PAVE 92

THE VARIATION IN DURABILITY OF CONCRETE SEGMENTAL PAVING UNITS

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SUMMARY

The variability in durability and quality of concrete segmental blocks was studied using criteria from the Australian Concrete Masonry Association's Specification for Concrete Segmental Paving Units (MA20). The study concentrated on the use of compressive strength and abrasion resistance as block quality indicators and an attempt was made to correlate abrasion index with compressive strength. A study was also undertaken to determine the sensitivity of the abrasion resistance test to procedural variations in test method. The results of the study indicated that the MA20 abrasion resistance test had limited applicability in the evaluation of segmental units. It was found that the limitations were due in part to variability in areas of the test method such as water flow rate and time allowed for bedding-in. There was no strong correlation found between compressive strength and abrasion index although there appeared some relationship between abrasion index and block age and strength. Block compressive strength was found to provide a measure of total block (macro) quality but did not appear useful for evaluation of surface durability.

INTRODUCTION

Over the last 10 years the use of segmental concrete paving units as wearing surfaces on pavements has greatly increased with applications ranging from extensive use in pedestrian malls and lightly loaded road pavements to heavy industrial roads and storage areas. Initially very little was understood of either the degrading processes of concrete paving units or of the mechanisms causing the degradation. The lack of knowledge has been instrumental in the premature failure of many pavements due to inadequate paving unit durability, a major problem being the lack of an appropriate test procedure for evaluation of paver durability.

The Concrete Masonry Association of Australia (CMAA) published the Interim Specification for Interlocking Concrete Paving Units (MA15) in 1980 which provided some guidelines for sampling and testing. The MA15 document did not provide any information on the evaluation of unit abrasion resistance or durability and guidelines for the evaluation of abrasion resistance (durability with respect to surface abrasion) did not appear until 1986 when the CMAA published the Specification for Concrete Segmental Paving Units (MA20). The MA20 abrasion test is not described as a durability test but as the "Interim Guide for Abrasion Resistance". The test is however, used extensively and perhaps incorrectly, to qualify the durability of paving units. The abrasion test is described by the CMAA as being cheap to perform, inexpensive and repeatable and as having been adopted after an exhaustive world-wide evaluation of alternatives. Since it is a commonly held tenet that good abrasion resistance is a good indication of durability (in the form of resisting applied surface loads), the MA20 abrasion test is used extensively as a measure of paver durability. Since the release of MA20 it has been periodically suggested that the guidelines concerning abrasion resistance and compressive strength be upgraded.

DURABILITY

Durability may be defined as the ability to resist wear and decay (degradation) while maintaining serviceability. Segmental paving units, as a pavement surfacing material, have to resist chemical attack, skewing and braking loads caused by vehicles, dynamic and impact loads from pedestrian traffic and dead loads from stacked goods and stationary vehicles. In many cases failure cannot be attributed to any one effect but to combined effects. The tests most frequently used to evaluate unit durability are listed below :

(i) salt attack (AS1226.10) [1]
(ii) efflorescence (AS1226.6) [1]
(iii) compressive strength (MA20, Appendix C) [2]
(iv) abrasion resistance (MA20, Appendix D) [2]
(v) water absorption (AS1226.9) [1]

It has not been shown that any of the above tests provide an indication of unit durability or that the individual tests are able to be cross-correlated. A brief description of the function of each test is provided to highlight any facets which are able to be related to durability.

Salt Attack and Efflorescence Tests

The salt attack test assesses the ability to withstand repeated cycles of soaking and drying in a highly saline environment. The mechanism of failure is physical rupture of the specimen by internal pressure set up by salt dissolution/crystallisation. The salt solution penetrates into the paver sample with the depth of penetration depending on the exposure time and sample permeability. The sample is then dried by the action of the sun and the salt solution evaporates leaving behind salt crystals within the internal pores of the paver. Repeated cycles cause a build up of crystallised salts and internal stresses, eventually causing surface exfoliation or total sample collapse. The salt attack test finds relevance for testing paving units which are to be used near the sea or as paving around pool areas where a ready supply of salts exist and sun drying occurs.

The efflorescence test is essentially a means of evaluating the possible loss of aesthetic appeal of concrete paving units due to efflorescence caused by the leaching of salts held within the matrix of the paver, to the surface. Drying results in furry whitish salt deposits building up on the exterior of the paver. This accumulation of unsightly salts does not constitute failure in the engineering sense and the test cannot be considered as a measure of durability.

Compression Test

The compressive strength does not provide any direct measure of paver durability but does provide a simple and useful method for gauging overall quality of a paving unit [2]. Once compressive strength is corrected for paver aspect ratio and shape it may provide a quantitative measure of unit durability. It is reasonable to accept the premise that a lot of paving units with a characteristic strength of, say 60MPa, has better durability to resist applied surface loads than a lot of paving units with a characteristic strength of say, 20MPa. Areas subjected to heavy pedestrian traffic have a MA20 recommended characteristic compressive strength of 30MPa [2] but research has shown however, that loads under high heeled shoes often exceed 50MPa [3].

Abrasion Test

The MA20 abrasion resistance test has been utilised extensively for the evaluation of paver durability since its inception. The test does not claim to be a measure of durability but of abrasion resistance. Advocates of use of the test to measure durability suggest that surface abrasion equates to surface wear, which in turn indicates use of the abrasion test. The abrasion test does not measure impact loads which are the major cause of paving unit failure in pedestrian malls and there have been a number of pavements around Australia which have been replaced due to excessive loss of paver surface material. MA20, by specifying a minimum value of abrasion index for heavy pedestrian traffic provides a de facto durability specification. Several pedestrian mall areas, which originally met the MA20 abrasion resistance specification, have had be replaced.

Water Absorption Test

This test provides an ad hoc measure of durability in that it is a measure of internal paver voids and of paver permeability. Reduced permeability in concrete provides better durability with respect to salt attack and carbonation. The test also provides a measure of the amount of solid material available to resist wear but not of the quality of those solids (aggregate and cement paste). The test fails to provide any information on durability with respect to surface degradation by dynamic loads.

PAVER SELECTION

Besser (Queensland) Limited, provided the paving units used throughout the project. The total plant production for one day was sampled where a production run was defined as the total number of pavers produced in one day from the same mould. Several production runs would be required to produce enough pavers for any major paving project. Each production run consisted of approximately twenty batches where a batch was defined as the total pavers produced from one batch load of concrete mix. A number of drops were produced from each batch where a drop consisted of one cycle of the paver machine which produced sixteen pavers. The sampling procedure was to randomly select 4 pavers from each of 40 drops (also selected randomly), during one day production run. The sampling technique provided a total of 160 pavers, to represent a single days production, which were then used for testing for compressive strength, abrasion index, water absorption and salt attack.

TESTING PROGRAMME

The primary aim of the testing programme was to determine the variability of durability of paving units using compressive strength and abrasion resistance as indicators. The MA20 abrasion test was considered to warrant the most attention as the processes involved in compressive strength testing have been fully proven and documented. The special attention devoted to the abrasion resistance test stemmed from the apparent problems inherent in the test procedure. Variables such as age of the ball-race, seating time, sample levelling, aggregate particulate problems and rate of water flow to the race all were thought to be possibly contributors to testing errors.

The MA20 document recommends that 5 pavers be tested for abrasion resistance and compressive strength. It was decided early in the project that such a small sample size may not be representative of the lot of pavers and that it was more appropriate to expand the test sample to 10 pavers based on quality control operating characteristics (Tables 3 and 4). The test programme was designed to test the following hypotheses.

(i) Paver durability is related to both paver compressive strength and abrasion resistance. A correlation should exist between paver compressive strength and abrasion index for a lot of pavers produced during the same production run from identical concrete mixes.

(ii) Paver compressive strength should increase with paver age due to the normal concrete curing phenomena (cement hydration). An increase in compressive strength should result in an increase in abrasion index if a correlation exists between the two tests.

(iii) The abrasion index is dependent upon testing variables such as ball race wear, water flow rate, aggregate particulate and levelling.

TEST RESULTS

Flow/Abrasion Index Relationship

The rate of water flow to the ball-race was considered to have a high possibility to cause variability within the abrasion index testing procedure. The MA20 specification simply states that it is necessary to "ensure water is flowing at a sufficient flow rate to clear grinding debris" without further qualification. It may be assumed that a high flow rate will give a lower ball race penetration than a low flow rate due to debris removal from around and within the ball race. The main problem was to determine the lower threshold value of water flow at which problems with abrasion measurement occur. To find the critical flow rate it was necessary to minimise the effects of all other experimental variables and eliminate paver variability.

Table 1

Constant Flow on Different Pavers

Paver No.	Penetration (mm)	Flow L/sec
1	0.57	0.076
2	0.64	0.076
3	0.55	0.076
4	0.65	0.076
5	0.68	0.076
6	0.57	0.076
Average Stand. Dev.[1] % Variation	0.61 0.05 8.2	0.076 0.0 0.0

1. Standard Deviation

In preliminary abrasion testing, variations in measured ball-race penetration appeared to occur due to variability in aggregate size in the pavers. Particulate size variation at the surface resulted in inconsistent values of abrasion index when the ball-race was abrading large aggregate particles much harder than the cement paste matrix. To eliminate these effects 6 rectangular (230mm x 110mm x 110mm) concrete pavers were manufactured from medium river sand, washed pit sand and Portland Type A cement. Paver homogeneity was ensured by manufacturing all pavers from the same concrete batch, in identical moulds with constant compaction effort (mould vibration). All 6 pavers were then cured under the same standard conditions and tested at the same age of 28 days. The use of the 6 pavers ensured that paver variability would not unduly influence abrasion index values obtained during the study of water flow rate.

Table 2

Investigation of Abrasion Test

Flow L/sec	Paver No.	Average[1]	Standard Dev.
0.190	1	0.89	0.04
0.152	2	0.93	0.12
0.114	3	0.89	0.13
0.076	4	0.74	0.10
0.042	5	0.82	0.07
0.005	6	1.13	0.11

1. Average of testing 4 paver faces

The pavers were tested as per MA20 with a calibrated flow meter included in the water supply line to the ball-race. The effect of ball-race seating was minimised by using a constant seating time of 3.0 +/- 0.1 seconds. Initially abrasion testing was carried out on one face of each of the 6 pavers at a constant flow rate of 0.076L/sec. The results from the constant flow rate tests are summarised in Table 1. After paver consistency was established, 4 faces of each paver were tested for abrasion resistance. Each paver was subjected to a different flow rate as shown in Table 2. The adopted procedure identified variations in ball-race penetration caused by change in water flow rate.

COMPRESSIVE STRENGTH

The effect of compressive strength of abrasion index was investigated by carrying out compressive strength tests and abrasion index tests on pavers at various ages after manufacture. A total of 10 pavers were tested at 8, 13, 21, 28 and 35 days and the results are summarised in Table 3.

Table 3.

Compressive Strength and Abrasion Index

Identity & Stats.	8 days		13 days		21 days		28 days		35 days	
	AI	CS	AI	CS	AI	CS	AI	CS	AI	CS
1	1.2	53	2.4	35	4.1	52	2.4	63	2.7	66
2	1.4	62	2.6	53	2.7	61	2.6	49	2.5	63
3	0.6	35	2.6	49	-	-	2.5	69	2.3	87
4	1.4	34	2.8	60	4.1	88	2.5	73	2.1	62
5	1.3	45	2.5	63	4.3	71	1.8	39	3.1	53
6	1.9	64	3.3	60	3.4	64	3.5	67	5.2	57
7	2.2	67	4.7	63	2.6	45	3.6	46	8.9	88
8	2.4	50	2.4	55	4.8	67	2.4	38	4.2	54
9	1.8	60	2.9	55	2.0	44	4.3	58	2.8	60
10	3.0	73	3.1	48	2.9	62	3.0	53	2.6	46
Average	1.7	54	2.9	54	3.4	62	2.9	55	3.6	64
Std Dev	0.7	13	0.7	8	0.9	14	0.8	13	2.1	14
% Var.[3]	40%	25%	24%	16%	27%	22%	26%	23%	58%	22%

1. AI - Abrasion Index
2. CS - Compressive Strength
3. Coefficient of Variation

The data in Table 3 is also presented graphically in Figure 1 to illustrate any, overall correlation between compressive strength and abrasion index. The information in Table 4 is the characteristic strengths and abrasion indices of the pavers tested in groups of 10 units. The characteristics values for the 10 pavers are presented as two sub-samples of 5 units each and as a combined single sample of 10 units.

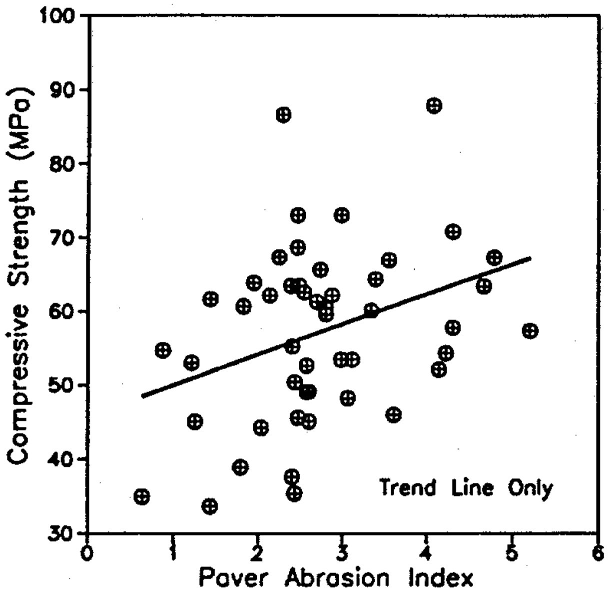

Figure 1. Compressive Strength versus Abrasion Index

Table 4

Characteristic Strengths and Abrasion Indices

Sample Age (days)	Samples 1-5		Samples 6-10		Samples 1-10	
	AI[1]	CS[2]	AI	CS	AI	CS
8	0.56	26.05	1.47	48.69	0.58	32.22
13	2.34	34.26	1.86	46.64	1.79	40.14
21	2.58	42.66	1.40	38.27	1.88	39.15
28	1.83	35.09	2.19	33.83	1.64	34.78
35	1.91	45.86	0.52	34.64	0.21	40.95

1. AI - Abrasion Index
2. CS- Compressive Strength

SAMPLING STATISTICS

The MA20 specification for compressive strength is based on the characteristic strength of 5 paving units where equation 1 is used to determine the reported value. Such a sampling scheme is commonly termed a "variables" sampling scheme as acceptance is based on the distribution of property values which are assumed normally distributed.

The abrasion index is determined by the lowest value from a set of 5 paving units. Such a scheme may be compared to an attributes sampling scheme where the paver is deemed acceptable if its attribute of abrasion index exceeds the lowest value of the sample set. The operating characteristics are calculated using the cumulative binomial distribution function and are readily available in tabulated form [4]. It is important to note that the MA20 specification for determination of the abrasion index of a lot of pavers is independent of the distribution of abrasion indices for the individual pavers.

$$C_k = C - 1.65*s \qquad \ldots . 1$$

where C_k characteristic compressive strength of the lot under test.
s unbiased standard deviation of 5 pavers.
C average compressive strength of 5 pavers.

The operating characteristics of the quality procedures used are provided in Table 5, where "n" represents the sample size and "r" the allowable number of defective units [4]. The characteristic values for the "variable" schemes are based on a single sided specification, unknown variability scheme with "K", the acceptance constant, being a function of sample size, proportion of defective units and of the assigned probability of acceptance [4]. In the "attributes" scheme the allowable number of rejects has been assumed as nil, to agree with the MA20 specification that the lowest value of abrasion index be adopted to represent the sample "n".

Table 5

Operating Characteristics of Sampling Procedures

Operation Characteristics - Probability of Acceptance								
Sample Size n	K[1] r[2]	Percentage Defective Material						
		1	3	5	10	20	30	40
5	1.65	85.5	68.5	56.5	36.5	16.5	7.0	3.0
10	1.65	92.5	71.5	54.0	26.0	6.0	1.0	0.0
5	0	95.0	86.0	77.5	59.0	33.0	17.0	8.0
10	0	90.5	74.0	60.0	35.0	10.5	3.0	1.0

1. K - acceptance constant
2. r - allowable defect level

DISCUSSION OF RESULTS

Variation in Abrasion Index

The preliminary testing carried out to evaluate the effect of seating time indicated that errors in the measured penetration of the ball race into the paver could occur if the recommended three seconds was not used. The method used to eliminate the effect of seating time was to allow for a seating time of 3.0 +/- 0.1 seconds for all the abrasion testing carried out. The results in Tables 1 and 2 indicate that the flow rate of water to the ball race has an effect on the measured abrasion index. The data in Table 1, for constant paver properties and constant flow rate is uniform for all the manufactured pavers tested. Any variations in abrasion index as water flow rate is varied should be free of paver quality effects and due only to flow rate variations. The data in Table 2 indicates that an increase in abrasion index occurs as the water flow rate drops to a lower critical value. The least variation in penetration and abrasion index occurred at moderate flow rates. At low flow rates detritus from the paver unit remains at the ball-race/paver interface and aids the abrading process by acting as a grinding paste.

An attempt was made to determine the effect of paver age on abrasion index and the results are presented in Figure 2. As may be seen from the plotted data, it was not possible to establish any significant correlation between the two variable and it was concluded that variability in paver abrasion resistance or inherent experimental errors in the test procedure masked the effects of paver age.

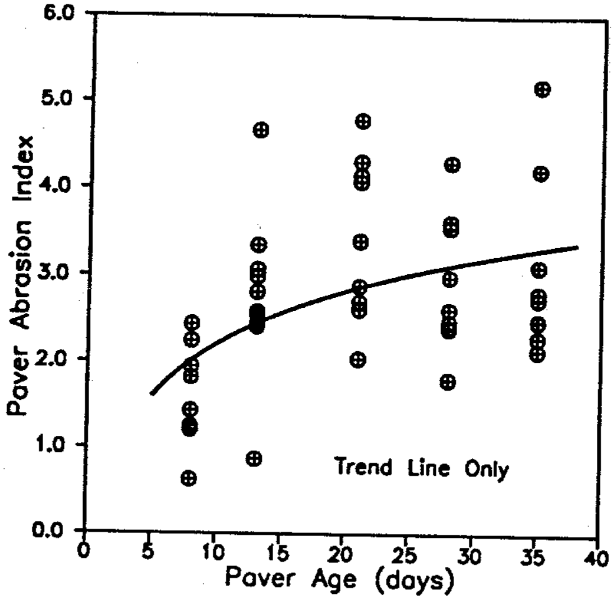

Figure 2. Variation in Abrasion Index with Paver Age.

Variation in Compressive Strength

It has been well established by numerous researchers [5],[6],[7] that compressive strength of concrete products increase with curing age in a predictable manner. The strength of the paving units tested should follow the established pattern by demonstrating an initial rapid increase in strength followed by a gradual decrease in rate of strength gain. The results from the study of effect of paver age on compressive strength are presented in Figure 3. It appears that there is a trend towards the classical strength/age curve but no strong correlation could be obtained between sample age and compressive strength.

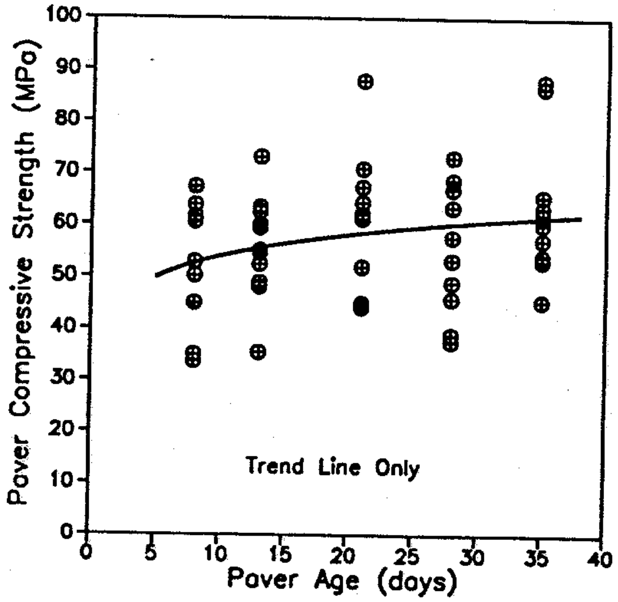

Figure 3. Variation in Compressive Strength with Age.

Compressive Strength and Abrasion Index

The possibility of a relationship between paver compressive strength and abrasion index, with increase in paver age was investigated [8]. Although there were no more than 10 pairs of observations of strength and abrasion index for each curing time, a regression analysis was done for each curing time to indicate the effect of time. Only the regression coefficients for the first group (8 days) was significant at the 5% level and that of the third group (21 days) at the 10% level. The correlations ranged from near zero to 0.73 and there was no indication of pattern with time. In the overall regression of abrasion index on strength, although strength was highly significant in its effect on abrasion index, with a correlation of approximately 0.5, there were a number of data pairs which had considerable effect, either through their strength or abrasion value. These data pairs caused a high estimate of standard deviation of abrasion index of over 1.1, after fitting strength. Omitting the data pairs whose influence or effect were questionable resulted in a decrease in correlation to less than 0.4, and raised queries about further points. The overall impression from the analysis was that although there was evidence of a link between strength and abrasion, experimental or inherent variation tends to hinder analysis of the link and its connection with time.

CONCLUSIONS

The measurement of abrasion resistance of concrete paving blocks is at present best described as an inexact science. The MA20 test could be made more effective if its methodology was reviewed and test variables, such as ball-race seating time and water flow to the ball-race, better specified.

The use of abrasion index as a measure of paver durability is only appropriate with respect to surface abrading loads. Its use in any other situation should be with great care (even actively discouraged) particularly for pedestrian mal areas where degradation due to impact/skew forces is the governing criteria.

Statistical analysis found that trends existed for increase in paver abrasion resistance and compressive strength with age but that those trends were not significant. It was found that the effect of paver compressive strength on abrasion resistance was statistically significant but that no correlation could be established due to inherent errors caused by MA20 test method or by variability within the pavers themselves.

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