Chapter 10

Critical Evaluation of Wirebrush Abrasion Test

10.1 Background, Introduction, and Overview

The abrasion resistance of concrete is not necessarily related to the compressive strength. Factors such as aggregate selection, binder selection, curing, floating, surface hardeners etc. profoundly influence the quality of the surface concrete and hence the abrasion resistance. Many of these factors also apply in concrete pavers (see chapter 2). Therefore in order to improve the wear resistance of concrete pavers, an accelerated abrasion test is required.

In this chapter, the ‘wirebrush’ abrasion test, the second of the three abrasion tests, is considered. The results of the 1987 laboratory tests, including the wirebrush test, were analysed in some detail in chapter 6. This chapter focuses more on the rationale and relevance of the test. A critical assessment is made of the different ways of measuring and reporting the results, as well as the variability, limiting criteria and the various strengths and weaknesses of the test.

In chapter 12 the various strengths and weaknesses of this test are evaluated against those of the two other abrasion tests.

Finally, in chapter 14, the 28-day laboratory results referred to in this chapter will be correlated with actual wear measurements after six years of traffic.

10.2 Historical Background

The first use of wire brushes to measure the abrasion resistance of concrete appears to have been in 1971 in Holland [Dreijer(1980)]. The brushes were the standard hand held type, generally used for scraping off rust prior to painting, where the bristles are anchored into a timber base. Twenty-four of these bushes were mounted to the base of a standard Amsler abrasion test machine (see appendix U.6.3) with their bristles pointing upwards to make contact with the specimen being tested. The test does not appear to have been used again.

Later the then National Building Research Institute of the CSIR developed a test apparatus, as shown in figure 10.1, (see also figure 4.7, 4.8 and appendix U.5.16.1) for measuring the abrasion resistance of concrete. The test was developed as it was realised that compression testing was unsuitable for monitoring such factors as aggregate hardness, curing, binder strength, etc.

This apparatus is a variation of the apparatus initially developed on the Böhme principle (explained in appendix U.5.02), where abrasion is achieved by feeding abrasive grit between the testing surface and a rotating disc.

However Addis(1989) states that the NBRI test has some shortcomings:

a. The test can be done only on dry concrete since the abrasive grit clogs in the presence of water. The SABS paving and cube specifications on the other hand call for 24 hour soaking prior to testing. This makes direct comparison between abrasion resistance and compressive strength somewhat inaccurate since the moisture condition of the specimen at the time of testing has a marked influence on the result. Sukandar(1993) found variations in abrasion resistance between wet and dry pavers of as much as 50% (ASTM C779 Proc C test).

b. The flow of grit is impeded after 3 to 4 mm of wear. (However where poor quality concrete is likely to abrade beyond the 4 mm zone, this may no longer be regarded as surface abrasion).

c. The wear pattern does not resemble the wear as can be seen in pavers. The aggregate and matrix components abrade at the same rate, resulting in a polished circular crater. However, traffic appears selectively to abrade the softer matrix, leaving aggregate particles protruding above the surface of the matrix: with further wear particles become dislodged to expose new areas of matrix to still further wear. [This is true for weak pavers only. Well made pavers seldom experience third and fourth degree abrasion (see chapter 8) as Addis alludes to here.]

For these reasons the Portland Cement Institute decided to replace the NBRI disc with an abrading medium that results in a wear pattern which they believe better resembles wear in pavers. The pattern of wear produced by their modified test is shown in figure 10.2, while a surface abraded in service may be seen in figure 10.3. There is a noticeable resemblance.

A wire brush of diameter 60 mm with bristles of length 20 mm was chosen (see figure 4.6). The wirebrush cup could be screwed directly into the existing apparatus. After some adjustments, this test, PCI.TM.7.11 (now C&CI. TM.7.11), became the standard test used by the PCI for testing the abrasion resistance of pavers.

The test apparatus is portable. It can therefore be used for insitu testing, although it is somewhat bulky.

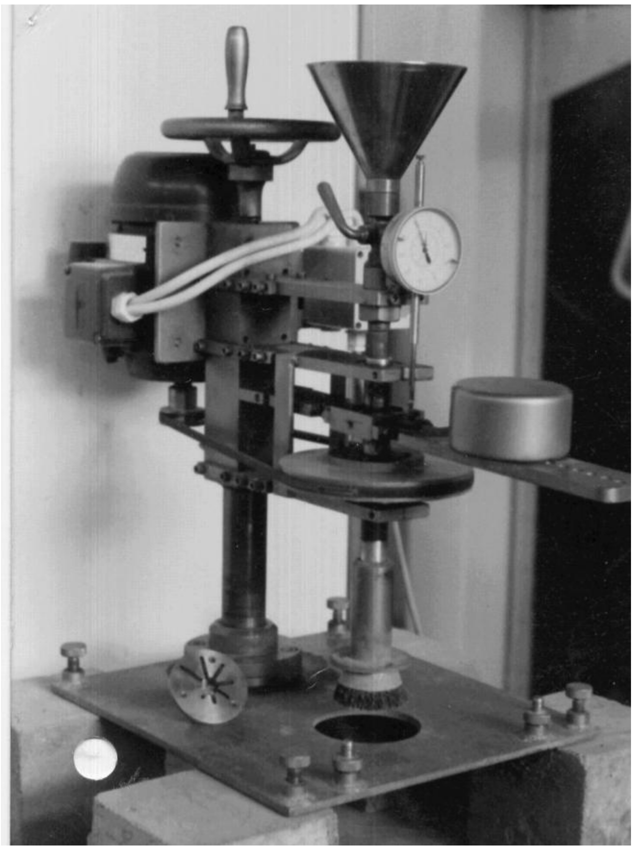

Figure 10.1 NBRI abrasion resistance test apparatus. Notice the circular disc, shown loose, for distributing the abrasive grit in the NBRI grit test, and the wirebrush, shown fastened to the machine for the PCI.TM.7.11 test.

Figure 10.2 Wear pattern of wirebrush test. The wear pattern produced on the surface of the blocks is that of a circular crater.

Figure 10.3 Wear pattern of concrete paver at Westgate bus terminus. Note similarity with figure 10.2

10.3 Description of Test

A detailed description of the test method is given in PCI.TM.7.11, (see appendix A.5), discussed in 4.6, and briefly summarised here.

The test consists of a motorised wirebrush rotating at a speed of 400 rpm on the surface of a concrete paver under a constant load of 165 N. The specimen is pre-soaked for 24 hours. A stream of water is applied at the test face to clear away the abraded material and to keep the wire bristles cool. The direction of the motor is reversed every 30 seconds to prevent a bias developing on the brush. A new brush must be used for every test, since new brushes have different wear characteristics to worn-in brushes. (New brushes are sharper and hence have a relatively severe abrasive action, and they also have a relatively low coefficient of variation [Addis(1989)]. This however was unknown at the time of this investigation, and one brush was used for testing five blocks).

The resultant wear was measured in three ways:

a. Wire-dial method: This method is fully described in 4.6.1. Briefly, the reading on a dial records the penetration of the brush at intervals. The results are analysed in some detail in 10.5.1.

b. Wire-vern method: This method is fully described in 4.6.2. Briefly, eight depth measurements of the final crater are recorded with a vernier depth gauge, and an average obtained. The results are analysed in some detail in 10.5.2.

c. Wire-clay method: This method is fully described in 4.6.3. Briefly, the final crater is filled with modelling clay to determine its volume. This volume is divided by the area of the crater, and an average depth of crater is obtained. The results are analysed in some detail in 10.5.3.

10.4 Wear Mechanisms of Wirebrush Abrasion Test

In order to arrive at an understanding of how the bristles work their way into the specimen under test it will be useful to magnify the two surfaces that come into contact with each other, i.e. the steel wire (of diameter 0.4 mm and length 20 mm) and the surface of the concrete block. If the two surfaces are sufficiently magnified it can be expected that each individual wire may be compared to a bar with a somewhat uneven surface, while the concrete will be characterised by peaks and troughs. On this scale the steel wire, or ‘bar’, is relatively stiff and inflexible.

As this ‘bar’ slides over the surface under load, it results in abrasion wear in three ways, which are discussed in 10.4.1 through 10.4.3.

10.4.1 Shearing of Squat Asperities

The diagram in figure 10.4A shows a bristle that is advancing on an asperity that is ‘squat’, i.e. it only just protrudes above the cutting level of the wire bristle. The length of the asperity relative to its height ensures that it does not shear off the asperity along its full length in one piece, but rather shears small pieces off at some oblique angle, as this represents a much shorter failure path. The result is a small wedge of abraded material immediately in front of the bristle. It is clear that the lower the height of the asperity, the shorter will be the failure path, and the likelihood of shearing is increased. It may be said that such shearing actions, on a microscopic scale, form the basis of all scratching, scraping and cutting. This process will occur even when the ‘cutting level of the bristle’ is undulating, given the ability of the wire to bend when it encounters a protrusion of macroscopic proportions. In other words the microscopic asperities on the macroscopic protrusions will be sheared off in similar fashion to that indicated in the diagram.

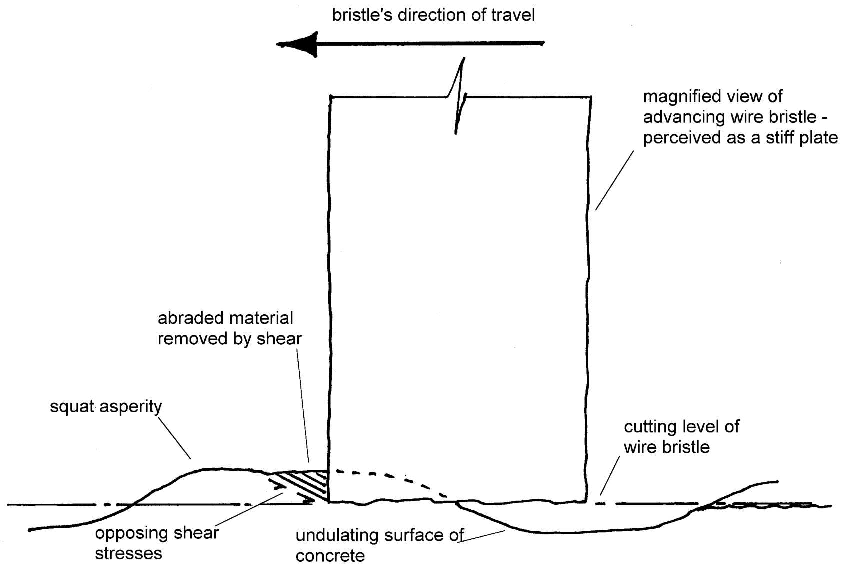

Figure 10.4A Microscopic presentation of wire bristle advancing on a *squat* asperity. Although the wear caused by a single pass of one wire is ‘infinitesimal’, after 2000 revolutions of the hundreds of steel bristles, a clearly noticeable trough or crater generally ranging between 1 mm to 3 mm in depth can be seen (see figure 10.2).

10.4.2 Shearing or Snapping-off of Tall Asperities

Where asperities are tall and slender, as indicated in figure 10.4B, added to the possibility of shearing off, is the possibility of snapping off as a result of flexural stresses induced by the leverage. Once again the lateral scale of the asperity is so much less than that of the bristle, that the latter behaves as a relatively unbending bar and is able to exert enough of a lateral force on the slender asperity to snap it off. However, according to Hutchings(1992), the angle of the asperities generally do not exceed 10^o, which means that this kind of failure mechanism will be relatively rare.

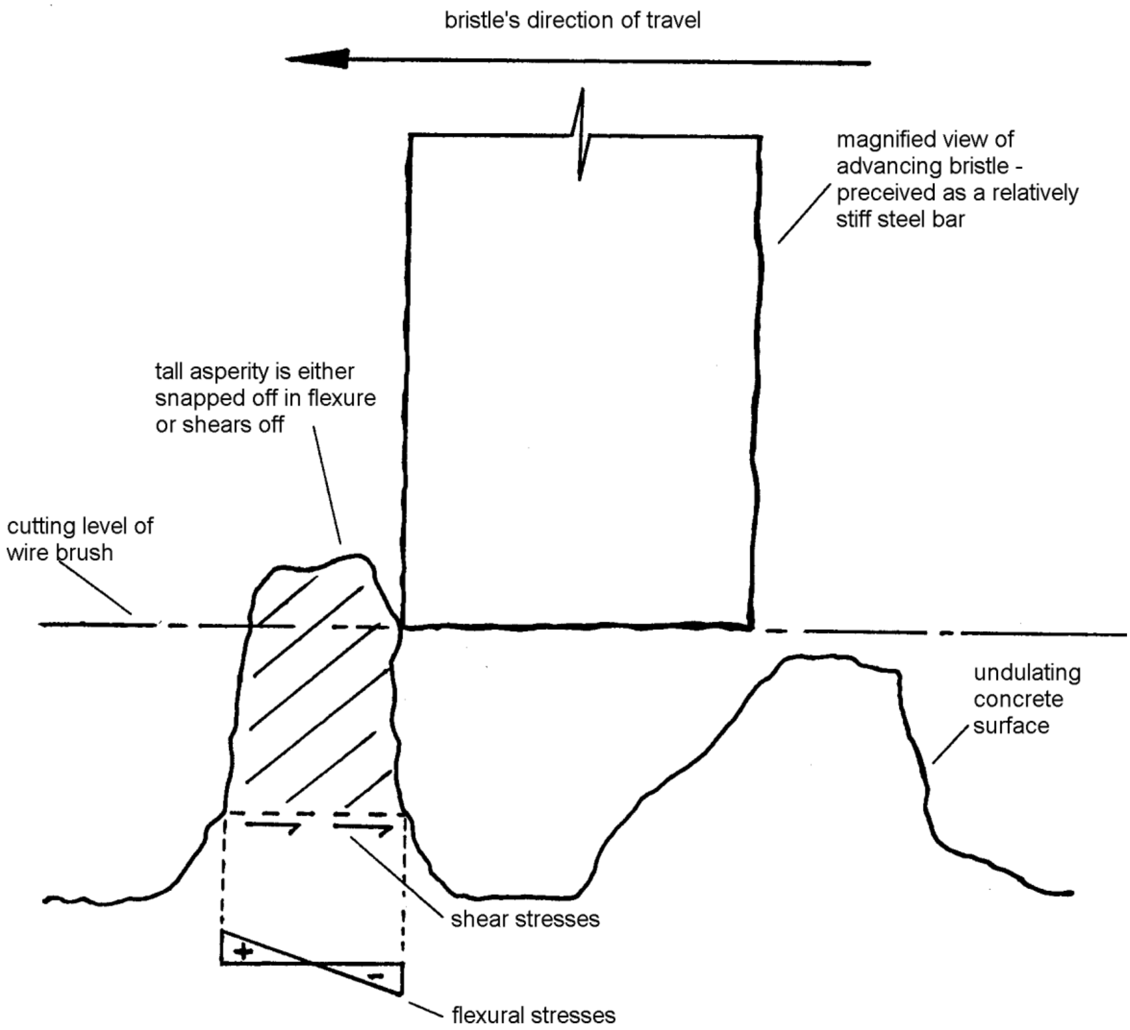

Figure 10.4B Microscopic presentation of wire bristle advancing on a *slender* asperity.

Mild Impact

The microscopic 'shearing' effect demonstrated diagrammatically in figure 10.4A and the shearing/snapping effect shown in figure 10.4B is accentuated by the speed of rotation of the wirebrush. At 400 rpm the individual wires on the outside perimeter are scraping a distance of 1.25 meters per second. In the process the bristles bend and rebound over the surface of the concrete at a considerable speed. As their tips rebound tangentially onto the face of the concrete the microscopic effect is that of a heavy 'bar' pendulum shearing off the protruding peaks of concrete.

10.4.3 **Aggregate loss**

Another form of abrasion occurs through aggregate loss. The onset of fine aggregate loss corresponds to 3rd degree abrasion while 4th degree sees the loss of course aggregate .It characterises a much accelerated rate of abrasion, since the dislodged particle represents a huge mass of material lost (relative to the rate of asperity attrition) in a single point of time.

There are generally two ways that the aggregate particle can be dislodged. The continual application and release of an eccentric load, from scraping of the bristles over the surface of the particle, results in a corresponding application and release of a torque that will eventually fatigue the bond between the aggregate and paste. Alternatively, the path of shear failure may be through the paste, particularly in an inferior paste with a large percentage of voids. Both paths are indicated in Fig 10.4C

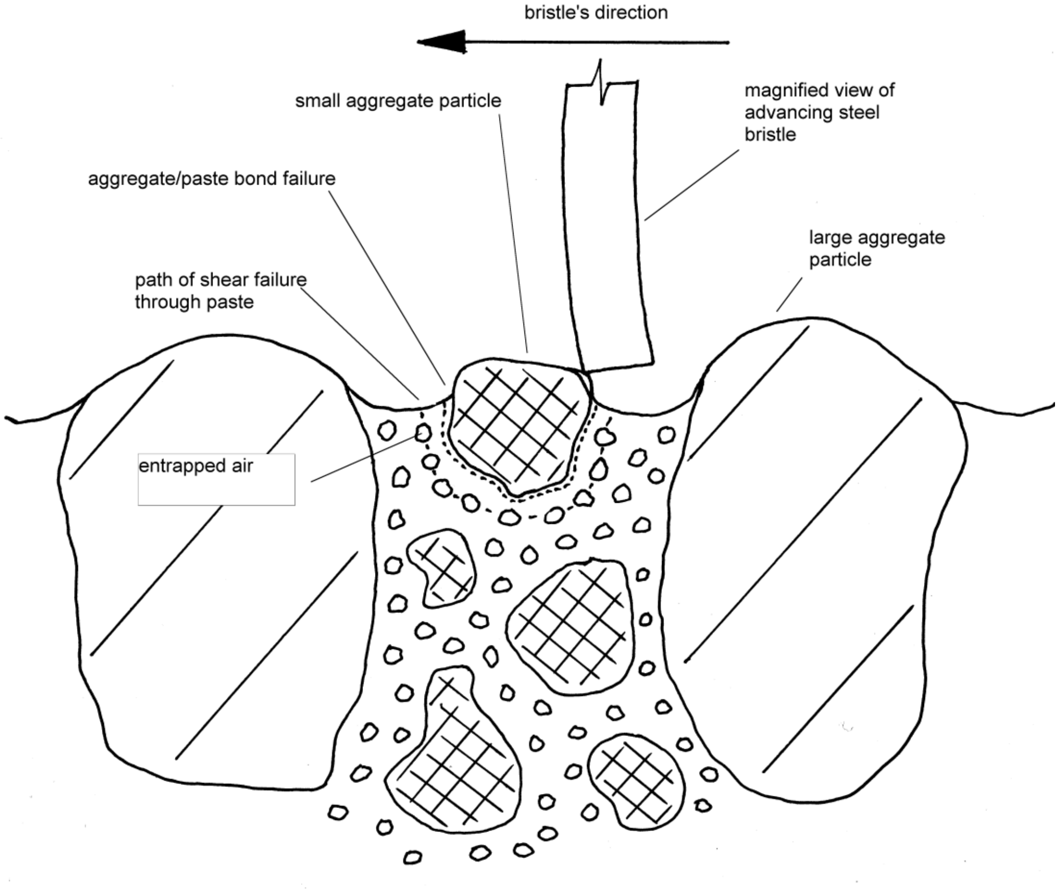

Figure 10.4C Magnified presentation of wire bristle advancing on an aggregate particle.

That aggregate loss is a sign of inferior paste is confirmed by the many photographs in appendix Z, which indicate a significant loss of aggregate in pavers that were made from mixes with inferior compressive strength. Gordon(1991) reports that ‘below 35 MPa (cube strength) the stone content affected the results as the bristles were able to pluck out loose stones. The volumes [of abraded material] for the concrete were thus larger for the concrete than for the mortar’.

10.4.4 Crushing

Clearly the downward force acting on the wirebrush applies compression to the concrete via the wire bristles. Given the many hundreds of bristles in a given brush, it follows that the compressive force in any one bristle will be relatively small. If for example if is assumed that there are 500 bristles in a brush, and that each bristle has a diameter of 0,4mm, and that the axial load on the brush is 165 N, and that all the bristles are in contact with the surface, then the compressive stress below a typical bristle is 2,6 MPa. Clearly this is too low for crushing to take place in all but the most inferior of mortars.

10.4.5 What other Authors say

Alexander(1987) makes reference to the abrasive action of the wirebrush test as ‘cutting and sliding friction of semi-rigid steel fibres’.

Robertson(1991) observes that ‘the wirebrush may involve some plucking of aggregate but is likely to involve primarily direct abrasion of high points and thus be primarily influenced by aggregate hardness once the initial paste coating has been eroded. Aggregate/paste bond will be important in cases of poorer abrasion resistance’.

Addis(1989) found that the ‘surface tested with a wirebrush closely resembled the surface of concrete worn under traffic’.

Doulgeris(1995) described the abrasive action as that of ‘scratching and cutting. Weakly cemented particles are removed by the shear action of the rotating brush. After the test the surface is left irregular and pitted with coarser harder particles left exposed. This is the precise appearance observed on the majority of reported cbp failures’.

10.4.6 Typical Applications

The shearing action of the wirebrush test is present in most applications where cbp is used, viz. vehicular and pedestrian traffic. The only difference is that this contact will be softer and hence the rate of abrasion slower than in the case of the steel wires of the wirebrush test.

In vehicular traffic, acceleration, braking, cornering, and slewing result in friction developing between tire and road and this will result in the kind of shearing effects that the wirebrush test simulates. Traction is even present in vehicles moving forward at constant speed, to overcome wind resistance, and this again gives rise to friction resulting in some shearing effects.

These same effects can be seen in foot traffic. Friction occurs between the sole of a pedestrian's shoe and the surface of the pavement as he (or she) propels himself forward. Friction also occurs as he places his heel down in taking the next step. If he is moving very quickly a degree of slipping and scraping will be noticeable. Some people drag their feet as they walk and others turn on their soles. This results in a tangential motion being applied to the surface.

The end result is that the protruding microscopic tips of the concrete are subjected to tangential shear stresses. However, the severity of these stresses is a function of how free the surface is of hard particles such as sand and grit. Where clean contact is made between rubber/leather and the surface, the compressive stress will be very small indeed, resulting in minimal friction, and hence the tangential load is likely to slide over the surface resulting in so little wear that it may amount to the transfer of no more than a few molecules by adhesion. On the other hand, should hard particles be present, and made to slide beneath a tyre or heel, the normal and shear stresses will be enough to cause some shearing of asperities even on hard surfaces, and deep gouging in weak surfaces.

10.4.7 Sectional Conclusion

It may be concluded that the primary mode of failure in this test is that of mild shearing of asperities, aided by a slight degree of tangential impact. Crushing effects are negligible. (These effects are quantified in the wear code of Table 4.2 in volume 2 by the symbols, S2I1R0). This may be regarded as a good simulation of the scratching/gouging that occurs when hard particles are made to slide over the surface in response to the sliding motions of pedestrian footwear and vehicular traffic.

Finally, the wirebrush test differs from the MA20 test in that it primarily simulates shearing actions whereas the MA20 test primarily simulates crushing effects. Clearly both effects are present in practice.

10.5 Results of Laboratory Tests September 1987

Five blocks from each of 48 mix designs were subjected to the wirebrush abrasion test. The test procedure is adequately described in 4.6. The abrasion-wear indices are given in appendices:

a. F.1 through F.8, Wire-dial method, see 4.6.1, expresses abrasion wear as depth of penetration, P.

b. G.1 through G.8, Wire-vern method, see 4.6.2, expresses abrasion wear as depth of penetration, P.

c. H.1 through H.9, Wire-clay method, see 4.6.3, expresses abrasion wear as volume of abraded material, V.

These results are summarised in columns F, G, and H of table 6.2, where each entry is the average of four blocks tested for each mix design. Initially five blocks were tested but the results of the first test of each of the 48 mixes could not be used. Excessive wear was recorded for the first block (see appendices H.1 through H.8), owing to the initial sharpness of the bristles in the new brush, (a new brush was used for every mix, i.e. after every 5 tests). The specification, PCI.TM.7.11, which was published subsequent to these tests, states that the brush should be replaced after every test. It does however state that the same brush, once worn in, can be used for comparative testing, up to five times.

Analysis of three test methods

Since three different methods for recording the abrasion-wear have been used to express the results of this test, these methods will be analysed separately in 10.5.1 through 10.5.3. Thereafter they will be correlated with companion compression test results in 10.5.4. Finally one of the three methods is recommended.

10.5.1 Results of wire-dial readings

The results of the wire-dial readings are recorded in appendices F.1 through F.8, and a graphical presentation is given in appendices F.9 to F.16. Figures 10.5 through 10.7 illustrate these results for mixes all made with a variation in binder type, but with the same binder content.

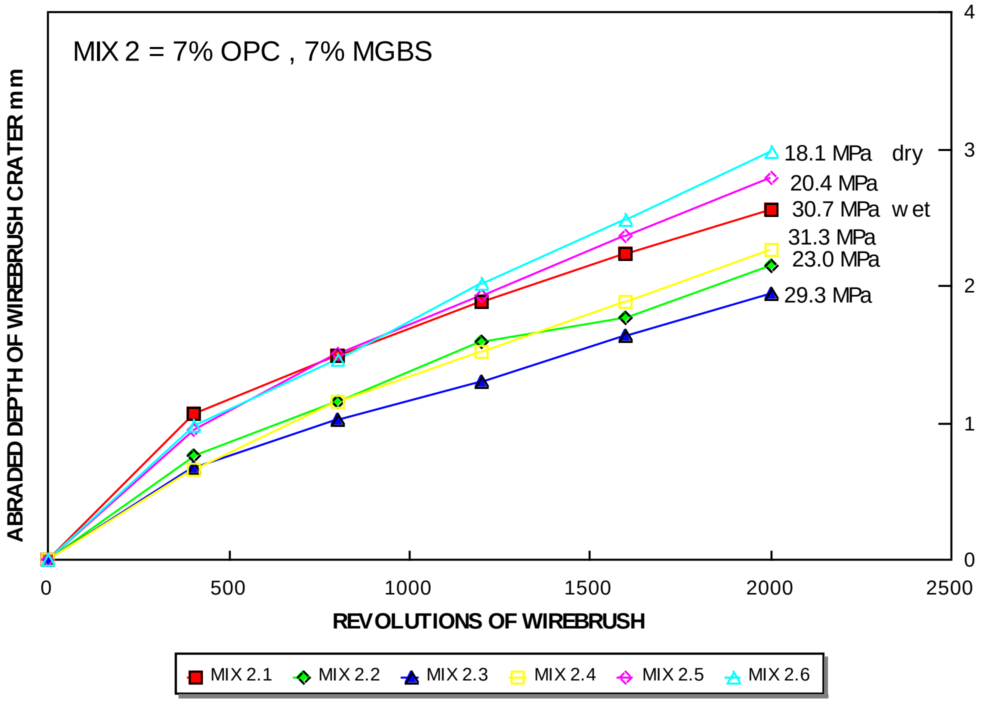

Figure 10.5 Relationship between revolutions of wirebrush (R) and abraded depth of wirebrush crater (P); Mix 2.

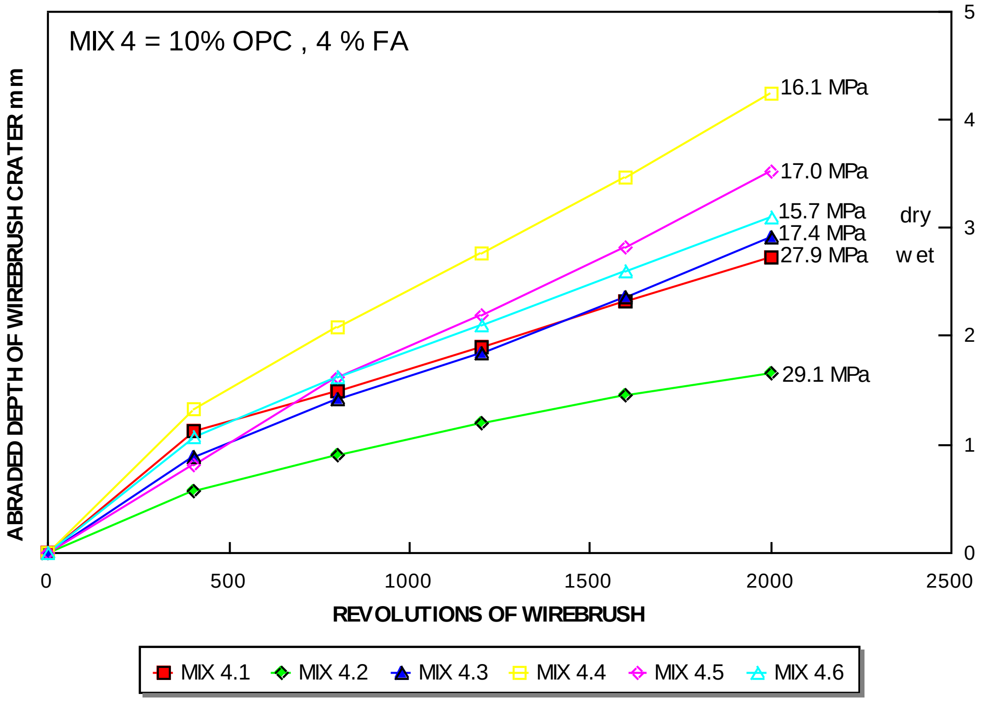

Figure 10.6 Relationship between revolutions of wirebrush (R) and abraded depth of wirebrush crater (P); Mix 4.

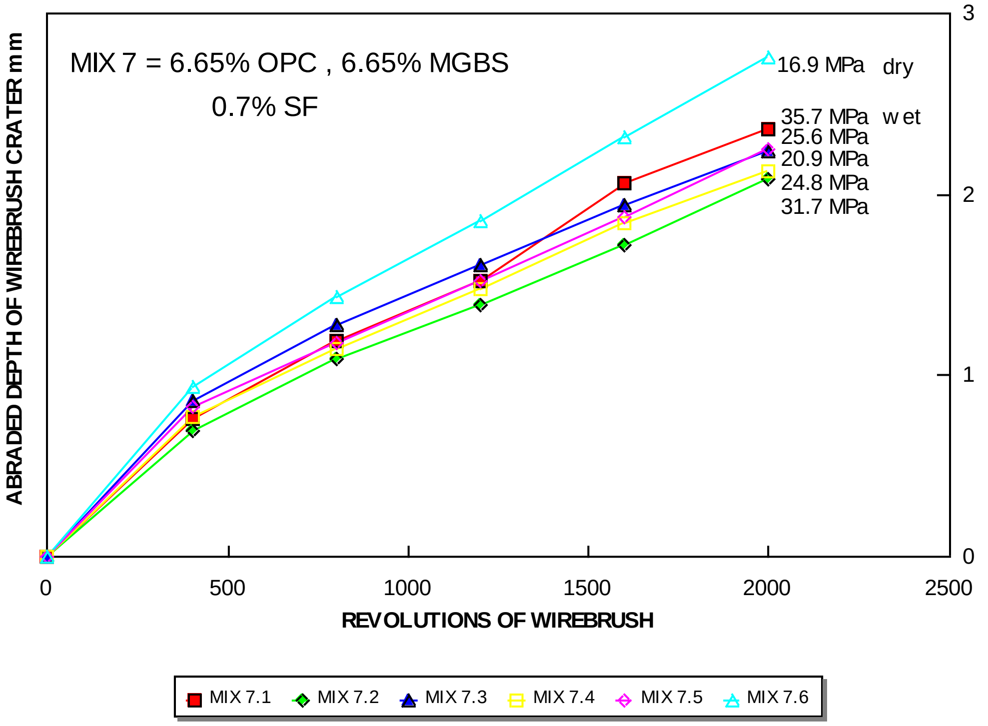

Figure 10.7 Relationship between revolutions of wirebrush (R) and abraded depth of wirebrush crater (P); Mix 7.

Observations from the graph

Linearity: A feature of the lines in figure 10.5 through 10.7 is that they are relatively linear apart from the first 400 revolutions. The linearity aspect is logical, since unlike the MA20 test the abraded area remains constant for the full duration of the test.

Steep till 400 revolutions: The steeper gradient for the first 400 revolutions may be attributed to three possible causes:

a. The initial smoothness of the specimen indicates a higher proportion of the relatively soft paste component near the surface. Initially the mortar/paste component takes the full brunt of the attack, hence the rapid rate of wear. Once abrasion has progressed to a degree the larger aggregate particles stand proud of the mortar/paste component and afford a measure of protection.

b. The water content in the upper surface of the block may be somewhat higher due to slight trowelling/suction effects between the tamper shoe and the surface during vibration. This may result in a lower c/w ratio and thus less strength.

c. The upper surface may have dried out to a degree and consequently curing was inhibited. This however is unlikely in this investigation, since careful attention was given to ensure uniform and continuous curing.

Advantages of P vs R graphs: An advantage of recording results, as penetration proceeds, as in the MA20 and wire-dial tests, is that the resultant curves can result in useful information regarding the surface of the block. For example a curve that is steep in the initial stage of the test, but which shows substantial flattening once a given penetration

has been reached, may be an indication that there is nothing inherently wrong with the mix design, but that the surface was allowed to dry out before curing commenced.
Brush induced problems: In spite of the obvious advantages of a wear-duration curve, it would appear that something is inherently wrong with this way of measuring wear in the wirebrush test. The now established trend that wet (and hence dense) mixes resist abrasion far better than dry mixes, is not confirmed in a number of the graphs of appendix F.9 through F.16. For example, in figure 10.5 (from appendix F.10) the wettest mix performs rather poorly. Its position relative to the other curves does not correlate as expected with the 30.7MPa value shown in the figure. It has the worst performance in the initial stages of the test.

In mix 4 (see figure 10.6) the curves have a wide envelope, whereas for mix 7 (see figure 10.7) the curves are grouped within narrow limits. However, the MPa ranges in the respective figures are similar to each other. This suggests that there is something inherently wrong. Furthermore, in figure 10.7 (as in figure 10.5), the MPa values shown in the graphs indicate a surprising degree of randomness.

The ‘spring’ in the bristles coupled with the ‘bias’ of the brush is a possible explanation for the anomalies occurring in the wear duration curves constructed using the dial method. Every time the machine is reversed in direction, the ‘bias’ of the bristles changes. They never quite come to rest at the same inclination. Furthermore a varying degree of elastic ‘spring’ is likely to be retained in the bristles, also resulting in different readings on the dial.

This method of analysing abrasion resistance is therefore not recommended for the wirebrush test. (By way of contrast the balls of the MA20 test are incompressible and the resultant wear-duration curves follow the expected trends).

10.5.2 Results of wire-vern method

The results of the wire-vern test are recorded in appendices G.1 through G.8, and summarised in column G of table 6.2. Unlike the wire-dial method, there are no wear versus duration graphs, since the depth of penetration measurements were made only at the end of the 5-minute test. The index used to express the degree of abrasion for this method is discussed in 10.6.2.

10.5.3 Results of wire-clay method

The results of the wire-clay test are recorded in appendices H.1 through H.8, and summarised in column H of table 6.2. As in the wire-vern method there are no wear-duration graphs, since only one one-off ‘volume of clay’ determination was made at the end of each test. The index used to express the degree of abrasion for this method is discussed in 10.6.3.

10.6 Abrasion Indices

The abrasion indices of the wirebrush test express abrasion wear rather than abrasion resistance. From section 10.5 it is plain that abrasion wear is either recorded as the depth of the penetration of the bristles into the block, or the volume of the abraded material.

It is furthermore possible to convert the abraded volume into abraded depth, merely by dividing by the abraded area, a constant. (This conversion was done in figure 10.10, allowing a comparison with figures 10.8 and 10.9). Having expressed abrasion wear as depth of penetration, it is also possible, if desired, to determine the equivalent abrasion resistance, since this is simply the reciprocal of the depth of abrasion-wear. (This conversion was done throughout table 6.15, allowing the wirebrush and sandblast tests to be compared with MA20).

10.6.1 Wire-dial index

The similarity between the wire-dial and the MA20 abrasion test is immediately apparent. In both instances readings are taken at strategic intervals as abrasion proceeds, making it possible to construct wear-duration curves that indicate the relationship between P and R. This suggests the calculation of an abrasion index (either for abrasion resistance or for abrasion wear) on a similar basis as the MA20 test in chapter 9.

Abrasion wear in the wirebrush test may be expressed in four ways, i.e.:

$$I_{a\ avg} = (R)^{1/2} / P \qquad (10.1)$$

$$P = 1/I_a.(R)^n \qquad (10.2)$$

$$\log P = n \times \log R - \log I_a \qquad (10.3)$$

$$V = n.R \qquad (10.4)$$

However, the effort of subjecting the data in appendices F.1 through F.8 to each of these expressions, and thereby establishing various tables, additional appendices, graphical relationships etc., as was done in chapter 9, is not warranted here for the following reasons:

Expression (10.1): Except for the first 400 revolutions, the relationship between P and R is linear, as illustrated in figures 10.5 through 10.7. A quadratic expression is therefore inappropriate.

Expression (10.2): Since the coordinates between P_{1000} and P_{5000} are in a straight line, n is unity in this expression. It is therefore of no use as a substitute abrasion index. In fact $1/I_a$ would in this case be the slope of the lines in the various graphs. However considering the confused order of some of the results obtained in figures 10.5 through 10.7, a detailed analysis would serve no purpose.

Expression (10.3): This expression is a more general statement of expression (10.1), in logarithmic form. Again in this expression is unity (for data in a straight line), and is therefore of little use as an abrasion index.

Expression (10.4): This expression is a variation of expression (10.2). ‘n’ in effect is the same as $1/I_a$ in expression (10.2). The only difference between the V (volume of crater) of expression (10.4) and P (depth of crater) of expression (10.2) is a constant, the area of the crater. Again a detailed analysis is not justified in the light of the confused results obtained in figures 10.5 through 10.7.

In the wirebrush test, limiting criteria (see table 10.2) are based on the average depth of the resultant crater. In keeping with this, and in the light of the problems with the expressions in (10.1) to (10.4), only the final reading on the dial at P_{2000} is used as an index to express wear in the 'wire-dial' method. It is appreciated that the P_{2000} readings are also problematic, but it will be useful to compare the results of this method of measurement with those described in 10.6.2 and 10.6.3.

10.6.2 Wire-vern index

Here a vernier depth gauge was used to take eight measurements after the block had been removed from the apparatus. The procedure followed is the same as that prescribed in PCI.TM.7.11, except that only eight and not 20 depth measurements were taken (see also 4.6.2). Obviously the problems associated with the 'spring' and 'bias' of the brush are eliminated in this method.

The index is defined as the average of the recorded depths.

10.6.3 Wire-clay index

Here the index is defined as the average depth of the crater, which is determined by dividing the volume of modelling clay required to fill the crater, by the area of the crater. The procedure followed is the same as that prescribed in PCI.TM.7.11 (see also 4.6.3.)

10.6.4 Critical evaluation of indices

In the three preceding sections, 10.6.1 through 10.6.3, three different indices were considered for the wirebrush abrasion test. These indices are shown in table 10.1, in parallel with the 'average' compressive strength, a value that represents 18 blocks tested (see chapter 7). (In the absence of an abrasion test with proven, established and meaningful indices, the results of the compression tests have been used as a yardstick for assessing abrasion resistance. This was motivated in 9.6 and does not bear repeating).

From table 10.1 the relationship between the respective wirebrush indices and the average compressive strength can be determined and this is graphically illustrated in figures 10.8 through 10.10. The corresponding R^2 coefficients are given in these figures to indicate the degree of correlation between the average compressive strength and the respective abrasion indices.

Note: The reader is again reminded that the wirebrush indices here are all a measure of depth of wear, and therefore indicate the extent of the abrasion-wear, rather than abrasion resistance (which may be expressed as the reciprocal of depth-of-wear).

TABLE 10.1 CORRELATION OF WIREBRUSH ABRASION INDICES WITH COMPRESSIVE STRENGTH

MIX	COMPRESSIVE STRENGTH		WIREBRUSH ABRASION INDICES PCI.TM.7.11		
	MA20 TEST	AVERAGE OF 3 TESTS	DIAL mm	VERNIER mm	CLAY cm^3/cm^2
1.1	44.9	38.5	1.660	1.19	0.068
1.2	45.8	39.5	2.090	1.28	0.085
1.3	39.3	32.6	2.050	1.49	0.090
1.4	28.4	23.1	2.930	2.06	0.145
1.5	28.0	23.6	2.760	2.31	0.163
1.6	22.0	18.1	2.400	2.31	0.149
2.1	35.3	30.7	2.560	2.01	0.128
2.2	36.0	31.3	2.150	1.82	0.105
2.3	35.2	29.3	1.950	1.80	0.100
2.4	26.2	23.0	2.260	2.35	0.132
2.5	25.0	20.4	2.790	2.63	0.152
2.6	21.6	18.1	2.990	2.85	0.162
3.1	25.0	20.9	2.590	2.63	0.134
3.2	22.8	19.1	2.740	2.50	0.145
3.3	18.5	16.1	3.430	2.62	0.158
3.4	16.6	13.7	3.160	3.06	0.187
3.5	15.0	12.5	4.110	4.19	0.221
3.6	16.6	13.4	3.480	3.16	0.187
4.1	32.3	27.9	2.730	2.18	0.125
4.2	32.9	29.1	1.650	1.85	0.096
4.3	20.2	17.4	2.910	2.82	0.157
4.4	19.4	16.1	4.250	3.63	0.211
4.5	21.3	17.0	3.530	3.34	0.204
4.6	19.5	15.7	3.100	2.91	0.164
5.1	37.9	32.3	2.250	1.76	0.108
5.2	30.0	26.6	2.940	2.06	0.129
5.3	24.0	20.7	2.800	2.18	0.137
5.4	25.0	21.5	2.630	2.34	0.137
5.5	21.0	18.8	3.240	2.96	0.162
5.6	16.5	14.1	4.340	3.89	0.226
6.1	34.7	31.2	1.930	1.71	0.102
6.2	32.9	29.4	1.620	2.18	0.093
6.3	24.4	23.2	2.950	2.84	0.150
6.4	22.6	19.4	2.960	3.03	0.155
6.5	19.6	16.7	3.060	2.92	0.147
6.6	16.7	13.4	2.810	2.90	0.156
7.1	42.3	35.7	2.360	1.60	0.105
7.2	39.8	31.7	2.090	1.62	0.106
7.3	32.0	25.6	2.240	1.79	0.114
7.4	31.0	24.8	2.130	2.04	0.112
7.5	26.3	20.9	2.250	2.19	0.124
7.6	21.1	16.9	2.760	2.69	0.152
8.1	40.2	33.8	1.850	1.32	0.087
8.2	42.4	35.0	2.230	1.76	0.103
8.3	43.6	35.5	1.750	1.47	0.084
8.4	28.8	23.9	2.240	2.16	0.117
8.5	27.8	22.3	2.440	2.51	0.137
8.6	25.0	20.3	3.010	2.93	0.156
MEAN	28.2	23.8	2.649	2.37	0.137
R^2			0.615	0.803	0.780
BASED ON	48	48	48	48	48

Comparison of indices

If the vernier measurements are taken at truly representative sights in the craters, the result (average depth) will be the same as for the wire-clay method, which clearly gives the true average depth. Tests done by Addis(1989) showed that the abraded depth determined by filling with modelling clay was ‘slightly less’ than that determined by measuring with a micrometer. In his measurements a template plate with 20 holes was used to achieve a random measurement pattern.

This difference is evidently small enough for there to be no differentiation in the limiting criteria in PCI.TM.7.11 (see table 10.2), irrespective of which method is used.

However, this was not the case in this investigation. The wire-clay method showed the average penetration for all the mixes to be 1.37 mm (see bottom of table 10.1) compared to 2.37 mm for the wire-vern method, a significant difference. This may be explained as follows: Instead of random depth measurements, the depth of an *average plateau* in the crater was measured at eight different places, spaced 45^o apart. At each measurement a low point was sought. Inevitably this led to a greater wire-vern reading relative to the wire-clay, which gives an accurate assessment of the true average depth. A further difference is that the wire-vern is based on 8 measurements not 20. From this it may be deduced that the technique of the operator is important in the wire-vern method.

Recommendation: The writer recommends that only the wire-clay method be adopted, in preference to the ‘wire-vern’ method. This virtually eliminates the subjective element so that and the true average height is obtained.

Correlation with compressive strength

The degree to which the respective indices correlate with compressive strength can be seen from the R² values of a regression line analysis for the respective indices, shown at the bottom of table 10.1, i.e.:

MPa vs P_{dial} $R^2 = 0,615$
MPa vs P_{vern} $R^2 = 0,803$
MPa vs P_{clay} $R^2 = 0,780$

This is illustrated in figures 10.8 through 10.10.

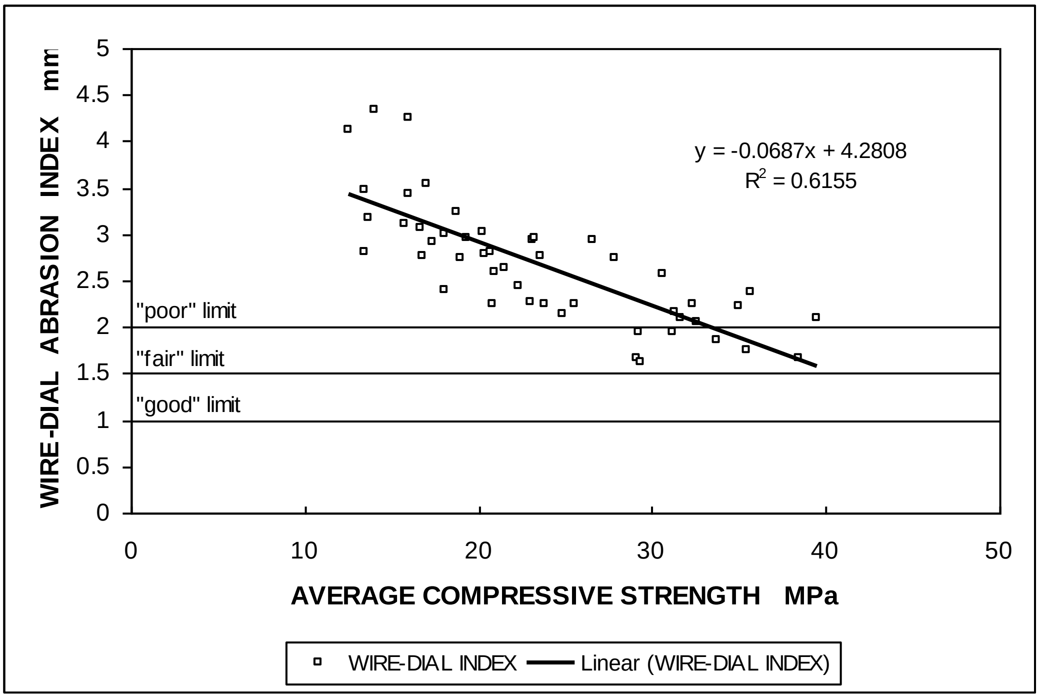

Figure 10.8 Correlation of wire-dial abrasion index with 'average' compressive strength

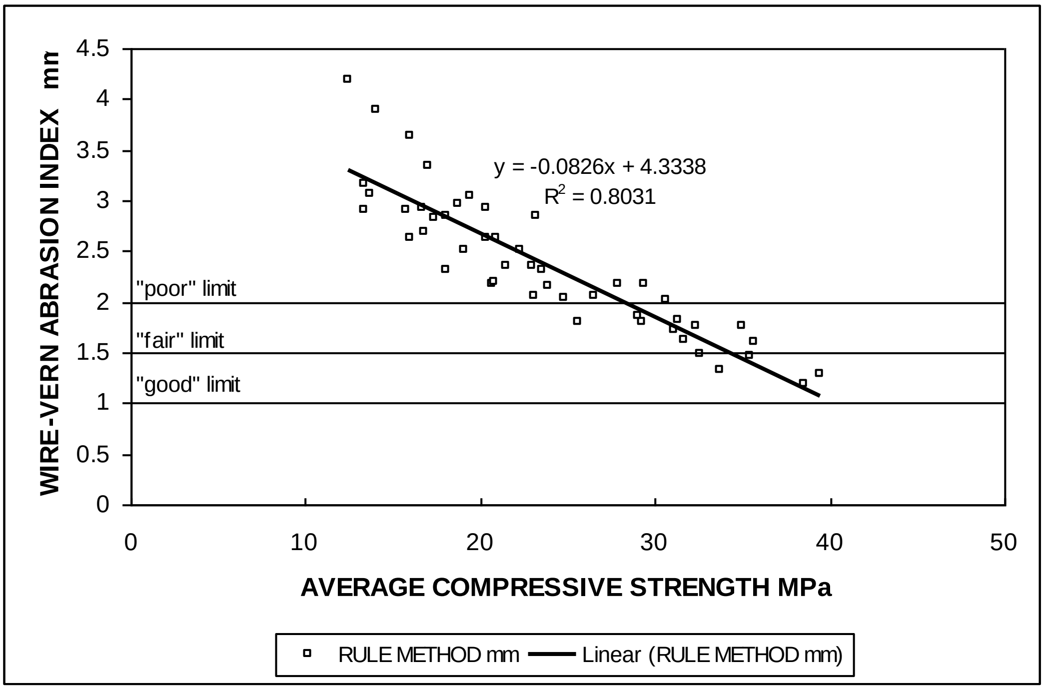

Figure 10.9 Correlation of wire-dial abrasion index with 'average' compressive strength

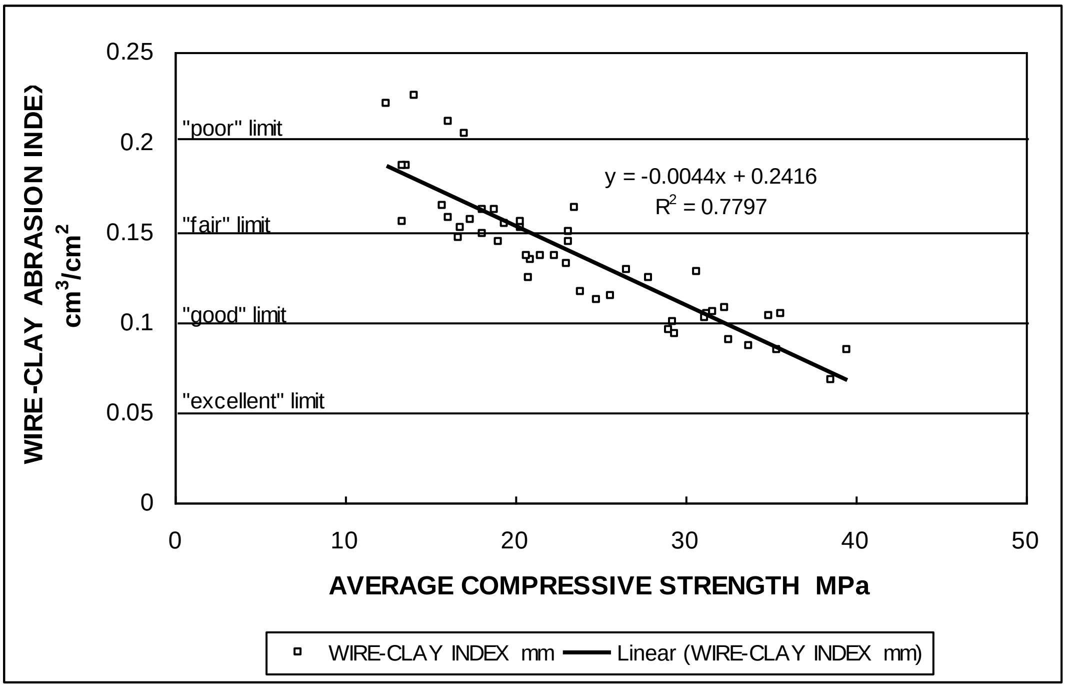

Figure 10.10 Correlation of wire-dial abrasion index with 'average' compressive strength

A number of conclusions can be made from the graphs:

a. The respective R^2 values of 0,780 and 0,803 indicate a significant correlation between compressive strength and abrasion index in the case of the wire-vern and wire-clay methods.

b. The relatively poor correlation of $R^2 = 0,615$ in the case of the P_{dial} index (see figure 10.8), once again confirms the erratic nature of the individual P vs R curves owing to the 'spring' and 'bias' effects of the wirebrush.

   Holland(1991) used this method in his investigation, and his coefficients of variation ranged between 5 % and 34 %, with three out of seven coefficients in excess of 30 %.

c. The limiting criteria recommended in PCI.TM.7.11 (see table 10.2) have also been plotted on figures 10.8 through 10.10. These limits show that most of the blocks are 'poor' when the wire-dial and wire-vern methods (figures 10.8 and 10.9) are used. However, the majority of the mixes performed acceptably in terms of their performance after six years of traffic, see chapter 14. The relative severity of these two methods may respectively be explained: (1) The deep penetrations of the wire-dial test may be partly a result of brush wear, and partly due to wire bias. (2) The wire-vern result reflects the average depth of the base of the crater, *according to the operator's judgement*, and depending on the pattern of wear, this may or may not be representative of the 'average' depth. It is therefore not appropriate to make comparisons with the PCI (C&CI) limits.

   On the other hand figure 10.10 shows a very good spread of results for the wire-clay test results. Based on the criteria in table 10.2 seven of the mixes are 'good', 22 mixes are 'fair', 15 are 'poor'. Four mixes are evidently worse than 'poor'.

10.7 Limiting Criteria

Table 10.2 shows the limiting criteria recommended in C&CI.TM.7.11. It classifies concrete surfaces into four categories based on the average depth of wear. It gives 'suggested limits' for the wirebrush test for the various applications. It is not stated how these limits were derived, but the results of this investigation appear to fit well into the respective limits, for the wire-clay method (see discussion in previous paragraph). It would appear that some careful thought went into these limits.

TABLE 10.2 CLASSIFICATION OF CBP SURFACES IN TERMS OF LIMITING CRITERIA - WIREBRUSH TEST

CLASS	DEPTH OF WEAR IN mm	RELATIVE PERFORMANCE	APPLICATION
1a	0 - 0.5	EXCELLENT	Very severe abrasive conditions. Steel wheeled traffic. Protection against erosion and cavitation. Concrete subject to impact. Ore passes in the mining industry. Certain quality proprietary surface hardeners and toppings.
1	0.5 - 1.0	GOOD	Industrial floors where abrasion resistance is important. Power trowelled finishes (Grade 25 MPa upwards). High strength off shutter concrete (> 50 MPa). Certain proprietary surface hardeners. Heavily trafficked roads and paved areas. Heavily trafficked public footways.
2	1.0 - 1.5	FAIR	Industrial and commercial floors where abrasion is not a prime requirement. Lightly trafficked roads and paved areas. Lightly trafficked public footways.
3	1.5 - 2.0	POOR	Ordinary applications where abrasion is of little significance. Domestic driveways and pathways.

Note: Typical concrete applications are included in this classification for comparison.

10.8 The Variability of the Wirebrush Test

The repeatability of the wirebrush test in this investigation is not as good as that of the ASTM C418 test, but better than that of the MA20. The averages of 48 coefficients of variation (5 samples per mix for the two other tests and 4 samples for the wirebrush) respectively measured 7,7%, 15,1%, and 24,3%. This should also be seen in the light of the averages of 48 coefficients of variation (6 samples per mix) for the three compression tests, respectively, 10,4 % for the SABS test, 9,2 % for the ASTM C140 test, and 8,7 % for the MA20 test.

Addis(1989) found a number of factors that contribute to the variability of the wirebrush test. Some of their findings offer an explanation for the relatively high average coefficient of 15,1 % in this investigation, discussed in 10.8.1 through 10.8.3:

10.8.1 Type of brush

The effect of the make of the wirebrush was investigated. Brushes made by Wolfcraft (imported) and the Transvaal Brush Company were tested on concrete cubes made from the same mix and tested at the same age.

Considering only the first 25 minutes of the test the following average coefficients of variation were obtained:

Transvaal Brush Company = 12,4 %
Wolfcraft = 9,8 %

It is not known if the two brush manufacturers are capable of maintaining these coefficients from day to day, year to year.

It was found that the variability of the Wolfcraft brush increased dramatically after 25 minutes (see table 10.3), but this would not have affected the results of this investigation as the brush was always changed after 25 minutes (i.e. a new brush for each mix). The Wolfcraft brushes were used in this investigation.

10.8.2 Age of brush

According to Addis(1989) both brushes generally showed an increase in variability with age. Table 10.3 sets out the respective coefficients of variation.

TABLE 10.3 % COEFFICIENTS OF VARIATION

MAKE OF BRUSH	TIME IN MINUTES					
	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30
Wolfcraft	8	8	7	14	12	33
Transvaal Brush Co.	5	14	13	12	18	14

It may be seen that the Transvaal Brush Company brush has the lowest coefficient of variation in the first five minutes of the test, and is therefore the preferred brush when using the PCI.TM.7.11 specification, which calls for only one block to be tested per brush.

The most relevant brush age information however, as far as this thesis is concerned, is the time span between 5 and 25 minutes for the Wolfcraft brush, with an average coefficient of 10,3 %.

10.8.3 Measurement of depth

Coefficients of variation of 2% and 8% were recorded when the same specimen was measured ten times using the clay and micrometer methods respectively. This is expected since it is unlikely that 20 random measurements of a rough surface will be as repeatable as clay worked into this surface.

It is therefore somewhat surprising to note that in this investigation the wire-vern apparently has a lower average variability:

Average of 48 wire-vern coefficients of variation = 12,3%
Average of 48 wire-clay coefficients of variation = 15,1%

(The coefficients are recorded in appendices G.1 through G.8 for the wire-vern method and H.1 through H.8 for the wireclay method. Each coefficient for each of the 48 mixes applies to the variation in four test samples. The two methods of measurement were applied to the same test specimens).

The somewhat improved coefficient of variation in the case of the wire-vern method may be an indication of the success of the operator (the writer) in visually reproducing the average basement depth of the craters in the specimens when taking the eight depth readings spaced at 45 degrees.

Sectional Conclusion

These findings give some insights into the average coefficient of variation obtained in this investigation, i.e. 15,1%. The contributing factors may be summed up as:

- variations within the blocks of the individual batches (unknown)
- variations in the brush with respect to type and age of brush (approximately 10%, see table 10.3)
- variations in the method used to measure the depth (reported as 2% in the case of the wire-clay method).

In his investigation Holland(1991) concludes that the variability of this test (he obtained coefficients of variation ranging between 5% through 35% depending on the site that the blocks were sourced) necessitates the use of the mean result as used by PCI, rather than the lowest of a test lot, and this has been the approach adopted in this investigation.

10.9 Strengths and Weaknesses of Wirebrush Test

The author believes that this test is reasonably well suited to the testing of paving blocks, although it does have some limitations. Some advantages and disadvantages are as follows:

10.9.1 Fast

It is fast enough to allow it to be used as a method of production control. The test takes about 8 minutes including the time taken to change the brush, correctly align the specimen and remove it afterwards.

10.9.2 Moderately severe

The reasonably high rate of attrition (a desirable attribute) can be ascribed to the multitude of relatively sharp wire bristles. The test therefore only gives a measurable result for weak to moderately strong pavers. However PCI found that where the concrete specimen had a compressive strength in excess of 50 MPa, the wear is minimal. This means that the test will not be able to discern between a hard surface corresponding to a 50MPa concrete, and an even harder surface of say 70MPa. In some special applications this knowledge may be important to the client.

Given its limited ability to scratch hard surfaces, the wirebrush test will generally not be able to discern between different *aggregate types*, except if inferior aggregates are used. In some applications special toppings with hardwearing aggregates are used, and an abrasion test should ideally be ably to discriminate between a topping with an aggregate of average hardness and one that has exceptional qualities. Its usefulness is therefore limited to measuring paste quality, and aggregate paste bond.

10.9.3 Capital outlay

It is carried out with relatively inexpensive equipment. The cost of this equipment, including drill, drill stand, optical rev counter, special chuck, clamp etc. is approximately R12000.00 (1994 estimate).

10.9.4 Portable

The equipment is portable and can be used for insitu testing.

10.9.5 Cost of abrasive

The wirebrush test is an expensive test on a test-by-test basis, particularly if the brush is changed after every test as recommended in PCI.TM.7.11. Alternatively, worn brushes can be used for comparative testing, such as in internal quality control in a factory, in which case the life of the brush is 30 minutes, or about five tests. (Thereafter the brush must be discarded as the coefficient of variation increases and wear in the bristle also increases). The cost of the brush is approximately R 25.00 (1994 price).

10.9.6 Unique test

It is unlike any other test and so the results cannot be compared to existing tests. However PCI have been using the test for some years in South Africa and have gathered some data, from which they have compiled a classification complete with limiting criteria for wear (see table 10.2). Their limiting criteria for 28-day old pavers seem to be correctly set, when judged against the 28-day and 6-year performance of the pavers in this investigation. This indicates that the test could be considered as a means of quality control in South Africa.

10.9.7 Reproducibility

The reproducibility of this test has not been confirmed since only one test apparatus is currently in use. This research was carried out using the PCI apparatus.

10.9.8 Sensitivity

The wirebrush test is not as sensitive to changes in mix variations as the MA20 test. The penetration of the bristles do not respond as clearly to mix design variations. This may be seen from Table 6.15 where the average ratio wet mix : dry mix is 2.50 for MA20 and 1.63 for the wirebrush.

10.9.9 Surface measurement

The wirebrush test is well suited to measuring the surface condition of cbp, except for surfaces made with concrete of the order of 50 MPa. The test does not abrade too deeply into the concrete (except for inferior concretes), and hence it can be considered a good indicator of the surface condition i.e. it is a true surface test.

10.9.10 Simulation of wear effects

In contrast to the MA20 test the abraded surface of the wirebrush test is relatively rough. The characteristic appearance of the abraded surface in plan is that of a circular crater of approximate diameter 75 mm. Clear protrusions of aggregate particles relative to the mortar component are visible (see figure 10.2). This was one of the primary reasons why PCI adopted this test. They felt that the test surface had the same visual appearance as abraded blocks on site (see figure 10.3).

Figure 10.2 shows that a distinctive wear mechanism of the wirebrush test is that it abrades the softer mortar component until it plucks out the aggregate particles. Clearly the test provides a good simulation of wear that occurs as the mortar constituent is gouged away by loose sand and grit, beneath footwear or tyres. However it is not realistic for relatively clean surfaces. In these surfaces the aggregate is the main contributor to the abrasion resistance of the surface, even for weak concretes, since the protecting aggregate particles are likely to remain well embedded if no grit/sand abrasive is there to scratch the paste/mortar out, and this also applies if the grit is relatively fine in relation to the size of the coarse aggregate. Clearly the depth of exposure of the aggregate in the presence of sand/grit abrasive is a function of the quantity and size of such abrasive. However, seldom will grit have the reach of the 20mm long wire bristles, used in the test.

Figure 10.11 below shows how relatively wear resistant aggregate particles stand slightly proud of the weaker mortar component. In doing so they afford a significant degree of protection so that the average leather sole or rubber tyre cannot attack this paste / mortar component discriminately. However in the wirebrush test, the brush *will* get down to the paste / mortar component and abrade it regardless.

It may therefore be concluded that the ability of this test to correctly simulate site conditions is a function of both the particle size and quantity of loose abrasive material on the surface, while the rate of wear is related to paste strength (which influences its hardness), and plays a major role in aggregate/paste bond.

Figure 10.11 Example of aggregate protecting mortar component, Van Wyk Street, Roodepoort

10.10 Summary and Conclusion

The origins of the wirebrush test date back to approximately 1986, and to the NBRI disc test prior to that. The wirebrush test is still used by the C&CI today.

The mechanism of the abrasive wear is essentially micro shearing; the protruding microscopic peaks of the concrete surface are sheared by the fine bristles of the wirebrush. This is a good simulation of the shearing actions associated with slewing, turning, acceleration, and deceleration of vehicles on the one hand, or turning-on-the-ball-of-the-foot effects in the case of pedestrian traffic on the other hand. Clearly these effects require an element of lateral sliding and are not nearly as common as the micro crushing elements (discussed in 9.4) associated with normal traffic loadings.

Wear duration-curves show that the brush penetrates slower into wet (high density) mixes with high cement contents, and more rapidly into dry (low density) mixes with low cement contents.

The three methods of measuring the wirebrush test results were correlated with the compression tests using regression analyses, the correlation being quantified by R^2 coefficients. The C&CI clay method of measuring the depth of the crater by using clay is to be preferred. The results of this investigation lie in the expected zones of the limiting criteria of the C&CI classification for wear in cbp.

Finally, the strengths and weaknesses of the wirebrush test are considered. Two weaknesses can be considered as serious. Firstly, the cost of the abrasive at R 25 per test (1994 cost) is prohibitive for routine quality control testing. Secondly, the test does not provide a measure of the contribution of the aggregate particles towards abrasion resistance.

For a comprehensive comparison between the MA20, wirebrush, and ASTM C418 abrasion tests, and a recommendation on which of the three tests is best suited for the industry, reference should be made to chapter 12.