Chapter 16

Summary,

Conclusions

and

Recommendations

16.1 Introduction

In this final chapter of volume 1 its main findings are summarised, some conclusions drawn, and recommendations are made.

Organisation of chapter

Volume 1 is primarily a study of the abrasion resistance of concrete pavers and is largely based on laboratory testing done in 1987 and site measurements of abrasion wear in 1993.

This satisfies the stated aim, namely to ‘provide a knowledge base that will lead to improved abrasion resistance in cbp’. To this end the six objectives that were outlined in chapter one are reviewed to see to what extent they have been met. Finally the chapter closes with a number of recommendations for future work.

However, before embarking on this course of action, it will be useful to place cbp in South Africa in its correct historical and functional perspective. This will be done by briefly summarising Chapter 2:

Background to Volume 1 – Review of Chapter 2

The origins of the product are traced to ancient times where stones were merely laid side by side. The product is shown to have evolved through several stages to its present form of precisely shaped concrete.

Thereafter a survey is conducted of cbp’s primary functions. These may be said to be (1) protecting the underlying layers from water, (2) contributing to the bearing capacity of these layers, (3) providing an aesthetically pleasing surface, (4) good economy and finally (5) resisting abrasive forces.

Next a worldwide survey is made of research done in abrasion resistance. Countries considered in the northern hemisphere included Belgium, Norway, Sweden, France, EU, USA, Japan. In the southern hemisphere eleven countries in Latin America are considered as well as Australia. It transpires that only 8 of 32 countries do abrasion testing.

Finally investigations into abrasion resistance in South Africa are appraised, along with the need for an abrasion test. Selection criteria are proposed for such a test, and the selection of the three abrasion tests used in this investigation are justified in this light.

Chapter two therefore gives the reader a broad understanding of the origins and development of the product, and sets this abrasion investigation against a backdrop of other research into abrasion resistance done locally and abroad.

16.2 Review of Objectives

16.2.1 Objective 1 - to improve the mix designs from which the blocks are made

To this end 48 different mixes were made in a typical paving factory, (see chapter 3). At age 28-days these mixes were subjected to ten different laboratory tests (see chapter 4). These tests included compression testing, tensile splitting testing, absorption testing, density determinations, and three different abrasion tests.

The results of these tests (see chapter 6) demonstrate that the abrasion resistance of cbp is greatly improved when:

- the water content is optimised
- the binder content is increased
- the effect of various cement replacement materials such as mgbs, fly ash, and silica fume, has a lesser influence. Fly ash retards the 28-day results; silica fume accelerates.

The order of importance of the mix design variables was found to be:

a. Water content

The correct dosage of water and the marked effect that it has on the density of the blocks makes it the most critical of the mix design constituents. The optimal water content is close to the point at which slumping begins. The additional compaction achieved by adding more water outweighs the negative effect of a lower c/w ratio, except close to the slump point.

Wet blocks are remarkably stronger than dry blocks in compression testing, tensile splitting, and abrasion resistance. Manufacturers should therefore aim for wet mixes. This is obviously the most economical way of increasing the strength of the blocks.

b. Binder content

Rich mixes (e.g. 18% binder) improve the strength of cbp both in compression, tensile splitting and abrasion resistance. Not only do they increase the c/w, but the increased proportion of binder increases the fluidity of the mix *in its own right* (even dry cement is fluid). This translates into reduced voids, increased density, and thus increased compressive strength and abrasion resistance. It is discussed more fully in chapter 2 of volume 2.

c. Binder type

The type of binder used has a lesser influence on abrasion resistance, but definite trends are nevertheless observable.

Silica fume accelerates the strength development at 28-days, while fly ash retards. This applies to the compressive strength, tensile splitting strength, and abrasion resistance. However site measurements after 6-years of traffic showed that fly ash outperformed the other mixes, i.e. had the least wear. This is consistent both with the known retardation of fly ash at 28-days (reflected in the laboratory tests), and the ongoing pozzolanic activity in the long term (evidenced by the results of ch 14 and 15).

In conclusion, the results of this investigation show that the correct application of the guidelines given in a. through c. result in mixes with improved compressive strength and abrasion resistance etc. Table 15.2, a mix design selection chart, is largely based on these guidelines, and is a useful aid to manufacturers who wish to use mixes with a proven abrasion resistance. Objective 1 is thus satisfied.

16.2.2 Objective 2 - To recommend an abrasion test to ensure that standards are maintained

Three abrasion tests were used to determine the abrasion resistance of the blocks. They were the MA20SA abrasion test (see chapter 9), the wire-brush abrasion test (see chapter 10), and the ASTM C418 abrasion test (see chapter 11). The respective tests were briefly described. Their ability to simulate wear was discussed. The results of the experimental work were given, and their strengths and weaknesses were analysed.

Two weaknesses of the wire-brush test can be considered as very serious. Firstly, the cost of the abrasive at R 25 per test (1994 prices) is too costly as a means of quality control in a production environment. Secondly, the test preferentially abrades the mortar constituent, leaving the aggregate particles protruding. This may be considered a realistic model where sand covers the paving and gouges out the mortar when traffic passes over. However it does not measure the contribution of the aggregate where loose surface gravel/sand is not a factor, and since aggregate is substantially harder than the cement paste in which it is embedded, the inability of the test to measure the aggregate’s contribution is seen as a serious deficiency.

As for the wire-brush test the ASTM C418 test is also fatally flawed in two respects. Firstly, the test is so severe that it penetrates deep into the face of the concrete in all but the strongest of mixes. This is not the ideal requirement for a test that is primarily there to determine the condition of the surface concrete. Secondly, the test dislodges the aggregate particles rather than measures their contribution to abrasion resistance.

One way around these deficiencies would be to vary the quantity of blasted sand, and redefine the abrasion index as that mass of sand required to penetrate 0,5mm and 1mm, of the surface.

By way of contrast the MA20 test:

- has a relatively cost effective abrasive
- is a true surface test
- measures the contribution of the aggregate

In chapter 12, 24 desirable attributes for an abrasion test were identified, and the three tests were considered in this light. Relative to these attributes the MA20 test (or more correctly the MA20SA test) had the best performance. In 1993 it was recommended to the industry as the preferred test, following some modifications to the apparatus and test procedure to improve its high variability. This version of the MA20 was to be known as CMA20 (described fully in appendix A.6). However, with the departure of the writer form the paving industry, coupled with concerns coming out of Australia and New Zealand, a wait and see approach was adopted by the CMA. Given that the Australians/New Zealanders have finally moved away from MA20 in favour of an impact test, there is little likelihood of the paving industry adopting MA20 or CMA20, even though the original and similar ASTM C779 ball bearing test appears to be gaining in favour in USA and Japan.

Given these developments, and considering the deficiencies of the sandblast and wire-brush tests, objective 2 cannot be said to have been met.

16.2.3 Objective 3 - To classify abrasion wear in terms of quantifiable ‘degrees of abrasion’. To classify cbp applications in terms of these degrees of abrasion (chapter 8).

In order to determine the degree of wear after 6-years of traffic, it was necessary to find a means of assessing wear. Visually this was done by introducing the concept of five ‘degrees of abrasion’, ranging from ‘zero degree’ showing virtually no signs of wear, to ‘fourth degree’ representing substantial loss of material. Quantitatively wear was measured by extruding clay from a modified plastic syringe (see appendix A.7), which allowed the craters and crevices to be filled. By dividing the volume of clay by the area over which it was applied, the average depth of the visible wear was obtained, called the ‘mean visible depth’ (mvd).

These methods of defining abrasion were applied to four sites, representing blocks from three manufacturers, to obtain a relationship between the observed degrees of abrasion and mvd.

The main characteristics associated with wear, e.g. colour shift, a rougher surface texture, a greater mvd, etc., were classified in terms of the five degrees of abrasion (see table 8.3). The degree of abrasion occurring in cbp should match the application for which it is intended. Some recommendations are made, e.g. wear should be limited to second degree in prestigious projects. Using this classification, the end user is in a position to specify the desired limit of wear.

A method of identifying and quantifying wear in cbp is thus proposed. Objective 3 is thus satisfied.

16.2.4 Objective 4 – ‘Calibrating’. (a) Correlating the results of the 28-day abrasion tests (done in the laboratory in 1987) with the observed 6-year wear on site (recorded in 1993). Establishing limiting criteria for the tests. (b) ‘Calibration’ of mix designs in terms of 6-year site abrasion.

By correlating both the mix designs and laboratory tests in terms of actual wear on site it is possible to predict that a particular mix will meet certain limiting criteria of a 28-day abrasion test, and once in service undergo a predetermined degree of abrasion.

To this end blocks from the same mixes as those tested in the laboratory were installed in the access road to a busy bus terminus, and a busy pedestrian sidewalk (see chapter 5).

After approximately 6-years, the actual wear in these blocks was measured in four ways:

- a visually (photographs, assessment of degrees of abrasion)
- b depth gauge measurements (mcd)
- c syringe method (mvd)
- d in terms of mass loss (still to be completed).

The correlation of the 28-day laboratory results with the wear on site at Westgate after 6-years is recorded in chapter 14.

Chapter 14

Considering all the 48 mixes together, the R^2 values were not able to discern which of the 28-day laboratory tests (i.e. dry density, compressive strength, tensile splitting, three abrasion tests, and ISAT) best related to the 6-year wear.

However, a clear relationship between the 28-day tests and 6-year wear emerges when the mix designs are considered individually. The MA20SA test, in particular, is capable of distinguishing relatively subtle changes in the mix design.

Eight design graphs are given for the MA20SA test whereby the relationship between the 6-year mvd and the 28-day MA20SA indices is given for each mix design, and the effect of variations in the water content and traffic regime are shown.

Chapter 15

A simplified mix design selection chart (see table 15.2) enables manufacturers to use the findings of this investigation to produce concrete pavers with predictable 6-year abrasion. The eight mix designs of this investigation are expanded to 21, to include mixes with RHC.

A method of establishing limits for an abrasion test is proposed. Local 28-day limits vary from factory to factory as a result in changes in the local manufacturing environment (lme), but are important as a pre-dispatch verification of the surface quality. They are based on a yet-to-be-determined national 90-day limit.

Objective 4 is thus partially satisfied. Although mix designs and abrasion tests have been calibrated in terms of actual wear on site, suitable limiting criteria are yet to be determined.

16.2.5 Objective 5 - Recommending an overall abrasion resistance quality assurance programme

A recommended design approach (see chapter 15) is given for manufacturing concrete pavers with good abrasion resistance. Essentially this amounts to the correct application of table 15.2. The following sequence should be observed:

a. Determine traffic loadings
b. Select permissible degree of abrasion
c. Select mix design from design chart (table 15.2)
d. Control manufacturing process
e. Control curing
f. Verify abrasion resistance
g. Despatch

Figure 15.3 flow charts these steps, and indicates the respective responsibilities of the specifier and manufacturer.

Conclusion:

The systematic application of this abrasion resistance quality assurance plan will ensure improved abrasion resistance. Objective 5 is thus realised.

16.2.6 Objective 6 - Highlighting shortcomings in the compressive strength test method as described in SABS 1058, and recommending suitable changes (chapter 7).

a The method used to determine the compressive strength in SABS 1058 should be revised in the direction of a more scientific specification such as the MA20(1986), which allows for aspect ratio correction and uses the base area of the block.

b It is shown that it is possible to convert ASTM and SABS results to equivalent MA20 results using coefficients to represent the differences between the tests, i.e. aspect ratio correction, net vs plan area, soaked vs dry blocks, capping vs plywood.

c The compressive strength test is generally a good indicator of the structural ability of cbp, and should therefore be retained for this purpose. At the same time it is recognised that it is not always a reliable indicator of abrasion resistance, as it may not detect inferior/superior surfaces relative to the bulk of the block. Furthermore it is not sufficiently sensitive to curing, and does not detect the effect of liquid surface treatments, carbonation, hard aggregates etc.

Conclusion: The shortcomings in the current specification have been highlighted, and an alternative test method is recommended, thus satisfying objective 6.

16.3 Recommendations for further work

Of the six objectives of this thesis, all but objective 2 (finding a suitable abrasion test for the industry) were attained. This is not to say that the abrasion tests considered proved quite useless. On the contrary meaningful relationships were established; and it seems reasonable that if certain adjustments/improvements are made to the MA20 test (i.e. CMA20) or if less sand is used in the ASTM C418 test, then certain objections could be overcome and the test adopted by the paving industry.

There are nevertheless a number of aspects that were not covered in this investigation, which should be considered in ongoing research programmes by undergraduate or postgraduate civil engineering students looking for suitable projects. The projects stemming from this investigation are described in 16.3.1 through 16.3.4, while those relating to ongoing CMA research are discussed in 16.4.1 through 16.4.6.

Some of them are relatively short, and could be considered as a four-month project tacked onto course-work modules. Others are involved, and would require a considerable degree of sponsorship by interested parties such as the cement companies, the Foundation for Research Development, etc. It is possible that the CMA members themselves may also be able to contribute, either with cash, or by making plant, material, and expertise available.

16.3.1 The effect of aggregate on abrasion resistance

The influence of the aggregate on abrasion resistance has been studied by a number of investigators, such as Abrams(1921), Scripture(1954), Smith(1958), Ozturan(1987), Addis(1989). Furthermore it is clear from Hutchings(1992) that hardness and toughness are very important characteristics, the former in regard to compression and shear loadings, the latter with respect to impact.

Therefore while the contribution of aggregates to abrasion resistance is well documented, not least of all in chapter 2 of volume 2, it would be useful to do comparative testing of the many commercially available aggregates in a relatively confined area such as for example the Witwatersrand. The effect of grading, surface texture, particle shape etc. of the fine aggregate can be expected to influence the cement / water ratio, and hence abrasion resistance. More importantly the hardness of the coarse aggregate can be expected to ‘protect’ the mortar constituent, again influencing abrasion resistance. Given that modern paving manufacturing machines are capable of applying a thin layer or topping, a proportionally small volume is required for this layer. Therefore the cost of hauling superior aggregates for this layer (from far off sources if necessary) would not be prohibitive.

It is also possible and practical to dramatically increase the hardness of the surface by applying a topping incorporating malleable iron balls mixed in with the fine aggregate. This could have application in situations where very abrasive conditions exist. Research suggests that the abrasion resistance, especially where impact forces exist, can be increased in the order of 300% using this method [reported by Chaplin(1972a)]

16.3.2 The effect of curing on abrasion resistance

It is well known that abrasion resistance of concrete is profoundly affected by curing. Generally this is an area that is neglected in many paving factories. Various systems are used in the industry such as primary curing under nylon covers, secondary curing in shrink-wrapped packs, sprayed on curing solutions, sprinklers in the storage yard etc. However the relative efficiencies and effects on abrasion resistance have not been quantified for local conditions.

16.3.3 The effect of surface hardeners

Chemical hardeners, such as a diluted sodium silicate solution, may also be used to increase the hardness of the paste component of concrete's surface. This reacts with the free lime near the surface to produce hard calcium silicate and also a sodium silicate glass in the pores [Chaplin(1972a)]. Providing the solution is quickly absorbed it would generally be practical to do this just prior to the stacking/cubing operation. At this stage the blocks would be 24 hours old.

Alternatively, where hot steam curing is possible, the surface can be impregnated with a hard polymer [Fukado(1984)].

Experimental procedure

In evaluating the effect of various aggregates, curing regimes, and surface hardeners (see 16.3.1 through 16.3.3), a similar experimental procedure is suggested as is used in this work. The pavers should be subjected to a suitable abrasion test. If possible companion pavers should be installed in a busy road and / or sidewalk as was done in this investigation, and a comparison made between the laboratory tests and site wear. Alternatively the approach outlined in figure 15.2 could also be used to link 28-day results to a '90-day national abrasion index'.

Factors such as density, cement / water ratio, cement content, manufacturing process etc. should be kept constant.

16.3.4 Determination of Mass Loss

The concept of 'absolute' wear was developed in chapter eight, i.e. the sum of the 'visible' and 'invisible' wear. In order to determine this wear pre-weighed blocks were installed in both the road and the sidewalk at Westgate.

In order to compensate for mass increase of these blocks due to ongoing hydration and carbonation effects, other pre-weighed blocks from the same mixes were also installed in the side of the road where there is no traffic. The blocks were thus subjected to the same climatic conditions, but not to traffic. Theoretically, these blocks may actually increase in mass due to the hydration and carbonation effects, and this change in mass can be used as a correction factor for the blocks subject to traffic, thus enabling the true wear to be determined.

Still other pre-weighed blocks were placed in a chamber at the University with a relative humidity of 60% at constant temperature 23° C, while others were submerged in water. It was hoped in this way to determine the maximum possible increase in mass from ongoing carbonation and hydration respectively, making it possible to determine the respective contributions of carbonation and hydration to the presumed increase in mass of the site blocks. However, owing to time and financial constraints, this aspect of the program is incomplete.

Two complications have arisen. Firstly, the pavers in the curing and carbonation chambers were inadvertently disposed of. Secondly, the site blocks have been subject to dissolution processes from rainwater that may be either very pure or alternatively acidic.

The current situation is that the installed blocks at the site are still undergoing traffic – and are now 14 years old. This makes the completion of this phase all the more worthwhile in terms of gauging total abrasion-wear, even though the presumed mass increase from ongoing hydration and carbonation can not be determined since the degree of mass loss from the dissolution is unknown.

Experimental Procedure

The current status of this work and experimental procedure thus far is detailed in 5.3.4. The results to date are recorded in appendices M.1 through M.8. A total of 1440 blocks have been weighed.

It remains for the three sets of blocks on site to be uplifted from the road and sidewalk (funds permitting). Once again they should be cleaned, dried to constant mass at 60 degrees centigrade and weighed.

These readings can then be compared to the values in appendices M.1 through M.8. From this it should be possible to calculate the loss in mass due to abrasion, even though no correction for site hydration, carbonation and dissolution will be possible. This investigation is nevertheless likely to lead to a relatively good estimate of the ‘absolute’ wear.

16.4 Ongoing CMA Research

In addition to the work described above, a number of other projects related to abrasion resistance have been identified by the CMA. Some of them are an overflow of this investigation, others are entirely separate. Once again these projects would be greatly accelerated if interested undergraduate and postgraduate students could be engaged.

16.4.1 Limiting criteria

In chapter 15 the need for determining both 'local' and 'national' limiting criteria for an abrasion test was discussed.

Experimental procedure

This was laid down in some detail in 15.4 and will not therefore be repeated here.

Once suitable indices have been established, the SABS should be approached to include them into SABS 1085, but this presupposes that a suitable abrasion test is adopted.

16.4.2 Tests on old pavers

All 720 blocks subjected to the 28-day abrasion tests in September 1987 were stored in the open, at Brickor Precast. They therefore benefited from periodic rain, and it is inevitable that their abrasion resistance has improved substantially through ongoing hydration, as well as carbonation. Since the blocks subjected to the MA20SA and wire-brush tests were tested on one half of their respective upper faces, there is sufficient space on the remaining half for a further test.

The main aim of this work is to determine the increase in abrasion resistance that occurs over a long period of time, in open exposed-to-the-sun-and-rain conditions. The results will be all the more interesting since different extenders were used in the eight mix designs.

Experimental procedure

This experimentation was in fact carried out in 1995, at the laboratories of Grinaker Duraset, and using the same original apparatus used for the 28-day September 1987 tests. The writer was in a position to carefully supervise these MA20SA tests. The results have been reported by Papenfus(1995) and reveal a very dramatic increase in abrasion resistance, thought mainly to be the result of carbonation.

16.4.3 Tests on clay pavers

Of concern to the CMA members is the abrasion resistance of concrete pavers relative to fired clay pavers.

Experimental procedure

The CMA decided that a number of the most commonly used clay pavers be obtained and subjected to the MA20SA test.

The experimental phase of this work was also carried out in 1995 under the writer's supervision, and supporting photographs of the various different types of clay paver were taken to identify them and to visually indicate the depth of the groove. To date this work has not been written up, and the CMA should be approached for sponsorship so that this may be done. However, it is already possible to report from the photographs that a wide variation in hardness exists depending on source.

16.4.4 Masonique concrete pavers

Grinaker Precast manufacture a paver (Masonique) such that the longest dimension of the paver is vertical during the manufacture process. This allows a degree of trowelling on the wearing surface during the demouldng process. Also any surface water that may tend to rise during the vibration process and in so doing reduce the c/w ratio, does not affect the eventual wearing surface.

It is commonly believed that, owing to these effects, these blocks have superior abrasion resistance. A method of quantifying this is described below.

Experimental procedure

Using the same mix design, process and equipment etc., a batch of 'Masonique' blocks will be made under careful supervision at the Rossway factory. Particular attention will be paid to keeping all six lme variables as constant as possible (i.e. water content, binder content, binder type, aggregate, curing, process control). The mould should then be changed to the more conventional type of paver (which is made in a face up position), and once again a batch should be made.

The abrasion resistance of specimens from both batches can then be tested at 24 hours and 28-days to determine the effect of orientation during the moulding process.

This exercise may prove to be very costly, firstly from the point of down time in changing the mould, and secondly the 'face up position' mould will in all probability have to be made from scratch. It may be possible to modify old/obsolete moulds to do this, as only a few specimens will be required.

16.4.5 CMA abrasion wear test sites

In 1990 ten test sites were identified around South Africa, three of which are in the Johannesburg area. Eighty blocks from each of the ten different sites were sampled and submitted for testing at PCI. The tests used were:

a. compressive strength to SABS 1058
b. tensile splitting strength to ISO 4108
c. rotating cutter test to ASTM C944
d. sand blast test to ASTM C418
e. wire-brush test to PCI.TM.7.11
f. ball bearing test to MA20

The original plan was to inspect each site at the beginning of the tests, as well as at two and a half years and five years to assess the abrasion. However, each site has very different traffic conditions. Furthermore blocks were supplied from different factories. Thus all of the six local manufacturing conditions would be different. In some cases the traffic conditions have changed considerably, and in other cases the pavers have been uplifted to access services.

As a result, it will be difficult to determine a correlation between the laboratory tests and inset performance. Subject to these limitations, the then CMA director, Mr. P. Kelly, made the following general observations:

General Observations

a The abrasion at the Crown Mine Golf Course under continuous traffic of golf spikes was by far the worst

b Aside from a. the abrasion by pedestrian traffic is generally less than vehicular traffic. [This is in line with the findings of the measurements at Westgate, where the vehicular traffic induced substantially more wear than pedestrian traffic.]

c With time and abrasion, not only is there a reduction in surface finish, there is also a marked increase in standard deviation i.e. difference from the best to the worst block.

d Turning of vehicles, particularly where gravel is present, is strongly abrasive, e.g. Randpark Ridge Mall.

e Heavy slow moving vehicles do not necessarily abrade more.

Experimental procedure

Monitoring of these sites was to be ongoing. Inspections at age 2 ½ years took place, but not at five years. The documentation for these sites is still available, and it may therefore still be possible to identify the pavers after some 11 years of abrasion, and assess them according to the criteria stipulated in table 8.4 of section 8.6. Once again, this may be an interesting project for an undergraduate student, although given the different intensities of loading and the various sources of the pavers, it will be difficult to make definite deductions.

16.4.6 Further CMA abrasion wear test site

When the various tests described above were done at PCI, there were a number of blocks left over from each batch. Given the different intensities of traffic encountered above at the various sites, the CMA considered installing these blocks sequentially, in a busy pedestrian sidewalk. The blocks were to be monitored both visually and by clay replacement (i.e. mvd), on a biannual basis. It was hoped that these results would make it possible to correlate the wear with that predicted by the various laboratory tests. Unfortunately this work was never undertaken, and it is unlikely at this distance of time that the pavers are still available.

16.4.7 Sectional Conclusion

The various projects described in 16.3 and 16.4 above present an opportunity for furthering understanding on abrasion resistance. The primary reason for the projects not being completed may be attributed to the departure of the then CMA director as well as the writer’s move to a different industry. A fresh re-evaluation should be made by the CMA of the various projects listed, with the writer in attendance. Projects deemed worthy of further consideration could possible be undertaken by a post graduate student.

16.5 Closing Remarks

Fourteen years ago the author approached Prof. M G Alexander (then a senior lecturer at the University of the Witwatersrand, now Head of the Department of Civil Engineering at the University of Cape Town) with a proposal for an M.Sc. The initial ideas were developed and over the course of several years the scope of the project increased steadily. It was eventually decided that the project should be upgraded to a PhD.

The aim of the thesis has always been ‘to provide a knowledge base that will lead to improved abrasion resistance in cbp’, and the attainment of five of the six objectives listed earlier means that this has, to a large extent, been done.

As a result of this work:

1. A clearer understanding now exists of how water content, binder content and various binder types influence the abrasion resistance of concrete pavers.

   The accelerated strength gain of silica fume mixes at 28-days was noteworthy, but this was eclipsed by the fly ash mixes at six years, which had substantially less wear.

   A somewhat unexpected result was that pavers made with very low w/c ratios, in the region of 0,21, which would normally be considered too dry to be adequately lubricated, had high compressive strengths and abrasion resistances, providing a relatively high binder content was used. The high binder content compensates for reduced water content to achieve excellent densities. The combination therefore of void minimization *and* a low w/c ratio produces pavers with high abrasion resistance.

2. Three abrasion tests have been studied. Although MA20SA emerged as the best of the three, its inherently high variability and consequent developments in Australia have prevented this test being implemented locally.

3. Wear has been classified, both quantitatively and visually. A mix design chart makes it possible to select a mix with a predictable long-term wear performance.

The importance of research of this nature must be seen against the backdrop of an ever changing and dynamic market. A sobering reminder of how market trends can change, even in the paving industry, is to be found in some of the ancient materials that were used to surface roads of antiquity. The large stone sets used by the Romans, the triangular cast iron blocks and wood-block roads used in the nineteenth century are today gone and forgotten.

The cbp industry is currently in a stable position. This is largely due to the efforts of certain manufacturers that have over the years developed products with excellent abrasion resistance, and are prepared to pay for the additional cost of the superior materials and processes required to ensure that even after many years of traffic the surface is still serviceable with minimal loss in aesthetic appeal. Unfortunately other manufactures have not been as informed or responsible. This has resulted in the industry losing ground in some areas. For example the Johannesburg municipality has moved away from concrete pavers in certain applications, preferring exposed aggregate slabs, partly because of their perceived superior abrasion resistance. Furthermore, if a new diesel resistant asphalt were developed, many garage forecourts may revert back to this cheaper method of surfacing, to the detriment of the paving industry.

It is therefore crucial that the findings of this work are widely disseminated and skilfully exploited.

One way of doing this would be to discriminate between pavers with excellent abrasion resistance and those that are ordinary or inferior, by introducing abrasion testing into SABS 1058. This would renew the confidence of some sceptical end users, particularly professionals from the ranks of architects, engineers and developers that have had some bad experience with cbp. Their confidence in the product would be restored if they were able to specify ‘abrasion resistant concrete pavers’.

Providing manufactures use face concrete devices on their machines, the additional cost of the higher binder proportion and carefully selected aggregates etc. will be minimal. Generally this cost can be passed on to the client, who would only be paying a little more money for a lot more abrasion resistance. Thus increased market share will be assured. It is the writer’s persuasion that ‘to improve the abrasion resistance of cbp’ will in the long term financially benefit all those associated with this industry.

Transition from Volume 1 to Volume 2

Part of the motivation for *volume 2* was the recognition of the importance of having an abrasion test in the national specification to promote ‘abrasion resistant concrete pavers’, coupled with the realization that the three tests reported on in the experimental phase of this thesis (i.e. volume 1) were not acceptable to the industry. Therefore Chapter 4 of volume 2 considers an almost exhaustive list of surface tests, 66 in all, and concludes by recommending three further tests for experimental evaluation. In making this selection, considerable emphasis was placed on understanding the mechanisms of wear for all 66 tests. Clearly tests that do not simulate the wear mechanisms that take place in actual traffic conditions should be ruled out. Accordingly chapter 3 deals with the preparatory theory for understanding the various mechanisms of abrasion, establishing the necessary platform for chapter 4. Finally, in chapter 2, a very extensive survey/literature research is made of the many factors that affect abrasion resistance.

Volume 1 as it appears here is essentially a substantial enhancement (done in 2000 and 2001) of what was informally submitted in 1994, whereas *volume 2* was written from scratch in 2000 and 2001. It adds to rather than repeats what is covered in *volume 1*, considering abrasion resistance from a different perspective. Moreover its conclusions are largely based on the writer’s extrapolation of evidence presented in its very extensive literature survey. By way of contrast the discussions of *volume 1* are predominantly based on the experimental work done in 1987and 1988, and the wear measurements taken in 1993.

The experimental work reported on in volume 1, considered together with the theoretical considerations that follow in volume 2, may well constitute the most intensive investigation ever undertaken into abrasion resistance of cbp.