, coupled with a substantial flattening out of the curve thereafter is possible evidence of a lack of surface curing. The bulk property of the block was unaffected, relative to an upper surface that never achieved its potential.

The value of having a profile of the strength of the surface is judged 'important', hence a weight of (4).

Performance of test

ASTM C418 In this test no intermediate measurements are taken. It is therefore a 'poor' (1) test with regard to surface information.

Wirebrush: From figures 10.5 through 10.7 it may be seen that the resultant wear duration curves are not always reliable. This is probably the result of the 'bias' and 'spring' effects of the wirebrush test. The 'performance' of the test is therefore only 'fair' (2) with regard to supplying surface information.

MA20: The ability of the resultant wear duration curve associated with this test, to supply useful information on the surface, can be considered as 'very good' (5), especially when compared with the other two tests.

12.2.9 Simulation of appearance

Figures 12.1 and 12.2 show the appearance of blocks that respectively have good and poor abrasion resistance.



Figure 12.1 Polished appearance of high strength blocks after five years of traffic at Westgate. The blocks were made from high water and binder contents. The strong binder abrades only slightly faster than the aggregate, which takes the brunt of the attack.



Figure 12.2 Highly exposed aggregate particles of blocks in service for 8 years at factory entrance. They are usually the result of either insufficient water or binder content.

Performance of test

MA20: The smooth circular groove formed by the ball bearings on the test surface (see figure 4.15) in the MA20 test is a 'reasonable' (3) representation of the polished appearance of blocks with good abrasion resistance, as seen in figure 12.1. On the other hand it is a 'poor' (1) representation of the highly exposed aggregate particles seen in figure 12.2. Taking an average of the two, it may be said that the 'performance' of the MA20 in its ability to simulate the appearance of wear is 'fair' (2).

Wirebrush: This test will expose the aggregate particles in inverse proportion to the strength of the binder. For weak binders the similarity between figure 12.2 and 4.15 is apparent. For strong binders there is little wear⁴⁷. It may therefore be said that the simulation of the appearance is 'very good' (5), for blocks with both strong and weak binders.

ASTM C418: The simulation of wear in blocks with weak binders may be said to be 'very good' (5) (compare figure 4.15 with figure 12.2). Both have rounded coarse aggregate particles. Both show signs of loss of aggregate. The simulation of blocks with 'strong' binders is clearly 'poor' (1). The pneumatically blasted sand always abrades the softer mortar constituent at a greater rate, even where binder strength is good. Taking an average of the two, the ASTM test is assessed as 'acceptable' (3).

Importance of attribute

A weight of 2 is selected for this attribute, since the similarity in appearance between the test surface and insitu wear is of 'secondary' importance and given a weight of (2). The visual simulation of abrasion wear is not necessarily synonymous with abrasion resistance.

12.2.10 Simulation of 'crushing'

Importance of attribute

In 9.4 an explanation was given of how wear on a microscopic scale occurs on the surface of the block. The microscopic peaks of the block are in effect crushed by the corresponding protrusions of the attacking medium. Normal vehicular and pedestrian traffic would have just such an effect. Although wear would occur at an 'infinitesimal' pace, it is the authors conviction that this microscopic crushing effect is the principle means whereby wear occurs on most pavers. This attribute is therefore 'very important' and given a weight of (5).

Performance of test

The extent to which the three tests simulate this 'crushing' effect has been discussed in detail in 9.4, 10.4 and 11.4, and only a brief summary is given here to compare the three tests.

MA20: The rolling action of the balls induces 'very good' (5) micro crushing effects.

Wirebrush: It should be stated that although the wirebrush test principally applies forces tangential to the test surface, there is some degree of vertical pressure from the weight applied to the brush/bristles. A 'fair' (2) degree of microscopic crushing occurs.

ASTM: The degree to which the air blasted sand particles simulate the wear mechanism of microscopic 'crushing' is 'good' (4). Some 'shearing' or cutting also occurs.

12.2.11 Simulation of 'shearing'

Importance of attribute

In chapter 10 it is explained that tangential forces do occur in paved surfaces in such places as corners in roads, at traffic lights where acceleration and deceleration occur, or in transport parks where a significant degree of slewing may occur. Even pedestrian traffic causes shear forces from acceleration, deceleration or just the action of turning on the sole of a persons foot in walking.

However, in general, although most paved areas will be subjected to some loading of such tangential forces, the bulk of the wear occurs from crushing effects. Therefore 'shearing' is only given an 'intermediate' weight of (3) for 'relative' importance.

Performance of test

MA20: A degree of shearing takes place in this test by virtue of Heathcote slip. (This is a phenomenon that takes place whenever a ball rolls in a groove, and is explained in 4.2.2.1(b) of volume 2). On the other hand it should be recognized that the primary means of abrasion in this test is that of micro crushing effects, not shearing. The simulation of 'shearing' is thus judged 'intermediate'(3).

Wirebrush: In this test the individual wires scrape over the surface. The simulation of 'shearing' is clearly 'very good' (5).

ASTM C418: The sharp edges of a silica sand particle cuts into the surface of the test specimen, particularly where the matrix is relatively weak, resulting in deep holes. 'Shearing' and cutting mechanisms are therefore very effective in weak concretes i.e. 'excellent' (5), and 'acceptable' (3) in strong concretes, where a relatively shallow yet clearly defined crater may be seen. Taking an average of the two, the ASTM test's performance on this attribute is assessed as 'good' (4).

12.2.12 Wear with respect to volume

Importance of attribute

The volume of material that is abraded is a very simple concept to understand and is the most basic way of expressing wear. This is useful when dealing with end users who are not technically minded. It is an easier concept to understand than the MA20 index which is based on the inverse of depth, rather than the volume of wear.

An 'intermediate' weight of (3) is assigned to signify the relative importance of this attribute.

Performance of test

MA20: In its present form this test is not officially defined in terms of volume loss, although the depth of the groove can be related to volume by applying a formula (see 9.5.2). Alternatively clay may be applied to the groove to determine the volume. The possibility of using either system to measure the abraded volume affords this test a (5) for performance.

Wirebrush and ASTM C418: In the case of these tests, the abraded volume is measured with clay as a matter of course. However the irregular shape of the craters makes direct measurement with a vernier a less repeatable means of establishing the abraded volume by depth measurements. Finally, using depth measurements to establish the abraded volume is not a practical option in the sandblast test. The wirebrush is given a (4) for performance and the sandblast test a (3).

An Analysis of the Three Abrasion Tests in Terms of Volume

At this point in the analysis, it will be useful to cover some groundwork necessary for assessing some of the remaining attributes.

In table 12.2 below the last three columns express abrasion-wear for the three abrasion tests in terms of volume, thus making it possible to do some meaningful comparisons. This data has been compiled from appendices J.9 through J.16 (MA20), H.1 through H.8 (Wirebrush), I.1 through I.8 (ASTM C418).

The second, third and fourth columns summarise the corresponding compressive strength results for the three test methods and are compiled from appendices B.1 through B.8 (SABS), C.1 through C.8 (ASTM), and D.1 through D.8 (MA20).

The fifth column is an average of the three compression tests. This increases the statistical base for the x-axis values – 'average compressive strength'. [Previously it has been explained that since each result for the respective compression tests is the result of six specimens, the average expressed in the fifth column is an average of 18 specimens, a very good indication of the strength of the mix, even though it does not relate to a specific test method]. Using this fifth column as the x-axis, and columns 6, 7 and 8 respectively as the y-axes, three graphs were plotted as shown in figure 12.1 through 12.3 below. An expression for a best-fit trend line is given in each case, as well as the correlation coefficient.

TABLE 12.2 RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND ABRASION RESISTANCE IN cm ³							
MIX	SABS-MPa MPa	ASTM-MPa MPa	MA20-MPa MPa	AVG-MPa MPa	MA20 cm ³	WIREBRUSH cm ³	ASTM C418 cm ³
1.1	35.3	35.4	44.9	38.5	1.4	2.8	1.4
1.2	36.6	36.1	45.8	39.5	1.3	3.5	1.2
1.3	30.9	27.5	39.3	32.6	2.0	3.7	2.0
1.4	22.0	19.0	28.4	23.1	4.3	6.1	4.2
1.5	22.6	20.1	28.0	23.6	4.8	7.2	4.8
1.6	15.9	16.4	22.0	18.1	6.9	6.6	6.9
2.1	29.2	27.5	35.3	30.7	5.0	5.3	4.5
2.2	30.3	27.6	36.0	31.3	4.2	4.5	4.6
2.3	27.9	24.8	35.2	29.3	4.7	4.2	4.6
2.4	23.9	18.9	26.2	23.0	7.2	5.6	7.2
2.5	19.1	17.1	25.0	20.4	6.3	6.4	6.4
2.6	18.0	14.7	21.6	18.1	9.9	7.4	7.3
3.1	18.9	18.9	25.0	20.9	8.9	5.8	7.7
3.2	15.9	18.5	22.8	19.1	11.7	6.1	10.1
3.3	15.1	14.6	18.5	16.1	13.6	7.1	10.5
3.4	12.5	12.0	16.6	13.7	21.6	9.1	16.3
3.5	11.4	11.1	15.0	12.5	36.1	10.2	21.8
3.6	11.9	11.8	16.6	13.4	26.0	9.0	16.1
4.1	25.4	26.1	32.3	27.9	5.6	5.6	5.6
4.2	28.1	26.3	32.9	29.1	5.2	4.0	5.2
4.3	16.4	15.6	20.3	17.4	14.9	7.0	11.4
4.4	14.3	14.5	19.4	16.1	18.4	10.4	13.6
4.5	15.5	14.3	21.3	17.0	19.3	10.2	12.1
4.6	13.4	14.3	19.5	15.7	20.0	8.0	11.5
5.1	29.9	29.2	37.9	32.3	3.0	4.8	3.0
5.2	22.7	27.0	30.0	26.6	2.9	5.8	2.9
5.3	19.8	18.3	24.0	20.7	4.5	6.2	4.5
5.4	19.3	20.2	25.0	21.5	5.1	6.7	5.1
5.5	18.2	17.2	21.0	18.8	10.6	7.4	9.1
5.6	13.7	12.1	16.5	14.1	17.6	11.2	14.3
6.1	28.6	30.2	34.7	31.2	4.6	4.2	4.6
6.2	27.2	28.1	32.9	29.4	4.9	2.9	4.9
6.3	22.1	23.2	24.4	23.2	5.8	6.8	5.9
6.4	16.4	19.2	22.6	19.4	10.7	7.7	9.3
6.5	14.0	16.4	19.6	16.7	15.8	7.3	12.1
6.6	12.3	11.3	16.7	13.4	27.4	8.0	16.9
7.1	31.6	33.2	42.3	35.7	2.0	4.3	2.3
7.2	26.1	29.1	39.8	31.7	2.2	4.1	2.2
7.3	23.0	21.9	32.0	25.6	4.2	4.5	4.2
7.4	20.1	23.4	31.0	24.8	4.2	5.0	4.2
7.5	20.0	16.3	26.3	20.9	6.6	5.4	5.0
7.6	16.0	13.5	21.1	16.9	15.1	6.8	11.5
8.1	28.6	32.6	40.2	33.8	2.3	3.7	2.3
8.2	32.1	30.4	42.4	35.0	1.7	4.7	1.7
8.3	31.1	31.7	43.6	35.5	2.0	3.7	2.0
8.4	24.0	18.9	28.8	23.9	3.6	5.2	3.6
8.5	18.1	21.1	27.8	22.3	4.4	6.2	4.4
8.6	17.8	18.2	25.0	20.3	7.2	7.3	6.8

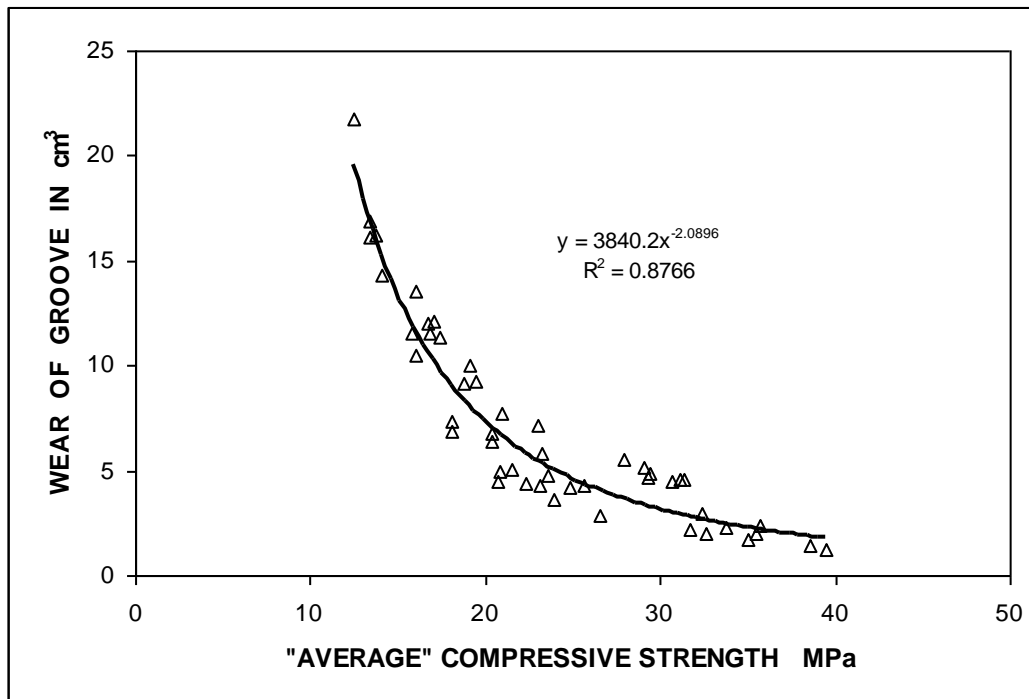


Figure 12.3 Correlation of MA20 (volume of groove) with 'average' 28-day compressive strength

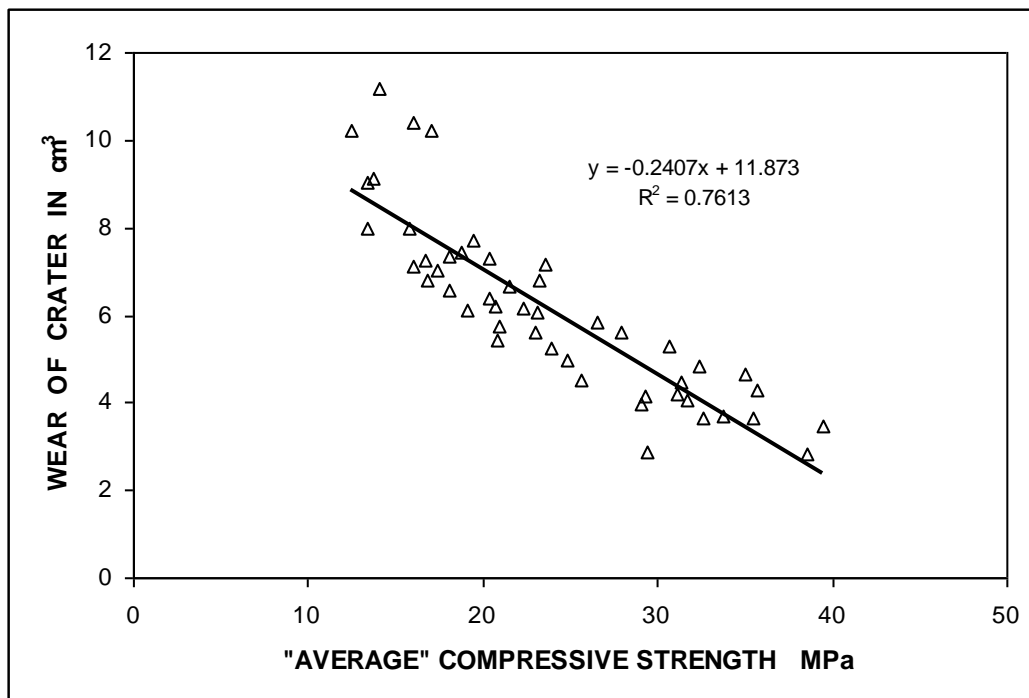


Figure 12.4 Correlation of Wirebrush (volume of crater) with 'average' 28-day compressive strength

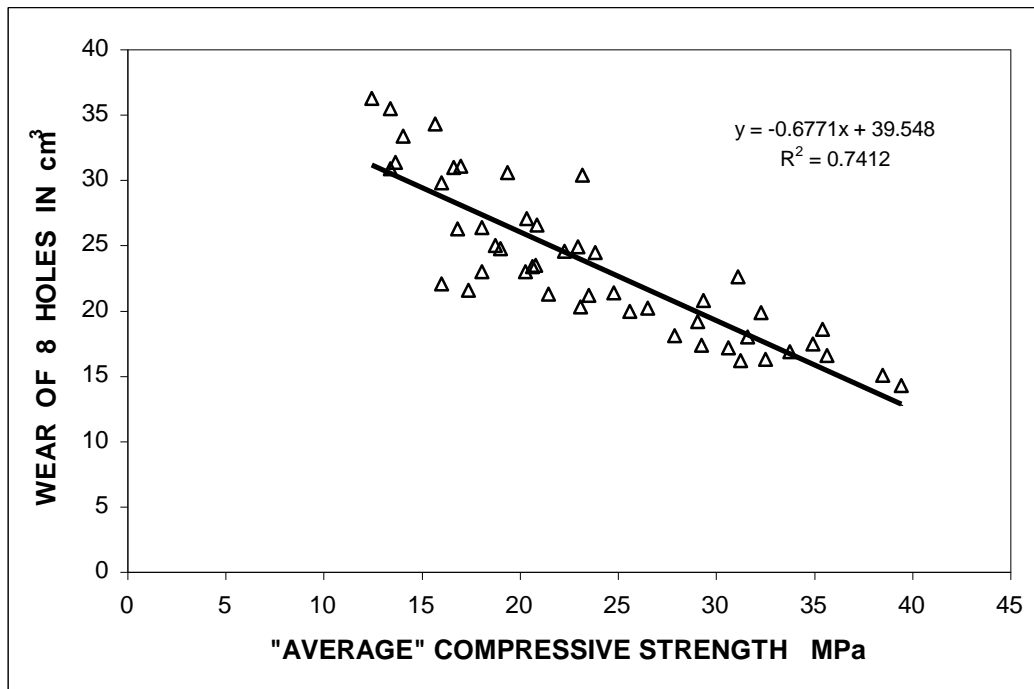


Figure 12.5 Correlation of ASTM C418 (volume of eight craters) with corresponding 'average' 28-day compressive strength

The compressive strengths plotted on the x-axes represent a common strength denominator against which the three abrasion tests [all expressing abrasion-wear as cm^3] can be compared. The graphs allow a visual appreciation of the relative scatter of the results with respect to the trendline. The correlation coefficients are summarised in table 12.3.

Abrasion test	R^2	Type of trendline
MA20	0.8766	Power function
Wirebrush	0.7613	Straight line
ASTM C418	0.7412	Straight line

Discussion

Some interesting observations can be made from the trend lines of figures 12.3 through 12.5:

- relatively high R^2 values indicate that a definite correlation exists between compressive strength and abrasion wear in all three tests.
- the MA20 test has the best correlation, with the wirebrush and ASTM C418 some way behind, but still good.
- a power function best fits the data in the case of the MA20 results (better than exponential, polynomial, logarithmic or straight line).
- expressing abrasion-wear in terms of volume (apart from other advantages stated earlier) makes a meaningful comparison of the three tests possible, as is done in section 12.2.13, and 12.2.14.

Other research

Figure 12.6 is a graph that was taken from an investigation on concrete pavers, [Sukandar(1993)] where the ASTM C779 test (similar to MA20) was used. The graph plots the relationship between the depth of penetration of the balls and the compressive strength and has a very similar shape to figure 12.3. (Given that the *volume* of the groove is reasonably linearly related to the *depth* of penetration (see figure 9-10), and given that the MA20 is a derivative of ASTM C779, it is not surprising to find that figures 12-3 and 12-6 are similar in shape).

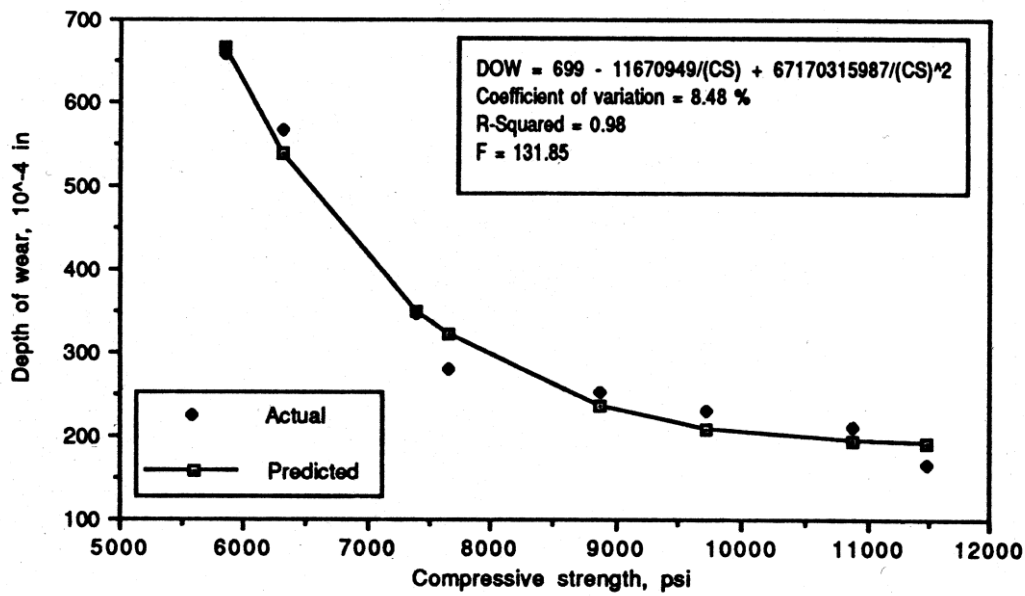


Figure 12.6 Sukandar(1993): Relationship between depth of wear and compressive strength using ASTM C779 Proc.

Sukandar's found that by 'using 5% significance levels the most suitable regression equation was of quadratic form'.

Sukandar's R^2 value of 0,981 points to a very strong non-linear correlation between abrasion-wear (ASTM C799 Proc C) and compressive strength. It confirms the results of this investigation, where a relatively high $R^2 = 0,89$ is indicated in figure 12-3.

12.2.13 Sensitivity

Importance of attribute

That an abrasion test be sensitive to changes in quality is 'very important' and it is therefore given a weight of (5). A sensitive test will detect small shifts in quality, and allow corrective measures to be taken in the production process.

Performance of test

An abrasion test may be said to be sensitive if for a given change in the quality of the concrete (expressed here in terms of the compressive strength), there is a significant corresponding change in volume of abraded material. The trendlines in figure 12.7 show that for any give compressive strength, the ratio of 'volume of wear' / 'volume of least wear' (Y axis) is greatest for the MA20 test, followed far behind by the respective ratios representing the wirebrush and ASTM C418 tests. Note that figure 12.7 has 48 points (corresponding to 48 mixes) for each of the three tests. The various ratios were obtained by manipulating the data of table 12.2.

Clearly a high ratio means that there is a large difference between the weakest and strongest specimen. It may be seen that for stronger mixes these ratios are almost identical for all three tests, but the MA20 is more far more discerning with weaker mixes.

The greater sensitivity of the MA20 test is confirmed by the findings of table 6.7, where MA20 results are calculated in the traditional sense as an abrasion index expressed as $\sqrt{R_{5000}/P}$.

From figure 12.7 the following may be said about the relative sensitivities of the respective tests: the MA20 is 'very good' (5), the Wirebrush is 'fair' (2) and the ASTM C418 is 'poor' (1).

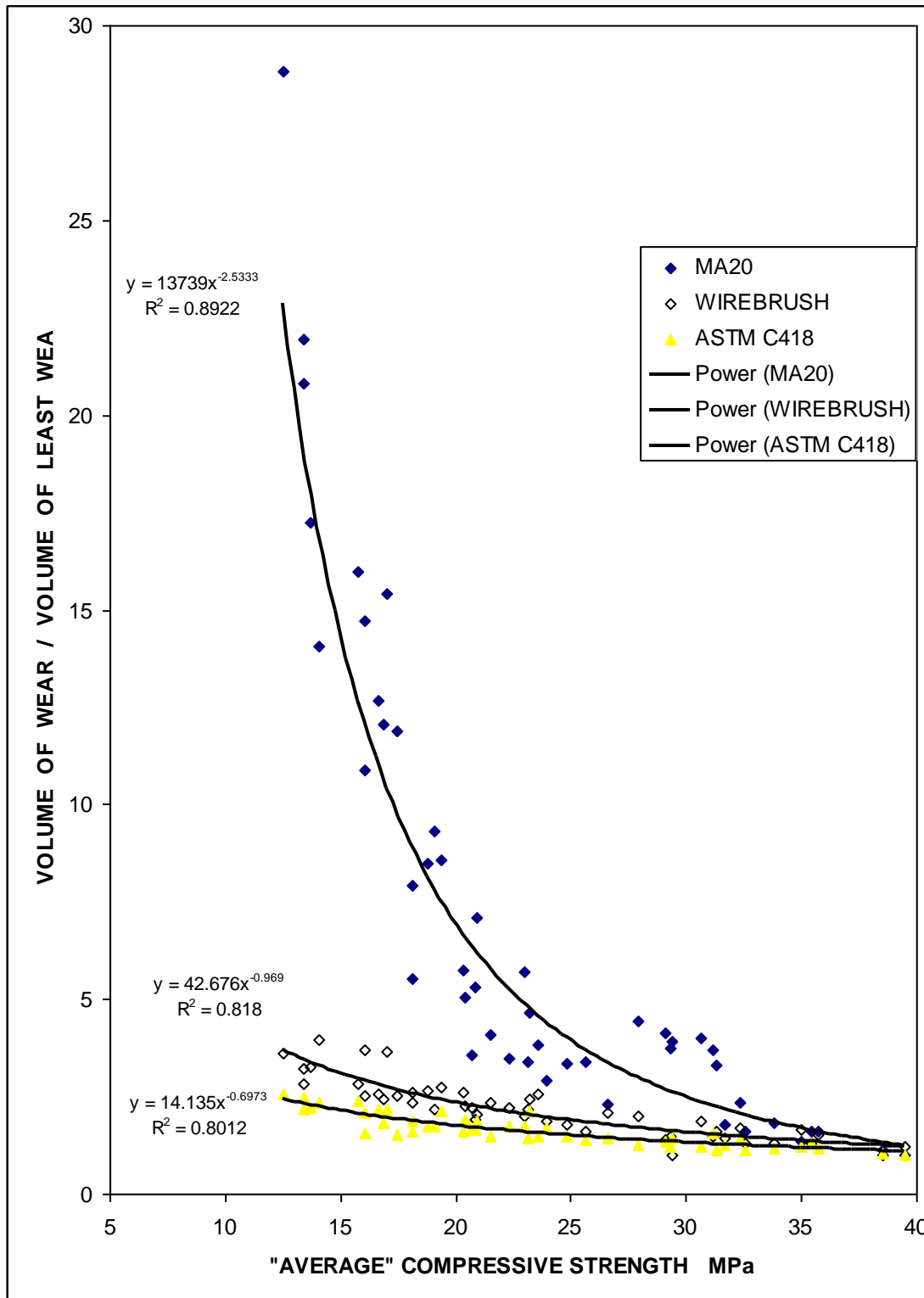


Figure 12.7 Relationship between volume of wear ratios and 'average' compressive strength

12.2.14 Correlation with respect to compressive strength

Performance of test

The correlation of the abrasion indices (expressed in terms of volume) with 'average' compressive strength can be seen from the respective R^2 values in table 12.3:

MA20	=	0,8766	($\equiv V_{5000}$ of chapter 9)
Wirebrush	=	0,7613	
ASTM C418	=	0,7412	

As a point of interest it may be observed from table 9.3 that an almost identical correlation coefficient is obtained, $R^2 = 0,8801$, when the MA20 index, $\sqrt{(R/1000)/P}$, is correlated with the 'average' compressive strength. Consideration may therefore be given to using V_{5000} as the MA20 index.

Therefore the relative performance of these tests with regard to this attribute may be stated as: MA20 'good' (4), Wirebrush and ASTM C418, 'acceptable' (3).

Importance of attribute

Good correlation between compressive strength and abrasion wear can be expected where cbp has been made in a carefully controlled environment, e.g. good curing, consistent density throughout the block etc. Therefore a poor correlation in this instance would indicate that the abrasion test/s in question are not good quality monitors, and vice versa. The correlation with compressive strength is therefore considered 'important' and a weight of (4) is given.

12.2.15 Wear with respect to depth

Abrasion-wear is ideally expressed as the depth of the material removed in the abrasion process, while abrasion resistance is the reciprocal of this expression. This also has the advantage of being a simple concept and even non-technically minded end users should have no trouble with this.

Performance of test

All three tests readily lend themselves to depth measurements, directly or indirectly, from which the abrasion indices can be calculated.

MA20: The depth is measured directly from a gauge mounted on the apparatus, and the abrasion index is calculated from the final reading, either P_{5000} or P_{2000} .

Wirebrush and ASTM C418: The *average* abraded depth is in effect the abrasion index, calculated from the volume of clay used to fill the crater/s, divided by the surface area of the craters. It has been shown that the coefficient of variation is as low as 2% when repeated clay volume measurements are taken on the same wirebrush crater, and this can also be expected for the ASTM test.

For this attribute the performance of $MA20_{P5000}$ can be considered as 'very good' (5) relative to an 'acceptable' (3) for the sandblast and wirebrush tests. ($MA20_{P5000}$, unlike the sandblast and wirebrush tests requires no subsequent measurement with clay followed by a calculation of the 'average' depth).

Importance of attribute

This attribute is considered 'intermediate' and is given a weight of (3). It simplifies the rather abstract concept of 'abrasion resistance $\propto 1/P$ ' to a simple depth measurement, P .

12.2.16 Severity

Importance of attribute

It is considered 'very important' of a laboratory test of this nature that the resultant wear should be clearly measurable, and a weight of (5) is given.

Performance of test

Measurable abrasion wear was recorded for all three tests for even the strongest blocks in this investigation (46MPa at 28 days).

MA20: The very high contact pressures of the MA20 test in the initial stages means that this test has a 'good' (4) performance. The resultant groove for the strongest blocks (46 MPa) was 1 mm deep.

ASTM C418: The sandblast test has shown itself to be even more severe with measured average depths of 2,7 mm being recorded for the strongest blocks (mix 1.2), i.e. a 'very good' (5) performance with respect to the attribute of severity.

Wirebrush: The wirebrush test yields a measurable result for most concretes, and a not-insignificant depth of 2,7 mm was determined for the strongest blocks of this investigation. However, Addis(1989) has reported that the steel bristles of the wirebrush test cannot be relied upon to make a clear impression on concretes above 50 MPa. Given these considerations, this test may be said to have an 'acceptable' (3) performance.

12.2.17 Surface measurement

Performance of test

Although a test should be sufficiently severe to penetrate even the strongest concrete pavers, it should not penetrate so deeply that it becomes more of a measurement of the bulk property of the concrete. The ideal abrasion test should measure the quality of the surface, rather than the deeper zones of the block.

MA20 and Wirebrush: The wirebrush and MA20 tests are true surface tests, and their penetration is generally limited to 2 mm, except with vastly inferior mixes. Their performance is therefore 'very good' (5).

ASTM: On the other hand the ASTM C418 quickly cuts through the surface into the deeper zones of the block, and is therefore not ideal. Only two of 48 of the ASTM results have an average penetration of less than 3 mm. Its performance is therefore 'poor' (1).

(However, Dreijer(1980) reports that this test can be made surface sensitive simply by reducing the amount of blasted sand-abrasive. This statement is backed up with experimental evidence in The Netherlands, whereby the quantity of blasted sand was reduced from 3500grams to 1000grams, to make a single 64mm diameter crater).

The insensitivity of the current test can thus be rectified by blasting with 100 grams, 200, 300, and if deemed necessary, 600 grams (the current specified amount). Thus it will be possible to plot the quantity of abrasive required to reach an average depth of 0,5mm, and 1 mm, and a very meaningful abrasion resistance index may be formulated on *this* basis, expressed in terms of grams/mm of penetration. However, until this has been agreed upon, this test should be considered as a poor surface test).

Importance of attribute

This aspect can be said to be of 'cardinal' importance (weight = 10) since it represents the very essence of what an abrasion test should do, i.e. measure the surface quality.

12.2.18 Compatibility - Lab

Importance of attribute

It can be a matter of great inconvenience if test specimens are smaller than the area of attack. To rectify this situation it would be necessary to carefully fit pavers together in a jig, possibly even involving some cutting. These measures clearly translate into additional costs.

The equipment must furthermore be of such a size, mass and nature as to cause no undue problems.

This attribute is therefore weighted as 'very important', (5).

Performance of test

All three of the abrasion tests can be said to have a 'very good' (5) performance in this regard. No problems were experienced in 'fitting' the test onto the block.

Noise: Although this aspect has not been taken into account in this attribute, it may be a consideration in some laboratories, i.e. in a teaching institution where the laboratories are in close proximity to the lecture rooms. The MA20 test is by far the noisiest of the three, and it is recommended that ear muffs be worn. The Wirebrush is the quietest test; the relatively flexible wire bristles not producing any appreciable vibration as they move at a slower pace over the surface. The noise generated by the sandblast test is that of a hissing sound, but this is largely a function of the type of enclosure used. The enclosure shown in the ASTM C418 specification (used in the SABS laboratories in Pretoria) brings the noise levels down to a comfortable level.

12.2.19 Compatibility insitu

Performance of test

Wirebrush: This equipment has been designed for testing both in the laboratory and insitu. The equipment has been used on various industrial floors to monitor quality etc. It fits into the boot of a car and can easily be lifted by two persons. Its performance for this attribute is therefore 'very good' (5).

MA20: The stand which holds the MA20 test equipment can also be modified to fulfil the same insitu functions described above. This however has not been done yet (to the author's knowledge). It is assumed that the test will have an 'intermediate' (3) performance.

ASTM C418: The sandblast test could also be modified for insitu testing. However unless compressed air is available on site it would be a major operation to do insitu testing. It can therefore be said to have a 'poor' performance (1) in this regard.

Importance of attribute

Since insitu testing is very seldom called for in cbp, and since it is nearly always more practical to remove blocks from the suspect area and transport them to the laboratory, 'minor' importance is ascribed to this attribute, and a weight of (1) is given.

Note: It is not always possible to obtain meaningful test results from blocks that are already heavily abraded. Therefore when blocks are extracted from a site for testing, it may be necessary to uplift representative blocks from a remote area, which still have a relatively smooth upper face.

12.2.20 Repeatability

A test method/type may be said to have perfect repeatability if 'identical' batches register both the same mean *and* a zero standard deviation. The mean is clearly a measure of the average characteristic (strength, density etc.) of the individual results in the sample, while the unbiased standard deviation indicates the extent that the results are scattered about the mean. Finally, the coefficient of variation is obtained by dividing the standard deviation by the mean and is typically expressed as a percentage. Clearly it is dimensionless.

These statistical calculations (mean, unbiased standard deviation, coefficient of variation) have been computed for compressive strength, abrasion resistance etc. and are recorded in appendices B.1 through K.8. They apply to 4, 5 or 6 specimens per mix. The respective formulae for the above three statistical indicators are given in appendix A.8.

Coefficient of Variation

The average coefficient's of variation are summarised in table 12.4 below, for both the experimentation done by the writer in 1987, and that done by Robertson(1991).

1987 Results

Each value in table 12.4 is an average of 48 coefficients, each based on the number of specimens indicated next to the test in question.

1991 Results (Robertson)

Each value in the table is an average of 10 coefficients per test type, with each individual coefficient based on ten samples.

TEST	DESCRIPTION	Papenfus's 1987 tests		Robertson's 1991 tests	
		% COEFF	SPECIMENS	% COEFF	SPECIMENS
SABS 1058	COMPRESSIVE STRENGTH	10.4	48 x 6	13.4	10 x 10
ASTM C140	COMPRESSIVE STRENGTH	9.2	48 x 6		
MA20	COMPRESSIVE STRENGTH	8.7	48 x 6		
ISO 4108	TENSILE SPLITTING STRENGTH	15.4	48 x 6	12.3	10 x 10
MA20	ABRASION RESISTANCE	24.3	48 x 5	29.2	10 x 10
WIREBRUSH	ABRASION RESISTANCE	15.1	48 x 4	18.6	10 x 10
ASTM C418	ABRASION RESISTANCE	7.7	48 x 5	5.1	10 x 10
ASTM C642	DRY DENSITY	1.1	48 x 6		
SABS 0164	INITIAL ABSORPTION	25.5	48 x 6		
ASTM C944	ABRASION RESISTANCE			26.0	10 x 10

Because the coefficient of variation is dimensionless, it is a very useful means of assessing the relative repeatability of *different* test *types*, as may be seen in table 12.4. Given that the three abrasion tests were done on companion specimens, the widely divergent coefficients seen in the table indicate a fundamental difference in repeatability/variability.

It may further be argued that even within *one* test method, the coefficient of variability is a more informative and reliable indicator of variability/repeatability than the standard deviation. Whereas the standard deviation can be misleading if not referenced against the mean, the coefficient of variation automatically references the standard deviation to the mean. For example, two batching plants may both report a standard deviation of 5MPa.

However, if the first standard deviation relates to mixes that had a mean of 20 MPa, while the second to a mean of 60 MPa, clearly the control is substantially better in the second plant. While both plants had the same standard deviation, their respective coefficients of variation are 25% and 8.3%. Therefore even within one test method, it is easier to interpret the coefficient of variation.

For this reason repeatability is simplistically taken as synonymous with the coefficient of variation in this thesis, although it is appreciated that more precise and refined definitions for repeatability exist. For example Alexander(1984), defined repeatability (r) as: Quantitative expression of the random error associated with a single test operator in a given laboratory obtaining successive results with the same apparatus under constant operating conditions on identical test material. It is defined as that difference between two such single results as would be exceeded in the long run in only one case in twenty in the normal and correct operation of the test method.

Expressed mathematically:

$$r = 1.96\sqrt{(2s_1)} \dots\dots (12-1)$$

where s_1 is the single operator standard deviation within a laboratory.

Clearly the repeatability r is proportional to the square root of the standard deviation. It is therefore also proportional to the square root of the coefficient of variation, since the standard deviation is equal to the coefficient of variation x the mean. This is the basis on which repeatability used interchangeably with the coefficient of variation.

However, the term repeatability can be confusing. Usually a process that is thought of as having a high repeatability has a low variability i.e. a low coefficient of variation, which would imply a low r coefficient. But according to expression (12-1), a high repeatability, r , signifies a high variability.

The reader is advised to take cognisance of the context, since generally this term is used elsewhere in this document in the sense of: high repeatability = low variability.

Note also that generally the term 'high variability' is used in a generic sense to signify a high coefficient of variation, and vice versa.

The coefficients of variation in Table 12.4, both for the 1987 and the 1991 experimentation are significantly higher relative to what may be expected of concrete cubes manufactured from the same mix. Doulgerous(1995) ascribes this to 'the high variability in quality of manufactured pavers, even between pavers from a single pallet'.

He attributes this primarily to a variation in density: 'Examination of existing paved areas frequently reveals the high degree of differential wear that takes place. The variability is easily observed just after a rainstorm and is evident from the different rates at which pavers dry out'. The writer fully concurs with Doulgerous that there is ample evidence of variation in density in many paved surfaces. The writer believes this to be principally a function of:

- variations in moisture content from *mix to mix*: Unless a carefully tuned water control system is in operation, such as a Michenfelder conductivity meter that duplicates the moisture content of each mix, variations in moisture content owing to differences in the moisture content in the fine aggregate will result in different moisture contents in consecutive mixes. Differences of as little as 0,5 % can alter the final density by as much as 150 kg/m³ (see figure 6.1). Thus the pavers from successive mixes may have different densities.

- variations in *vibration intensity* from place to place on a single machine pallet. This occurs when the fixed supports are not all the same relative to the vibrator table, of if one of the vibrators is not performing to standard, see figure 2.6 of volume 2.
- variations in moisture content in *different compartments* of the mould owing to variations in moisture content of incoming mixes that are not fully interblended during the feeding and filling operation of the mould. Patches of mix that have additional moisture content, will with a given amount of vibration, fill one or more mould compartments with additional concrete during the pre-vibration/feed-wagon process. Adjacent compartments that have slightly less moisture will end up with perhaps 5% less mix. Finally, when the filling process is complete, and the tamper comes to bare on the upper surface concurrent with the final vibration cycle, the compartment/s with more mix very quickly becomes fully compacted and thereafter behaves as a *solid block*, preventing the tamper from further compacting the adjacent compartments with less mix. Blocks in these compartments will therefore be under-compacted and have substantially lower compressive strength and abrasion resistance. Moisture content variations of this nature are potentially more detrimental than having *all* the compartments filled with a too-dry mix, since in this case the tamper is free to continue its downward movement and hence compaction for as long as the vibrators run.

By way of contrast, the manufacturing of laboratory cubes can be done with very tight controls on the amount of water used for the mix, uniformity of vibration, and uniformity of filling. Hence the substantial improved variability/repeatability for laboratory made cubes.

Performance of test

The relative rating of the three tests are based on table 12.4.

ASTM C418: The average of the 48 coefficients of variation for this test is 7,4%, and the performance of this test is therefore 'very good' (5). This value is even lower than that of the compressive strength coefficients. However, the low coefficient is largely attributable to the eight holes made in each block. (The writer found that if only one hole in each of the blocks is considered the coefficient goes up to 15%).

MA20: Relative to the two other tests, the repeatability of this attribute, with an average of 24,3%, can be described as 'poor' (1).

Wirebrush: The wirebrush coefficient (15,1%) is intermediate between the ASTM and MA20, and its performance can therefore be described as 'acceptable' (3).

These rankings are further substantiated from a consideration of the various components that make up the repeatability:

Since repeatability is derived from the 'single operator standard deviation within a laboratory', and since the various tests were each done by the same operator using the same equipment in one laboratory, then it is clear that variation is derived from one of three areas:

1. operator error
2. machine error
3. material error

If it is further assumed that the operators were well trained and performed the tests according to all the laid down procedures, then it is evident that repeatability (r in this instance), is proportional to the sum of machine error and material error. Accepting the simplification that the coefficient of variation may represent repeatability ($1/r$ in this instance), and assigning an arbitrary value of 5% for the coefficient of the material used in

each of the three tests, then it is evident that the variability of the three test apparatuses is equal to:

MA20	$24,3\% - 5\% = 19,3\%$
Wirebrush	$15,1\% - 5\% = 10,1\%$
ASTM C418	$7,4\% - 5\% = 2,4\%$

This exercise, although based on an assumption, indicates that the sandblast test is very much more repeatable than MA20 (x 8) and wirebrush test (x 4). It reinforces the performance ratings ascribed earlier to the various tests.

Importance of attribute

Repeatability (1/r in this instance) creates confidence in the test method and makes the results more believable. It is therefore considered 'very important' and is consequently given a weight of (5).

Comments made on MA20 variability

Hudson(1992) achieved coefficients of variation of between 12% and 14% for the MA20 test, on concrete beams made in a laboratory, compared with 5% for compressive strength tests done on the same mixes. This would indicate that when compared to compressive strength testing the MA20 has an increased coefficient of variation of approximately 160%, which is almost identical to that obtained in this investigation (i.e. the equivalent increase is 159%, see table 12.4, based on the average of the three compression test coefficients).

Hudson's results indicate an improvement in the MA20 coefficient of variation of approximately 20% if ten blocks instead of 5 are tested.

Ghafoori(1992), used the ASTM C779 Proc. C method and achieved coefficients of variation ranging between 6,7 % and 23,2% (the average was 11%) on production made pavers. These averages are similar to those of Hudson's, but with a noticeably greater range in variability. Notwithstanding it is unusual to find that machine made pavers have average variabilities that compare with laboratory made beams. It should be noted that while the two authors used the same generic test, it seems possible that ASTM C799 Proc C has a lower variability than does the MA20, and that this assisted in keeping down Ghafoori's coefficient of variations.

The proposed CMA20 specification (see appendix A.6), recommends a number of modifications to MA20 in the light of Shackel(1992)'s findings. Hopefully these changes will improve the coefficient of variation. These findings are discussed in some detail in 9.7.

12.2.21 Reproducibility

If a test method gives statistically similar results on duplicate apparatuses at different places operated by different operators then it can be said to be reproducible.

This has been expressed more precisely by Alexander(1984). He described reproducibility (R) as the 'quantitative expression of random error associated with test operators working in different laboratories, each obtaining single results on identical test material when applying the same method. It is defined as that difference between two such single and independent results as would be exceeded in the long run in only one case in twenty in the normal and correct operation of the test method. Mathematically it may be stated as:

$$R = 1.96\sqrt{2}\sqrt{(s_1^2+s_2^2)}$$

where:

s_1 is the single-operator standard deviation within a laboratory,

s_2 is the standard deviation applicable to all causes of variability other than repeatability of testing when results of different operators in different laboratories are compared.

Performance of test

MA20: Research done in Australia [Shackel(1992)] showed that there was 'little agreement' between 'different laboratories', unless six or more sets of test results on equivalent cubes were lumped together. This was ascribed to variability in the test procedures, such as worn bearings, inclination of the block, etc. If proper attention is given to these aspects, it is likely that reproducibility will be much improved. (These aspects are incorporated in the proposed 'CMA20' abrasion specification, see appendix A.6).

Wirebrush: There is only one wirebrush testing rig in South Africa, situated at Portland Park, and it has not been established if this test is reproducible.

ASTM C418: The incorporation of the ASTM C418 test into the ASTM C936 paving specification, and the long history of the test, suggests that it may be reproducible. However the author has no evidence to date to confirm this.

In the absence of more specific data, particularly for the wirebrush and ASTM C418 tests, it is not possible to rate the tests relative to each other. Thus the three tests are assumed to all perform in an 'acceptable' (3) manner.

Importance of attribute

As with repeatability, reproducibility is deemed a 'very important' attribute, particularly if it is to become a national standard. A weight of (5) is therefore given.

12.2.22 Aggregate hardness

It is well known that the hardness of the aggregate plays an important role in the abrasion resistance of concrete [Sadegzadeh(1984), Connel(1985), Addis(1989)].

Ozturan(1987) did abrasion tests with DIN52108, a test that is ideal for measuring the respective contributions of both the aggregate and the mortar in abrasion resistance. He showed that the abrasion resistance of the concrete could be explained in terms of the abrasion resistance of both the mortar and the aggregate components, considering them as separate constituents. He found that the following relationship applied:

$$1/h_c = 1/h_m \cdot V_m + 1/h_a \cdot V_a \quad (12-3)$$

In words this may be stated as: The abrasion resistance of the concrete ($1/h_c$) is equal to the abrasion resistance of the mortar ($1/h_m$) multiplied by the fraction of mortar (V_m) plus the abrasion resistance of the aggregate ($1/h_a$) multiplied by the fraction of aggregate (V_a). Note that $V_a + V_m = 1$.

The implication of expression (12-3) is that the aggregate constituent has a definite role to play in the abrasion resistance of concrete. Consideration should therefore be given to which of the three tests of this investigation is best suited to measuring the abrasion resistance of the aggregate constituent of cbp.

The smooth circular groove of the MA20 test is in marked contrast to the rough appearance of the ASTM C418 holes and the rough crater of the wirebrush test.

In the former test the relatively hard aggregate particles protect the softer binder / mortar component as abrasion proceeds. This is very much like the DIN52108 test. The MA20 test therefore measure both the contribution of the aggregate's abrasion resistance as well as that of the mortar, and in this respect expression (12-3) may be expected to apply.

Contrariwise the ASTM C418 and wirebrush tests in effect largely discount the contribution of the aggregate. The wire bristles and sand particles attack the surface indiscriminately, until the softer binder / mortar component is sufficiently abraded for the aggregate particles to be dislodged. These tests are therefore somewhat unrealistic. Only in applications where excessive grit is present and is trampled into the cbp surface will the mortar component be under continuous attack as in the ASTM and wirebrush tests.

In most other cbp applications, relatively free of grit, and where attention is given to correct mix design and process control, abrasion will not proceed beyond degree 2 because of the protection afforded by the aggregate particles.

Performance of test

From the foregoing discussion it may be said that the MA20 has a 'very good' (5) performance with regard to measuring the contribution of the aggregate in abrasion resistance. The ASTM and Wirebrush tests by way of comparison are 'poor' (1).

Importance of attribute

Since more than 80% of a concrete paver consists of aggregate, it's contribution to the final abrasion resistance of the block can hardly be questioned. An abrasion test capable of measuring the wear properties of the aggregate must therefore be considered of 'cardinal' importance, and a weight of (10) is assigned.

The above ratings have been based purely on the observed wear patterns of the three tests, and the observed wear patterns on numerous paving sites. They have not been studied as a separate exercise in the laboratory. Since only one aggregate type was used

in this programme it has not been possible to test the MA20's assumed superiority in regard to measuring aggregate contribution to abrasion resistance. (This research principally was confined to variations in the water and binder components).

Recommendations

- It is recommended that comparative abrasion testing of the three tests used in this investigation be carried out on blocks made from aggregates of differing hardness.
- It would also be useful to establish the extent that Ozuran's equation applies to MA20.
- The effect of the strength of the aggregate/paste bond should be investigated.

From observing many cbp surfaces over many years the writer does not anticipate that the aggregate/paste bond will be a crucial factor in cbp applications where quality paving with good abrasion resistance has been installed. Only where third and fourth degree abrasion occur, will the protruding aggregate particles and the associated reduction in aggregate / paste interface, place greater importance on this bond.

Finally it may be stated that whereas all three tests have the ability of 'punishing' poor quality mortar/paste in terms of dislodging aggregate particles, only the MA20 measures the aggregate's contribution in pavers with acceptable/good quality paste (where the aggregate is unlikely to be dislodged).

12.2.23 Abrasive obtainability

Performance of test

MA20 test: The bearing used in this programme is easily obtainable from any SKF stockist under the part number:

Thrust Ball Bearing 51310

The performance of this test relative to this attribute is 'very good' (5).

Wirebrush test: The wirebrush is obtainable from most reputable hardware shops. (It is normally used for cleaning rust off steel surfaces). The performance is thus also 'very good', (5).

In this programme the imported Wolfcraft brush was used. More recently however Addis and Addis(1989) have found that the local 60 mm brush made by Transvaal Brush Company is more repeatable, particularly in the first five minutes.

ASTM C418: The silica sand is obtainable from Consol, Philippi, Cape Province. It is commonly known as 'cement testing sand'. The sand falls between the grading limits of 600 microns to 850 microns and is carefully packaged into weatherproof 25 kg bags. The most economical means of transportation is a 3 tonne PX railway container. This would be enough to test 625 blocks. The transportation cost of such a container to the Reef is approximately R 500 (1994 prices). Should this test become an industry standard, it would probably be possible to arrange for local manufacturers to collectively obtain a container and share the contents. However the effort of obtaining what amounts to a fairly bulky abrasive is clearly more than the other tests. The performance is thus 'fair' (2).

Importance of attribute

It is obviously 'important' to be able to obtain the abrasive medium with relative ease, and a weight of (4) is given.

12.2.24 Relationship with insitu wear

This aspect is not discussed in great detail here, as it is fully developed in chapter 14.

Importance of attribute

However it is clear that the relationship of the respective tests with insitu wear is of 'cardinal' importance, and the corresponding weight of (10) is therefore assigned. Note that this does not refer to visual similarities, but to equivalent abrasion resistance (MA20) or abrasion wear (wirebrush and sand blast).

Performance of test

Figures 14.23 through 14.28 show the relationship between the measured insitu wear (mvd) and the respective indices of the three abrasion tests. For each test, two graphs are used, to show these relationships for two traffic regimes, i.e. buses and pedestrians. Each graph is plotted from 18 coordinates representing variations in water content and binder content.

For all three graphs a noticeable relationship exists. The degree of correlation between 6-year site-wear and the respective abrasion indices is summed up in table 12.5 below:

MA 20		Wirebrush		ASTM	
Sidewalk	Bus lane	Sidewalk	Bus lane	Sidewalk	Bus lane
0,8790	0,8311	0,7835	0,7593	0,9055	0,8998

The performance of the three tests, based on table 12.5 may be stated as:

MA20 'good' (4)
 Wirebrush 'acceptable' (3)
 ASTM C418 'very good' (5)

12.3 Conclusion and Recommendations

In this chapter, the three tests have been analysed in terms of 24 attributes considered desirable for an abrasion test.

It bears repeating that deciding on the 'performance' of the three tests with respect to each attribute, and the 'relative importance' of the 24 attributes, is a matter of judgement. The values selected were chosen on the basis of the results of this research as well as the writer's 16 years experience in the field of cbp. Although a degree of subjectivity is inevitable, he has made every attempt to be impartial.

The results of this analysis are shown in table 12.1. Although all three tests have their strengths and weaknesses, the superiority of the MA20 test is indicated by a significantly higher total relative to the other two tests.

Initially the CMA accepted this conclusion, and the larger producers were to obtain the 'CMA20' test apparatus (see appendix A.6) in order to commence routine testing, with a view to ultimately incorporate CMA20 into the national standard, SABS 1058. However, as the tide began to turn against MA20 in Australia and New Zealand, the CMA adopted a wait and see approach. The Australians and New Zealanders eventually decided on a tumbler test (see appendix U.2.03), including it in their 1997 specification, AS/NZS 4456.

It would appear that today the CMA have a choice between three tests currently in use in the USA, the European standard, PrEN 1338:1996 (see appendix U.5.12), and AS/NZS 4456.9 There is also the possibility of adopting the UK C&CA steel wheel test. This test has several merits and was incorporated into BS8204:part2:1999. It does however require some sample preparation owing to the 225mm OD of the circular track (see appendix U.4.6). Finally the ASTM C779 Proc A test (see appendix U.5.15) also has merits, but again has a relatively large wear path, requiring specimen preparation.

Chapter 4 of volume 2 classifies 66 abrasion tests, with special reference to the mechanism of abrasion wear, concluding that three tests meet the most important criteria:

- AS/NZS 4456.9 (tumbling steel balls test)
- C&CA machine (steel wheel test)
- ASTM C779 Proc A (sliding fine abrasive test)

Ideally these three tests should be pitted against the MA20 and ASTM C418 test, but with two provisos. The MA20 test apparatus should be enhanced to embody the features of the CMA20 test, while in the ASTM C418 test the abrasion index should be based on the quantity of abrasive required to blast a crater of average depth 0,5mm.

Further to this, the test specimens should be cubes made under the strictest laboratory conditions. This will enable the true variability of the tests to be established. The influence of aggregate hardness should be given special attention. Binder quantity and w/c ratio should ideally also be included as variables.

The writer believes that a carefully planned experimental programme to find the most suitable abrasion test can succeed, given the considerable experience and understanding gained in the field of abrasion resistance from this and other investigations.