THE ABRASION TESTING OF CONCRETE PAVERS

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SUMMARY

This paper describes an in-depth evaluation of an abrasion testing procedure for concrete pavers developed in Australia. The test involves abrasion of the paver surface by a rapidly rotating ball race under load. Water is used both to lubricate the race and to remove debris. The investigation included the study of factors affecting the test results such as the load applied to the ball-race, the speed inclination and numbers of revolutions of the race, the speed inclination and numbers of revolutions of the race, the water flow and the hardness and wear of the ball bearings. Additional tests were conducted to establish the intrinsic variability of the test procedure. Based on the test results both the advantages and limitations of the test as a means for characterising the abrasion resistance of pavers are outlined and discussed.

INTRODUCTION

The initial development of concrete block paving occurred in Europe. Here resistance to frost required high strengths and therefore high cement contents in paver manufacture. Consequently, abrasion wear was not a major problem and measures of wear resistance were not generally included in European paver specifications (1). When concrete block paving spread to warmer climes, such as Australia, the absence of freezer-thaw durability problems led to the use of lower paver strengths (and cement contents) than those customary in Europe or North America. However, following European precedents, local specifications did not initially include abrasion criteria. As a result significant wear occurred in many block pavements laid in warm climates during the 1970's and early 1980's. In Australia this problem was first addressed in 1986 by the issue of an interim industry specification for pavers (MA20) which included abrasion testing (2).

There is little agreement on what constitutes an adequate abrasion test for pavers. Whilst, in France, specialised abrasion tests for pavers have been developed (3) in most countries existing procedures for evaluating concrete slabs have been adapted to pavers. For example, American paver specifications require sand blasting in accordance with ASTM method C148 (4) although it has been suggested ASTM method C944 can provide a simpler alternative (5).

In Australia a simplified version of ASTM test C779-82 has been widely applied for concrete pavers. (6) This uses the apparatus shown in Figure 1. A vertically mounted electric drill drives a hollow shaft bearing on a ball race running on the paver surface. Water is run through the drive shaft whilst the equipment is running. The abrasion resistance is measured in terms of the penetration of the ball race into the paver

surface for a given number of revolutions (6). An Abrasion Index, I_a, has been defined as

$$I_a = \frac{\sqrt{N}}{p} \qquad (1)$$

Where N is the number of ball race revolutions (thousands) and p is the penetration (mm). The interim MA20 specification for pavers recommended the limiting values of I_a given in Table 1 (6). Here $I_{a\ min}$ represents the smallest (worst case) value obtained tests of 5 pavers.

TABLE 1 INTERIM ABRASION LIMITS

Pavement Use	Minimum 28 Day I_a
Heavy Pedestrian use	2.0
Road and Industrial traffic	1.5
Footpaths	1.2
Car parks	1.2

By 1988 it had become apparent that the procedures set down in MA20 did not yield results that were consistent between laboratories and the Concrete Masonry Association of Australia commissioned the senior author to conduct comparative trials of abrasion testing in collaboration with several companies within CMAA. This paper summarises the results of these trials.

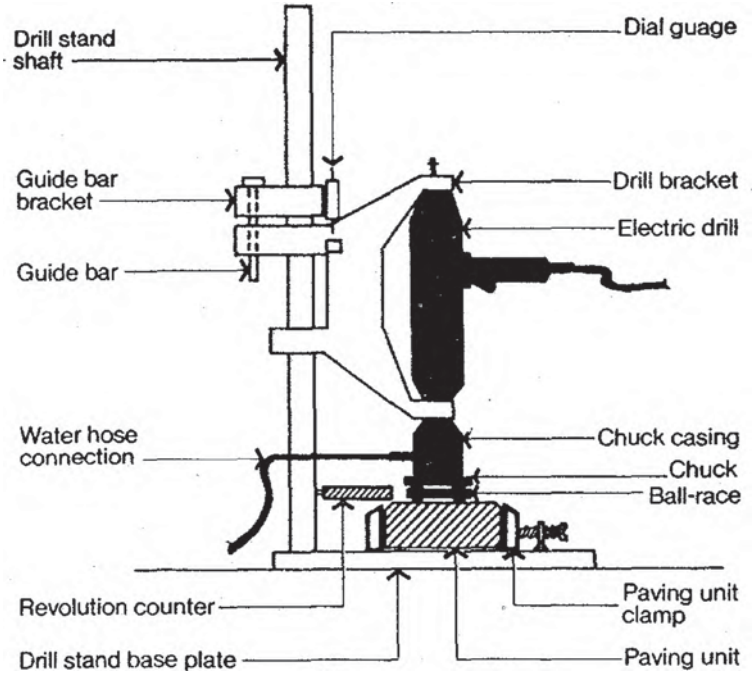

Figure 1 The Australian MA20 Abrasion Apparatus.

ORGANISATION OF THE TESTS

The tests were conducted in two stages. These comprised

i) Comparative tests involving 4 independent laboratories designed to explore test variability.

ii) Tests designed to evaluate the abrasion test equipment and procedures conducted wholly in the University laboratories.

Comparative Testing

The methodology adopted in the comparative study was to manufacture samples on each of which several independent abrasion tests could be conducted. By circulating these samples amongst the participating laboratories each laboratory could test the same samples as the other laboratories. Twelve 100 mm cubes were prepared from a single batch of zero slump concrete having the composition described in Table 2. These were tested in two batches each comprising 6 cubes after 6 and 11 months continuous moist curing. These are hereinafter referred to as Series I and II tests. At the commencement of each series of abrasion tests the compressive strength was measured. The values for the Series I and II tests were 56.6 and 56.0MPa respectively. Accordingly, variations in strength can be eliminated as a source of variability in the test results.

TABLE 2 CONCRETE MIX PROPORTIONS

Cement	10.5 kg
Sand	22.0 Kg
Gravel	32.0 Kg
Water	5.4 1

Only the four vertical faces of each cube were tested. Each of the 4 participating laboratories tested only one face on each cube. The cubes were sealed in plastic wrap between tests and were soaked for at least 24 hours prior to test

Evaluation of The Abrasion Test Equipment and Procedures

In these tests, conducted at the University of New South Wales (UNSW), the samples again comprised 100 mm cubes prepared as described above. The samples were stored in a fog room at all times except during the abrasion tests themselves. Again only the four vertical faces of each cube were tested.

The objectives of the UNSW tests were

(i) To study factors influencing the abrasion test results. The factors studied comprised
   a) The ball-race speed
   b) The weight of the drill assembly
   c) The water flow
   d) The inclination of the test specimen relative to the ball race.
   e) The ball-race wear
   f) The number of revolutions needed initially to set the ball-race.

(ii) To investigate the intrinsic variability of the abrasion test with the factors listed in (i) above set to the values given in Table 3 or as otherwise described.

Details of the test procedures are given later.

TABLE 3 TEST CONDITIONS

Drill Speed	1024 rpm
Drill Mass	16 kg
Bedding-In Period	30 revs
Water Flow	1.3 1/m

TEST RESULTS

Comparative Tests

The nominated test conditions are summarised in Table 3. However, the results of the Series I tests revealed discrepancies in terms of drill weight which varied from 15.0 kg to 16.0 kg. Also, the water flow sometimes varied from the specified 1.3 1/m. These discrepancies were rectified in. the second series of tests.

To overcome the problem of test variability the penetration results were averaged over each test series for each participating laboratory. Typical penetration curves, averaged over all tests, are shown in Figure 2. On the basis of the average of 6 or less tests, there was little agreement either between the results of two series of tests within each laboratory or between different laboratories. Similar comments apply to average Abrasion Indices calculated at 5000 revolutions in accordance with MA20 which ranged between 2.63 and 3.49 with standard deviations between 0.07 and 1.72. Significantly, despite attempts to improve the control of the test conditions in the Series II tests the standard deviations in I_a decreased in only half the sets of results but increased in the other tests. This suggested that much of the variability evident in the comparative tests was inherent to the test procedures and was not readily amenable to reduction by more careful control of laboratory techniques. This problem of variability is now considered in more detail.

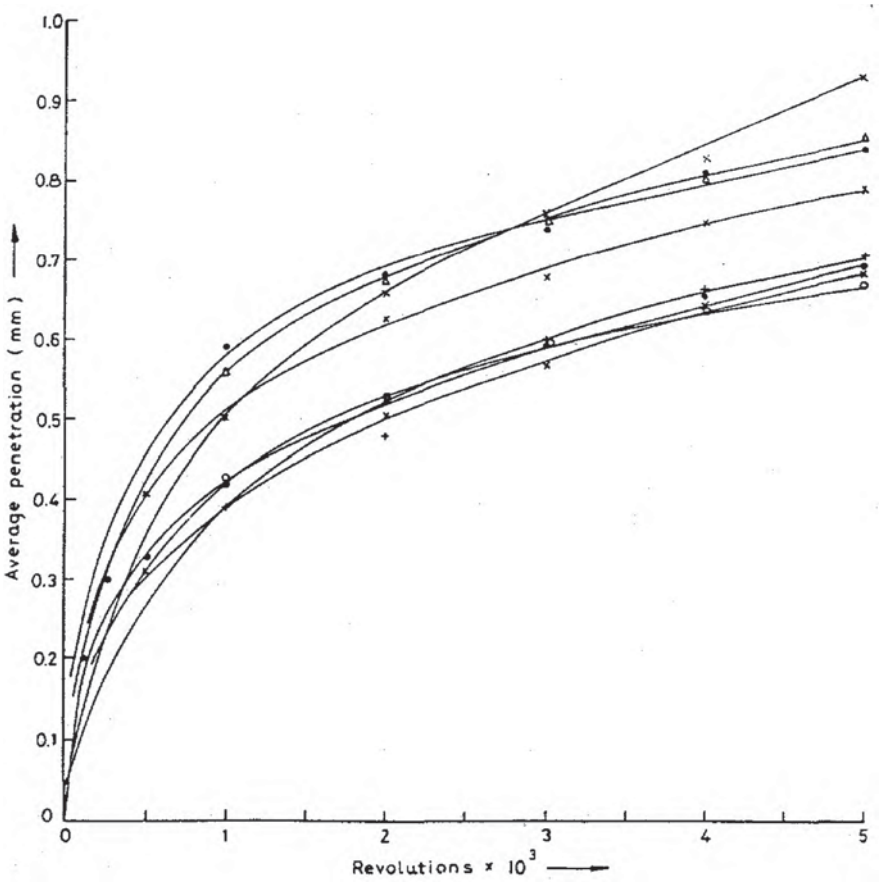

Figure 2. Test data averaged over each group of specimens for the Series I and U tests.

UNSW Tests

Effects of Ball Race Speed

The effects of varying the drill speed were studied using 10 identical 100 mm concrete cubes. Test conditions, except for drill speed, were as set out in Table 3. Drill speeds of 500, 820 and 1024 rpm were

examined. For each speed at least 8 cube faces were tested. The results of the experiment are shown in Table 4. From this table it may be seen that, with decrease in drill speed, the average Abrasion Index tended to increase. This increase was accompanied by an increase in test variability expressed as the standard deviations of I_a.

TABLE 4 EFFECTS OF DRILL SPEED

Parameter	Drill Speed (rpm)		
	500	820	1024
mean I_a	3.52	3.43	2.94
std dev. I_a	0.78	0.62	0.35
no of tests	8	8	22

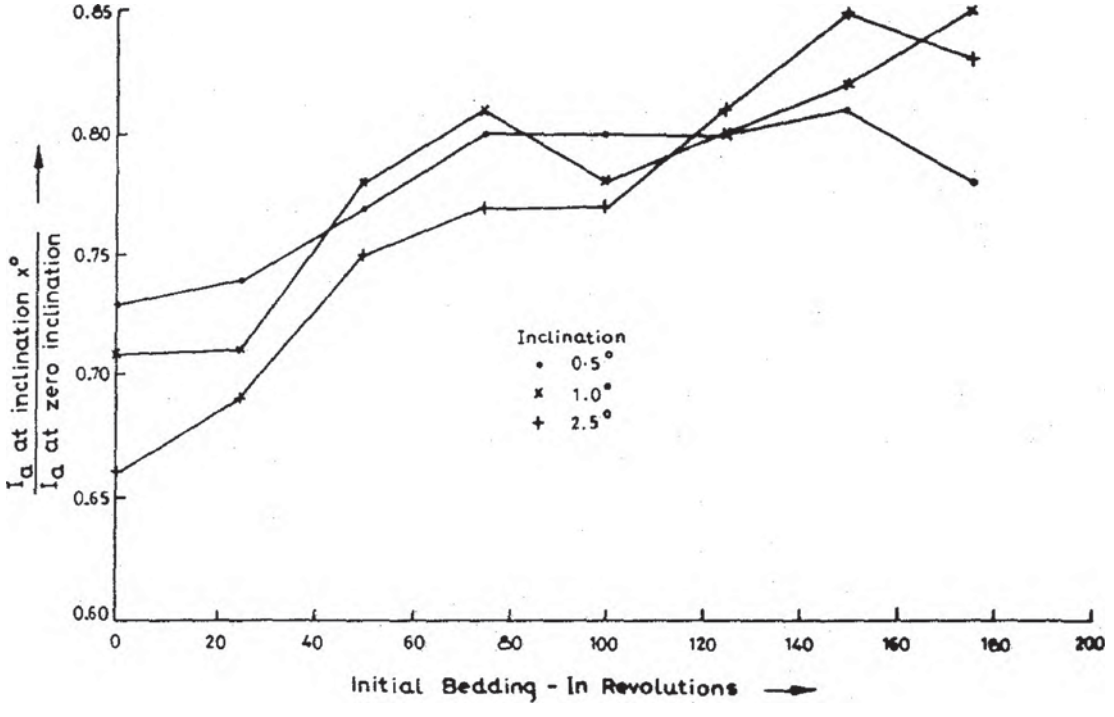

Figure 3. Effects of ball-race inclination on Abrasion Resistance

Effects of the Weight of the Drill Assembly

The weight of the drill assembly was varied in 2 Kg increments from 16 Kg to 20 Kg. With all other variables set to the conditions in Table 3 the effects on the abrasion were found to be negligible.

Effects of Water Flow

Water flows of 0.6 and 2.0 1/min were studied but had little effect on the abrasion resistance expressed as average values of I_a or as the standard deviations in I_a. However, there was a tendency for the variance of the penetrations measured during the test to decrease with increase in water flow.

Effects of Ball-Race Inclination

The effects of misaligning a specimen in the abrasion test rig were investigated by inclining the top surface of the test specimen at angles of 0.5°, 1.0° and 2.5° to the plane of rotation of the drill chuck. (Angles of 1° or more proved difficult to achieve and such massive misalignments would be unlikely to occur in practice).

The effects of varying the inclination of the specimen to the drill chuck are summarised in Figure 3 averaged over 10 tests. As shown in Figure 3, the Abrasion Indices, I_a, declined by up to about 35% as the result of not aligning the specimen parallel to the drill chuck In general, the reduction in I_a caused by the misalignment tended to decrease with increase in the number of the revolutions used to 'bed in' the ball-race at the commencement of each test In general, there was no clear relationship between the angle of inclination and I_a. Overall, it may be concluded that misalignment of the specimen by as little as 0.5' relative to the drill chuck can give significant errors in the measurement of the abrasion index, I_a.

Effects of Ball-Race Wear

It would be expected that, in the course of several abrasion tests, some damage to the balls in the race would occur. To quantify this, two sets of experiments were carried out

In the first experiment one set of balls was used in 3 tests of 6 cubes. In these tests each cube was successively tested on one face. Then, in subsequent tests, a second face was tested on each cube in the same sample order as before. This was repeated a third time. In this way each face on each test sample was tested with a ball-race that had received approximately the same increase in wear between faces. This was the wear caused by 3.3×10^4 ball-race revolutions.

In the second experiment the balls in the race were replaced after each set of 10 abrasion measurements. These tests comprised the evaluation of the effects of ball race inclination described above.

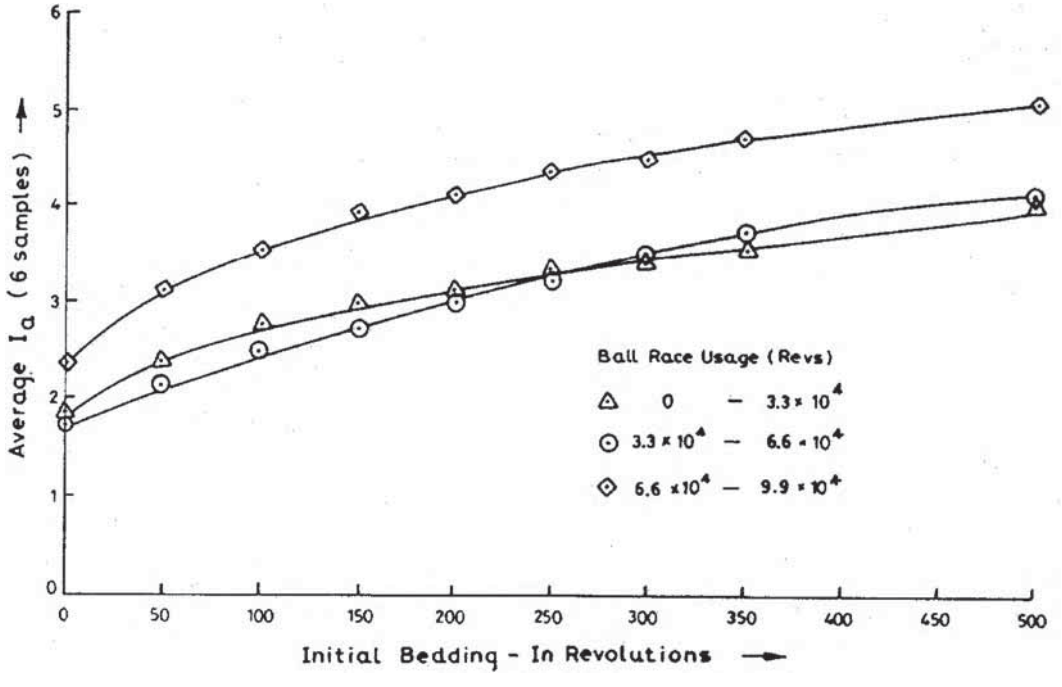

Figure 4. Effects of ball-race wear on Abrasion Index, I_a

The results of these experiments are shown in Figure 4. Both the average value and the variance of I_a increased with increase in ball-race usage irrespective of the number of revolutions used to seat the race at the commencement of a test. From Figure 4 it may be seen that the average value of I_a tended to increase once the balls in the race had experienced more than 6.6×10^4 revolutions Le. after some 12-13 tests. This suggests that the balls in the race may need to be replaced after every 12 tests conducted to 5000 ball-race revolutions.

The variance in I_a tended to increase both with increase in ball usage and with increase in the numbers of revolutions used to seat the ball-race irrespective of the angle between the specimen and the drill chuck

To assess the wear of the balls, measurements were made both of the diameter and the hardness (Rockwell C) of the balls before and after test. In both cases the data represented the means of three measurements per ball in the race. Both the average diameter and average Rockwell C hardness of the balls tended to decrease slightly as the results of ball wear.

Seating the Ball-Race

One likely cause of test variability was thought to be the number of ball-race revolutions used at the commencement of a test to seat the ball-race on the test specimen. Bedding-in periods between 20 and 500 revolutions were studied. It was found that the variance in I_a (averaged over 6 or more samples) increased with increase in the number of revolutions used to seat the ball-race. In other words, it was not possible to reduce the variability in I_a by increasing the number of revolutions applied to the specimen prior to measurements of penetration commencing.

Test Variability

To assess the intrinsic variability in the abrasion test, 6 identical 100 mm concrete cubes were cast using the mix described in Table 2. These cubes were moist cured for 14 days. The 4 vertical faces of each cube were tested under the conditions summarised in Table 3. Two of the tests failed because of operator error but 22 good sets of data were obtained. These comprised readings of penetration at 50, 100, 250, 500, 1000, 2000, 3000, 4000 and 5000 revolutions. The mean abrasion index at 5000 revolutions, I_a, was found to be 2.94 with a standard deviation of 0.35.

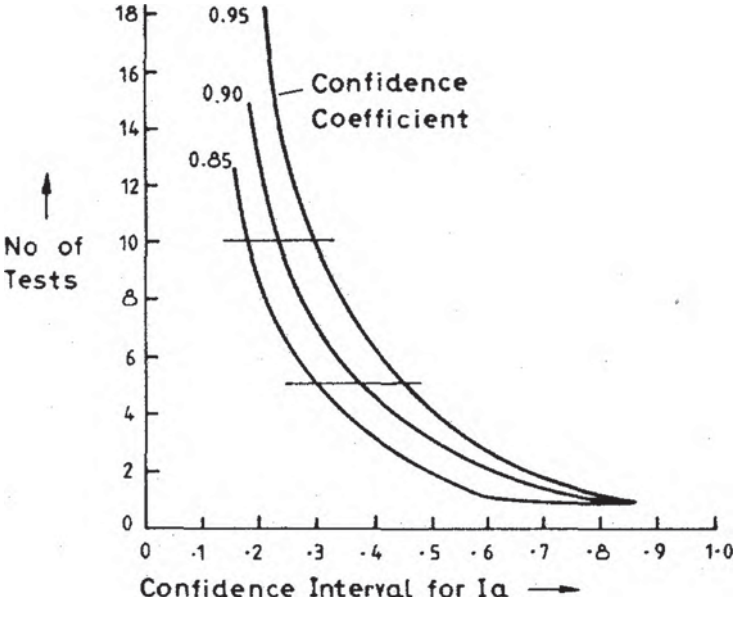

Figure 5. Confidence limits for abrasion index.

From these data the numbers of abrasion tests necessary to yield confidence coefficients between 0.85 and 0.95 for the Abrasion index, I_a, were calculated. These are shown in Figure 5. Figure 5 allows the viability of the interim MA20 specification to be assessed. As shown in Table 2 the specification recommended minimum Abrasion Indices of 1.2, 1.5 and 2.0 to discriminate amongst the qualities of paver needed in common paving applications. Figure 5 shows that, for one test, the confidence interval for I_a is approximately +0.9 at the 95% confidence level. Clearly, basing the acceptance or rejection of pavers on the results of a single (worst-case) result is inadequate to discriminate amongst the 3 classes of abrasion resistance set out in the Interim specification.

To provide better discrimination, it is necessary to increase the number of test results that form the basis of acceptance. The Interim Guide required 5 pavers to be tested. If the mean Abrasion Index from 5 pavers is used as the basis of acceptance then the confidence interval for penetration is ±0.6 mm whilst that for I_a is approximately ±0.45 at the 95% confidence interval. These values still do not provide adequate discrimination.

It may be concluded that the use of either a single worst-case value or the mean of 5 abrasion values is inadequate to delineate the abrasion resistance. The best way to improve the MA20 abrasion test is to increase the number of samples and to base the acceptance criteria on statistics such as the mean or characteristic Abrasion Index.

Figure 5 shows that increase in the number of tests is beneficial to the precision of the tests. However, increase in the number of tests beyond, about 10 determinations yields only limited improvements in the confidence intervals for the Abrasion Index, I_a.

There is a strong negative correlation between the penetration at 2000 revolutions and I_a. at 5000 revolutions. Moreover, there is a correlation between the penetration determined at 2000 revolutions and that measured at 5000 revolutions both for the UNSW tests and for the Series I and II industry tests. This is shown in Figure 6. It would therefore appear practical to terminate abrasion tests at 2000 revolutions rather than the 5000 revolutions required hitherto.

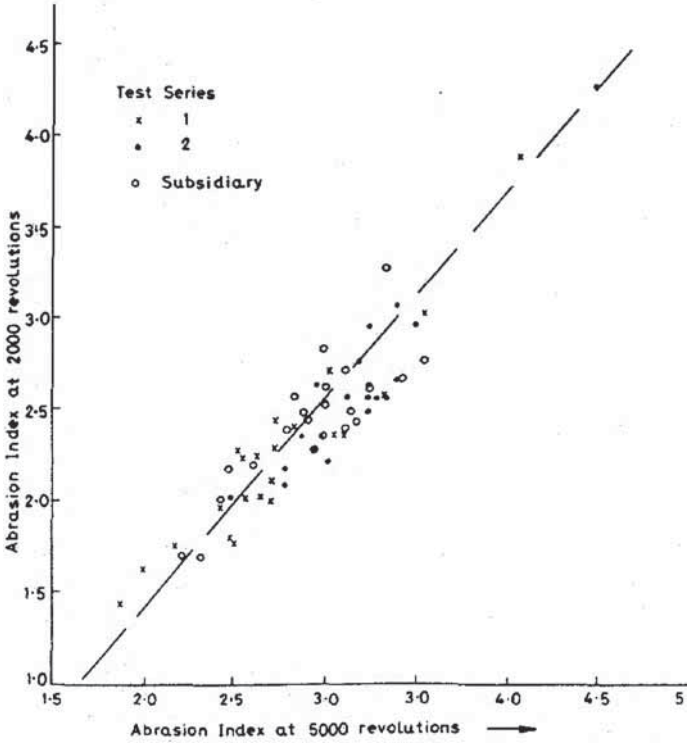

Figure 6. Abrasion Index at 2000 revolutions as a function of that at 5000 revolutions

SUPPLEMENTARY TESTS

Following the assessment of the MA-20 abrasion test, further studies of abrasion resistance have been undertaken at UNSW. Although these tests are still in progress the following tentative conclusions can be drawn:

In Service Performance Criteria

Tests of pavers extracted from serving block pavements indicate that values of I_a below 1.0 are generally associated with unsatisfactory wear performance. However, it has not yet proved possible to verify the abrasion performance limits set out in Table 1 for different categories of pavement use.

Mix Design

The following factors have been found to affect abrasion resistance

Cement Content. Increasing the cement content tends to increase the abrasion resistance, I_a.

Water/Cement Ratio. Increase in the water/cement ratio is associated with a reduction in I_a.

Aggregate. Mixes incorporating crushed aggregates tend to have higher abrasion values than those using river gravels.

In addition it has been found that

Under laboratory conditions and for specific concrete mixes there is a good correlation between Schmidt Rebound Hammer readings (averaged over 12 or more readings per sample) and the mean values of I_a (averaged over 10 or more samples).

There is a good correlation between I_a and the 28-day concrete compressive strength for the mixes studied to date.

These results are based on a limited range of mix designs for specimens manufactured, cured and tested under carefully controlled laboratory conditions. Accordingly, caution should be exercised before extrapolating these findings to routine paver production.

CONCLUSIONS

Factors likely to influence the MA20 abrasion test results have been studied and identified. However the influence of most of the factors that can be readily controlled e.g. the weight of the drill, the rate of water flow, the ball-race speed and the bedding-in period have only a small influence on the overall test variability.

The variability of the MA20 test has been quantified. This does not appear to have been done for most other paver abrasion tests currently in use.

Statistical analyses of confidence intervals show that the MA20 abrasion test is not suitable for acceptance procedures based on a single worst-case result. Rather the abrasion resistance should be reported as a statistic such as the characteristic abrasion value based on the results of not less than 10 tests.

The abrasion resistance depends on the drill speed. Both the Abrasion Index, 1^ and the variability in I_a increase with decrease in drill speed.

5. The Abrasion Index is sensitive to misalignments as small as 0.5" between the test specimen and drill chuck.

6. The balls used for abrading the test specimen show a decrease in both diameter and Rockwell C hardness with use. The test data suggest, that the balls should be replaced once they have served in about 6.5 x 10^4 ball-race revolutions.

7. The Abrasion Indices at 2000 and 5000 revolutions correlate with one another. Thus there appears to be little reason to continue the abrasion tests beyond 2000 revolutions.

Overall the test data available to date indicate that, provided an adequate amount of data is obtained, the MA-20 abrasion test can provide a simple and rapid indicator of the abrasion resistance of pavers. The test is not, however, suitable for a single value assessment of paver abrasion. Further work needs to be done to determine the limiting values of the Abrasion Index appropriate to different levels of pavement service. In the meantime it can be concluded that pavers exhibiting I_a values less than 1.0 are unlikely to yield satisfactory abrasion performance in service.

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