Chapter 15

Designing for

Improved Abrasion Resistance

15.1 Introduction and Overview

This chapter is founded on all the afore-going chapters. It focuses on the practical engineering aspects of this thesis, and should be of value to the concrete paving industry.

At the heart of this chapter is the ‘Mix Design Selection Chart’, to assist manufacturers in selecting a mix design that has a predictable long-term performance.

‘Local’ and ‘national’ limits for the 28-day abrasion test are proposed, to verify the abrasion resistance of the selected mix design.

Finally a design approach is suggested, giving guidelines both to the specifier and the manufacturer.

15.2 Limitations of Design Graphs

Chapter 15 is a natural progression of chapter 14, and starts where chapter 14 stops. Chapter 14 correlates most of the 28-day laboratory tests with wear at Westgate after 6-years. It concludes with eight mix design graphs, based on the MA20SA test.

Although the design graphs give a detailed relationship between the MA20SA indices and the wear after 6-years, for two typical traffic regimes, they are nevertheless limited in some respects. These deficiencies are discussed in 15.2.1 through 15.2.3.

15.2.1 Inconsistent indices for 28-day MA20SA test

Ideally the limiting criteria for abrasion resistance in pavers should be based on the actual wear performance of the blocks after some years of traffic. Accordingly chapter 14 classifies wear as follows:

a. pavers with a mvd that does not exceed 0,5 mm have second degree abrasion, (or less).

b. pavers with a mvd which does not exceed 1,0 mm have third degree abrasion.

c. pavers with a mvd that exceeds 1,25 mm have fourth degree abrasion.

(Transitional zones also exist, see chapter 14).

The 28-day MA20SA indices (from the design graphs) corresponding to the above stated limiting criteria are given in table 15.1. It is evident that for the limiting criteria, mvd = 0,5 mm, and mvd = 1,0 mm there is a great variation in MA20SA indices.

Figure 15.1, (similar to figure 14.31) reinforces this point. For example, the fly ash (FA) mix has vastly inferior indices, but superior 6-year mvd, particularly for the dry mixes. An obvious explanation is that the fly ash mixes are significantly retarded at 28-days, and hence register low indices, but owing to the ongoing pozzolanic activity have the lowest wear after 6-years of traffic.

It is therefore not possible to establish meaningful limiting criteria in terms of 28-day indices. Consideration to linking the variable 28-day indices to more settled 90-day indices is given in 15.4.

TABLE 15.1 MA20SA INDICES - TAKEN FROM DESIGN GRAPHS, CORRESPONDING TO MVDs OF 0,5 mm AND 1,0 mm

MIX	2 ND DEGREE MVD = 0,5 mm		3 RD DEGREE MVD = 1,0 mm	
	SEVERE TRAFFIC	NORMAL TRAFFIC	SEVERE TRAFFIC	NORMAL TRAFFIC
1	2.22	1.77	1.15	+
2	-	0.99	0.83	0.72
3	-	-	-	0.55
4	-	-	0.63	0.43
5	-	1.21	0.53	+
6	0.94	0.82	+	+
7	-	1.51	1.03	0.78
8	-	1.79	1.3	0.88

Notes
1. A "-" means the mix is underdesigned, and therefore has insufficient abrasion resistance for the application.
2. A "+" means the mix is overdesigned, and will not reach the mvd limit for the application.

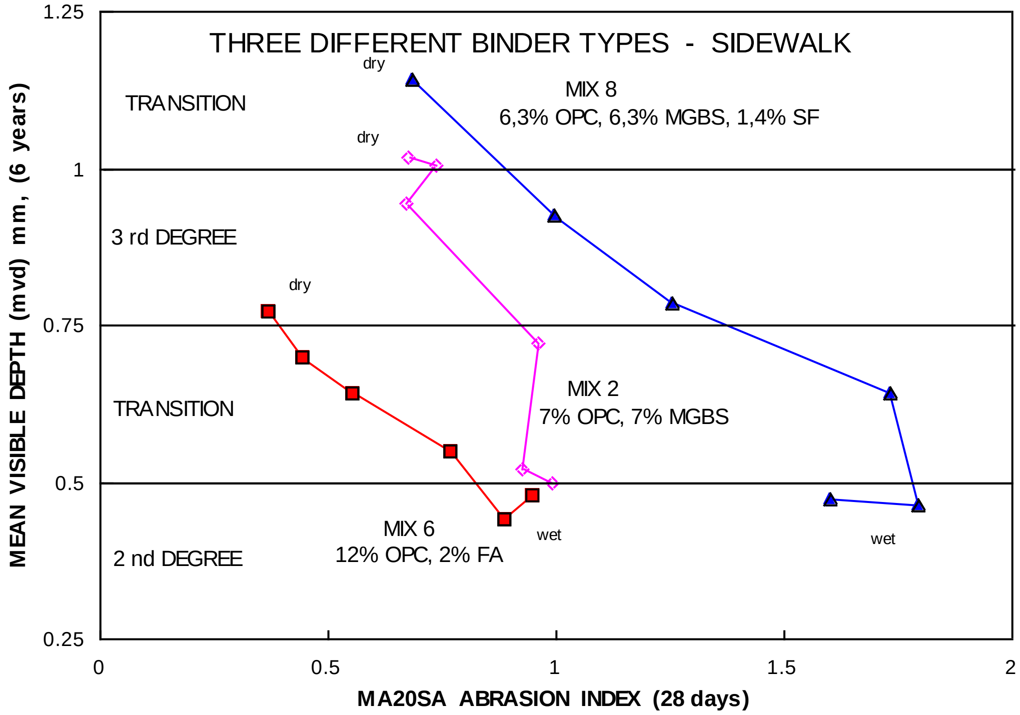

Figure 15.1 Relationship between 28-day MA20SA indices and mvd, illustrating how the indices bear little relation to the recorded wear unless a distinction is made in binder type.

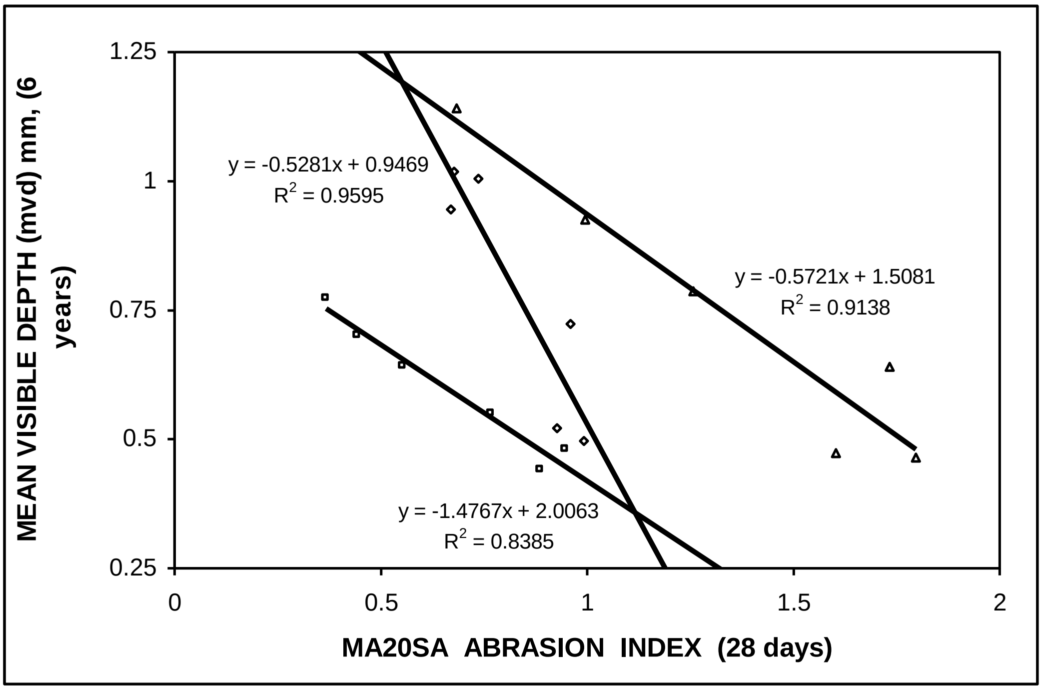

Figure 15.1-R^2 Trend lines for figure 15.1 show that binder type plays a large role in the relationship between the 28 day abrasion index and the long term wear.

15.2.2 Limited number of design graphs

A second limitation of the design graphs is that only eight (see figures 14.39 through 14.46) are available. The graphs cover variations in:

a. Water content: Six water contents ranging from very wet to very dry are sufficient to plot meaningful curves on the graphs.

b. Binder content: Binder contents of 10 %, 14% and 18% generally cover the full range that can be expected in cbp, but intermediate contents, of 12% and 16% would have been useful. Manufacturers using such intermediate contents may wish to plot intermediate curves as an estimate or guideline.

c. Binder type: The binder types and the selected cement replacement levels closely followed what was typically being supplied by the cement industry. For example cement replacement levels with fly ash of 14%, 21% and 28% (mixes 6, 5, 4 respectively) closely followed the 15%, 25%, and 30% ready blended OPC substitutions being used in the industry. Substitution of 50% with milled granulated blast furnace slag (mix 1, 2, 3) simulated ‘Portland blast furnace cement’ and were ideal where economy is desired. Binder replacement with 5% and 10% silica fume (mix 7 and 8) followed the supplier's recommendation.

   Note that with the adoption of the EU Standards in the cement industry in 1997 some of these blends have changed and others are no longer marketed. This will however only affect very small producers who use bagged cement, as large producers invariably do their own blending from a nest of two or more silos.

   There are also some other shortcomings with the binder types and blends used in this investigation. No mixes with 100% OPC were made, and RHC was entirely omitted from the program. The scope of this investigation did not allow for these additional variations. Their performance is nevertheless well known relative to the mixes that were made, and provision is made for these cements in table 15.2.

15.2.3 The local manufacturing environment

A third limitation of the design graphs is that they do not account for *all* the variables that affect the abrasion resistance of concrete pavers.

These variables may be listed as:

a. water content
b. binder content
c. binder type
d. aggregate
e. curing
f. process control (includes the degree of compaction, direction of moulding process, possible application of liquid surface hardeners, etc).

Collectively these variables are referred to as the ‘<u>local manufacturing environment’</u> (lme), to stress that they vary from one factory to another.

In this investigation the water content, binder content and binder type were the variables, and their effect on the design graphs has been discussed in 15.2.2.

On the other hand the aggregate, the curing regime, and the process control were constants. In practice however, these parameters will not be constants and will vary from factory to factory. This further limits the application of the design graphs.

It is thus clear that the variables that comprise the lme will differ from one locality to another, and this increases the difficulty of arriving at a 'national' or global abrasion index. This matter is fully addressed in 15.4.

15.2.4 Abrasion Test

Many of the conclusions and deductions hitherto have been based on the MA20 abrasion test (or rather MA20SA). This is perhaps unfortunate, given that MA20 is no longer used in Australia and New Zealand, and is no longer being considered as a possible abrasion test in South Africa either, mainly because it has high variability. Nevertheless, the principles of arriving at limits, as given in this chapter, are 'generic', and can be applied to any abrasion test. The main difficulty in doing so would be to obtain a correlation between 28-day laboratory testing and 6-year wear under traffic, as was done in chapter 14.

This could be done by making up pavers for 28-day lab testing, similar to those used in this program, and subjecting them to both the MA20SA and the 'new' abrasion test. This effectively calibrates the new test, although difficulties may be experienced in simulating all the same 'lme' conditions of the 1987 pavers.

Recognising that MA20 is no longer in widespread use in N Z and Australia (although ASTM C779 Proc C is), and that some other abrasion test could be calibrated in terms of 6-year wear, and that the principles of arriving at limits are generic, the term 'abrasion test' will be used hereafter instead of MA20SA or MA20, unless the text specifically requires its use.

15.3 Mix Design Selection Chart

15.3.1 Overview

The information in the design graphs of chapter 14 can be both simplified and expanded by means of a 'mix design selection chart', as shown in table 15.2. This is a useful design tool that assists manufacturers and specifiers who may have difficulty in interpreting the design graphs of the preceding chapter.

The eight mix designs of this investigation are shown as mixes M, N, P, Q, R, S, T, and U in Table 15.2. They were ranked according to their 6-year performances, based on figures 14.39 through 14.46. (See also explanatory notes 15.3.1 through 15.3.5).

It should be emphasized that in ranking the mixes in Table 15.2, only *mvd* was considered, and the 28-day abrasion indices were ignored. The table can therefore be used regardless of what abrasion test is preferred. Clearly the only variables are the mix constituents, the severity of the traffic, and the degree of abrasion required.

Accordingly, the design chart makes it possible for the manufacturer to select a mix design with a predictable performance i.e. wear limited to 2nd or 3rd degree abrasion, for either 'severe' or 'normal' traffic. In other words, for a defined degree of abrasion-wear and traffic intensity, the end user can select the appropriate binder content, how the binder should be constituted, and the water content required in the production process.

15.3.2 Interpretation of Table 15.2

Readers should acquaint themselves with the important explanatory notes at the base of table 15.2. The table is best illustrated with an example. Considering mix design N, it is apparent that abrasion-wear will:

- exceed '2nd degree' under 'severe' traffic, irrespective of how much mix water is used in the production process. The mix is therefore '-', i.e. under-designed for this application.
- not exceed '2nd degree' under 'normal' traffic, providing the pavers were made from a 'wet' mix.
- not exceed '3rd degree' under 'severe' traffic, providing the pavers were made from a mix that had an 'int' (intermediate) amount of mix water, i.e. less then 'wet', but more than 'dry'.
- not exceed '3rd degree' under 'normal' traffic, regardless of the water content of the pavers. I.e. Even dry mixes have mvd values that do not exceed the limits of 3rd degree abrasion wear. The mix is therefore '+', i.e. over-designed for this application.

15.3.3 Explanatory notes on table 15.2

Whereas the design graphs only apply to one specific aggregate type, and are also restricted to eight mix designs, the design chart (table 15.2) has a much wider application.

The chart covers four of the six lme variables, discussed in greater detail in 15.3.3.1 through 15.3.3.4.

TABLE 15.2 ABRASION RESISTANCE MIX DESIGN SELECTION CHART

MIX	SELECT MIX DESIGN		SELECT WATER CONTENT:			
	MIX PROPORTIONS	BINDER CONTENT	FOR 2 nd DEGREE WEAR AFTER 6 YEARS TRAFFIC		FOR 3 rd DEGREE WEAR AFTER 6 YEARS TRAFFIC	
		%	SEVERE TRAFFIC	NORMAL TRAFFIC	SEVERE TRAFFIC	NORMAL TRAFFIC
A	15:3:82 RHC:FA:AGGR	18	wet/int	int/dry	+	+
B	18:82 RHC:AGGR	18	wet/int	int/dry	+	+
C	13.5:4.5:82 RHC:FA:AGGR	18	wet/int	int/dry	+	+
D	15:3:82 OPC:FA:AGGR	18	wet	int	+	+
E	18:82 OPC:AGGR	18	wet	int	+	+
F	13.5:4.5:82 OPC:FA:AGGR	18	wet	int	+	+
G	9:9:82 RHC:MGBS:AGGR	18	wet	int	+	+
H	12:2:86 RHC:FA:AGGR	14	wet	int	+	+
I	14:86 RHC:AGGR	14	wet	int	+	+
J	11:3:86 RHC:FA:AGGR	14	wet	int	+	+
K	10:4:86 RHC:FA:AGGR	14	-	int	+	+
L	7:7:86 RHC:MGBS:AGGR	14	-	int	+	+
M	12:2:86 OPC:FA:AGGR	14	-	wet	+	+
N (mix 1)	9:9:82 OPC:MGBS:AGGR	18	-	wet	int	+
O (mix 6)	14:86 OPC:AGGR	14	-	wet	int	+
P (mix 5)	11:3:86 OPC:FA:AGGR	14	-	wet	int	+
Q (mix 4)	10:4:86 OPC:FA:AGGR	14	-	wet	wet	dry
R (mix 8)	6.3:6.3:1.4:86 OPC:MGBS:SF:AGGR	14	-	wet	wet	int
S (mix 2)	7:7:86 OPC:MGBS:AGGR	14	-	-	int	int
T (mix 7)	6.65:6.65:0.7:86 OPC:MGBS:SF:AGGR	14	-	-	wet	int
U (mix 3)	5:5:86 OPC:MGBS:AGGR	10	-	-	-	wet

Notes:

1. This table ranks from top to bottom 21 mixes according their expected performance with respect to abrasion resistance
2. The mix designs designated 'mix 1' through 'mix 8' are those tested at Westgate. The others are conservative extrapolations of these mix designs, taking into account the predictable effects of increased binder content (14% vs 18%) and different cement types(RHC vs OPC).
3. The principles embodied in the design graphs (i.e. figures 14.39 through 14.46) were used to construct this chart.
4. Replacing 5 % or 10 % of the binder with silica fume results in accelerated abrasion resistance in the short term, but wear is substantially the same at six years relative to the central, mix 2. Conversely fly ash retards the abrasion resistance in the short term but results in a significant reduction of wear in the long term.
5. "Wet" blocks are made with a water content that will facilitate full compaction. Generally the optimum moisture content is close to slump point, (approximately 0,5% less). "Dry" blocks appear to be pourous, and are approximately 10 % lighter than "wet" blocks. "Int" refers to blocks with an intermediate water content.
6. A "+" means that the mix is overdesigned (even dry mixes will exceed the wear criteria), and a "-" means that the mix will have insufficient abrasion resistance even for a wet mix.
7. "Severe" traffic refers to large volumes of vehicular traffic including large trucks. Typical applications include bus lanes, busy intersections, car park entrances where slewing action occurs, industrial hardstandings etc.
8. "Normal" traffic refers to large volumes of pedestrian traffic or vehiclar traffic consisting mainly of lighter vehicles. Typical applications include sidewalks, malls, park walkways, suburban roads, parking areas and driveways.
9. Note that 2nd degree abrasion implies less than 0,5mm wear after 6 years of traffic, while 3rd degree abrasion implies less than 1mm.
10. It is assumed that the aggregates are hard and sound, e.g crushed andesite, dolerite, granite, dolomite, quartzite.

15.3.3.1 Water content

Certain procedures were followed in transferring the water contents from the design graphs to Table 15.2. The consistency of the mix is referred to as ‘wet’, ‘intermediate’ or ‘dry’. ‘Wet’ mixes are taken as the second wettest mix in the design graphs, and this is the ideal water content to aim for. These blocks are well compacted and have minimal voids. (The wettest mix in the design graphs was ignored as it was slightly slumped and would therefore be unsuitable for manufacturing pavers). ‘Dry’ mixes are taken as the driest and second driest. Pavers made from these mixes generally have approximately 10 % voids. Mixes referred to as ‘int’ are intermediate, generally the third or fourth wettest mix in the design graphs.

Note that when these criteria are applied to table 6.2, the following averages are obtained for the three categories of water content:

‘Wet’ mix = 6,5%
‘Int’ mix = 5,5%
‘Dry’ mix = 4,8%

The importance of being able to replicate the required moisture contents within the mix are illustrated by the small difference in percentage between ‘wet’, ‘int’ and ‘dry’, and the effect that this has on mix selection in table 15.2.

15.3.3.2 Binder content

Binder contents of 18 %, 14 % or 10 % were used in the design graphs and these are shown under the heading of ‘binder content’ in table 15.2.

15.3.3.3 Binder type

The eight mix designs in the design graphs used combinations of OPC, MGBS, FA and SF. These mixes are identified as M, N, P, Q, R, S, T, and U in the chart. The other mixes in the chart include 100% OPC (mix E, N), and 100% RHC (mix B, H), as well as RHC blended in various proportions with MGBS, FA and SF.

Improved wear performance for the RHC mixes is reflected by their relative position on the chart. Although this does not rest on any experimental data in this investigation, RHC is known to be approximately 15% to 20% stronger than OPC in compression testing, and since abrasion resistance is related to compressive strength (favourable curing conditions, etc.), it is therefore possible to position these mixes in the table. In doing this the trends in the eight mix design graphs were considered, and the wear performance and selected water contents of the RHC mixes adjusted, albeit with an element of conservatism.

Based on the results of this investigation, it is probable that mixes with up to 20% fly ash will eventually outperform the respective 100 % OPC and RHC mixes in the long term. This explains why for example mix M, which only had 14% binder content (12%OPC, 2% FA) is ranked higher than mix N, which had 18% binder content (9%OPC, 9% MBBS). A small fly ash replacement level (14%) is thus shown to be very beneficial. Therefore in table 15.2 these blends are shown to perform slightly better than the 100 % RHC and OPC mixes.

15.3.3.4 Aggregate

The aggregate used in this investigation was reef quartzite. It follows that the chart will be conservative if aggregates that are harder than reef quartzite are used, and therefore the chart may still be used with confidence. Aggregates crushed from rock deposits of granite, some dolomites, dolerite, and andesite have been shown to wear as well or better than reef quartzite [Addis(1989)]. The table does not apply if decomposed aggregates are used, such as decomposed granites, decomposed sandstone, etc. Consideration must also be given to such aspects as grading, surface texture and particle shape, which all have an influence on the water demand and hence c/w ratio.

15.3.3.5 Curing and process control

In the case of the last two lme variables the chart assumes that the process control is such that the pavers are well cured, and that the manufacturing equipment allows full and uniform compaction can be achieved, at least in the case of the wetter mixes. A method of evaluating and ‘calibrating’ the process control at a particular factory is discussed in 15.4 check

15.3.4 Limitations

Although the design chart is quite extensive in that it covers some 21 mix designs, with permutations including three water contents, three binder contents and eighteen combinations of five binder types, only eight of these are based on experimental work. The ranking of the other mixes is therefore a matter of engineering judgement based on the known performances of the materials, general principles of concrete technology, and trends observed in this investigation.

It is regrettable that some of the highest ranked mixes in table 15.2 were not included in the investigation. Clearly this would reduce the degree of extrapolation and increase the level of confidence.

15.4 Local and National Limits for Abrasion Test

Subject to the limitations of 15.3.4, table 15.2 allows the manufacturer to select a mix design which will limit the degree of long term wear (i.e. mvd = 0,5 mm for second degree, mvd = 1,0 mm for third degree) for a given traffic intensity. Providing the correct binder content, binder type, and water content are selected according to table 15.2, and further providing that a hard aggregate is selected, and that the compaction and curing processes are correct, then table 15.2 indicates the abrasion wear for two traffic intensities.

Unfortunately most of these inputs are open to interpretation. For example, the performance of the various cementitious materials that make up the 'binder' will vary from day to day and from source to source (since different cement factories produce different and variable quality) and clearly the hardness of the aggregate also varies according to source. Moreover, no two paving manufacturers will define a 'wet' or 'dry' mix in the same way. Likewise the compaction and curing processes will differ. In other words every paving factory is a unique 'local manufacturing environment' (lme).

For these reasons it is clear that the 28-day abrasion test indices will vary from one lme to another. For example figure 15.1 illustrates how significantly the selection of the cement extender alters the 28-day indices, and this is only one of the six lme variables.

The solution lies in the establishment of 'local' 28-day limits, which are linked to global or 'national' 90-day limits. The latter can be used industry wide as a national standard, while the former will vary from factory to factory, depending on the lme variables.

The determination of a national 90-day abrasion index should involve all the major paving producers countrywide. As a first step installed paving should be inspected nationwide, where the history of the mix designs is known. Surfaces should be divided into three groups; (1) those that have performed well, with significant levels of traffic over many years; (2) those that show significant levels of third and fourth degree abrasion; and (3) those that are neither good nor bad – i.e. the intermediate group. Next the mix designs corresponding to the 'good performers' and the 'intermediate' performers should be obtained, and the binder and aggregate type assessed. An appraisal should be made of the corresponding manufacturing processes if possible, i.e. type of production machine, level of competence, curing regime etc.

Thereafter abrasion tests should be made on both the 'good' and the 'intermediate' performers. Clearly this will involve some lift-and-replace. Only an abrasion test should be used that has the ability to measure both the hardness of the aggregate and the strength of the aggregate/paste bond. Some of the test specimens should be prepared by grinding off sufficient of the surface to expose a face that has not benefited from carbonation. All specimens should be immersed in water for 24 hours prior to testing.

In addition, pavers from current production, which should as far as possible correspond to 'good' and 'intermediate' performing field pavers from the identical mix designs and production processes, should be cured in water for 90-days and tested, in their saturated condition.

Finally the results should be evaluated considering all peripheral information and assumptions. The 90-day national abrasion limit should lie above the 'intermediate' abrasion resistance values, and just below the 'good' values.

Once a 'national' 90-day abrasion index has been determined, the various producers will be in a position to determine corresponding 28-day and 24-hour abrasion resistance indices for their specific 'local manufacturing environments'. Such indices are referenced from the 90 day index as shown in figure 15.2.

Essentially figure 15.2 shows the results of 18 abrasion resistance determinations using the CMA20 (or other) apparatus. These indices are derived from tests on specimens that come from three mixes, where the only difference between the said mixes is the amount of water added, such that pavers made from the first mix will be 'wet', those made from the second will be 'int' (intermediate)' while the third batch will come from a mix with a 'dry' consistency. Half the pavers from each mix are well cured, by keeping them in a moist environment; the other half are uncured, or more correctly air cured at a RH of approximately 50%. There are thus six different groups of blocks. From each of these groups, specimens are tested at 24hrs, 28-days (alternatively 14 days), and 90 days. From the results three curves may be plotted as shown in figure 15.2. From the point where the top curve (90 day curve) intersects the horizontal line representing the 90-day national index, a line may be dropped to intersect the 28-day and 24-hour curves. From these intersection points horizontal lines may be projected to the Y-axis, thus defining the 28-day and 24-hour indices that are based on the 90-day national index. This means that for a given batch of pavers, if these intermediate indices are achieved, then the 90day national index should also be achieved, and this in turn guarantees the long term performance of the blocks, given that the 90 day index has been referenced to long term performance. One proviso is that the lme must remain as it existed when the 'figure 15.2 calibration' of the lme was done.

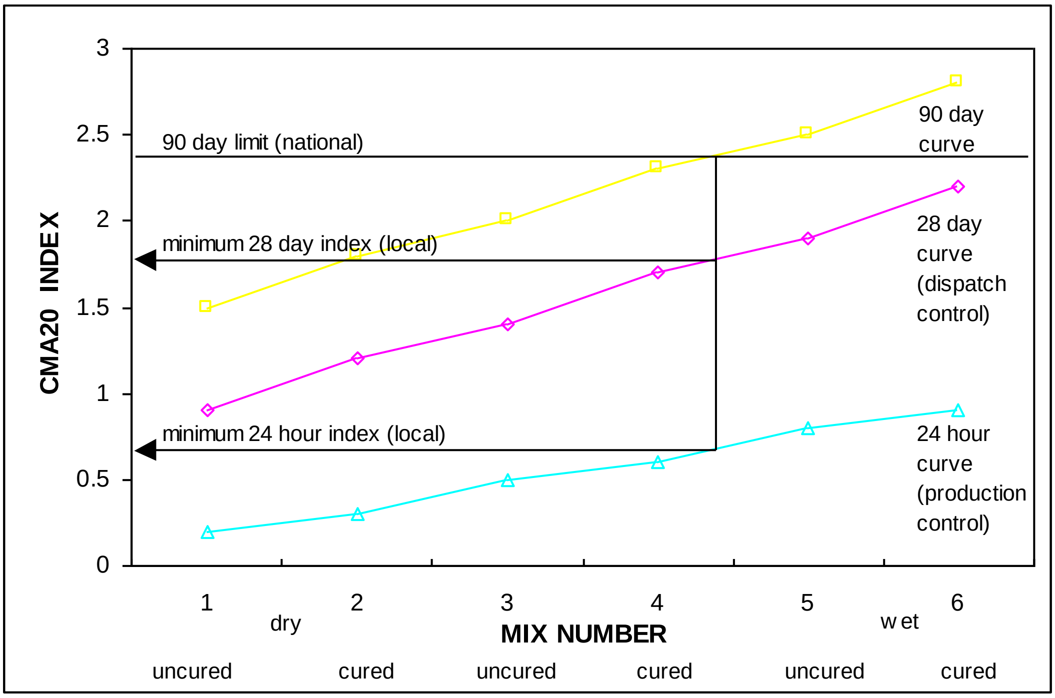

Figure 15.2 28-day and 24-hour abrasion indices corresponding to the 90 day national index, for a number of mixes (made from three water contents and subjected to two curing regimes).

Figure 15.2 effectively describes the relationship between the 'variables', and abrasion indices for a given lme. It is evident that the figure has two variables. The other four lme inputs should be kept constant:

Constants	- binder content, binder type, aggregate selection, process control
Variables	- water content, curing regime.

The graph shown in figure 15.2 also gives the manufacturer a good indication of how important curing and water content are in his process. The minimum moisture content for his mix at a minimum curing regime, can be seen by extending the vertical drop to the X axis.

It is also possible to generate other relationships, where for example curing and moisture content are kept as ‘constants’, while the binder content and/or binder type are varied. Again, the manufacturer benefits by discovering the optimal binder content and type.

This process of determining a ‘local’ abrasion index/limit (i.e. a 28-day limit) from the ‘national’ 90 day limit, need be done only once, providing no subsequent changes are made to any of the ‘constants’. On the other hand certain producers may later wish to depart from some of the initial agreed manufacturing parameters. For example they may decide to use a greater binder content with less curing. This will not matter, providing they can demonstrate that their mix complies with the 90-day national abrasion index/limit. Thereafter they can correlate this mix with a 28-day and 24-hour abrasion test as before.

It is believed that the ‘90 day’ test is a fair reflection of the long-term abrasion resistance, and compensates for blends with fly ash. It bears repeating that the ‘24-hour index’ is a useful early quality indicator, whereas the ‘28-day index’ serves as the official test to determine if blocks can be dispatched to site.

Sectional Conclusion

The correct selection of a mix design from table 15.2 will satisfy a particular long term wear requirement for a given traffic loading. The local 28-day abrasion index will thereafter depend on the manufacturer's lme, and is verified by means of a ‘local’ 28-day index that is linked to a ‘national’ 90-day index.

15.5 Design Approach and Quality Assurance

A step-by-step approach of ensuring that concrete pavers with an acceptable abrasion resistance are specified and produced is the focus of this section. Nine steps for achieving this are discussed from 15.5.1 through 15.5.9.

15.5.1 Traffic loadings

The specifier (or his engineer) must evaluate the expected traffic loadings of the proposed project. He must consider the frequency, magnitude and duration of the loads. In table 15.2, two categories of loading are given to choose from:

a. ‘severe’ - large volumes of heavy vehicular traffic
b. ‘normal’ - large volumes of pedestrian traffic (or normal vehicular traffic)

In applications where the aesthetic appeal of the blocks is very important, the specifier may wish to over design by using the ‘severe’ column in ‘normal’ applications, and vice versa for very lightly trafficked areas.

15.5.2 Degree of abrasion

The specifier must decide what degree of abrasion is acceptable. Generally the long-term wear in prestigious projects should be limited to second degree, whereas third degree abrasion may be considered acceptable in industrial applications. Reference should be made to table 8.3 for a classification of the different degrees of abrasion.

15.5.3 Selection of Manufacturer

Ultimately the specifier has the right to decide on the manufacturer who is to produce the pavers. Sometimes this is done solely on the basis of the lowest price tendered. In other instances an ISO 9002 listing with SABS is a pre-tender requirement, meaning that the manufacturer has an approved quality assurance system.

Although this may be a reflection of a manufacturers ability to consistently reproduce pavers that meet a minimum requirement, in South Africa, this may also ‘guarantee’ uniformly sub-standard quality, since the compressive strength requirement is too low to ensure adequate abrasion resistance in the absence of mandatory abrasion testing. It is therefore possible for a manufacturer who produces to a low standard deviation to make 50 mm thick bevelled-pavers that just comply with the 25 MPa requirement (20MPa for individual units). As explained in 2.5.1, these pavers may have an equivalent cube crushing strength of only 12,5 MPa (10 MPa for individual units), resulting in grossly inferior abrasion resistance. If they were only air cured this will lower the expected abrasion resistance, since it is more sensitive to poor curing than is compressive strength.

Therefore in the absence of an approved abrasion index, it is necessary for the specifier to have knowledge of the many factors that affect the abrasion resistance of pavers including the intricacies of the production process, or he may find himself in the embarrassing situation where *all* the pavers on a site supplied by an ISO 9002 supplier, perform uniformly poorly. Few specifiers or engineers have the experience to detect poor abrasion resistance merely by observing the mix designs or production processes, and the paving industry in South Africa continues to be vulnerable in this regard.

Wagenmaker (1984) stressed that it is important that, the quality control department reports *directly* to a level of management that is responsible for *both* the production division *and* the marketing/customer-satisfaction division. Usually this is the general manager or managing director or CEO.

Ultimately it is the responsibility of the CEO to instil such a sense of pride in the company and its products, and to so empower every employee, that everyone feels responsible for quality control. The production operators should feel responsible for product quality, the suppliers for the provision of quality materials, the sales team for customer satisfaction at the point of sale, the transport contractor for timely delivery and company image on the road, the marketing team for developing product awareness in the market and shifting trends in customer demand, the admin team for accurate billing and rapid processing of credits, the technical team for good technical advice both in-house and to customers.

Finally everyone should understand that the quality control department is not there to guarantee the quality, merely to quantify it. They should not be seen as informers to top management, but rather as an information resource to help everyone aspire to greater heights.

The attitudes described above are perhaps the best means of moving away from a culture of a quality control system, consisting of many checks and tests in an attempt to contain poor quality, to a quality assurance system, where employees and customers alike are confident, free from doubt, certain about their collective contribution towards a superior product and service.

‘Quality assurance’ however does not do away with ‘quality control’, on the contrary it ensures that the controls are respected and adhered to. A comprehensive list of controls for the manufacture of concrete pavers is reproduced in table 15.3 from Wagenmaker(1984).

Sectional Conclusion: This section has attempted to show that ‘lowest price’ is not the only criteria that a specifier should consider when awarding a contract to manufacture pavers. Producers in South Africa should take note of the care taken by the Dutch manufactures in their production processes as demonstrated by table 15.3, and moreover include an abrasion test in the quest for quality assurance.

15.5.4 Mix design selection

The Manufacturer, having satisfied the supplier of his capabilities in respect of 15.5.3, is now in a position to select from table 15.2 a mix design that satisfies the criteria in steps 15.5.1 and 15.5.2, as required by the Specifier. He will consider the binder content and the binder type of the twenty-one mixes. He will also consider the corresponding water contents. Mix designs with ’int’ or ‘dry’ water content limits can be considered safer options than those which must be ‘wet’ in order to meet the requirements of a specific traffic regime. During manufacture, an experienced operator will aim to maximise the moisture content in the mix. However a certain degree of drying out in the discharge hopper beneath the mixer always takes place, especially at lunch breaks, or during breakdowns etc. It follows that a lower permissible water content limit (i.e. ‘dry’) will still comply in such situations, particularly if the operator originally made a ‘wet’ mix.

To this end it is important that regular moisture content readings are taken of the mix, and the calcium carbide method described in 4.11.4 is ideal for factory conditions. In this investigation, and using the calcium carbide method, average moisture contents of 6,5%, 5,5% and 4,8% were obtained for ‘wet’, ‘int’ and ‘dry’ mixes. These moisture contents are likely to vary from one lme to another.

An experienced operator who can gauge from the appearance of the freshly demoulded blocks if sufficient water is present is a valuable asset.

A final aspect of mix design selection is that the aggregates should be hard, sound, and have an acceptable grading, surface texture and particle shape. In particular aggregates should be as hard or harder than reef quartzite. Table 15.2 does not apply to soft or decomposed aggregates such as decomposed sandstones or decomposed granites.

15.5.5 Manufacturing controls

The manufacturer should ensure that the mechanical equipment used to make the blocks is in a good state of repair, and that the operators are well trained. Weighing, mixing, filling, vibration, and handling systems should all be fine tuned if concrete pavers with good abrasion resistance are to be made. For example the water dosage (that takes place concurrently with the mixing operation) determines all-important moisture content of the blocks, whereas the filling and vibration cycle determines the degree of compaction in the blocks. Both Dowson(1998) and Howland(1998) give a detailed review of the various manufacturing controls, beginning with the receipt of the various raw materials, through to processes such as proportioning, mixing, curing, to finished product testing employing various statistical methods.

15.5.6 Testing of newly de-moulded pavers

Not many manufactures test newly de-moulded pavers. Few even bother with a 24-hour test. Yet early testing of this nature will, sooner of later, save the manufacturer a huge sum of money, time, and even his reputation in the market.

Several methods may be used, with varying degrees of effectiveness in regard to abrasion resistance, and these are outlined below:

15.5.6.1 Density measurements

Humpula(1996) measured the density of the newly made blocks by weighing them and dividing by the volume. He concluded that ‘early paver bulk density could be used as a good estimate of the engineering serviceability properties of compressive strength and abrasion resistance’. However this finding will only apply where the density of the block is uniform throughout, which is not always the case.

For example, where a topping is used, it is possible to have a dense base concrete by virtue of a relatively high water content, and at the same time a poorly compacted topping by virtue of a dry mix. For a given vibration the well ‘lubricated’ base concrete will attain a substantially greater density that the ‘unlubricated’ topping. Therefore while density measurements of newly made blocks are very likely to correlate well with compressive strength, as showed by Humpula(1996), abrasion resistance correlations will not always follow.

15.5.6.2 Finger test

A very simple, quick and effective quantitative test for ascertaining the density of the surface is to apply a certain pressure with the tip of the finger. A force of about 50N (the equivalent of 5 kg) should leave only the slightest impression. Clearly there is a subjective element in this, but it allows an experienced operator to determine if something in the production process has changed. Usually this will be a machine setting, or a change in the moisture content of the mix.

The writer has observed over many years that this test is very reliable. It is truly a surface-test that measures the compaction of the surface zone. Moreover as the operator is normal only a few paces from the machine, he is in a position to verify at least on pallet form each mix.

15.5.6.3 Papenfus's penetrometer

For a more quantitative indication of the hardness of the surface, a simple penetrometer powered by a hand pump may be used. This equipment is illustrated in figure 15.A below.

The pressure on the pressure gauge should be observed at a deflection of 0,5mm, 1mm and 2mm, and the equipment should be calibrated against a 28-day abrasion test. Note that by using a larger hydraulic cylinder with a substantially larger footprint, meaningful correlations with compressive strength are also possible.

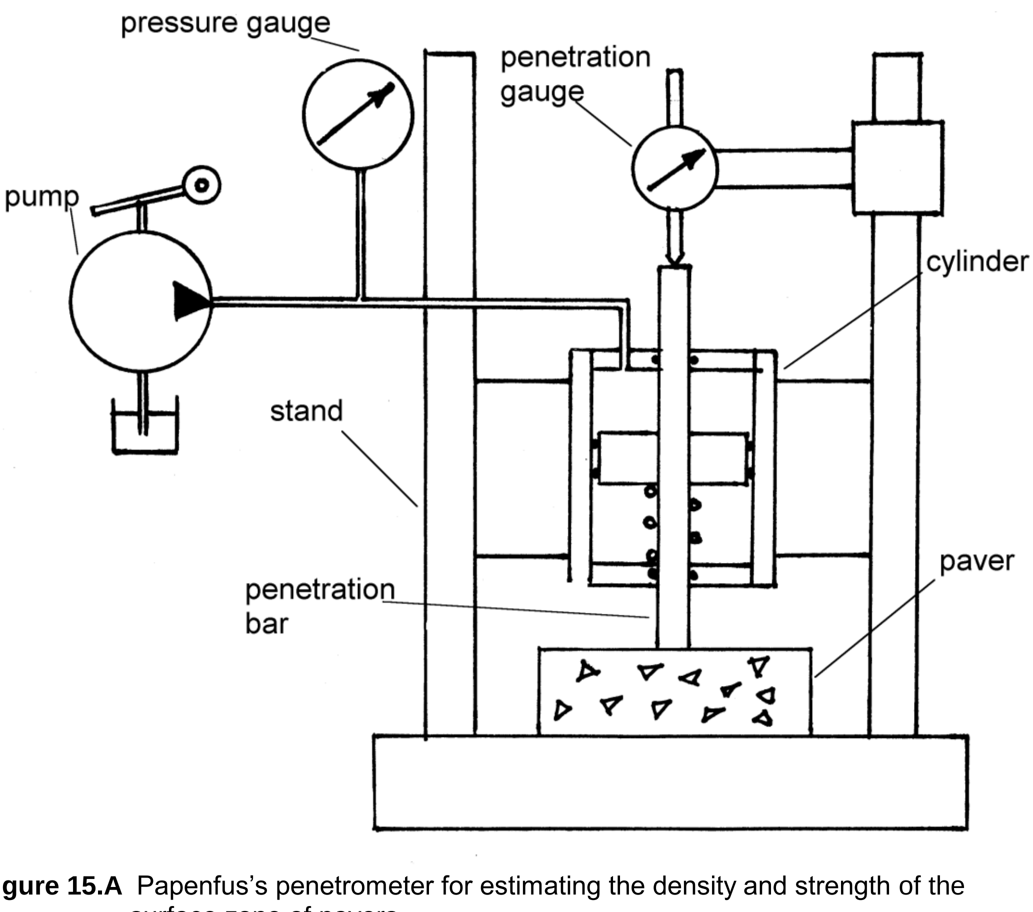

Figure 15.A Papenfus's penetrometer for estimating the density and strength of the surface zone of pavers

15.5.6.4 24-hour testing

Although 24-hour testing cannot be considered a test of a 'newly demoulded paver', it is just as important. The writer has on several occasions been involved in investigations of bad quality where the fault was eventually traced to a cement extender being pumped into the cement silo, leading to pavers being made with 100% extender and no cement. In such instances the operator may not notice anything wrong. The density of the pavers in terms of the thumb test is unlikely to indicate the problem. By doing a 24-hour abrasion test, the problem manifests itself the next morning, so that production may be halted immediately and the silo emptied, thus limiting the loss.

A faulty cement or aggregate scale is another problem that occurs. In this case the 24-hour abrasion resistance may either show a marked increase or decrease, depending on the nature of the fault. The writer has seen huge stock losses occur that are only detected at month end when stock reconciliations are done. A marked increase in the 24-hour abrasion resistance/compressive strength should sound an early alarm.

15.5.7 Curing

In as far as the quality control process is affected by curing it logically should be discussed at this point. It can be regarded as a separate process apart from the other production activities. However, the importance of a suitable method of curing concrete pavers has been mentioned variously in earlier sections, and is also discussed in some detail in 2.2.1.3 of volume 2.

Essentially the designer must satisfy himself that the curing regime used by the manufacturer is adequate. The surface of the blocks should remain sufficiently moist to allow for ongoing curing. Covering pre-soaked blocks in a plastic shroud is ideal. Overhead sprinklers may also be used to keep them moist where packs are bound solely with steel straps.

15.5.8 Verification

After the manufacturing and curing process, the abrasion resistance of the surface of the blocks should be checked by using an abrasion test.

A minimum curing period of 14 days should precede this test, ideally 28-days. The index should not be less than the 'local' limit determined from the 'national' limit as discussed in 15.4.

An agreed number of blocks should be selected at random from the day's production. Wagenmaker(1984) emphasised that the quality control system should include a rigorous sampling procedure to ensure that pavers are tested at random. In this regard Howland(1998) gives additional guidelines for sampling of paving blocks that include defining the quantity of paving blocks, the sampling frequency, the division into sub-lots, and the working out of a sampling plan.

If the results are borderline, the sample size should be increased significantly according to established statistical sampling procedures. It should be evenly distributed over the whole days production to determine the extent of the problem, and if possible isolate the suspect blocks. Only batches passing the abrasion test may be despatched to site.

The specifier can either accept the manufacturer's abrasion resistance test results, particularly if he operates an ISO 9002 quality management system, or he may sample blocks as they are delivered to site and have them tested by a recognised commercial laboratory. This would apply not only to the abrasion resistance test, but also the compressive strength test, should he wish to obtain an indication of the bulk strength of the blocks. Adequate compressive strength reduces the incidence of such aspects as macro chipping, splitting, spalling etc.

If the specifier is in any doubt of the manufacturer's commitment/capability, he should inspect the factory prior to awarding the order, to satisfy himself on aspects such as curing, process control and quality management.

15.5.9 Despatch

The manufacturer should only despatch batches that have passed the 28-day abrasion test. This should ensure that the resultant surface does not manifest third or fourth degree abrasion in the longer term.

15.5.10 Flowchart

The design and quality assurance programme set out in 15.5.1 through 15.5.9 above is now summarised in figure 15.3 in the form of a flow chart.

Specifier determines expected traffic loadings

heavy or light vehicles
vehicular or pedestrian
expected traffic densities etc.

▼

Specifier decides on permissible degree of wear after 6-years depending on application

2nd, 3rd, 4th degree abrasion

▼

Specifier selects a manufacturer capable of manufacturing quality cbp

well-maintained and adjusted machines
well-trained personnel
ISO 9002 quality management system

▼

Manufacturer selects appropriate mix design

binder content
binder type
water content
aggregate quality, especially hardness

▼

Testing of newly demoulded pavers

density testing
finger test
penetrometer testing
24-hour testing

▼

Manufacturer cures blocks for 14 days, minimum

▼

Verification of abrasion resistance

random sampling
internal abrasion resistance test by manufacturer prior to despatch
blocks are despatched to site
external abrasion tests by specifier, from on site blocks (if deemed necessary)

Figure 15.3 Flow chart summarising design, manufacturing and quality assurance programme for providing adequate abrasion resistance in concrete pavers

Table 15.3 Framework schedule for internal quality control on concrete roadpaving blocks according to NEN 7000

[Reproduced from Wagenmaker(1984)]

What has to be tested		Which item has to be tested	How to be tested	Frequency of testing	Notation
CONCRETE	mixing time	adjust time, dry mixture	through timing	once a day, each mixture apparatus	yes
		adjusted time, wet mixture	through timing	once a day, each mixture apparatus	yes
	mixture composition	compare ideal mixture with practical mixture	through sieving and specimen analysis	when changing and when doubtful	yes
PRODUCTION	filling of the mould	exact filling	visually	3 times a day, each machine	yes
	consolidation	exact consolidation time	by timing	3 times a day, each machine	yes
	Brushes	position and quality	visually	3 times a day, each machine	yes
	pallets, boards	wastage	visually	once a day, each machine	yes
	stamps, moulds	position and quality	visually	once a day, each machine	yes
	height of new product	aimed value	by measuring	when starting and during production twice a day, each machine	yes
	hardening[6]	aimed hardening time	by timing	once a day	yes
	relative humidity in hardening room[6]	aimed value	by measuring	once a day	yes
	assort	external defects	visually	3 times a day, each machine	yes
	after-treatment[6]	exact way of sprinkling.	visually	once a day	yes
		exact way of dipping	visually	once a day	yes
	voluminous mass of the fresh product	aimed value	by underwater weighing method by weighing and measuring	5 blocks a day, each machine	yes
FINISHED PRODUCT AFTER 7 DAYS	dimensions	aimed value	according to NEN 7000	once a day, 5 blocks each machine	yes
	skid resistance apparatus[7]	aimed value	according to NEN 7000	once a day, 5 blocks each machine	yes
	bending strength	aimed value	according to NEN 7000	once a day, 5 blocks each machine	yes
FINISHED PRODUCT AFTER 28-dayS	dimensions	according to requirements	according to NEN 7000	once a week each machine	
	skid resistance apparatus	according to requirements	according to NEN 7000 {-}	15 blocks out of day- production	yes
	bending strength	according to requirements	according to NEN 7000	15 blocks out of day- production	yes
	mass loss	according to requirements	according to NEN 7000	once a month 5 blocks out of above mentioned sample	Yes

What has to be tested		**Which item has to be tested**	**How to be tested**	**Frequency of testing**	**Notation**
DRYING PLACE	weather conditions	minimum temperature	by reading thermometer	once a day	yes
		maximum temperature	by reading thermometer	once a day	yes
	finished product	external defects	visually	once a day	yes
	production date	legibility and exactly recorded	visually	once a day	yes
	marking	presence and legibility of the KOMO-mark	visually	once a day	yes
	storage	separate storage KOMO-production	visually	once a day	yes
LABORATORY /MEASURING EQUIPMENT	bending machine	according to requirements	through external gauging by competent body	once every 2 yrs	yes[1]
	scales	reliability	through internal gauging by means of gauging weights	once a year	yes
	sieves	NEN 2560	visually	before use	yes, once every quarter
	marking gauges	reliability	through internal gauging	once every quarter	yes
	moulder gauges	reliability	through internal gauging	once very quarter	yes
	sand-blast apparatus (optional)	according to requirements[2]	through internal gauging by means of plate-glass	before every sample series and when testing continuously after every 25 specimen	yes
	skid resistance apparatus (Leroux)	according to requirements[3]	through internal gauging[3] by means of a gauge-file	before every sample series	yes, once every quarter
	temperature gauge	reliability	through internal gauging	once every quarter	yes
DOSAGING/ WEIGH OUT AND MIXING EQUIPMENT	for cement	reliability	through external gauging	once only, by supplier of the equipment issued gauge certificate	yes[4]
			through internal gauging	once every quarter	yes
	for aggregates	reliability	through external gauging	once only, by supplier of the equipment issued gauge certificate	yes[4]
			through internal gauging	once every quarter	yes
	for additives[5]	relliabilty	through internal gauging	once very quarter	yes
	for-colouring matter	reliability	through internal gauging	once every quarter	yes
	for-mixing equipment	defects and fouling	visually	once a day	yes

What has to be tested		Which item has to be tested	How to be tested	Frequency of testing	Notation
RAW MATERIAL AND STORAGE	cement[5])	type nomination and class	stamp or signature on receipt	each delivery	yes
		required properties according to NEN 3550	inspection report or valid certificate	once every quarter	yes
		storage	visually	each delivery	no
	aggregates	type nomination	stamp or signature on receipt	each delivery	yes
		required properties	visually	each delivery	no
			sieving analysis	minimum once every 2 weeks	yes
		fouling	visually	each delivery	yes
			test according to NEN 3542	when doubtful	yes
		storage	visually	each delivery	yes
	additives[5]	required properties	stamp or signature on receipt	each delivery	yes
	colouring-matter	required properties	stamp or signature on receipt	each delivery	yes
		storage	visually	each delivery	yes
	mixing water, with the exception of potable water	noxious substances	by a fitness test (for instance British Standard 3148)	when applying well-water: at least once a year and when changing well	yes
				using surface water: minimum 6 times a year	yes
TRANSPORT	bill of lading	presence of KOMO-stamp NEN 7000	visually	once a day, all bills of lading	yes
		production date if the stones are not older then 28-days, this in accordance with KOMO certificate	visually	once a day, all bills of lading	yes

Foot Notes

1 certificate of gauging
2 draft NEN 2875
3 draft NEN 2873
4 only with new delivered equipment
5 statement of sort and class, report charges in sort and/or class to the inspection institute
6 dependent on system
7 only when – results after 28-days testing are insufficient
- reference investigation, executed by external laboratory, in connection with skid resistance are insufficient
-findings of inspection institute concerning the skid resistance are insufficient

Radical changes in as well the production process as the mixture composition should be reported to the inspection institute.

15.6 Summary and Conclusion

This chapter focuses on the practical engineering benefits of this thesis with regard to ‘designing for improved abrasion resistance’. Thus it fulfils the stated aim, of ‘improved abrasion resistance in cbp’.

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

The manufacturer's quality is assured by the correct mix design selection according to the time-tested mixes of table 15.2. The subsequent abrasion test in conjunction with figure 15.2 thereafter merely serves as an internal verification of the surface quality.

The abrasion resistance of concrete pavers can thus be controlled, in a way that does not disqualify materials such as fly ash, which have retarded 28-day indices, but promote superior abrasion resistance. This is an important requirement as abrasion wear in concrete pavers is a long term slow process, and a product whose surface strength increases with time should not be wrongly judged by a slow start.

Finally a recommended design approach is given for manufacturing concrete pavers with good abrasion resistance. This specifically fulfils the fifth objective, i.e. ‘recommending an overall abrasion resistance quality assurance programme’.