Chapter 14

Correlation of Mix Designs

and

Laboratory Tests

with

Wear on Site

14.1 Introduction and Overview

In order for accelerated abrasion testing to be truly meaningful it should be calibrated with long-term abrasion wear under operational conditions

This has long been recognised and several investigators have attempted to do this.

As early 1928 Ahlers(1928) did accelerated abrasion testing using steel wheels (see appendix U.4.4) and calculated that a 16-hour test was equivalent to 10 years and 11 months under traffic conditions that used similar wheels.

Gjorv(1990) did abrasion testing using a rig consisting of studded tyres, each connected to a horizontal arm that in turn is connected to a central vertical rotating shaft (see appendix U.3.3). He determined that a testing regime totalling to 150000 revolutions simulated 10 years of traffic.

Ahlers and Gjorv both used the abrading medium in their respective tests that was used under real traffic conditions (i.e. caster wheels and studded tyres respectively). They were also in a position to replicate the vertical load on the test wheels. Their correlations amounted to doing sufficient test cycles to simulate the equivalent number of passes that would occur from years of traffic. This is an accurate way of projecting abrasion wear, and the results can be used with some confidence.

However, this type of direct simulation is only practical where the abrading medium used in operational conditions is relatively severe, allowing significant abrasion wear under test rig conditions in a matter of some hours, or a few days at worst. This is not the case in today’s conditions, where virtually all tyres are made of rubber which is very much softer than concrete. Similarly, pedestrian surfaces are subjected to footwear made of relatively soft plastic/leather. Hutchings(1992) showed from theoretical considerations (see chapter 3 of volume 2) that the rate of abrasion is very slow whenever the abrading medium is softer than the surface being trafficked. This is supported by the findings of Jackson(1924) who found negligible abrasion wear (less than 0,5mm) even in relatively weak concretes with minimal finishing after as much as 55 000 passes of a steel-wheel lined with solid rubber that was meant to simulate abrasion under loaded trucks. However, once the tyres were fitted with steel chains wear proceeded rapidly. It is therefore not always practical to use the same abrading medium and loads when simulating traffic.

Other factors that affect accurate correlation are variations in the mix such as the c/w, cement content, aggregate hardness, or down the line processes such as curing, finishing processes, surface treatments. Thereafter weathering processes such as dissolution from acid rain or pure water on the one hand, and hardening processes such as carbonation on the other hand, affect the rate of abrasion. Clearly the volume and severity of the traffic will also affect the degree of abrasion.

Given these many factors that can affect abrasion wear, an all-inclusive correlation with even one selected abrasion test would involve a very large and very expensive research program.

A compromise would be to select a few typical variations in the mix and/or production process, and subject the resultant test surfaces to one or more *accelerated* abrasion tests. These results may later be compared to actual abrasion wear that resulted in companion surfaces subjected to years of traffic. This approach was adopted in this investigation.

In August1987, a sufficient number of pavers were manufactured at a paving factory to allow for extensive 28-day laboratory testing, as well as six-year measurements of companion pavers that were installed at Westgate Bus Terminus in October 1987. These pavers represented eight mix designs incorporating various binder types and contents.

Furthermore, each of these mix designs was replicated six times, but with different moisture contents, so that the consistency of the mix varied from very ‘wet’ to very ‘dry’.

Thus 48 mixes were both tested in the lab and under traffic. The ‘Westgate’ pavers were installed in the main access to the bus terminus, and in a nearby sidewalk (see chapter 5, figures 5.2 and 5.3 respectively).

The purpose of this chapter therefore is to *correlate* eight mix designs made in August 1987, and the corresponding laboratory tests done at PCI in September 1987, with the measured wear at Westgate bus terminus in September 1993. In this way 6-year abrasion wear may be predicted from 28-day abrasion testing, satisfying objective 4, given in 1.6.4. Clearly architects, town planners and end users in general, would all be very interested in knowing what a paved surface will look like in ten or twenty years.

All references to wear should be understood as ‘visible’ (see 8.2.3) wear, measured both with a depth gauge (see 5.3.2) and by application of clay (see 5.3.3).

The relationship between the quantitative mean visible depth (mvd) (see 8.2.3), and the visually assessed degrees of abrasion (see table 8.3), is established for the 48 mixes at Westgate, and is comprehensively supported by photographs in appendix Z.

The correlation between the laboratory tests (described in chapter four) and the measured wear after 6-years is given. None of the tests correlate well with the mvd (relatively low R^2 values) when all 48 mixes are considered on one graph. A far more clearly defined relationship appears when each mix design is considered in isolation.

The MA20SA abrasion test appears to have the clearest correlation with on site wear measurements. It is particularly sensitive to mix design variations.

A set of design curves shows the relationship between the wear after 6-years and the 28-day MA20SA indices, and makes it possible for a manufacturer to select certain mix designs with proven long term performances for both heavy and normal traffic.

The problem of establishing meaningful limiting criteria is discussed.

14.2 6-year wear at Westgate

The abrasion wear at the Westgate site was measured both after 5 ½ years as well as 6-years. The following two sections (14.2.1 and 14.2.2) describe the wear at 5 ½ years. Some shortcomings are noted, explaining the need to re-measure at 6-years (see 14.2.3).

14.2.1 **Mean visible depth vs mean crater depth at 5 ½ years**

In May 1993, after 5 ½ years of pedestrian and vehicular traffic, both the mean crater depth (mcd) and the mean visible depth (mvd) were measured on *one and the same* block, for each of the 48 mixes in both the sidewalk and bus lane. (These tests are respectively described in 5.3.2 and 5.3.3). The results are recorded in columns B, C, D and E of table 14.1.

Next the mcd in the sidewalk was correlated with the mc d in the bus lane (see figure 14.1), and likewise the mvd in the sidewalk with the mvd in the bus lane (see 14.2). A straight-line regression analysis was done to determine the respective R^2 values. Since the same mix was being measured on both sites, for each of the 48 mixes, a reasonably good correlation was expected. Unfortunately the goodness of the correlation was reduced by the fact that only *one* block per site from each mix was measured. Nevertheless the greater R^2 value of 0.670 for the mvd (compared to 0.612 for the mcd) indicates that this is a more accurate and reliable method of expressing the visible wear. This is to be expected, as the syringe method takes into account every crater and every uneven spot over the full upper surface of the block, whereas the mcd only averages five craters per block. Moreover, only in the case of a discerning operator, will the five craters be truly representative of the true mean crater depth, whereas the mvd is much less susceptible to operator error.

For these reasons the mvd is used in the rest of this chapter as the preferred method of expressing the visible wear.

TABLE 14.1 SIX YEAR WEAR AT WESTGATE

MIX	ONE BLOCK MEASURED MAY 93				AVERAGE OF 8 BLOCKS MEASURED OCTOBER 93			
	SIDEWALK		BUS LANE		SIDEWALK		BUS LANE	
	MCD mm	MVD mm	MCD mm	MVD mm	MVD mm	DEG OF WEAR	MVD mm	DEG OF WEAR
A	B	C	D	E	F	G	H	I
1.1	0.50	0.25	0.86	0.42	0.34	2	0.42	2
1.2	1.02	0.36	1.12	0.64	0.42	2	0.63	2.5
1.3	0.84	0.27	1.46	1.25	0.51	3	0.79	2.5
1.4	1.42	0.68	1.92	0.77	0.66	2.5	0.77	2.5
1.5	1.18	0.76	2.38	0.80	0.70	3	0.83	3
1.6	1.84	0.82	2.38	1.41	0.75	3	1.19	3.5
MN	1.13	0.52	1.69	0.88	0.56	2.58	0.77	2.67
2.1	1.36	0.38	0.92	0.54	0.50	2	0.69	2
2.2	0.86	0.33	1.52	0.83	0.52	2	0.71	3
2.3	1.82	0.79	1.46	0.38	0.72	3	0.90	3
2.4	1.92	0.90	1.78	0.99	0.95	3	0.88	3
2.5	1.58	0.71	2.12	1.22	1.00	3	1.08	3
2.6	2.94	1.20	2.66	1.51	1.02	3.5	1.47	4
MN	1.75	0.72	1.74	0.91	0.78	2.75	0.96	3.00
3.1	1.58	0.57	1.62	1.25	0.69	3	1.33	3.5
3.2	1.80	0.55	2.78	1.44	0.91	3.5	1.37	4
3.3	1.72	0.93	2.12	1.54	1.25	4	1.87	4
3.4	2.52	1.86	3.26	2.88	1.39	4	2.52	4
3.5	2.80	1.91	3.44	2.28	1.39	4	2.50	4
3.6	2.78	1.91	3.32	1.96	1.37	4	2.53	4
MN	2.20	1.29	2.76	1.89	1.17	3.75	2.02	3.92
4.1	1.34	0.38	1.42	0.51	0.55	2	0.61	2
4.2	1.22	0.41	2.16	0.83	0.47	2	0.83	2.5
4.3	1.44	0.82	1.58	0.99	0.89	3	0.87	3
4.4	1.86	0.79	1.94	1.03	0.87	3	1.03	3.5
4.5	1.54	0.87	2.20	1.25	0.94	3.5	1.24	3.5
4.6	2.00	0.74	3.12	1.70	1.03	3.5	1.17	3.5
MN	1.57	0.67	2.07	1.05	0.79	2.83	0.96	3.00
5.1	0.60	0.38	0.96	0.54	0.38	2	0.58	2
5.2	1.02	0.41	2.04	0.77	0.48	2.5	0.68	2.5
* 5.3	1.40	0.55	1.76	0.64	0.55	3	0.78	2.5
5.4	1.30	0.68	2.10	0.83	0.65	3	0.83	2.5
5.5	1.46	0.66	2.42	1.06	0.77	3	1.02	3.5
5.6	1.96	0.87	2.04	0.80	0.79	3	1.01	3
MN	1.29	0.92	1.89	0.77	0.60	2.75	0.82	2.67
6.1	0.92	0.27	1.02	0.26	0.48	2	0.49	2
6.2	1.24	0.44	1.32	0.58	0.44	2	0.60	2
* 6.3	1.24	0.55	1.10	0.61	0.55	2	0.56	2.5
6.4	1.44	0.68	1.98	0.83	0.64	3	0.92	3
6.5	1.22	0.74	1.98	0.99	0.70	3	0.93	3
6.6	1.60	0.82	1.74	0.96	0.77	3	0.98	3.5
MN	1.28	0.58	1.52	0.71	0.60	2.50	0.75	2.67
7.1	0.92	0.38	0.92	0.67	0.42	2	0.67	2.5
7.2	1.16	0.57	1.38	0.71	0.67	2.5	0.74	2.5
7.3	1.64	0.63	2.02	0.90	0.77	3	0.83	3
7.4	1.44	0.74	2.22	0.96	0.84	3	0.95	3
7.5	1.96	0.96	1.74	0.83	1.08	3	1.09	3
7.6	2.28	1.20	2.50	1.67	1.11	3.5	1.23	4
MN	1.57	0.75	1.80	0.96	0.82	2.83	0.92	3.00
8.1	1.06	0.52	0.70	0.35	0.47	2	0.72	2.5
8.2	1.40	0.44	1.60	0.74	0.46	2	0.75	2.5
8.3	1.62	0.63	1.08	0.67	0.64	2.5	0.77	3
8.4	2.16	0.96	2.14	1.03	0.79	3	1.03	3.5
8.5	2.54	1.04	3.20	1.41	0.93	3.5	1.18	3.5
8.6	2.10	1.04	2.54	1.60	1.14	3.5	1.35	4
MN	1.81	0.77	1.88	0.97	0.74	2.75	0.97	3.17
O/MN	1.57	0.78	1.92	1.02	0.76	2.84	1.02	3.01

* Use column C value for column F as insufficient blocks were available for 8 measurements.

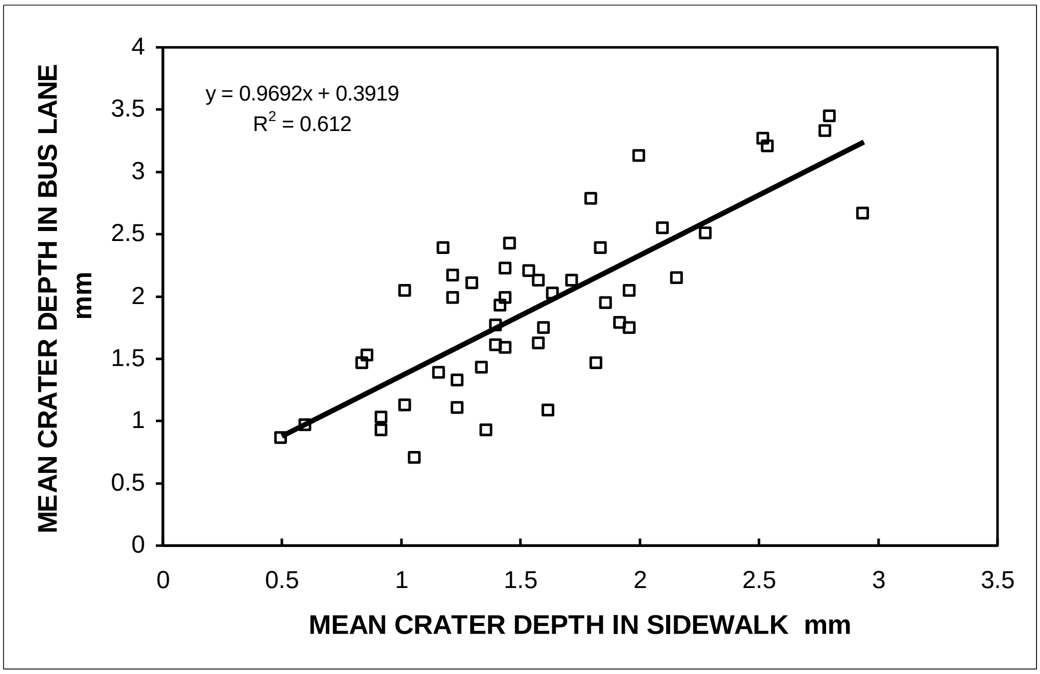

Figure 14.1 Relationship between mcd (mean crater depth) in the **bus lane** and mcd in the **sidewalk** after six years of traffic. Each point represents one block in both the sidewalk and bus lane – 48 mixes.

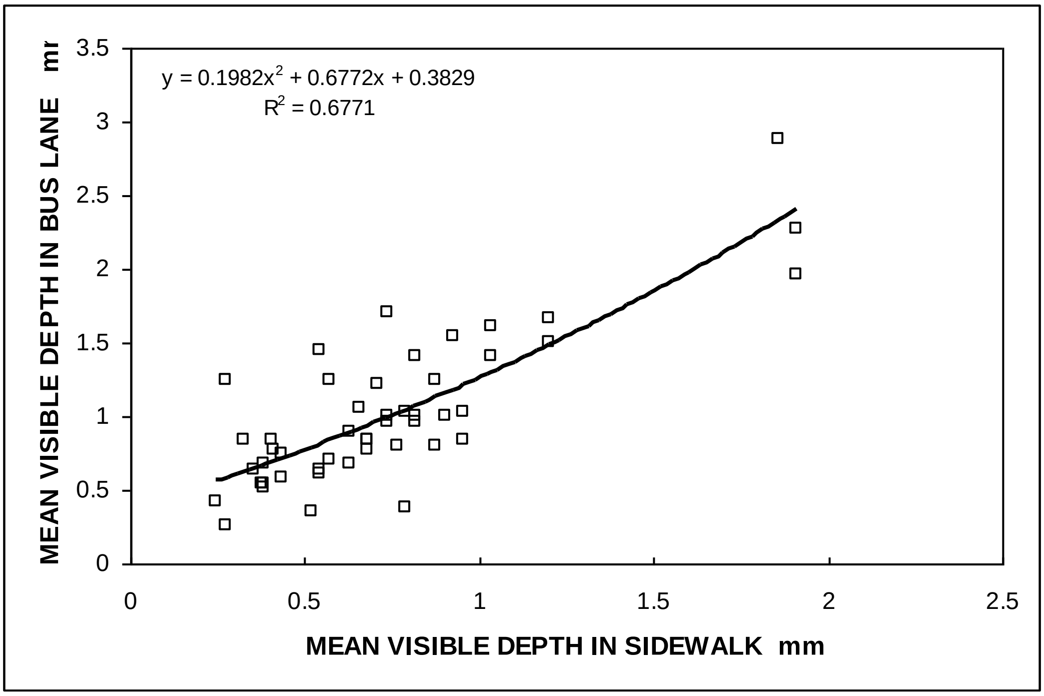

Figure 14.2 Relationship between mvd (mean visible depth) in the **sidewalk** and mvd in the **bus lane** after six-years of traffic. Each point represents one block in both the sidewalk and bus lane – 48 mixes.

It is interesting to note that the ratio of mcd/mvd for the 48 mixes in the sidewalk (determined from the bottom line averages in table 14.1) is 1,57 / 0,78 = 2,01, and this is similar to the same ratio for the bus lane, i.e. 1,92 / 1,02 = 1,88. Thus the mcd is approximately twice the mvd. In effect the average crater depth (measured with a depth gauge from the crest of a protruding aggregate particle to the deepest point in an adjacent trough) is twice the true average depth of wear as determined by the syringe method. However, this ratio is much closer to unity for blocks that have fourth degree abrasion, as explained in 8.4.5. Therefore the lower average in the bus lane indicates that those blocks were, on average, more severely abraded.

14.2.2 A Visual Appreciation of Abrasion Wear at 5 ½ years

Each of the 96 blocks measured in the sidewalk and bus lane (see columns B through E in table 14.1) were also photographed after five and a half years. One photo was taken from approximately 400 mm up, while a second photo was taken from approximately 70 mm, using a special lens. These results are comprehensively recorded in appendix Z.1 through Z.196. The photographs thus give a visual appreciation of the mvd and mcd readings of table 14.1. Figure 14.4 and 14.5 are reproduced here from appendix Z by way of example. (For a full discussion on how to interpret the various degrees of abrasion from the visual appearance of the surface, see chapter 8).

Figure 14.3 shows a newly installed block, indicating the pre-wear appearance of a typical block. (Refer to appendix Y.1 through Y.48 for a comprehensive pre-wear presentation of all the 48 mixes, as they appeared in October 1987 immediately after installation).

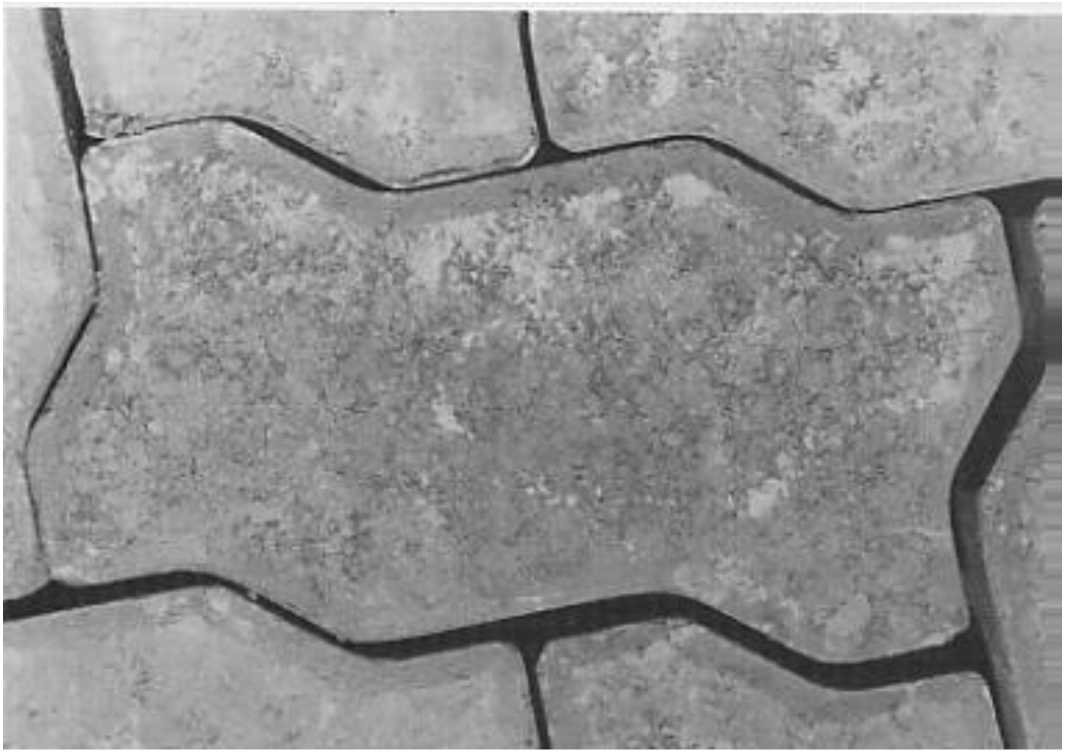

Figure 14.3 Visual appearance of a newly installed block at Westgate, October 1987.

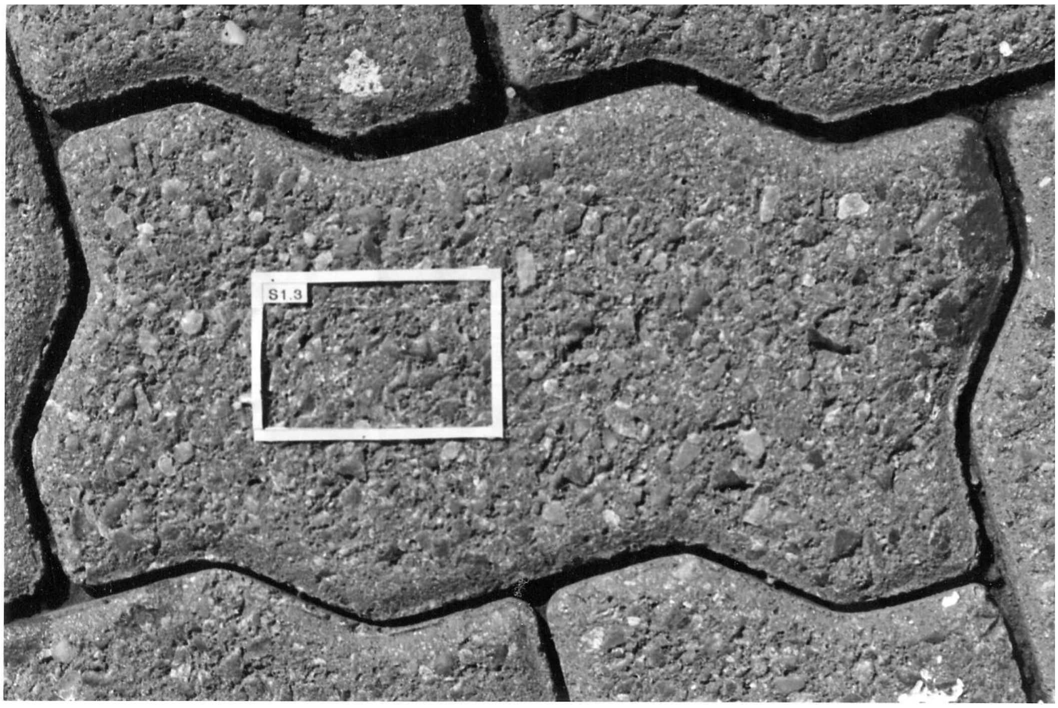

Figure 14.4 Visual presentation of wear in the sidewalk, for mix 1.3. The area enclosed by the rectangle in figure 14.4 is magnified in figure 14.5. A mcd of 0,84 mm and a mvd of 0,27 mm were recorded in this instance. (See column B and C of table 14.1).

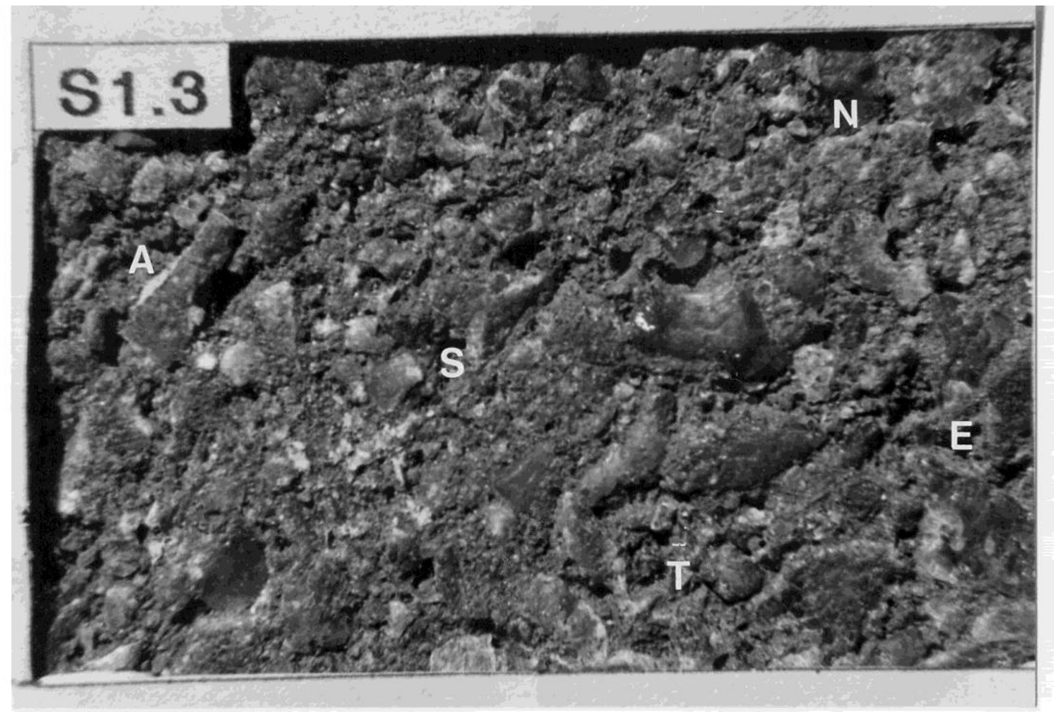

Figure 14.5 Magnified view of figure 14.4. Note the 'S' refers to sidewalk, and '1.3' indicates that it is the third wettest mix of mix design 1.

14.2.3 Relationship between wear in the sidewalk and bus lane – at 6-years

It was realized that only testing one paver in the May93 measurements was the most likely reason for the relatively poor correlation between the mvd in the sidewalk and the bus lane (R^2 = 0,670).

Therefore Columns F, and H of table 14.1 record the average mvd of eight blocks measured during Oct93, in the sidewalk and bus lane respectively, for each of the 48 mixes. Thus clay was applied to a total of 384 blocks in both areas.

The average mvd in the sidewalk for the 384 pavers was 0,76 mm, and the corresponding value for the bus lane is 1.02 mm. This indicates that heavy vehicular traffic is more abrasive than busy pedestrian traffic (by approximately 34 % in this investigation).

An R^2 value of 0,8741 was obtained from a regression analysis (see figure 14.6), indicating a much better correlation of the wear at the two sites. (Clearly this compares favourably with the R^2 value of 0,670, justifying the Oct93 re-measure). Therefore when measuring wear in a paved surface it is always advisable to measure a number of blocks, as abrasion wear will invariably differ from block to block, sometimes quite substantially.

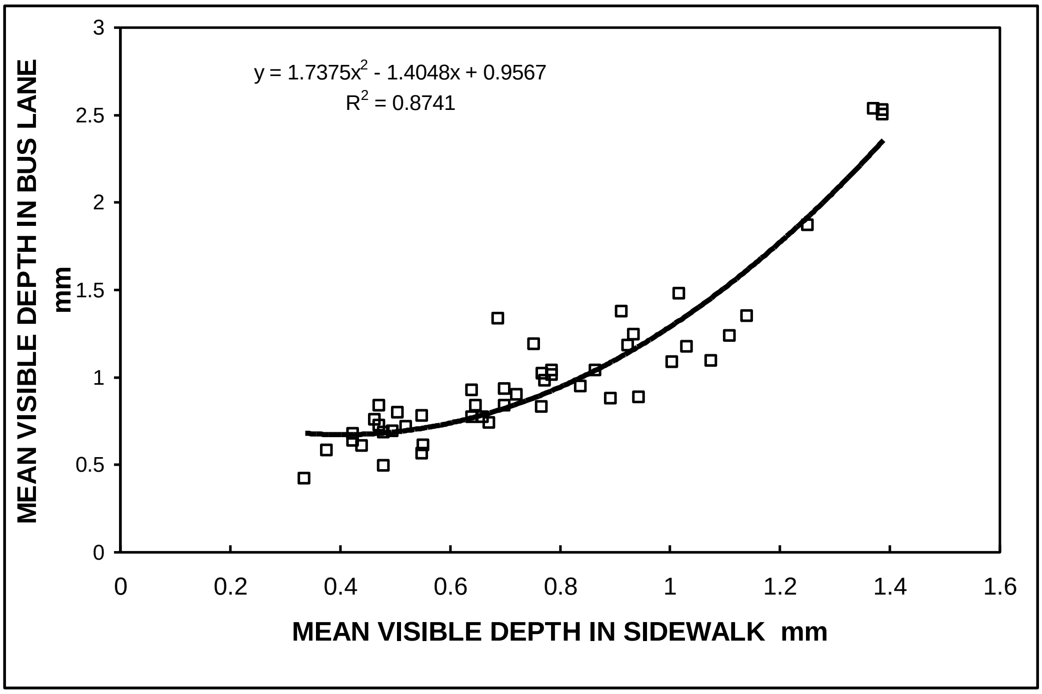

Figure 14.6 Relationship between mvd in the **sidewalk** and mvd in the **bus lane** after six years of traffic. Each point represents eight blocks in both the sidewalk and bus lane – 48 mixes.

Note that it was decided to opt to re-measure mvd rather than mcd for two reasons:

Firstly, it is more time consuming to take say five depth gauge readings per block than it is to apply clay to a block, especially when this additional time is multiplied by eight. Furthermore, far fewer recordings are required, and thus the need to exchange measuring equipment for pen and paper, and vice versa, is much reduced. In the case of mcd, 5 readings & recordings x 8 pavers per mix x 48 mixes x 2 sites = 3840 recordings are required, whereas in the case of mvd only 1 reading and recording per mix x 48 mixes x 2 sites = 96 recordings are required. Clearly the much-reduced number of recordings substantially adds to the time saved.

Secondly, the mvd is more 'reproducible' than is mcd, as indicated by the R^2 coefficient of 0,670 (figure 14.1) relative to 0,612 (figure 14.2).

14.2.4 Degrees of abrasion

The visually assessed degrees of abrasion for the 48 mixes corresponding to the sidewalk and bus lane are respectively recorded in columns G and I of table 14.1.

In figure 14.7 and 14.8, the 48 mvd values respectively in the sidewalk and bus lane fall into five bands, i.e. 'second degree', 'transition', 'third degree', 'transition', 'fourth degree'. The corresponding visually assessed degrees of abrasion are plotted on the X axis, i.e. 2, 2,5, 3, 3,5, and 4, where the two intermediate degrees, shown as 2,5 and 3,5, imply a degree of wear intermediate between 2nd and 3 rd, and 3rd and 4th respectively. Note that mixes judged 2,5 for example may have some blocks showing 3 rd degree and others showing 2nd degree.

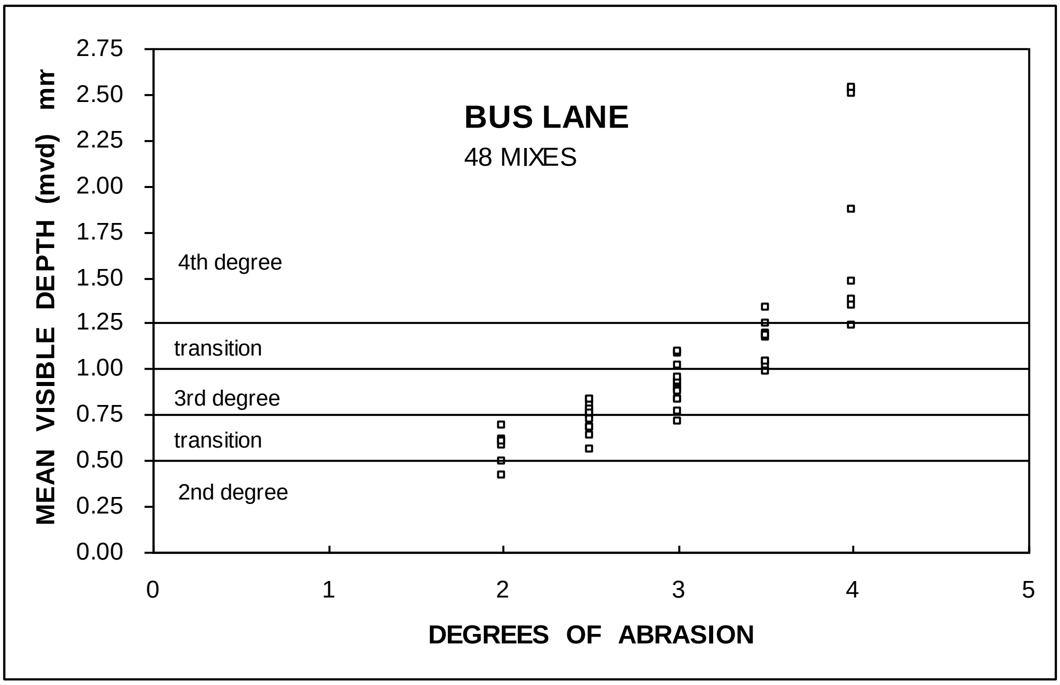

Figure 14.7 Relationship between mean visible depth quantitatively measured by clay method and degrees of abrasion (visually assessed). **Bus lane**.

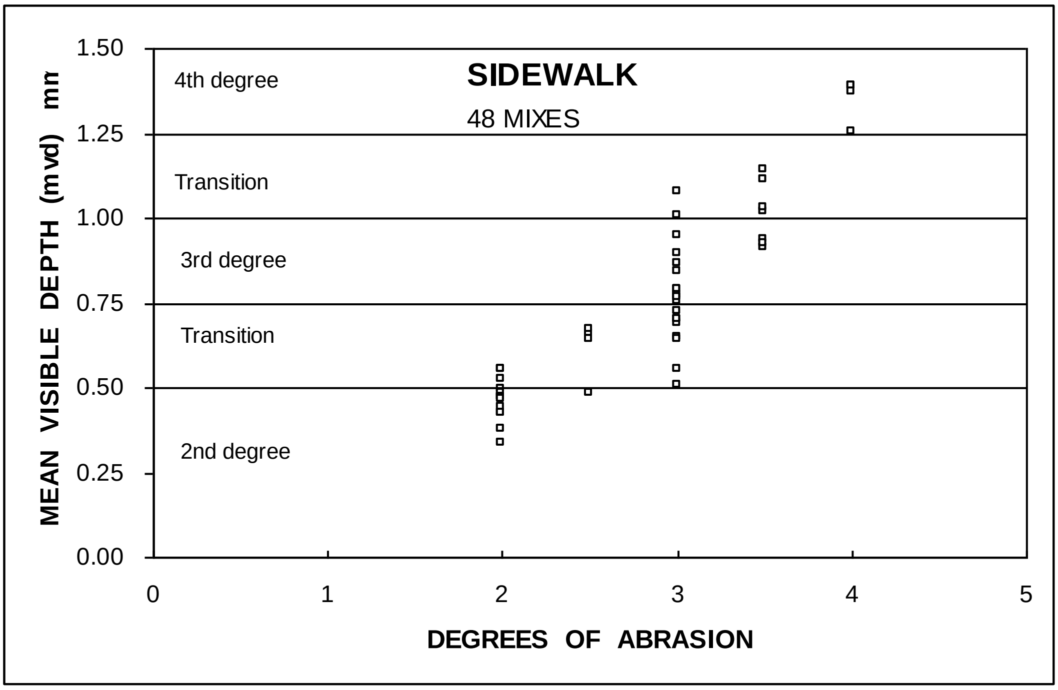

Figure 14.8 Relationship between mean visible depth quantitatively measured by clay method and degrees of abrasion (visually assessed). **Sidewalk**.

The graphs reveal that there is a measure of overlap between adjacent degrees, where for example some pavers that were visually assessed to have ‘2,5 degree’ abrasion, when measured had a lower mvd than some ‘2nd degree’ pavers etc.

These measurements and visual assessments allow some quantitative boundaries to be established as follows:

a All values less than 0,5 mm have 2nd degree wear
b Values between 0.75 mm and 1.0 mm have 3rd degree wear
c All values greater than 1,25 mm have 4th degree wear
d A transitional band or zone exists between 2nd and 3rd degree, where readings range between 0,5 mm and 0,75 mm.
e A second transitional zone exists between 3rd and 4th degree, where readings range between 1,0 mm and 1,25 mm.

Where mvd values fall in the transitional bands, the assessor must use other indicators described in table 8.3, such as loss of fine aggregate (3rd degree), loss of coarse aggregate (4th degree), etc. to determine which degree of abrasion applies.

Figure 8.51 records wear measurements (mvd) at four sites (excluding the Westgate site) in the Johannesburg area. The blocks were also visually assessed in terms of the five degrees of abrasion. The blocks were made by three different producers, and represent a variety of different aggregates, binders, process controls etc. Nevertheless the mvd values associated with the various degrees of abrasion also fit into the five bands used to classify the Westgate pavers, as defined above.

It therefore seems reasonable to accept 0,5 mm, 0,75 mm, 1,0 mm and 1,25 mm as appropriate divisions for the five bands.

These five bands will be extensively referred to hereafter.

14.3 Degree of Correlation between Laboratory Tests and Measured Wear

Since the blocks installed at Westgate are from the same mixes as those tested in the laboratory, the recorded wear on site can be tabulated with the laboratory results. This is done in table 14.2.

This table may be used to plot the relationship between the recorded wear and seven of the laboratory tests, i.e. dry density, compressive strength, tensile splitting strength, the three abrasion tests, and initial surface absorption. In each case the laboratory result is recorded on the X-axis, and the mvd on the Y-axis. Two graphs are plotted for each laboratory test to show the respective mvd values in the sidewalk and bus lane.

The degree of correlation in each graph is expressed in terms of a R^2 coefficient, associated with a best-fit trend line based on regression analysis.

TABLE 14.2 SUMMARY OF 1987 LABORATORY RESULTS AND 1993 WEAR MEASUREMENTS AT WESTGATE

MIX	COMPRESSIVE STRENGTH			TSS	ABRASION			DRY DENS	WATR ABSRP	ISAT	Water content -	AVERAGE OF 8 BLOCKS MEASURED			
					WIRE	SAND	BALL					SIDEWALK		BUS LANE	
	SABS 1058	ASTM C140	MA20	ISO 4108	CLAY	ASTM C418	MA20	ASTM C642	ASTM C140	SABS 0164	CaC_2 method	MVD	DEG OF WEAR	MVD	DEG OF WEAR
	MPa	MPa	MPa	MPa	cm³/cm²	cm³/cm²	Index	kg/m³	%	%	%	mm		mm	
A	B	C	D	E	G	I	J	K	L	M	S	P	Q	R	S
1.1	35.3	35.4	44.9	3.80	0.068	0.290	2.18	2308	1.50	0.06	7.15	0.34	2	0.42	2
1.2	36.6	36.1	45.8	4.00	0.085	0.276	2.30	2308	1.41	0.05	6.15	0.42	2	0.63	2.5
1.3	30.9	27.5	39.3	3.60	0.090	0.314	1.67	2266	2.18	0.09	6.10	0.51	3	0.79	2.5
1.4	22.0	19.0	28.4	2.50	0.145	0.392	0.99	2160	5.21	0.35	5.63	0.66	2.5	0.77	2.5
1.5	22.6	20.1	28.0	2.70	0.163	0.408	0.91	2159	5.80	0.40	5.60	0.70	3	0.83	3
1.6	15.9	16.4	22.0	2.20	0.149	0.443	0.70	2113	6.50	0.50	4.90	0.75	3	1.19	3.5
MEAN	27.2	25.8	34.7	3.13	0.117	0.354	1.46	2219	3.77	0.24	5.92	0.56	2.58	0.77	2.67
2.1	29.2	27.5	35.3	3.20	0.128	0.322	0.99	2283	1.85	0.08	7.60	0.50	2	0.69	2
2.2	30.3	27.6	36.0	3.30	0.105	0.312	0.93	2298	1.61	0.06	6.80	0.52	2	0.71	3
2.3	27.9	24.8	35.2	3.30	0.100	0.336	0.96	2242	3.09	0.10	6.30	0.72	3	0.90	3
2.4	23.9	18.9	26.2	2.50	0.132	0.481	0.67	2175	5.82	0.27	5.60	0.95	3	0.88	3
2.5	19.1	17.1	25.0	2.20	0.152	0.523	0.74	2110	7.54	0.40	5.30	1.00	3	1.08	3
2.6	18.0	14.7	21.6	2.10	0.162	0.509	0.68	2108	7.42	0.65	4.90	1.02	3.5	1.47	4
MEAN	24.7	21.8	29.9	2.77	0.130	0.414	0.83	2203	4.56	0.26	6.08	0.78	2.75	0.96	3.00
3.1	18.9	18.9	25.0	1.80	0.134	0.514	0.74	2188	3.54	0.07	7.20	0.69	3	1.33	3.5
3.2	15.9	18.5	22.8	1.60	0.145	0.478	0.55	2194	3.92	0.07	7.15	0.91	3.5	1.37	4
3.3	15.1	14.6	18.5	1.50	0.158	0.575	0.50	2109	6.99	0.24	5.70	1.25	4	1.87	4
3.4	12.5	12.0	16.6	1.10	0.187	0.607	0.40	2037	9.93	0.95	5.00	1.39	4	2.52	4
3.5	11.4	11.1	15.0	1.00	0.221	0.702	0.34	1995	10.44	1.70	4.44	1.39	4	2.50	4
3.6	11.9	11.8	16.6	1.30	0.187	0.686	0.38	2016	10.03	1.39	4.50	1.37	4	2.53	4
MEAN	14.3	14.5	19.1	1.38	0.172	0.594	0.48	2090	7.48	0.74	5.67	1.17	3.75	2.02	3.92
4.1	25.4	26.1	32.3	2.50	0.125	0.349	0.84	2243	3.52	0.08	6.80	0.55	2	0.61	2
4.2	28.1	26.3	32.9	2.70	0.096	0.370	0.86	2259	2.90	0.07	5.80	0.47	2	0.83	2.5
4.3	16.4	15.6	20.2	1.70	0.157	0.417	0.48	2121	6.61	0.34	4.75	0.89	3	0.87	3
4.4	14.3	14.5	19.4	1.80	0.211	0.426	0.43	2110	6.53	0.41	5.00	0.87	3	1.03	3.5
4.5	15.5	14.3	21.3	1.70	0.204	0.601	0.46	2117	6.52	0.35	4.60	0.94	3.5	1.24	3.5
4.6	13.4	14.3	19.5	1.50	0.164	0.662	0.42	2076	7.80	0.51	4.90	1.03	3.5	1.17	3.5
MEAN	18.9	18.5	24.3	1.98	0.160	0.471	0.58	2154	5.65	0.29	5.31	0.79	2.83	0.96	3.00
5.1	29.9	29.2	37.9	2.80	0.108	0.384	1.28	2267	3.15	0.06	7.20	0.38	2	0.58	2
5.2	22.7	27.0	30.0	2.60	0.129	0.390	1.28	2230	3.63	0.07	5.75	0.48	2.5	0.68	2.5
5.3	19.8	18.3	24.0	1.80	0.137	0.451	1.04	2170	5.36	0.18	5.60	0.55	3	0.78	2.5
5.4	19.3	20.2	25.0	2.10	0.137	0.410	0.93	2202	4.53	0.15	5.40	0.65	3	0.83	2.5
5.5	18.2	17.2	21.0	2.10	0.162	0.482	0.54	2102	7.02	0.41	4.60	0.77	3	1.02	3.5
5.6	13.7	12.1	16.5	1.80	0.226	0.645	0.39	2055	8.16	0.79	4.30	0.79	3	1.01	3
MEAN	20.6	20.7	25.7	2.20	0.150	0.460	0.91	2171	5.31	0.27	5.48	0.60	2.75	0.82	2.67
6.1	28.6	30.2	34.7	2.90	0.102	0.437	0.95	2242	4.20	0.06	6.90	0.48	2	0.49	2
6.2	27.2	28.1	32.9	3.00	0.093	0.401	0.89	2220	3.50	0.06	7.00	0.44	2	0.60	2
6.3	22.1	23.2	24.4	2.40	0.150	0.587	0.77	2166	5.36	0.18	5.47	0.55	2	0.56	2.5
6.4	16.4	19.2	22.6	2.10	0.155	0.591	0.55	2121	6.51	0.26	5.30	0.64	3	0.92	3
6.5	14.0	16.4	19.6	1.80	0.147	0.598	0.44	2058	8.15	0.64	4.90	0.70	3	0.93	3
6.6	12.3	11.3	16.7	1.50	0.156	0.596	0.37	2021	9.27	1.16	4.70	0.77	3	0.98	3.5
MEAN	20.1	21.4	25.2	2.28	0.134	0.535	0.66	2138	6.17	0.39	5.71	0.60	2.50	0.75	2.67
7.1	31.6	33.2	42.3	3.60	0.105	0.320	1.50	2286	1.52	0.06	7.10	0.42	2	0.67	2.5
7.2	26.1	29.1	39.8	3.40	0.106	0.346	1.55	2263	2.04	0.07	6.10	0.67	2.5	0.74	2.5
7.3	23.0	21.9	32.0	2.90	0.114	0.385	0.98	2208	3.88	0.18	5.40	0.77	3	0.83	3
7.4	20.1	23.4	31.0	2.60	0.112	0.413	1.20	2175	5.06	0.29	5.60	0.84	3	0.95	3
7.5	20.0	16.3	26.3	2.40	0.124	0.453	0.77	2110	7.24	0.64	5.10	1.08	3	1.09	3
7.6	16.0	13.5	21.1	2.30	0.152	0.507	0.48	2073	7.86	0.83	4.20	1.11	3.5	1.23	4
MEAN	22.8	22.9	32.1	2.87	0.119	0.404	1.08	2186	4.60	0.35	5.58	0.82	2.83	0.92	3.00
8.1	28.6	32.6	40.2	3.80	0.087	0.326	1.60	2262	1.54	0.05	7.40	0.47	2	0.72	2.5
8.2	32.1	30.4	42.4	3.60	0.103	0.338	1.80	2279	1.42	0.05	7.10	0.46	2	0.75	2.5
8.3	31.1	31.7	43.6	3.30	0.084	0.359	1.73	2285	1.41	0.05	6.30	0.64	2.5	0.77	3
8.4	24.0	18.9	28.8	2.90	0.117	0.472	1.26	2103	6.79	0.60	5.30	0.79	3	1.03	3.5
8.5	18.1	21.1	27.8	2.30	0.137	0.475	1.00	2100	6.77	0.69	5.30	0.93	3.5	1.18	3.5
8.6	17.8	18.2	25.0	2.30	0.156	0.444	0.68	2092	7.03	0.61	4.95	1.14	3.5	1.35	4
MEAN	25.3	25.5	34.6	3.03	0.114	0.402	1.35	2187	4.16	0.34	6.06	0.74	2.75	0.97	3.17
O/MN	21.7	21.4	28.2	2.5	0.137	0.454	0.92	2168.4	5.21	0.36	5.73	0.76	2.84	1.02	3.01

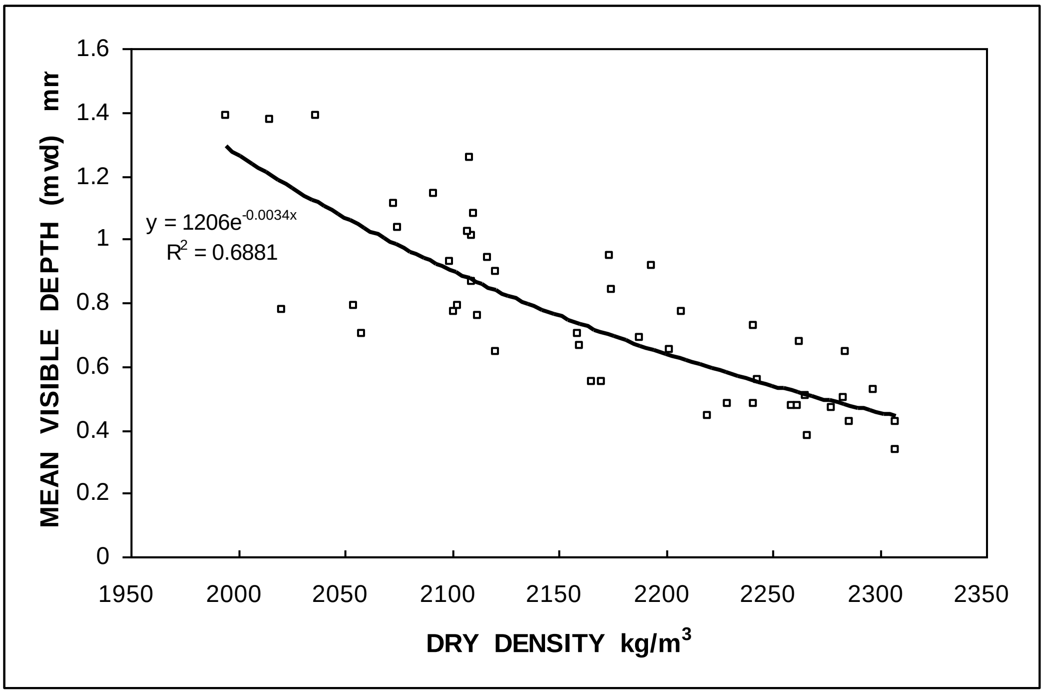

Figure 14.9 Correlation between dry density and mean visible depth.
Sidewalk

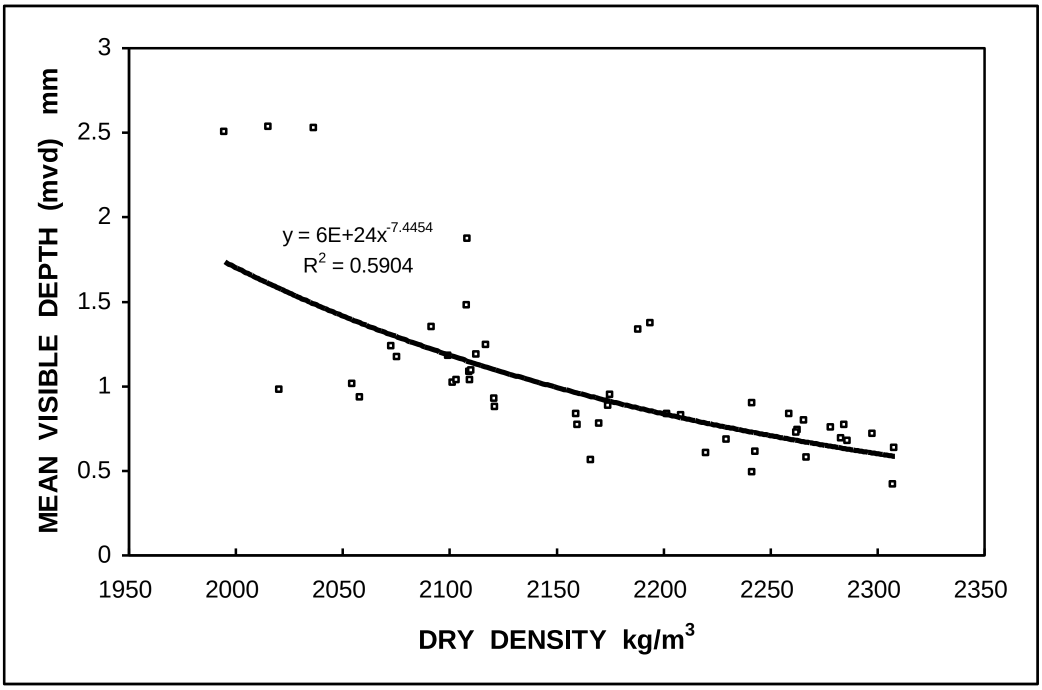

Figure 14.10 Correlation between dry density and mean visible depth.
Bus lane

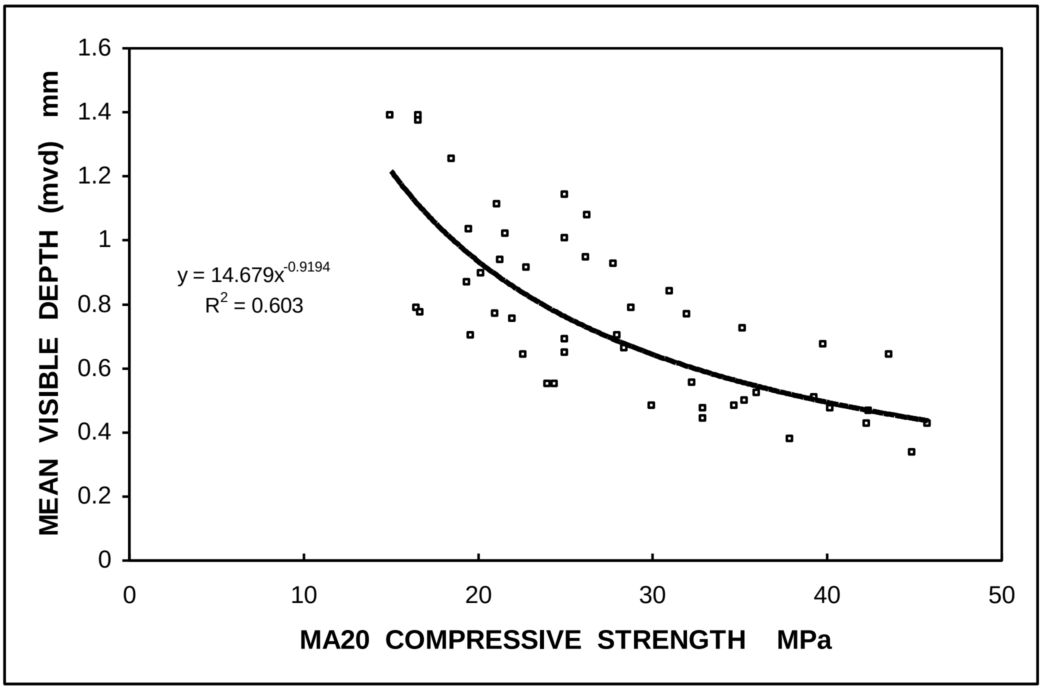

Figure 14.11 Correlation between MA20 compressive strength and mean visible depth. **Sidewalk**

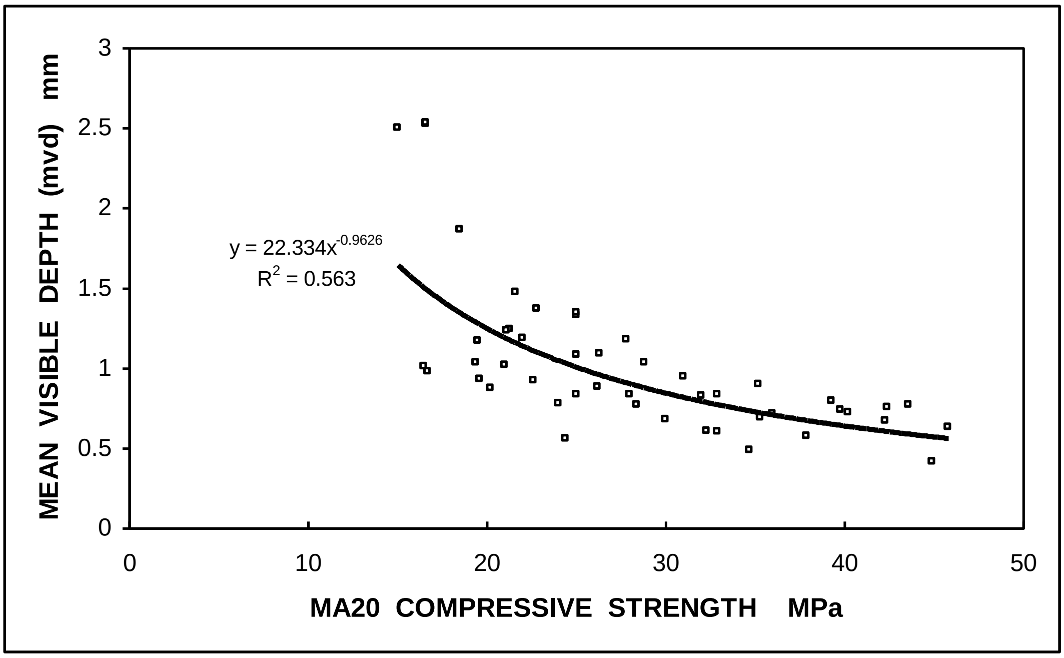

Figure 14.12 Correlation between MA20 compressive strength and mean visible depth. **Bus lane**.

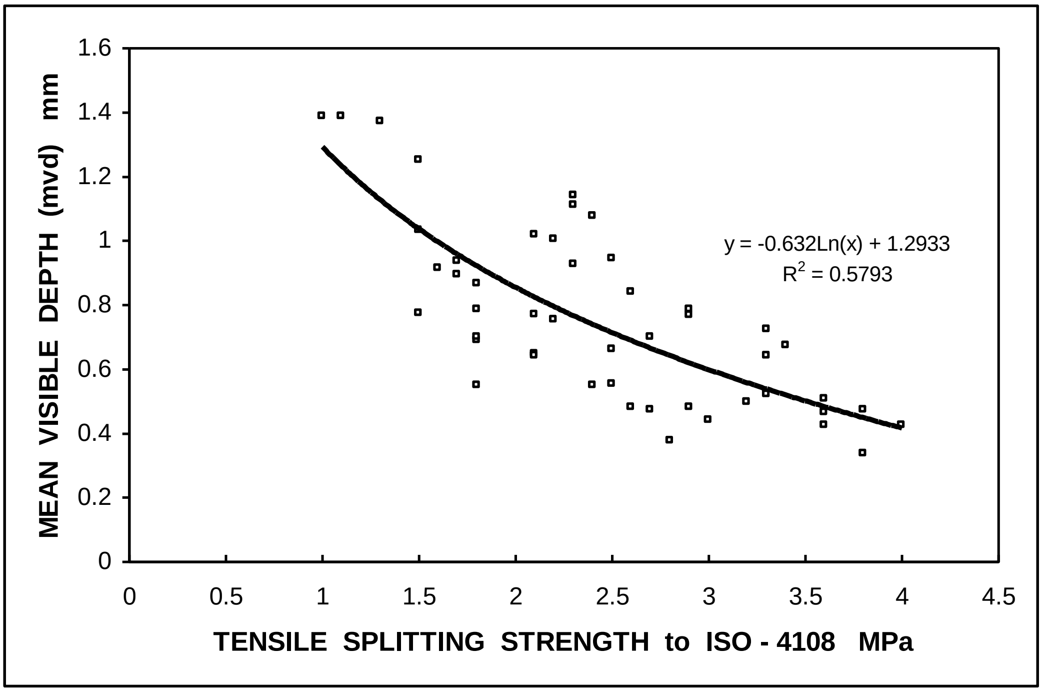

Figure 14.13 Correlation between tensile splitting strength and mean visible depth. **Sidewalk**

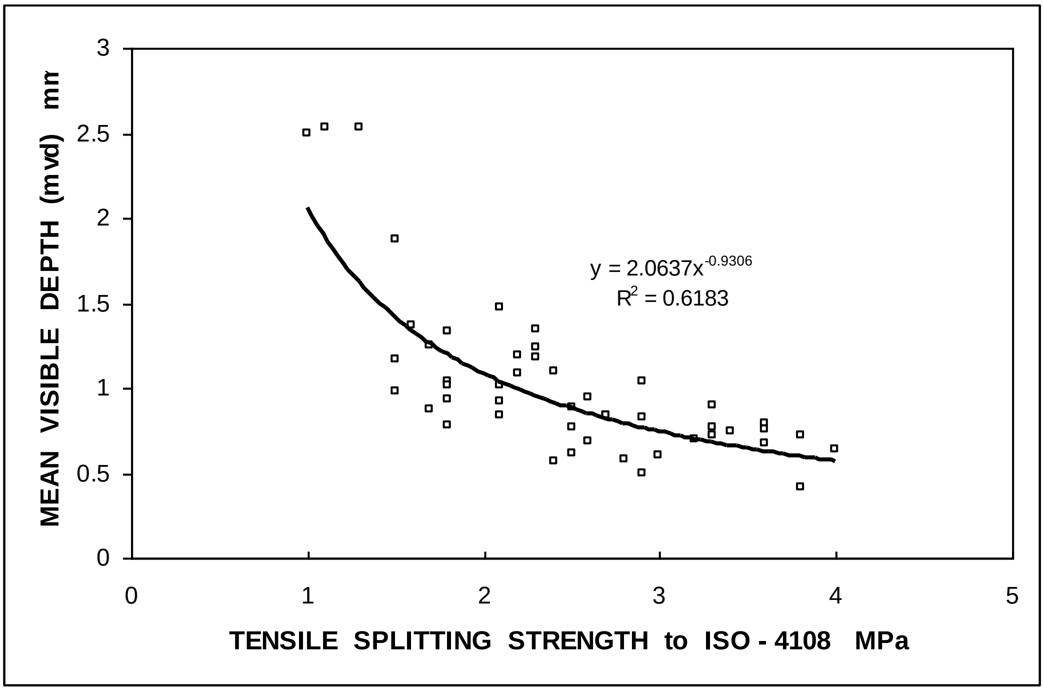

Figure 14.14 Correlation between tensile splitting strength and mean visible depth. **Bus lane**

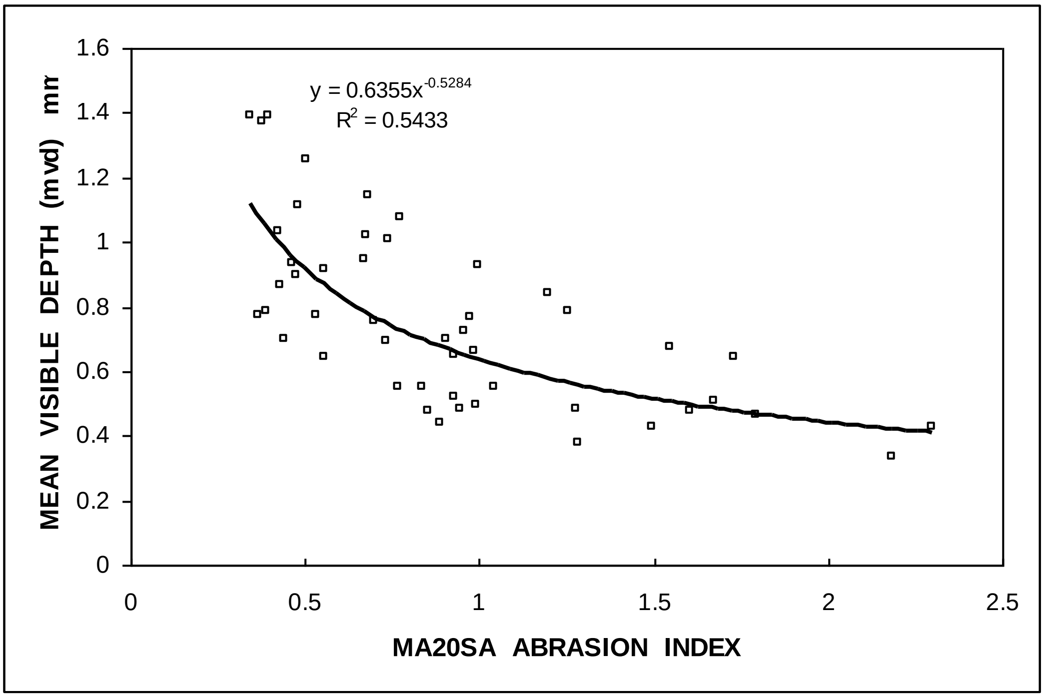

Figure 14.15 Correlation between MA20 abrasion index and mean visible depth. **Sidewalk**.

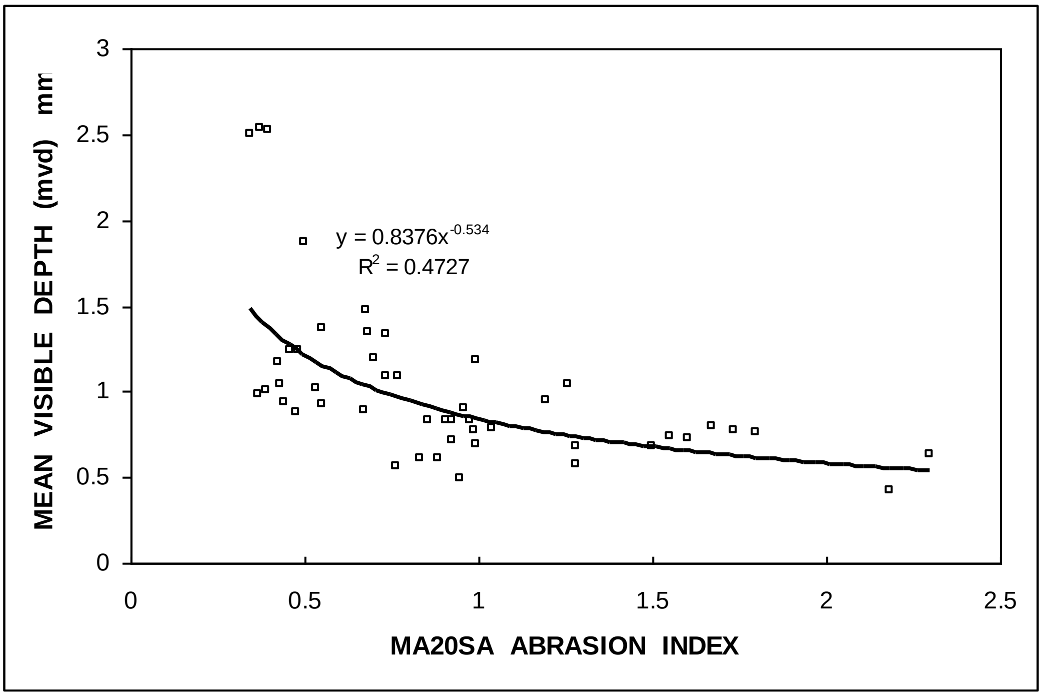

Figure 14.16 Correlation between MA20 abrasion index and mean visible depth. **Bus lane.**

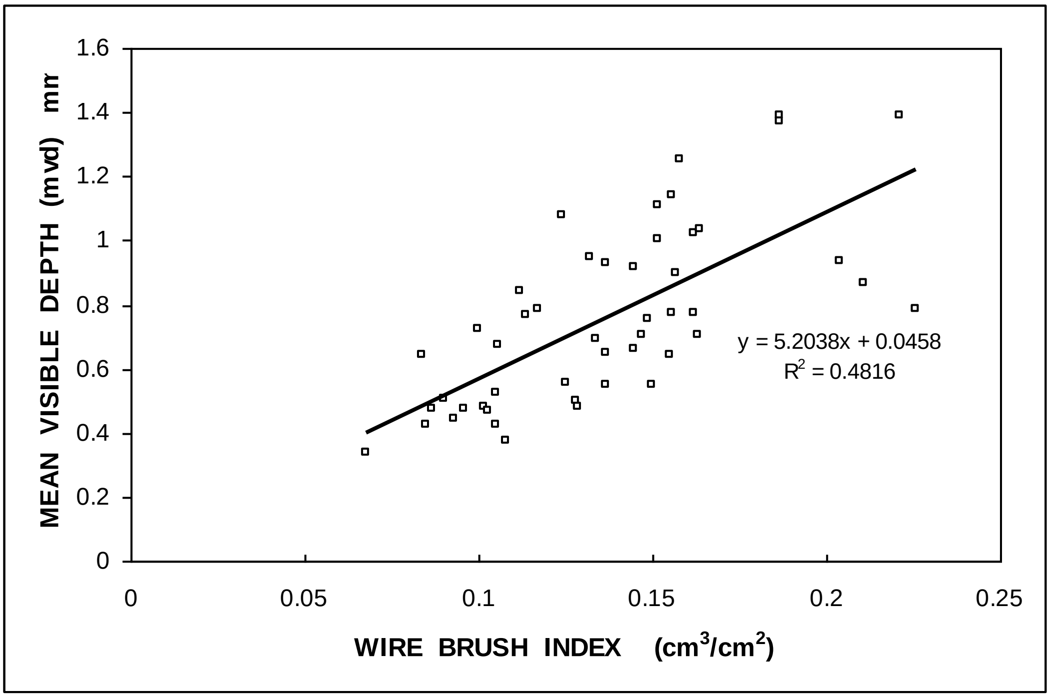

Figure 14.17 Correlation between wirebrush abrasion index (clay method) and mean visible depth. **Sidewalk**.

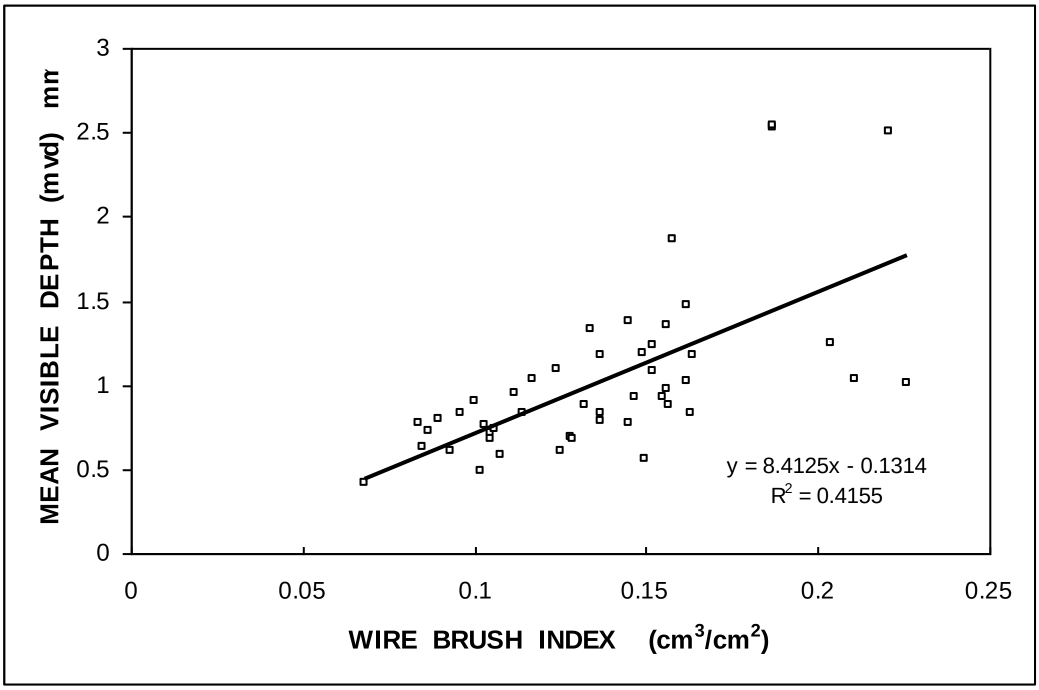

Figure 14.18 Correlation between wirebrush abrasion index (clay method) and mean visible depth. **Bus lane**.

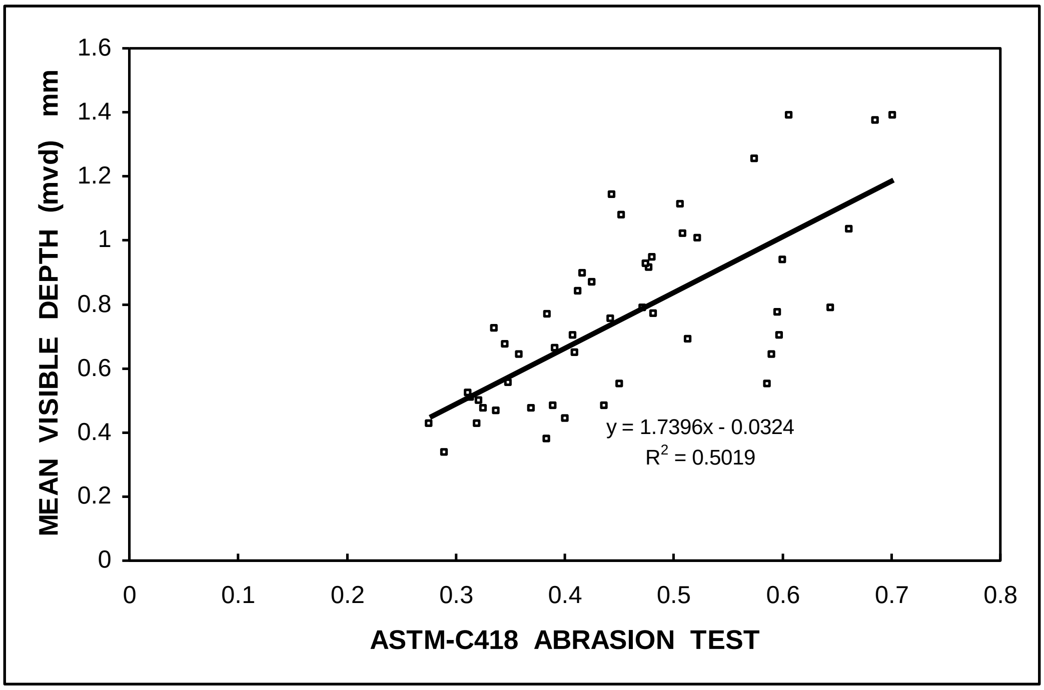

Figure 14.19 Correlation between ASTM C418 abrasion index (clay method) and mean crater depth. **Sidewalk**.

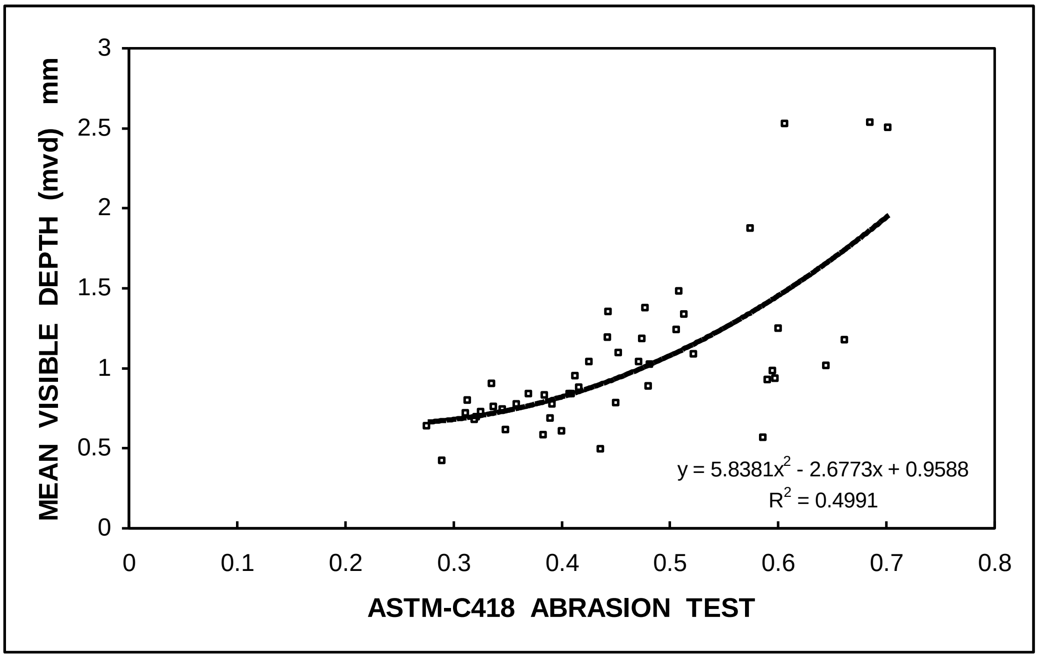

Figure 14.20 Correlation between ASTM C418 abrasion index (clay method) and mean visible depth. **Bus lane**.

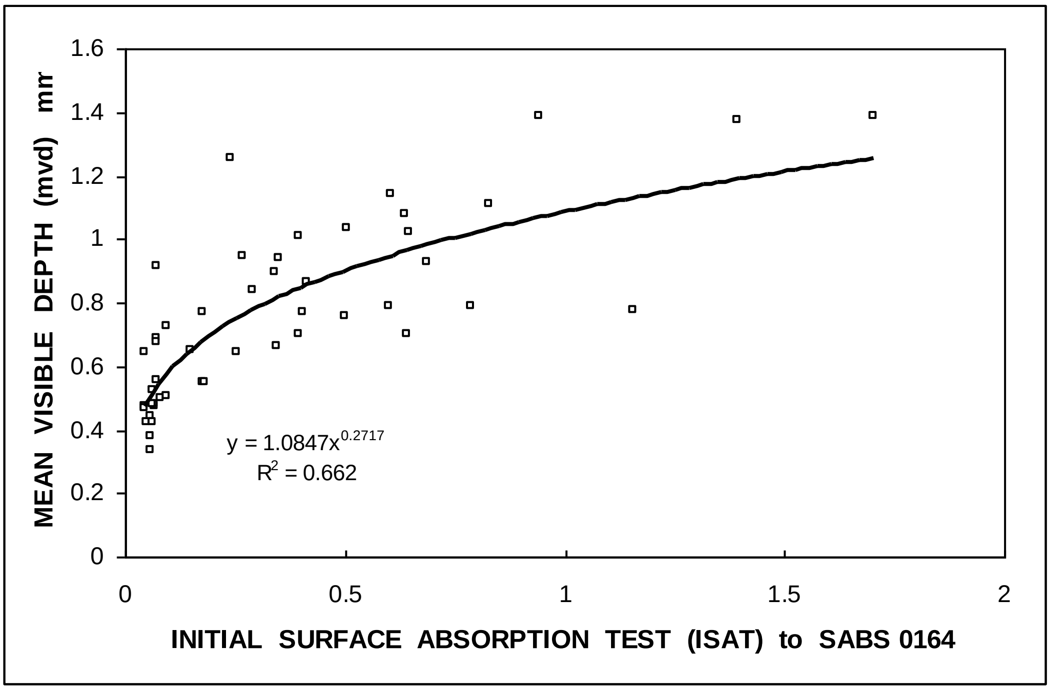

Figure 14.21 Correlation between ISAT and mvd in **bus-lane**

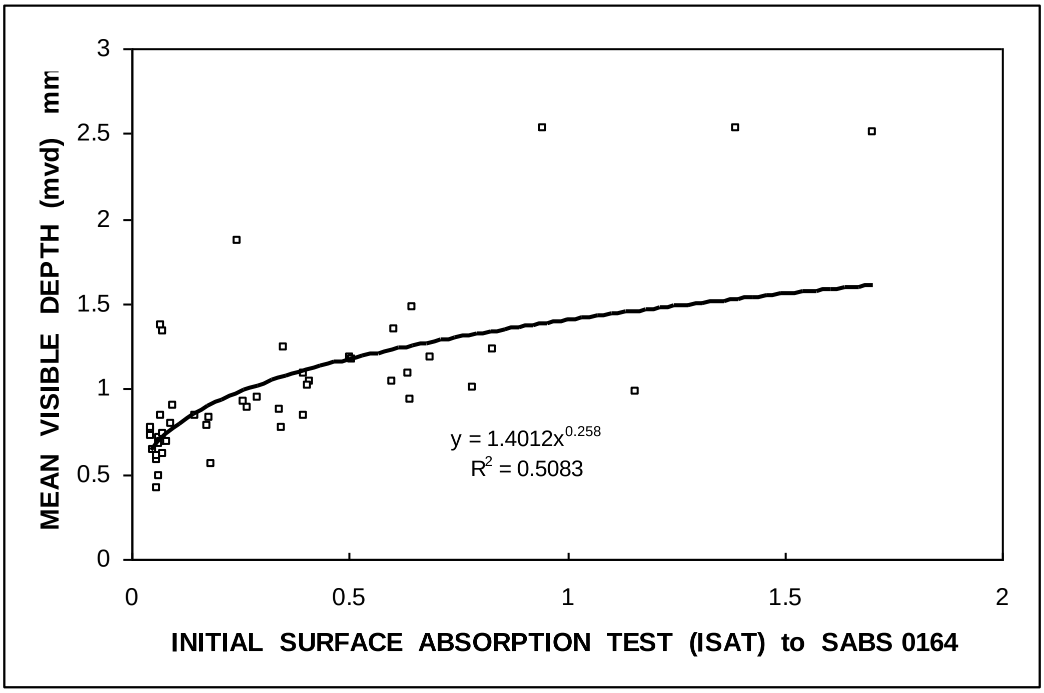

Figure 14.22 Correlation between ISAT and mvd in **side walk**.

The R^2 values representing the different laboratory tests are summarised in table 14.3:

TABLE 14.3 DEGREE OF CORRELATION BETWEEN MVD AND LABORATORY TESTS		
LABORATORY TESTS	R^2 VALUES	
	MVD SIDEWALK mm	MVD BUS LANE mm
BULK PROPERTY TEST		
DRY DENSITY (ASTM-C642)	0.688	0.590
COMPRESSIVE STRENGTH (MA20)	0.603	0.563
TENSILE SPLITTING STRENGTH (ISO-4108)	0.579	0.618
SURFACE TEST		
ABRASION RESISTANCE (MA20)	0.543	0.473
ABRASION RESISTANCE (WIRE BRUSH)	0.482	0.416
ABRASION RESISTANCE (ASTM-C418)	0.502	0.499
% INITIAL SURFACE ABSORPTION (SABS0164)	0.662	0.508

It would seem logical that a ‘surface’ test such as an abrasion test would correlate better with surface wear than would a test that determines the ‘bulk property’ of the block. Surprisingly table 14.3 indicates that on the whole the bulk indicators such as dry density, compressive strength and tensile splitting strength correlate better with the observed wear than the abrasion tests. Two factors likely contributed to this somewhat unexpected result. The first is the acknowledged lower coefficient of variation of compression testing relative to most abrasion tests, and the second is that carbonation effects would have influenced abrasion testing to a much greater degree than compression testing (carbonation testing done on these batches by Papenfus(1995) confirm this).

In spite of the general trend of bulk indicators been better correlated to long term wear than are the surface indicators, it is clear that all the tests have low coefficients. This may be explained by significant differences in strength development from one mix design to the next. In this investigation binder type was a variable. It is well known that fly ash, as a cement extender, retards the strength development process (unless used in relatively low proportions), and conversely, silica fume accelerates 28-day development, but has minimal post 28-day development. On the other hand, fly ash has a significant strength development profile after 28-days, whereas silica fume does not.

To summarise, the variations in binder type resulted in poorly related 28-day and 6-year abrasion resistance, compressive strength etc., thus accounting for the relatively wide scatter seen in figures 14.9 through 14.22. Therefore variability of mix designs rather than poor repeatability of the various tests accounts for the low R^2 coefficients.

These assertions are shown to be correct in the next section, where a number of graphs are plotted to show that distinct relationships appear when the 48 mixes are analysed in their separate mix designs.

14.4 Relationship Between Surface Tests and Wear for Individual Mix Designs

This section sets out to prove there is a distinct relationship between traffic induced wear and the various surface tests (i.e. the three abrasion tests and ISAT) when the individual mix designs are considered in isolation.

Moreover, where the same binder type is used, i.e. mix designs 1, 2 and 3, it is possible to determine clearly defined limiting criteria for the collective data, even though the binder content varied from 18% through 10%.

On the other hand where different binder types are used, it is necessary to establish limiting criteria for each mix design.

Discriminating between mix designs of different binder content and type, the relationship between 28-day abrasion testing and 6-year wear under traffic is now considered under three headings:

14.4.1 The effect of binder content variation will be considered for each of the four surface tests.
14.4.2 Limiting criteria for the three abrasion tests will be proposed for mixes 1, 2 and 3 (same binder type).
14.4.3 The effect of binder type variation will be considered. The problem associated with establishing universal or collective limiting criteria where different binder types are used is discussed.

In each case the sidewalk and bus lane traffic are considered separately.

14.4.1 The effect of variations in binder content on the mvd considering each of the three mix designs (mix 1, mix 2, mix 3) individually and collectively

General Trends

Figures 14-23 through 14-28 show that rich mixes are more abrasion resistant than lean mixes, as seen by their higher abrasion resistances (or lower abrasion-wear) and lesser wear under traffic. Furthermore the familiar trend of wet mixes being more resistant to abrasion than dry mixes is apparent regardless of the binder content. The only exception is that sometimes the second wettest mix is more abrasion resistant than the wettest. (This occurs when the wettest mix has slightly too much water, more than what is required for optimum compaction, resulting in a slightly lower than optimum c/w ratio).

Figures 14-23R^2 through 14-28R^2 show trend-lines for the 18 points (corresponding to the three binder contents each with six moisture contents). That there is a relationship between the 28-day abrasion tests and 6-year wear is seen from the relatively high R^2 values in these graphs. These correlations are better in the sidewalk, which experienced less abrasion than did the bus lane. For example the R^2 coefficient for the MA20SA vs sidewalk mvd was 0,879, for the ASTM C418 it was 0,9055 and for the wirebrush it was

0,7835. The equivalent correlations for the bus lane were 0,8311, 0,8998, and 0,7593. (The wirebrush correlations proved to be somewhat weaker).

It may therefore be asserted that MA20SA is a useful 28-day test for predicting long-term abrasion wear, particularly where abrasion is limited to third degree. (Note that the horizontal lines demarcating the boundaries of 2^{nd}, 3^{rd}, and 4^{th} degree abrasion in figures 14-23 through 14-28 show that sidewalk abrasion was mostly 2^{nd} and 3^{rd} degree, while bus lane abrasion was mostly 3^{rd} and 4^{th} degree).

The good correlations achieved in these graphs may be contrasted to the much lower R^2 coefficients shown in table 14.3, which ranged between 0,416 and 0,688. It may therefore be deduced that only where the same binder type is used can high correlations be expected between abrasion tests and wear under traffic. Note that table 14.3 represents all 48 mixes and therefore includes fly ash and silica fume in addition to MGBS and OPC. The different rates of strength gain of these various binder types are responsible for the high scatter in figures 14.9 through 14.22 (discussed in more detail in previous section).

Furthermore the good correlations reflected in figures 14.23 through 14.28 indicate that variations in binder content and moisture content result in a predictable shift in the abrasion resistance and abrasion wear, as indicated by the trend-lines.

Note that unlike the MA20SA test, the wirebrush and sandblast abrasion indices are, strictly speaking, a measure of the abrasion wear rather than abrasion resistance. Effectively they measure the average depth of penetration of the respective abrasive mediums and in this sense model the wear under traffic, which may also be represented as a depth measurement (e.g. mvd). This significantly contributes to the *linearity* in the correlations. On the other hand the MA20SA index is proportional to the inverse of the penetration, and this contributes to the distinct *non-linearity* of those graphs.

Individual tends

MA20SA vs mvd: Figures 14.23 and 14.24 indicate a distinct relationship, albeit non linear power functions for binder content variations of 18 %, 14 %, and 10 %, with the richer mixes showing higher 28-day indices and lower mvd. Note too the improved indices for wetter mixes.

Wirebrush vs mvd: Figures 14.25 and 14.26 indicate a more linear relationship, but with a greater scatter than in the case of the MA20SA graphs (note the lower R^2 coefficients). Otherwise behaviour is similar to MA20SA.

ASTM C418 vs mvd: Figures 14.27 and 14.28 also indicate relative relationships, but with the least scatter of the three tests as evidenced by the highest correlation coefficients for both the sidewalk and bus lane.

ISAT vs mvd: Figures 14.29 and 14.30 indicate distinct non-linear relationships for each of the three binder content variations; each curve follows its own unique path. A distinct feature of these curves is that the wetter mixes have very low ISAT values, which indicates that the wetter pavers are dense with relatively few voids and capillaries. Once again this illustrates the role the mix water plays in lubrication, facilitating compaction, and minimising capillaries.

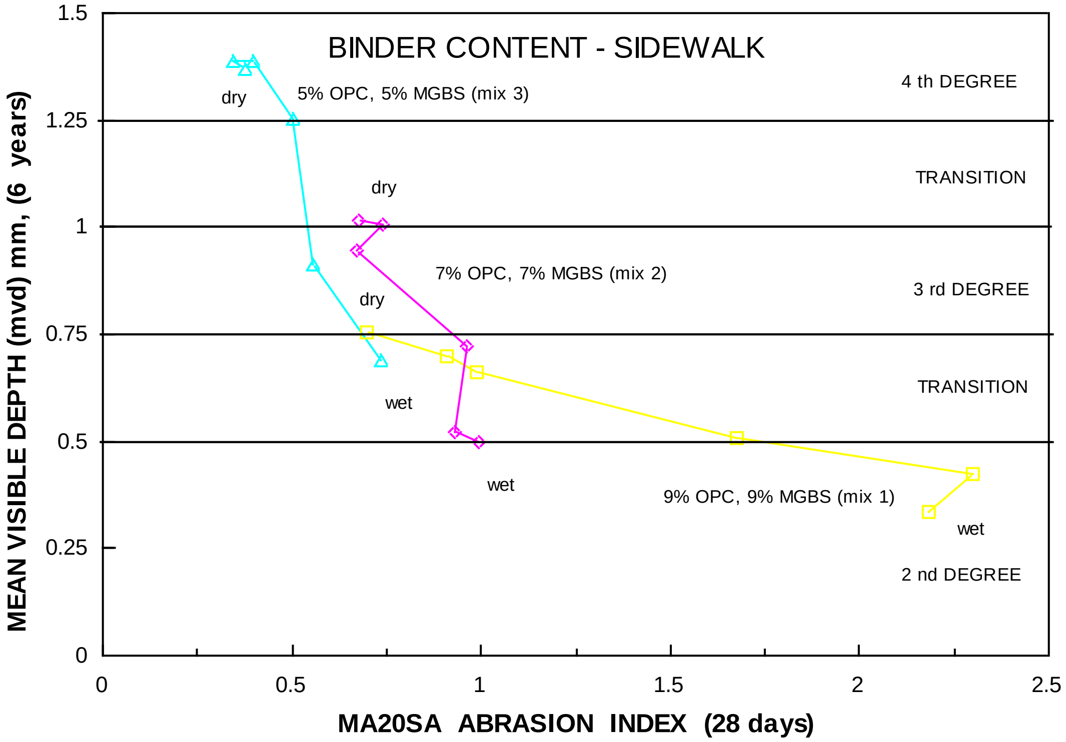

Figure 14.23 Relationship between 28-day MA20SA abrasion index and mean visible depth after 6-years, for different binder contents – **sidewalk**

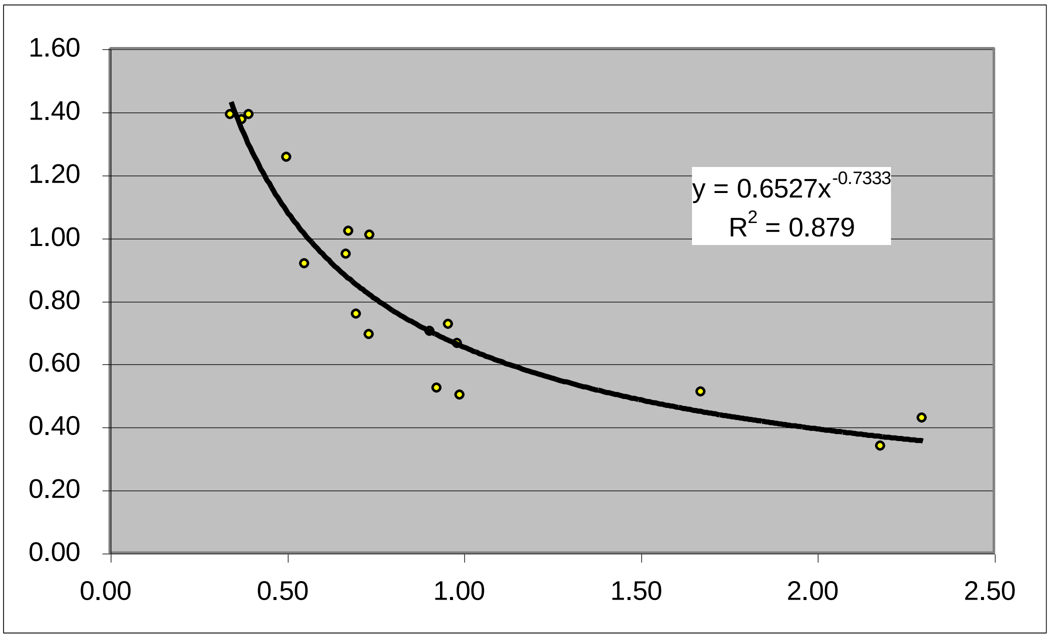

Figure 14.23-R² R^2 coefficients of figure 14.23, considering all 18 points together

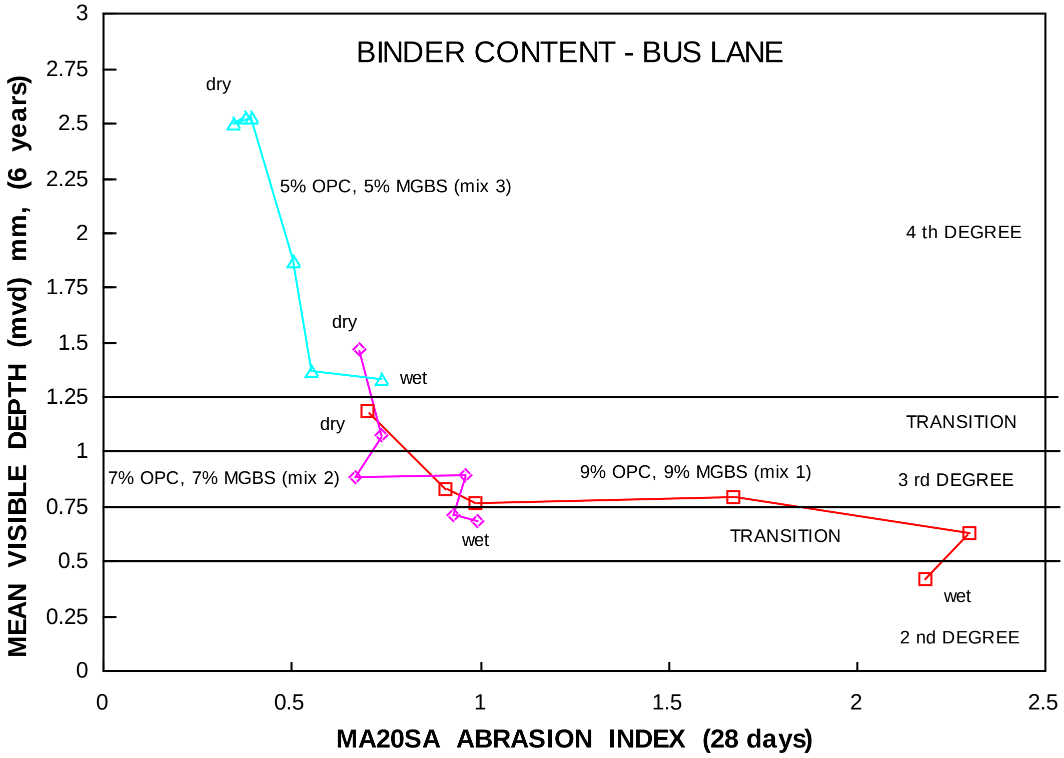

Figure 14.24 Relationship between 28-day MA20SA abrasion index and mean visible depth after 6-years, for different binder contents - **bus lane**

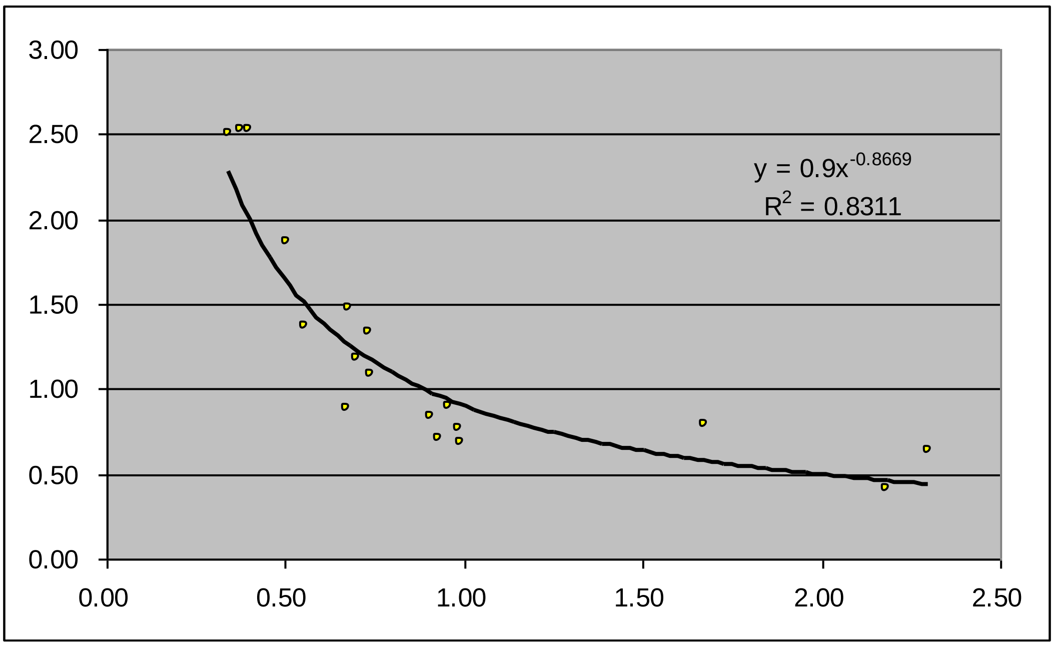

Figure 14.24-R^2 R^2 coefficients of figure 14.24, considering all 18 points together

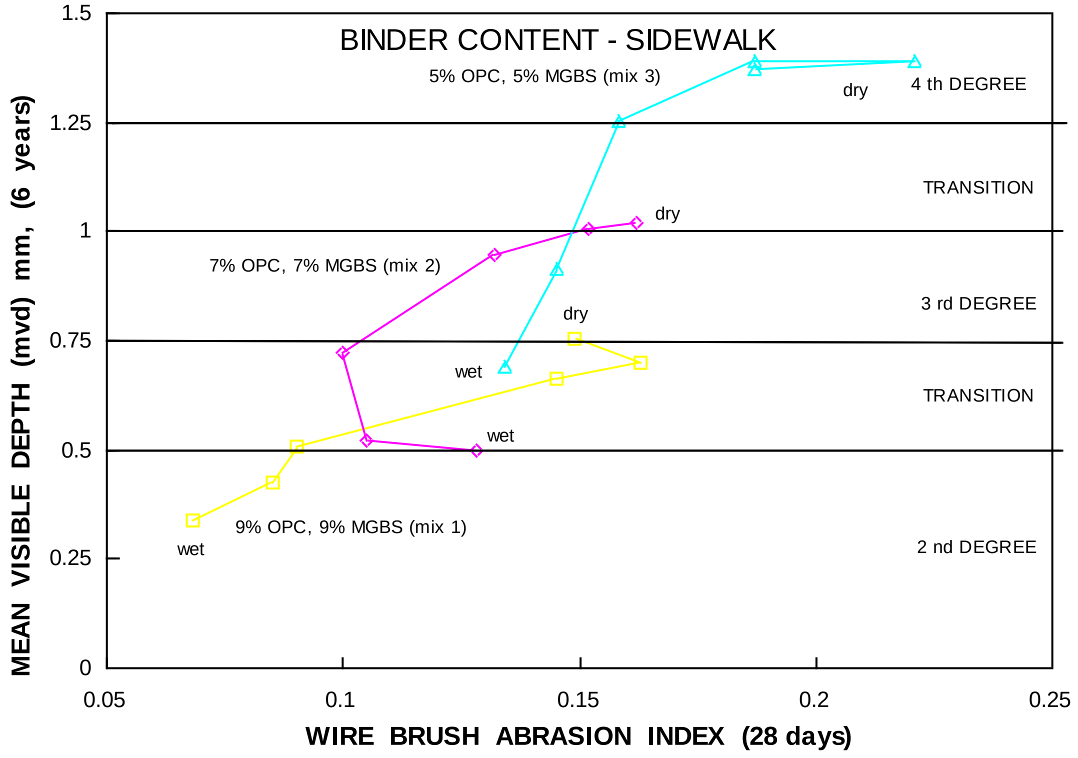

Figure 14-25 Relationship between 28-day wirebrush abrasion index (cm^3/cm^2) and mean visible depth after 6-years, for different binder contents - **sidewalk**

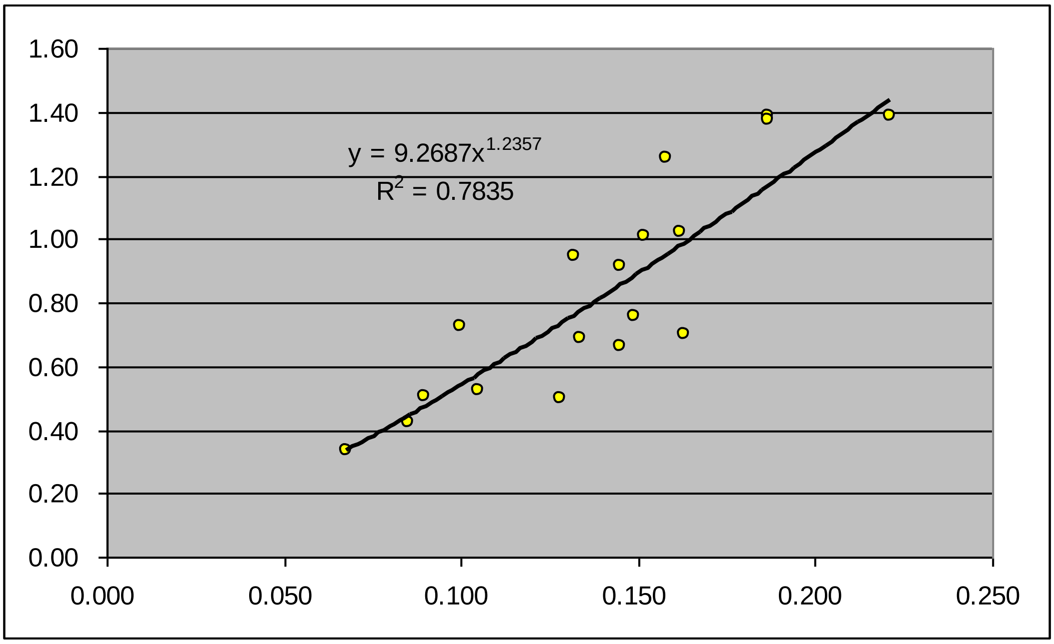

Figure 14.25-R² R^2 coefficients of figure 14.25, considering all 18 points together

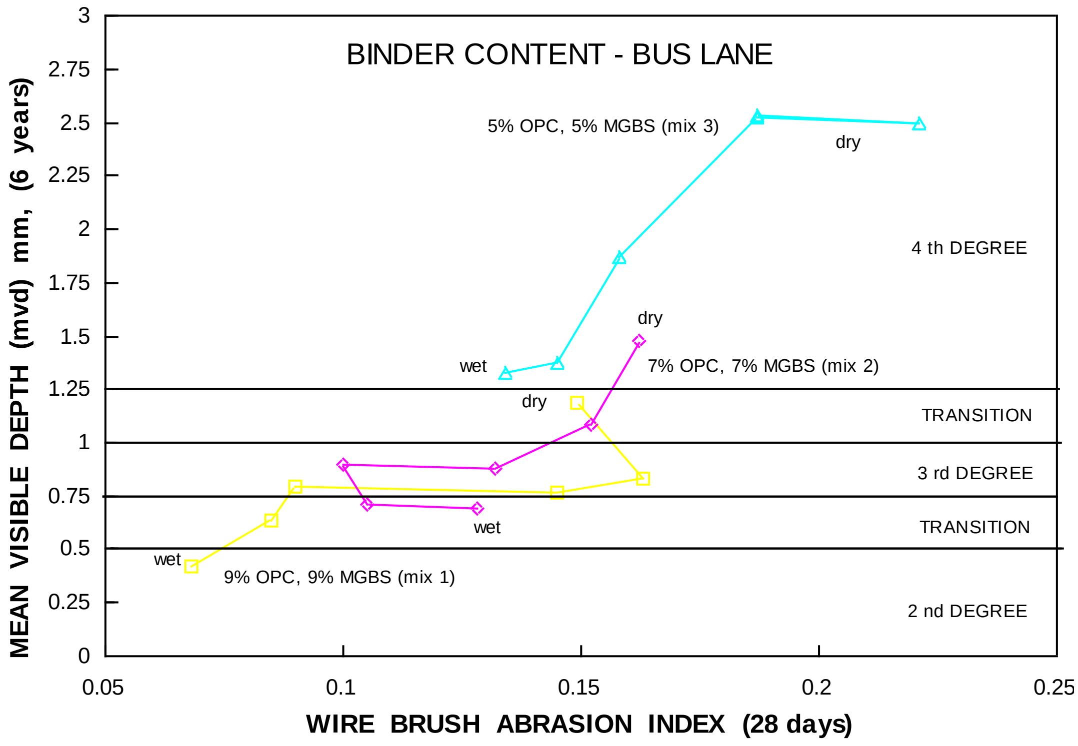

Figure 14-26 Relationship between 28-day wirebrush abrasion index (cm^3/cm^2) and mean visible depth after 6-years, for different binder contents - **bus lane**

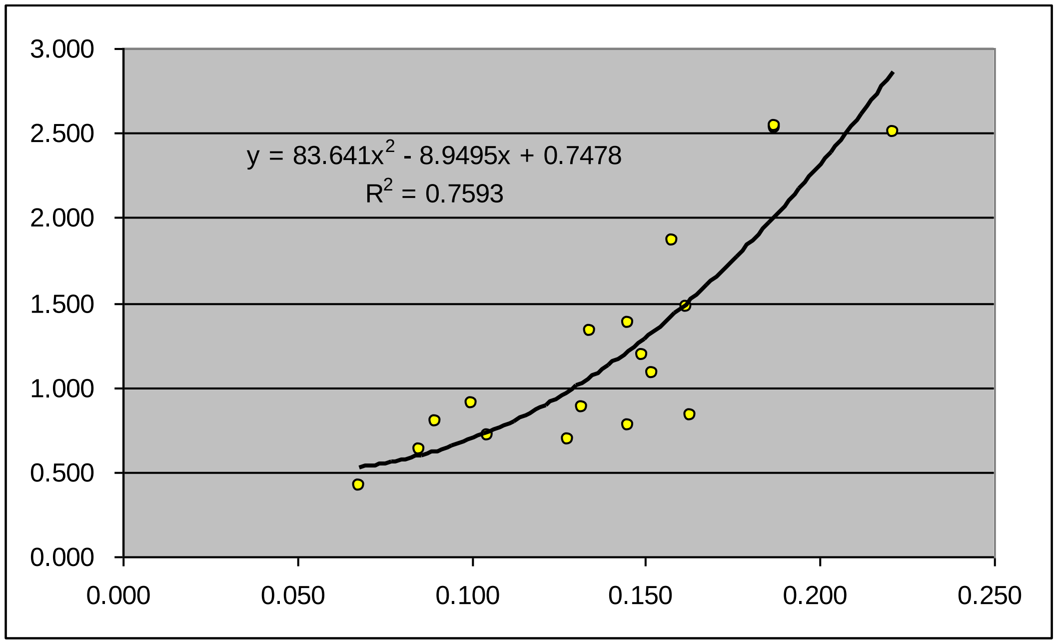

Figure 14.26-R^2 R^2 coefficients of figure 14.26, considering all 18 points together

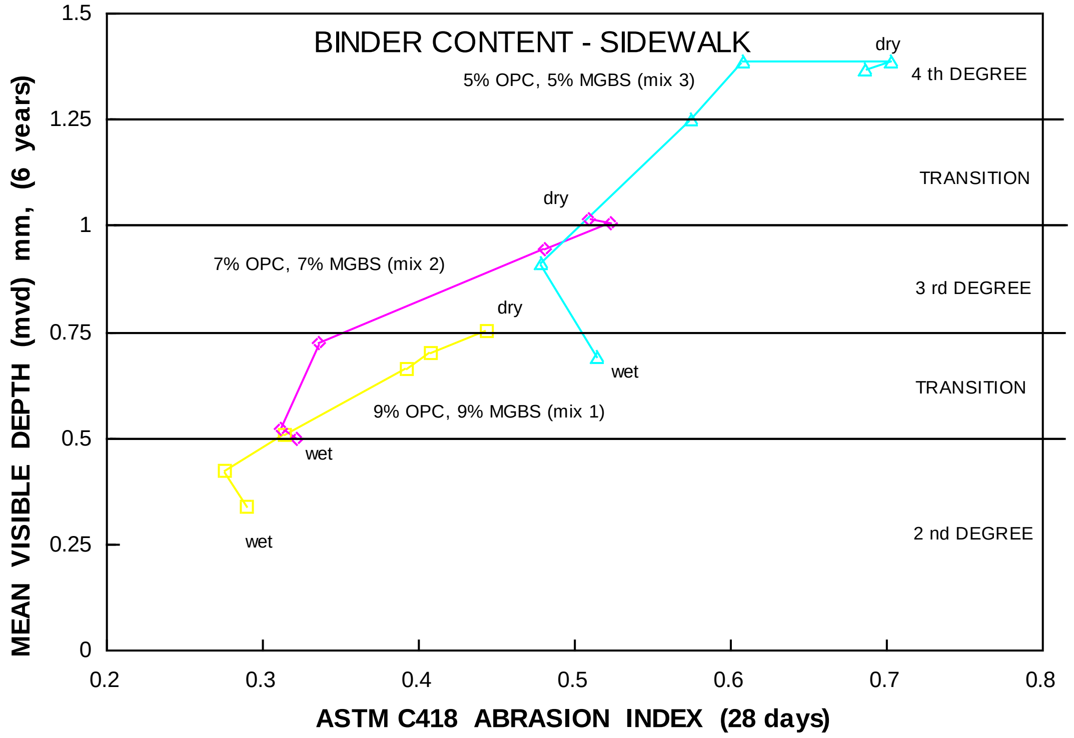

Figure 14-27 Relationship between 28-day ASTM C418 abrasion index (cm^3/cm^2) and mean visible depth after 6-years, for different binder contents – **sidewalk**

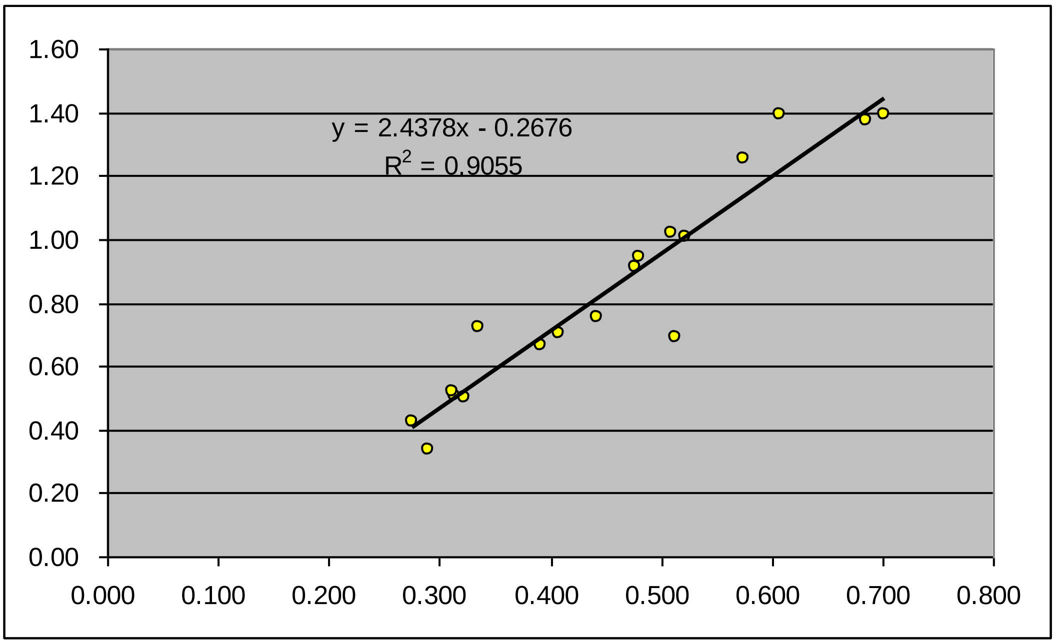

Figure 14.27-R^2 R^2 coefficients of figure 14.27, considering all 18 points together

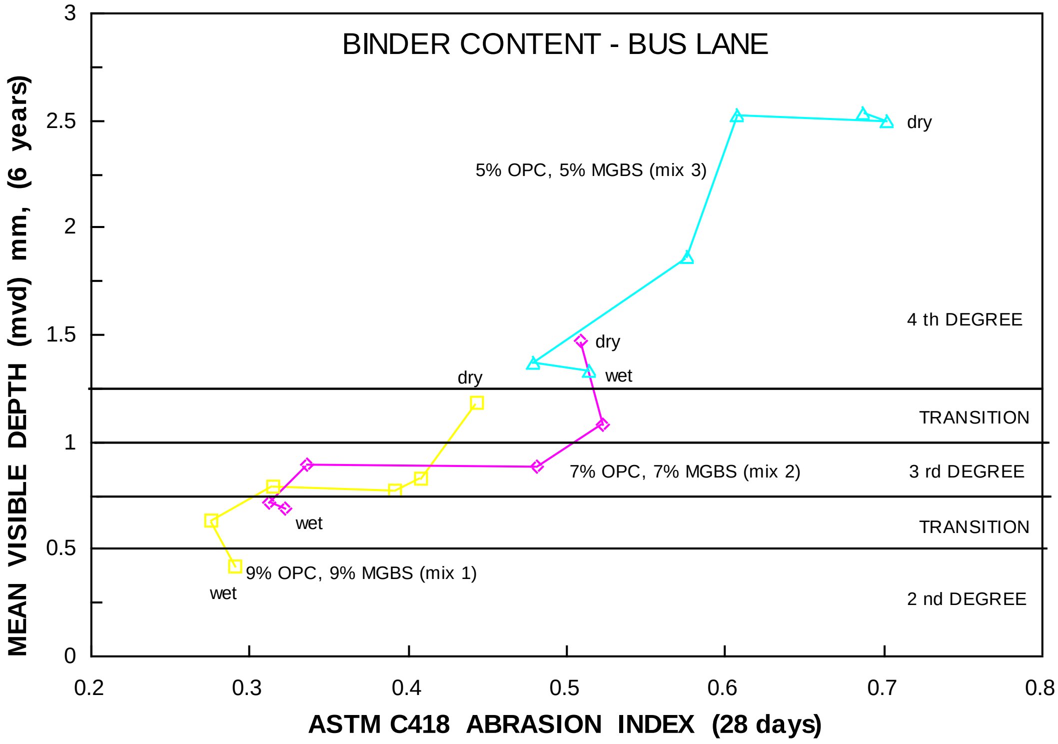

Figure 14-28 Relationship between 28-day ASTM C418 abrasion index (cm^3/cm^2) and mean visible depth after 6-years, for different binder contents - **bus lane**

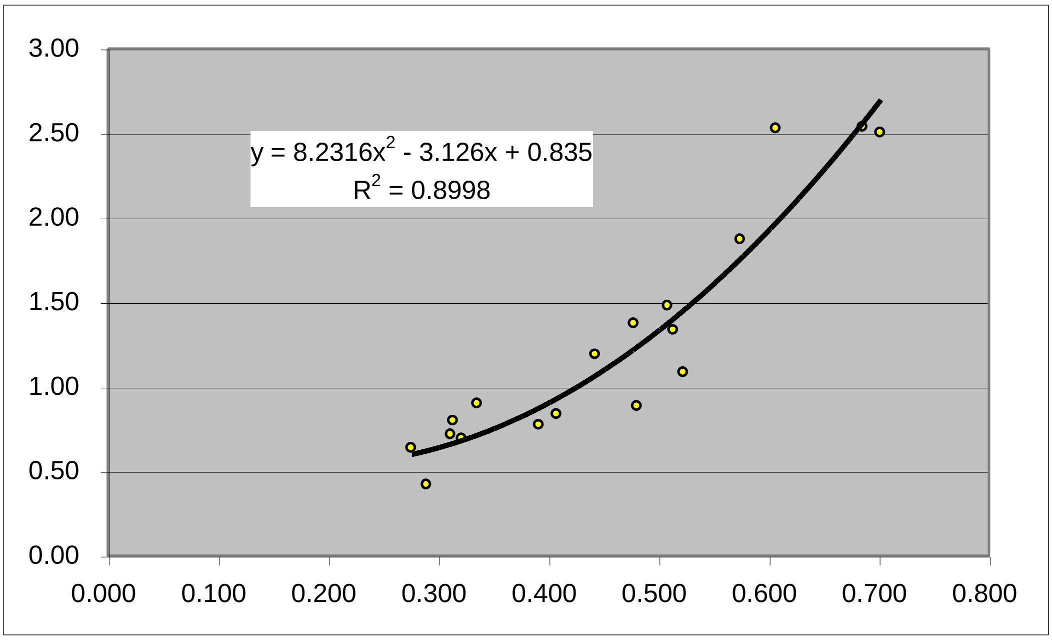

Figure 14.28-R^2 R^2 coefficients of figure 14.28, considering all 18 points together

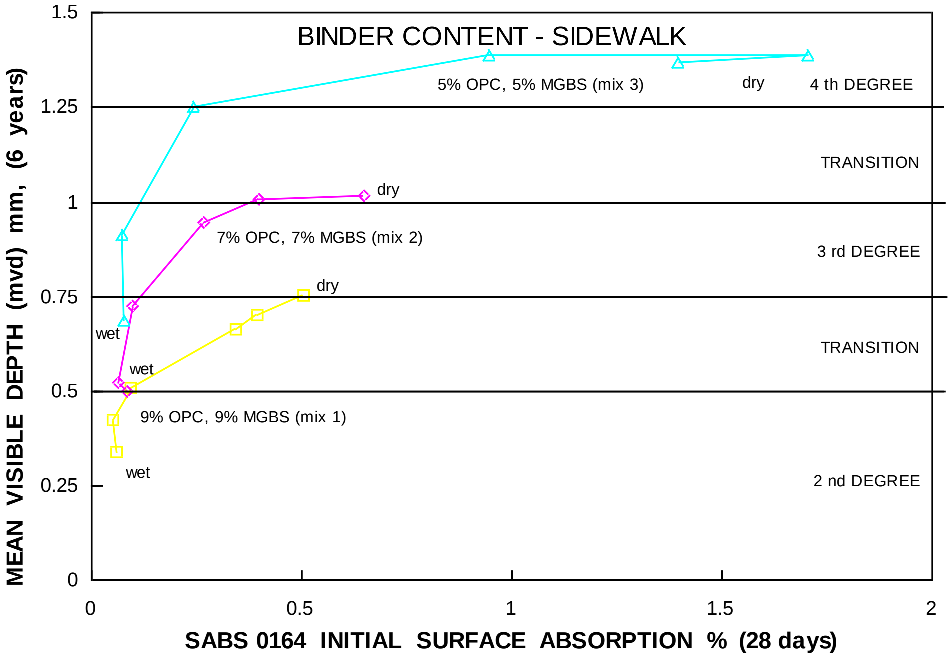

Figure 14.29 Relationship between 28-day ISAT and mean visible depth after 6-years, for different binder contents - **sidewalk**

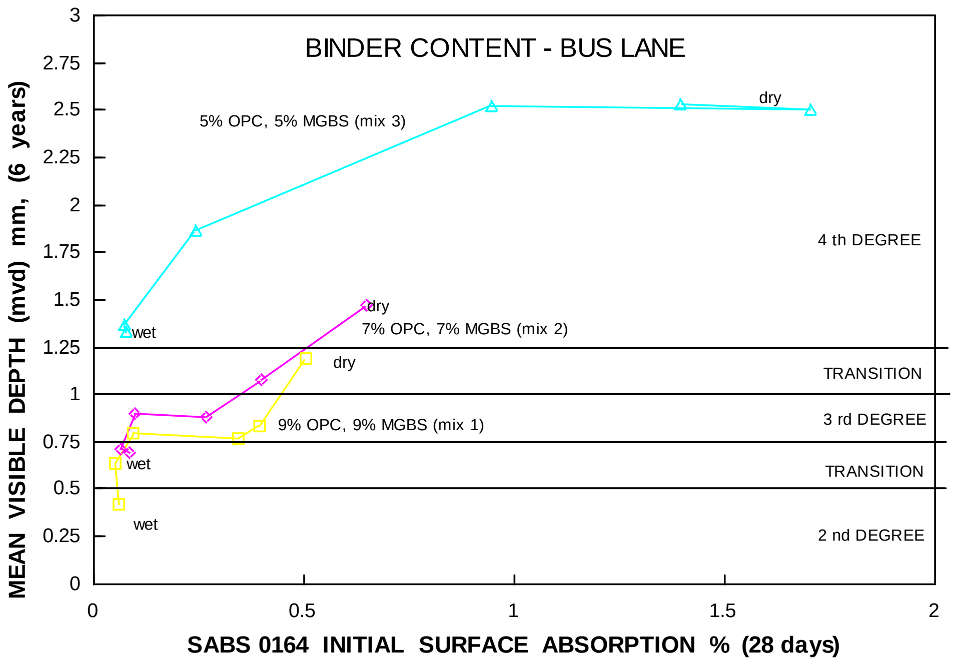

Figure 14.30 Relationship between 28-day ISAT and mean visible depth after 6-years, for different binder contents - **bus lane**

Sectional Conclusion

Clear relationships exist between 28-day abrasion testing and 6-year wear under traffic. This applies across a range of water contents (mixing water) and binder contents, providing that same binder type is used.

14.4.2 Limiting criteria for the three abrasion tests, considering mixes 1, 2 and 3 (same binder type).

In 14.2.1 it was demonstrated that where the same binder type is used, i.e. mix designs 1, 2 and 3, relatively strong correlations exist between mvd and the various indices, particularly for the ASTM and MA20 tests.

It will now be shown that it is possible to determine clearly defined limiting criteria for this group of mixes, even though the binder content varies from 10% through 18%.

This will be demonstrated by replotting figures 14-23 through 14-28 in a slightly different format, and these figures may appropriately be named 14-23a through 14-28a. In each graph all 18 points (corresponding to mixes 1, 2, and 3) will still be shown. However the connecting lines between the points will not be shown. Instead a line representing the upper mvd envelope of the 18 points will be drawn. (On some of the graphs one or two points lie outside this line, in which case the line may said to represent the 90th or perhaps 95th percentile envelope).

The corresponding x-axis values of the intersection of the mvd = 0,5 mm and mvd = 1,0 mm lines with this envelope may therefore be considered the limit for second and third degree abrasion respectively. The various limits for the three abrasion tests and the two traffic conditions are shown diagrammatically in figures 14-23a through 14-28a, and summarised in table 14.4.

The official limiting criteria of the specifications are also included in table 14.4 to enable comparisons to be made. This has required a degree of ‘fitting and interpretation’ to conform with the format used in this investigation, as shown in the table, and the reader should refer to the various sections where the official description of the traffic conditions are given, i.e. 9.3, table 10.2 and 11.3.3.

TABLE 14.4 28-day LIMITING CRITERIA FOR THREE ABRASION TESTS

ABRASION TEST	FOR 2nd DEGREE WEAR AFTER 6-years TRAFFIC		FOR 3 rd DEGREE WEAR AFTER 6-years TRAFFIC	
	SEVERE TRAFFIC	NORMAL TRAFFIC	SEVERE TRAFFIC	NORMAL TRAFFIC
MA20SA - results	2.9	1.7	0.9	0.7
MA20 - interim limits of 1986	2.0	1.5	1.2	-
WIREBRUSH – results (cm^3/cm^2)	0.073	0.085	0.105	0.136
WIREBRUSH - official limits (cm^3/cm^2)	0.050	0.100	0.150	0.200
ASTM C418 – results (cm^3/cm^2)	0.250	0.305	0.360	0.475
ASTM C936 - official limits (cm^3/cm^2)	0.300	0.300	-	-

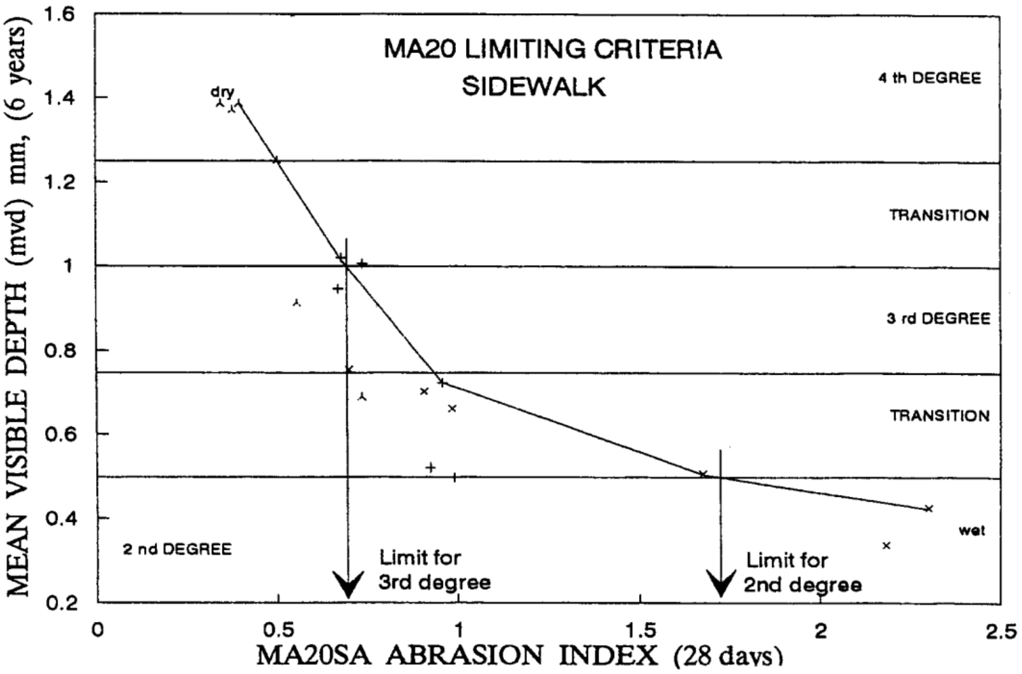

Figure 14.23a 28-day MA20SA abrasion index limiting criteria, for different binder contents - **sidewalk**

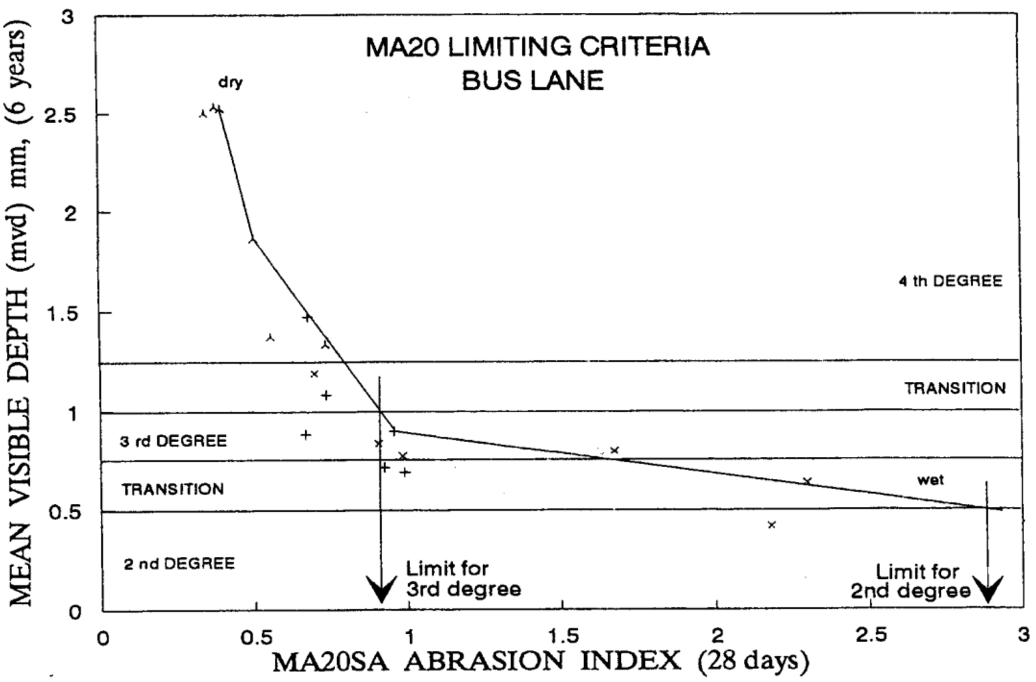

Figure 14.24a 28-day MA20SA abrasion index limiting criteria, for different binder contents - **bus lane**

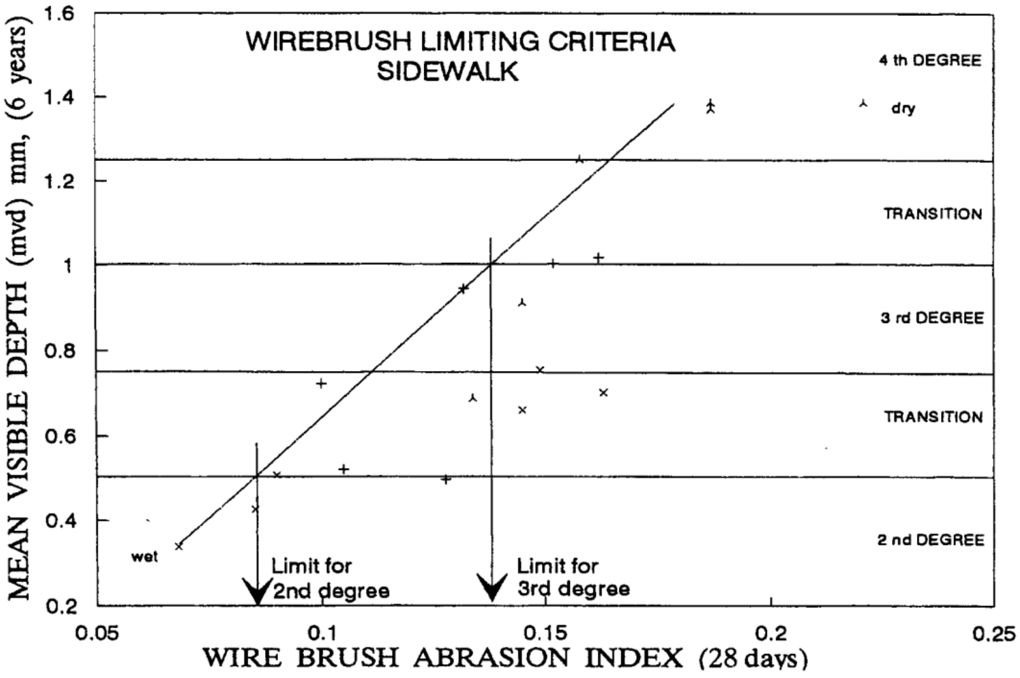

Figure 14.25a 28-day wirebrush abrasion index limiting criteria, for different binder contents - **sidewalk**

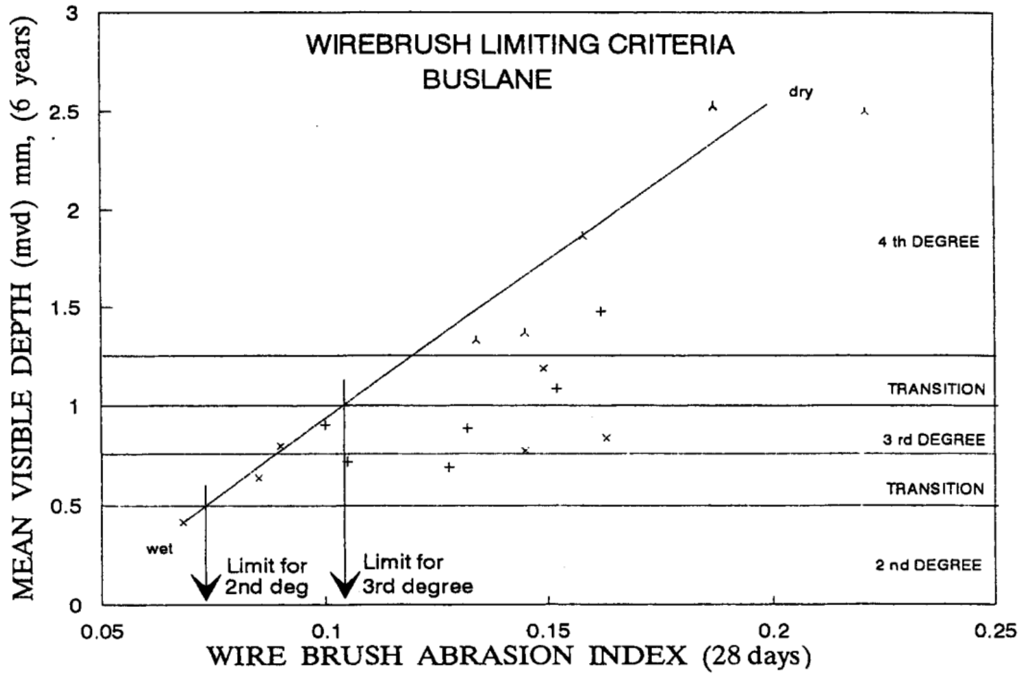

Figure 14.26a 28-day wirebrush abrasion index limiting criteria, for different binder contents - **bus lane**

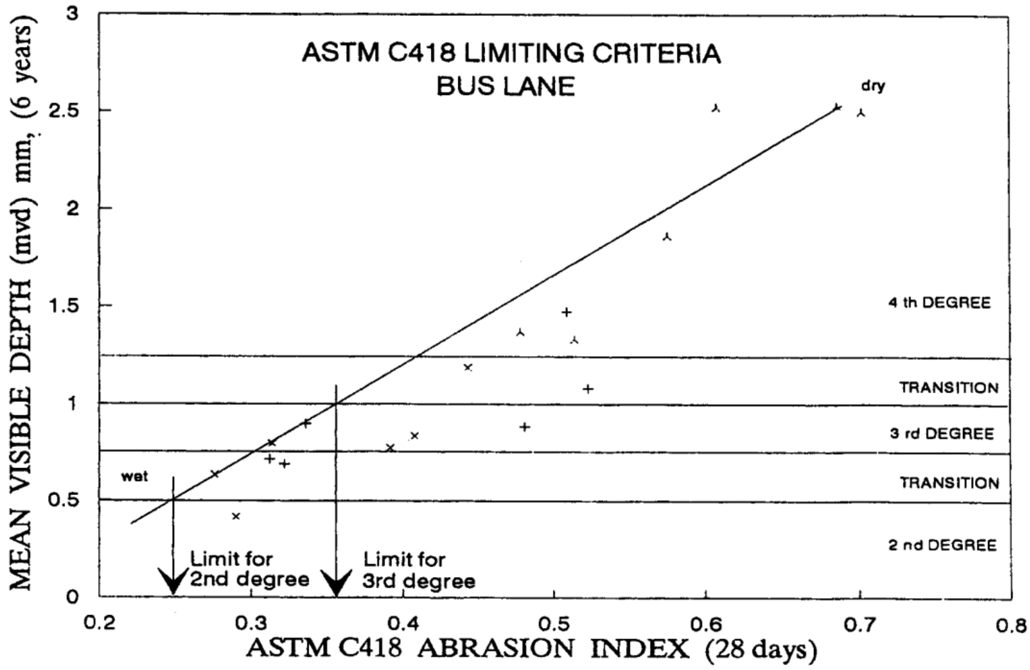

Figure 14.27a 28-day ASTM C418 abrasion index limiting criteria, for different binder contents - **sidewalk**

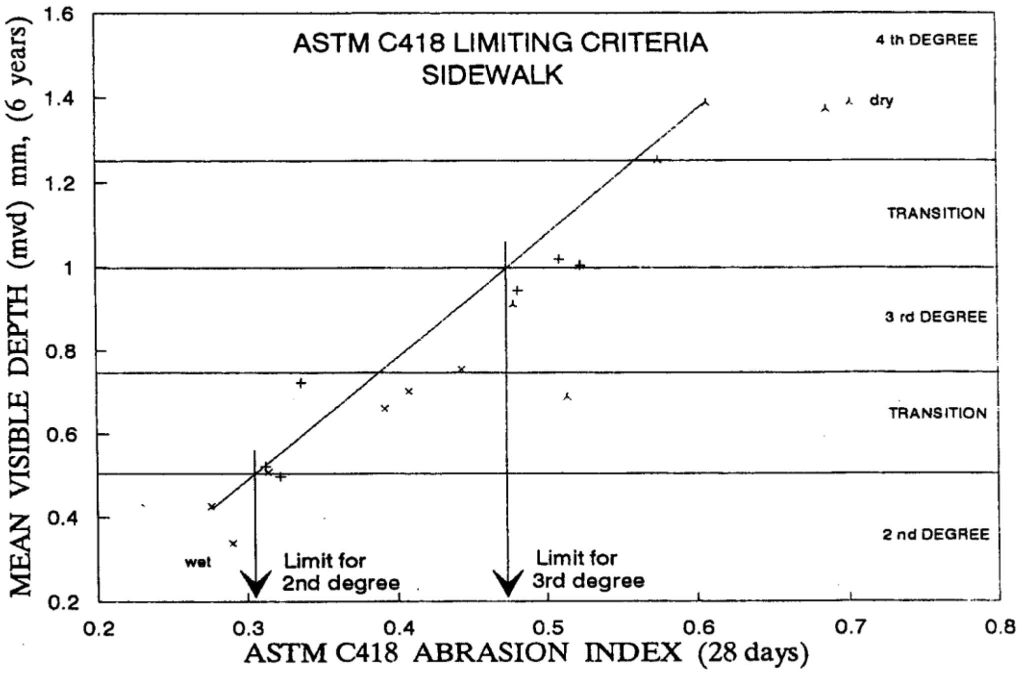

Figure 14.28a 28-day ASTM C418 abrasion index limiting criteria, for different binder contents - **bus lane**

The limits given in the figures and table above have the potential to make the results of the three abrasion tests meaningful. They enable both the designer and manufacturer to verify the expected long-term performance of a batch of pavers.

The limits specifically apply to Reef quartzite aggregate. This is not so great a restriction, since several aggregates are as hard or harder than reef quartzite, such as dolerite, andesite, granite etc. Where such aggregates (which are generally superior to reef quartzite are used, these limits are likely to be conservative, and can therefore be safely applied, providing the grading, surface texture and particle shape do not result in a substantially higher water demand.

Of far greater significance than aggregate type in this investigation are the variations in binder type. This dramatically influences the 28-day results and corresponding abrasion indices, so that it is no longer possible to arrive at universal 28-day limits.

This is considered in the next section.

14.4.3 The effect of variations in binder type on the mvd, considering each of the five mix designs individually

A general feature depicted in the following graphs (figures 14-31 through 14-38) is that the total binder content is the same for all five mix designs, i.e. 14%.

Observations

It is evident that mixes incorporating fly ash have retarded 28-day MA20SA indices, while the inclusion of silica fume results in accelerated 28-day indices (relative to the control mix, mix 2). However, the fly ash mixes, particularly mix 5 and 6 have the least wear after 6-years. This is consistent with the known early retardation of fly ash mixes, and their superior long-term strength owing to pozzolanic activity.

MA20SA vs mvd: Figures 14.31-R^2 and 14.32-R^2 indicate a series of trend lines, with the degree of experimental scatter indicated by the R^2 coefficients. (Note that these 'R^2' graphs plot precisely the same data as the 'parent' graphs (figures 14.31 and 14.32) shown above them, but the volume of information justifies two graphs for each mix design to avoid clutter). It is evident that the trend-lines are approximately parallel to each other, or they tend to converge at lower values of mvd. This then appears to be a characteristic feature of varying binder type with various cement extenders including MGBS, fly ash, and silica fume.

Wirebrush vs mvd: In figures 14.33-R^2 and 14.34-R^2 the various trend lines are not as linear as in the MA20SA graphs. The individual lines also either tend to run parallel, or converge at lower mvd values.

ASTM C418 vs mvd: Once again these curves (see figures 14.35-R^2 and 14.36-R^2) are not as linear as the MA20SA curves. Again the same general trends discussed above are evident.

ISAT 0164 vs mvd: The graphs indicate a series of non-linear curves, with increasing scatter as % ISAT increases.

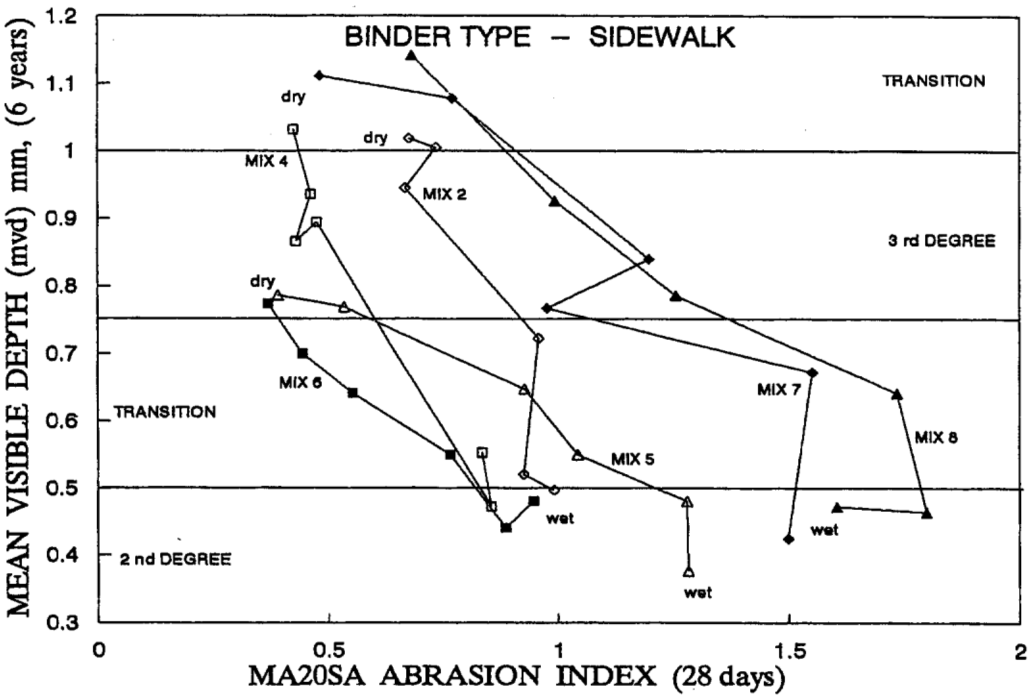

Figure 14.31 Relationship between the 28-day MA20SA abrasion index and mean visible depth after 6-years, for different binder types - **sidewalk**

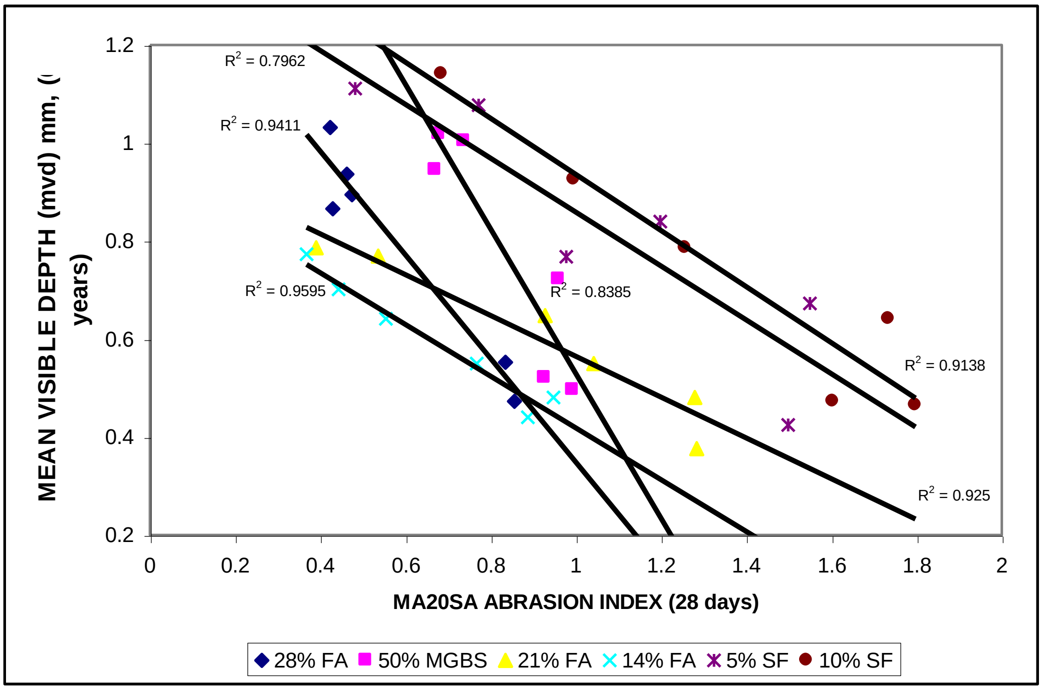

Figure 14.31-R^2 R^2 -coefficients of figure 14.31, showing the six trend lines of the six binder types -- **sidewalk**

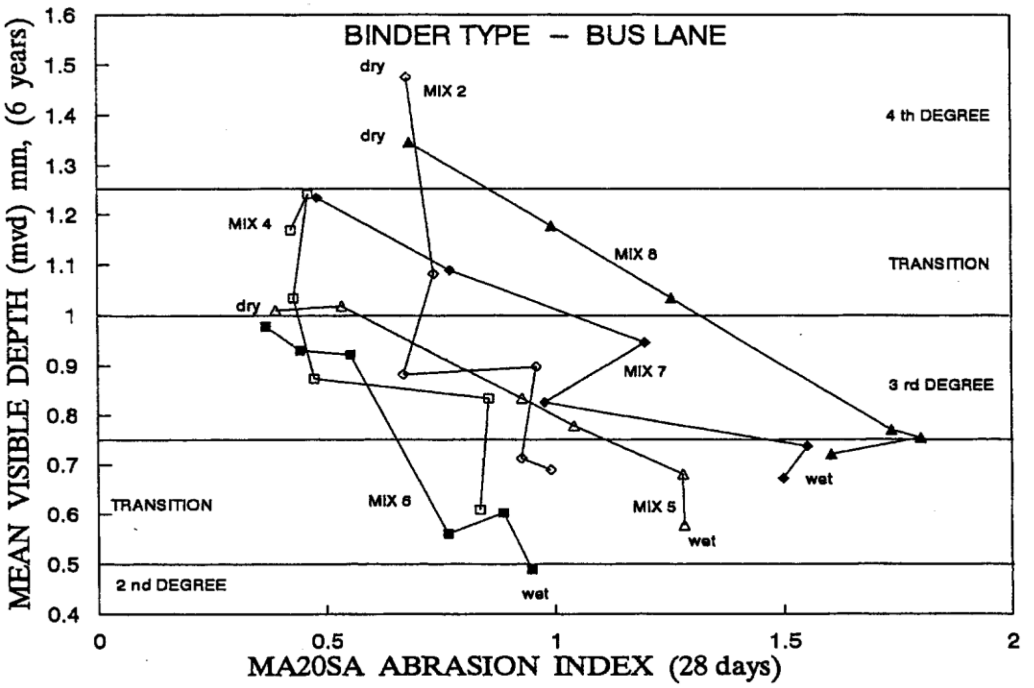

Figure 14.-32 Relationship between the 28-day MA20SA abrasion index and mean visible depth after 6-years, for different binder types - **bus lane**

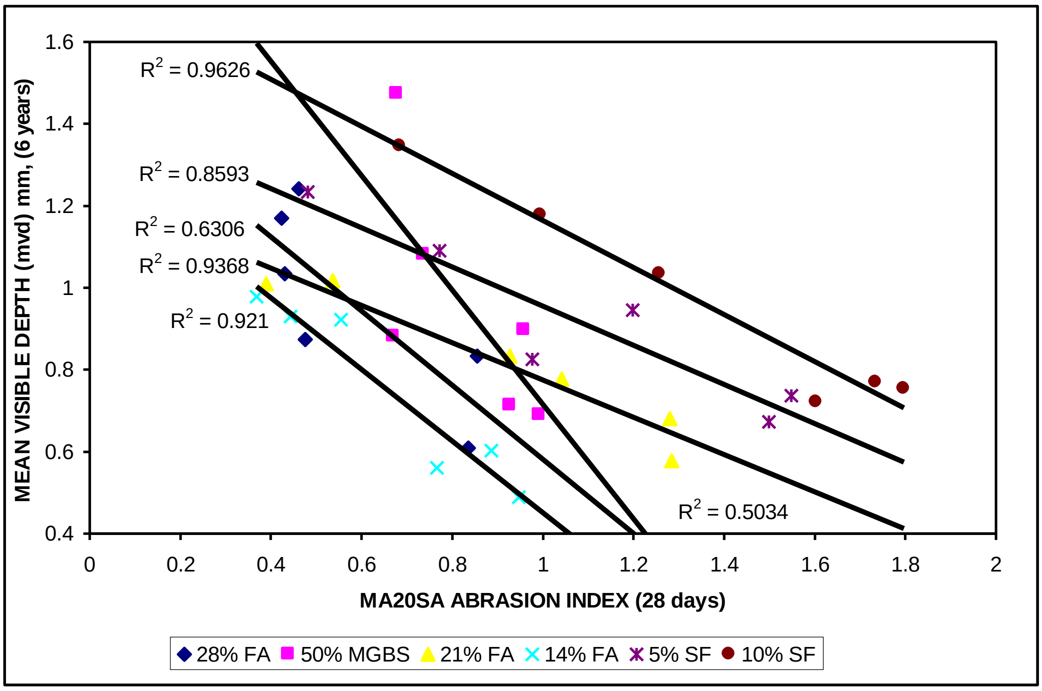

Figure 14.32-R^2 R^2-coefficients of figure 14.32, showing the six trend lines of the six binder types – **bus lane**

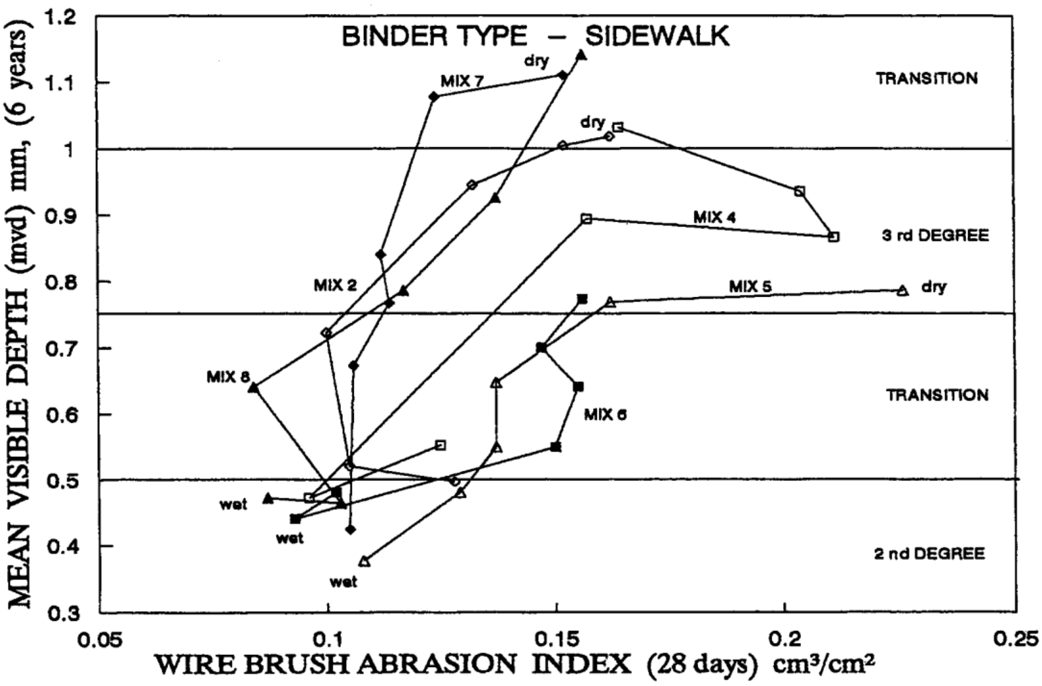

Figure 14-33 Relationship between the 28-day wirebrush abrasion index and mean visible depth after 6-years, for different binder types - **sidewalk**

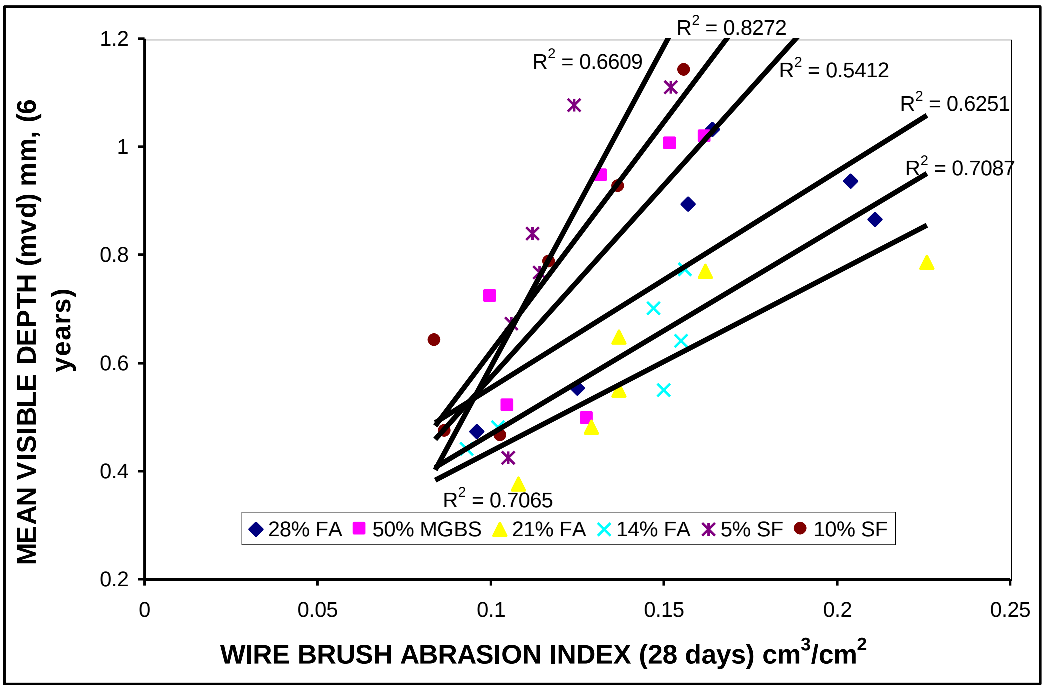

Figure 14.33-R^2 R^2-coefficients of figure 14.33, showing the six trend lines of the six binder types – **sidewalk**

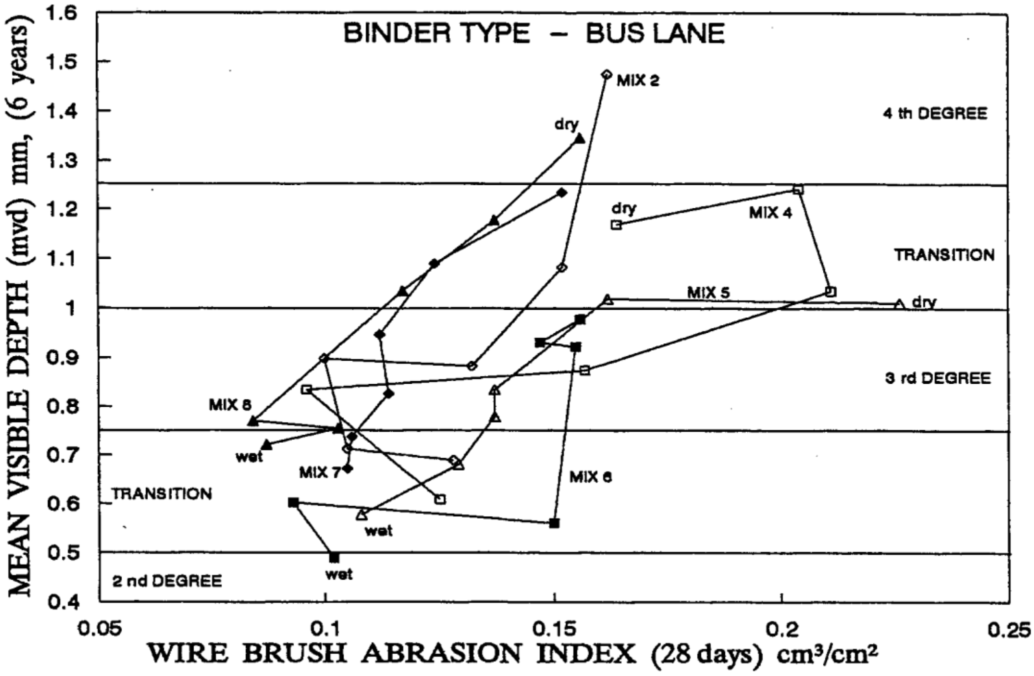

Figure 14-34 Relationship between the 28-day wirebrush abrasion index and mean visible depth after 6-years, for different binder types – **bus-lane**

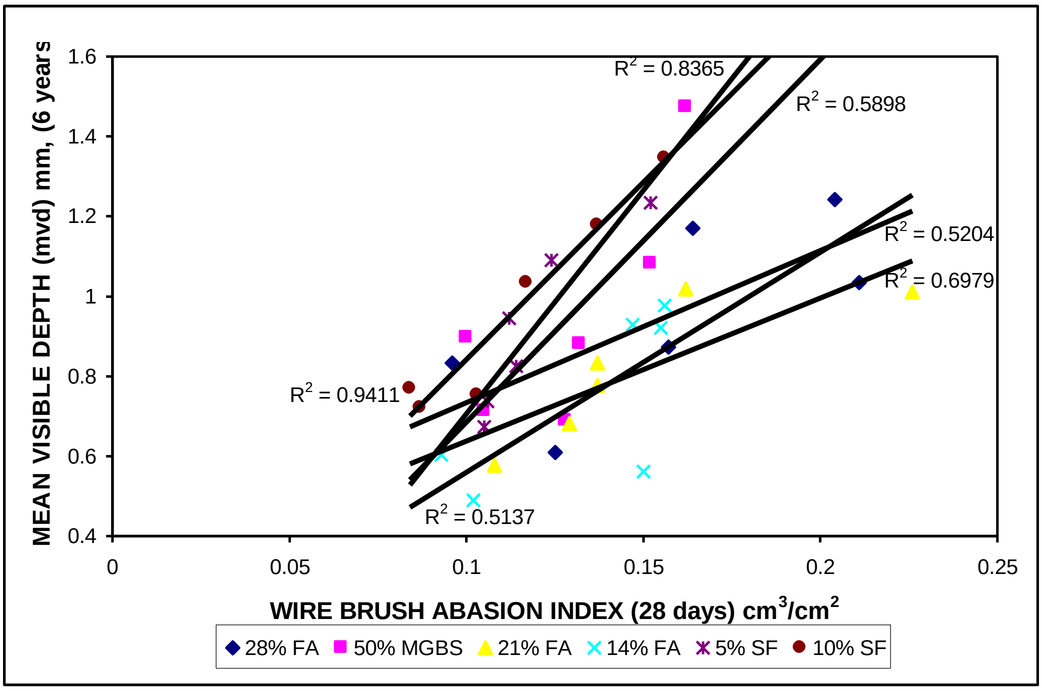

Figure 14.34-R^2 R^2-coefficients of figure 14.34, showing the six trend lines of the six binder types – **bus lane**

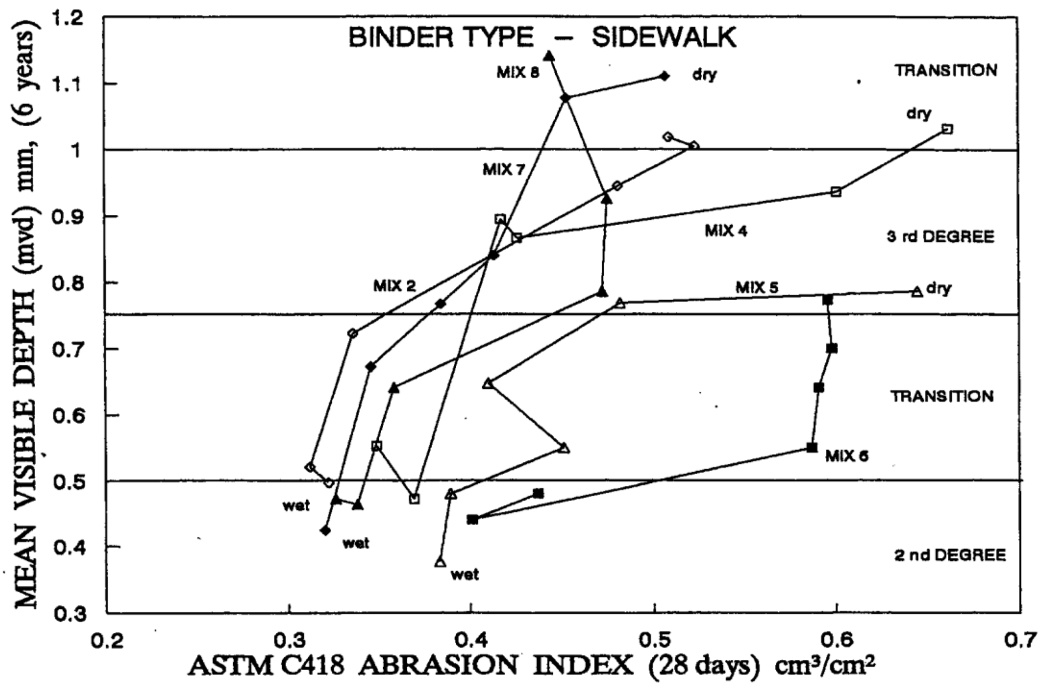

Figure 14.35 Relationship between the 28-day ASTM C418 abrasion index and mean visible depth after 6-years, for different binder types - **sidewalk**

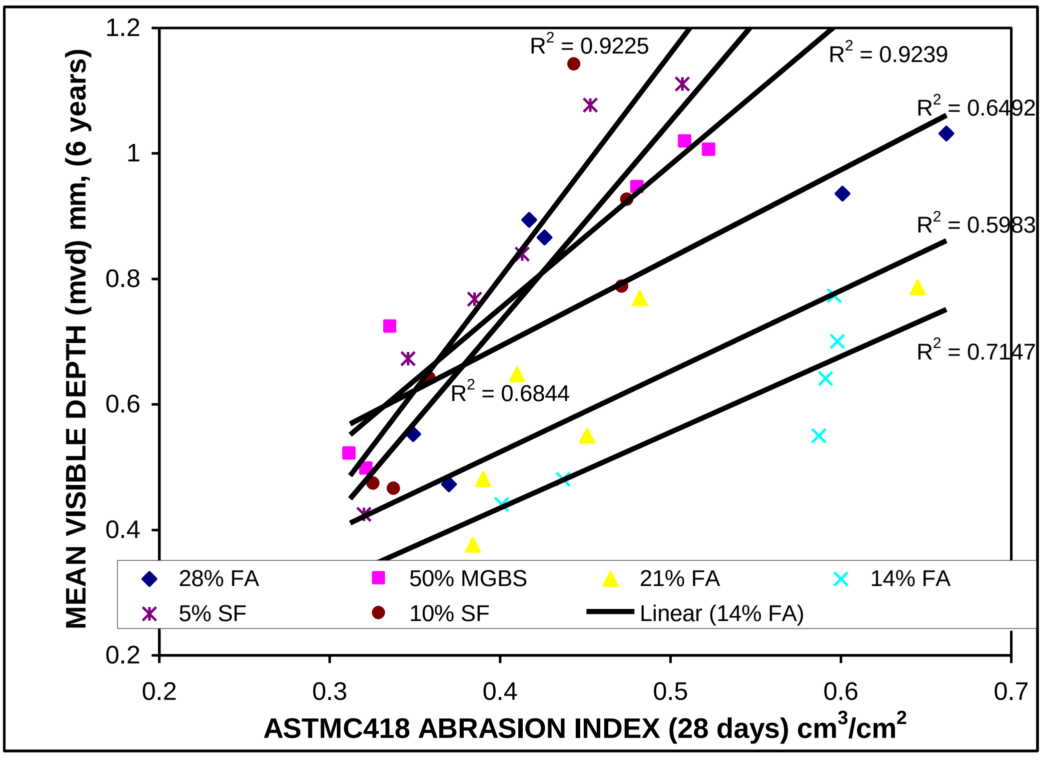

Figure 14.35-R^2 R^2-coefficients of figure 14.35, showing the six trend lines of the six binder types – **sidewalk**

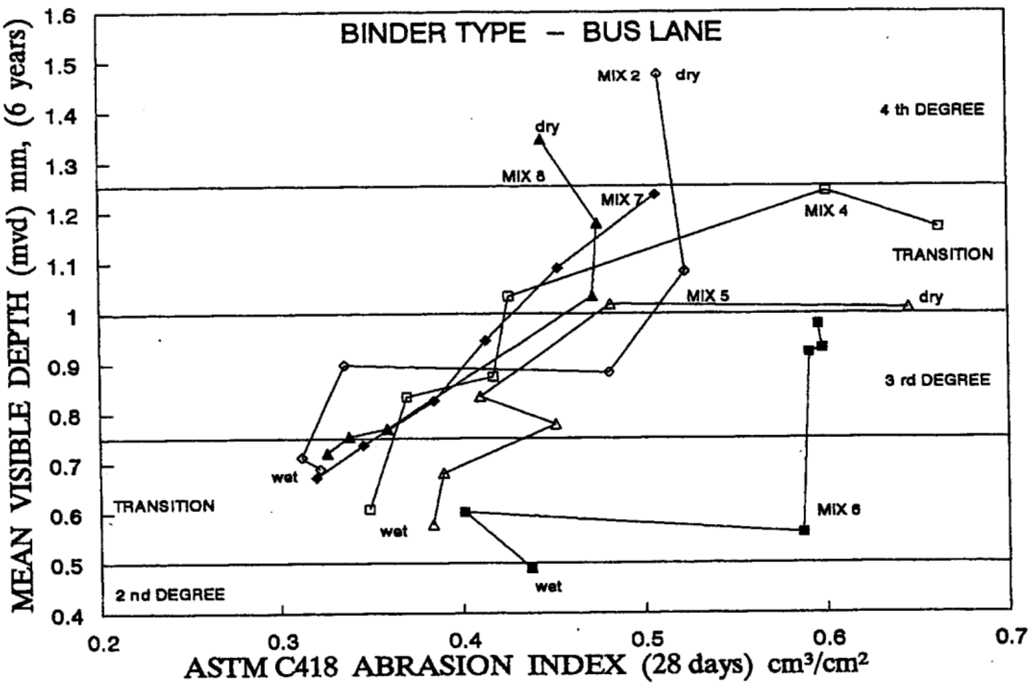

Figure 14-36 Relationship between the 28-day ASTM C418 abrasion index and mean visible depth after 6-years, for different binder types – **bus lane**

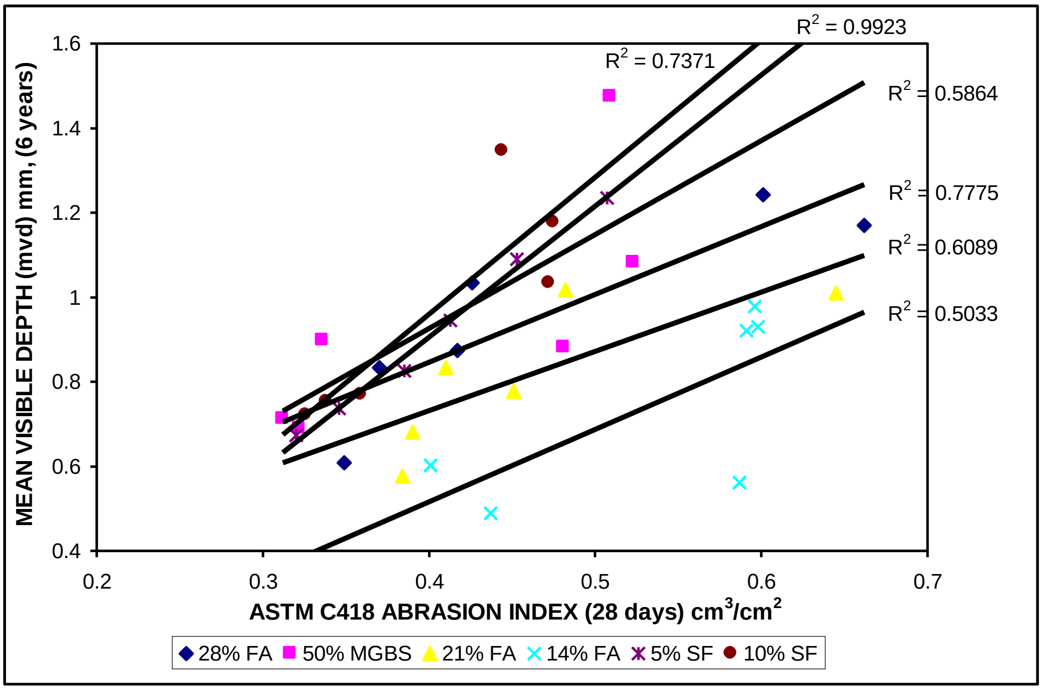

Figure 14.36-R^2 R^2-coefficients of figure 14.36, showing the six trend lines of the six binder types – **bus lane**

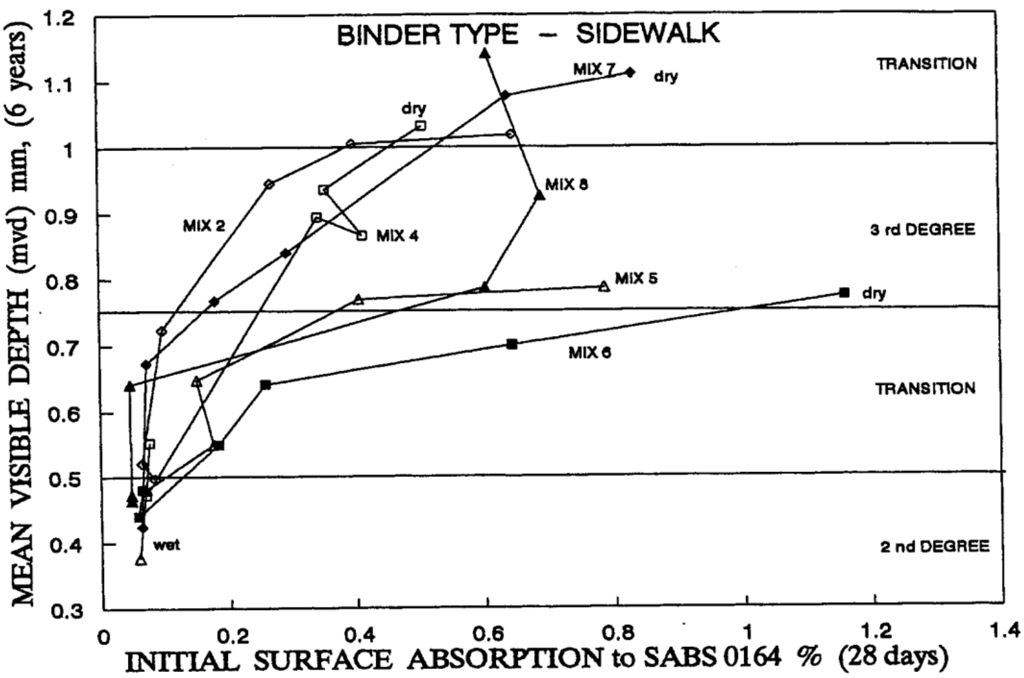

Figure 14-37 Relationship between the 28-day ISAT and mean visible depth after 6-years, for different binder types - **sidewalk**

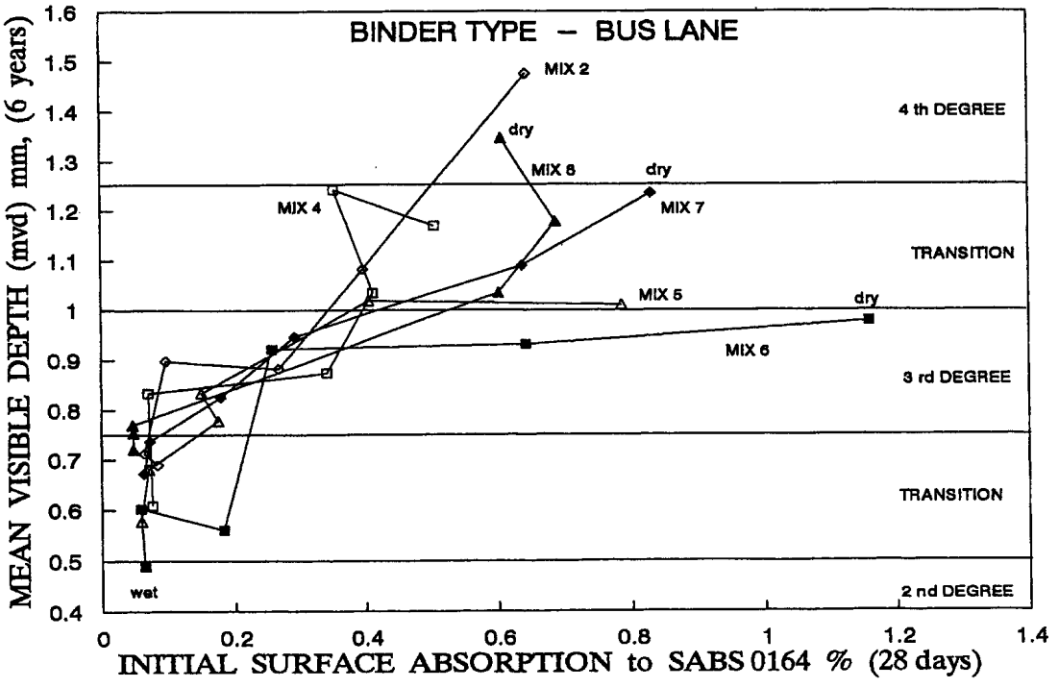

Figure 14-38 Relationship between the 28-day ISAT and mean visible depth after 6-years, for different binder types – **bus lane**

Discussion

When the individual mix designs are plotted separately (by connecting the six points corresponding to the different moisture contents) distinct trends emerge, from what formally appeared as a wide scatter of points seen in figures 14.15 through 14.20. Now the effect of different binder contents and binder types is evident.

Earlier it was seen that limiting criteria can be determined for all three abrasion tests where the type of binder is the same, but where binder type is varied this is no longer a simple matter. It is evident that mixes incorporating fly ash have retarded 28-day indices, while the inclusion of silica fume acts as an accelerator. However, the lack of early strength in the fly ash mixes is more than compensated for by ongoing pozzolanic activity, so that the fly ash mixes had the lowest mvd values after 6-years. Conversely the silica fume mixes had accelerated 28-day strength development, but the slowest strength development after 28-days

These opposite trends in early and later strength development account for the individualism of the trend lines. Furthermore in the MA20 test they are separated but parallel, while in the wirebrush and sandblast tests the trend lines have more of a tendency to converge as the abrasion wear (28-day indices and 6-year mvd) decreases. (In 14.6 a method of establishing limits for individual mix designs with different binder types is discussed, with a view to establishing limiting criteria).

Except for a few mix designs, the data for the individual curves may be visually judged as reasonably linear, although the degree of scatter about the trend line varies considerably. For example, mix 7 of figure 14.36 has an R^2 coefficient of 0,9923, while that for mix 6 is 0,5033.

The average R^2 values for the six figures (figure 14.31- R^2 through figure 14.36- R^2) is summarised in table 14.5

The relatively high average R^2 coefficients shown in the table for the various straight line regression analyses confirms that the data for the individual mix designs is reasonably linear, although clearly the best results are obtained for the sidewalk graphs. It may further be seen the MA20 has the best linearity of the three abrasion tests, i.e. over a range of mix designs the MA20 test has the most linear relationship with wear under traffic. This is somewhat surprising, since both the wirebrush and ASTM effectively measure abrasion wear, (in the form of the average depth of penetration) and mvd is in effect also a measure of abrasion-wear. MA20 on the other hand is proportional to the inverse of the penetration of ball bearings into the surface.

Table 14.5 Average R^2 coefficients of 6 water contents/mix designs for all 6 mix designs

	Side walk	Bus lane	Average for both
MA20SA	0,8957	0,8023	0,8490
Wirebrush	0,6783	0,6832	0,6808
ASTM C418	0,7488	0.7009	0,7249

Sectional Conclusion

Where different binder types are used in mixes, distinct relationships emerge between accelerated 28-day abrasion testing and mvd at 6-years. This complicates the process of establishing abrasion indices.

14.5 The MA20SA Test

In chapter 12 the three abrasion tests were compared, and for various reasons the MA20SA test was selected as the most suitable. Consequently the CMA20 test, a refinement of MA20SA, was recommended as an industry standard.

The ASTM C418 test has the best average correlation coefficient (abrasion index vs mvd) of all the trend-lines in figures 14.23 through 14.30, with MA20 the second best. However in figures 14.31 through 14.38 this situation is reversed.

Moreover the figures indicate that the MA20SA test is the most sensitive (compare figure 14.24 against 14.26 and 14.28), and can therefore best distinguish changes in the mix design such as a change in binder content. Figure 14.31 and 14.32 show that it can also ably discern changes in binder type.

These results reinforce the selection of the MA20SA test in chapter 12. For these reasons the MA20SA is considered the most appropriate test for developing design graphs in the next section.

14.6. Design Graphs

In this section design graphs are developed from the MA20SA vs mvd results. They are designed to facilitate the correct mix design selection for given traffic conditions. Eight design graphs are given in figures 14.39 through 14.46 for specific mixes. The curves are constructed from the data in table 14.2, and thus represent variations in binder content, binder type and water content.

In each case the wear after 6-years of traffic (Y axis) can be predicted from the 28-day results of the MA20SA abrasion test (X axis) for two traffic regimes, one for ‘severe’ vehicular traffic (‘bus lane’), and the other for heavy pedestrian traffic (‘sidewalk’). The latter may generally be considered suitable for most ‘normal’ applications. The second Y-axis on the right hand side shows how water content variation affects both the MA20SA abrasion index and long term wear.

Generally the wettest mix design was so wet that the blocks were slightly slumped. This created some problems during the installation process at Westgate. For this reason the lines in figures 14.39 through 14.46 between the wettest and second wettest point should not be considered by the designer / manufacturer.

The design graphs can be considered to be conservative, since the curves appearing on the respective graphs are generally plotted to coincide with the respective upper envelopes. The ‘smoothing’ command of Lotus 3.4 was used to obtain a relatively smooth curve between the selected points. The occasional obvious outlier however is ignored.

The different degrees of abrasion appear as horizontal bands, and allowance is also made for transitional zones as explained in 14.2.4.

The corresponding x-axis values of the intersection of the two traffic regime lines with the 0,5 mm and 1,0 mm mvd values become the **limits** for the MA20SA abrasion test for the respective mixes. These are shown by vertical arrows, and are tabulated in table 15.1. Horizontal arrows show the corresponding water contents.

It is apparent that each graph has its own unique limits. The establishment of an industry wide ‘national’ limit is discussed in chapter 15.

14.6.1 How to read and interpret the nomograms

Figure 14.39 has been marked with the markers ‘a’ through ‘m’, to signify the steps in interpreting these nomograms:

Marker ‘a’ represents the intersection of the ‘severe’ mvd vs MA20SA curve and a horizontal line representing the upper limit of 3rd degree abrasion wear. From this point drop a vertical to intersect the x-axis, at **marker ‘b’**, which represents the minimum MA20SA abrasion index to be obtained in a 28-day abrasion test if abrasion-wear is not to exceed 3rd degree. **Marker ‘c’** is at the intersection of the vertical (projected up from marker ‘b’) with the curve representing the relationship between the MA20SA abrasion index and the water contents of the respective mixes. **Marker ‘d’** is on the 2nd y-axis obtained by a horizontal projection from marker ‘c’, and represents the minimum water content required in the mix if abrasion wear under traffic at 6-years is to be limited to 3rd degree.

Marker ‘e’ represents the intersection of the ‘normal’ mvd vs MA20SA curve and a horizontal line representing the upper limit of 2nd degree abrasion wear. From this point drop a vertical to intersect the x-axis, at **marker ‘f’**, which represents the minimum MA20SA abrasion index to be obtained in a 28-day abrasion test if abrasion-wear is not to exceed 2nd degree. **Marker ‘g’** is at the intersection of the vertical (projected up from marker ‘f’) with the curve representing the relationship between the MA20SA abrasion index and the water contents of the respective mixes. **Marker ‘h’** is on the 2nd y-axis obtained by a horizontal projection from marker ‘g’, and represents the minimum water content required in the mix if abrasion wear under traffic at 6-years is to be limited to 2nd degree.

Marker ‘j’ represents the intersection of the ‘severe’ mvd vs MA20SA curve and a horizontal line representing the upper limit of 2nd degree abrasion wear. From this point drop a vertical to intersect the x-axis, at **marker ‘k’**, which represents the minimum MA20SA abrasion index to be obtained in a 28-day abrasion test if abrasion-wear is not to exceed 2nd degree. **Marker ‘l’** is at the intersection of the vertical (projected up from marker ‘k’), with the curve representing the relationship between the MA20SA abrasion index and the water contents of the respective mixes. **Marker ‘m’** is on the 2nd y-axis obtained by a horizontal projection from marker ‘l’, and represents the minimum water content required in the mix if abrasion wear under traffic at 6-years is to be limited to 2nd degree.

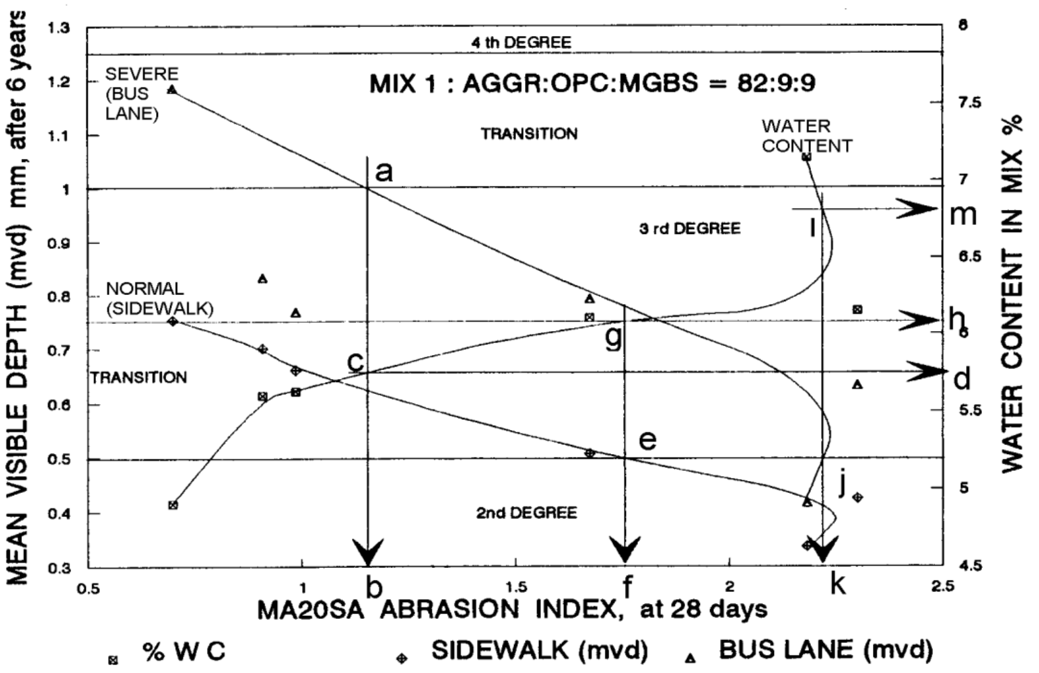

Figure 14.39 Design graph for **mix 1** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

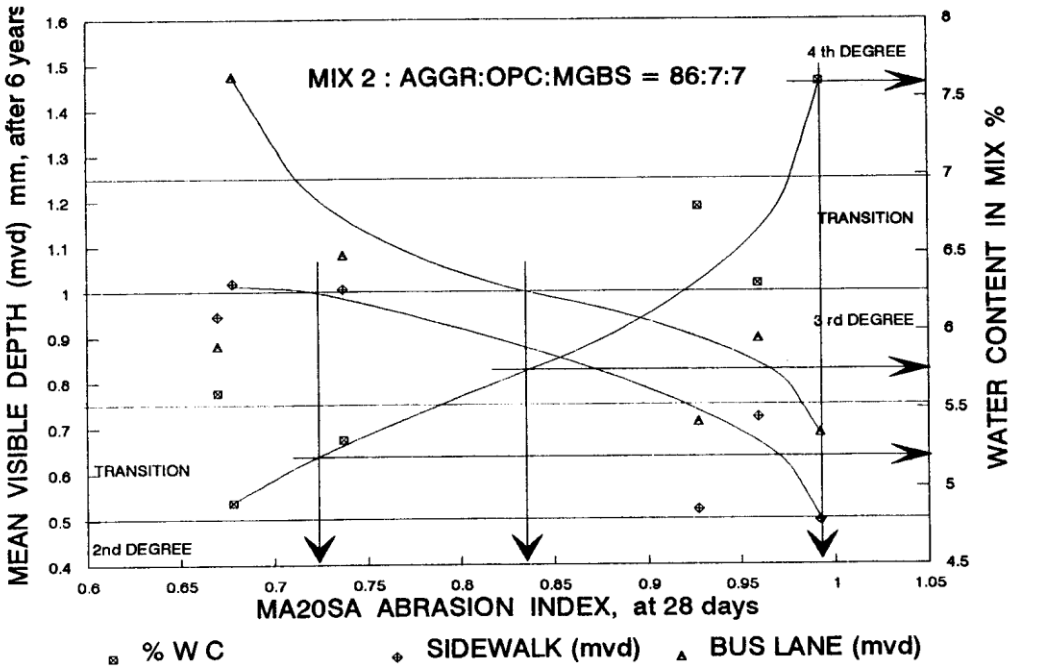

Figure 14.40 Design graph for **mix 2** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

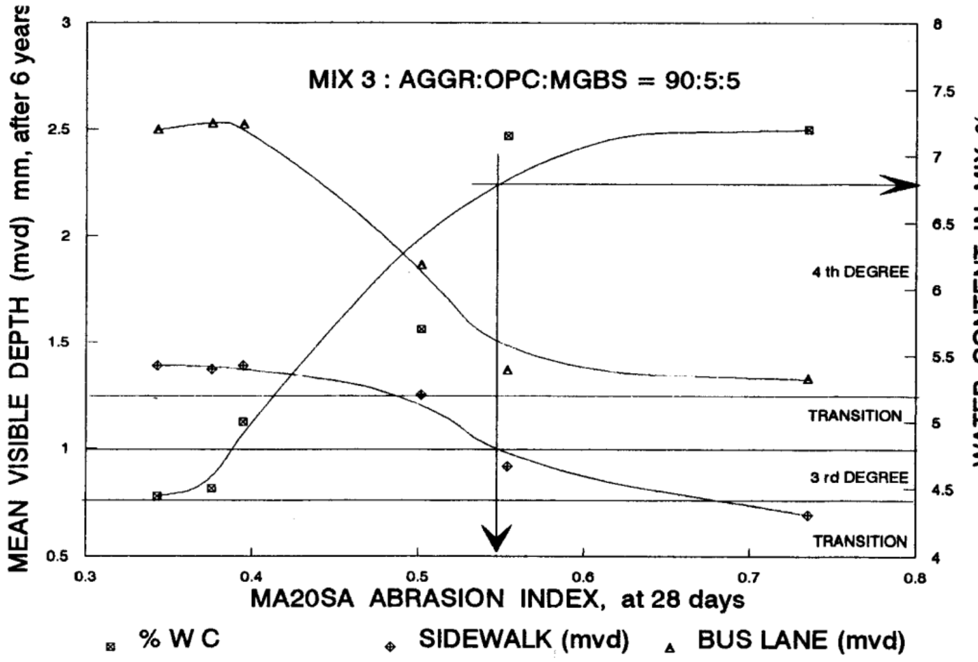

Figure 14.41 Design graph for **mix 3** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

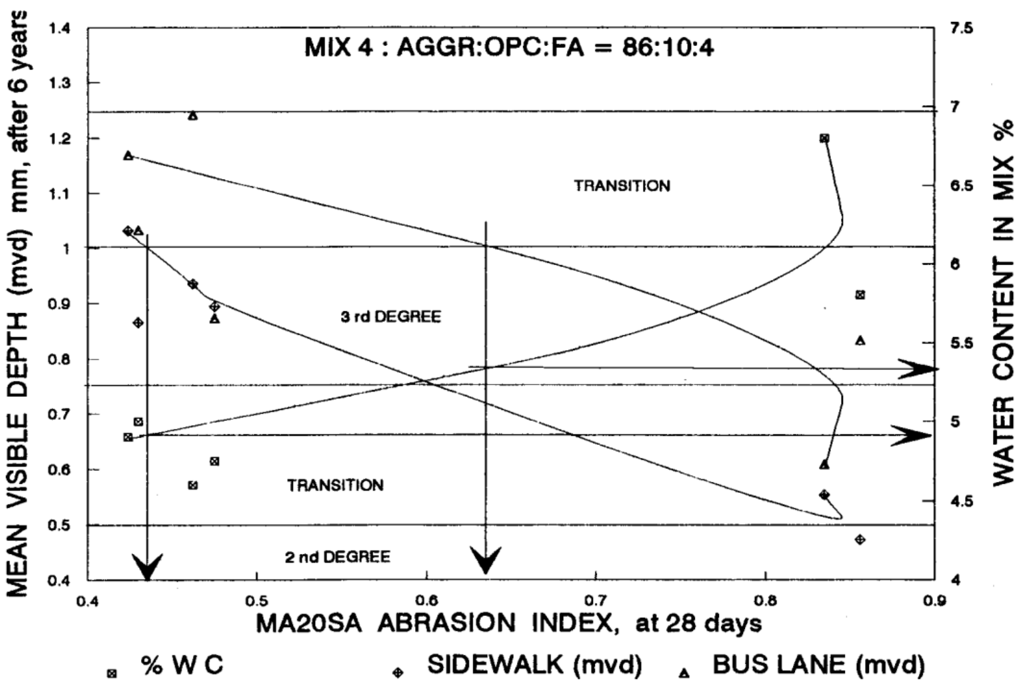

Figure 14.42 Design graph for **mix 4** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

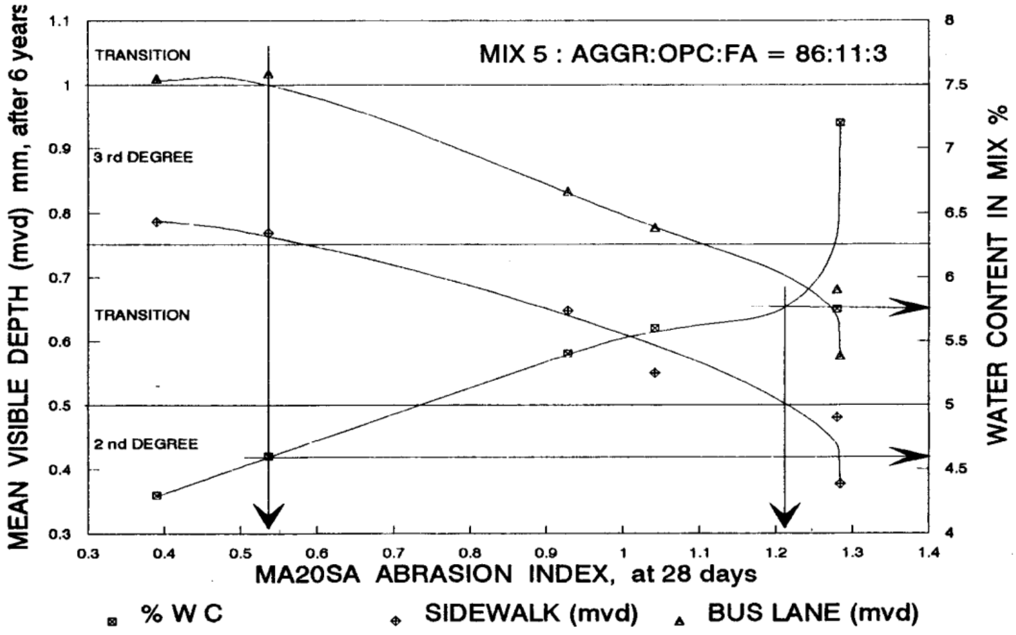

Figure 14.43 Design graph for **mix 5** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

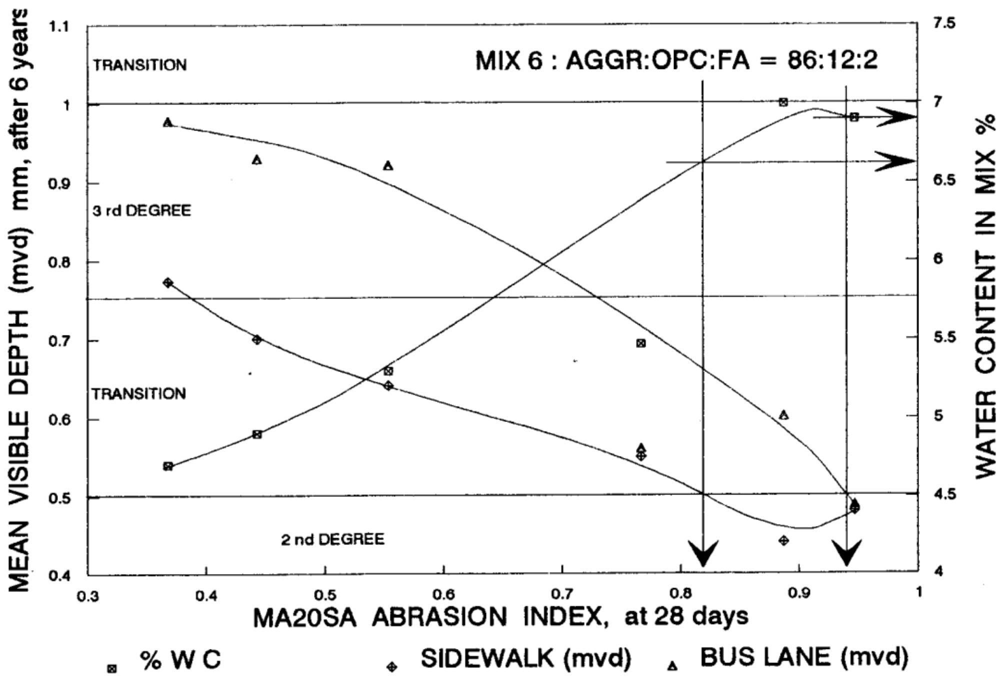

Figure 14.44 Design graph for **mix 6** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

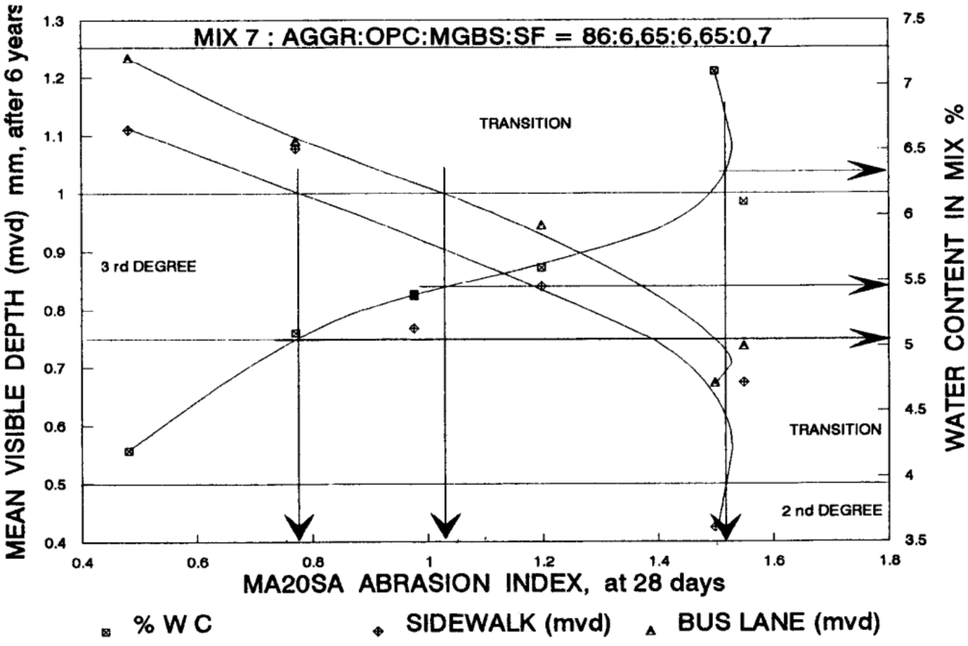

Figure 14.45 Design graph for **mix 7** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

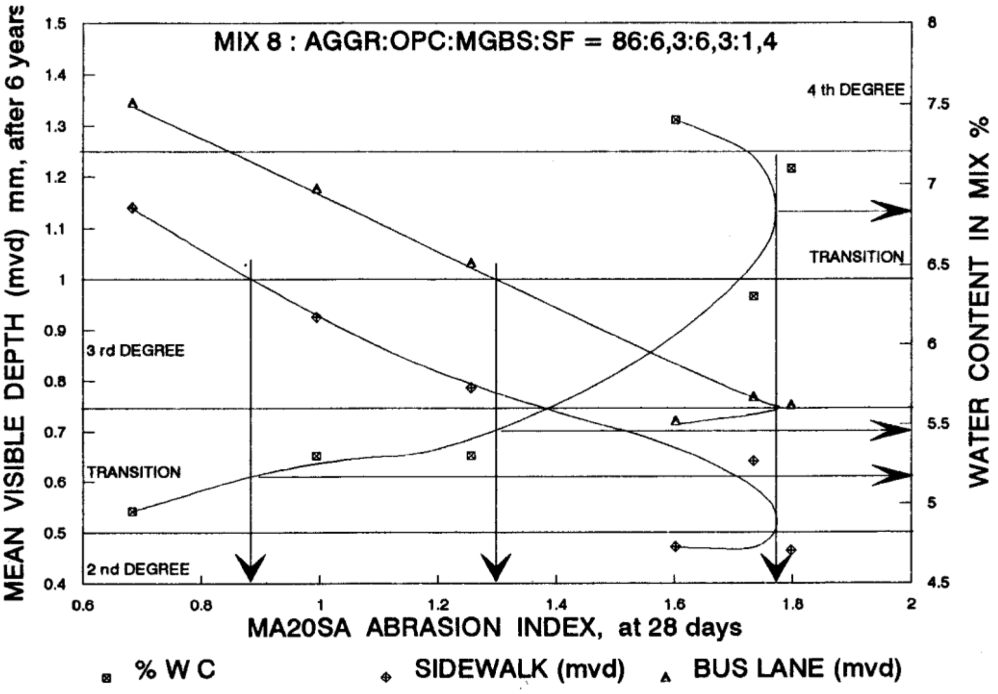

Figure 14.46 Design graph for **mix 8** indicating relationship between 28-day MA20SA index and mvd after 6-years. The effect of different traffic regimes and water content is shown.

14.7 Summary and Conclusion

This chapter correlates 28-day laboratory tests with abrasion wear in pavers subject to 6-years of traffic. Both ‘normal’ and ‘severe’ traffic were considered.

The wear at Westgate is quantified in terms of the **mean visible depth**, and visually assessed in terms of **degrees of abrasion**. These wear indicators are illustrated by means of a full **photographic presentation** of the Westgate sites (appendices Y.1 through Z.196).

Considering all the 48 mixes together, the R^2 values for 28-day laboratory tests versus 6-year wear did not show strong correlations for any of the tests, including dry density, compressive strength, tensile splitting, three abrasion tests, and ISAT.

On the other hand, definite trends emerge between the 28-day tests and 6-year wear when the mix designs are considered individually. Where the same binder type is used, i.e. mixes 1, 2 and 3, it is possible to establish a common trend line for all three abrasion tests, even though the binder content may vary from 10% to 18%. But where variations in binder type are made, this is no longer possible, owing to different rates in strength development, both at 28-days and long term.

The **MA20SA** test, has relatively low R^2 values for the MA 20 abrasion index vs 6-year mvd (comparable with ASTM C418 but significantly better than the wirebrush test). It is also the most sensitive to mix design variations and in chapter 12 is judged the best test. For these reasons it is selected as the preferred method of measuring abrasion resistance.

Eight **design graphs** are given for the MA20SA test, whereby it is possible to assure a desired long-term abrasion wear (mvd) under a given traffic intensity, for a specified mix design and moisture content.

The design graphs are however not simple to read, particularly for someone without a technical or scientific background. Therefore chapter 15 provides a much simplified ‘mix design selection chart’.

The design graphs give a very detailed performance for eight **specific** mix designs. (The scope of this thesis did not allow blends with rapid hardening cement to be tested, or different aggregates, or differing curing regimes.) The design graphs therefore have limited application.

This short coming is addressed in Chapter 15, which has a much wider application and makes provision for including all the relevant variables in establishing both ‘local’ and ‘national’ limits.