Chapter 6

The Effects of Water Content, Binder Content and Binder Type on the Strength of Cbp

6.1 Introduction

Consistent with the aim of promoting a knowledge base that will lead to improved abrasion resistance in concrete paving blocks, the author sets out in this chapter to show the extent to which some selected mix design parameters are important, viz. water, binder quantity and binder type (see objective 1, chapter 1).

On the 9th to 12th September 1987, extensive laboratory testing was carried out at Portland Park. At this stage the blocks were 28-days old. The tests included compression tests, tensile splitting tests, and abrasion resistance tests. In addition water absorption tests were conducted in the Civil Engineering laboratory of the University of the Witwatersrand, and water content tests were carried out at McLachlin and Lazar, a commercial laboratory in Johannesburg.

Table 6.1

All in all a total of 2304 blocks were subjected to ten different tests, as indicated in Table 6.1.

The results of these tests are recorded in appendices B through L. This is also indicated in table 6.1.

TABLE 6.1 LABORATORY TESTING PROGRAMME

	TYPE OF TEST	BLOCKS	TESTS	SEE COLUMN IN TBL 6.2	SEE APPENDIX
1	COMPRESSIVE STRENGTH TO: SABS 1085	288	288	B	B1 - B8
2	COMPRESSIVE STRENGTH TO: ASTM C140	288	288	C	C1 - C8
3	COMPRESSIVE STRENGTH TO: MA20	288	288	D	D1 - D8
4	TENSILE SPLITTING TO: ISO 4108	288	288	E	E1 - E8
5	ABRASION RESISTANCE TO WIREBRUSH TEST: - DIAL METHOD - VERNIER METHOD - CLAY METHOD	 240 * *	 240 240 240	 F G H	 F1 - F8 G1 - G8 H1 - H9
6	ABRASION RESISTANCE TO: ASTM C418	240	240	I	I1 - I9
7	ABRASION RESISTANCE TO: MA20	240	240	J	J1 - J16
8	WATER ABSORPTION TO ASTM C140 AND DRY DENSITY TO ASTM C642	288	288	K,L	K1 - K8
9	INTIAL SURFACE ABSORPTION TO: -ISAT TO SABS-164	*	288	M	K1 - K8
10	WATER CONTENT BY: DRYING AT 100 ° C FIRING AT 1000 ° C SUGAR METHOD CALCIUM CARBIDE METHOD	 144 * * * * *	 144 144 * * * *	 P Q R S	 L1 - L8 L1 - L8
	TOTAL	2304	3216		

* Same samples as above test also used for this test
* * Fresh concrete used for these tests

Table 6-2

While a full account of each individual result corresponding to every block tested is recorded in the appendices, the mean values are conveniently presented in table 6-2. As such it is a very useful overview of the complete laboratory phase of this thesis.

Frequent reference will be made to table 6.2. The author would strongly advise any person reading this thesis to make a photocopy of table 6.2 for easy reference, in subsequent chapters.

Column A of table 6.2 shows the identity number of the 48 mix variations (8 mix designs x 6 water contents for each mix design), whereas columns B through S contain the corresponding results of the 10 tests referred to in table 6.1.

Table 6-2 readily lends itself to the generation of graphs that show the relationship between various parameters, e.g. dry density vs water content, abrasion resistance vs compressive strength etc. Accordingly a number of graphs are reproduced from the table, both in this and subsequent chapters, to illustrate the relationships discussed in the text.

The relationships considered in the remainder of this chapter are centred on the following experimental variables:

- water content versus dry density (see 6.3)
- density versus various strength parameters (see 6.3)
- binder content versus strength (see 6.4)
- binder type versus strength (see 6.5)

TABLE 6.2 SUMMARY OF TEST RESULTS

MIX	COMPRESSIVE STRENGTH			TSS	ABRASION RESISTANCE					DRY	WATR	ISAT	WATER CONTENT				
					WIREBRUSH			SAND	BALL	DENS	ABSRP		DIAL	100	1000	SUGR	CaC2
	SABS	ASTM	MA20	ISO	PCI.TM.7.11			ASTM	MA20	ASTM	ASTM	SABS	SET	°C	°C		
	1058	C140		4108	DIAL	VERN	CLAY	C418		C642	C140	0164					
	MPa	MPa	MPa	MPa	Index	mm	cm^3/cm^2	cm^3/cm^2	Index	kg/m^3	%	%		%	%	%	%
A	B	C	D	E	F	G	H	I	J	K	L	M	N	P	Q	R	S
1.1	35.3	35.4	44.9	3.80	0.851	1.19	0.068	0.290	2.18	2308	1.50	0.06		3.8	10.2	7.85	7.15
1.2	36.6	36.1	45.8	4.00	0.677	1.28	0.085	0.276	2.30	2308	1.41	0.05	600	3.0	15.9	9.20	6.15
1.3	30.9	27.5	39.3	3.60	0.690	1.49	0.090	0.314	1.67	2266	2.18	0.09	550	3.2	3.7	6.00	6.10
1.4	22.0	19.0	28.4	2.50	0.483	2.06	0.145	0.392	0.99	2160	5.21	0.35	500	2.8	5.5	9.85	5.63
1.5	22.6	20.1	28.0	2.70	0.512	2.31	0.163	0.408	0.91	2159	5.80	0.40	450	3.2	10.3	4.96	5.60
1.6	15.9	16.4	22.0	2.20	0.589	2.31	0.149	0.443	0.70	2113	6.50	0.50	400	2.8	11.3	4.25	4.90
MEAN	27.2	25.8	34.7	3.13	0.634	1.77	0.117	0.354	1.46	2219	3.77	0.24	416.7	3.1	9.5	7.02	5.92
2.1	29.2	27.5	35.3	3.20	0.552	2.01	0.128	0.322	0.99	2283	1.85	0.08	650	5.6	12.7	6.52	7.60
2.2	30.3	27.6	36.0	3.30	0.658	1.82	0.105	0.312	0.93	2298	1.61	0.06	600	4.4	13.7	8.17	6.80
2.3	27.9	24.8	35.2	3.30	0.725	1.80	0.100	0.336	0.96	2242	3.09	0.10	550	4.1	12.5	6.70	6.30
2.4	23.9	18.9	26.2	2.50	0.625	2.35	0.132	0.481	0.67	2175	5.82	0.27	500	3.6	11.4	5.63	5.60
2.5	19.1	17.1	25.0	2.20	0.507	2.63	0.152	0.523	0.74	2110	7.54	0.40	450	3.3	10.0	8.54	5.30
2.6	18.0	14.7	21.6	2.10	0.473	2.85	0.162	0.509	0.68	2108	7.42	0.65	400	2.9	9.5	9.60	4.90
MEAN	24.7	21.8	29.9	2.77	0.590	2.24	0.130	0.414	0.83	2203	4.56	0.26	525	4.0	11.6	7.53	6.08
3.1	18.9	18.9	25.0	1.80	0.547	2.63	0.134	0.514	0.74	2188	3.54	0.07	575	5.6	13.5	7.90	7.20
3.2	15.9	18.5	22.8	1.60	0.517	2.50	0.145	0.478	0.55	2194	3.92	0.07	525	5.5	10.4	8.90	7.15
3.3	15.1	14.6	18.5	1.50	0.413	2.62	0.158	0.575	0.50	2109	6.99	0.24	475	4.4	15.7	6.55	5.70
3.4	12.5	12.0	16.6	1.10	0.447	3.06	0.187	0.607	0.40	2037	9.93	0.95	425	3.2	7.9	4.86	5.00
3.5	11.4	11.1	15.0	1.00	0.344	4.19	0.221	0.702	0.34	1995	10.44	1.70	375	3.0	12.4	5.62	4.44
3.6	11.9	11.8	16.6	1.30	0.407	3.16	0.187	0.686	0.38	2016	10.03	1.39	325	3.2	10.1	4.44	4.50
MEAN	14.3	14.5	19.1	1.38	0.446	3.03	0.172	0.594	0.48	2090	7.48	0.74	450	4.2	11.7	6.38	5.67
4.1	25.4	26.1	32.3	2.50	0.519	2.18	0.125	0.349	0.84	2243	3.52	0.08	650	5.0	13.2	4.69	6.80
4.2	28.1	26.3	32.9	2.70	0.857	1.85	0.096	0.370	0.86	2259	2.90	0.07	625	4.4	12.7	4.55	5.80
4.3	16.4	15.6	20.2	1.70	0.486	2.82	0.157	0.417	0.48	2121	6.61	0.34	575	3.4	12.3	5.00	4.75
4.4	14.3	14.5	19.4	1.80	0.333	3.63	0.211	0.426	0.43	2110	6.53	0.41	525	3.1	10.5	4.94	5.00
4.5	15.5	14.3	21.3	1.70	0.401	3.34	0.204	0.601	0.46	2117	6.52	0.35	475	3.0	12.2	5.00	4.60
4.6	13.4	14.3	19.5	1.50	0.456	2.91	0.164	0.662	0.42	2076	7.80	0.51	425	2.9	10.3	4.30	4.90
MEAN	18.9	18.5	24.3	1.98	0.509	2.79	0.160	0.471	0.58	2154	5.65	0.29	545.8	3.6	11.9	4.75	5.31
5.1	29.9	29.2	37.9	2.80	0.629	1.76	0.108	0.384	1.28	2267	3.15	0.06	650	4.5	12.5	6.23	7.20
5.2	22.7	27.0	30.0	2.60	0.481	2.06	0.129	0.390	1.28	2230	3.63	0.07	625	3.9	18.4	4.83	5.75
5.3	19.8	18.3	24.0	1.80	0.505	2.18	0.137	0.451	1.04	2170	5.36	0.18	600	3.2	9.8	5.26	5.60
5.4	19.3	20.2	25.0	2.10	0.539	2.34	0.137	0.410	0.93	2202	4.53	0.15	550	3.5	10.2	5.56	5.40
5.5	18.2	17.2	21.0	2.10	0.437	2.96	0.162	0.482	0.54	2102	7.02	0.41	500	3.3	9.9	4.63	4.60
5.6	13.7	12.1	16.5	1.80	0.326	3.89	0.226	0.645	0.39	2055	8.16	0.79	450	3.0	9.5	4.44	4.30
MEAN	20.6	20.7	25.7	2.20	0.486	2.53	0.150	0.460	0.91	2171	5.31	0.27	562.5	3.6	11.7	5.16	5.48
6.1	28.6	30.2	34.7	2.90	0.731	1.71	0.102	0.437	0.95	2242	4.20	0.06	650	4.6	11.5	4.12	6.90
6.2	27.2	28.1	32.9	3.00	0.875	2.18	0.093	0.401	0.89	2220	3.50	0.06	625	4.4	11.4	5.70	7.00
6.3	22.1	23.2	24.4	2.40	0.479	2.84	0.150	0.587	0.77	2166	5.36	0.18	600	3.5	10.9	5.64	5.47
6.4	16.4	19.2	22.6	2.10	0.477	3.03	0.155	0.591	0.55	2121	6.51	0.26	550	3.1	11.2	4.39	5.30
6.5	14.0	16.4	19.6	1.80	0.462	2.92	0.147	0.598	0.44	2058	8.15	0.64	500	2.8	11.5	3.75	4.90
6.6	12.3	11.3	16.7	1.50	0.503	2.90	0.156	0.596	0.37	2021	9.27	1.16	450	2.1	9.0	4.10	4.70
MEAN	20.1	21.4	25.2	2.28	0.588	2.60	0.134	0.535	0.66	2138	6.17	0.39	562.5	3.4	10.9	4.62	5.71
7.1	31.6	33.2	42.3	3.60	0.599	1.60	0.105	0.320	1.50	2286	1.52	0.06	625	3.6	13.3	7.06	7.10
7.2	26.1	29.1	39.8	3.40	0.677	1.62	0.106	0.346	1.55	2263	2.04	0.07	600	3.1	10.5	5.64	6.10
7.3	23.0	21.9	32.0	2.90	0.632	1.79	0.114	0.385	0.98	2208	3.88	0.18	550	3.2	12.4	3.63	5.40
7.4	20.1	23.4	31.0	2.60	0.666	2.04	0.112	0.413	1.20	2175	5.06	0.29	500	3.4	10.4	5.60	5.60
7.5	20.0	16.3	26.3	2.40	0.629	2.19	0.124	0.453	0.77	2110	7.24	0.64	450	3.0	11.1	4.95	5.10
7.6	16.0	13.5	21.1	2.30	0.513	2.69	0.152	0.507	0.48	2073	7.86	0.83	400	2.7	10.0	4.77	4.20
MEAN	22.8	22.9	32.1	2.87	0.619	1.99	0.119	0.404	1.08	2186	4.60	0.35	520.8	3.2	11.3	5.28	5.58
8.1	28.6	32.6	40.2	3.80	0.764	1.32	0.087	0.326	1.60	2262	1.54	0.05	625	2.4	13.1	7.49	7.40
8.2	32.1	30.4	42.4	3.60	0.615	1.76	0.103	0.338	1.80	2279	1.42	0.05	600	2.4	13.4	7.96	7.10
8.3	31.1	31.7	43.6	3.30	0.808	1.47	0.084	0.359	1.73	2285	1.41	0.05	550	3.5	11.1	6.63	6.30
8.4	24.0	18.9	28.8	2.90	0.632	2.16	0.117	0.472	1.26	2103	6.79	0.60	500	3.3	9.8	5.34	5.30
8.5	18.1	21.1	27.8	2.30	0.580	2.51	0.137	0.475	1.00	2100	6.77	0.69	450	3.2	9.4	5.72	5.30
8.6	17.8	18.2	25.0	2.30	0.469	2.93	0.156	0.444	0.68	2092	7.03	0.61	400	3.1	9.7	5.83	4.95
MEAN	25.3	25.5	34.6	3.03	0.645	2.03	0.114	0.402	1.35	2187	4.16	0.34	520.8	3.0	11.1	6.50	6.06
O/MEAN	21.7	21.4	28.2	2.5	0.565	2.37	0.137	0.454	0.9182	2168.4	5.2096	0.3606	513	3.504	11.2	5.90	5.73

Notes:

1. Each point in columns B, C, D, E, K, L and M is the average of 6 specimens tested.
2. Each point in columns I and J is the average of 5 specimens tested.
3. Each point in columns F, G, and H is the average of 4 specimens tested.
4. Each point in columns P and Q is the average of 3 specimens tested.
5. Each point in columns R and S is the result of a sample of fresh mix tested.

6.2 Water Content

The water content of the mix plays a crucial role in the density (and hence compressive strength, abrasion resistance etc.) of concrete pavers, with ‘wet’ mixes being stronger than ‘dry’ mixes. The observation that some manufacturers seemed unaware of this (judging from the poor performance of the product on some sites) was for the author the initial motivation behind this research.

Note that the terms ‘wet’ and ‘dry’ as used in the above context applies to semi-dry mixes and hence a ‘wet’ mix is one that still has a zero slump, although its m.c. may be at the point where it is just about to slump or possibly already has a very slight slump.

It is perhaps unfortunate for the industry that relatively ‘dry’ mixes can very often present a number of apparent advantages to the producer. Firstly, no sticking takes place between the shoe of the press and the upper surface of the block. With ‘wet’ mixes this is always a possibility as the wetter concrete tends to adhere to the shoes during the pressing / vibration cycle, resulting in holes appearing on the surface of the blocks when demoulding takes place seconds later. Secondly, ‘dry’ mixes can result in blocks with a very smooth surface texture preferred by some customers. (The effect of the water content on the appearance of pavers is illustrated photographically in appendices Y.1 through Y.48, and the dry mixes may be seen to be very smooth).

However, notwithstanding these apparent advantages, ‘dry’ mixes negatively effect both compressive strength and abrasion resistance, as will be shown later.

The correct water dosage is considered such an important part of this investigation, that five different methods (see 6.2.1 through 6.2.5) were used to measure the water content of each of the 48 mixes. The corresponding measurements/results are reflected in columns N through S in table 6.2. These methods are given further consideration below:

6.2.1 Conductivity Meter

The operation and principle of the Michenfelder water meter is explained in 4.11.

Using this device each of the eight mix designs were made with six different water contents varying from very ‘wet’ to very ‘dry’. (The settings of the potentiometer used to change the water contents are recorded in column N of table 6.2). For example figure 6.1 shows how the six potentiometer settings for mix 1 resulted in six different water contents (see appendices Y.1 through Y.6 for corresponding visual appearance). However, although the potentiometer of the instrument was adjusted in equal increments from the ‘wet’ to ‘dry’ setting, the water contents did not necessarily respond in equal increments. For example figure 6.1 shows a large change in the water content from the wettest to the 2nd wettest mix, while the 4th and 5th water contents are virtually superimposed. The instrument did nonetheless succeed in generating a wide range (from wettest to driest) of water content variations.

Finally it should be noted that while this instrument is good at reproducing a m.c., it does not measure it. Therefore four other methods were devised for doing this, described in 6.2.2 through 6.2.5 below.

6.2.2 Calcium Carbide

This method is described in chapter 4.11.4 and the results are recorded in column S of table 6.2.

Of the five methods used this one gave the most meaningful results, in that the water contents generally followed the settings of the Michenfelder water meter. The appearance of a wet block is noticeably different from that of a dry block (once it is known what to look for, e.g. demoulding smear marks appear only on wet blocks), and both the readings on the water meter and the settings of the pressure vessel followed the visual appearance of the blocks.

In this method a relatively small quantity of mix is added to the pressure vessel, i.e. 15 grams, (in addition to the CaC_2 capsule). This places a limitation on the accuracy of the m.c. results, since the grading of such a small sample, even though taken from the same mix, is likely to vary. In particular, a few additional coarse aggregate particles are likely to reduce the total moisture content within the pressure vessel. However the poor results obtained from the other moisture content tests (see 6.2.3 through 6.2.5) meant that only the results of this method could be used to determine the relationship between water content and density (e.g. see figure 6.1 and 6.2).

6.2.3 Drying at 100^o C

This method is described in chapter 4.11.1 and the results are recorded in column P of table 6.2.

Generally the results follow the expected trend, showing greater moisture contents for the wetter mixes and vice versa. However they do not follow the expected trend as well as the calcium carbide method.

A further disadvantage with this method is that most of the water that combines with the cement during the hydration process will not be released at the relatively low temperature of 100^o C. The results therefore do not indicate the true moisture content of the mix, but rather the amount of free un-hydrated water in the mix.

6.2.4 Firing at 1000^o C

This method is described in detail in chapter 4.11.2 and the results are given in column Q of table 6.2.

Unfortunately, in some of the mixes the results do not make any sense at all. In some instances the drier mixes (as determined by the settings of the Michenfelder water meter) appear to have higher water contents than the wetter mixes. This work was done by a large commercial laboratory, McLachlin and Lazar, at a considerable fee. It is only possible to speculate what went wrong. The writer was relying on these results to give the most accurate readings, since at 1000^o C all the moisture in the mix should be driven off, including all hydrated water.

6.2.5 Sugar Method

This method is described in detail in chapter 4.11.3 and the results given in column R of table 6.2.

The idea behind adding a pre-weighed solution of sugar to a given mass of fresh concrete was to inhibit the hydration process, thus leaving all the water in a free state. However, the subsequent drying of the water in an oven was not carefully controlled (some specimens were left to dry longer than others). As with the firing at 1000^{o} C some of the results also do not make any sense, with mixes that were observably wetter showing lower water contents than dry mixes.

Sectional Summary and Conclusion

Although the Michenfelder water meter was successful in generating varying water contents, in hindsight it would have been better not to use the conductivity-driven-solonoids, but rather to have measured the water added to the mix. This could have been done by determining the m.c. in the sand, in tandem with measuring all further additions of water at the mixer, as required to achieve the various desired moisture contents. Fortunately the CaC_2 method gave reasonable and realistic results – but these were probably affected to a degree by small variations in grading within the 15g sample of the fresh mix.

The problem of less than perfect m.c. readings is overcome in the next section, firstly by showing the general relationship between m.c. and density, and then reverting to changes in density as the basis for studying variation in abrasion resistance, compressive strength etc. It will be noted that density and m.c. are generally linearly related, for all but the wettest mix, where it may be seen that when increasing m.c. from 2nd wettest to wettest, no further increase in density was achieved, see figures 6.1 and 6.2).

6.3 Density

The reason that such great pains were taken to attempt to accurately determine the water content is that it has a profound effect on the density of the block. This can be seen for all of the graphs (corresponding to the eight mix designs) plotted from columns S and K of table 6.2, and recorded in appendices T.1 through T.8. Figures 6.1 and 6.2 below are reproduced from appendices T.1 and T.2 and illustrate how blocks made with a high water content are superior to those with lower water contents, i.e. wet mixes are denser than dry mixes. The effect of the extra water in the wetter mixes is to lubricate and ensure compaction of the mix.

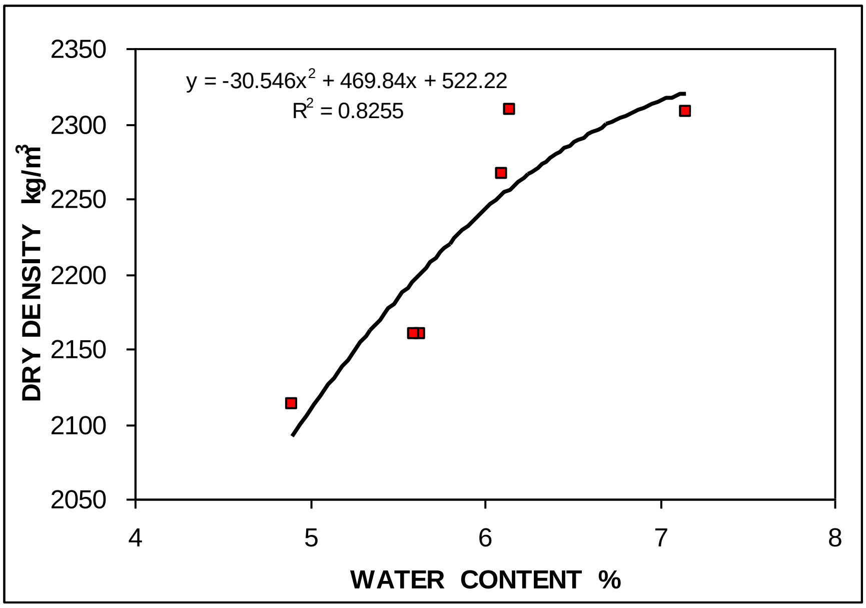


Fig 6.1 Relationship between water content and dry density - Mix 1

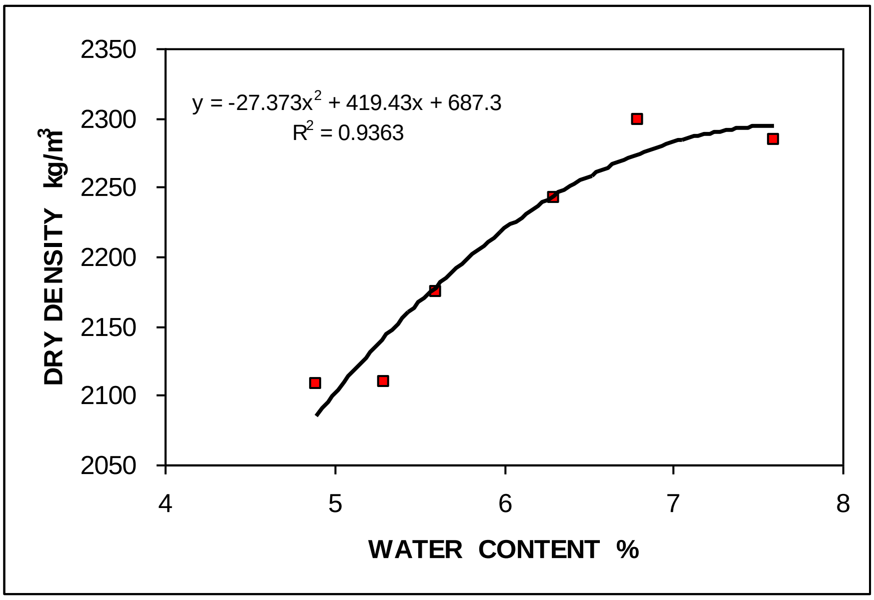


Fig 6.2 Relationship between water content dry density - Mix 2

Explanation: Freshly made semi-dry concrete as used in the manufacture of cbp has the distinctive characteristic of being relatively dry and crumbly and lacks cohesion and plasticity compared to conventional fresh concrete. There is also considerable particle interference both within the fine and coarse aggregate. The mix is therefore not easily compacted (even with many kilowatts of compacting power) owing to the high internal friction of this no-slump concrete. In effect the relatively low water content of this concrete means that it is poorly lubricated.

On the other hand, it is apparent that more water surrounding the aggregate and cement particles means greater fluidity and hence greater density for a given compactive effort.

Sectional Summary and Conclusion

It bears repeating that in studying the effect of m.c. on such characteristics as compressive strength and abrasion resistance, density was chosen as the independent variable to represent m.c. It was explained in 6.2.2 that the water contents (CaC_2 method) while 'reasonable and realistic', were not as accurate as was initially hoped, evidenced by some of the density versus water-content graphs, which have kinks in unexpected places, (see appendices T.1 through T.8). The method of using a very small 15g sample of the mix (see 4.11.4) to determine the moisture content of a 1,3 tonne mix is not ideal. Even though the mix was mixed for about 6½ minutes and hence variations in moisture content within the mix would be minimal, the presence of a few extra coarse particles in such a small sample would affect the reading. Unfortunately the problems experienced with the firing at 1000^o C method, and other methods, meant that the results of the calcium carbide method had to be used. However this does not in any way detract from the validity of the results since the graphs show a clear trend in the relationship between water content and density.

On the other hand the six samples used to determine the dry density in accordance with ASTM C642 (see 4.9) total to approximately 25 kg in mass, are therefore much more representative of the 1,3 tonne mix. Even so, the densities are not as accurate as they should be, since they were obtained from blocks that were cured for nine weeks, while the companion blocks tested for compressive strength and abrasion resistance were only 28-days old (see note in 4.9). However, this only means that the dry densities are slightly overstated for all the mixes, and once again, the general trends in the various relationships are still valid.

Having established that the density is governed by the water content (other things being equal such as cement content, aggregate quantity, grading and type, compactive effort etc.) the remainder of this chapter will examine the relationship between dry density (representing water content) and three strength characteristics of cbp viz. the compressive strength (in 6.3.1), tensile splitting strength (in 6.3.2), and abrasion resistance (in 6.3.3).

6.3.1 The influence of density on compressive strength

The graphs in appendices T.9 through T.16 detail the relationship between compressive strength and dry density for the eight mix designs. Figures 6.3, 6.4, 6.5 and 6.6 reproduced from these appendices, illustrate this relationship for a range of mixes.

The compressive strength is shown using two test methods, SABS 1058 and MA20. The lower values obtained for SABS 1058 are primarily the result of a lack of aspect ratio correction for the 100 mm thick blocks.

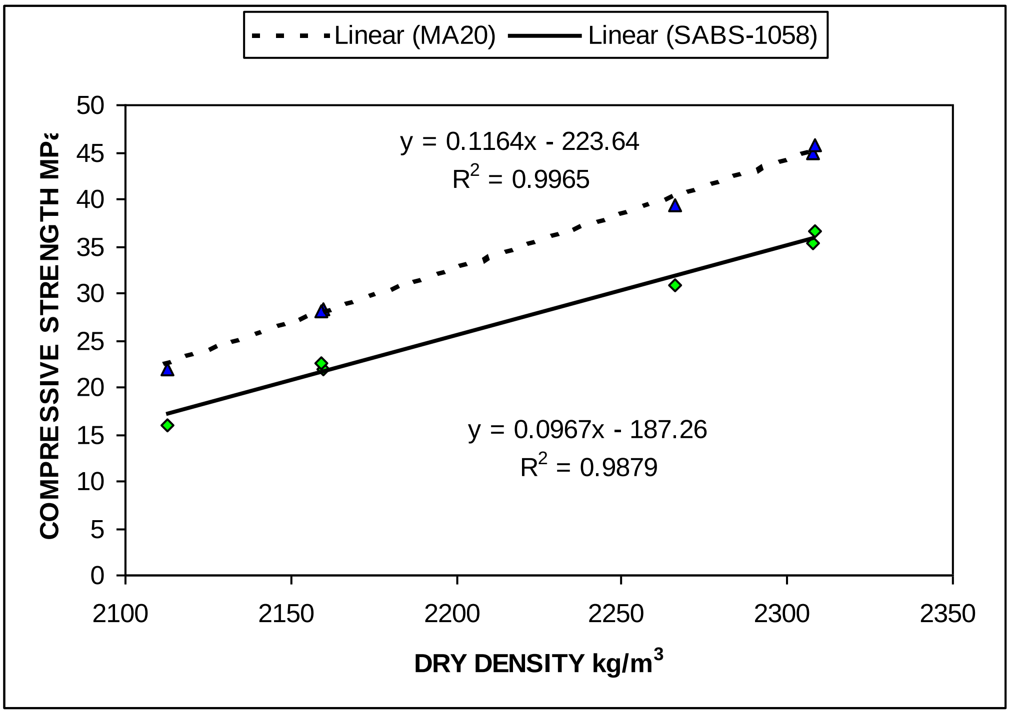


Figure 6.3 Relationship between dry density and compressive strength
Mix 1 = 9% OPC, 9% MGBS

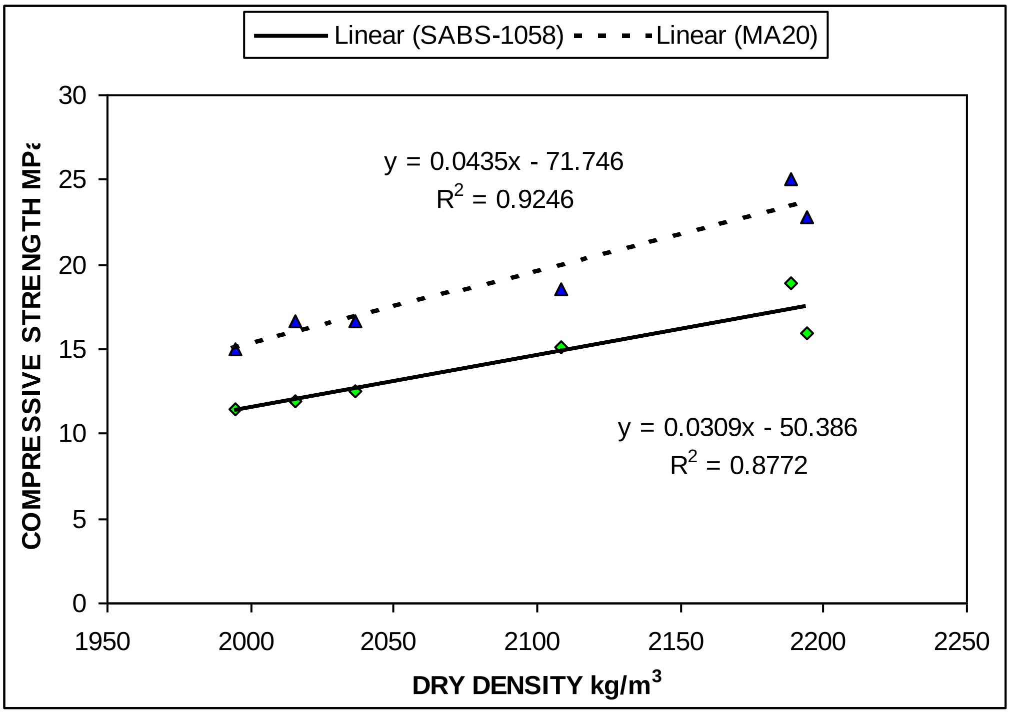


Figure 6.4 Relationship between dry density and compressive strength
Mix 3 = 5% OPC, 5% MGBS

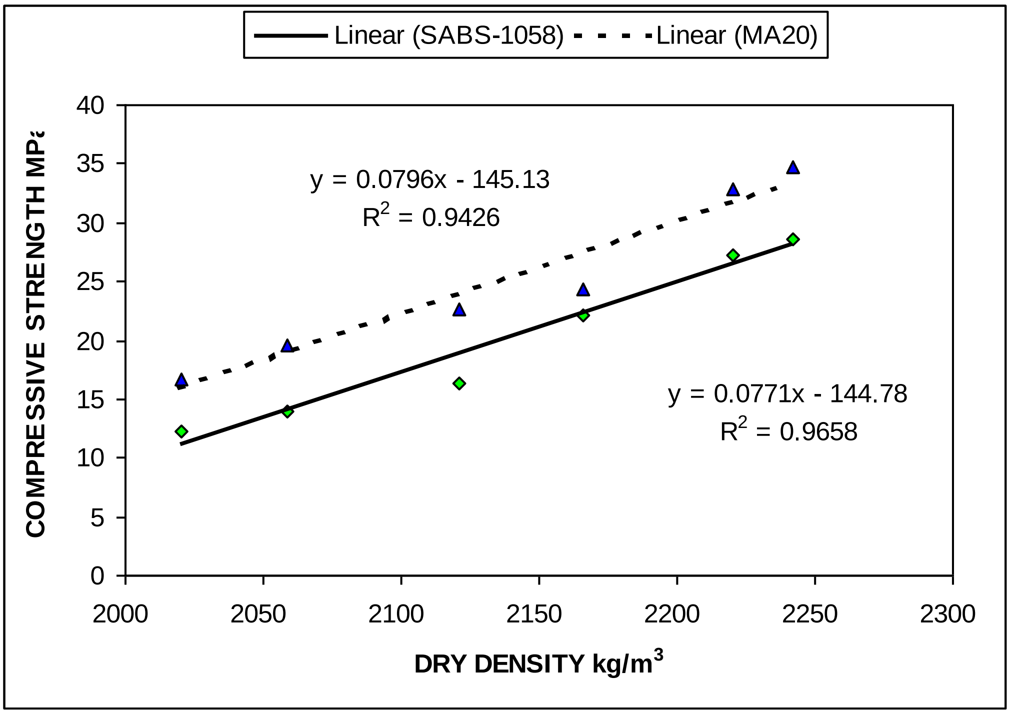


Figure 6.5 - Relationship between dry density and compressive strength
Mix 6 = 12% OPC, 2% MGBS

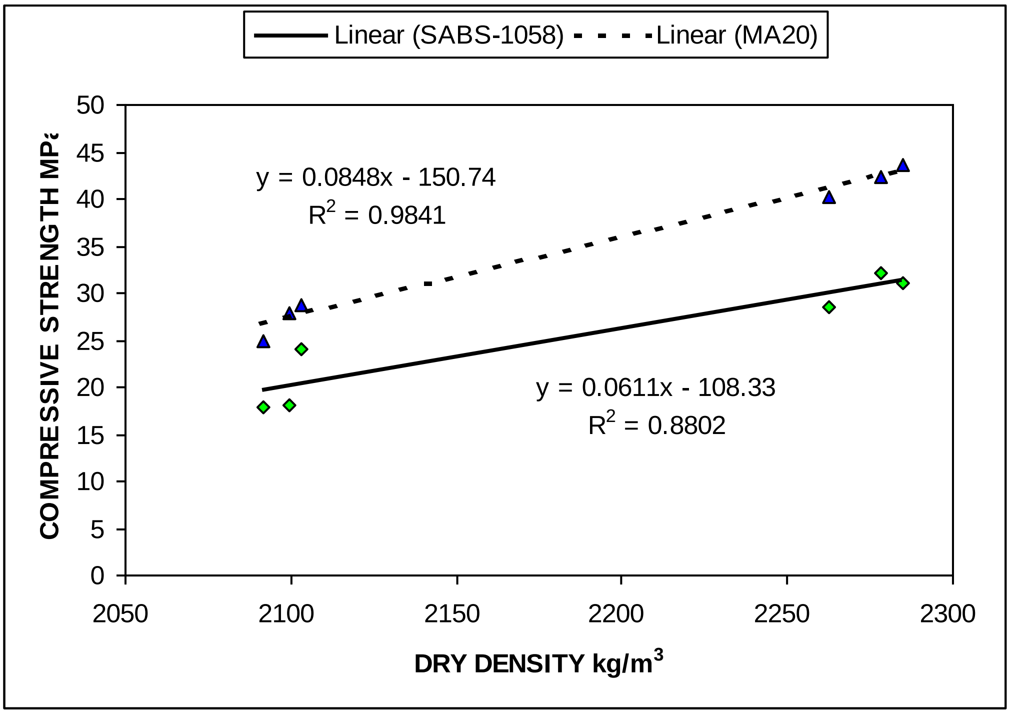


Figure 6.6 Relationship between dry density and compressive strength
Mix 8 = 6,3% OPC, 6,3% MGBS, 1,4% SF

Observations and Discussion

Although a strong correlation between density and compressive strength is indicated by high R^2 values in most of the graphs, a certain degree of experimental scatter is noticeable. Certain trends are clearly observable:

The graphs show that a dramatic decrease in strength occurs as the density decreases. For example considering the MA20 curve in figure 6.3, the wettest mix has a strength of 45 MPa whereas the driest mix has a strength of 22 MPa (the cement content is the same for each point on the curve). In other word the mixes with high water content (and thereby relatively low c/w) performed much better than those that had low water contents (and relatively high c/w ratios). This appears to contradict the well-known c/w ratio rule whereby concretes made from high c/w ratios should have superior strength characteristics.

This can be explained as follows. The manufacturing process is such that the resultant paving blocks made from such mixes are ejected from the machine press in a matter of one or two minutes after the mix is discharged from the mixer. At this point in time the fresh blocks will be free standing on a pallet. Of necessity therefore the consistency of the mix is relatively stiff, with even the wettest of mixes showing only the slightest evidence of slumping (slumped paving blocks would be unable to fit together). With so little water (compared to conventional concrete) the c/w ratio is relatively high anyway, and an explanation for such a remarkable drop in strength from wet mixes to dry mixes must be found elsewhere.

The sharp drop off in strength can be explained from another well-established rule of concrete technology that states that a small increase in the voids content results in a far greater decrease in strength. An often-quoted figure is that an increase of 1% in the voids content will result in an accompanying 5% loss in the compressive strength. For example the first point (wettest mix) on the MA20 graph has a compressive strength of 44,9 MPa and a density of 2308 kg/m^{3}compared to 22,0 MPa for the last point (driest mix) with a density of 2113 kg/m^3. This represents a reduction of 8,5 % in density with a corresponding loss of 51 % in the compressive strength. (In fact this works out at a ratio of 6 % loss in compressive strength for every 1 % loss in density).

These findings are discussed in greater depth in volume 2 under 2.3.2. Using Feret’s formula it is shown that a very good correlation exists between dry density and compressive strength when air voids (inversely related to density) are factored in alongside c/w ratio. This is shown to be so for both this investigation and those of Sukandar(1993). By making an allowance for both air voids and water voids, Feret’s formula (1896) has anticipated Power’s gel space law [Powers(1958)], which states that the strength of the hardened cement paste is proportional to the cube of the ratio [volume of gel] / [volume of available space]. Accordingly too much air space (e.g. in low density mixes) increases the ‘available space’ and thus rapidly lowers the potential strength.

A closer examination of the curves shows that the wettest mix does not always have the highest compressive strength. For example in figures 6.3 and 6.6 the second wettest or even third wettest mixes have higher compressive strengths (and densities) than the wettest. This indicates that the wettest mix in fact had somewhat too much water, more than what was required to lubricate the mix for the given compactive effort. The excess water therefore merely contributed to a lower c/w ratio with no compensation in density. (Such excess water is not required for hydration and actually increases the microscopic cavities within the gel structure, thus lowering the Powers’s gel space ratio). Alternatively the strength of this ‘wet’ concrete may be predicted by Feret’s formula, only in this case the w/c ratio alone determines the compressive strength, and the air/c may be presumed not to negatively affect the strength, assuming that the excessive water allows full expulsion of air voids).

However, in order to understand the relative importance of overdosing on the one hand and under-dosing on the other it will be useful to examine more closely the values in the graphs corresponding to the mixes where a transition occurred between overdosing and under-dosing, as in figures 6.3 (Mix 1) and 6.6 (Mix 8). (See also appendices T.10 and T.12 for similar trends in mixes 2 and 4 respectively).

Table 6.3 compares the strength ratio of [wettest mix] / [strongest mix] for a given mix design, and likewise the ratio of the [driest mix] / [strongest mix] for that same mix design.

TABLE 6.3 RATIO OF COMPRESSIVE STRENGTHS

MIX	"WET" MIX / OPTIMUM W CONTENT MIX	"DRY" MIX / OPTIMUM W CONTENT MIX
1	0.98	0.48
2	0.98	0.60
4	0.98	0.59
8	0.98	0.57

In the above table the ‘optimum water content mix’ is taken as the mix with the highest density and greatest strength, while ‘wet’ and ‘dry’ respectively refer to the wettest and driest mixes. Clearly the difference in strength between the wettest and strongest mix is minimal, while that between the driest and optimum is considerable. This means that the effect of overdosing with water is not nearly as serious as under-dosing. Or put another way, for a given mix design with a given cement content the danger of having insufficient water to adequately lubricate the mix is far more serious than a mix which is somewhat over lubricated.

On a very practical note, a useful rule of thumb expounded by John Lane (past CMA Director) is to continue to add water to the mix until such time as slumping of the corresponding blocks starts to occur. Then cut the water slightly and the chances are that the water content will be close to optimum for semi-dry concrete as required in the manufacture of cbp.

The reasoning put forward in this section confirms the wisdom in Lane's rule of thumb. If properly adhered to any error of judgement on the part of the mixer operator is likely to err on the wet side of the optimum water content with minimal loss of strength.

However, in maximising the water content, care should be taken not to be too close to slump point. Apart from the problems associated with blocks not fitting together, there are other negative effects associated with having too much water in the mix. Fenwick(1988) listed these as:

- Concrete sticking to the tamper heads
- The filler box becoming heavily encrusted with concrete
- Difficulty in filling the mould cavities
- Products falling out of the bottom of the mould (multi-layer machines only)

Nevertheless, he acknowledged the importance of maximising the water content, concluding that as much water should be used ‘as permitted by the constraints of the production process’.

In figures 6.4 (mix 3) and 6.5 (mix 6) no optimum or transitional water content was positively established since the wettest water content also had the strongest compressive strength. This suggests that an even wetter mix may have produced a denser and even stronger block.

A comparison of figures 6.3 through 6.6 reveals that the different strength values of the respective ‘wet’ mixes differ greatly from one graph to the next, thus indicating that water content is not the only determining factor in the strength of cbp. The same can be seen for the dry mixes.

The variations in binder content and binder type are responsible for these differences and are discussed in some detail in 6.4 and 6.5.

6.3.2 The influence of density on tensile splitting strength (tss)

Figures 6.7 through 6.10 are reproduced from the graphs in appendices T.17 through T.24 (constructed from columns B, E and K in table 6.2) and detail the relationship between tensile splitting strength and dry density for the eight mix designs.

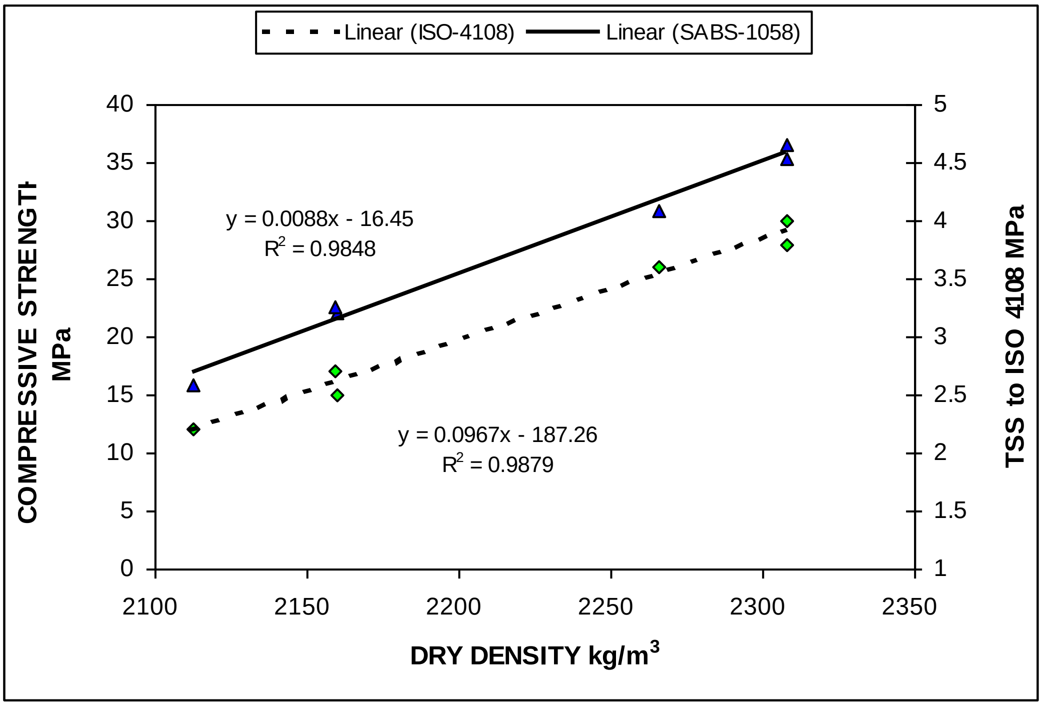


Figure 6.7 Relationship between dry density and tensile splitting strength
Mix 1 = 9% OPC, 9% MGBS

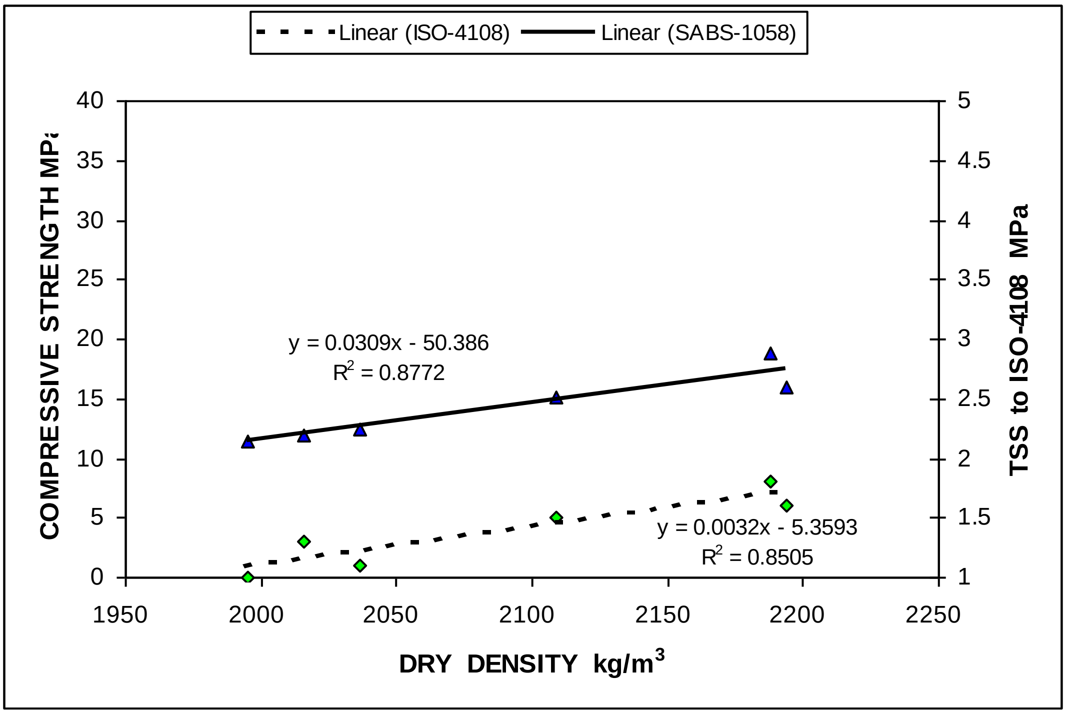


Figure 6.8 Relationship between dry density and tensile splitting strength
Mix 3 = 5% OPC, 5% MGBS

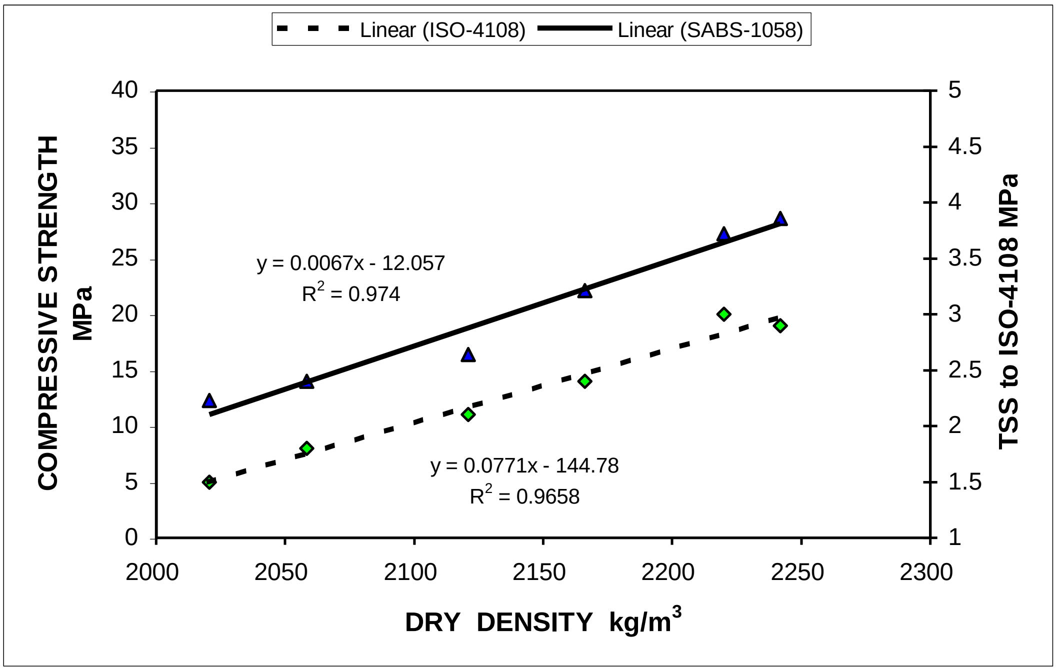


Figure 6.9 Relationship between dry density and tensile splitting strength
Mix 6 – 12% OPC, 2% Fly ash

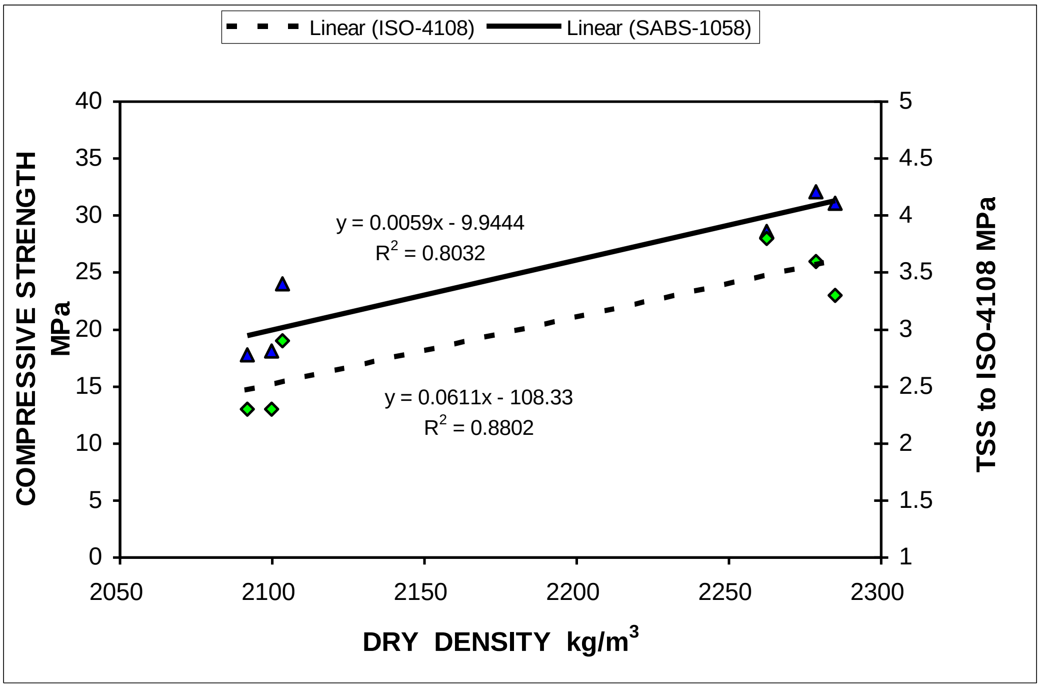


Figure 6.10 Relationship between dry density and tensile splitting strength
Mix 8 = 6,3% OPC, 6,3% MGBS, 1,4% SF

It is clear from these graphs that as in the case of the compressive strength a dramatic decrease in tss occurs as the density decreases. For example, in figure 6.7, the wettest mix has a strength of 3,8 MPa (dry density 2308 kg/m^3) whereas the driest mix has a strength of 2,2 MPa (dry density 2113 kg/m^3). This represents a reduction of 8,5 % in density with a corresponding loss of 42,1 % in the tss. (This works out at a ratio of 5 percent loss in tss for every 1 percent reduction in dry density). The classical drop in strength that occurs as voids increase can once again explain this sharp drop off in strength.

Figure 6.7 (from appendix T.17) again shows that the wettest mix does not always have the highest strength (this is clearer in appendix T.17.) Again this indicates that the wettest mix in fact had somewhat too much water, more than what was required to lubricate the mix for the given compactive effort. The excess water therefore merely contributed to a lower c/w ratio with no compensation in density. (See similar comments under 6.3.1 for a more detailed explanation.)

In figures 6.7 through 6.10 the compressive strength (according to SABS 1958) and tss (according to ISO – 4108) have been plotted on two different Y axes. The close proximity of the compressive strength curve in relation to the tss curve in each figure shows that they are similarly related to density, the relationship being linear in both cases.

It can be seen from the Y-axes that the tss is approximately an order of magnitude less than the compressive strength. This suggests that smaller manufacturers who have limited capital could use this test with a relatively inexpensive press to monitor quality. DuPlessis(1989) confirms that the ‘apparatus necessary is cheaper and simpler than that used in the compressive strength test and acceptance of this test can offer a significant saving on the cost of quality control measures in respect of concrete paving units’.

Considering the average of 288 blocks for both tests, the correct magnification correction factor is 8,7 (i.e. compare the averages of columns B (21,73 MPa) and E (2,5 MPa) of table 6.2). If the average for the MA20 compressive strength test is used instead, where geometric shape is taken into account, this ratio is calculated as 11,3. Du Plessis(1989) found that the ratio was 11,5 for 855 determinations done comparing the results of a 50 mm cube (cut from the off-cuts of the paving blocks subjected to the tss tests).

Whereas the ISO 4108 tss test does not have a correction factor for variations in geometry, evidence suggests that thicker sections fail at lower stresses, although not all authors agree on the extent of this variation. For example DuPlessis(1989) indicated that variation in tss was 'not significantly' influenced by geometric properties; Spooner(1969) found that 150 mm cylinders split at 94% of the load of 100mm cylinders; and Hendrikx(1994) reported that the new Belgium standard for concrete paving blocks (NBN B21-311), which replaced compression testing with tss testing, uses a correction factor of 0.9 for 60mm thick pavers and 1,1 for 100mm pavers.

It would therefore appear that while the aspect ratio of the cross section is less important for tss testing relative to compression testing, tss testing is not immune to geometry.

Given these findings, the writer is of the opinion that the tss test should be allowed as a means of quality control, adopting the Belgium paving standard aspect ratio correction factors.

6.3.3 The Influence of Density on Abrasion Resistance

Three abrasion tests were used to determine the abrasion resistance of the blocks:

a. Wire brush test to PCI.TM.7.11
b. Sand blast test to ASTM C418
c. Ball bearing test to MA20

A detailed description of these tests is given in 4.6 through 4.8.

The indices of these tests do not all mean the same thing. The wire brush and sand blast indices represent the mean depth of the abraded area, while the MA20 is related to the reciprocal of depth-of-penetration of the balls into the block. The former two tests are therefore an indication of the *abrasion-wear* resulting from a given amount of applied abrasion, while the MA20 is an indication of the *abrasion resistance.*

One way of comparing these tests 'on an equal footing' would be to determine the abraded volumes in each case, and this exercise has been done in chapter 12. Clearly this amounts to a comparison of abrasion-wear. Alternatively the ASTM and Wire brush indices may be inverted, so that a comparison of the reciprocal-of-depth may be made between the tests. In this case the abrasion *resistance* is obtained for *each* test. (This exercise was done further on in table 6.7).

However, in this investigation, the official indices have generally been retained, to allow results to be compared with other work where these tests are in use (e.g. other MA20 results in Australia, other ASTM C418 tests in USA). . This has meant that the graphical presentations will refer to abrasion resistance for MA20, but abrasion-wear for the sandblast and wire brush test.

Always making a distinction between abrasion wear and abrasion resistance can be very long-winded and tedious. Therefore, the term abrasion resistance is sometimes used generically for abrasion-wear. The reader should understand this in the light of: high abrasion resistance = low-abrasion-wear, and vice versa.

Where the term abrasion index is used, this should be understood as abrasion resistance in the case of the MA20 test, and as abrasion-wear in the other two cases. The term abrasion-index is thus inherently generic in nature.

The graphs in appendices T.25 through T.40 detail the relationship between the official abrasion indices of the three abrasion tests and density, for the eight mix designs.

Figures 6.11 through 6.16 below are reproduced from these appendices to illustrate the relationship between density and the abrasion indices, for three of the mix designs (with six m.c. per mix design). These graphs are constructed from columns K, H, I, and J in table 6.2.

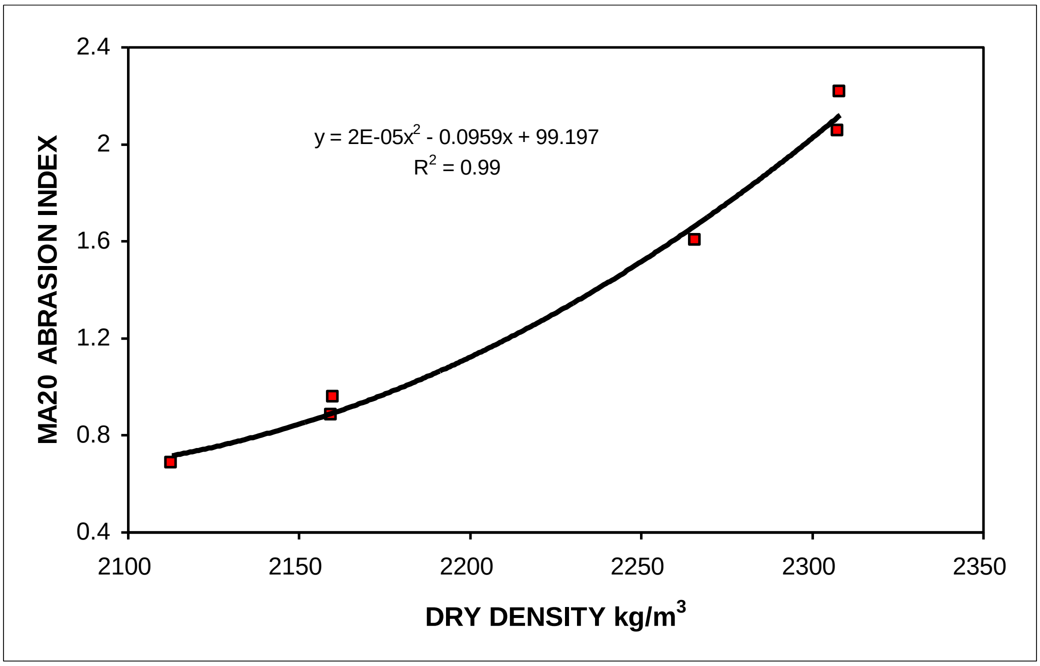


Fig 6.11 Relationship between dry density and abrasion resistance to MA20
Mix 1 = 9% OPC, 9% MGBS

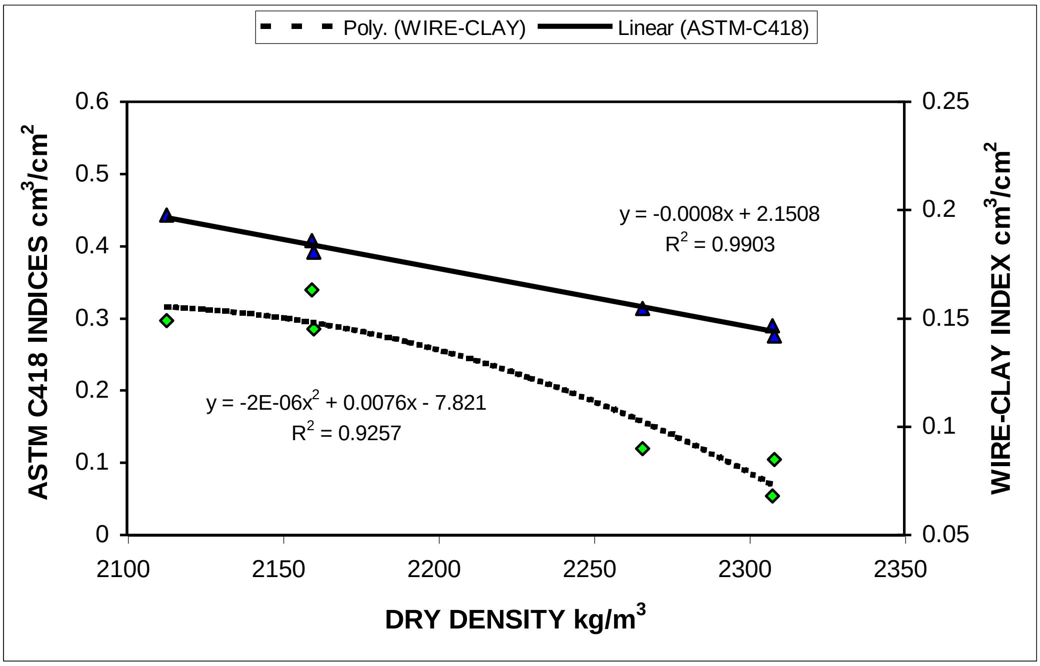


Fig 6.12 Relationship between dry density and abrasion-wear to ASTM C418 and Wire brush PCI.TM.7.11 (clay method)
Mix 1 = 9% OPC, 9% MGBS

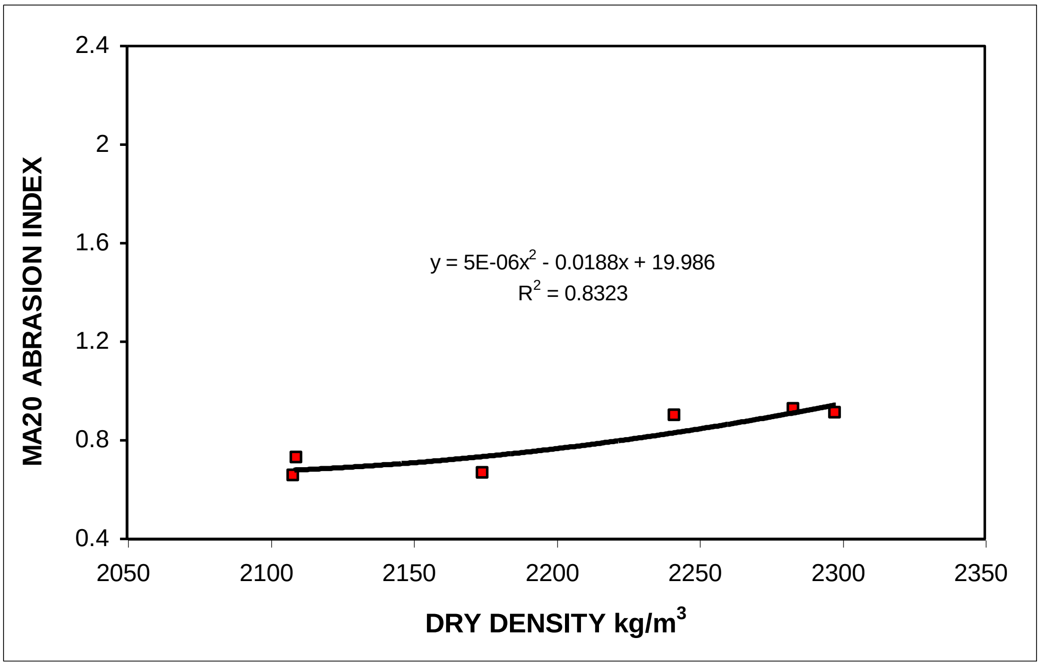


Fig 6.13 Relationship between dry density and abrasion resistance to MA20
Mix 2 = 7% OPC, 7% MGBS

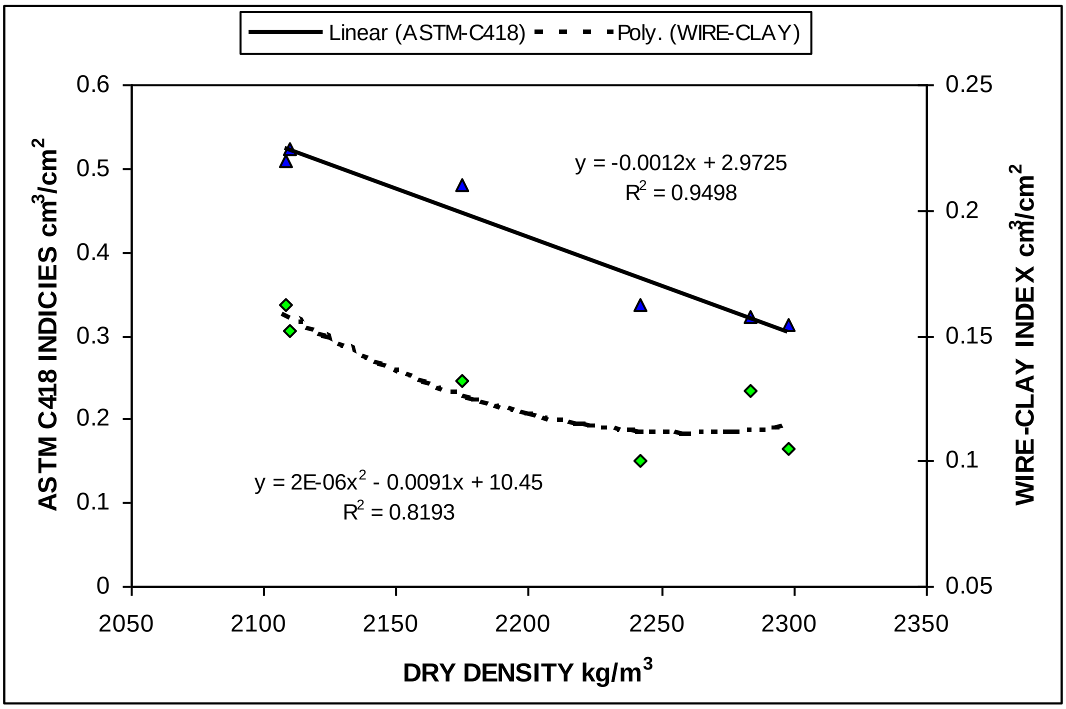


Fig 6.14 Relationship between dry density and abrasion-wear to ASTM C418 and Wire brush PCI.TM.7.11
Mix 2 = 7% OPC, 7% MGBS

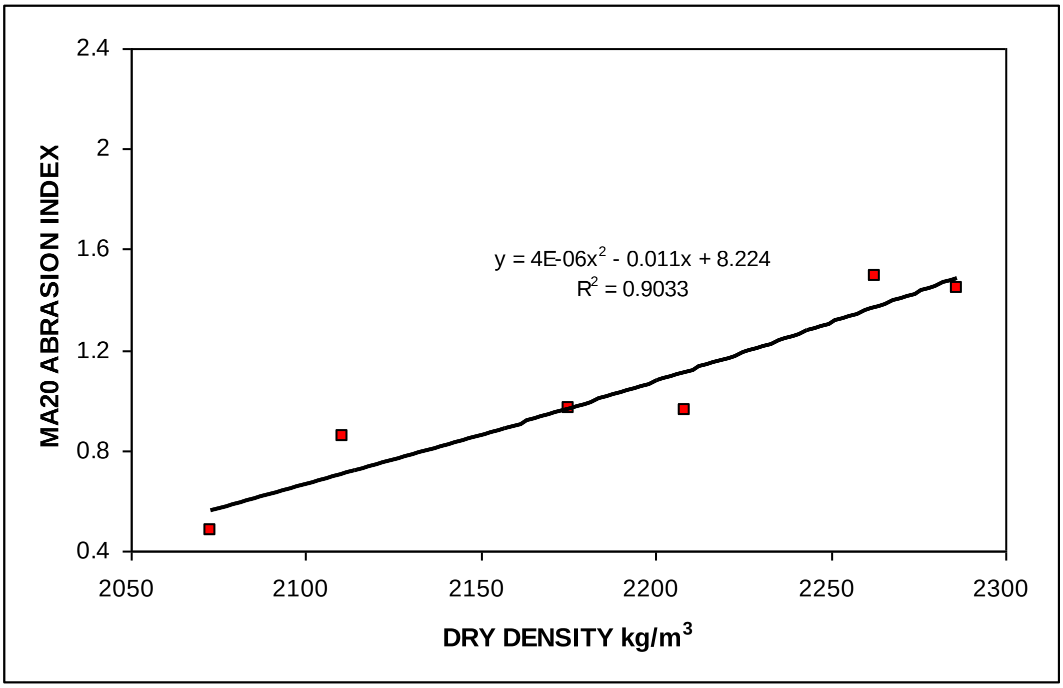


Fig 6.15 Relationship between dry density and abrasion resistance to MA20
Mix 7 = 6.65% OPC, 6.65 MGBS, 0.7 % SF

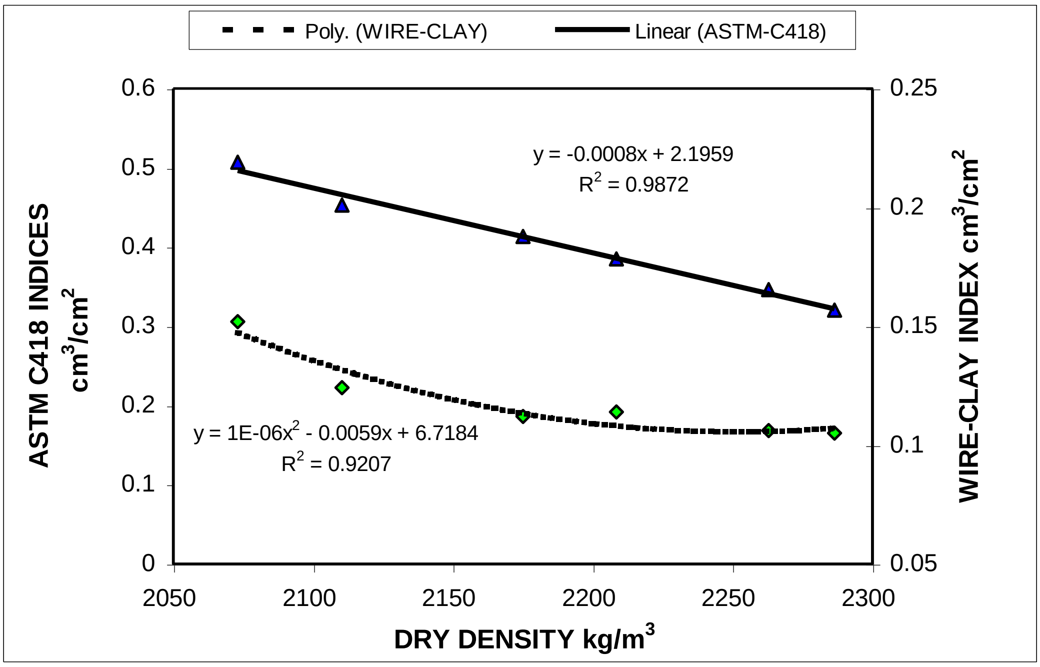


Fig 6.16 Relationship between dry density and abrasion-wear to ASTM C418 and Wire brush PCI.TM.7.11
Mix 7 = 6.65% OPC, 6.65 MGBS, 0.7 % SF

Observation and Discussion

It may be seen from figure 6.11 through 6.16 that as in the case of compressive strength and tensile splitting strength, a clear decrease in abrasion resistance (generic sense) occurs as the density decreases. For example, considering figure 6.11, the wettest mix has an abrasion resistance index of 2,182 (dry density = 2308 kg/m^3) whereas the driest mix has an index of 0,699 (dry density of 2113 kg/m^3). This represents a reduction of 8,5 % in density with a corresponding loss of 66,6 % in the MA20 abrasion resistance index, a loss of 7,8 percent in index for every 1 percent loss in dry density. This sharp drop off in index can once again be explained by the classical drop in strength that occurs as voids increase.

Figure 6.11 also shows that the wettest mix does not always have the highest abrasion resistance (better seen in appendix T.25), again indicating that the wettest mix in fact had somewhat too much water, more than what was required to lubricate the mix for the given compactive effort. The excess water therefore merely contributed to a lower c/w ratio with no compensation in density. (See similar comments under 6.3.1 for a more detailed explanation.)

For each mix design, the two graphs have been paired together on one page to simplify comparisons. For example, a glance at the Y axes numeration corresponding to each test immediately reveals that for any mix the MA20 curve has the highest ratio of Ia_{wet} / Ia_{dry}, and is therefore the most sensitive of the three tests. Conversely the Wire-clay is the least sensitive.

A glance at the R^2 values in these graphs shows that the ASTM C418 test has substantially less scatter than MA20 and the wire brush test. It may also be observed that the best fit line is only linear in the case of ASTM C418. (See chapter 12 for a more detailed discussion on statistical trends for the three abrasion tests).

Sectional Conclusion: A full discussion of the three abrasion tests and how the abrasion resistance indices are calculated and interpreted follows in chapters 9 through 12. Suffice it to say here that the abrasion resistance follows the same trends as the compressive strength and tss tests with regard to density (which in turn is related to the water content.) This is an expected trend for homogeneously cast, uniformly cured, non-surface treated blocks.

6.4 Binder Content

6.4.1 The Influence of Binder Content on Compressive Strength

If the variation in water content plays the most dominant role in the strength of the block due to its influence on the density of semi-dry concrete and the c/w ratio, then the second most important variable is the binder content, for the same reasons, but possible in reverse order (i.e. its effect on b/w is greater than on density.) This will be considered in greater depth further on.

The influence of binder content on concrete has been widely researched over many years and plays a crucial role not only on the compressive strength, but also on the abrasion resistance [Chaplin(1972a), Sadegzadeh(1984)].

To investigate the effect of binder content on compressive strength, tss and abrasion resistance, three variations in cement content were selected as follows:

Mix design 1 = 18% binder
Mix design 2 = 14% binder (control)
Mix design 3 = 10% binder

For each of the above binder contents the percentage quoted refers to the proportion of binder relative to the total mass of the mix before water addition.

The value of 14% was selected as a control as this approximates the norm used in the cbp manufacturing industry.

The value of 18% would not normally be selected (for economic reasons) except in heavy-duty applications. The selection of this binder content is nevertheless justified in order to achieve a better understanding of the strength gains that can be obtained, and this will be useful where heavy traffic loadings are anticipated.

The low binder content of 10% was purposely selected with a view to manufacturing inferior blocks in order to accentuate the problems that can occur where insufficient binder is used.

The binder in each case was a 50/50 blend of Ordinary Portland Cement (OPC) and Milled Granulated Blastfurnace Slag (MGBS). (See appendices A2 and A3 for a detailed physical and chemical analysis of these materials). Such a blend of OPC and MGBS is preferred by some manufacturers for the economic advantages afforded, particularly where blocks are to be coloured all the way through with very costly imported iron oxides. (The MGBS does not dull the pigmentation to the same extend as the OPC and hence less oxide is required to achieve a given colour.) Furthermore at 28-days the compressive strength of an adequately cured blend of 50/50% OPC/MGBS is equivalent to that of 100% OPC. This means that the laboratory results of this investigation (the blocks were 28-days old when the laboratory tests were done) can therefore still be meaningful to manufactures who do not blend with MGBS).

The effect of binder content on the compressive strength of the blocks is immediately noticeable from figure 6.17, constructed from the MA20 compression results (column D of table 6.2) The ‘wet’ and ‘dry’ results are each the average of the 6 blocks crushed respectively from the wettest and driest mixes, whereas the ‘average’ is the result of 36 determinations (6 mixes of varying water content x 6 blocks per mix). Using these average values, table 6.4 may be constructed to further demonstrate the relative strengths of mixes

1,2 and 3. [Note that the SABS results are consistently lower and misrepresent the strength of the blocks since no aspect ratio correction is made (see chapter 7). Therefore the SABS results have largely been left out in favour of MA20 compression results].

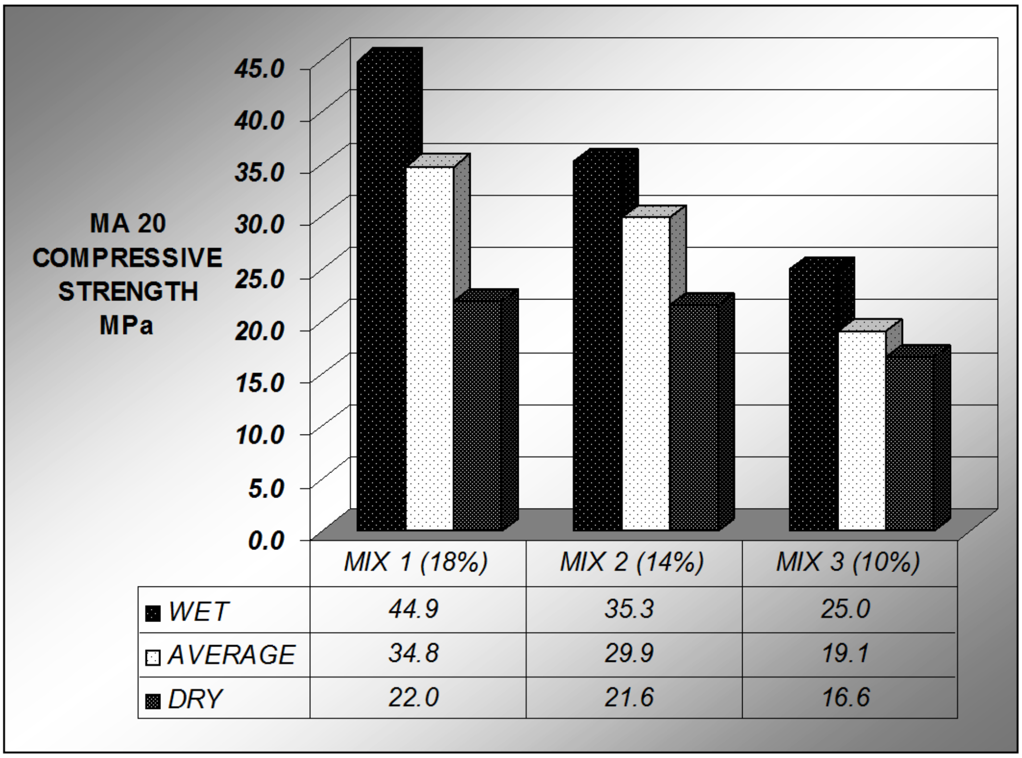


Figure 6.17 Relationship between binder content and compressive strength

TABLE 6.4 AVERAGE COMPRESSIVE STRENGTH RESULTS - MA20			
MIX	% BINDER (Proportion by mass)	AVERAGE MPa (Average of 36 blocks)	RATIO: STRENGTH / CONTROL
1	18	34.7	116 %
2	14 = CONTROL	29.9	100 %
3	10	19.9	64 %

Observations and Discussion

A closer look at figure 6.17 indicates:

a. The effect of varying the cement content has a significant effect on the strength of the blocks (all other things being equal).

b. The effect of the water content can also be readily seen. Wet mixes are far superior to dry mixes. For example it can be seen that a wet mix with only 10 % binder is stronger than a dry mix with 18 % binder. This underlines the importance of aiming for a moisture content that facilitates compaction.

c. Dry mixes are relatively insensitive to binder content. This indicates that increased binder content does not compensate for inadequate lubrication in the mix. For example the compressive strength of the driest mix with 18 % binder is only 29 % stronger than the driest mix with 10 % binder, whereas the same ratio is 80 % for the wettest mixes.

d. The compressive strength variations resulting from water content variations are very pronounced in rich mixes, but not nearly so in dry mixes. For example, considering the mixes made with 18% binder, the wet mix is approximately 100 % stronger than the dry mix. This difference is less noticeable for wet vs dry mixes with 14% binder, while mixes with 10% binder are relatively insensitive to water content (here the ratio of wet to dry is approximately 47%).

A possible explanation for why there is a large difference in the ratio [MPa wet/MPa dry] between 18% and 10% mixes may be that the thickness of the binder or paste coating the individual aggregate particles is much thicker in the case of the 18 % binder. This means that the 'columns' separating adjacent aggregate particles are relatively high in the case of the 18 % blocks.

Conversely the 10 % 'columns' are far squatter and therefore have a more favourable aspect ratio. As the paste between the individual aggregate particles fails, the crushed paste particles are not easily pressed out of the way (in the case of the 10 % binder), due to relatively high frictional effects between the limited crushed paste particles and the aggregate particles.

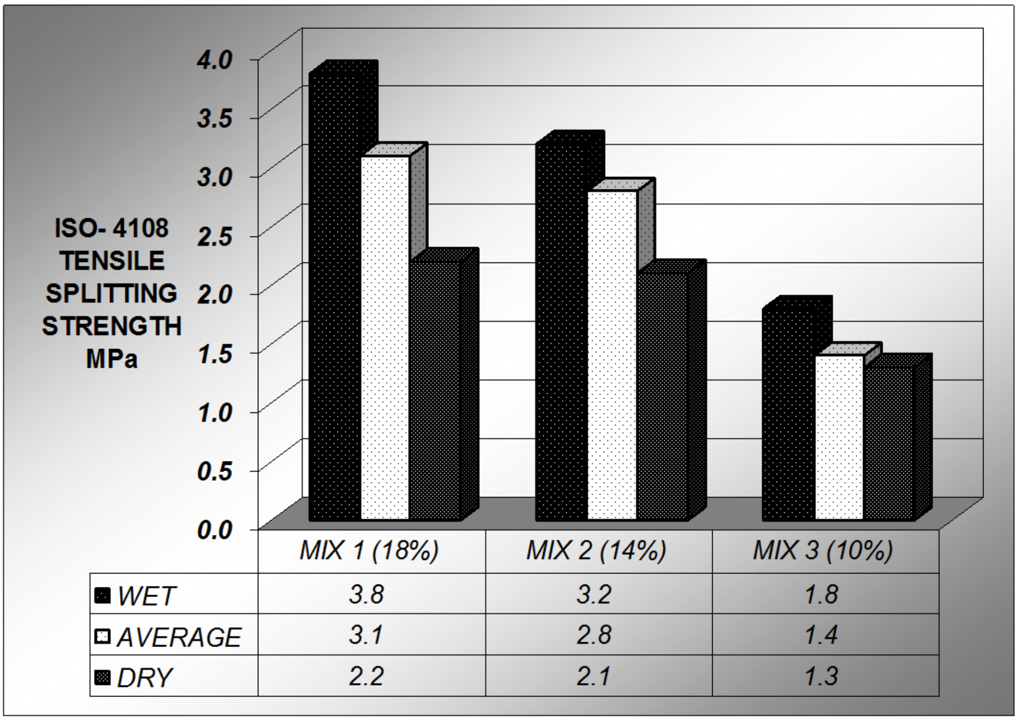
In the case of the 'tall' 18 % 'columns' the aspect ratio is such that once the columns of the relatively thick paste have yielded, the crumbly residue encounters less frictional resistance and is pushed out laterally more easily, thus allowing an overhead aggregate particle to 'collapse' into the particle beneath it more easily. Therefore to withstand the unfavourable aspect ratio in the 18% 'columns', the paste must be inherently strong, as with the 18% wet mix.

The above stated hypothesis is offered merely as a possible explanation why the wet / dry strength ratios are substantially different in the 18 % and 10 % mixes.

6.4.2 The Influence of Binder Content on Tensile Splitting Strength

The same general comments that were made at the beginning of 6.4.1 also apply here and do not need to be repeated. In each case blocks from the same mixes as for compressive strength tests described above were split, and thus it is possible to make a meaningful comparison between compressive strength and tensile splitting strength.

Figure 6.18 below was reconstructed from column E of table 6.2. As for the compressive strength analyses, the 'wet' and 'dry' results are each the average of 6 determinations, while the 'average' is the result of 36 determinations (6 mixes of varying water content x 6 block per mix.)



	MIX 1 (18%)	MIX 2 (14%)	MIX 3 (10%)
WET	3.8	3.2	1.8
AVERAGE	3.1	2.8	1.4
DRY	2.2	2.1	1.3

Figure 6.18 Relationship between binder content and tensile splitting strength

Observation and Discussion

A closer look at figure 6.18 indicates that the results for the tss follow a similar trend to the compressive strength, summarised below:

a. Cement content has a significant effect on the tss.

b. Water content also has a great effect, with wet mixes being significantly stronger than dry mixes.

c. Water content variations are very pronounced in rich mixes, less so in dry mixes. In the case of mixes made with 18 % binder, wet mixes are 73 % stronger than dry mixes, whereas this ratio is reduced to 38 % in the case of mixes with 10 % binder.

A likely explanation is that the weaker a mix is, the easier it is for the block to split around the aggregate particles. Thus the relatively small difference in tss in the 10 % binder mixes may represent a scenario where the aggregate particles are left largely intact for both wet and dry mixes, whereas for the 18 % mixes, the paste in the wet mixes is sufficiently strong to ensure that the break takes place along the shortest path, i.e. through the aggregate particles. Thus the wettest mix measures the composite strength of aggregate and paste, whereas the driest mix only measures the relatively weak paste strength.

Although the above explanation may sound somewhat theoretical, the author has observed this principle in action over many years in the production of ‘rockface’ bricks, which are produced in a similar fashion to the splitting action of the tss test. A knife-edge guillotines a solid block in half resulting in two ‘rockface’ bricks. However it is vitally important that the bricks are sufficiently strong (i.e. well aged) before the guillotining action takes place, or the concrete will split around the aggregate (not aesthetically desirable) instead of through the aggregate.

The phenomenon of splitting through vs around the aggregate is a likely explanation for the relatively small difference in strength between the 18 % and 14 % binders, compared to the significant difference between the 14 % and 10 % binders as illustrated in table 6.5 below. It would appear that the critical cement content for breaking through the aggregate lies somewhere between 10 % and 14 %.

TABLE 6.5 AVERAGE TENSILE SPLITTING STRENGTH RESULTS TO ISO 4108

MIX	% BINDER (Proportion by mass)	AVERAGE MPa (Average of 36 blocks)	RATIO: STRENGTH / CONTROL
1	18	3.13	113 %
2	14 = CONTROL	2.77	100 %
3	10	1.38	50 %

In table 6.6 below a comparison is made between the ratios of the average compressive strength and tss results. (I.e. Table 6.6 is a comparison of table 6.4 and 6.5).

TABLE 6.6 RATIO:AVERAGE COMPRESSIVE / TSS

MIX	% BINDER (Proportion by mass)	MPa (Average of 36/36 blocks)	RATIO: f'c / TSS
1	18	34.7 / 3.13	11.1
2	14 = CONTROL	29.9 / 2.77	10.8
3	10	19.1 / 1.38	13.8

In the case of the 10 % binder mixes, the compressive strength performs relatively well against the tss. The favourable ‘aspect ratio’ effects discussed in point d. under 6.4.1 are reflected in the numerator, while the unfavourable ‘splitting around the aggregate’ effects discussed in point c. of 6.4.2 are reflected in the denominator, resulting in a higher ratio. Thus it may be said that the tss is a more sensitive test for low strength concrete.

6.4.3 The Influence of Binder Content on Abrasion Resistance

The same general comments that were made at the beginning of 6.4.1, once again, also apply here and do not bear repeating. In each case blocks from the same mixes as for compressive strength tests and tss were subjected to the three abrasion tests. The influence of binder content on the abrasion resistance index of each test is illustrated in figures 6.19 through 6.21 respectively. The indices used in figures 6.19 through 6.21 and table 6.7 were taken from columns H, I and J of table 6.2.

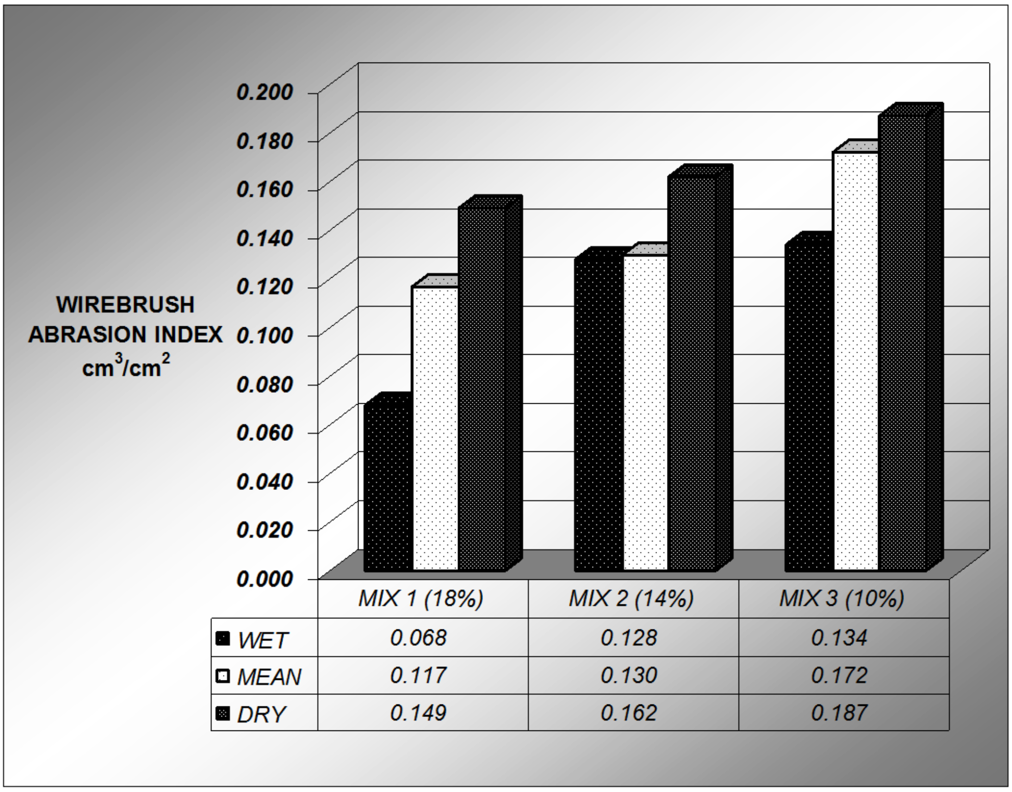


Figure 6.19 Relationship between binder content and wire brush abrasion wear

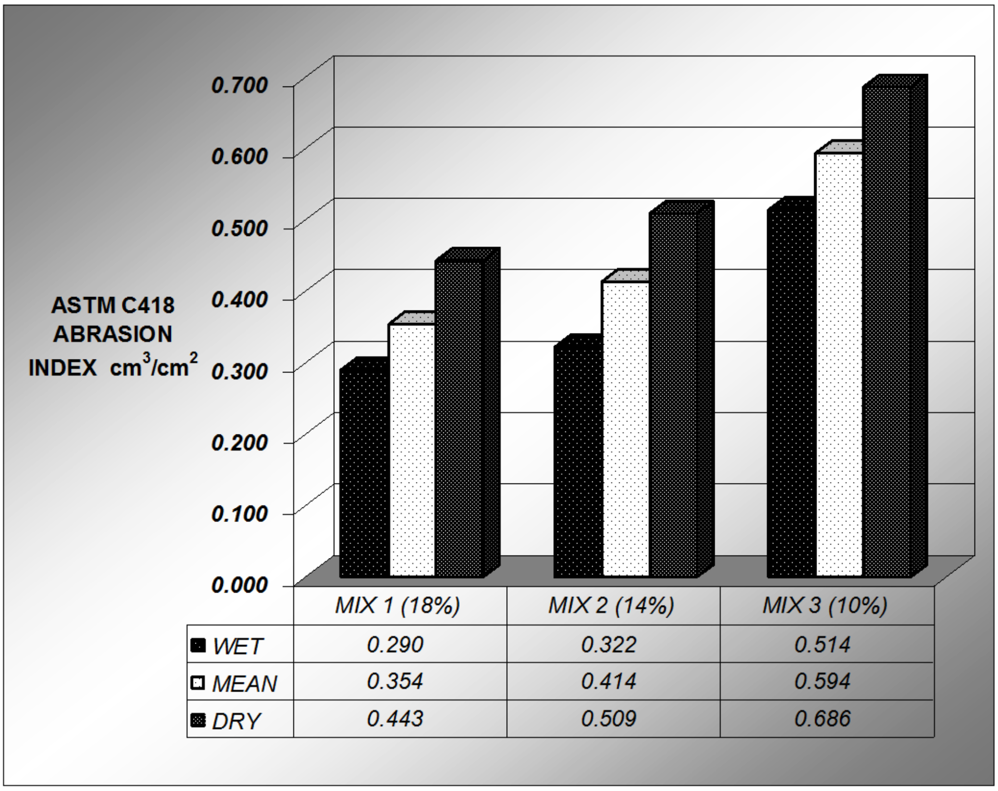


Figure 6.20 Relationship between binder content and ASTM C418 abrasion wear

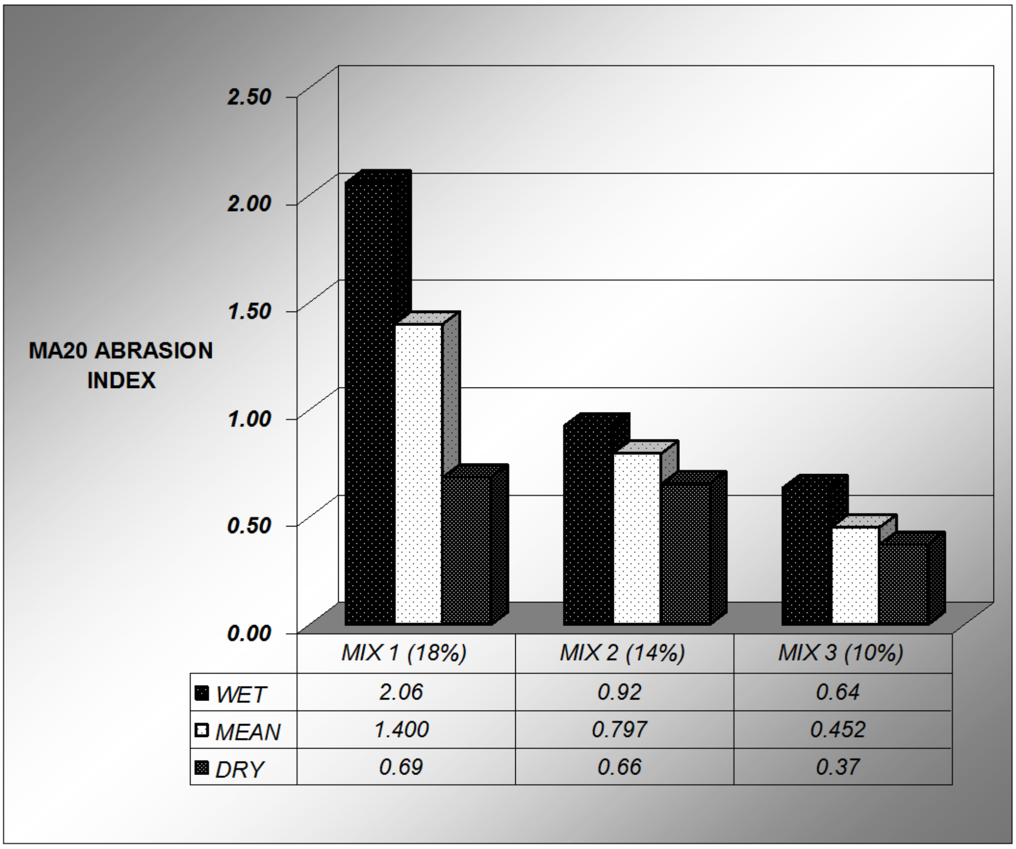


Figure 6.21 Relationship between binder content and MA20 abrasion index

6.4.3.1 Relative Sensitivity of the three abrasion tests

Considering the Y-scales of the above three figures, it is immediately apparent that the MA20 tests is the most sensitive of the three test, i.e. it is able to distinguish best between variations in binder content, as well as differences arising between ‘wet’ and ‘dry’ mixes.

It is also possible to see the relative sensitivities of the three abrasion tests from columns H, I, and J of table 6.2. However before a direct comparison can be made it is necessary to invert the indices of the wire brush and ASTM C418, so that all three tests are proportional to the inverse of penetration. In other words all three will now express abrasion resistance. The results of this manipulation are shown in table 6.7. The table specifically expresses the abrasion resistance values of the 10% and 18% binder content mixes relative to the 14% cement content.

TABLE 6.7 AVERAGE ABRASION RESISTANCE INDICES

MIX	%BINDER	WIREBRUSH		ASTM C418		MA20	
	(Proportion by mass)	$(\text{INDEX})^{-1}$	%	(INDEX)-1	%	INDEX	%
1	18	8.55	111	2.82	117	1.46	176
2	14 = CONTROL	7.69	100	2.42	100	0.83	100
3	10	5.81	75.6	1.68	70	0.48	58

It is clearly apparent that the MA20 has the widest % range and is therefore the most sensitive, while the wire brush and sandblast tests have approximately the same sensitivity.

6.4.3.2 Observations and Discussion

As for the compressive strength test and tss the following trends emerge from the graphs:

a. Cement content has a significant effect on the abrasion resistance.

b. For each of the three cement contents, the water content also has a great effect, with wet mixes having significantly higher abrasion resistance (or lower abrasion wear) relative to dry mixes.

c. The effect of water content variations are very pronounced in rich mixes, less so in dry mixes. This is especially noticeable for the MA20 test, where the indices of wet mixes made with 18 % binder, are 212 % stronger than dry mixes. This ratio is reduced to 95 % in the case of mixes with 10 % binder.

   A possible explanation may be that the weaker a mix is, the easier it is for the individual aggregate particles to be loosened from the paste matrix. Thus the relatively small difference in abrasion resistance in the 10 % binder mixes may represent a scenario where the aggregate particles are not sufficiently bonded, for both wet and dry mixes, whereas for 18 % mix the bonding between paste and aggregate is strong enough to allow the aggregate particles (which have superior wearing properties) to take the brunt of the attack without being loosened. However the bonding ability of the dry paste corresponding to 18 % cement, is not strong enough to prevent the aggregate particles from being loosened and removed. Thus the tests measure the abrasion resistance of the aggregate component in the case of the wetter mix with 18 % binder, while for the drier mixes and mixes with 10 % binder it is principally the abrasion resistance of the binder that is measured. For a fuller discussion refer to chapters 9, 10, 11, and 12.

Sectional Conclusion

It may be said that abrasion resistance follows the same trends with regard to binder content as compressive strength and tss, i.e. rich mixes and wet mixes are more wear resistant than lean mixes and dry mixes.

6.4.4 The Combined Influence of Binder Content and Moisture Content on Abrasion Resistance

In section 6.3 it was shown that water content has a profound effect on density, and hence on abrasion resistance. Likewise section 6.4.3 shows that binder content also strongly influences abrasion resistance. In this section, 6.4.4, their influence on abrasion resistance is shown to be interdependent, and it is possible to identify some trends/relationships, illustrated in figure 6.A. Note that the inverse of the ASTM C418 abrasion *wear* results (table 6.2) are plotted; the equivalent of plotting the abrasion *resistance*. (Note that the trends shown in figure 6.A are also observable in the wire brush and MA20 abrasion result, but are most clearly demonstrated in the ASTM results).

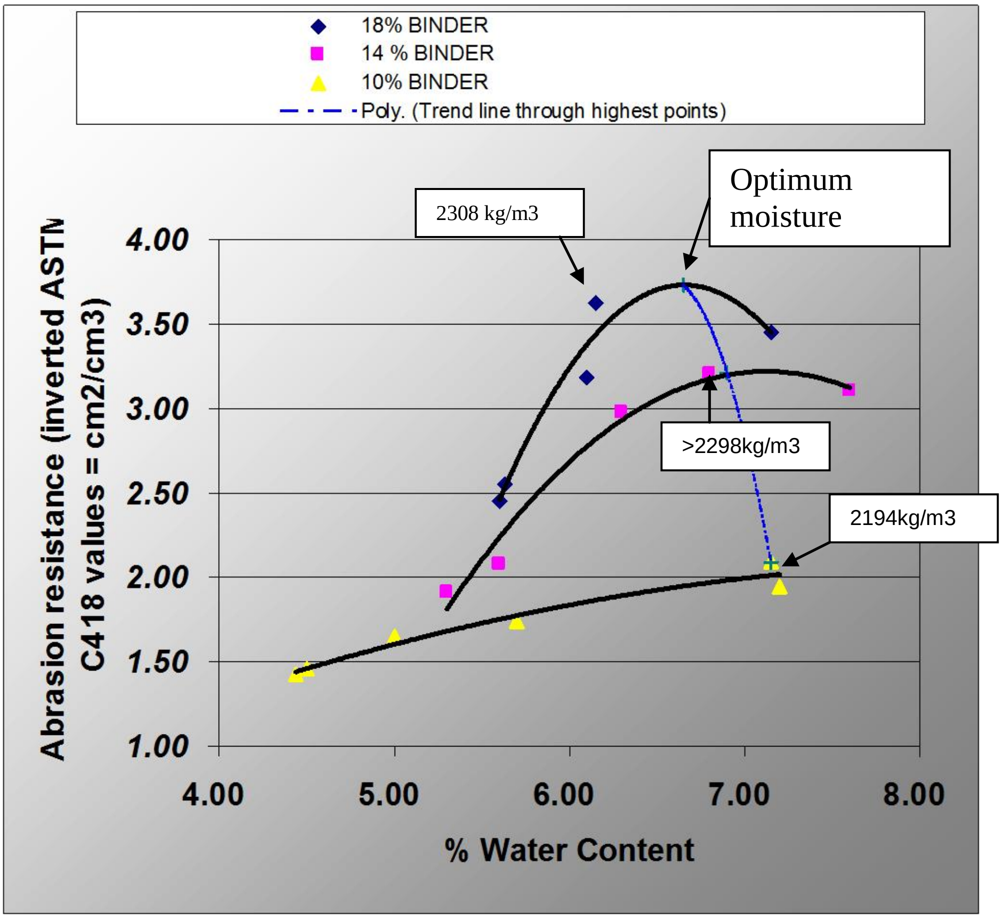


Figure 6.A Relationship between abrasion resistance (inverted at ASTM C418) and % water content.

Observations

1. Considering the three binder contents of mix designs 1, 2 and 3, corresponding to 18%, 14%, and 10%, it is clearly evident that the trend-line with the highest binder content has the highest abrasion resistance, and vice versa. Clearly the greater binder content helps to increase the b/w ratio, over a range of water contents, but equally clearly it also increases the density.

2. The effect that water content has on each of the individual curves is also evident, whereby low water contents result in very substantial reductions in the optimum abrasion resistance. This again is the result of reductions in density (see table 6.2), and the corresponding decreases in w/b as mixes become drier do not compensate for the increase in air voids. On the other hand, it may be seen from the three trend-lines that too much water also results in a lowering of abrasion resistance. These 'very-wet' mixes, represented by the extreme right point on each curve on figure 6.A, were already slumping or on the verge of slumping. They therefore represent the maximum drop in abrasion resistance from a mix with more than the optimum water content. (In this case the additional water only reduces the w/c ratio, while not enhancing density). Clearly this drop is so minor, relative to the loss in abrasion resistance from a too-dry mix (this was also illustrated in table 6.3), that the rule of thumb of seeking out the slump-point, and then cutting back slightly on water, is justified.

3. The optimum moisture content shifts to the right as binder content decreases, and it follows a path approximately indicated by the thin trend-line. In other words, binder-rich mixes can attain optimum compaction (and hence abrasion resistance) with a lower moisture content relative to lean mixes, with the same vibration input. It may therefore be postulated that the volume of paste contributes significantly to the rheology of the mixes. It may be seen that the higher the binder content the greater the density, in spite of less water per unit of binder. Or put another way, *more of a viscous paste is better able to reduce voids than less of a more fluid paste*. The greater quantity of the viscous paste is able to 'bed-in' the aggregate particles more easily with fewer voids. Where there is more paste, even though it may be less fluid, the relative movements of adjacent cement particles *can* afford to be less, as there are more of them at any given section, so that c*umulatively their capacity for movement/displacement during compaction can still be greater*. Essentially more lubricating material between aggregate particles (increase in paste content), allows a greater viscosity in the lubricating material (decrease in w/b). This means that greater paste contents allow reductions in w/b without sacrificing compactability. Thus adequate flow during compaction is achieved by virtue of the greater volume of paste even though it has a lower moisture content.

Clark(1993) made concrete pavers with aggregate cement ratios of 5:1 and 3:1, and the corresponding cement contents were 370kg/m^3 and 570 kg/m^3. While the moisture content for both mixes was 6.9%, the rich mix had a w/c of 0,30 while for the lean mix this had to be increased to 0,44.

Sukandar(1993) did abrasion tests on pavers with cement contents varying from 455 kg/m^3 to 153 kg/m^3. The corresponding w/c ratios varied between 0,21 and 0,34, and the densities of the low w/c mixes were approximately 9% greater than the higher values. Sukandar concludes that high cement content 'enhances workability and compactability of the matrix'.

This confirms that the moisture content per unit quantity of cement can be reduced and still result in improved density providing the total quantity of binder is increased. Thus Sukandar's blocks made with the higher density, higher cement content, and lower w/c, had about 300% more abrasion resistance compared to the low cement content mixes.

From the above it may be concluded that in the case of concrete paving increasing the cement content has a marked effect on the strength of the blocks, firstly by increasing density, and secondly by reducing the w/b.

Sectional Conclusion

The above discussions and explanations are near to the writer's heart in that they embody some of his earliest ideas as to what promotes good abrasion resistance. The writer's original thinking was that a higher *water content* in a semi-dry mix, improved density and abrasion resistance, and indeed for a given cement content this is so. Yet, what came as fresh revelation was that by increasing the binder content a corresponding increase in density is achieved at a *lower water content* per unit of binder.

It may be concluded that an increase in the proportion of binder results in a greater abrasion resistance because the accompanying improvement in the rheology of the mix allows an increased density (less voids) at a lower w/c.

These concepts are considered more fully in volume two under the headings '2.2.1.1 w/b'; '2.2.1.1.2 Binder quantity'; '2.3.3.2 Effect of relative proportioning of paste on entrapped voids'.

6.5 Binder Type

6.5.1 The influence of binder type on compressive strength

The foregoing sections have shown how the water content and cement content affect the compressive strength of the blocks. In this section the influence of the type of cementitious material (or binder) on the compressive strength is examined.

Four different materials were used:

Ordinary Portland Cement - OPC
Milled Granulated Blastfurnace Slag - MGBS
Fly Ash - FA
Silica Fume - SF

Of the eight mix designs six of them contained the same total quantity of binder and it is therefore possible to evaluate the relative performance of the various binder combinations shown in table 6.8.

TABLE 6.8 MIX DESIGNS (Relative proportions by mass %)

MIX	AGGREGATE	OPC	MGBS	FLY ASH	Si FUME
2	86 = control	7	7		
4	86	10		4	
5	86	11		3	
6	86	12		2	
7	86	6.65	6.65		0.7
8	86	6.30	6.30		1.4

Results and Discussion

Figure 6.22 below shows the relationship between compressive strength (values are from column D of table 6.2) and binder type, for the six mix designs of table 6.8.

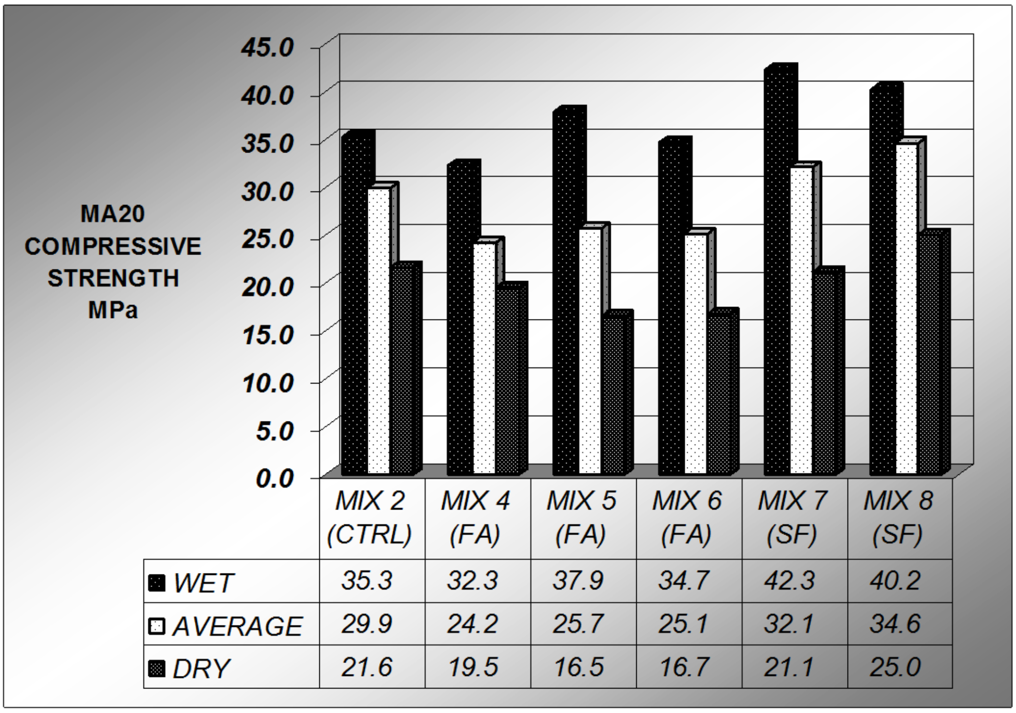


Figure 6.22 Relationship between binder type and MA20 compressive strength (all mixes have a total binder content of 14%)

It may be seen that the mixes containing SF performed the best while those with FA performed relatively poorly. Once again the crushing results of the MA20 test have been used since it is the only test that compensates for aspect ratio, (explained in chapter 7). Each point on the 'average' bar height is the result of 36 blocks tested, i.e. 6 mixes of varying water content per binder type x 6 blocks per mix. The bar heights corresponding to 'wet' and 'dry' are respectively the averages of six blocks for the wettest and driest mixes.

The 'average' bar heights are compared in the table below:

TABLE 6.9 AVERAGE MA20 COMPRESSIVE STRENGTH RELATIVE TO CONTOL

MIX	% BINDER (Proportion by mass)	AVERAGE MPa (Average of 36 blocks)	% RATIO: STRENGTH / CONTROL
2	14=CONTROL	29.9	100.0
4	14 (4% FA)	24.3	81.3
5	14 (3% FA)	25.7	86.6
6	14 (2% FA)	25.1	83.9
7	14 (0.7% SF)	32.1	107.4
8	14 (1.4% SF)	34.6	115.7

It is evident that the 28-day compressive strength of fly ash mixes are retarded while the silica fume mixes are accelerated.

Performance of Fly Ash

The relatively poor performance of the mixes containing fly ash is largely due to the poor performance of fly ash in the 'dry' mixes. This may be seen from Figure 6.22, particularly for mix designs 5 and 6.

In table 6.10 the compressive strengths of the 'wet' mixes are tabled using the same format as table 6.9, and this time it can be seen that overall FA performs about as well as the control.

TABLE 6.10 WETTEST MA20 COMPRESSIVE STRENGTH RELATIVE TO CONTROL

MIX	%BINDER (Proportion by mass)	MPa OF WET MIX (Average of 6 blocks)	%RATIO:STRENGTH/ CONTROL
2	14 = CONTROL	35.3	100.0
4	14 (4% FA)	32.3	91.5
5	14 (3% FA)	37.9	107.4
6	14 (2% FA)	34.7	98.3
7	14 (0.7% SF)	42.3	119.8
8	14 (1.4% SF)	40.2	113.9

It may therefore be said that fly ash is not well suited to the production of paving blocks unless great care is taken to maximise the water content. Interestingly this position is completely reversed at six years, where site measurements revealed the lowest wear for the fly ash mixes – see chapter 14.

Gordon(1991) found that the beneficial properties of fly ash are largely characterised by its fineness. Since Lethabo Field 2 fly ash is considerably finer than the Matla fly ash used in this investigation, enhanced 28-day and long term results may be expected in pavers made from this source.

Performance of Silica Fume

Figure 6.22 shows that silica fume enhances the compressive strength of paving blocks. It would appear that the 0.7% SF mix appears to perform better than the 1,4% SF mix. This is because the 'wet' mix in the latter case was far too wet, demonstrated by the way the third wettest mix for the 1.4% SF mix performs noticeably better than any of the 0.7% SF mixes (see table 6.2).

A comparison of figure 6.22 and figure 6.17 shows that incorporating 1.4% of SF into a 14% binder gives, on average, the same compressive strength as a mix with 18% binder. Even considering the relatively high cost of SF this represents a positive saving, providing SF is readily available.

However, it should be noted that silica fume is known to 'slow down' after 28-days. This is confirmed in chapter 14, where the silica fume mixes tended to have the highest 'mean visible depth'.

Sectional Conclusion – Generally fly ash retards the 28-day compressive strength, unless great care is taken to make the blocks with as much water as possible. On the other hand silica fume noticeably increases 28-day strength at all moisture contents.

6.5.2 The influence of binder type on tensile splitting strength

Generally the tensile splitting strength follows the same trend as the compressive strength and the discussion in this section will therefore be kept brief.

Figure 6.23 below (from column E in table 6.2) shows the relationship between tensile splitting strength and binder type. This graph shows that the mixes containing SF performed the best while those with FA performed poorly. Each point on the ‘average’ bar line is the result of 36 blocks tested, i.e. 6 mixes of varying water content x 6 blocks per mix. The bar line corresponding to ‘wet’ and ‘dry’ is respectively the average of the six blocks from the wettest mix and six blocks from the driest mix.

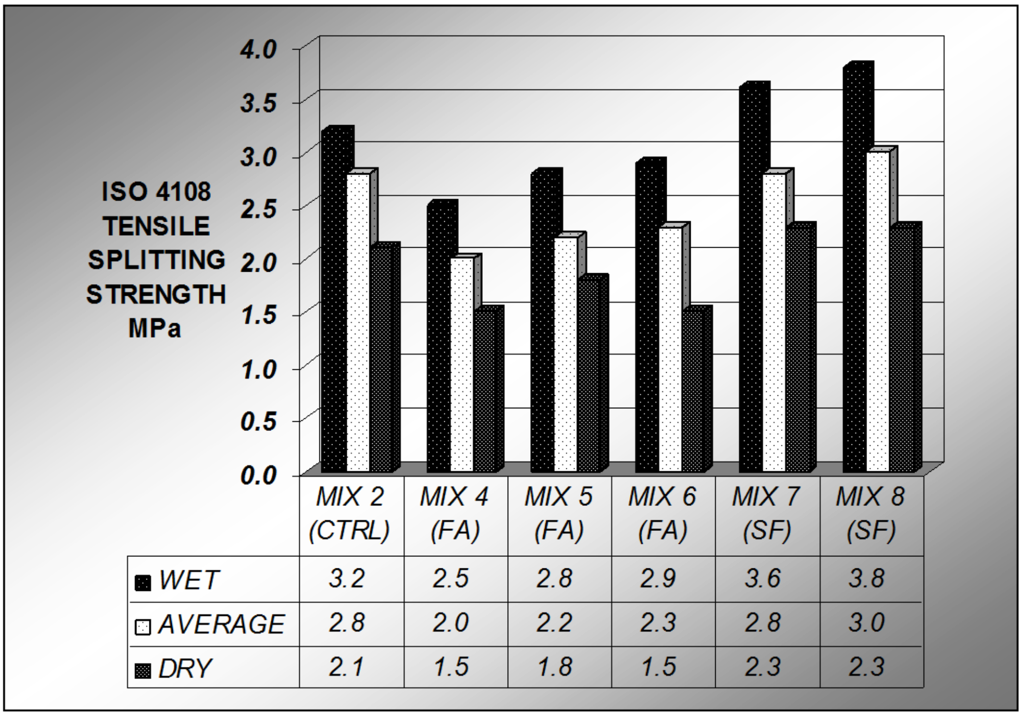


Figure 6.23 Relationship between binder type and tensile splitting strength (all mixes have a total binder content of 14%)

The ‘average’ bar lines are compared in the table below:

TABLE 6.11 AVERAGE TENSILE SPLITTING STRENGTH RELATIVE TO CONTROL

MIX	% BINDER (Proportion by mass)	AVERAGE MPa (Average of 36 blocks)	% RATIO: STRENGTH / CONTROL
2	14 = CONTROL	2.77	100.0
4	14 (4% FA)	1.98	71.5
5	14 (3% FA)	2.20	79.4
6	14 (2% FA)	2.28	82.3
7	14 (0.7% SF)	2.86	103.2
8	14 (1.4% SF)	3.03	109.9

Again the relatively poor performance of the mixes containing fly ash is largely due to the poor performance of fly ash in the drier mixes. This is plain from Figure 6.23, as well as tables 6.11 and 6.12. The former table is concerned with the ‘average’ result, the latter with the tss for blocks made from the ‘wettest’ mixes.

TABLE 6.12 WETTEST TENSILE SPLITTING STRENGTH RELATIVE TO CONTROL

MIX	% BINDER (Proportion by mass)	MPa (Average of 6 blocks)	% RATIO: STRENGTH / CONTROL
2	14 = CONTROL	3.2	100.0
4	14 (4% FA)	2.5	78.1
5	14 (3% FA)	2.8	87.5
6	14 (2% FA)	2.9	90.6
7	14 (0.7% SF)	3.6	112.5
8	14 (1.4% SF)	3.8	118.8

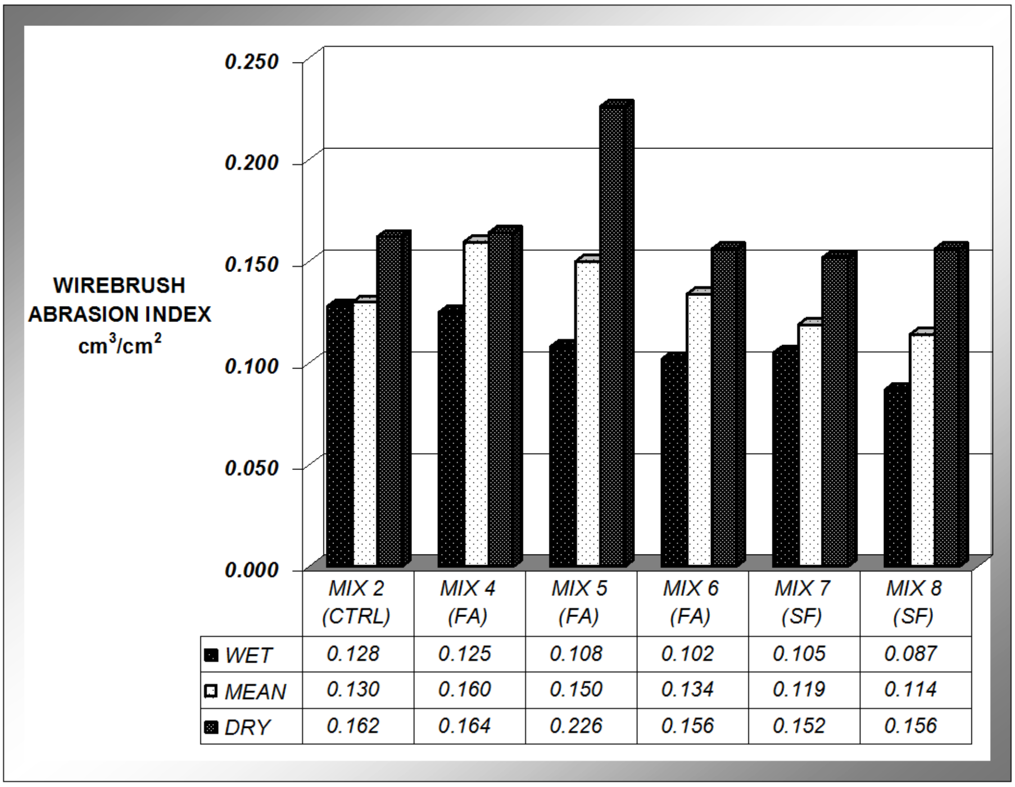
These results indicate that including fly ash as part of the binder significantly reduces the 28-day tss of cbp, particularly for dry mixes. Conversely including SF significantly enhances the 28-day tss of cbp, particularly for wet mixes.

The reader is again reminded that had the fly ash been sourced from Letabo a better 28-day (and long term) result could have been expected.

6.5.3 The influence of binder type on abrasion resistance

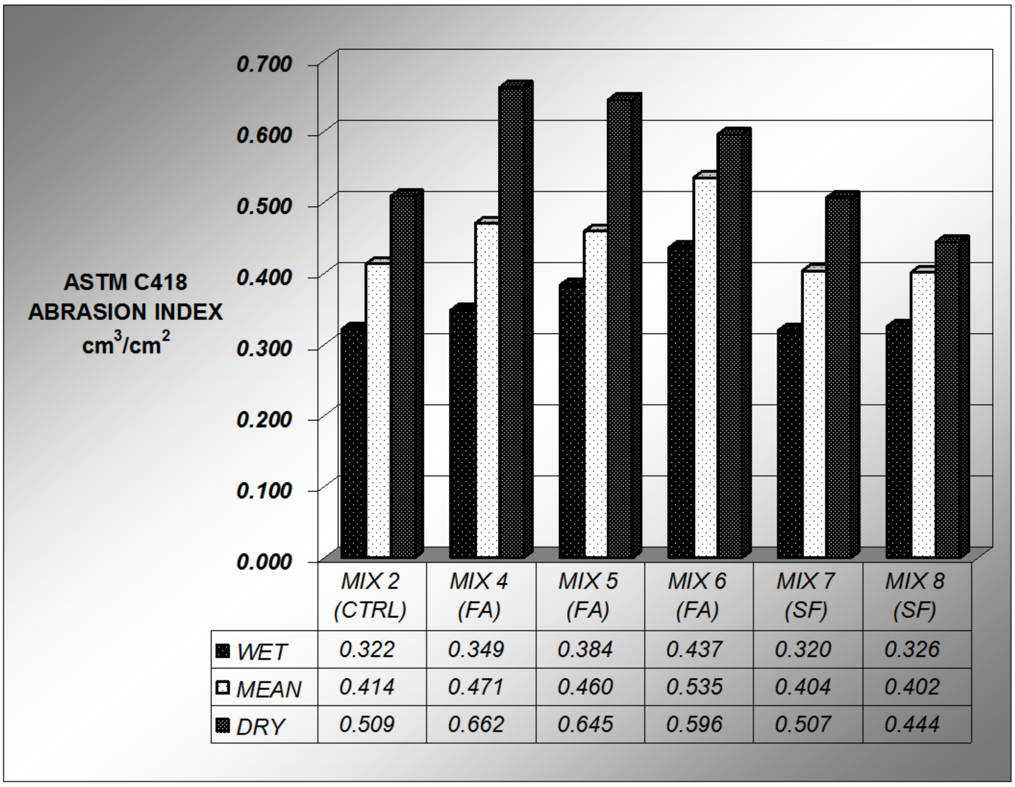
Generally the abrasion resistance follows the same trend as the compressive strength and tss. Therefore the discussion in this section will again be kept brief.

Figures 6.24, 6.25, 6.26 respectively plot the ‘average’, ‘wet’ and ‘dry’ abrasion indices for each of the three abrasion tests (constructed from values in columns H, I, J of Table 6.2) for each of the six binder types. Each point on the ‘mean’ bar line is the result of 30 blocks tested, i.e. 6 mixes of varying water content per binder type x 5 blocks per mix, while each bar line on the ‘wet’ and ‘dry’ graphs is the average of five blocks tested. However, in the case of the wire brush test (figure 6.24) the result corresponding to the first of the five blocks tested in each mix had to be discarded (see chapter 10).



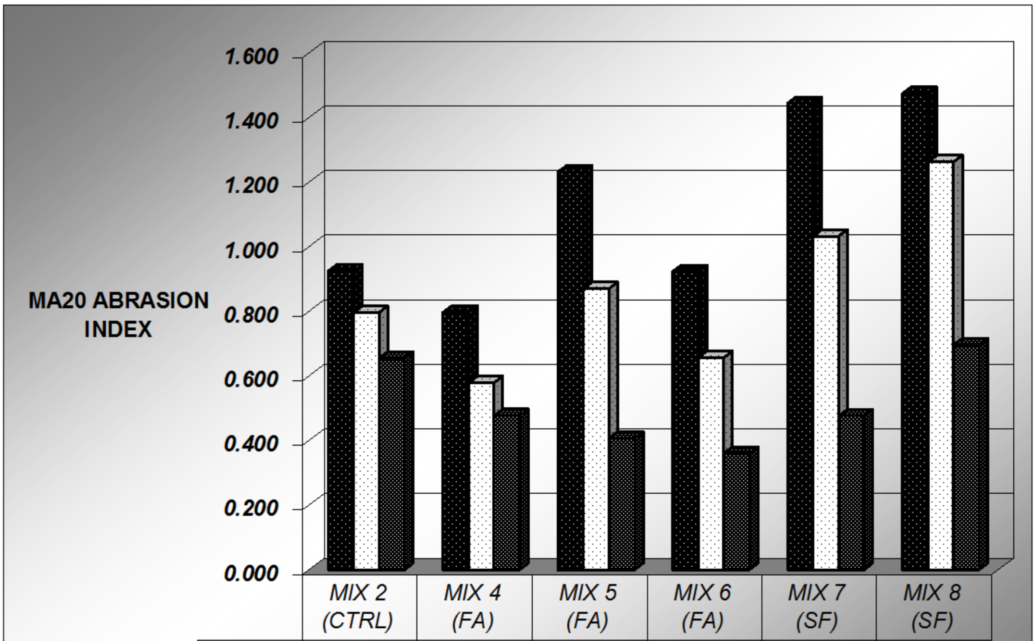
	MIX 2 (CTRL)	MIX 4 (FA)	MIX 5 (FA)	MIX 6 (FA)	MIX 7 (SF)	MIX 8 (SF)
WET	0.128	0.125	0.108	0.102	0.105	0.087
MEAN	0.130	0.160	0.150	0.134	0.119	0.114
DRY	0.162	0.164	0.226	0.156	0.152	0.156

Figure 6.24 Relationship between binder type and Wire-brush abrasion wear. (All mixes have a total binder content of 14%)



	MIX 2 (CTRL)	MIX 4 (FA)	MIX 5 (FA)	MIX 6 (FA)	MIX 7 (SF)	MIX 8 (SF)
WET	0.322	0.349	0.384	0.437	0.320	0.326
MEAN	0.414	0.471	0.460	0.535	0.404	0.402
DRY	0.509	0.662	0.645	0.596	0.507	0.444

Figure 6.25 Relationship between binder type and ASTM C418 abrasion wear



	MIX 2 (CTRL)	MIX 4 (FA)	MIX 5 (FA)	MIX 6 (FA)	MIX 7 (SF)	MIX 8 (SF)
WET	0.924	0.797	1.231	0.923	1.444	1.475
MEAN	0.797	0.579	0.871	0.657	1.032	1.263
DRY	0.655	0.477	0.407	0.360	0.476	0.696

Figure 6.26 Relationship between binder type and MA20 abrasion index

From the graphs the following may be concluded:

a. The type of binder used generally has a lesser effect on the abrasion index than does the binder content. This may be observed by comparing the MA20 results in table 6.13 to table 6.7.

   Note that as in table 6.7 the wire brush and sandblast indices have been inverted to obtain an equivalent abrasion resistance.

b. Water content has a great effect on abrasion resistance (generic sense) irrespective of what binder type is being used (see figures 6.24 through 6.26).

c. Comparing the Y axes of figures 6.24 through 6.26, it may be seen that the `Y axis of the MA 20 test has by far the widest range, and is therefore the most sensitive to changes in mix design, while the sandblast test is the least sensitive.

d. There appears to be an anomaly in Mix 5 (3% FA, 11% OPC) since the abrasion resistance values are noticeably higher than both Mix 4 (4% FA, 10% OPC) and Mix 6 (2% FA, 12% OPC). Intermediate values would be more realistic.

Table 6.13 and 6.14 specifically indicate the relative strengths and weaknesses of the various binder types relative to the control.

TABLE 6.13 WETTEST ABRASION RESISTANCE RELATIVE TO CONTROL				
MIX	% BINDER (by mass)	WIREBRUSH $(INDEX)^{-1}$ %	ASTM C418 $(INDEX)^{-1}$ %	MA20 INDEX %
2	14 = CONTROL	100.0	100.0	100.0
4	14 (4% FA)	81.2	87.9	69.9
5	14 (3% FA)	86.7	90.0	109.6
6	14 (2% FA)	97.0	77.4	79.5
7	14 (0.7% SF)	109.2	102.5	130.1
8	14 (1.4% SF)	114	103.0	162.7

TABLE 6.14 WETTEST ABRASION RESISTANCE RELATIVE TO CONTROL				
MIX	% BINDER (by mass)	WIREBRUSH $(INDEX)^{-1}$ %	ASTM C418 $(INDEX)^{-1}$ %	MA20 INDEX %
2	14 = CONTROL	100.0	100.0	100.0
4	14 (4% FA)	102.4	92.3	84.2
5	14 (3% FA)	118.5	83.9	129.4
6	14 (2% FA)	125.5	73.7	95.5
7	14 (0.7% SF)	121.9	100.6	151.1
8	14 (1.4% SF)	147.1	98.7	161.6

The Wire-brush ratios indicate that including fly ash as part of the binder enhances the abrasion resistance, but only if the mix is very wet. On the other hand the MA20 ratios for fly ash are generally low. The ASTM C418 ratios are low for both the silica fume and fly ash mixes. The most possible explanation for these ratios is that the control was too high in the case of the ASTM and too low in the wire brush, as a result of experimental scatter or operator error.

The results show that silica fume enhances the 28-day abrasion resistance of cbp (ASTM C418 excluded).

6.6 Summary and Conclusions

The three mix design variables of this investigation all have an impact on the strength of the blocks in the following order of importance:

1 Water content
2 Binder content
3 Binder type

The results of this chapter have been summarised in ratio form in table 6.15 and confirm this order of importance. In effect the table is a consolidation of the all the foregoing ratio tables.

Interpretation table 6.15: Following is a brief summary of some of the main points of table 6.15:

6.6.1 Water content

The correct dosage of water and the marked effect that it has on the density of the blocks makes it the most critical of the mix design constituents. From point 1 of table 6.15 it can be seen that relative to dry mixes wet mixes are on 'average':

85% stronger in compression testing according to MA20
63% stronger in tensile splitting according to ISO 4108
63% more abrasion resistant according to the wire brush test
54% more abrasion resistant according to the ASTM C418 test
150% more abrasion resistant according to the MA20 test

These figures represent the ratio between the mean of the six wettest blocks and the mean of the six driest blocks for each of the eight mix designs, averaged over the eight mix designs.

Since blocks from the same mix were subjected to each of these tests for each mix, it is possible to say that 'apples are being compared with apples'. This means that the percentages given above also serve as an indication of the relative sensitivities of the different tests to changes in the strength of the blocks. Thus the order of sensitivity in descending order would be:

1. MA20 abrasion resistance test
2. MA20 compressive strength test
3. Wire brush abrasion resistance test
4. Tensile splitting strength test
5. ASTM C418 abrasion resistant test

6.6.2 Binder content

From point 2 in table 6.15 it can be seen that rich mixes (with 18% binder) are on average stronger than the control (14% binder) by a factor of:
16% in compression
13% in tensile splitting
11% in abrasion resistance according to wire brush
17% in abrasion resistance according to ASTM C418
76% in abrasion resistance according to MA20

TABLE 6.15 SUMMARY OF RESULTS - CRITICAL RATIOS OF STRENGTH CRITERIA

1. EFFECT OF DRY DENSITY ON STRENGTH CRITERIA

INDEPENDANT VARIABLE	CRITICAL RATIOS OF DENSITIES	COMPRESSIVE STRENGTH ref TBL 6.2 (column D)	TENSILE SPLITTING STRENGTH ref TBL 6.2 (column E)	ABRASION RESISTANCE * READINGS INVERTED TO COMPARE WITH MA20 ref TBL 6.2 (column H,I,J)		
		MA20	ISO 4108	WIRE - CLAY *	ASTM C418 *	MA20
WATER CONTENT	MIX 1 WET / MIX 1 DRY	2.04	1.73	2.19	1.53	3.26
	MIX 2 WET / MIX 2 DRY	1.63	1.52	1.27	1.58	1.46
	MIX 3 WET / MIX 3 DRY	1.51	1.39	1.40	1.33	1.95
	MIX 4 WET / MIX 4 DRY	1.66	1.67	1.31	1.90	1.97
	MIX 5 WET / MIX 5 DRY	2.30	1.56	2.09	1.68	3.29
	MIX 6 WET / MIX 6 DRY	2.08	1.93	1.53	1.36	2.57
	MIX 7 WET / MIX 7 DRY	2.00	1.57	1.45	1.58	3.11
	MIX 8 WET / MIX 8 DRY	1.61	1.65	1.79	1.36	2.34
	AVERAGE	1.85	1.63	1.63	1.54	2.50

2. EFFECT OF BINDER CONTENT ON STRENGTH CRITERIA

INDEPENDANT VARIABLE	CRITICAL RATIOS OF BINDER CONTENTS	COMPRESSIVE STRENGTH ref TBL 6.4	TENSILE SPLITTING STRENGTH ref TBL 6.5	ABRASION RESISTANCE * READINGS INVERTED TO COMPARE WITH MA20 ref TABLE 6.7		
		MA20	ISO 4108	WIRE - CLAY *	* ASTM C418	MA20
BINDER	MIX 1 AVG / CONTROL AVG	1.16	1.13	1.11	1.17	1.76
CONTENT	MIX 3 AVG / CONTROL AVG	0.64	0.50	0.76	0.70	0.58

3. EFFECT OF BINDER TYPE ON STRENGTH CRITERIA

INDEPENDANT VARIABLE	CRITICAL RATIOS OF BINDER TYPES	COMPRESSIVE STRENGTH		TENSILE SPLITTING STRENGTH		ABRASION RESISTANCE * READINGS INVERTED TO COMPARE WITH MA20					
		MA20		ISO 4108		WIRE - CLAY *		* ASTM C418		MA20	
		AVG	WET	AVG	WET	AVG	WET	AVG	WET	AVG	WET
		ref TBL 6.9	ref TBL 6.10	ref TBL 6.11	ref TBL 6.12	ref TBL 6.13	ref TBL 6.14	ref TBL 6.13	ref TBL 6.14	ref TBL 6.13	ref TBL 6.14
BINDER TYPE	MIX 4 / CONTROL	0.81	0.92	0.71	0.78	0.81	1.02	0.88	0.92	0.70	0.84
	MIX 5 / CONTROL	0.86	1.07	0.79	0.88	0.87	1.19	0.90	0.84	1.10	1.29
	MIX 6 / CONTROL	0.84	0.98	0.82	0.91	0.97	1.26	0.77	0.74	0.80	0.96
	MIX 7 / CONTROL	1.07	1.20	1.03	1.13	1.09	1.22	1.03	1.01	1.30	1.51
	MIX 8 / CONTROL	1.16	1.14	1.09	1.19	1.14	1.49	1.03	0.99	1.63	1.62
	AVERAGE OF AVG & WET	0.95	1.06	0.89	0.98	0.98	1.23	0.92	0.90	1.10	1.24

These values are obtained from the ratio of the mean of the six mixes of varying water content for mix design 1 x 6 blocks per mix (‘MIX 1 AVG’ = avg. of 36 blocks) and the corresponding mean for mix design 2 (‘CONTROL AVG’ = avg. of 36 blocks).

Lean mixes (with 10% binder) are weaker than the control by a factor of:

36% in compression
50% in tensile splitting
24% in abrasion resistance to Wire brush
30% in abrasion resistance to ASTM C418
42% in abrasion resistance to MA20

These values are obtained from the ratio of the mean of the six mixes of varying water content for mix design 3 x 6 blocks per mix (‘MIX 3 AVG’ = avg. of 36 blocks) and the corresponding mean for mix design 2 (‘CONTROL AVG’ = avg. of 36 blocks).

Generally, it would appear that whereas a moderate increase in strength (considering all five tests) can be achieved in increasing the binder from 14 % to 18 %, a considerably greater decrease in strength occurs when the cement is reduced to 10 %.

Reducing the binder content below 14 % is therefore not advisable.

6.6.3 Binder type

From the results in Table 6.15 the relative performance of the mixes containing 14% binder can generally be graded (considering an overview of the compressive strengths, tss, and abrasion resistance tests) in descending order as follows:

Mix 8 - 1.4% Si fume
Mix 7 - 0.7% Si fume
Mix 2 - Control
Mix 5 - 3% Fly ash
Mix 6 - 2% Fly ash
Mix 4 - 4% Fly Ash

This ranking is based, in the first instance, on the ratio of the *mean* of the six mixes of varying water content x 6 blocks per mix for mix designs 4, 5, 6, 7, 8 respectively (e.g. ‘MIX 4’ = avg. of 36 blocks) and the corresponding *mean* for mix design 2 (‘CONTROL’ = avg. of 36 blocks), and appear under the sub headings shown as ‘AVG’. In the second instance the values appear under the sub heading ‘WET’, and represent the ratio of the mean of the wettest water content for mix designs 4, 5, 6, 7, 8 respectively (6 blocks in each case) and the mean of the wettest water content of the control mix (6 blocks). Generally the ‘wet’ ratios follow the ‘mean’ ratios.

6.6.4 Relative importance of water content, binder content, and binder type

In all cases considered below the MA20 compression test shall be used for comparing the relative importance of the three criteria.

a. Water content: Blocks from wet mixes are 85 % stronger than blocks from dry mixes. (See table 6.15, where the result is the average of 96 blocks, i.e. 8 mix designs x [6 ‘wet’ blocks + 6 ‘dry’ blocks]).

b. Binder content: Blocks from mixes with 18 % binder are on average 82 % stronger than blocks from mixes with 10 % binder. (See table 6.2, where the result is the average of the two mix designs in question i.e 2 mix designs x six mixes of varying water content x 6 blocks/mix = 72 blocks).

c. Binder type: The average of the strongest SF mix design is 34,5 % stronger than that of the average of the strongest FA mix design. (See table 6.2, where the result is the average of the two mix designs in question, i.e. 36 blocks / 36 blocks; 34.6 MPa / 25,7 MPa).

The above analyses have all been based on the MA20 compressive strength results. These conclusions may also be extended to abrasion resistance, for the following reasons:

(1) The various graphs of this chapter that show the relationship between abrasion resistance and density, abrasion resistance and binder content, abrasion resistance and binder type, clearly follow the same trends as the compressive strength tests. This is further evidenced by relatively good correlations shown in figure 7.1 between the abrasion tests and compression testing, as evidenced by R^2 values of 0.806, 0.795 and 0.833, respectively for the MA20, Wire brush and ASTM C418 abrasion tests.

(2) Every effort was made to ensure that the surface of the blocks would have the same properties as their cores. This was done by ensuring that the surface of the blocks were not allowed to dry out during the curing process, that the blocks were made without a special surface topping, and that no special finishing process or sealer was applied.

6.7 Practical Implications for the Industry

Clear trends emerge from the results of the laboratory tests:

a. **Water content**: Wet blocks are remarkably stronger than dry blocks in compression testing, tensile splitting, and abrasion resistance. Manufacturers should therefore aim at optimising the water content at about the second wettest water content. This is obviously the most economical way of increasing the strength of the blocks.

In this investigation water contents were deliberately varied from a very ‘dry’ 4,2% to a very ‘wet’ 7,6%. Considering figures 6.1 and 6.2 it would appear the optimum density is obtained when the water content is in the range of 6,5% to 7,0 %. This is confirmed by Dowson(1980) who found water contents to typically vary between 5% and 7%. Clearly the exact values will vary depending on the quantity and nature of the binder used, the type of aggregate etc.

It will be well worth any manufacturers time to determine the moisture content corresponding to the onset of slumping i.e. the point at which the lateral dimension of the paver begins to increase (changes in height will probably not even be discernable).

This moisture content is determined simply by progressively increasing the water content until the first signs of slumping appear.

The optimum moisture content, where strength and abrasion resistance are at a maximum for a given binder content and compactive effort is likely to be about 0.5% less than slump point.

This may be expressed as:

$\% \, MC_{\text{optimum}} = \% \, MC_{\text{slump onset}} . - 0.5\%$ (6-1)

b. **Binder content**: Rich mixes improve the strength of cbp both in compression, tensile splitting and abrasion resistance. It is understood that it is really the effect of the increased b/w ratio that goes with a rich mix which is responsible for the increase of strength. However, it has been shown (see figure 6A), that increasing binder content also contributes to increased density, and hence to strength and abrasion resistance.

Making the blocks too wet only lowers the b/w ratio marginally, since the ‘slump point m.c’. is very close to the ‘optimum m.c’. Even for blocks that have started to slump and would not therefore be installed on any site, the difference in compressive strength between such blocks and blocks made from the optimum water content is only 2 %, as shown in table 6.3. Therefore it is acceptable to talk in terms of increasing strength by increasing binder content.

Specifiers and manufacturers should be aware that in cases where severe service conditions exist, increasing the binder content is necessary, since there is very limited scope for increasing the b/w by means of reducing the m.c. if voids are to be minimised.

Table 6.16 below gives an indication of what strengths (i.e. compressive strength, tss, abrasion resistance) can be expected from different binder contents. These figures are the mean of the wettest and second wettest mixes for 18 % , 14 % , and 10 % binder respectively, since it is assumed that manufacturers will aim for well-lubricated mixes. Note that the ASTM C418 and Wire brush indices have been inverted to convert them from abrasion-wear to abrasion resistance, thus allowing comparison with the MA20 abrasion test.

TABLE 6.16 28 DAY STRENGTH DESIGN VALUES FOR DIFFERENT BINDER CONTENTS

MIX DESIGNS (RELATIVE PROPORTIONS BY MASS)				AVERAGE OF TWO WETTEST MIXES (12 BLOCKS)				
				COMPRESSIVE	TSS	ABRASION RESISTANCE		
MIX	AGGREGATE	% BINDER		STRENGTH	ISO	WIRE	ASTM	MA20
		OPC	MGBS	MA20	4108	CLAY	418C	
				MPa	MPa	cm³/cm²	cm³/cm²	INDEX
1	82	9%	9%	45	3.9	0.08	0.28	2.24
2	86	7%	7%	35	3.2	0.12	0.32	0.96
3	90	5%	5%	24	1.7	0.14	0.50	0.64

These design values should be used as a general guide only. It is advisable to make a correction for the 'local manufacturing environment' (lme), such as fluctuations in cement quality, aggregate selection, mixing regime, machine characteristics, curing regime etc. Note also that the compressive strength values are those for the MA20 compression test, which corrects for aspect ratio and also uses the gross area of the block in the calculation. (See chapter 7 for a fuller discussion of compressive strength testing).

c. **Binder type**: The type of binder used is also important, but to a lesser degree. Table 6.17 gives an indication of what 28-day strengths/abrasion resistances can be expected from different binder types. Once again these figures apply to mixes where care has been taken to maximise the water content.

TABLE 6.17 28 DAY STRENGTH DESIGN VALUES FOR DIFFERENT BINDER TYPES

MIX DESIGNS (RELATIVE PROPORTIONS BY MASS)						AVERAGE OF TWO WETTEST MIXES (12 BLOCKS)				
						COMPRESSIVE	TSS	ABRASION RESISTANCE		
MIX	AGGRE-GATE	% BINDER				STRENGTH	ISO	WIRE	ASTM	MA20
		OPC	MGBS	FLY ASH	Si FUME	MA20	4108	CLAY	418C	
						MPa	MPa	cm²/cm³	cm²/cm³	INDEX
2	86	7	7			36.7	3.25	8.5	3.2	0.96
4	86	10		4		32.6	2.60	9.0	2.8	0.85
5	86	11		3		34.0	2.70	8.4	2.6	1.28
6	86	12		2		33.8	2.95	10.2	2.4	0.92
7	86	6.65	6.65		0.7	41.1	3.50	9.4	3.0	1.52
8	86	6.30	6.30		1.4	41.3	3.70	10.5	3.0	1.70

At 28-days silica fume positively enhances the compressive strength, tensile splitting strength, and abrasion resistance of cbp. On the other hand the 28-day fly ash results indicate that it is not well suited to the production of products made with semi dry concrete. If fly ash is selected as a mix constituent it will perform acceptably at 28 days only if great care is taken to maximise the water content. However there is a danger in trying to make the blocks 'as-wet-as-possible' - slumping may occur, as was the case in the wettest mixes in this investigation, resulting in excessively large gaps appearing between blocks during installation.

In spite of its relatively poor performance in the 28-day laboratory tests, site measurements after six years of traffic showed that fly ash outperformed the other mixes, i.e. had the least wear. This trend applied to all water contents from ‘wet’ through ‘dry’. Fly ashes convincing long-term superiority was confirmed by further MA20 abrasion tests on seven years old blocks [Papenfus(1995)]. These findings are consistent both with the known retardation of fly ash at 28-days, and the ongoing pozzolanic activity in the longer term (see chapter 14,15).

Fly ashes ongoing pozzolanic activity, is further confirmed by Gordon(1991), who showed that the 90-day abrasion resistance of concrete with substitutions of up to 50% was equivalent to that of a 100% OPC concrete.

Since abrasion is a long-term process, the long-term results can be considered most important, and therefore a binder that incorporates, up to 28% of fly ash has been shown in this investigation to be a high performance material.

The degree to which silica fume, fly ash, or mgbs is selected is also a question of economics. This in turn will depend largely on the location of the manufacturer in relation to the source of the binder in question.

d. The **tensile splitting test** is a viable alternative to the existing SABS 1058 compression test. It can be done on relatively small and inexpensive testing presses. It also shows a high degree of sensitivity to weak mixes. A review of the literature indicates that it is not as sensitive to aspect ratio as compression testing is, with 100mm blocks requiring a correction factor of 1,1 and 60mm blocks a factor of 0,9 [Hendrikx(1994)].

The author concurs with DuPlessis(1989) that this test should be accepted by the SABS as an alternative to the compression test.

e. Of the three abrasion tests the **MA20 test** responds most sensitively to changes in quality. This makes it an ideal test for monitoring surface quality. However there are other factors that also need to be considered before an abrasion test is selected. The three abrasion tests are more fully dealt with in chapters 9, 10, 11, and critically compared in chapter 12.