Table 8.7a

Creep, shrinkage and elastic deformation of PPC opc concrete with 13,2 mm stone (Mix 1)

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Totalde formation (microstrain)
0	303	0	268
1	303	19	402
2	303	51	459
3	303	70	494
5	303	89	537
8	303	89	572
13	303	107	636
16	303	131	679
22	303	134	722
28	303	153	794
35	303	174	851
41	303	188	894
50	303	199	945
61	303	228	1012
68	303	244	1044
82	303	263	1079
103	303	266	1114
202	303	357	1315

Table 8.7b

Creep, shrinkage and elastic deformation of PPC opc concrete with 19,0 mm stone (Mix 2)

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Total deformation (microstrain)
0	286	0	252
1	286	43	400
2	286	72	427
4	286	86	467
7	286	86	510
12	286	99	558
15	286	118	606
21	286	121	639
27	286	140	727
34	286	153	775
40	286	177	816
49	286	180	867
60	286	204	915
67	286	217	947
81	286	231	987
102	286	231	1020
201	286	317	1136

Table 8.7c

Creep, shrinkage and elastic deformation of BC opc concrete with 13,2 mm stone (Mix 3)

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Total deformation (microstrain)
0	303	0	268
1	303	24	362
2	303	64	445
3	303	86	483
5	303	107	537
8	303	107	588
13	303	121	665
16	303	137	716
22	303	150	781
28	303	177	869
35	303	201	936
41	303	220	982
50	303	236	1052
61	303	268	1143
68	303	290	1181
82	303	314	1237
103	303	314	1291
202	303	408	1511

Table 8.7d

Creep, shrinkage and elastic deformation of PPC PC 15 FA concrete with 13,2 mm stone (Mix 4)

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Total deformation (microstrain)
0	289	0	255
1	289	13	480
2	289	56	531
3	289	83	569
5	289	94	614
8	289	94	652
13	289	110	714
16	289	131	743
22	289	142	789
28	289	182	867
35	289	185	918
41	289	207	945
50	289	220	985
61	289	247	1036
68	289	263	1063
82	289	279	1095
103	289	282	1116
202	289	365	1283

Table 8.7e

Creep, shrinkage and elastic deformation of BC PC 15 FA concrete with 13,2 mm stone (Mix 5)

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Total deformation (microstrain)
0	316	0	279
1	316	67	437
2	316	91	475
4	316	105	515
7	316	113	566
12	316	131	644
15	316	153	687
21	316	177	767
27	316	204	845
34	316	223	912
40	316	250	953
49	316	276	1041
60	316	303	1087
67	316	319	1124
81	316	341	1170
102	316	346	1213
201	316	427	1457

Table 8.7f

Creep, shrinkage and elastic deformation of PPC PC 30 FA concrete with 13,2 mm stone (Mix 6)

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Total deformation (microstrain)
0	285	0	252
1	285	30	341
2	285	70	376
4	285	83	467
7	285	86	494
12	285	107	561
15	285	134	612
21	285	153	660
27	285	172	716
34	285	196	767
40	285	217	802
49	285	223	945
60	285	250	899
67	285	266	910
81	285	287	955
102	285	290	985
201	285	368	1159

Table 8.8

Specific creep for OPC and fly ash mixes (Series I)

Age after loading(days)	Specific creep (microstrain) values for					
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
0	0,0	0,0	0,0	0,0	0,0	0,0
1	20,9	10,3	8,8	11,3	8,8	5,6
2	21,7	10,7	11,0	13,7	10,1	6,1
3	22,8		12,6	15,2		
4		12,7			12,7	12,6
5	26,2		15,6	17,6		
7		17,0			16,9	14,9
8	29,9		20,7	21,0		
12		20,4			22,5	19,2
13	34,4		27,0	25,5		
15		23,3			24,6	21,6
16	35,2		30,5	27,3		
21		26,3			30,0	24,4
22	38,6		35,4	31,2		
27		33,1			34,9	28,0
28	42,3		41,5	36,5		
34		36,8			39,6	30,5
35	47,1		45,7	39,9		
40		39,2			40,9	31,8
41	47,6		48,3	42,9		
49		43,0			46,8	35,4
50	50,3		53,6	46,7		
60		45,3			48,6	38,0
61	52,6		59,3	50,4		
67		47,2			50,7	37,5
68	53,7		60,9	52,0		
81		49,9			53,0	39,8
82	55,3		64,1	53,6		
102		53,0			56,6	42,3
103	57,1		69,3	56,7		
201		56,2			72,4	51,6
202	665,3		81,7	67,5		

Table 8.9a

Creep, Shrinkage and elastic deformation of PPC opc, 13,2 mm stone concrete: wet cured, sealed

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Total deformation (microstrain)
0	288	0	288
1	288	–24	319
3	288	–19	335
7	288	–19	352
11	288	–21	368
17	288	0	419
24	288	0	443
31	288	0	459
38	288	–8	486
64	288	27	561
73	288	19	564
80	288	11	574
91	288	48	612
101	288	54	633
113	288	51	636
130	288	59	674
218	288	56	698
322	288	78	765

Table 8.9b

Creep, Shrinkage and elastic deformation of PPC opc, 13,2 mm stone concrete: dry cured, exposed

Age after loading (days)	Elastic deformation (microstrain)	Total shrinkage deformation (microstrain)	Shrinkage deformation after loading (microstrain)	Total deformation (microstrain)
0	419	145	0	419
1	419	145	0	582
3	419	145	0	631
7	419	148	3	711
11	419	161	16	738
17	419	201	56	856
24	419	220	75	907
31	419	236	91	969
38	419	244	99	1006
64	419	292	147	1157
73	419	301	156	1178
80	419	319	174	1205
91	419	360	215	1312
101	419	373	228	1339
113	419	386	241	1363
130	419	413	268	1449
218	419	427	282	1538
322	419	470	325	1650

Note: The shrinkage on the exposed specimens was monitored from age 3 days when the specimens were exposed to the ambient conditions in the laboratory. Column 3 gives the total shrinkage, while column 4 gives the shrinkage that occurred during the creep test.

Table 8.9c

Creep, Shrinkage and elastic deformation of PPC PC30FA, 13,2 mm stone concrete: wet cured, sealed

Age after loading (days)	Elastic deformation (microstrain)	Shrinkage deformation (microstrain)	Total deformation (microstrain)
0	247	0	247
1	247	–16	295
3	247	–13	298
7	247	–35	306
11	247	–38	303
17	247	–21	354
24	247	–21	360
31	247	–30	357
38	247	–38	357
64	247	–8	397
73	247	–43	384
80	247	–27	389
91	247	3	445
101	247	11	464
113	247	11	464
130	247	27	488
218	247	27	510
322	247	70	569

Table 8.9d

Creep, Shrinkage and elastic deformation of PPC PC30FA, 13,2 mm stone concrete: dry cured, exposed

Age after loading (days)	Elastic deformation (microstrain)	Total Shrinkage deformation (microstrain)	Shrinkage deformation after loading (microstrain)	Total deformation (microstrain)
0	502	145	0	448
1	502	148	3	644
3	502	156	11	708
7	502	158	13	773
11	502	169	24	835
17	502	215	70	942
24	502	239	94	978
31	502	252	107	1044
38	502	260	115	1081
64	502	317	172	1221
73	502	309	164	1246
80	502	327	182	1256
91	502	360	215	1320
101	502	365	220	1342
113	502	370	225	1363
130	502	397	252	1411
218	502	400	255	1484
322	502	440	295	1610

Note: The shrinkage on the exposed specimens was monitored from age 1 day when the specimens were exposed to the ambient conditions in the laboratory. Column 3 gives the total shrinkage, while column 4 gives the shrinkage that occurred during the creep test.

Table 8.10

Specific creep for opc and fly ash mixes
sealed or exposed

Age after loading (days)	Specific creep (microstrain) values for			
	Mix 1	Mix 2	Mix 3	Mix 4
0	0,0	0,0	0,0	0,0
1	8,5	1,9	6,4	4,9
3	9,5	6,7	6,4	10,6
7	11,1	14,4	9,4	16,8
11	13,0	15,8	9,4	21,9
17	15,9	23,5	12,8	28,2
24	18,3	26,7	13,4	30,3
31	19,9	31,3	13,9	34,7
38	23,3	34,2	14,7	37,7
64	27,3	44,4	15,8	46,1
73	28,4	45,7	17,9	49,3
80	30,2	46,5	16,8	48,5
91	30,2	53,2	19,5	51,8
101	31,8	54,5	20,6	53,4
113	32,3	55,6	20,6	55,0
130	35,2	61,5	21,4	57,2
218	37,9	68,9	23,5	64,2
322	42,4	75,9	25,1	72,9

CHAPTER 9

9. DURABILITY

Fulton[299] has defined the durability of concrete as "the ability of concrete to retain its strength, impermeability, dimensional stability and appearance over a long period of service under the conditions for which it was designed."

Although durability of concrete is one of its more desirable characteristics it is an extremely difficult property to measure. In the past the durability of concrete was taken for granted with the assumption that if the concrete strength was adequate then the durability was assured. Since the 1980's, however, the topic of durability has come more to the fore with many countries reporting serious problems with deterioration of concrete structures and escalating maintenance costs. Since then a great deal of attention has been given to researching durability problems and there is now a greater understanding of the factors which influence the durability of concrete. Details of the suggested mechanisms can be found in most recent books on concrete technology; such mechanisms will only be referred to where relevant in the following paragraphs (as some of the mechanisms are unlikely to develop in a typical South African exposure).

The characteristics of concrete which are believed to contribute most to good durable concrete structures in a typical South African environment are as follows:

- impermeability and low porosity,
- abrasion resistance,
- resistance to attack by soft water, carbon dioxide and sulphates,
- resistance to chloride ion diffusion
- low sensitivity to alkali silica reaction

9.1 Impermeability and low porosity

Permeability of concrete is defined as that property that characterizes the ease with which a fluid flows within a material due to a pressure differential and is measured by the volume of liquid or gas transmitted per unit area per unit of time per unit of pressure[135,299].

The permeability of concrete should be as low as possible as this will slow the rate of ingress of liquids or gases through the concrete and thus improve the level of durability.

Aggregates used in concrete seem to have a wide range of permeabilities. Fulton[300] reported on several different aggregate types; dolerite was reported as having a lower permeability than that of mature cement–water pastes by about one order of magnitude. Dolerite coarse aggregate was used in the concretes with Matla fly ash from which the test specimens were made for some of this work. It has been assumed that the differences noted in the permeabilities of the different concretes made are due to the differences in the permeability of the paste fraction and the aggregate permeability has not played any significant role.

Fresh paste consists of solid particles of cement and possibly other cementitious materials dispersed in water. The volume of the space between the particles depends on the initial ratio of cementitious materials to water. As the cementitious materials hydrate these spaces become occupied by gel. The unfilled portion of this space represents capillaries and it is these capillaries that permit the flow of fluids through the concrete. Obvious factors that will determine the degree of permeability are the original cementitious/water ratio and the degree of hydration of the cementitious materials in the concrete.

In this study work has been done to determine the effect of incorporating fly ash in a concrete mix on the permeability of the concrete.

The water reduction permitted by the use of fly ash has been reported on in chapter 5. The reduction in the water content of the concrete mix will, if the cementitious/water ratio of the mix is increased to provide the desired level of 28 day compressive strength (see chapter 6), result in an increased initial concentration of the paste. For a given degree of hydration therefore it would be reasonable to expect the fly ash mix to have a lower permeability than would be the case for the equivalent ordinary portland cement mix.

9.1.1 Tests with Matla fly ash

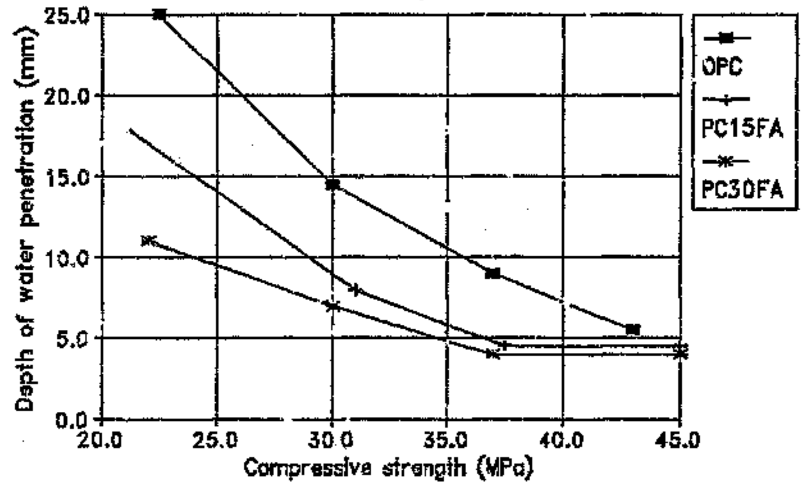
This characteristic was evaluated in concrete mixes made using ordinary portland cement from PPC Jupiter together with the Matla fly ash at 0, 15 and 30 % replacement levels, but with all mixes designed to give the same level of 28 day compressive strength. The mix proportions used are detailed in table 9.1a. The cement used was OPC ex PPC Jupiter with Matla fly ash. 13,2-mm dolerite stone was used together with a granite crusher sand. It was found necessary to use the granite sand as the mixes using the Kendal sand were found to give too little water penetration. The granite sand resulted in a mix with greater permeability facilitating comparisons of depth of penetration for the different mixes.

The specimens that were made were 150 mm cubes and they were tested after 28 days of wet curing (in accordance with SABS Method 663[285]) using the procedure of DIN 1048.[288]

In this test the specimens are exposed to water pressure of 1 bar for 48 hours, 3 bar for a subsequent 24 hours and 7 bar for a further 24 hours. At the end of the pressure exposure the specimens are removed from the apparatus and split along a plane at right angles to the plane of pressure exposure. The depth to which the water has penetrated is marked and the average depth is determined. The data from this first series of tests is given in table 9.1b and shown in figure 9.1.

Table 9.1b shows that a reasonable degree of similarity was obtained with the compressive strength of the three sets of specimens, ie the OPC, PC 15 FA and PC 30 FA. There is a marked difference between the depths of penetration of the three mixes however: the depth of penetration of these well cured specimens showing a decrease as the fly ash content increases. This indicates that the permeability of the fly ash mixes is lower (i.e. better) than that of the control ordinary portland cement mixes.

Figure 9.1
Results of DIN 1048 penetration tests



The DIN 1048 test has a prescribed limit for the maximum penetration for water retaining structures of 50 mm. It should be noted that this is for standard test conditions which implies water curing for the full 28 day period, as was the practice followed in the experimental work reported in table 9.1b. It can be seen that all of the mixes tested here fell well within this value.

The PCI would normally recommend a minimum cement/water ratio of 1,7 (ie approximately 33 MPa target compressive strength) for concrete to be used in water retaining structures.

9.1.2 Comparison against another method of test: Matla fly ash

In order to get a better idea of the actual permeability of the concrete in these specimens the CSIR were asked to assist by doing a parallel series of tests using A gas/water permeability test developed by themselves. The results of this parallel series of tests are given in tables 9.2a and 9.2b. In table 9.2b use has been made of a formula developed by Valenta[301] to calculate the permeability from the results of the DIN 1048 test. The formula is as follows: Coefficient of permeability K :–

$K = d^2 \times v/2 \times T \times h$, where

d = depth of penetration (mm)

v = porosity of the concrete

T = Time to penetrate to depth d (s)

h = head of water pressure applied (mm)

In calculating the permeability using this formula a degree of hydration has been assumed in order to calculate the porosity needed in the formula. The capillary porosity of the paste fraction of the concrete has been calculated using formula No 1 on page 32 given by Fulton[302] as follows:

capillary porosity = $1-(NmcV_c)/(w_0+mcV_c)$ where,

N = Vol. of gel solids formed by hydration of one cubic centimetre of cement = 2,2

m = degree of hydration of the paste (assumed to be 0,5, 0,7, and 0,9)

c = original mass of cement

V_c = Specific volume of cement = 0.319 and

w_0 = original mass of water.

The porosity of the paste is not what is required in the Valenta formula, but is probably the most conservative value that can be determined, ie the dolerite aggregate is less porous than the paste, and even in fairly extreme cases the porosity of concrete resulting from the entrapment of bleed water is not likely to result in the porosity of the concrete being markedly greater than that of the paste component.

It can be seen from table 9.2a and 9.2b that there is a fairly substantial difference between the levels of permeability measured by the CSIR and those values obtained by calculation from the DIN test results on the same concrete. In each case the permeability as measured by the CSIR was higher than the PCI calculated values. The difference varies from about 1000 times greater for the lean mix to about 200 times for the rich mix.

Note that the Valenta formula was developed for concretes made with European quality cements and may therefore not apply to concretes made with South Africa cements. Nevertheless, tables 10 and 11 from the Concrete Society Conference on Permeability of Concrete[301] show values for concrete permeability that are similar in magnitude to those recorded in table 9.2b of this study providing some support for the permeability values obtained with the DIN test.

There is still a substantial difference between the results given by the two different methods. Some of the difference can probably be ascribed to the use of the paste porosity in the Valenta formula, although the DIN test results appear to be of the expected magnitude. The calculation does not appear to be particularly sensitive to the value assumed for the degree of paste hydration as can be seen from table 9.2b.

The major part of the difference can probably be ascribed to the fact that in preparing the specimens for the CSIR (DBT) test the specimens are dried at a fairly early age in an oven for some time before being exposed to the steady flow conditions of the permeability test. It is believed that the specimens may suffer a substantial degree of micro–cracking of the paste due to this desiccation, resulting in a far higher apparent permeability for the concrete. It appears that low permeability concretes are slightly less susceptible to this desiccation than is the case for the lean mixes.

The fact that the results obtained do not correspond with other reports of permeability should not be construed as making the CSIR method unsuitable, as with a history of use of the method they have been able to generate guidelines for the interpretation of the results thus providing a useful service to recipients of their test results. The method may unfortunately prejudice blended cements that have a slower rate of strength gain and a greater susceptibility to poor curing than is the case for ordinary portland cement. Modifications that take such factors into consideration could improve the method.

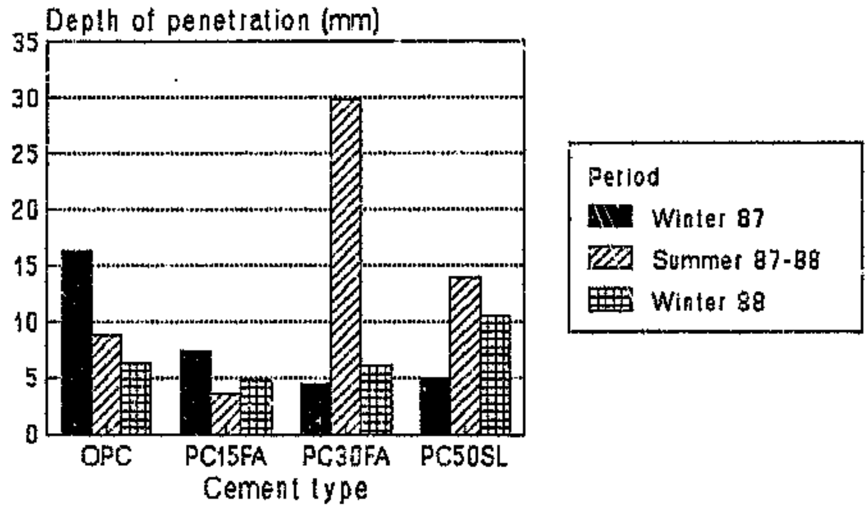
9.1.3 Effect of poor curing on permeability; Matla fly ash

A further series of tests was done to evaluate the effect of poor curing of specimens on the depth of penetration obtained in the DIN 1048 test. Specimens of 150 mm diameter were cored from the large blocks made to examine the effect of curing on the compressive strength described in paragraph 7.1.3. As mentioned before the concrete in these large blocks (620 x 710 x 600 mm) was not cured other than retaining the formwork in position for the first 2 days. The permeability test was carried out on the outer skin surface of all the specimens – ie that zone most likely to suffer the worst impact of the poor curing. This same test was carried out three times for blocks exposed on different occasions (i.e. winter 1987, winter 1988 and summer 1987–88). Note that while the specimens were exposed to ambient conditions outside the laboratory, they were protected from rain. As before the concretes tested included a mix containing ggbs.

The results of these permeability tests are given in table 9.3 and illustrated graphically in figure 9.2. It can be seen that the depths of penetration of the poorly cured concretes are all much greater than is the case when the curing follows the requirements of DIN 1048 (ie 28 days submerged) as nearly all specimens achieved conditions of flow through the test specimen inside the time allowed for the test. The effect is more marked in the case of the two winter exposures than for the summer exposure as the opc specimen did resist flow for the summer experiment, thus indicating that the degree of hydration in summer is better than in winter – a not unexpected finding.

Figure 9.2 shows that for the cured cube specimens the PC 15 FA mixes generally had the lowest permeability. Apart from the single high penetration for the PC 30 FA mix in Summer 87–88 the fly ash tend to confirm the trend shown in figure 9.1. The slag mixes generally had higher penetrations than the fly ash mixes tested.

Figure 9.2
Depth of DIN 1048 water penetration in water cured cubes (mixes ex table 7.3a)



Larbi and Bijen[303] have shown that the transition zone between the aggregate and the hardened cement paste is the weak link in an ordinary portland cement concrete, particularly as far as the permeability of the concrete is concerned. They ascribed this to the high concentration of calcium hydroxide crystals at the interface. They pointed out that when a pozzolan such as fly ash is incorporated in the mix then this zone is reduced in size, and the thickness of the layer of calcium hydroxide crystals is also reduced, thereby reducing the permeability of the concrete. They indicated that the additional gel formed by the hydration of the pozzolan also contributes to the reduction of the permeability. They noted that these beneficial effects can be negated by desiccation. These effects could explain the results obtained in this study.

9.1.4 Test results using Lethabo fly ash

The mixes used in this part of the investigation are detailed in table 4.9 and 7.2a. In this case the coarse aggregate used was a reef quartzite material from Cooke Shaft ie a mine waste material. Such material is commonly finely micro-fractured due to the release of internal stress after removal from the great depths at which the mines operate. The permeability of this aggregate can therefore be expected to be higher than for the dolerite used with the Matla fly ash mixes.

Studies were done on the mixes described in table 7.2a to determine the depth of water penetration in the DIN 1048 test. The specimens were exposed to the three curing regimes discussed in section 7.1.5.2, namely oven (c. 30 °C), standard (c. 23 °C) and cold (c. 7 °C) and were either wrapped in plastic or exposed to the atmosphere in these areas. It was soon found that under these conditions the water rapidly penetrated through the specimens (as found with the "site cured" specimens reported on above) and it was not possible to detect differences between the resistance levels of the different mixes.

The pressure regime to which the specimens were exposed was then modified to 1 bar for 3 days only. Even under these conditions the specimens which were not protected against desiccation were still rapidly saturated – no results are therefore presented as no differences could be detected from this undetermined point. The wrapped specimens however gave results which appear to indicate differences between the water penetrations of the different cementitious mixes used.

The results of these tests are given in table 9.4 and are shown in figures 9.3a to 9.3f. Figures 9.3a, 9.3c and 9.3e show the depths of penetration for mixes proportioned to give equivalent 28 day compressive strength to the ordinary portland cement mixes. Figures 9.3b, 9.3d and 9.3f give similar data for mixes proportioned by direct replacement of the fly ash cement for ordinary portland cement. The mixes were exposed to hot (c. 30 °C), standard (c. 23 °C) or cold (c. 7 °C) conditions. All specimens were protected in sealed plastic bags. It should be noted that as the specimens used in this case were 150-mm cubes, any result showing the water penetration depth to be 150-mm indicates a saturated specimen (eg. figures 9.3e and 9.3f); such results can not be used.

The equivalent 28 day fly ash mixes generally have similar to lower depths of penetration than the ordinary portland cement mixes, although there are exceptions to this. Under cold conditions some of the specimens allowed the water to penetrate right through; comparisons cannot be drawn for these specimens.

Figure 9.3a
Water penetration depth (Oven, EQ 28)

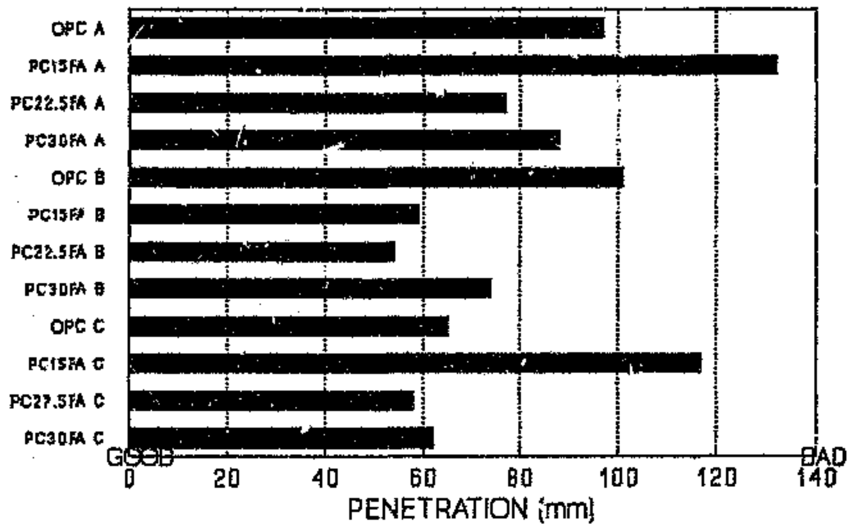
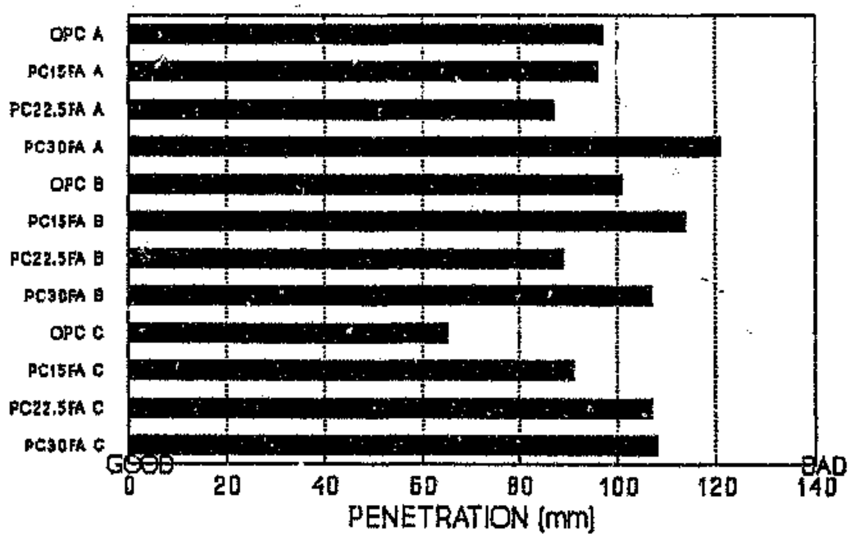


Figure 9.3b
Water penetration depth (Oven, DR)



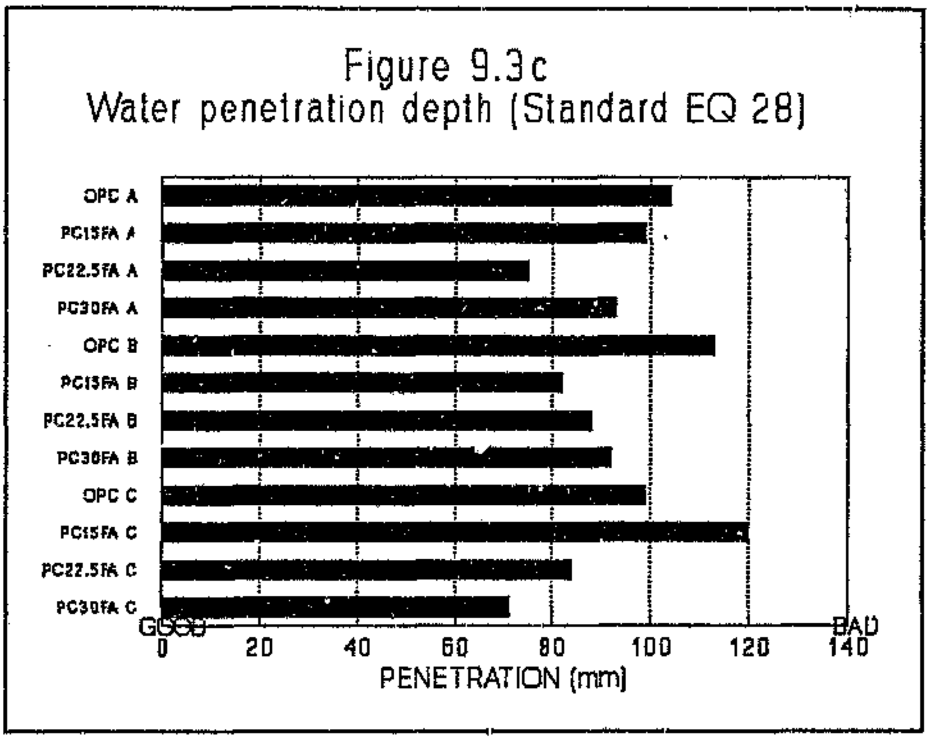


Figure 9.3c
Water penetration depth [Standard EQ 28]
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
GOOD
BAD
0
20
40
60
80
100
120
140
PENETRATION (mm)

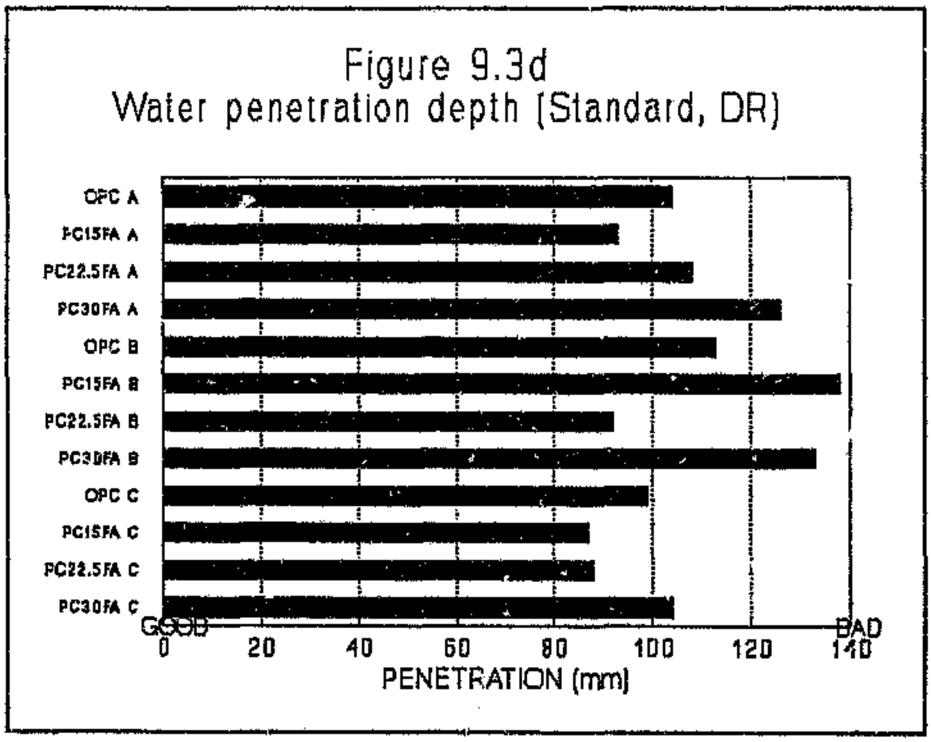


Figure 9.3d
Water penetration depth [Standard, DR]
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
GOOD
BAD
0
20
40
60
80
100
120
140
PENETRATION (mm)

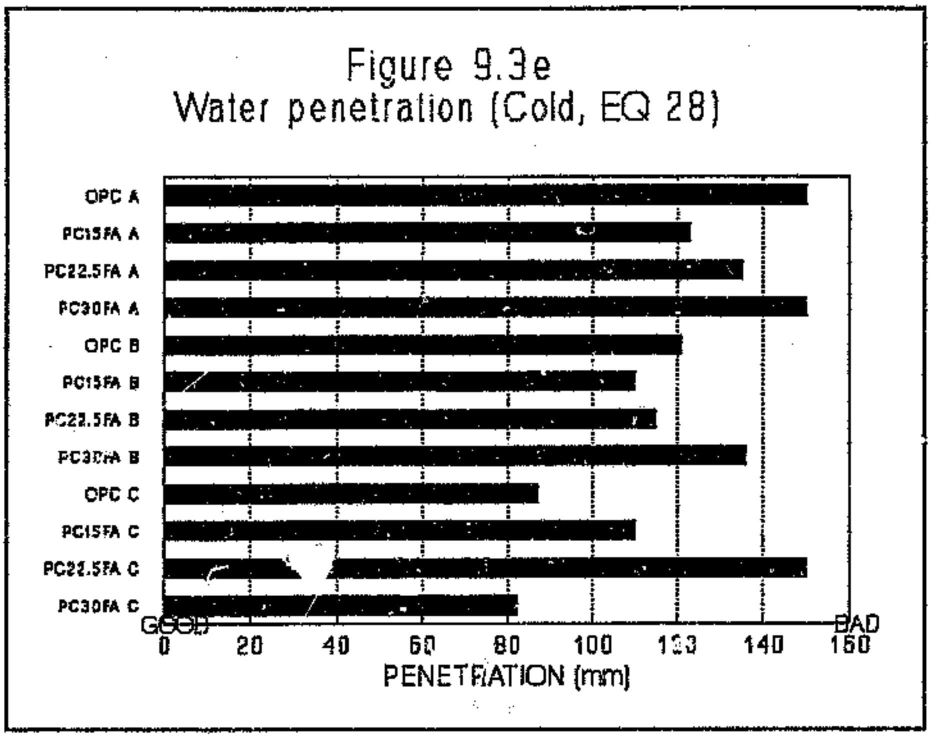


Figure 9.3e
Water penetration (Cold, EQ 28)
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
GOOD
BAD
0
20
40
60
80
100
140
160
PENETRATION (mm)

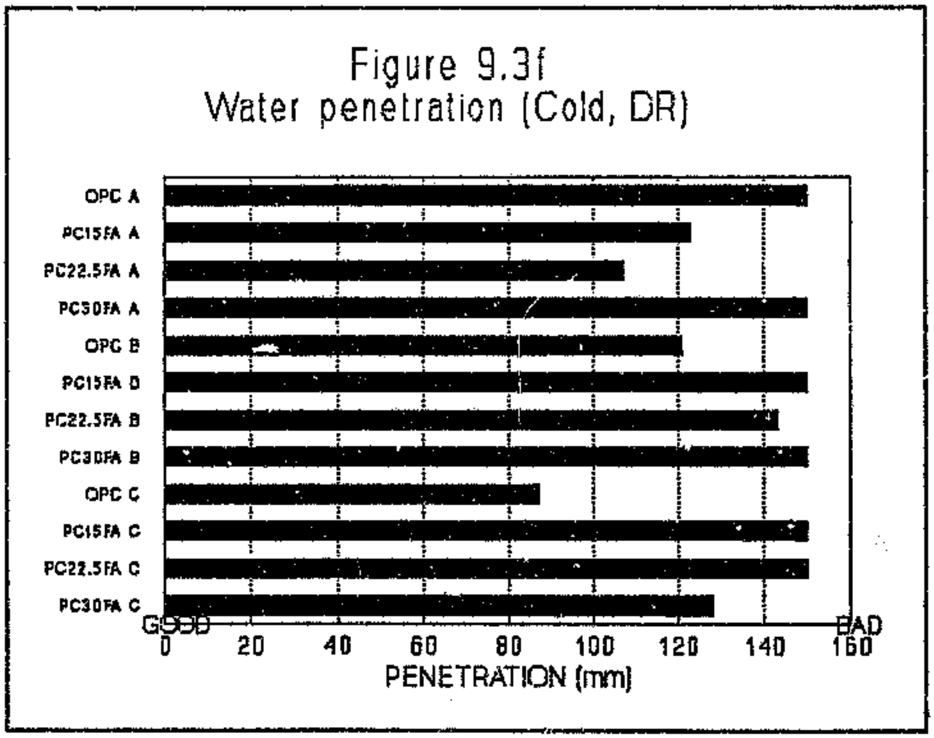


Figure 9.3f
Water penetration (Cold, DR)
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
GOOD
BAD
0
20
40
60
80
100
120
140
160
PENETRATION (mm)

Under direct replacement conditions the fly ash mixes did not perform as well, particularly under the oven conditions It should be noted that while every precaution was taken to seal the specimens in plastic bags, at the end of the test some of the bags were found to be perforated, probably during handling. The holes probably allowed the escape of moisture, particularly in the dry conditions in the oven. As the relative humidity in the cold room was high (+90 % RH) there is little apparent impact of the bags being perforated.

Generally, however, the depth of penetration for the fly ash mixes fell within the range of results obtained for the ordinary portland cements used. The impact of the fly ash on the permeability can thus be regarded as insignificant in practical terms.

There is some confirmation in these results for the contention that the DIN permeability test does not give very reproducible results.

9.1.5 Summary of findings on permeability

Fly ash seems to have a beneficial effect on the depth of water penetration that occurs in the standard DIN 1048 permeability test, as well as with the DIN test modified as discussed at the beginning of section 9.1.4. This is generally true for both sources of fly ash tested, and seems to apply whether the concrete is well cured or not. As the depths of penetration measured in this work were substantial, it is possible that this does not prove that the fly ash concretes will be more durable as the results have not categorically shown that the skin concrete will provide adequate protection to the reinforcing steel, i.e. the use of fly ash in a mix, although providing a probable reduction in permeability, might not overcome the negative effects of poor curing.

9.2 Abrasion resistance

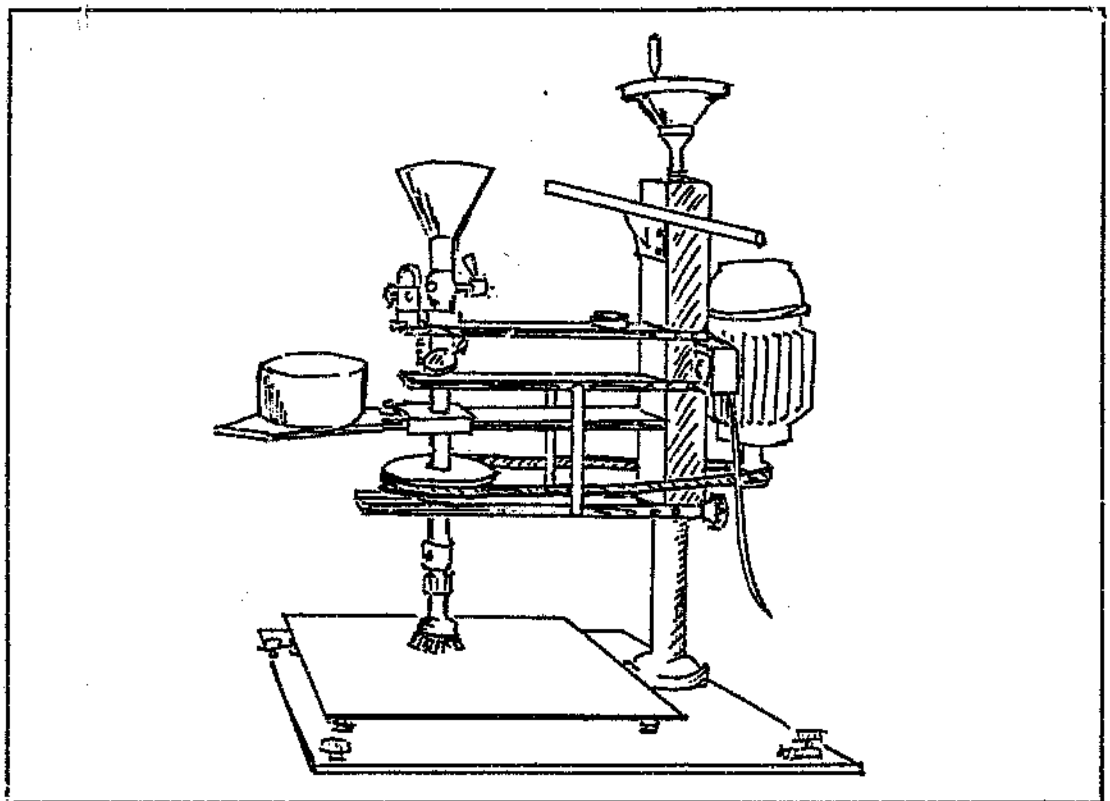
A concrete exposed to wear should exhibit an acceptable degree of resistance to removal of surface material in order to be regarded as durable. The most commonly occurring condition of exposure to wear is that of a floor or road pavement surface exposed to wear due to the action of the wheels of the traffic, although other factors such as wind or water can sometimes be involved in abrasion problems.

The references consulted and detailed in section 3.7.2 indicated that fly ash does not seem to have an influence on the abrasion resistance of well cured concretes of similar 28 day compressive strength; some reports indicated that the fly ash mixes might be more sensitive to poor curing, thus resulting in reduced resistance to abrasive forces. In order to evaluate this characteristic for South African conditions and materials two series of tests were done namely:

- abrasion testing of standard laboratory cured cube specimens, and

- abrasion testing of the uncured surfaces of large concrete blocks which were exposed to ambient conditions outside the laboratory at PCI.

The abrasion testing of concretes has been tackled in different ways in different countries. The PCI, in looking for a suitable test, made use of apparatus developed by the National Building Research Institute (now renamed the Division of Building Technology) of the CSIR which used the principle of an abrasive medium under a rotating steel disc with a fixed applied load. The apparatus was modified after some experimentation to make use of a wire brush as an alternative form of abrasion as this was found to give a wear pattern that more closely approached that recorded under traffic in site concrete.[904] This is the apparatus used in the tests described below. The PCI Laboratory method for this test is given in Appendix B. The apparatus is shown in the sketch below.



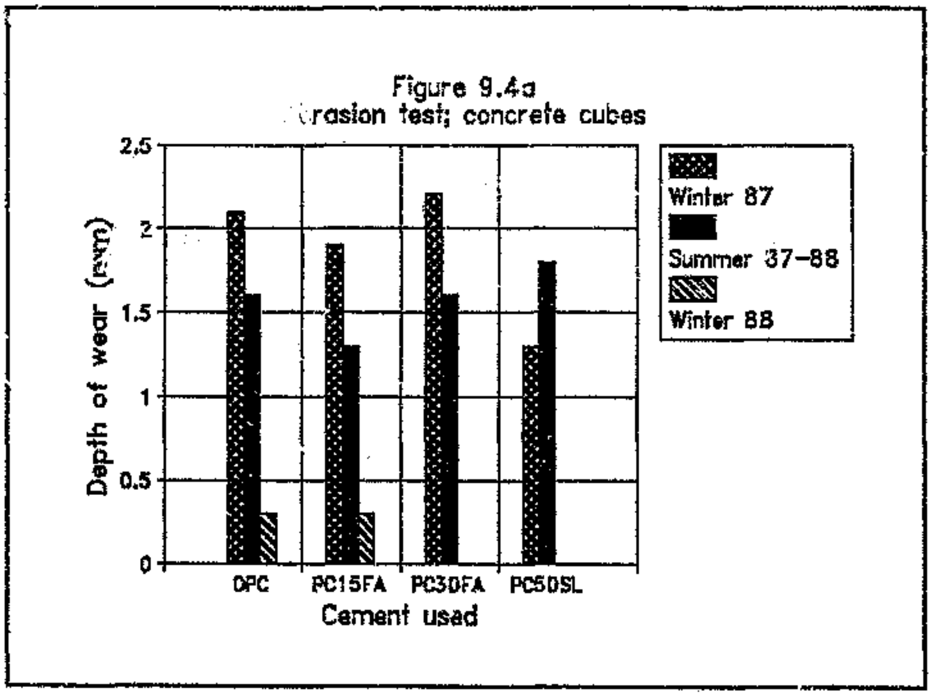
Sketch of the PCI abrasion testing apparatus

Briefly the apparatus applies a standard wire brush to the surface to be tested under a load of 165 Newton. The brush is rotated at 400 rpm for 4 minutes with the direction of rotation being reversed every 30 seconds. A flow of water through the brush keeps the wearing area cool and helps to remove abraded material. The depth of penetration is measured at the end of the test.

9.2.1 Abrasion testing of cube specimens; Matla fly ash

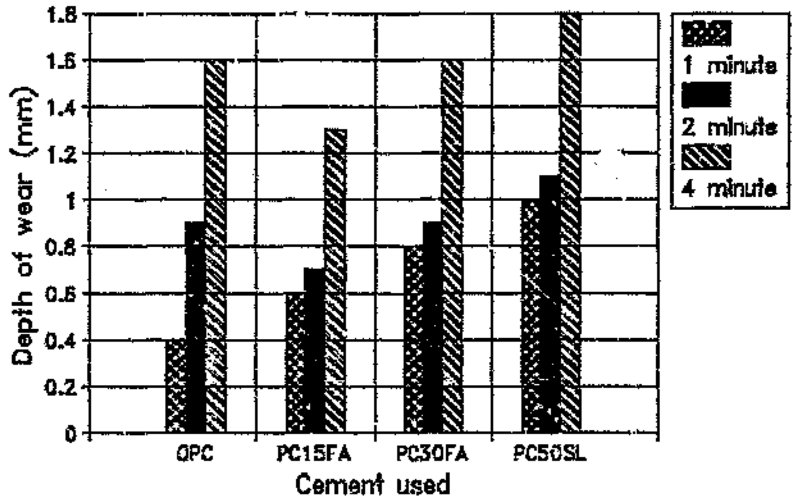
During the manufacture of the large block specimens for the evaluation of the effect of site curing on the compressive strength testing of the various concretes listed in table 7.3a, additional cube specimens were made to be used to evaluate the effect that the incorporation of fly ash might have on the abrasion resistance of the concrete in the cubes. The large blocks were also tested to evaluate the effect of the poor site curing on the abrasion resistance of the same concretes. The tests on the large blocks will be described in the next section.

The curing of these cube specimens was done in accordance with SABS method 863[285] to age 28 days. The results of the abrasion tests on the cube specimens are summarised in table 9.5 for the three exposure occasions of winter 1987, summer 1987–88 and winter 1988. All these cube specimens were exposed to standard laboratory curing conditions and would not show the effect of the exposure. If not stated otherwise, the result given in each case is for an abrasion test duration of 4 minutes, this being the standard for the method developed by the PCI. These data are shown graphically in figure 9.4a. Note that the cube specimens for winter 1988 PC30FA and PC 50 SL were mislaid and were not available for testing.



It can be seen in figure 9.4a that in the case of the standard cured specimens the abrasion resistance of the extended mixes using fly ash is generally better than or equal to that of the opc mixes. In the case of the PC50SL mix the abrasion resistance appears to be poorer than that of the opc or fly ash mixes.

Figure 9.4b
Abrasion rate; cubes, Summer 1987-88



Consideration should also be given to the fact that as the wire brush penetrates through the mortar of the surface, so more and more large sand particles are exposed. This is likely to result in the reduction of the rate of penetration. If the data in table 9.5 are considered it can be seen that while the penetration at 1 minute in cubes made in summer 1987–88 for the opc mix is the lowest of the values obtained, at 2 and 4 minutes the picture has changed. These data are shown in figure 9.4b. Apart from the initial low loss of the cpc mix, the fly ash mixes seem to have a better resistance against abrasion in these well cured specimens. In contrast to this the opc/slag mix showed a poorer abrasion resistance than the opc mix.

This finding does not agree with the results reported by Gordon[293] in which he found the 28 day abrasion resistance to decrease with the percentage of fly ash in the mix. He found the fly ash mixes to perform better than ordinary portland cement mixes at later ages when all specimens were exposed to standard curing and concluded that under these conditions the abrasion resistance was related to the compressive strength.

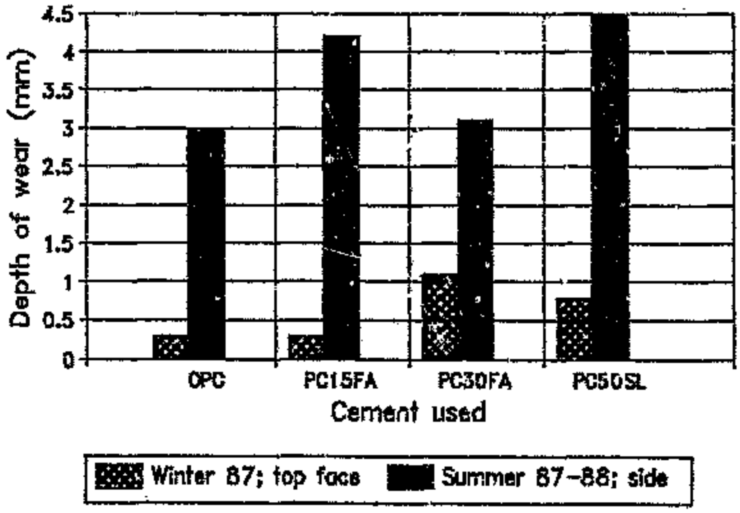
The fly ash used in his work was derived from a field 2 precipitator at Lethabo power station. The analysis for this particular sample is given in table 5.10b. It can be seen that there is fairly good agreement between the average analysis for classified Lethabo fly ash and that for the Gordon sample, although the silica content of the selected ash is lower than the average for the classified ash and the alumina and alkali contents are higher. Gordon's fly ash sample was however obtained using electrostatic selection rather than dynamic air flow selection as was the case for the fly ash used in this work. The different methods of selection were shown in chapter 5 (section 5.3.3) to lead to significant differences in the effect of the fly ashes on setting times; it is possible this factor is responsible for the differences in the results obtained between Gordon and this study.

9.2.2 Abrasion testing on poorly cured large concrete blocks; Matla fly ash

Further tests were undertaken to evaluate the effect of poor curing on the abrasion resistance of the various concretes used in the manufacture of the large concrete blocks exposed to "site" curing conditions outside the PCI laboratory, Midrand. The curing conditions to which these blocks were exposed are given in section 7.1.3.

The initial test on the abrasion resistance of the concretes was by means of the wire brush test applied to the trowelled top surface of the blocks. There was some suspicion that the quality and extent of the finishing process might have influenced the abrasion resistance test results, as with different times of setting, and different degrees of bleeding it was not possible to finish the different concretes at the same time. The subsequent tests were therefore done on one of the side faces of the blocks, ie a shuttered surface. The results of these tests are given in table 9.5 and shown in figure 9.4c.

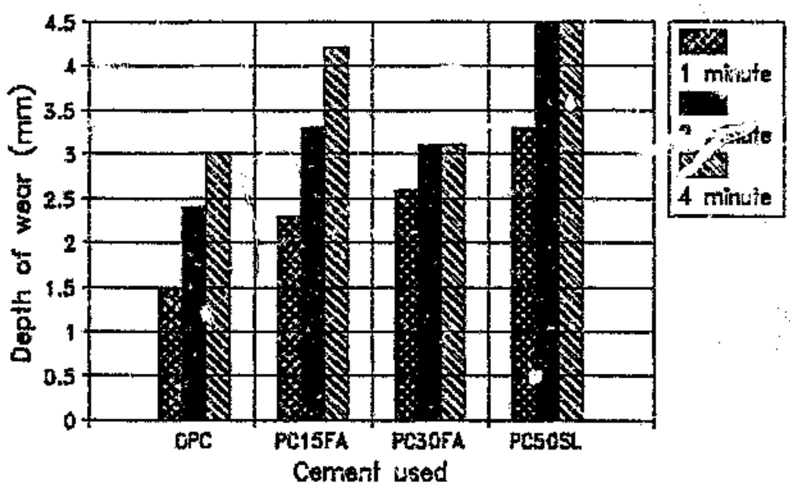
Figure 9.4c
Abrasion test; large concrete blocks



There appears to be an anomaly in the picture presented by figure 9.4c as while the first winter results (trowelled surface) show the opc and the 15 % fly ash mix to have similar degrees of abrasion resistance, the 30 % fly ash mix and the opc/slag mix are not as good. In the summer tests (cast face) the opc and the 30 % fly ash mixes are similar with the 15 % fly ash mix following behind. The slag mix in this case has a poorer abrasion resistance. It is interesting to note the significant difference that trowelling appears to make on the abrasion resistance if the effect of curing temperature and degree of surface desiccation can be ignored.

As in the case of the concrete cubes, the summer test was done over three time durations. These data are presented in figure 9.4d. In this figure it seems that the opc mix has the best abrasion resistance of all the mixes for all test durations. In the case of the 30 % fly ash mix and the opc/slag mix the penetration appears to stop at 2 minutes. This was as a result of the brush having worn the concrete down to the extent of exposing the coarse aggregate, and not being able to abrade further. It is possible that even for the 2 minute test the penetration of the brush might have been impeded by the stone.

Figure 9.4d
Abrasion rate; large blocks;summer 87/8



9.2.3 Abrasion tests on cubes; Lethabo fly ash

Similar abrasion tests were done at age 28 days on cube specimens made from the mixes detailed in table 7.2a and exposed to the three curing regimes (hot, standard and cold) in both wrapped (plastic bags) and unwrapped conditions. The results of these tests are given in table 9.7 and are shown graphically in figures 9.5a, 9.5b and 9.5c for the equivalent 28 day compressive strength mixes, and 9.5d to 9.5f for the direct replacement mixes.

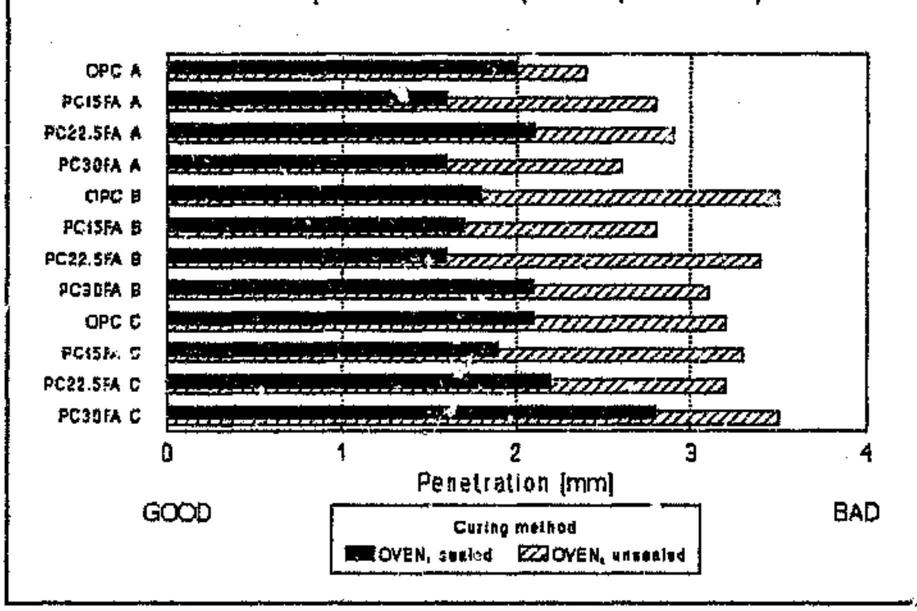


Figure 9.5a
Abrasion penetration (Oven, EQ 28)

In the case of the sealed specimens (wrapped in plastic bags) the trend is for the abrasion resistance of the fly ash mixes to be similar to or better than that of the ordinary portland cement mixes. This is also true for the unsealed specimens. Direct replacement fly ash mixes are more likely to perform more poorly in abrasion tests than the ordinary portland cement mixes, although the differences are generally small.

The differences in abrasion resistance between the sealed and unsealed specimens under cold conditions is small as the average relative humidity in the cold room was 97 % during the duration of the tests. This meant that there was little chance of desiccation of the uncured specimens.

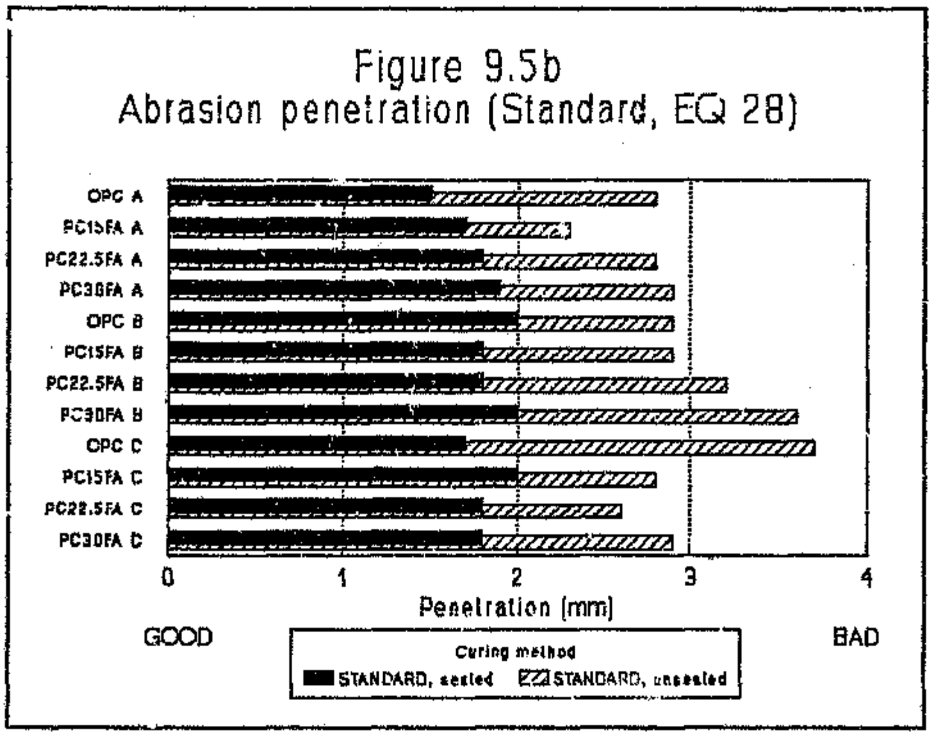


Figure 9.5b
Abrasion penetration (Standard, EQ 28)
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
0
1
2
3
4
Penetration (mm)
GOOD
BAD
Curing method
STANDARD, sealed
STANDARD, unsealed

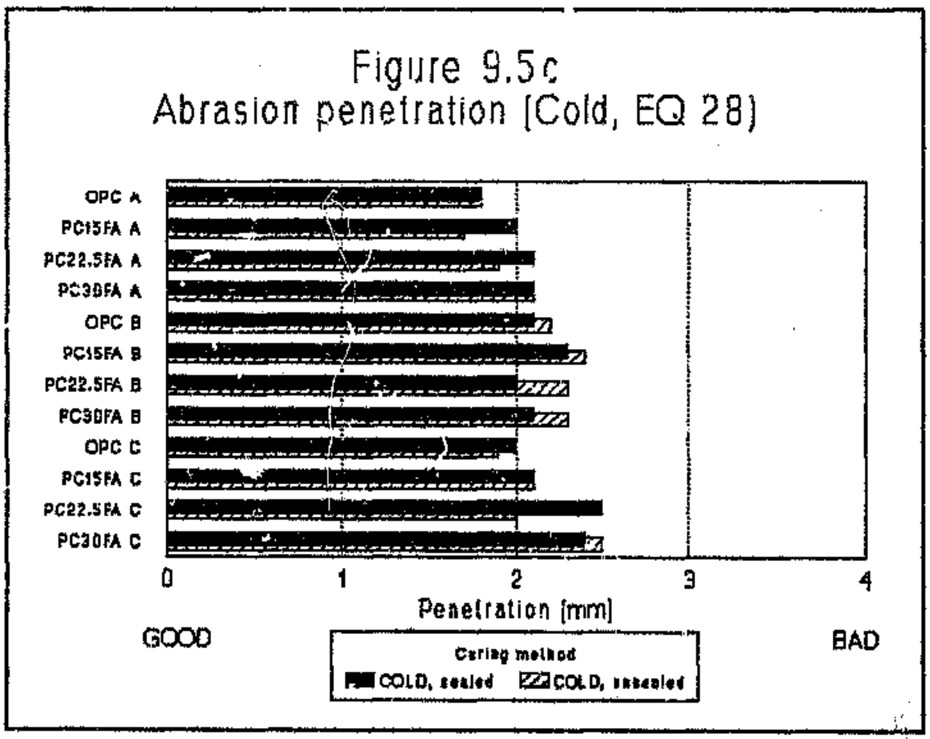


Figure 9.5c
Abrasion penetration (Cold, EQ 28)
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
0
1
2
3
4
Penetration (mm)
GOOD
BAD
Curing method
COLD, sealed
COLD, unsealed

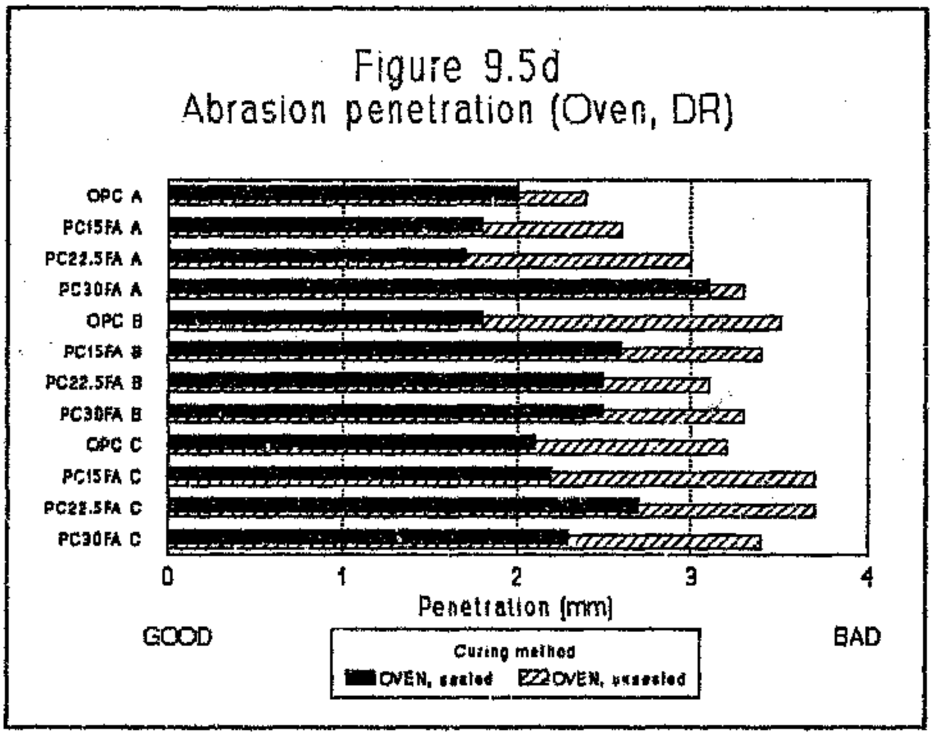


Figure 9.5d
Abrasion penetration (Oven, DR)
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
0
1
2
3
4
Penetration (mm)
GOOD
BAD
Curing method
OVEN, sealed
OVEN, unsealed

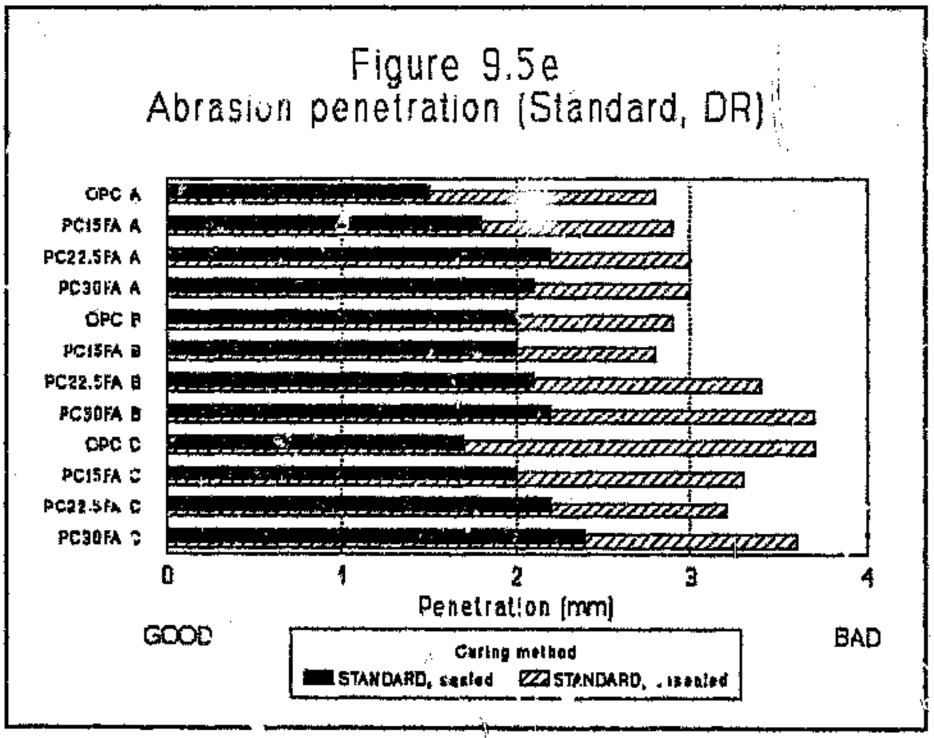
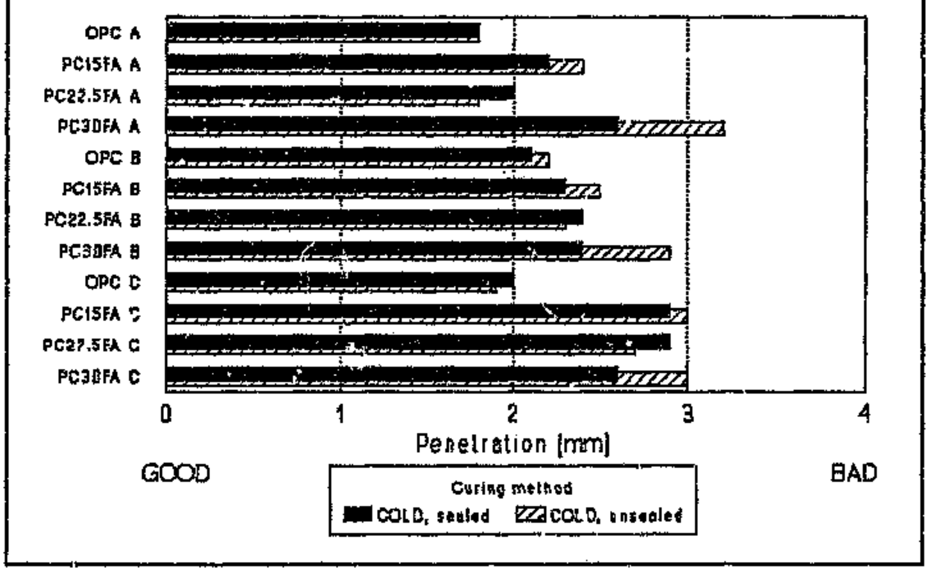


Figure 9.5e
Abrasion penetration (Standard, DR)
OPC A
PC15FA A
PC22.5FA A
PC30FA A
OPC B
PC15FA B
PC22.5FA B
PC30FA B
OPC C
PC15FA C
PC22.5FA C
PC30FA C
0
1
2
3
4
Penetration (mm)
GOOD
BAD
Curing method
STANDARD, sealed
STANDARD, unsealed

Figure 9.5f
Abrasion penetration (Cold, DR)



9.2.4 Summary of abrasion test findings

It appears that under poor "site" curing conditions concretes made using both Matla fly ash and slag as extenders seem to show a greater reduction in the abrasion resistance relative to that offered by well cured concrete. In the case of Lethabo fly ash this effect is not as noticeable where the concrete is designed for similar 28 day compressive strength to the control mix, although there is some indication that direct replacement mixes will have poorer abrasion resistance than the control opc mix.

Further research is required into the effect that the use of various types of curing membranes might have on this property as this aspect is of fundamental importance to the understanding of the application of fly ash in paving concrete mixes and the performance of such concretes under traffic.

Under laboratory conditions and standard curing the fly ash seems to improve the abrasion resistance of concrete.

Gordon[293] suggests that the greater improvement in compressive strength of the fly ash concretes between 28 and 90 days is grounds for considering a change in the age at which the desired characteristics in concrete should be specified. As he has shown that under standard curing conditions the abrasion resistance of such concrete only matches that of ordinary portland cement concrete at 90 days this would seem to be sufficient reason for not considering a revision of the specification The possibility of poor site curing conditions and the greater sensitivity of the abrasion resistance of some of the extended mixes would seem to make this revision even less desirable.

9.3 Carbonation

As mentioned in chapter 3 there is a wide diversity of opinion on the issue of whether fly ash contributes to reducing the rate of carbonation or not. Some concern has been expressed for the possibility that during the pozzolanic reaction the fly ash might so reduce the calcium hydroxide content of the mix that the durability of the mix might be impaired.

In a recent internal PCI publication Addis[305] calculated the theoretical quantity of fly ash that, when fully reacted, would consume all the calcium hydroxide available from the hydration of a typical portland cement to be about 56 %. If all the calcium hydroxide in the cementitious mix is consumed by the pozzolanic reaction then there is no further calcium hydroxide available to react with carbonic acid or gaseous carbon dioxide, should the mix be exposed to this mode of attack. The lack of calcium hydroxide might also result in the pH of the mix being lower than is necessary for the passivation of the reinforcing steel in the mix.

This theoretical figure of 56 % has been given some support after discussion with Messrs. Ash Resources who feel, after doing some unpublished research work, that no further increase in compressive strength is noted once the fly ash content exceeds 60 to 70 %. It should be noted that full reaction of the fly ash is unlikely as there is normally a proportion of non reactive mullite and quartz present.

Generally the level of fly ash used in concrete is well below 56 % and therefore it can be assumed that there will be some residual calcium hydroxide to provide resistance to the neutralising effects of carbon dioxide and to provide the alkaline environment for the necessary passivation to the reinforcing steel present in the mix.

In this work, the depth of carbonation has been determined using phenolphthalein indicator sprayed on freshly fractured surfaces of the exposed concrete. Rahman and Glasser[212] pointed out that this test will not indicate the width of the intermediate zone in which the pH is below 9,8. It has been assumed for this work that this intermediate zone is similar for all cementitious materials tested, and that the edge of the pink zone indicates the position of the carbonation front.

The carbonation resistance of fly ash mixes in this study has been determined using two tests; the first test made use of the large blocks previously described under section 7.1.3 and the second test was carried out on sets of cubes exposed to different curing regimes.

These tests are described more fully in the following paragraphs. Note that all the work described here has been done on Matla fly ash only.

9.3.1 Carbonation of large poorly cured blocks

The mixes and curing conditions to which these blocks were exposed have been described in chapter 7.

Only the blocks cast in the summer of 1987–88 and in the winter of 1988 were tested for depth of carbonation. The depth to which these concrete mixes had carbonated is given in table 9.8a. The age at which the carbonation was determined was 10 months in the case of the summer blocks, and 4 months in the case of the winter blocks. This information is depicted graphically in figure 9.6a.

It can be seen from this figure that the carbonation depth is lowest at these ages for the ordinary portland cement mix, and all the mixes containing extenders show greater depths of carbonation. It is interesting to see that the PC50SL mix performed slightly better than the PC30FA mix on both occasions. This is not totally unexpected, as the slag does not consume calcium hydroxide during its hydration, and should therefore be better able to withstand the carbon dioxide attack with its greater degree of neutralising ability derived from the higher calcium hydroxide content.

The finding that the fly ash mix concrete carbonates faster than the OPC control mix contradicts the finding given in Fulton[306], but is in agreement with a majority of the research findings consulted during the literature study phase of this work.[92,156,157,164,175,213,214,215,216,217]

9.3.2 Carbonation of cube specimens

In order to evaluate the effect of poor curing more fully it was decided that cube specimens should be made and sets exposed to different curing regimes in the laboratory. Accordingly two mixes were made aiming at the same slump and same 28 day compressive strength, with the control mix made with OPC and the second mix using PC 30 FA. Details of the mix proportions used (intended to give simiiar 28 day compressive strength) are given in table 9.8b.

The cubes were moulded and then placed in the fog room for the first 24 hours. After demoulding, the specimens were treated in the following way;

4 sets had no further curing
4 sets had 2 days further curing under water
4 sets had 6 days further curing under water
4 sets had 13 days further curing under water
4 sets had 27 days further curing under water

In each case the water was at the standard laboratory curing temperature of 22 to 25 °C. A set of each of the above methods of curing was tested using phenolphthalein indicator to determine the depth of carbonation at ages of 28, 56, 91 and 182 days.

At each age compressive strength tests were done on dry specimens, although for the 28 day test some cubes were also crushed wet to show how well the target of equal 28 day compressive strength had been met. The data on depth of carbonation and compressive strength are given in table 9.8c. This information is shown graphically in figures 9.6b, 9.6c, 9.6d and 9.6e for the ages 28 days, 56 days, 91 days and 182 days respectively.

Figure 9.6a
Depth of carbonation on large blocks

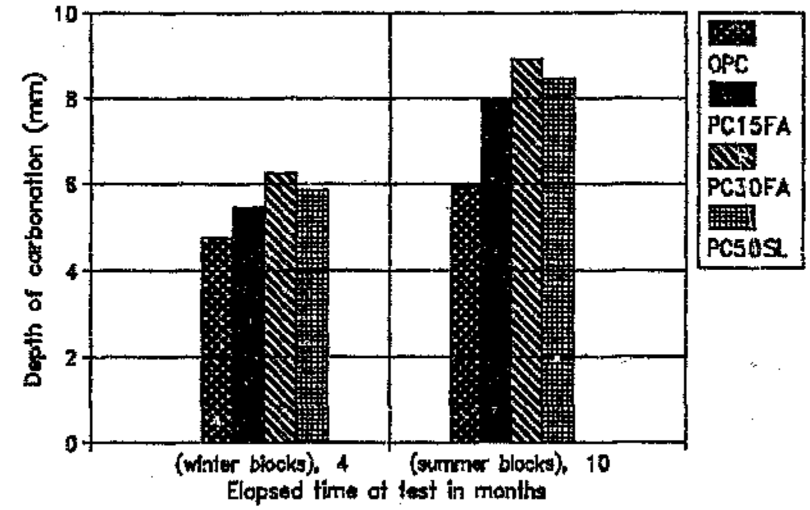


Figure 9.6b
Depth of carbonation at age 28 days

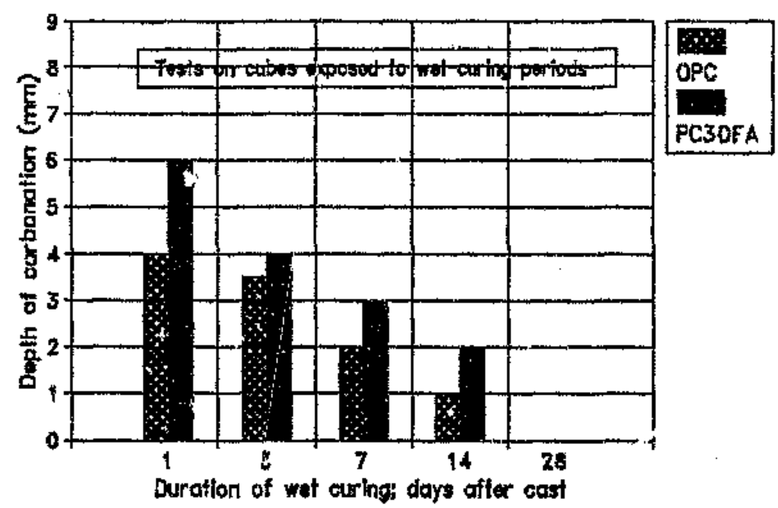


Figure 9.6c
Depth of carbonation at age 56 days

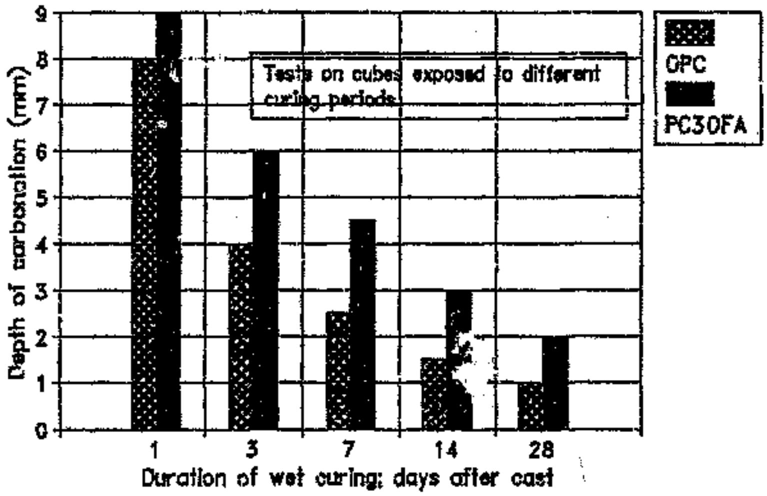
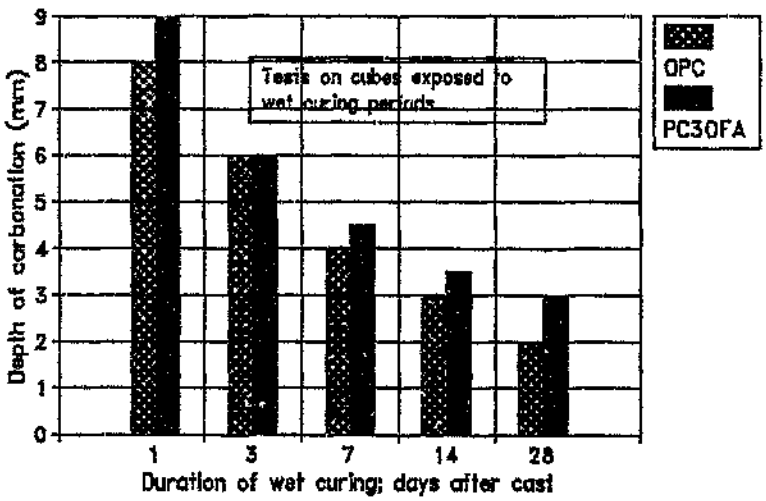


Figure 9.6d
Depth of carbonation at age 91 days



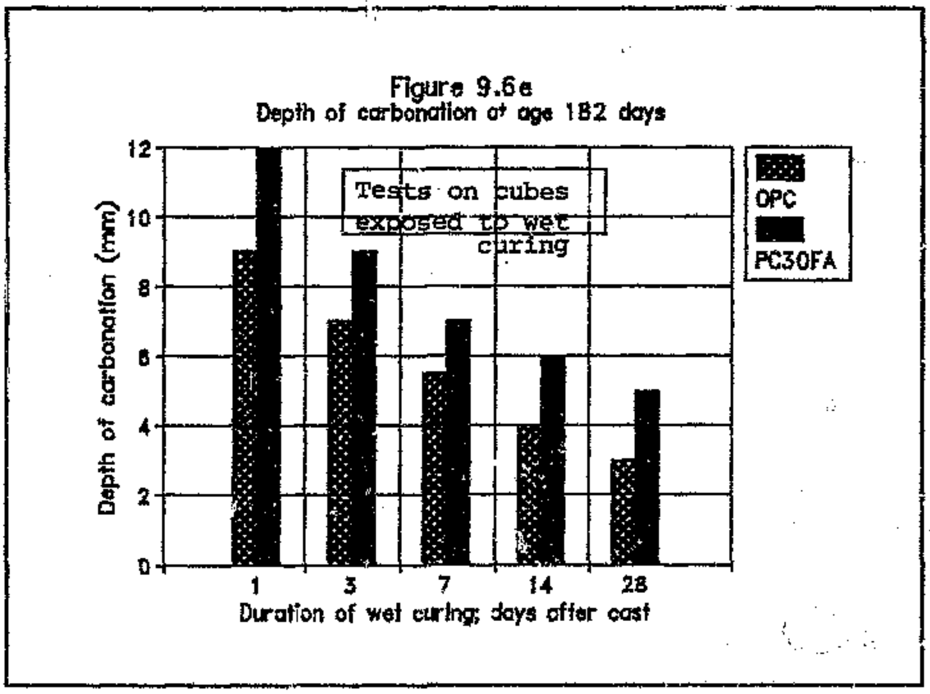


Figure 9.6e
Depth of carbonation at age 182 days
Tests on cubes
exposed to wet
curing
OPC
PC30FA
Depth of carbonation (mm)
Duration of wet curing; days after cast
12
10
8
6
4
2
0
1
3
7
14
28

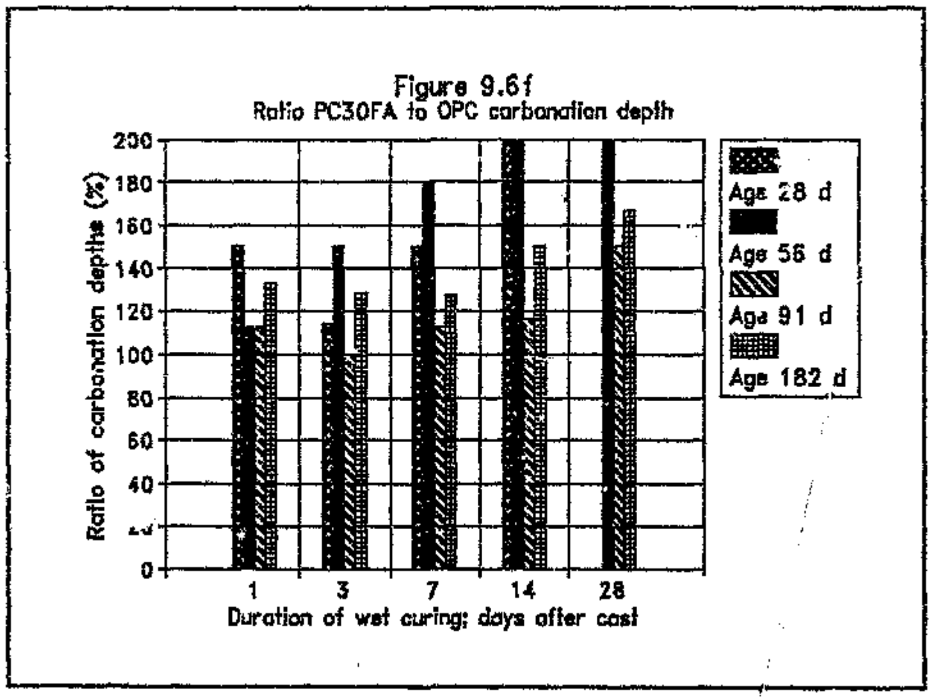


Figure 9.6f
Ratio PC30FA to OPC carbonation depth
Age 28 d
Age 56 d
Age 91 d
Age 182 d
Ratio of carbonation depths (%)
Duration of wet curing; days after cast
200
180
160
140
120
100
80
60
40
0
1
3
7
14
28

It is evident from these graphs that the depth of carbonation for the OPC mixes is always lower than the PC30FA mix for the same age and same method of curing.

In Figure 9.6b it seems that to ensure a similar depth of carbonation at 28 days it is necessary to cure the PC30FA mix for longer periods than is necessary in the case of the OPC mix. For example, to give similar resistance to an OPC mix that has been cured for 3 days, it is necessary to cure the PC30FA mix for about 7 days.

A similar picture emerges for figures 9.6c, 9.6d and 9.6e.

It is however noteworthy (when looking at the difference between figure 9.6c and 9.6d for example) that although the OPC mix continues to carbonate as the specimens age, the PC 30 FA mix carbonation seems to stabilise around 56 days allowing the OPC carbonation depths to catch up to some extent. This is not quite so evident at age 182 days so the trend is not fully established.

The ratio of carbonation depth of OPC to PC 30 FA reduces from about double at 56 days, to roughly 50 % more than the OPC mix at 91 and 182 days. This is shown by the graph of these ratios in figure 9.6f.

Unfortunately, the scatter in these results makes it difficult to draw firm conclusions about this trend.

This finding that the carbonation rate of the fly ash mix appears to stabilise is of some interest when attempting to understand the durability of fly ash mixes. There seems to be some conflict in the fly ash concretes between the effect of the reduction of permeability and the reduction of the calcium hydroxide content brought about by the use of the fly ash. This phenomenon has previously been referred to by Alexander[307].

It is believed necessary that this work should be repeated with a wider range of combinations of materials to confirm the trend shown here, and to try to identify the mechanism responsible. It is also important that the time for the carbonation front to reach the point where the steel might become susceptible to corrosion is determined for both OPC and fly ash mixes.

9.3.3 Possible mechanism for slowing of carbonation rate

A suggestion for the mechanism is offered as follows. In section 9.1 the results described show that the fly ash mixes are more susceptible to poor curing in that the permeability of the skin concrete is greater than that of the control OPC mix; the depth to which this effect on the permeability occurs is not certain however. It is possible that the harmful effect of the poor curing only extends to a few millimetres below the skin, and that beyond that point the fly ash mix is more dense than the OPC mix, as is the case for the results for the properly cured specimens.

Once the carbonation front reaches the denser concrete the rate slows. As the OPC concrete, under proper curing, is more permeable than the fly ash mix, the slowing of the penetration of the carbonation front is not as evident.

It is also possible that the pozzolanic reaction of the fly ash in the desiccated zone on the outside never gets the chance to take place with the result that the actual cement/water ratio in that zone can be assumed not to have the fly ash included and is accordingly lower than the OPC mix. This would result in a more permeable outer skin, and a more rapid penetration of aggressive elements.

Looking at the rate at which the carbonation front penetrates the two concretes between 28 and 56 days, and between 28 and 91 days, it seems that the rate of penetration for the OPC mix decreases with time. If the rate of carbonation is taken as

$$d = k \times t^x$$

where d = depth of carbonation (mm)
k = constant
t = time (days)
x = variable dependant on type of cement

In the case of the OPC mixes, the value of x seems to fall in the range from 0,8 to 0,9. For the PC30FA mixes the value of x seems to be smaller but also has more scatter and lies in the range from 0,1 to 0,67. This means that the rate of carbonation of the fly ash mixes tested slows down more with time than is the case for the OPC mixes.

This supports the contention that the effect of the poor curing is only as deep as permitted by the loss of moisture from the skin; deeper fly ash concrete being more dense than the ordinary portland cement concrete, will slow the process of desiccation and carbonation down.

This finding is in agreement with other reports mentioned in the literature study where, after an initial fairly rapid rate of carbonation the rate decreases in the fly ash mix to have a similar depth of carbonation to that of ordinary portland cement concrete at later ages[117,147,181,205,220,221].

9.3.4 Summary of findings on carbonation

There seems to be evidence that the influence of fly ash on concrete is to increase the initial sensitivity to poor curing relative to the effect of poor curing on ordinary portland cement concrete. It is possible, however, that this effect might not be detrimental with normal depths of cover to the reinforcing steel as by that stage the rate of carbonation is similar to that of the ordinary portland cement concrete.

This is an aspect that needs wider research under a range of different conditions and mixes to evaluate the possible impact on the durability of the concrete.

A further point to be considered in evaluating the impact of fly ash on the rate of carbonation at various ages is that of the effect of curing membranes on this rate as this would be of particular significance to concrete paving applications.

9.4 Alkali aggregate reaction

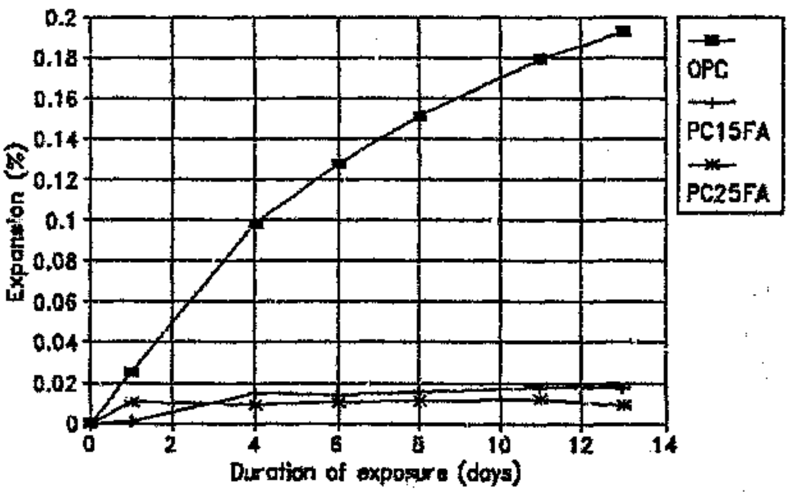
Concrete "cancer", as alkali aggregate reaction became known in Europe and the U.S.A., came to the attention of South African concrete technologists in the mid 1970's. Pioneering work undertaken by the National Building Research Institute of the CSIR (now renamed the Division of Building Technology) led to an understanding of the problem. The DBT also developed recommendations on how to prevent the reaction occurring in new concrete. In the process of the studies undertaken, the NBRI developed a test for evaluating the sensitivity of an aggregate to the alkaline environment in concrete[308]; this test, with a duration of 2 weeks, was much more practical than the full ASTM C227-81 test[309] which has a duration of 6 months. (The CSIR has now shown that for the South African type of hornfels the ASTM test duration needs to be 52 weeks.)

In 1987 PCI participated in an exercise with the CSIR to evaluate the human and test environment factors affecting the results of the test they had developed. The results of these inter-laboratory tests are available in a report from the CSIR.[310]

One of the preventative measures recommended by the CSIR where the aggregate showed indications of sensitivity, was to incorporate a minimum of 15 % fly ash in the cementitious fraction of the concrete.

In this work some results are given of tests done to the method developed by the CSIR. The efficacy of the use of fly ash was evaluated by doing comparative tests with and without the use of the fly ash. These results are given in table 9.9 and are shown graphically in figure 9.7

Figure 9.7
Effect of FA on Alkali Silica Reaction



These data are derived from tests on a rhyolitic type of sand using an ordinary portland cement of Italian origin with or without fly ash from Matla.

It is immediately apparent how effective the introduction of fly ash is in reducing the expansion of the specimens. While the opc mix showed expansion which exceeded the DBT criterion for slowly expansive aggregate,[311] ie between 0,08 and 0,20 % expansion at 10 days, the incorporation of 15 % fly ash to the mix reduced the expansion to well below the minimum criterion for slowly reactive aggregate. In this case the expansion at the end of the test was showing a slight increase with time. The mix using 25 % fly ash showed very little increase in expansion with time but otherwise was only marginally better at reducing the expansion than the mix using 15 % fly ash.

This information does not serve as direct proof that concrete made with such aggregate will not expand when exposed to actual site environmental conditions; however, large blocks made and exposed over a long period of time have been shown by the DBT to support the limits of expansion they have set for the results from their test[308].

It is from the results found in these long term exposure tests that the data has been derived to enable DBT to set recommended limits on the fly ash, slag or silica fume content of concrete to control the undesirable expansions due to alkali silica reaction. The current (end 1990) level of fly ash that has been recommended for controlling these expansions is 20 %.[312]

9.5 Summary of findings on durability

The use of fly ash appears to have a beneficial effect on the water permeability of concrete as measured by the DIN 1048 permeability test whether the concrete is adequately cured or not. The results do not show if the outer skin is likely to provide adequate protection to the reinforcing steel.

Abrasion resistance of poorly cured fly ash concretes made with Matla fly ash seems to be slightly poorer than for control opc concretes. In the case of Lethabo fly ash there is little difference between the abrasion resistance of the opc and fly ash concretes where the mixes are designed for equal 28 day compressive strength, although a direct replacement mix will tend to have poorer abrasion resistance. Where concrete is well cured the fly ash seems to have a beneficial effect.

The carbonation rate of fly ash concretes appears to be greater than for the equivalent opc concrete for any given curing regime, although it seems that the rate might slow down relative to the opc rate once the carbonation front gets into a more dense concrete zone. More work is needed on this aspect.

The findings on the abrasion resistance and the carbonation tend to indicate that the permeability of the outer skin fly ash concrete might initially be higher than that for opc concrete; if the permeability were to reduce deeper into the concrete the overall permeability of the concrete shown by the DIN 1048 test could then still be similar to that of the opc concrete. It is believed that until there is categorical evidence to the contrary, these findings should be taken to indicate that fly ash concretes are more sensitive to poor curing than is the case for ordinary portland cement concretes, and therefore more care with curing is indicated, particularly at high levels of fly ash, to ensure good durability. Curing is essential for all concrete; if site practice could be improved then all concretes would benefit.

The use of adequate quantities of fly ash in a concrete have been shown to reduce the expansions due to alkali silica reaction to negligible proportions, at least as shown in the relatively short term test results so far available.

Table 9.1a

Mix proportions for concrete mixes used for DIN water penetration tests. PPC Jupiter OPC and Matla fly ash used. Quantities given in kg/m³.

OPC mixes				
Materials	cement/water ratio			
	1,40	1,60	1,80	2,00
water	212	210	208	210
OPC	297	336	375	420
fly ash	–	–	–	–
13,2-mm stone	970	980	990	1000
granite sand	982	945	908	856
PC 15 FA mixes				
Materials	cement/water ratio			
	1,49	1,70	1,90	2,11
water	204	201	199	200
OPC	258	290	321	359
fly ash	46	51	57	63
13,2-mm stone	981	993	1005	1017
granite sand	973	938	900	848
PC 30 FA mixes				
Materials	cement/water ratio			
	1,58	1,81	2,04	2,26
water	197	194	192	193
OPC	218	246	274	305
fly ash	93	105	118	131
13,2-mm stone	993	1007	1020	1035
granite sand	962	920	876	819

Table 9.1b

Average depth of penetration for OPC and fly ash mixes detailed in table 9.1a

OPC		PC 15 FA		PC 30 FA	
28 d Comp. strength (MPa)	Penetration (mm)	28 d Comp. strength (MPa)	Penetration (mm)	28 d Comp. strength (MPa)	Penetration (mm)
23,1	26,5	31,1	19,3	21,6	10,1
29,6	14,3	30,4	8,0	29,8	7,8
36,8	9,1	37,4	4,3	36,7	4,3
43,1	5,5	42,9	4,0	45,3	3,9

Note: The tests were performed on standard cured 100 mm laboratory cubes; the results above represent the average of three individual test results.

Table 9.2a

Permeability results ex Division of Building Technology, CSIR

Cement used	C/W ratio	Gas perm, (ℓm^2/min)	1 h coefft. water perm. (10^{-7}mm/s)	3.5 h coefft. water perm. (10^{-7}mm/s)	24 h coefft. water perm. (10^{-7}mm/s)
PC 30 FA	1,58	14,6	21,93	22,56	–
PC 30 FA	2,26	2,23	–	–	0,423

Table 9.2b

Measured depth of penetration and calculated permeability for DIN 1048 tests on mixes in table 9.1a

Cement used	C/W ratio	Max depth penetration (mm)	Ave depth penetration (mm)	Calculated* coefft. of perm. (10^{-7}mm/s)		
				m=0,5	m=0,7	m=0,9
PC 30 FA	1,58	28,5	10,1	0,0275	0,0211	0,0156
PC 30 FA	1,81	21,2	7,8	0,0149	0,0108	0,0074
PC 30 FA	2,04	13,4	4,3	0,0041	0,0028	0,0017
PC 30 FA	2,26	10,8	3,9	0,0031	0,0019	0,0010
* Calculated from Valenta[300] and Fulton[301]						

Table 9.3

Depths of penetration in DIN tests on standard cured cubes and site cured cores for mixes detailed in table 7.3a

Cement used	Winter 1987		Summer 1987–88		Winter 1988	
	Ave pen depth (mm) on cubes	Ave pen depth (mm) on cores	Ave pen depth (mm) on cubes	Ave pen depth (mm) on cores	Ave pen depth (mm) on cubes	Ave pen depth (mm) on cores
OPC	16,3	Flow	8,75	103,6	6,3	Flow
PC 15 FA	7,40	Flow	3,58	Flow	4,77	Flow
PC 30 FA	4,40	Flow	29,81	Flow	6,03	Flow
PC 50 SL	5,00	Flow	13,85	Flow	10,54	Flow

Flow signifies when the water penetrated the full depth of the specimen; This was therefore an indeterminate result as the time to full depth penetration was not known.

Table 9.4

Penetration depth in modified DIN 1048 test (Lethabo fly ash) from mixes detailed in table 7.2a

CEMENT BLEND	TEMP	DEPTH (mm) sealed	CEMENT BLEND	TEMP	DEPTH (mm) sealed	CEMENT BLEND	TEMP	DEPTH (mm) sealed
OPC A (EQ 28)	HOT	97	OPC B (EQ 28)	HOT	101	OPC C (EQ 28)	HOT	65
	STD	104		STD	113		STD	99
	COLD	150		COLD	121		COLD	87
PC15 A (EQ 28)	HOT	132	PC15 B (EQ 28)	HOT	59	PC15 C (EQ 28)	HOT	117
	STD	99		STD	82		STD	120
	COLD	123		COLD	110		COLD	110
PC22.5 A (EQ 28)	HOT	77	PC22.5 B (EQ 28)	HOT	54	PC22.5 C (EQ 28)	HOT	58
	STD	75		STD	88		STD	84
	COLD	135		COLD	115		COLD	150
PC30 A (EQ 28)	HOT	88	PC30 B (EQ 28)	HOT	74	PC30 C (EQ 28)	HOT	62
	STD	93		STD	92		STD	71
	COLD	150		COLD	136		COLD	82
PC15 A (DR)	HOT	96	PC15 B (DR)	HOT	114	PC15 C (DR)	HOT	91
	STD	93		STD	138		STD	87
	COLD	123		COLD	150		COLD	150
PC22.5 A (DR)	HOT	87	PC22.5 B (DR)	HOT	89	PC22.5 C (DR)	HOT	107
	STD	108		STD	92		STD	88
	COLD	107		COLD	143		COLD	150
PC30 A (DR)	HOT	121	PC30 B (DR)	HOT	107	PC30 C (DR)	HOT	108
	STD	126		STD	133		STD	104
	COLD	150		COLD	150		COLD	128

Table 9.5

Abrasion testing of concrete cubes for mixes detailed in table 7.3a. Cubes cured under water at 22 to 25 °C.

Period	Time tested (min)	Depth of wear (mm)			
		OPC	PC15FA	PC30FA	PC50SL
Winter '87	4	2,1	1,9	2,2	1,3
Summer '87–88	1	0,4	0,6	0,8	1,0
Summer '87–88	2	0,9	0,7	0,9	1,1
Summer '87–88	4	1,6	1,3	1,6	1,8
Winter '88	4	0,3	0,3	–	–

Table 9.6

Abrasion testing of large concrete blocks for mixes detailed in table 7.3a. Blocks subject to site curing outside laboratory.

Period	Time tested (min)	Depth of wear (mm)			
		OPC	PC15FA	PC30FA	PC50SL
Winter '87	4	0,3	0,3	1,1	0,8
Summer '87–88	1	1,5	2,3	2,6	3,3
Summer '87–88	2	2,4	3,3	3,1	4,5
Summer '87–88	4	3,0	4,2	3,1	4,5
Winter '88	4	–	–	–	–

Table 9.7

Abrasion penetration (mm) of cube specimens at age 28 days (Lethabo fly ash) from mixes detailed in table 7.2a

CEMENT BLEND	REGIME	PEN (mm) sealed	PEN (mm) unsealed	CEMENT BLEND	REGIME	PEN (mm) sealed	PEN (mm) unsealed	CEMENT BLEND	REGIME	PENN (mm) sealed	PEN (mm) unsealed
OPC A (EQ 28)	HOT	2	2,4	OPC B (EQ 28)	HOT	1,6	3,5	OPC C (EQ 28)	HOT	2,1	3,2
	STD	1,5	2,8		STD	2	2,9		STD	1,7	3,7
	COLD	1,8	1,8		COLD	2,1	2,2		COLD	2	1,9
PC15 A (EQ 28)	HOT	1,9	2,8	PC15 B (EQ 28)	HOT	1,7	2,8	PC15 C (EQ 28)	HOT	1,9	3,3
	STD	1,7	2,3		STD	1,6	2,9		STD	2	2,6
	COLD	2	1,7		COLD	2,3	2,4		COLD	2,1	2,1
PC22.5 A (EQ 28)	HOT	2,1	2,9	PC22.5 B (EQ 28)	HOT	[illegible]	3,4	PC22.5 C (EQ 28)	HOT	2,2	3,2
	STD	1,8	2,8		STD	1,8	3,2		STD	1,8	2,6
	COLD	2,1	1,9		COLD	2	2,3		COLD	2,6	2
PC30 A (EQ 28)	HOT	1,6	2,6	PC30 B (EQ 28)	HOT	2,1	3,1	PC30 C (EQ 28)	HOT	2,8	3,5
	STD	1,9	2,9		STD	2	3,6		STD	1,8	2,9
	COLD	2,1	2,1		COLD	2,1	2,3		COLD	2,4	2,6
PC15 A (DR)	HOT	1,8	2,6	PC15 B (DR)	HOT	2,6	3,4	PC15 C (DR)	HOT	2,2	3,7
	STD	1,8	2,9		STD	2	2,8		STD	2	3,3
	COLD	2	1,8		COLD	2,3	2,5		COLD	2,9	3
PC22.5 A (DR)	HOT	1,7	3	PC22.5 B (DR)	HOT	2,5	3,1	PC22.5 C (DR)	HOT	2,7	3,7
	STD	2,2	3		STD	2,11	3,4		STD	2,2	3,2
	COLD	2,2	2,4		COLD	2,4	2,3		COLD	2,9	2,7
PC30 A (DR)	HOT	3,1	3,3	PC30 B (DR)	HOT	2,5	3,3	PC30 C (DR)	HOT	2,3	3,4
	STD	2,1	3		STD	2,2	3,7		STD	2,4	3,6
	COLD	2,6	3,2		COLD	2,4	2,9		COLD	2,6	3

Table 9.8a

Depth of carbonation of concrete in large exposed blocks made to mix proportions detailed in table 7.3a

Time of cast	Elapsed time (months)	OPC	PC15FA	PC30FA	PC50SL
Winter 88	4	4,7	5,5	6,3	5,9
Summer 87–88	10	5,9	8,0	8,9	8,5

Table 9.8b

Mix proportions for mixes for carbonation investigation

Mix details	OPC Mix 1 (kg/m^3)	PC30FA Mix 2 (kg/m^3)
C/W ratio	1,7	1,95
OPC (FPC Jup)	340	259
FA (Lethabo)	–	111
19 mm granite	971	971
Crusher sand	874	843
Water	200	190
Slump (mm)	85	110

Table 9.8c

Depth of carbonation (mm) for cube specimans to mixes detailed in table 9.8b for different periods of wet curing

Cement type used	Comp. strength (28d wet) (MPa)	Age at test (days)	Duration of wet curing (days)				
			1	3	7	14	28
OPC	34,0	28	4,0	3,5	2,0	1,0	0,0
PC30FA	32,0	28	6,0	4,0	3,0	2,0	0,0
OPC	48,0	56	8,0	4,0	2,5	1,5	1,0
PC30FA	45,5	56	9,0	6,0	4,5	3,0	2,0
OPC	49,5	91	8,0	6,0	4,0	3,0	2,0
PC30FA	46,0	91	9,0	6,0	4,5	3,5	3,0
OPC	53,0	182	9,0	7,0	5,5	4,0	3,0
PC30FA	52,5	182	12.0	9,0	7,0	6,0	5,0

Table 9.9

Effect of fly ash on expansion in the DBT accelerated testfor alkali aggregate reaction

Duration of exposure (days)	Expansion (%) for mixes using		
	OPC	PC15FA	PC25FA
1	0,0250	0,0010	0,0104
4	0,0984	0,0147	0,0091
6	0,1280	0,0141	0,0103
8	0,1511	0,0157	0,0112
11	0,1792	0,0177	0,0121
13	0,1926	0,0177	0,0090

CHAPTER 10

10. MISCELLANEOUS

This chapter covers aspects that do not comfortably fall within the ambit of any of the previous chapters.

10.1 Ternary blends

Ternary blends in the context of this study are regarded as three component blends of portland cement, fly ash and another cementitious extender such as ggbs or silica fume.

10.1.1 History of use of ternary blends

This is not a practice that has found wide support in South Africa up until the present. It is however likely that concrete technologists working for contractors will experiment with such three way blends in the future in attempts to find cheaper ways of producing concrete. This has occurred at least once in South Africa in the case of the South African Development Bank at Midrand where Murray & Roberts Construction used a combination of rapid hardening portland cement, ggbs and silica fume as the cementitious materials in the concrete used for the structure.[313] Another example is that of a precast block manufacturer on the Witwatersrand who has for many years been using a ternary blend of ordinary portland cement, ggbs and fly ash.[23]

In other countries the impetus for such experimentation seems to have come from the Ready Mixed Concrete industry as they have both the necessary degree of technical sophistication and a strong motivation to try to reduce operating costs as they work in a high concrete volume business. Australia seems to have been at the forefront of much of this research[31,70,314] with experience dating back to 1966 for the first use of a ternary blend incorporating ordinary portland cement, ggbs and fly ash.[70]

No specific reference was made in the paper by Potter[70] to the durability of concrete made with this blend of cementitious materials although a comment would have been expected had any negative aspects been detected.

Panuccio[314] indicated that the introduction of 30 % fly ash to an ordinary portland cement mix or to a mix using a PBFC (60 % opc and 40 % slag ground to a fineness such that the PBFC mix gives the same 28 day compressive strength as the ordinary portland cement mix) had no effect on the 28 day strength obtained with either mix. He did however report that relative to the ordinary portland cement or 40 % slag mixes, the setting time was extended and 7 to 28 day compressive strength ratio was reduced.

10.1.2 Experimental work

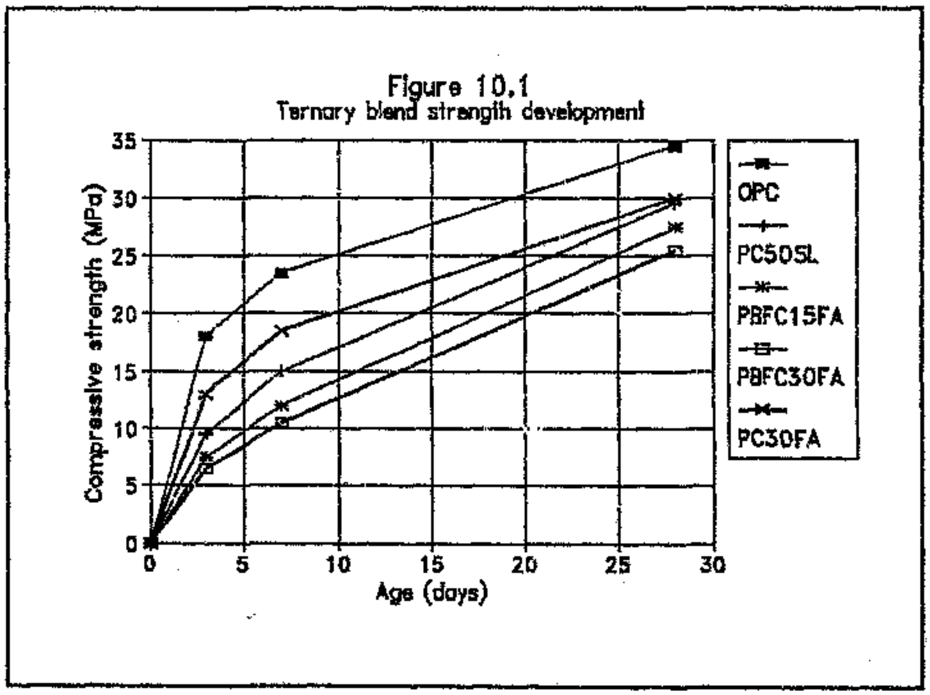
It was thought advisable to undertake some preliminary tests to see what effect the characteristics of a concrete. These are only regarded as preliminary tests as the number of possible permutations of material combinations becomes impractically large for such a broad investigation as this: a full investigation would serve as a substantial basis for a further thesis.

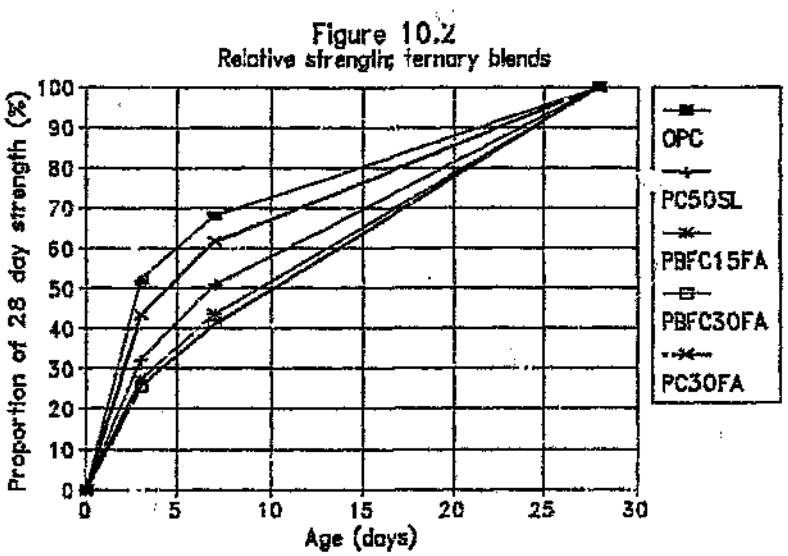
A series of mixes was made in the laboratory to evaluate the effect of combinations of ordinary portland cement, slag and fly ash on the development of compressive strength of concrete. The mix proportions used for the mixes and relevant ratios are given in table 10.1.

The materials used for these mixes were decomposed granite sand and 19 mm stone from Jukskei quarry (Hippo quarries), the ordinary portland cement came from the PCI silo (PPC Jupiter), the slag from Slagment, VanderBijlPark, and the fly ash from Matla.

10.1.3 Discussion of results

The results of the compressive strength tests on these concrete mixes are given in table 10.2. The results are also presented graphically in figures 10.1 and 10.2. Figure 10.1 presents the curves of compressive strength development for the 5 mixes given in table 10.1. It is noteworthy however that the compressive strength at 28 days for the mixes with extenders is lower than that for the opc mix even though the cement/water ratios were adjusted to give a similar order of strength at that age.





Because of the differences in 28 day compressive strength results the values in table 10.2 have been recalculated to show ratios of the compressive strength at each age relative to the 28 day compressive strength. This information is shown in figure 10.2.

It can be seen from figure 10.2 that the ternary blends do not perform as well as either the ordinary portland cement/slag or the ordinary portland cement/fly ash combinations. It is also evident that the PC 30 FA mix performed better at early ages than the PC 50 SL mix.

The pattern that emerges is that when all three cementitious materials are used together then the early compressive strength is reduced relative not only to that found for the ordinary portland cement mix, but also for the PC 50 SL, and the PC 30 FA mixes. There seems to be little difference in the proportions of 28 day compressive strength developed by the two levels of fly ash used in the ternary blends although the PBFC 30 FA mix did show a further depression in compressive strength relative to the PBFC 15 FA mix in figure 10.1.

The changes in concrete properties associated with the use of ternary blends made with similar combinations of South African cementitious materials can be therefore be expected to be more marked than is the case with a simple ordinary portland cement/fly ash combination at a similar total extender content or cementitious/water ratio.

There may nevertheless be economic advantages to using such combinations; this will encourage further investigation, particularly by organisations that regularly use large volumes of cement such as suppliers of Ready Mixed Concrete.

The findings reported here are believed to be similar to preliminary findings by the South African producers of extenders.[315,316] The performance of the combinations used here do not seem to match that reported by Pannuccio[314] for Australian materials.

This is an area that needs further work as, with the potential for cost savings, many contractors will be tempted to experiment. The suppliers of cement and extenders would be well advised to know the implications of such experimentation before it occurs.

10.2 Use of Admixtures

Most sophisticated users of portland cement make use of chemical admixtures in the manufacture of concrete generally with the aim of reducing the cost of the concrete. If the inclusion of fly ash in a concrete mix is likely to have an impact on the performance of the admixture this would be of concern to such users.

10.2.1 History of the use of chemical admixtures with fly ash

Many of the authors referred to in Chapter 3 have indicated that the carbon content of the fly ash used has an impact on the required dosage of admixtures in the mix, with the dosage increasing with the carbon content.

Reference to Table 5.10a will show that the carbon content (as expressed by the Loss on Ignition (LOI)) of the Matla fly ash used in most of this work is relatively constant around 1 %. The limited data given in Table 5.10b indicates that the average level of carbon content in the fly ash from Lethabo is lower at about 0,5 % and also appears to be fairly constant. The average carbon contents of the Matla and Lethabo fly ashes are however low relative to the figures commonly reported for fly ashes used in some of the experimental work reviewed in chapter 3.

10.2.2 Experimental work

The influence of the fly ash content and source on the effectiveness of an admixture was evaluated in a small series of laboratory tests at PCI. Only a single water reducing admixture was used and this is intended to give an indication only of the potential effect. The number of permutations of tests needed to give a definitive answer to this question is so large as to make this topic a subject for a thesis on its own.

The experimental work covered in these paragraphs was done using the same aggregates, fly ash and ordinary portland cement as covered in paragraph 10.1.2. Additional mixes were made with Lethabo fly ash to evaluate the influence that the small decrease in carbon content between the Matla and Lethabo fly ashes might have on the effectiveness of the water retaining admixture used. The admixture selected for this work was Multiflow 606N from Multi Construction Chemicals used at a dosage rate of 300 ml/100 kg of cementitious material used.

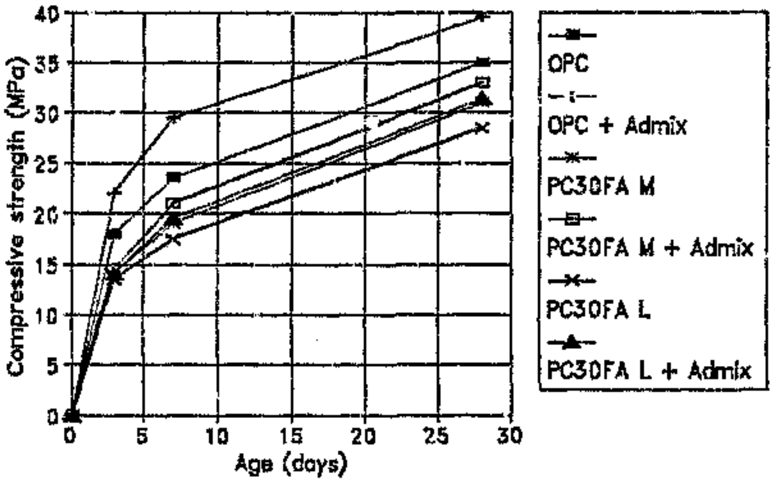
The mix proportions used in this evaluation are given in table 10.3

The effectiveness of the admixture was assessed from the slump and dosage relationship revealed in table 10.3. The compressive strength at ages 3, 7 and 28 days was also determined for these mixes: this information is given in table 10.4.

10.2.3 Discussion of results

The results shown in table 10.3 indicate that the small difference between the carbon content of the fly ashes from the two different sources has an insignificant effect on the effectiveness of the admixture used with this specific combination of materials as indicated by the slump test done to assess the workability in these tests.

Figure 10.3
Compressive strength; mixes with admix



The reduction in the water requirement brought about by both the fly ash samples is higher than usual as both ashes resulted in a reduction of 20 litres per m^3.

What is also noticeable is the fact that at the dosage of the admixture used the admixture is more effective in reducing the water requirement of the OPC mix than is the case for the fly ash mix. When the ordinary portland cement mix was dosed with admixture the water requirement of the mix was reduced by 15 litres per m^3. In the case of the PC 30 FA mixes, the admixture resulted in a further reduction of water requirement of only 5 litres per m^3 above the reduction provided by the use of the fly ash itself.

This would seem to indicate that the admixture is either only effective on the ordinary portland cement fraction, or certainly more effective on the ordinary portland cement than on the fly ash fraction of the blend. The results would seem to support those who advocate that the admixture dosage should only be calculated on the portland cement content of the mix and not the cementitious content as has been applied here.

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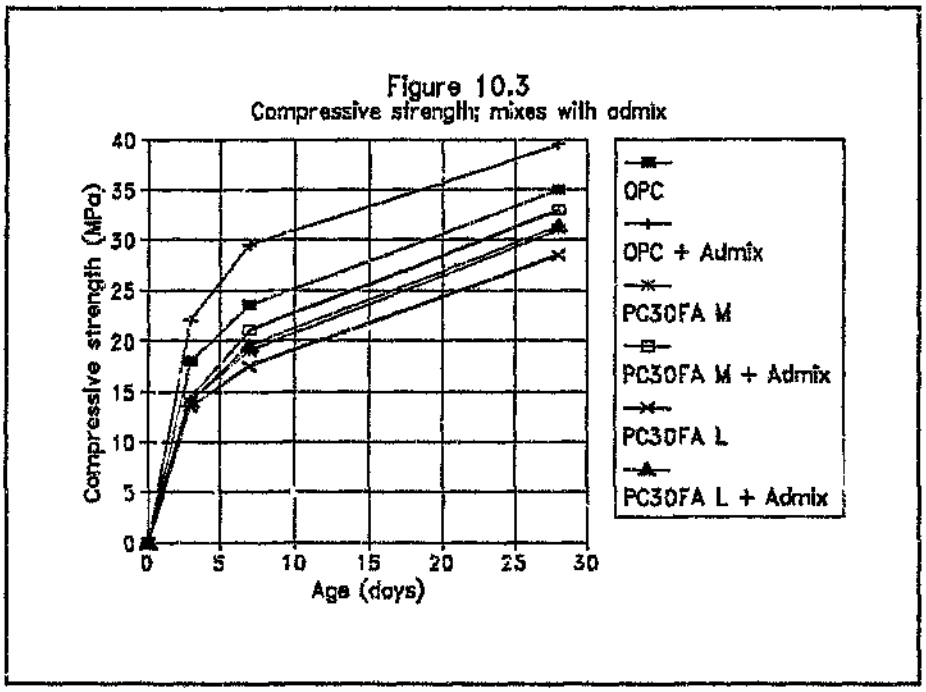

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This would seem to indicate that the admixture is either only effective on the ordinary portland cement fraction, or certainly more effective on the ordinary portland cement than on the fly ash fraction of the blend. The results would seem to support those who advocate that the admixture dosage should only be calculated on the portland cement content of the mix and not the cementitious content as has been applied here.

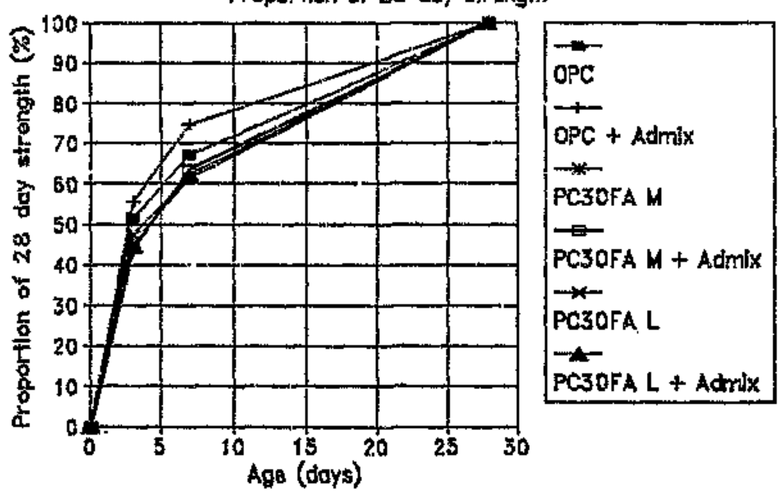
It may be argued that the fly ash had already brought about much of the potential dispersion of the mix in its own right as suggested by other researchers[41,85,86,258]. This could lead to the conclusion that there was then little that the admixture could do to further reduce the water requirement of the mix.

It would seem that the economic viability of the admixture in a fly ash mix is considerably inferior to the case with a pure portland cement mix. It is possible that the fly ash could be regarded as combined admixture and cementitious extender; no further recourse to chemical admixtures may then be warranted. This is an aspect that requires further evaluation with other combinations of materials.

It is apparent, however, that the source of the fly ash has little impact on the water reduction brought about by the admixture. This finding was confirmed on discussion with Messrs. Ash Resources.[315] The trend that the magnitude of the water reduction due to an admixture is less with the fly ash mix than with an ordinary portland cement mix was also confirmed, although the general experience was reported to be that the orders of water reductions were closer to that shown with ordinary portland cement mixes than revealed in these results.[315]

The compressive strength results for these mixes are given in table 10.4 and figure 10.3. Looking at the early strength results it seems that there is a further confirmation of the dispersive effect of the fly ash.

Figure 10.4
Proportion of 28 day strength



In the case of the ordinary portland cement mix the admixture, probably by reducing the flocculation of cement particles, results in greater compressive strength development with an increase in compressive strength over the plain mix of about 4 MPa at 3 days. In the case of the fly asn mixes the difference between 3 day compressive strength in the fly ash mix and the mix with fly ash and admixture is much reduced with an increase of only 0,5 MPa occurring in both the Matla and Lethabo mixes. It could be argued that the reduction in the benefit offered by the admixture is as a result of the fact that the incorporation of the fly ash has already contributed to the effective deflocculation of the cement particles, leaving little room for further improvement in the compressive strength.

At 7 days the picture is a little different in the case of the fly ash mixes with a slightly larger difference between the plain fly ash mixes and those with admixture. The development in compressive strength between 7 and 28 days seems to occur at the same rate for all mixes as can be seen in figure 10.4 where the lines appear to be parallel between 7 and 28 days.

The increase in 28 day compressive strength due to the use of the admixture in the case of the ordinary portland cement mix is the greatest at about 4,5 MPa while the comparative data for the fly ash mixes varies from 2 to 3 MPa. It is also possible that the admixture has a retarding effect on the pozzolanic reaction of the fly ash leading to the small improvement in compressive strength at early ages and larger improvement at 28 days.

It is apparent that the adjustment in the cement/water ratio used for the fly ash mixes was not sufficient to compensate for the impact on the compressive strength at 28 days. In order to compare the mixes on an equal basis the strength at each age has been plotted as a percentage of the 28 day compressive strength for that mix. This information is shown in figure 10.4. It is clear from this graph that the influence of the admixture is more significant on the ordinary portland cement mix and that the admixture has relatively little impact on the compressive strength development of the fly ash mixes from either source.

This finding therefore tends to confirm that noted earlier where the effect of a water reducing admixture is greater for an ordinary portland cement mix than for fly ash mixes, i.e. that the admixture is more effective and probably more cost effective when used on the ordinary portland cement mix.

10.3 Recommendations

The tests described above can be regarded as giving an only a first impression of the possible order of effects of these rather more esoteric combinations of materials. There is certainly a need for further work on such combinations as the economic advantages offered by both techniques will provide sufficient spur to cement users to do their own experimentation.

Table 10.1

Mix proportions (in kg/m³) used to evaluate the effect of using a ternary blend of OPC, slag and fly ash on compressive strength development of concrete.

Material	Units	Mix no. 1	Mix no. 2	Mix no. 3	Mix no. 4	Mix no. 5
c/w ratio		1,7	1,8	1,8	1,9	1,9
Cement	(kg)	366	194	161	136	273
Slag	(kg)	–	194	161	136	–
Fly ash	(kg)	–	–	57	117	117
Sand	(kg)	765	733	740	729	739
Stone	(kg)	1007	1007	1007	1007	1007
Water	(l)	215	215	210	205	205
100xs/c+s+f	(%)	0	50	43	35	0
100xf/c+s+f	(%)	0	0	15	30	30
Slump (mm)		55	60	60	65	70

Table 10.2

Compressive strength results (MPa) for concrete cubes cured under standard SABS 863 curing conditions for mixes detailed in table 10.1

Age (days)	Mix No. 1	Mix No. 2	Mix No. 3	Mix No. 4	Mix No. 5
3	18,0	9,5	7,5	6,5	13,0
7	23,5	15,0	12,0	10,5	18,5
28	34,5	29,5	27,5	25,5	30,0

Table 10.3

Mix proportions (in kg/m^3) used to evaluate the influence of two sources of fly ash on the effectiveness of an admixture regarding the compressive strength development of concrete

Material	Mix No. 1	Mix No. 2	Mix No. 3	Mix No. 4	Mix No. 5	Mix No. 6
(c+f)/w	1,70	1,70	1,85	1,85	1,85	1,85
Cement	374,0	349,0	259,0	252,5	259,0	252,5
Fly ash M	–	–	111,0	108,2	–	–
Fly ash L	–	–	–	–	111,0	108,2
Sand	744,9	806,0	740,7	762,5	740,7	762,5
Stone	1007,4	1007,4	1036,6	1036,6	1036,6	1036,6
Water	220,0	205,0	200,0	195,0	200,0	195,0
Admixture (ml)	–	1047,0	–	1082,1	–	1082,1
100xf/c+f	0,0	0,0	30,0	30,0	30,0	30,0
Slump (mm)	65	65	60	65	60	70

Note: Fly ash M sourced from Matla; L was sourced from Lethabo.
MCC Multiflow 606N admixture dosed at 300ml/100kg cementitious material content of mix.

Table 10.4

Compressive strength from mixes detailed in table 10.3

Age (days)	Mix No. 1	Mix No. 2	Mix No. 3	Mix No. 4	Mix No. 5	Mix No. 6
3	18,0	22,0	14,0	14,5	13,5	14,0
7	23,5	29,5	19,0	21,0	17,5	19,5
28	35,0	39,5	31,0	33,0	28,5	31,4

CHAPTER 11

11. SUMMARY OF FINDINGS AND CONCLUSIONS

11.1 Preamble

The intention at the outset of this project was to try to contribute to a better understanding of the performance of cementitious mixes made using fly ash as part of the cementitious binder.

The work done, although providing more information on the subject, can only be regarded as providing some further pieces in the jigsaw puzzle of knowledge about the behaviour of concrete made with ordinary portland cement and other hydraulic or pozzolanic materials. This is partly due to the fact that concrete is an inherently variable material made using imperfect batching procedures from variable raw materials; in concrete technology there are few absolutes!

A further reason for not considering the results of this work to be all embracing is that the combination of materials used in the testing represents only a small fraction of the full spectrum available to the users in the target market for this study i.e. the PWV area let alone the whole of South Africa.

The findings and recommendations summarised below must be regarded in this light i.e. that this work is only part of the overall picture.

11.2 Summary of findings on fresh concrete

The conclusions reached at the end of each section covered under the category of properties of fresh concrete are summarised here. The typical trends in the behaviour of the fresh concrete that occur as the fly ash content of a mix increases from 0 % up to the highest level tested in this work of 50 % are shown in table 11.1

11.2.1 Effect on workability

The incorporation of selected or classified fly ash from either Matla or Lethabo power stations in a concrete mix will probably result in a noticeable reduction in the water requirement of the mix. The extent of the reduction has been shown to depend to some extent on the source of the ordinary portland cement used, and to a lesser extent on the source of the fly ash used.

There is no apparent link between the "water demand" of the cement and the magnitude of the water reduction on the addition of fly ash in the results of this work. The effect of the incorporation of fly ash to the mix on the overall grading of the concrete does not seem to be a likely cause of the water reduction.

The improvement (ie reduction) in the water requirement in litres per m^3 due to the incorporation of fly ash from either source can be roughly regarded as being numerically equal to half the percentage fly ash used. While both ashes actually give slightly better water reductions than this, this is an easily remembered rule of thumb for practical use on site. The magnitude of the water reductions measured in this work would seem to indicate that the South African fly ashes have a greater impact on the workability of the concrete than is the case in other countries, although this contention could only be proved in parallel trials under identical conditions.

Other authors have made mention of the improvement of the flow properties of concrete made using fly ash in the literature. As this change is a subjective rather than a measurable property little comment has been made in this work about this aspect.

11.2.2 Effect on viscosity of pastes

Results of tests done in this work have indicated a change in the viscous behaviour of paste when Matla fly ash forms a part of the mix. The shear stress developed in the co-axial cylinders viscometer with a fly ash mix is generally less than for an ordinary portland cement mix under the same conditions, although the magnitude of the change appears to be dependent on the source of the ordinary portland cement.

It is expected that fly ash from Lethabo will have a similar effect on the viscosity of pastes, although results showed that the fly ash from Duvha had a very different effect on the viscosity. Duvha fly ash, with its high proportion of non-spherical debris, is not regarded as a high quality fly ash.

The use of fly ash has been shown to reduce the inclination of a cementitious paste to become more viscous with time. At high levels of fly ash incorporation this effect is particularly marked. It is likely that this phenomenon is associated with the effective retardation of setting time that is widely reported when fly ash is used to replace some of the ordinary portland cement in a mix. This property will be covered in more detail in the following section on setting time.

The viscosity tests are a little difficult to interpret, differing as markedly as they do from the condition to which paste is exposed in concrete. While the tests may contribute to the understanding of the viscous behaviour of paste it is believed that the slump test on concrete is a more simple and more meaningful test to demonstrate the effect of the fly ash on the flow characteristics of site concrete.

11.2.3 Effect on setting time

The relative difference in setting times between ordinary portland cement and fly ash mixes have been shown to be of similar order whether it is measured in concrete or mortar. Most of the setting time determinations reported on in this work have been done on mortars as this is a less time consuming operation.

The incorporation of Matla fly ash has been shown to generally result in the retardation of both initial and final setting times of the mortar mixes. The magnitude of the retardation is inversely proportional to the cement/water ratio of the mix used as the richer the mix, the smaller the extent of the retardation. The magnitude of the retardation is proportional to the fly ash content of the mix with high fly ash contents having the greatest impact on the setting times.

This effect should however be considered in the light of the differences between the setting times of ordinary portland cements from different sources. The effect of introducing 15 % fly ash to the setting time might be similar to that which could occur when switching from one source of ordinary portland cement to another. The effect of higher fly ash contents will probably be more obvious.

In an attempt to provide an explanation for the retardation effect of Matla fly ash some further tests were done by introducing various anions and cations to mortar mixes. The most likely cause of the retardation of those tested was shown to be changes in the boron content of the fly ash, although consideration was also given to changes in alkalis, in sulphates or in phosphates.

The use of Matla fly ash has been shown to make mixes more sensitive to changes in curing temperature when setting time is being measured. Matla fly ash tends to make the impact of low temperatures on setting time worse, but can reduce the deleterious effects of high temperatures on the setting time.

In the case of Lethabo fly ash the impact on the retardation of setting times seems to be smaller than for the Matla fly ash, and the effect can be regarded as being almost insignificant. This seems to be true for the range of hot, standard and cold curing temperatures covered in the tests. The setting time of the Lethabo fly ash blends tested generally fell within the range of setting times of the ordinary portland cements tested.

11.2.4 Effect on bleeding

The Rilem test method for mortars was shown to be inappropriate for mixes with fly ash, particularly when the fly ash content is high due to the fact that the retardation of initial set caused by the use of the high fly ash content has the effect of allowing bleeding to continue beyond the normal duration of the Rilem test method.

As mentioned in the preceding paragraphs the incorporation of fly ash tends to increase the setting time of a cementitious mix to some extent. This then allows a longer period during which settlement and bleeding can occur.

The bleed rate has been shown to be similar to that for an opc mix with the same cement/water ratio when fly ash is used. A fly ash mix with the same 28 day compressive strength will also probably have a similar bleed rate, but, as the time available over which the bleeding can occur is longer, the total bleed volume is likely to be greater than, or similar to that of a similar ordinary portland cement mix.

11.2.5 Effect on heat of hydration

The use of fly ash in concrete has been shown to reduce the peak temperature reached relative to an ordinary portland cement concrete mix having a similar 28 day target strength, and to show an initial greater reduction in the rate of heat developed. The compressive strength development has been shown not to be deleteriously affected by the lower temperatures that occur during the curing period; in fact the development of compressive strength under the raised temperatures that occur under temperature matched curing conditions in the adiabatic calorimeter is better than that for the ordinary portland cement mix exposed to even higher temperatures.

A modification to the maturity formula was attempted to account for the benefits shown in the compressive strength development. Much more work is required to evaluate this aspect fully, and to get a better understanding of the behaviour of fly ash mixes under moderately high curing temperatures.

11.3 Summary of findings on hardened concrete

The conclusions reached at the end of each section covered under the category of properties of hardened concrete are summarised here. The typical trends in the behaviour of hardened concrete that occur as the fly ash content of a mix increases from 0 % up to the highest level tested in this work of 50 % are shown in table 11.2

11.3.1 Effect on compressive strength; standard curing

Some discussion was required to define the different methods of proportioning fly ash mixes and the terminology used. The method recommended after this study was the partial replacement method although the method does not, in fact, consider replacement of sand in the mix.

It has been shown that the use of Matla fly ash in direct replacement results in a drop in the compressive strength of the concrete throughout the range of ages to 28 days. The difference between the OPC mix and the fly ash mix increases as the fly ash content increases. This difference is small for fly ash contents up to 15 %. The difference has been shown to decrease as the target strength increases, i.e. as the cementitious/water ratio increases.

Direct replacement mixes may eventually reach parity with a comparative ordinary portland cement mix but the age at which this occurs increases as the fly ash content increases. With high fly ash contents parity may only be reached at ages greater than 120 days.

Using a partial replacement method of proportioning mixes, and taking into account the modifications in the normal PCI mix design method i.e. an increased stone content, a water reduction and an increase in the cementitious/water ratio it has been shown that generally a fly ash mix will have a slightly greater cementitious content than the control ordinary portland cement mix. The increase in total cementitious content for the fly ash mixes will be greater with higher fly ash contents. The difference may be insignificant in the case of low fly ash content mixes; such mixes might permit direct substitution of the fly ash blend cement for ordinary portland cement without obvious performance differences being apparent on site.

The Lethabo fly ash blends were generally also shown to perform to the levels indicated by the curves in figure 11.4 in Fulton[286], although one of the opc sources used in the investigation did not perform to these expectations.

The rate of compressive strength development beyond 28 days has been shown to be greater for the fly ash mixes than is the case for ordinary portland cement mixes. It could be suggested that this could be used to reduce the cementitious content of a mix if early strength was not a requirement.

11.3.2 Effect on compressive strength; site curing

Site curing seldom approaches the "ideal" laboratory conditions to which cubes should be exposed. Some work has been done to show the impact of poor curing on the fly ash mixes. The effect of the poor curing on the compressive strength has been shown not to be more significant on the fly ash mixes than is the case for the ordinary portland cement mix; this may be due to the fact that, in accordance with the requirements of SABS Method 865, the outer 50 mm of concrete (i.e. the more exposed portion) was trimmed off before testing.

11.3.3 Effect on compressive strength; temperature effects

The compressive strength development of cubes made from fly ash mixes has been shown to suffer a greater impact from exposure to low temperatures at early ages. Exposure to moderately high temperatures appears not to benefit the fly ash cubes as much as ordinary portland cement cubes.

Under temperature matched curing conditions it seems that the fly ash mixes show greater benefit to the high temperatures (+ 30 °C) that occurred in the adiabatic calorimeter i.e. a greater sensitivity to high curing temperatures.

In summary it seems that the fly ash mixes show a greater degree of temperature sensitivity than is the case with OPC.

11.3.4 Effect on flexural strength

The effect of fly ash on the flexural strength of concrete has been shown to be relatively insignificant in the range of flexural strengths that are important for paving quality concrete. The fact that the flexural strength of a fly ash concrete is greater at ages above 28 days than is the case for OPC concrete is not regarded as an opportunity for savings to be effected in the cementitious content of fly ash concretes as this presumes exposure of the pavement to "ideal" curing.

11.3.5 Effect on elastic modulus

The results have shown that with the combinations of materials tested there is little difference between the elastic modulus of OPC and fly ash concretes, nor is there any significant difference between their ratios of elastic modulus to compressive strength.

11.3.6 Effect on movement properties

The effect that fly ash has on drying shrinkage is small relative to the differences that occur between the drying shrinkages of similar strength concretes made using different sources of ordinary portland cement. The impact of fly ash on drying shrinkage of properly proportioned concretes can therefore be regarded as not being significant.

The use of fly ash has been shown to reduce the specific creep of concrete relative to an ordinary portland cement concr[illegible] with similar compressive strength at 28 days. There is some indication that the use [illegible] fly ash makes both the shrinkage and creep of concrete more sensitive to poor curing although more information is required on this aspect.

11.4 Durability aspects

The long term ability of the concrete to withstand the ravages of the environment to which it is exposed is mainly the concern of the owner of the concrete article or structure. The following paragraphs cover the effect that the use of fly ash has on the durability of concrete.

11.4.1 Effect on permeability

The DIN water absorbtion test indicates that under the "ideal" standard curing conditions required in the test the permeability of concrete decreases as the fly ash content increases.

Initial attempts to evaluate the effect of poor curing on the skin permeability were inconclusive. Subsequent modifications of the pressure regime to which the specimens were exposed showed that with appropriate mix proportioning methods the impact of poor curing on fly ash concretes appear to be no more significant than is the case for ordinary portland cement concretes. A[illegible] the depths of penetration recorded in the standard and modified DIN 1048 permeability tests were substantial this should not be regarded as an indication of equivalent concrete "skin" durability.

11.4.2 Effect on abrasion resistance

In cube specimens exposed to standard curing the results of wire brush abrasion tests have shown that the use of Matla fly ash enhances the abrasion resistance of concrete. Gordon has indicated the contrary for Lethabo fly ash mixes.

Under poor "site curing" conditions it appears that the use of both Matla and Lethabo fly ash concrete mixes exhibit a greater sensitivity to poor curing than is the case with ordinary portland cement concrete mixes. This would probably mean a need for greater emphasis on proper curing for surfaces exposed to abrasion when fly ash is used in the concrete mix.

11.4.3 Effect on carbonation

The results have shown that the use of fly ash increases the sensitivity of a concrete to poor curing and allows a faster penetration of the carbonation front into the concrete than is the case with ordinary portland cement concretes. The fact that the fly ash concrete might enjoy a lower permeability of the heart concrete seems to result in a greater slowing of the rate of penetration than is the case with ordinary portland cement concrete; the durability of the fly ash concrete under conditions favourable to steel corrosion might therefore not be impaired when compared against the ordinary portland cement mix.

11.4.4 Effect on alkali silica reactivity

The results of an accelerated test for alkali silica reactivity have shown that the use of even low levels of fly ash incorporation have a significant effect on the expansion resulting from a reactive aggregate being exposed to an alkaline environment.

The accelerated test has been shown by the CSIR to be capable of predicting the long term behaviour of structural concrete made with the same materials; their current recommended procedures for preventing deleterious expansions resulting from the presence of an reactive aggregate type include the incorporation of at least 20 % of fly ash in the concrete.

11.5 Effect on other miscellaneous properties

Once further cementitious extenders or admixtures are introduced to the equation the number of possible permutations becomes prohibitively large and each aspect could and should form a complete study on its own. The work done here does however provide some indication of possible trends.

11.5.1 Effect of ternary blends

The indication given by the series of tests carried out here is that the introduction of slag and fly ash to a mix results in a further reduction in early compressive strengths.

11.5.2 Effect on admixtures

In the series of tests performed for this work the results have been interpreted as indicating that the fly ash performs in a similar way to a water reducing admixture by dispersing the ordinary portland cement particles more effectively through the mix. This could explain the water reducing effect described in paragraph 11.2.1.

It appears, on the basis of the small number of tests done here, that the use of chemical admixtures might become less economically viable if used in a mix with fly ash as the fly ash seems to give most of the available water reduction. This might be because there is little residual dispersion after the fly ash has had its effect on the water reduction. More work should be done to evaluate this effect with a wider spectrum of materials.

The difference in carbon content as expressed by the Loss On Ignition (LOI) of the two sources of fly ash (a characteristic widely reported to influence the dosage requirement of admixtures) does not seem to result in any significant difference in the dosage requirement of the admixture used. The difference between the LOI values for the two fly ashes is therefore believed to be too small to result in such an effect.

11.6 Conclusion

Fly ash concrete, when proportioned using an appropriate method, should provide fresh concrete properties that are a little different to those of ordinary portland cement concrete. Knowledge of these differences will allow contractors to take advantage of the economies offered by the use of fly ash as a partial replacement for portland cement. The hardened concrete properties of fly ash mixes, apart from a possible greater sensitivity to temperature and curing effects, will generally be comparable with those of ordinary portland cement concrete. 30 % fly ash would be an economic choice here.

Where a fly ash blended cement is likely to be used as a direct replacement for ordinary portland cement without the desirable adjustments being made to the mix proportioning, the effects of the fly ash will probably be more apparent, although these less sophisticated users are less likely to be able to perceive the differences. The direct replacement use will probably succeed in a majority of cases although there will be some classes of users that will be disadvantaged by this practice. For this class of users a blend of maximum 15 % fly ash is probably more appropriate; such a blend will offer many of the advantages without accentuating the disadvantages.

As time passes the exposure that the less sophisticated users get to the use of 30 % fly ash blends by others will result in the expectations of performance being revised. For a growing proportion of users the performance of the 30 % fly ash cement will become the norm, and the switch to this type of cement will become easier.

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Table 11.1

Summary of the influence of fly ash on the properties of fresh mortar or concrete designed to a given 28 day compressive strength and workability as inferred from the tests done in other chapters

Property	Fly ash content of mix (%)			
	0	15	30	50
Water requirement	control	circa 5l less than control	circa 15l less than control	circa 25l less than control
Setting time	control	slightly longer than control	circa 1–3h longer than control	up to 8h longer than control
Bleed rate	control	similar to control	similar to control	similar to control
Bleed volume	control	similar to control	similar to control	similar to control
Heat of hydration	control	similar to control	lower than control	much lower than control

Table 11.2

Summary of the influence of fly ash on the properties of hardened mortar or concrete designed to a given 28 day compressive strength and workability as inferred from the tests done in other chapters

Property	Fly ash content of mix (%)			
	0	15	30	50
Compressive strength	control	similar to control	lower up to 7 days, higher after 28 days	much lower at 7 days, better after 28 days
Flexural strength	control	similar to control	ratio of flexural to compressive better than control	ratio of flexural to compressive better than control
Elastic modulus	control	similar to control	similar to control	similar to control
Shrinkage	control	similar to control	similar to control	similar to control
Creep	control	slightly less than control	less than control	less than control
Permeability	control	slightly less than control	less than control	less than control
Abrasion resistance	control	similar to control	better than control if well cured, poorer if not cured	better than control if well cured, poorer if not cured
Carbonation	control	similar to control	deeper if poorly cured	deeper if poorly cured

APPENDIX A

Computer programme for the control and monitoring of the adiabatic calorimeter apparatus assembled for this study

```
{$R+}   {Range checking on}
{$B+}   {Boolean complete evaluation on}
{$S+}   {Stack checking on}
{$I+}   {I/O checking on}
{$N-}   {no 8087}

program calorimeter;

        {--------------------------------}
        {            by                  }
        {        .G.J.Gibbon             }
        {    Faculty of Engineering      }
        {       Wits University          }
        {--------------------------------}

Uses
  Crt,
  Dos,
  Printer.
  {Graph.}
  gdriver.
  gkernel.
  gshell.
  gwindow.
  sml4gtb:

const
    ADlsb     = $700; {lsb from A/D Converter}
    ADmsb     = $701; {msb from A/D Converter}
    ADcon     = $702; {Control and Multiplexe. Selection}
    ADset     = $703; {Control Word for A/D PPI}
    portA     = $708; {Port A}
    portB     = $709; {Port B}
    portC     = $70A; {Port C}
    portset   = $70B; {Control Word For PPI}

var
   cement,extender,sand1,sand2,stone1,stone2,
   admixture,file_body,file_name:screen_message;
   test_day,hour,min,sec,sec100,year,month,day,dayofweek:word;
   s_hour,s_min,s_sec,s_sec100,s_year,s_month,s_day,s_dow:word;
   X_last,temp,cem,ext,water,admix:real;
   lim_large,lim_small,san,ston:array[1..2] of real;
   data,last_data:array[0..2] of real;
   data_file:text;
   data_drive:string;
   responce:char;
   port_a:byte;
```

```
  option,no_of_options:integer;
  first_plot,test_cont,power_off,file_there:boolean;
  ExitSave:pointer;


{--------------------------------------------------------------------
-------}

procedure open_file;{opens data file and reads parameters}

var
  id_status,file_status,file_ok:boolean;
  IO_error,I:integer;

begin
    file_status:=true;
    while file_status do
    begin
        file_ok:=false;
        while not file_ok do
        begin
            ps_wfst('ENTER FILE NAME ',file_name);
            if length(file_name)<9 then file_ok:=true;
            if not file_ok then
            begin
                es_write('Name must be less than 9 characters');
            end;
        end;
        ps_clear;es_clear;
        file_body:=data_drive+file_name;
        file_name:=data_drive+file_name+'.txt';
        file_check(file_name,file_status);
        if file_status then
        begin
             es_write('FILE ALREADY PRESENT');
             responce:=' ';
             while not (responce in ['y','Y','n','N']) do
                   ps_wfsy('DESTROY OLD FILE (Y/N)',responce);
             ps_clear;es_clear;
             if responce in ['y','Y'] then
                  file_status:=false;
        end;
        if not file_status then
        begin
            assign(data_file,file_name); {checks for valid file name}
            {$I-}
            rewrite(data_file); {opens data file}
            {$I+}
            IO_error:=IOResult;
```

```
            if IO_error=2 th n
            begin
                file_status:=true;
                es_write('Illegal Charaters used in File Name');
            end;
            if (IO_error<>0) and (IO_error<>2) then
              rewrite(data_file); {opens data file to determine error}
         end;
     end;
end;
{-----------------------------------------------------------------------
-------}
procedure checklist;
begin
     ps_wfsy('IS PRINTER READY ',responce);
     ps_wfsy('ARE PUMP/STIRRER OPERATING ',responce);
     ps_wfsy('ARE THERMOCOUPLES CONNECTED ',responce);
     ps_wfsy('IS THERE POWER TO THE HEATERS ',responce);
     ps_wfsy('IS THERE SUFFICIENT WATER IN TANKS ',responce);
     ps_clear;
end;

{-----------------------------------------------------------------------
-------}
procedure input_details;
begin
     responce:='n';
     repeat
          scr_format;
          ps_wfst('CEMENT TYPE ',cement);
          ps_wfst('EXTENDER TYPE ',extender);
          ps_wfst('SAND TYPE 1 ',sand1);
          ps_wfst('SAND TYPE 2 ',sand2);
          ps_wfst('STONE TYPE 1 ',stone1);
          ps_wfst('STONE TYPE 2 ',stone2);
          ps_wfst('ADMIXTURE TYPE  ',admixture);
          ps_wfr('CEMENT CONTENT (kg/cubm) ',cem);
          ps_wfr('EXTENDER CONTENT (kg/cubm) ',ext);
          ps_wfr('SAND 1 CONTENT (kg/cubm) ',san[1]);
          ps_wfr('SAND 2 CONTENT (kg/cubm) ',san[2]);
          ps_wfr('STONE 1 CONTENT (kg/cubm) ',ston[1]);
          ps_wfr('STONE 2 CONTENT (kg/cubm) ',ston[2]);
          ps_wfr('WATER CONTENT (l/cubm) ',water);
          ps_wfr('ADMIXTURE CONTENT (l/cubm) ',admix);
          ps_wfr('SAMPLE TEMPERATURE ('+chr(248)+'C) ',temp);
          GetTime(hour,min,sec,sec100);
          GetDate(year,month,day,dayofweek);
          open_file;
          writeln(data_file,'CEMENT TYPE     : ',cement);
```

```
      writeln(data_file,'EXTENDER TYPE  : ',extender);
      writeln(data_file,'SAND TYPE 1    : ',sand1);
      writeln(data_file,'SAND TYPE 2    : ',sand2);
      writeln(data_file,'STONE TYPE 1   : ',stone1);
      writeln(data_file,'STONE TYPE 2   : ',stone2);
      writeln(data_file,'ADMIXTURE TYPE : ',admixture);
      writeln(data_file);
      writeln(data_file,'CEMENT CONTENT      :   ',cem:3:0,' (kg/cubm) ');
      writeln(data_file,'EXTENDER CONTENT    :   ',ext:3:0,' (kg/cubm) ');
      writeln(data_file,'SAND 1 CONTENT      :  ',san[1]:4:0,' (kg/cubm) ');
      writeln(data_file,'SAND 2 CONTENT      :  ',san[2]:4:0,' (kg/cubm) ');
      writeln(data_file,'STONE 1 CONTENT     :  ',ston[1]:4:0,' (kg/cubm) ');
      writeln(data_file,'STONE 2 CONTENT     :  ',ston[2]:4:0,' (kg/cubm) ');
      writeln(data_file,'WATER CONTENT       :   ',water:3:0,' (l/cubm) ');
      writeln(data_file,'ADMIXTURE CONTENT : ',admix:6:2,' (l/cubm) ');
      writeln(data_file,'SAMPLE TEMPERATURE :  ',temp:4:1,' (',chr(248),'C) ');
      writeln(data_file);
      writeln(data_file,day:2,'-',month:2,'-',year:4);
      writeln(data_file);
      close(data_file);
      ClearScreen;
      home;
      ms_load(file_body);
      responce:='n';
      ps_wfsy('CORRECT (Y/N)',responce);
   until (responce='y') or (responce='Y');
   scr_format;
end;
{-----------------------------------------------------------------------
------}
procedure draw_axis;

var
  I,J:integer;

begin
   ClearScreen;
   DrawBorder;
   DefineWorld(1,0,100,14.0);{x=14days y=0-100 deg C}
   SelectWorld(1);
   for J:= 1 to 2 do
   begin
      SelectScreen(J);
      SelectWindow(J);
      if J=2 then
      begin
         SetLineStyle(0);
         DrawBorder;
      end;
```

```
        SetLineStyle(8);
        for I:=1 to 13 do
           DrawLine(I,100,I,0);
        for I:=1 to 9 do
           DrawLine(0,I*10,14,I*10);
        DrawTextW(0.2,2,1,'0');
        DrawTextW(0.2,22,1,'20');
        DrawTextW(0.2,42,1,'40');
        DrawTextW(0.2,62,1,'60');
        DrawTextW(0.2,82,1,'80');
        DrawTextW(0.2,95,1,'deg C');
        DrawTextW(1.2,2,1,'1');
        DrawTextW(2.2,2,1,'2');
        DrawTextW(3.2,2,1,'3');
        DrawTextW(4.2,2,1,'4');
        DrawTextW(5.2,2,1,'5');
        DrawTextW(6.2,2,1,'6');
        DrawTextW(7.2,2,1,'7');
        DrawTextW(8.2,2,1,'8');
        DrawTextW(9.2,2,1,'9');
        DrawTextW(10.2,2,1,'10');
        DrawTextW(11.2,2,1,'11');
        DrawTextW(12.2,2,1,'12');
        DrawTextW(13.2,2,1,'13 Days');
    end;
    SetLineStyle(0);
    SelectScreen(1);
end;

{--------------------------------------------------------------------------------
-------}
procedure plot_data(initial_plot:boolean);

var
  X:real;
  I,J:integer;

begin
    X:=test_day+(((min/60)+hour)/24);
    for I:=1 to 2 do
    begin
        SelectScreen(I);
        SelectWindow(I);
        for J:=0 to 2 do
            if initial_plot then
               DrawPoint(X,data[J])
            else
               DrawLine(X_last,last_data[J],X,data[J]);
    end;
```

```
    X_last:=X;
    SelectScreen(1);
end;
{------------------------------------------------------------------
--------}
procedure store_data;

var
   I:integer;

begin
     Assign(data_file,file_name);
     Append(data_file);
     write(data_file,test_day:4,hour:4,min:4);
     for I:=0 to 2 do
         write(data_file,data[I]:6:1);
     writeln(data_file);
     close(data_file);
end;
{------------------------------------------------------------------
--------}
procedure power_check;

var
   present,power:boolean;
   power_file:text;
   failure_file:text;

begin
     assign(power_file,'power.lst');
     assign(failure_file,'power.dat');
     power:= (PORT[portB] and 1)=1;
     if (not power) and (not power_off) then
     begin
          power_off:=true;
          set_cp(23,2);
          write('********** POWER FAILURE **********');
          rewrite(power_file);
          writeln(power_file,file_name);
          writeln(power_file,s_year:6,s_month:4,s_day:4,s_dow:4);
          writeln(power_file,s_hour:4,s_min:4,s_sec:4,s_sec100:4);
          close(power_file);
          file_check('power.dat',present);
          if not present then
             rewrite(failure_file)
          else append(failure_file);
          writeln(failure_file,test_day:4,' Days',hour:3,' Hours',min:3,' Mins');
          close(failure_file);
     end;
```

```
    if (power) and (power_off) then
    begin
        Erase(power_file);
        power_off:=false;
        set_cp(23,2);
        write('                              ');
    end;
end;
{--------------------------------------------------------------------
-------}
procedure print_test;

var
  I:integer;
  message:string;

begin
    set_cp(21,2);
    clr_line;
    ps_wfsy('**** Print the Test (Y/N) ',responce);
    ps_clear;
    if (responce='y') or (responce='Y') then
    begin
        Assign(data_file,file_name);
        Reset(data_file);
        writeln(lst,'Data Filed in ',file_name);
        for I:=1 to 20 do
        begin
            readln(data_file,message);
            writeln(lst,message);
        end;
        writeln(lst);writeln(lst);
        SwapScreen;
        HardCopy(false,1);
        SwapScreen;
        writeln(lst,chr($C));
        ps_wfsy('** Print the Readings (Y/N) ',responce);
        ps_clear;
        if (responce='y') or (responce='Y') then
        begin
            Reset(data_file);
            repeat
                readln(data_file,message);
                writeln(lst,message);
            until eof(data_file);
            writeln(lst,chr($C));
        end;
        close(data_file);
    end;
```

```
end;
{-------------------------------------------------------------------------
-------}
procedure limit_set;{sets temp limits for both baths}

var
   file_status:boolean;
   cal_file:text;
   l:integer;
   resp:char;

begin
     scr_format;
     gotoxy(4,11);
     writeln('DATA DRIVE:- ',data_drive);
     gotoxy(4,12);
     writeln('SWITCH ON LIMIT  (SMALL BATH):- ',lim_small[1]:3:1,chr(248),'C');
     gotoxy(4,13);
     writeln('SWITCH OFF LIMIT (SMALL BATH):- ',lim_small[2]:3:1,chr(248),'C');
     gotoxy(4,14);
     writeln('SWITCH ON LIMIT  (LARGE BATH):- ',lim_large[1]:3:1,chr(248),'C');
     gotoxy(4,15);
     writeln('SWITCH OFF LIMIT (LARGE BATH):- ',lim_large[2]:3:1,chr(248),'C');
     repeat
           ps_wfsy('Change the Settings (Y/N) ',resp);
     until resp in ['Y','y','N','n'];
     ps_clear;
     if resp in ['y','Y'] then
     begin
         ms_menu('limit',no_of_options);
         gotoxy(53,4);
         writeln('[',data_drive,']');
         gotoxy(53,5);
         writeln('[',lim_small[1]:3:1,chr(248),'C]');
         gotoxy(53,6);
         writeln('[',lim_small[2]:3:1,chr(248),'C]');
         gotoxy(53,7);
         writeln('[',lim_large[1]:3:1,chr(248),'C]');
         gotoxy(53,8);
         writeln('[',lim_large[2]:3:1,chr(248),'C]');
     end;
     while resp in ['y','Y'] do
     begin
         ms_options(option,no_of_options);
         case option of
             0 : begin
                     if data_drive='A:' then
                         data_drive:='B:'
                     else
```

```
        begin
           if data_drive='B:' then
             data_drive:='C:'
           else
           if data_drive='C:' then
             data_drive:='A:';
        end;
        gotoxy(53,4);
        clr_line;
        writeln('[',data_drive,']');
     end;
  1 : begin
        ps_wfr('ENTER SWITCH ON LIMIT (SMALL BATH)',lim_small[1]);
        ps_clear;
        gotoxy(53,5);
        clr_line;
        writeln('[',lim_small[1]:3:1,chr(248),'C]');
     end;
  2 : begin
        ps_wfr('ENTER SWITCH OFF LIMIT (SMALL BATH)',lim_small[2]);
        ps_clear;
        gotoxy(53,6);
        clr_line;
        writeln('[',lim_small[2]:3:1,chr(248),'C]');
     end;
  3 : begin
        ps_wfr('ENTER SWITCH ON LIMIT (LARGE BATH)',lim_large[1]);
        ps_clear;
        gotoxy(53,7);
        clr_line;
        writeln('[',lim_large[1]:3:1,chr(248),'C]');
     end;
  4 : begin
        ps_wfr('ENTER SWITCH OFF LIMIT (LARGE BATH)',lim_large[2]);
        ps_clear;
        gotoxy(53,8);
        clr_line;
        writeln('[',lim_large[2]:3:1,chr(248),'C]');
     end;
  5 : begin
        assign(cal_file,'limit.cal');
        rewrite(cal_file);
        writeln(cal_file,data_drive);
        writeln(cal_file,lim_small[1]);
        writeln(cal_file,lim_small[2]);
        writeln(cal_file,lim_large[1]);
        writeln(cal_file,lim_large[2]);
        resp:='N';
        close(cal_file);
```

```
                end;
            end;{case}
            fs_clear;
        end;{while}
        ms_clear;
end;
{------------------------------------------------------------------------
------}
procedure data_capture;

var
    last_hour:word;
    I,J:integer;
    complete:boolean;
    resp:char;

procedure switch_off(heater:integer);
begin
        if heater=1 then
        begin
            if (port_a and 1)=0 then
            begin
                port_a:=port_a+1;
                PORT[portA]:=port_a;
            end;
        end else
        begin
            if (port_a and 2)=0 then
            begin
                port_a:=port_a+2;
                PORT[portA]:=port_a;
            end;
        end;
end;

procedure switch_on(heater:integer);
begin
        if heater=1 then
        begin
            if (port_a and 1)<>0 then
            begin
                port_a:=port_a-1;
                PORT[portA]:=port_a;
            end;
        end else
        begin
            if (port_a and 2)<>0 then
            begin
                port_a:=port_a-2;
```

```
            PORT[portA]:=port_a;
         end
      end;
   end;

FUNCTION ADSAMPLE (channel:INTEGER): INTEGER;
VAR
  I:INTEGER;

BEGIN
        PORT [ADcon] := (channel SHL 4) + 2; { channel selection and   }
                                   {clear software-clock bit }
        PORT [ADcon] := (channel SHL 4) + 3; {channel selection and    }
                                {setting of software-clock bit }
        FOR I:=1 TO 6 DO
          BEGIN                 {loop until end of conversion }
          END;

        ADSAMPLE :=((PORT[ADmsb] AND $0F) SHL 8) + PORT[ADlsb];
END;


begin
     test_day:=0;
     last_data[0]:=0;
     last_hour:=0;
     complete:=false;
     first_plot:=true;
     repeat
          repeat
               power_check;
               for I:=0 to 2 do
               begin
                   data[I]:=0;
                   for J:=1 to 100 do
                       data[I]:=data[I]+adsample(I);
                   data[I]:=data[I]/100;
                   data[I]:=data[I]*100/4096;
               end;
               set_cp(20,2);
               write('Reference   :  ',data[0]:5:1,'   ',chr(248),'C                    LAST
RECORD',last_data[0]:5:1,' ',chr(248),'C');
               set_cp(21,2);
               write('Small Bath: ',data[1]:5:1,' ',chr(248),'C');
               if data[1]>data[0]+1 then
                 write('  ',chr(24));
               if data[1]<data[0]-1 then
                 write('  ',chr(25));
               if (data[1]<=data[0]+1) and (data[1]>=data[0]-1) then
```

```
            PORT[portA]:=port_a;
        end
    end;
end;

FUNCTION ADSAMPLE (channel:INTEGER): INTEGER;
VAR
  I:INTEGER;

BEGIN
       PORT [ADcon] := (channel SHL 4) + 2; { channel selection and  }
                                   {clear software-clock bit }
       PORT [ADcon] := (channel SHL 4) + 3; {channel selection and   }
                               {setting of software-clock bit }
       FOR I:=1 TO 6 DO
         BEGIN                  {loop until end of conversion }
         END;

       ADSAMPLE :=((PORT[ADmsb] AND $0F) SHL 8) + PORT[ADlsb];
END;


begin
    test_day:=0;
    last_data[0]:=0;
    last_hour:=0;
    complete:=false;
    first_plot:=true;
    repeat
         repeat
              power_check;
              for I:=0 to 2 do
              begin
                  data[I]:=0;
                  for J:=1 to 100 do
                      data[I]:=data[I]+adsample(I);
                  data[I]:=data[I]/100;
                  data[I]:=data[I]*100/4096;
              end;
              set_cp(20,2);
              write('Reference   :  ',data[0]:5:1,'  ',chr(248),'C                    LAST
RECORD',last_data[0]:5:1,' ',chr(248),'C');
              set_cp(21,2);
              write('Small Bath: ',data[1]:5:1,' ',chr(248),'C');
              if data[1]>data[0]+1 then
                write('  ',chr(24));
              if data[1]<data[0]-1 then
                write('  ',chr(25));
              if (data[1]<=data[0]+1) and (data[1]>=data[0]-1) then
```

```
          write('  ',chr(18));
        if (port_a and 1)=0 then
          write('     HEATER ON ')
        else
          write('     HEATER OFF');
        set_cp(22,2);
        write('Large Bath: ',data[2]:5:1,' ',chr(248),'C');
        if data[2]>data[0]+1 then
          write('  ',chr(24));
        if data[2]<data[0]-1 then
          write('  ',chr(25));
        if (data[2]<=data[0]+1) and (data[2]>=data[0]-1) then
          write('  ',chr(18));
        if (port_a and 2)=0 then
          write('     HEATER ON ')
        else
          write('     HEATER OFF');
        if data[0]>data[1]+lim_small[1] then switch_on(1);
        if data[0]<data[1]-lim_small[2] then switch_off(1);
        if data[0]>data[2]+lim_large[1] then switch_on(2);
        if data[0]<data[2]-lim_large[2] then switch_off(2);
        GetTime(hour,min,sec,sec100);
        if (hour=0) and (last_hour=23) then test_day:=test_day+1;
        set_cp(24,2);
        write('Elapsed Time:',test_day:3,' Days,',hour:3,' Hours,',min:3,' Minutes');
        if (abs(data[0]-last_data[0])>1)
          or (hour>last_hour)
          or ((hour=0) and (last_hour=23)) then
        begin
            bleat;
            plot_data(first_plot);
            first_plot:=false;
            store_data;
            for I:=0 to 2 do
                last_data[I]:=data[I];
        end;
        last_hour:=hour;
until (keypressed) or (test_day>14);
bleat;
if keypressed then
begin
    resp:=ReadKey;
    if resp=#0 then
    begin
        resp:=ReadKey;
        if resp=#25 then print_test;
        if resp=#16 then complete:=true;
        if resp=#38 then
        begin
```

```
                    SwapScreen;
                    StoreWindow(2);
                    limit_set;
                    RestoreWindow(2,0,0);
                    SwapScreen;
                end;
            end;
        end else complete:=true;
    until complete;
    PORT[portA] := 3;        {set heaters off}
    port_a:=3;
    set_cp(20.2);
    clr_line;
    set_cp(21.2);
    clr_line;
    set_cp(22.2);
    clr_line;
end;{capture data}
{------------------------------------------------------------------------
--------}

procedure close_down;

var
  message:string;

begin
    scr_format;
    ps_wfsy('SWITCH OFF THE PUMP/STIRRER ',responce);
    ps_wfsy('SWITCH OFF THE HEATERS ',responce);
    ps_clear;
    file_check('power.dat',file_there);
    if file_there then
    begin
        writeln(lst,'POWER FAILURE/S AT THE FOLLOWING TIME/S :-');
        writeln(lst);
        assign(data_file,'power.dat');
        reset(data_file);
        repeat
            readln(data_file,message);
            writeln(lst,message);
        until eof(data_file);
        writeln(lst,chr($C));
    end;
end;
{------------------------------------------------------------------------
--------}
procedure plot_old_data;
```

```
var
  J,I,K:integer;
  message:string;
  ok:boolean;


function open_old_file:boolean;{opens data file and reads parameters}

var
  id_status,file_status,file_ok:boolean;
  I:integer;

begin
    file_status:=true;
    file_ok:=false;
    es_clear;
    if not test_cont then
    begin
        while not file_ok do
        begin
            ps_wfst('ENTER FILE NAME ',file_name);
            if length(file_name)<9 then file_ok:=true;
            if not file_ok then
            begin
                es_write('Name must be less than 9 characters');
            end;
        end;
        ps_clear;es_clear;
        file_name:=data_drive+file_name+'.txt';
    end else
    begin
        assign(data_file,'power.tst');
        reset(data_file);
        readln(data_file,file_name);
        readln(data_file,s_year,s_month,s_day,s_dow);
        readln(data_file,s_hour,s_min,s_sec,s_sec100);
        close(data_file);
    end;
    file_check(file_name,file_status);
    if file_status then
    begin
       assign(data_file,file_name);
       reset(data_file); {opens data file}
       open_old_file:=true;
    end else
    begin
        es_write('FILE NOT ON DISK !!!');
        delay(2000);
        open_old_file:=false;
```

```
        end;
    end;

    begin
        ok:=open_old_file;
        first_plot:=true;
        if ok then
        begin
            for I:=1 to 20 do
                readln(data_file,message);
            draw_axis;
            repeat
                read(data_file,test_day,hour,min);
                for J:=0 to 2 do
                    read(data_file,data[J]);
                readln(data_file);
                plot_data(first_plot);
                first_plot:=false;
                for K:=0 to 2 do
                    last_data[K]:=data[K];
            until eof(data_file);
            close(data_file);
            if not test_cont then
                print_test
        end;
    end;
{--------------------------------------------------------------------------
-------}
procedure re_start;
var
   X:real;
   hour_calc:integer;

begin
    plot_old_data;
    GetTime(hour,min,sec,sec100);
    GetDate(year,month,day,dayofweek);
    hour_calc:=hour;

    if min<s_min then
    begin
        min:=min+60;
        hour_calc:=hour_calc-1;
    end;
    min:=min-s_min;

    if hour_calc<s_hour then
    begin
        hour_calc:=hour_calc+24;
```

```
        day:=day-1;
    end;
    hour:=hour_calc-s_hour;

    if day<s_day then
    begin
        if s_month in [1,3,5,7,8,10,12] then
           day:=day+31;
        if s_month in [4,6,9,11] then
           day:=day+30;
        if s_month=2 then
        begin
            if s_year=1992 then
               day:=day+29
            else
               day:=day+28;
        end;
    end;
    day:=day-s_day;
    SetTime(hour,min,0,0);
    test_day:=day;
    power_off:=false;
    data_capture;
    test_cont:=false;
end;
{-----------------------------------------------------------------}
{$F+}
procedure Exit;{Controls termination process if there is an error}
{$F-}
begin
    PORT[portA] := 3;        {set heaters off}
    port_a:=3;
    LeaveGraphic;
    ExitProc:=ExitSave;
end;
{------------------------------------------------------------------
------}
procedure load_defaults;{loads values from default file}

var
   file_status:boolean;
   cal_file:text;

begin
    file_check('limit.cal',file_status);
    if not file_status then
    begin
         assign(cal_file,'limit.cal');
         rewrite(cal_file);
```

```
        data_drive:='B:';
        lim_sm     ':=0.2;{sets on then off limits}
        lim_sma  [2]:=0.5;
        lim_large[1]:=0.2;{sets on then off limits}
        lim_large[2]:=0.5;
    end
    else
    begin
        assign(cal_file,'limit.cal');
        reset(cal_file);
        readln(cal_file,data_drive);
        readln(cal_file,lim_small[1]);
        readln(cal_file,lim_small[2]);
        readln(cal_file,lim_large[1]);
        readln(cal_file,lim_large[2]);
    end;
    close(cal_file);
end;

{------------------------------------------------------------------------
-------}

begin
    PORT[ADset] := $92;      {Initialization of A/D  PPI}
    PORT[portset] := $8B;     {set parrallel port A-out,B&C-in)}
    PORT[portA] := 3;        {set heaters off}
    ExitSave:=ExitProc;
    ExitProc:=@Exit;
    load_defaults;
    port_a:=3;
    power_off:=false;
    InitGraphic;
    SelectScreen(2);{enlarged screen}
    DefineWindow(2,0,0,XMaxGlb,YMaxGlb);{graphic screen[main screen]}
    file_check('power.tst',test_cont);{check if rebooted after power failure}
    repeat
        SelectScreen(2);
        ClearScreen;
        SelectScreen(1);
        ClearScreen;
        scr_format;
        if not test_cont then
        begin
            ms_menu('main',no_of_options);
            ms_options(option,no_of_options);
            ms_clear;
        end else
          option:=0;
        case option of
```

```
        0: begin
              if not test_cont then
              begin
                   file_check('power.dat',file_there);
                   if file_there then
                   begin
                        ps_wfsy('DELETE   POWER   FAILURE   DATA   FILE
(Y/N)',responce);
                        if (responce='y') or (responce='Y') then
                        begin
                             assign(data_file,'power.dat');
                             erase(data_file);
                        end;
                        ps_clear;
                   end;
                   limit_set;
                   checklist;
                   input_details;
                   ps_wfsy('Press <Enter> to Start Test',responce);
              end;
              if test_cont then re_start
              else
              begin
                   draw_axis;
                   GetDate(s_year,s_month,s_day,s_dow);
                   GetTime(s_hour,s_min,s_sec,s_sec100);
                   SetTime(0,0,0,0);
                   test_day:=0;
                   data_capture;
              end;
              print_test;
              close_down;
         end;

        1: plot_old_data;
      end;{case}
   scr_format;
   until option=2;
end.
```

APPENDIX B

PCI Laboratory Test for the Determination of the Abrasion Resistance of Concrete: Method 7.11

CHAPTER 7

Section 11

DETERMINATION OF ABRASION RESISTANCE OF CONCRETE USING A WIRE BRUSH OR SILICON CARBIDE GRIT

1. INTRODUCTION

Resistance to abrasion is important in some structures, eg concrete floors, stilling basins, etc and can be assessed by a variety of tests. The two tests used at PCI are the wire-brush method and the silicon carbide-grit method.

The wire-brush method measures the depth to which a standard wire brush, under standard conditions, abrades the concrete.

The silicon carbide grit method measures the depth to which silicon carbide grit beneath a rotating steel disc, under standard conditions, abrades the concrete.

Where wear is caused mainly by abrasion of a relatively weak matrix the wire-brush method is preferred.

Where the abrasive action is resisted jointly by the matrix and any coarser aggregate particles present the silicon carbide-grit test is recommended. In this test the hardness and gradation of the aggregate used has a pronounced effect on penetrations obtained.

Both tests can be performed using the same test apparatus.

2. NATURE OF THE TEST

Abrading the surface of in situ concrete or a concrete specimen to assess its resistance to abrasion by determining the depth of penetration.

2.1 Important notes

2.1.1 When measuring the depth of penetration, care should be taken to measure the average depth to which the material has been abraded.

2.1.2 The volume of concrete abraded away can be measured using modelling clay which is brought to the required consistence with petroleum jelly.

2.1.3 Where comparative testing is being undertaken, the duration of test can be altered to suit the prevailing circumstances.

2.1.4 The wear penetration will be different when using a new or a worn brush. The standard test requires the use of a new brush which will give more reproducable results but is more costly as it can only be used once. Where comparative tests only are required, a "worn-in" brush can be used up to 5 times whilst still giving acceptable results, but the same acceptance criteria cannot be applied.

2.1.5 The depth to which the material has been abraded is measured using a straightedge and depth gauge. Sufficient readings must be taken to measure the average depth to which the material has been abraded. At least 20 measurements are to be taken per test area. For rough surfaces where readings must be taken before and after test, suitable datum points must be provided to suit the prevailing conditions eg using a jubilee clip on core specimens, forming a "dam" on an industrial floor using a 50/50 mix of OPC and plaster of paris levelled off with a glass plate. This will also provide a means of pre-soaking the test area.

3. EQUIPMENT

3.1 A machine which clamps the concrete specimen in position and rotates a wire brush (or rigid disc, in the case of the silicon carbide-grit test) at 400 rpm while a normal force of 165 N is applied to the brush or disc. The direction of rotation must be reversible. For in situ testing it must be possible to lower the brush (or disc) below the level of the apparatus.

3.2 Cup brush, 60-mm diameter, code 662142 made by Transvaal Brush Company.

3.3 Straight edge.

3.4 Depth gauge.

3.5 Stop watch.

3.6 70-mm-diameter steel disc with grooves, of different lengths radiating from the centre to distribute the grit over the entire test area.

3.7 C6/36 "Carborundum" silicon carbide-grit.

4. TEST PROCEDURE

Both the wire brush tests and the silicon carbide-grit tests can be performed in situ, on drilled cores, on various manufactured products or on laboratory prepared concrete specimens (usually 100 mm cubes), made and cured under the appropriate conditions.

4.1 The wire brush test

4.1.1 This is a wet test and the specimens must be soaked in water for a minimum of 24 hours prior to test (this also applies to the test area in the case of in situ testing).

4.1.2 The specimen is clamped into position on the machine. A new brush [see Important notes 2.1.4] is fixed to the spindle and a force of 165 N is applied to it in a direction perpendicular to the tested surface. The specimen is adjusted so that the test area is perpendicular to the spindle.

4.1.3 A regulated supply of water is passed through the brush and onto the specimen so as to cool the brush and help remove abraded material.

4.1.4 The brush is rotated at 400 rpm for 4 minutes, the direction of rotation being reversed every 30 seconds.

4.1.5 The specimen is removed from the machine and the abrasive wear is measured in one of the following two ways:

- Measuring the mean depth of wear as described in 2.1.5 of Important notes.
- Measuring the volume of abraded material using modelling clay. Using the areas abraded, this volume can be expressed in terms of mean depth of penetration.

4.2 <u>The silicon carbide-grit test</u>

4.2.1 This is a dry test. The presence of moisture will cause blockage of the silicon carbide-grit.

4.2.2 The specimen is clamped into position on the machine. The steel disc is fixed to the spindle and a force of 165 N is applied to it in a direction perpendicular to the tested surface. Great care must be taken to ensure that the test area is perpendicular to the spindle.

4.2.3 A supply of silicon carbide C6/36 grit is fed through the disc for the duration of test. If the flow of grit is being obstructed in any way then the waste material (used grit and abraded material) must be continuously brushed away during test to ensure that "fresh" grit is being used in the abrasive action so as to produce more consistent results.

4.2.4 The disc is rotated at 400 rpm for 2½ minutes in one direction only.

4.2.5 "Used" grit shall not be used a second time.

4.2.6 The specimen is removed from the machine and the abrasive wear is measured in one of the following two ways:

- Measuring the mean depth of wear as described in 2.1.5 of Important notes.
- Measuring the volume of abraded material using modelling clay. Using the areas abraded, this volume can be expressed in terms of mean depth of penetration.

5. <u>REPORTING OF RESULTS</u>

5.1 Calculate the average of all the valid measurements taken on one test area, and report to the nearest 0,1 mm.

5.2 Where possible a result should represent the mean of three tests (not always possible - eg, interlocking paving blocks. In this example it would be necessary to test several pavers due to variability in the manufacture of such a product).

6. INTERPRETATION OF RESULTS

The following information is supplied to assist in the interpretation of results:

6.1 The acceptance criteria provided below are applicable to -5 mm mortars. In most applications it is normal for a layer of mortar to be present at the concrete surfaces and hence the criteria can still be used. However, in special applications or where deep penetrations have occured, the presence of stone might influence the results obtained and this factor should be considered in the interpretation. At this stage a means of systematically allowing for such a variable factor has not been established. In the majority of situations wear of even 1 mm will be regarded as a failure of the surface.

6.2 Acceptance criteria for concrete surfaces

Classification for severe service conditions	Wire Brush Test		Silicon Carbide Test
	General concrete*	Concrete Pavers	
Excellent	<0,5	<0,5	<1,0
Good	0,5 to 1,5	0,5 - 1,0	1,0 - 2,5
Fair	1,5 to 2,0	1,0 to 1,5	2.5 to 3,5
Poor	>2,0	>1,5	>3,5

* This applies to concrete surfaces which have not been treated by delayed trowelling, eg off-shutter or tamped and screeded concrete.

6.3 Alternate acceptance criteria for concrete surfaces

The following table gives suggeste limits for abrasion resistance based on wire brush testing:

Class	Maximum penetration (mm)	Application
1a	0,5	Very severe abrasion conditions Steel wheeled traffic Protection against erosion and cavitation Concrete subject to impact Ore-passes in the mining industry Certain quality proprietary surface hardeners and toppings
1	1,0	Industrial floors where abrasion resistance is important Power trowelled finishes (Grade 25 MPa upwards) High strength off-shutter concrete (>50 MPa) Certain proprietary surface hardeners Heavily-trafficked roads and paved areas Heavily-trafficked public footways
2	2,0*	Industrial and commercial floors where abrasion is not a prime requirement Lightly-trafficked roads and paved areas Lightly trafficked public footways * 1,5 mm for concrete paving blocks
3	3,0**	Ordinary concrete applications where abrasion is of little significance Domestic garages and driveways and pathways ** 2,0 mm for concrete paving blocks
4	>3,0	Domestic applications where the concrete is to be covered by screeds, tile, etc

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