Chapter 7

Compressive Strength Tests

7.1 Introduction

7.1.1 Preview of chapter

The important role that compression testing plays in the quality control of concrete pavers was shown by Houben(1984), who reported that 12 of 16 countries surveyed used compression testing. (Austria and France used a tensile splitting strength, while Finland and the Netherlands did flexural testing).

Most studies in abrasion resistance include compression testing as a benchmark quality indicator. Accordingly the relative variability of abrasion testing is compared with that of compression testing in chapter 12, while the correlation between abrasion resistance and compressive strength is considered here. The factors that affect this correlation will also be briefly considered.

A critical assessment is made of three different compression tests used for testing concrete pavers. In this process some the serious shortcomings of the SABS test will come to light that have resulted in high abrasion-wear in a number of areas paved with cbp.

7.1.2 Relationship and Correlation between Abrasion Resistance and Compressive Strength

Many authors consider abrasion resistance to be closely related to compressive strength. Others have found very little correlation. This divergence in views is considered in considerable detail in chapter 2 of volume 2 (section 2.1.5). The factors that may lead to a poor correlation between compressive strength and abrasion resistance include:

- open curing in air, has a worse effect on the surface than on the core concrete
- carbonation effectively hardens the surface relative to the core
- liquid surface treatments, strengthen the surface, not the core
- finishing processes (e.g. power trowelling), harden the surface, not the core
- topping concrete of a different density/strength to the underlying core concrete
- bleeding is very detrimental to the b/w ratio at the surface, but improves b/w in the core
- freeze/thaw cycles damage the surface concrete more than the core
- the hardness of the aggregate affects abrasion resistance far more than compressive strength
- the type of abrasion test (e.g. very severe tests will not readily detect a relatively hard but thin surface)

However, given the right conditions, it is possible for the surface concrete to be virtually the same as the core, and in this case a good correlation will normally be found between abrasion resistance and compressive strength.

Conversely, it is equally evident that it is possible to have adequate compressive strength, owing to sound core concrete, but low abrasion resistance owing to inferior surface concrete, or the reverse of this; inferior compressive strength owing to weak core concrete, but high abrasion resistance owing to hard surface concrete.

The mechanisms resulting in failure in compression and abrasion testing also differ. In the former cracks are initiated and propagated in the direction of the applied load as crushing proceeds [Newman (1997a)]. In the latter the microscopic surface asperities are either crushed or sheared off, depending on the nature of the load. These mechanisms are discussed more fully in volume two in 'Chapter 3: Mechanisms of Abrasion'.

The relationship between compressive strength and abrasion resistance as characterized by the three abrasion tests is shown in Figure 7.1. Note that the indices for the ASTM C418 and Wire brush tests have been inverted so that the abrasion resistance for all three abrasion tests are proportional to the inverse of depth/penetration, facilitating easy comparison.

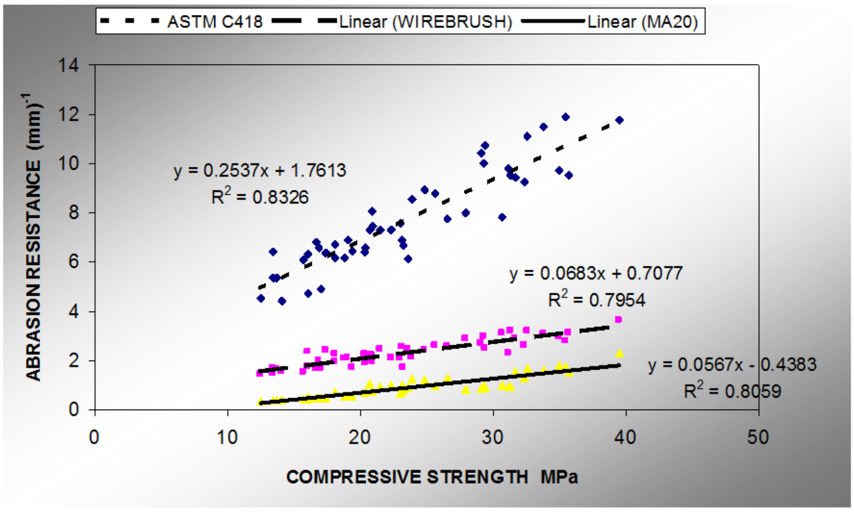

Figure 7.1 Relationship between abrasion resistance and compressive strength – 48 mixes

In this investigation a relatively good correlation was obtained between the three abrasion tests and compressive strength as follows:

	R^2
Abrasion resistance according to MA20 test:	0.806
Abrasion resistance according to Wire brush test:	0.795
Abrasion resistance according to ASTM C418 test:	0.833

However, it maybe argued that better correlations should have been achieved given that the many factors listed earlier that can potentially result in a poor correlation between abrasion resistance and compressive strength, were either not present, or were kept constant for both the core and the surface concrete. This suggests that either the abrasion testing, or compression testing had inherently high variability. Figure 7.5 shows R^2 values of 0.93 for compression testing, indicating that it is the abrasion tests that are mainly responsible for the lower-than-expected correlation values.

7.1.3 Rationale for Compression Testing

The rationale for using three compression tests [SABS 1058(1985), ASTM C140-82, MA20(1986)] was to make it possible to relate the results to work done in South Africa, U.S.A., and Australia respectively. This takes on added significance since the three abrasion tests used are also presently in use in these countries (MA20 in Australia, ASTM C418 in USA, Wirebrush in SA), thus making it possible to compare a local compression test with a local abrasion test.

The inclusion of compression tests into this investigation has also provided a basis for assessing the variability of the three abrasion tests (see chapter 12). Furthermore, at the time that this experimental work was done, compression testing was used as a means of assessing quality in concrete pavers in 12 out of 16 European countries, and was and still is the only strength criteria in the SABS standard for concrete pavers. Worldwide it is the most widely accepted strength indicator for concrete.

Chapter 2 of volume 2 goes to great lengths to show that may authors have found that compressive strength is closely related to abrasion resistance providing the surface and core concrete are similarly cured, compacted, proportioned etc.

It should be noted that each point on figure 7.1 for the ‘compressive strength’ axis represents one of the 48 mixes made in this study and is given in column 6 of table 7.1. It is an average of the results obtained from the three compressive strengths studied in this investigation. Although this means that this ‘compressive strength’ does not equate to any one of the three standards (it is however closely related), the compensation is that each result is the average of 18 blocks tested rather than six, and is therefore a better indicator of the average quality of the paver. Thus each Y-axis result of each abrasion test is compared against a common quality indicator, with enhanced reliability.

The writer concedes that there are advantages to using the local specifications in the chapters that deal with the individual ‘national’ tests, i.e. the MA20 compression test for the MA20 abrasion test (chapter 9, see figures 9.18 through 9.23), the SABS compression test for the witrebrush test (chapter 10, se figures 10.8 through 10.10) and the ASTM compression test for the ASTM C418 abrasion test (see figure 11.4). But in this case comparisons of the three tests would not be readily possible as has been done in figure 7.1.

The parallel usage of the three compression tests has also made it possible to compare the one against the other, and certain deficiencies become apparent in the SABS compression test.

7.1.4 Scope of Testing

A total of 864 blocks were tested (3 compression tests x 8 mix designs x 6 mixes of differing water contents x 6 blocks / mix). The results are recorded in table 7.1, which is a reconstruction of columns B, C, D and K of table 6.2. The last three columns under the heading of coefficient of variation were constructed from data in appendices B.1 through B.8, C.1 through C.8, and D.1 through D.8.

The sixth column is the average of the three compression tests (alluded to earlier).

TABLE 7.1 RESULTS OF COMPRESSION TESTING

MIX	DENSITY	COMPRESSIVE STRENGTH				COEFFICIENT OF VARIATION (%)		
	ASTM C140 kg/m3	SABS 1058 MPa	ASTM C140 MPa	MA20 APX-C MPa	AVERAGE OF 3 TESTS MPa	SABS 1058 MPa	ASTM C140 MPa	MA20 APX-C MPa
1.1	2308	35.3	35.4	44.9	38.5	15.4	5.7	4.9
1.2	2308	36.6	36.1	45.8	39.5	12.2	10.4	11.0
1.3	2266	30.9	27.5	39.3	32.6	13.9	15.0	9.9
1.4	2160	22.0	19.0	28.4	23.1	6.9	9.3	9.1
1.5	2159	22.6	20.1	28.0	23.6	10.7	6.5	11.0
1.6	2113	15.9	16.4	22.0	18.1	19.2	5.6	5.5
2.1	2283	29.2	27.5	35.3	30.7	8.6	7.2	5.8
2.2	2298	30.3	27.6	36.0	31.3	6.4	5.9	9.5
2.3	2242	27.9	24.8	35.2	29.3	12.1	7.5	8.8
2.4	2175	23.9	18.9	26.2	23.0	7.0	6.3	8.0
2.5	2110	19.1	17.1	25.0	20.4	5.0	8.2	7.5
2.6	2108	18.0	14.7	21.6	18.1	6.0	16.3	10.1
3.1	2188	18.9	18.9	25.0	20.9	6.5	4.8	4.7
3.2	2194	15.9	18.5	22.8	19.1	13.5	6.7	8.7
3.3	2109	15.1	14.6	18.5	16.1	11.5	6.4	7.1
3.4	2037	12.5	12.0	16.6	13.7	8.3	12.4	9.7
3.5	1995	11.4	11.1	15.0	12.5	14.8	12.8	13.0
3.6	2016	11.9	11.8	16.6	13.4	6.0	4.4	9.6
4.1	2243	25.4	26.1	32.3	27.9	9.5	8.7	4.5
4.2	2259	28.1	26.3	32.9	29.1	12.7	3.2	7.0
4.3	2121	16.4	15.6	20.2	17.4	12.5	9.7	7.4
4.4	2110	14.3	14.5	19.4	16.1	5.2	10.1	13.1
4.5	2117	15.5	14.3	21.3	17.0	13.6	10.4	10.2
4.6	2076	13.4	14.3	19.5	15.7	5.4	10.8	8.0
5.1	2267	29.9	29.2	37.9	32.3	9.2	7.2	5.1
5.2	2230	22.7	27.0	30.0	26.6	7.7	14.1	14.6
5.3	2170	19.8	18.3	24.0	20.7	5.1	14.4	7.1
5.4	2202	19.3	20.2	25.0	21.5	14.8	8.0	8.7
5.5	2102	18.2	17.2	21.0	18.8	18.7	5.6	5.5
5.6	2055	13.7	12.1	16.5	14.1	20.7	11.3	4.6
6.1	2242	28.6	30.2	34.7	31.2	4.2	4.4	5.1
6.2	2220	27.2	28.1	32.9	29.4	10.8	13.6	7.7
6.3	2166	22.1	23.2	24.4	23.2	19.8	20.3	4.5
6.4	2121	16.4	19.2	22.6	19.4	10.7	10.2	9.2
6.5	2058	14.0	16.4	19.6	16.7	11.6	12.1	8.8
6.6	2021	12.3	11.3	16.7	13.4	5.9	5.9	12.3
7.1	2286	31.6	33.2	42.3	35.7	13.2	5.2	13.5
7.2	2263	26.1	29.1	39.8	31.7	7.4	10.3	8.8
7.3	2208	23.0	21.9	32.0	25.6	7.7	19.3	10.7
7.4	2175	20.1	23.4	31.0	24.8	7.9	7.6	9.9
7.5	2110	20.0	16.3	26.3	20.9	3.8	6.1	7.1
7.6	2073	16.0	13.5	21.1	16.9	12.5	11.0	6.4
8.1	2262	28.6	32.6	40.2	33.8	6.2	10.8	13.8
8.2	2279	32.1	30.4	42.4	35.0	14.3	8.4	8.6
8.3	2285	31.1	31.7	43.6	35.5	10.8	6.5	5.8
8.4	2103	24.0	18.9	28.8	23.9	15.8	7.3	7.6
8.5	2100	18.1	21.1	27.8	22.3	10.4	6.7	12.0
8.6	2092	17.8	18.2	25.0	20.3	7.7	13.1	13.9
MEAN	2168	21.7	21.4	28.2	23.8	10.4	9.2	8.7

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7.2 Relative Performance of the Three Tests

The average result for each of the three compression tests is recorded at the bottom of the respective columns in Table 7.1, and are presented below:

SABS-1058 = 21,7 MPa η 'mean quality' of 48 mixes
ASTM-C140 = 21,4 MPa η 'mean quality' of 48 mixes
MA20 = 28,2 MPa η 'mean quality' of 48 mixes

7.2.1 Mean quality

Three sets of six blocks from each of the 48 mixes made in this programme were set aside for crushing tests, one set for each of the three compression tests. Just as it is possible to compare the one test against the other on a mix-by-mix basis, it is also possible to do so by comparing the average of the 48 mixes. In the first instance the statistical base consists of 3 x 6 blocks, while in the second instance this base is 3 x 288 blocks. Again, in the first instance a comparison is made using a known mix, and hence the results reflect the differences between the three test methods for that particular mix, but with a limited statistical base. In the second instance, the results reflect the difference between the three tests for the average of 48 mixes, with a very good statistical base.

It is therefore reasonable to assume that the physical properties (including compressive strength) of the 288 blocks subjected to the SABS test are identical (for all intents and purposes) to the physical properties of the 288 blocks subjected to each of the other two tests.

This common strength is defined as the 'mean quality', i.e. the average inherent compressive strength of the blocks from the mixes, regardless of the test method used to test them.

The fact that the three test types are all measuring the same value, i.e. the 'mean quality', but show different results, means that there are intrinsic differences in the three tests. The bulk of the remainder of this chapter will be devoted to analysing these differences.

If the 'mean quality' is compared with the requirements of the various specifications shown in table 7.2, it would appear that the blocks were generally inferior. In fact this is partly correct, since generally only the wetter mixes can be expected to be of an acceptable quality (see 6.3.1), and the 'mean quality' is lowered by the effect of the dry mixes. The statement is also somewhat unfair, since the results of the SABS and ASTM tests are not a true indication of the compressive strength they would have reflected had they only been 60mm or 80mm thick, instead of 100mm. (This will be discussed in more detail in 7.3.1).

TABLE 7.2 AVERAGE RESULTS OF COMPRESSION TESTS

TYPE OF TEST	SPECIFICATION	NORMAL CONDITIONS MPa	SEVERE CONDITIONS MPa
COMPRESSION	SABS 1058	25	35
COMPRESSION	ASTM C936	55	55
COMPRESSION	MA20	30	45

7.2.2 Relationship between compressive strength tests

The relationship between compressive strength and dry density is partly discussed in chapter six. In figure 7.2 through 7.4 the three compression tests are related to dry density values (i.e. the data is taken from columns B, C, D and K of table 6.2) to study the relationship between the respective test methods.

The ‘mean’ for the MA20 test is generally 30 % higher than the ASTM and SABS tests.

It is evident from the graphs (figure 7.2 through 7.4) representing binder contents, 18%, 14%, 10%, that the inclination of the various trend lines are almost identical, and that the difference between them is essentially one of scale. This means that one set of results may be ‘translated’ from one specification to another, merely by applying the appropriate ratios of ‘mean quality’. This factor also depends on the geometry of the block, e.g. aspect ratio, plan area, etc. This is more fully explained further on.

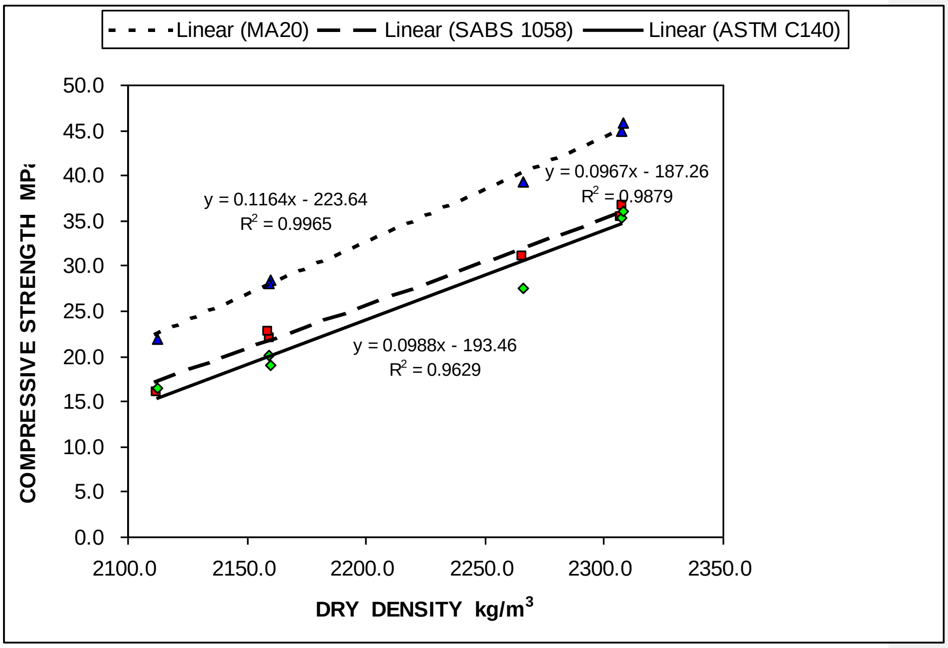

Figure 7.2 Relationship between compressive strength and dry density for each of the three compressive strength tests
Mix 1 = 9%OPC, 9%MGBS

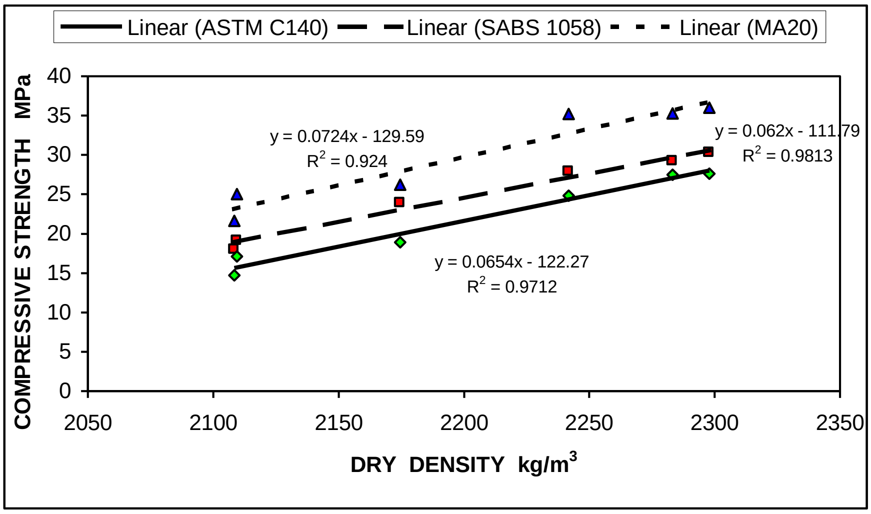

Figure 7.3 Relationship between compressive strength and dry density for each of the three compressive strength tests

Mix 2 = 7%OPC, 7%MGBS

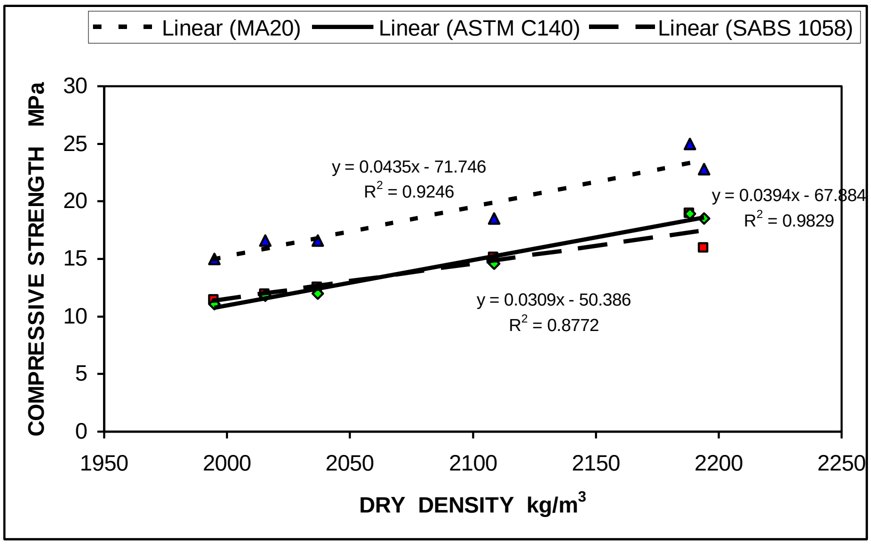

Figure 7.4 Relationship between compressive strength and dry density for each of the three compressive strength tests

Mix 3 = 5% OPC, 5%MGBS

In figure 7.5 the ASTM and SABS results have been plotted against the MA20 results for all 48 mixes. A straight trend line has been generated in each case to determine the correlation. The high R^2 values of 0,934 and 0,930 confirms that there is a direct relationship between the three tests; the difference between the tests is merely one of scale.

This is to be expected for similar tests done on blocks made from the same batch for each of the 48 mixes.

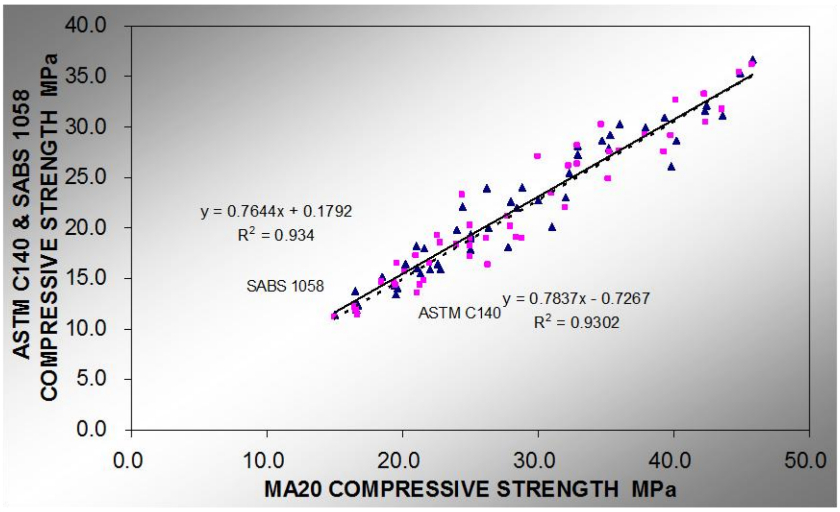

Figure 7.5 Relationship between the SABS 1058 / ASTM C140 compression tests and the MA20 compression test for 48 mixes.

The section that follows is now devoted to analysing the differences between the three tests, which arise from the different methods of preparation and testing. It will be shown that the tests can be equated by using certain coefficients to express these differences.

7.3 Differences in the Three Compression Tests

7.3.1 Aspect Ratio

It has long been recognised that the ratio of the height to the least lateral dimension of a concrete specimen, i.e. the width, substantially influences the outcome of a crushing test, and the lower this aspect ratio the higher will be the force required to crush the specimen. (The failed material in specimens with a low aspect ratio has difficulty in dilating laterally, owing to restraining friction induced shear stresses supplied by the platens of the press. Thus a 150mm concrete cube specimen (aspect ratio = 1) will fail at a compressive stress that will generally be 25% higher than that for a 150mm diameter x 300mm high cylinder specimen (aspect ratio = 2). The cylinder is a truer reflection of stresses that occur in compression members such as columns, since there is a central zone in a test cylinder that is unaffected by edge conditions. Conversely concrete pavers that are 50mm high and 100m wide have an aspect ratio of 0,5 and are thus very significantly affected by the lateral restraint supplied by the platens.

The paving specifications of countries such as Denmark, Norway, the UK and Italy, have taken cognisance of this, and in effect allow a lower failing force in taller blocks [Pagbilao(2000)].

MA20(1986) observes that 'Simple compression testing makes no allowance for the aspect ratio of the unit under test. A low squat unit will crush at a higher compressive load than a tall slender unit made of the same material. The procedure set out in appendix C (of MA20) introduces a shape factor to accommodate the aspect ratio effect; so that, for example, a paving unit which has a compressive strength of 45 MPa would contain the same quality of material no matter what its height, depth or breadth'.

The formula for calculating the compressive stress in MA20 is given by the expression:

$C = (W/A)(5/[((\sqrt{A})/H)+1.87]$ …… (7-1)

Where:
C = compressive strength in MPa
W = total load at which specimen fails, in newtons
H = nominal height of unit, in mm
A = nominal gross plan area, in mm²

The effect of increasing H in expression (7-1) is to increase the value of C, and *this compensates for lower lateral restraint in tall blocks.* (All the blocks used in this work were of a thickness of 100 mm which is very high, but this was the specification laid down by the City Council of Johannesburg for cbp in bus depots and termini). Accordingly expression (7-1) explains the higher values recorded for the MA20 test in this experimental work relative to the two other tests (SABS 1058 and ASTM C140) that do not incorporate a correction factor.

If the plan area of the block, A = 20408 mm², and the height of the block, H = 100 mm, are substituted into the expression $(5/[((\sqrt{A})/H)+1.87]$ of (7-1), it will be seen that the MA20 correction value is 1,516. Thus, relative to MA20, the ASTM and SABS results are undervalued by this amount.

7.3.2 The Area Used in the Calculation

Both the MA20 and the ASTM C140 test use the *gross plan area* of the block in the calculation of the compressive stress, while in the SABS test the *net surface area* is used, which may or may not be the same as the gross plan area depending on whether or not the block has a bevelled edge on its upper surface. The plan width of a typical bevel may be as much as 10 mm. In this case a rectangular block with a plan area of 100 mm x 200 mm will have a net surface area of 80 mm x 180 mm. When this block is tested in a compression machine the stress experienced in the block will correspond to the net surface area only in the top few millimetres. However this higher stress will not be the stress that ultimately causes the block to fail in compression given the considerable lateral restraint in this region from the platens of the testing machine albeit via the plywood packing. Further more any localised crushing that does take place in the bevelled region is not likely to be noticed by the operator, since the block has not failed as a whole and the dial of the testing machine therefore continues to show an upward movement. The point that the operator in fact records as the failing force is the maximum load that the block withstood before it failed. The corresponding stress generally relates to the area at mid height, namely the gross plan area. Here the restraint effects from the platens are least likely to prevent lateral dilation.

Figure 7.6 shows a typical bevelled paver in a compression machine.

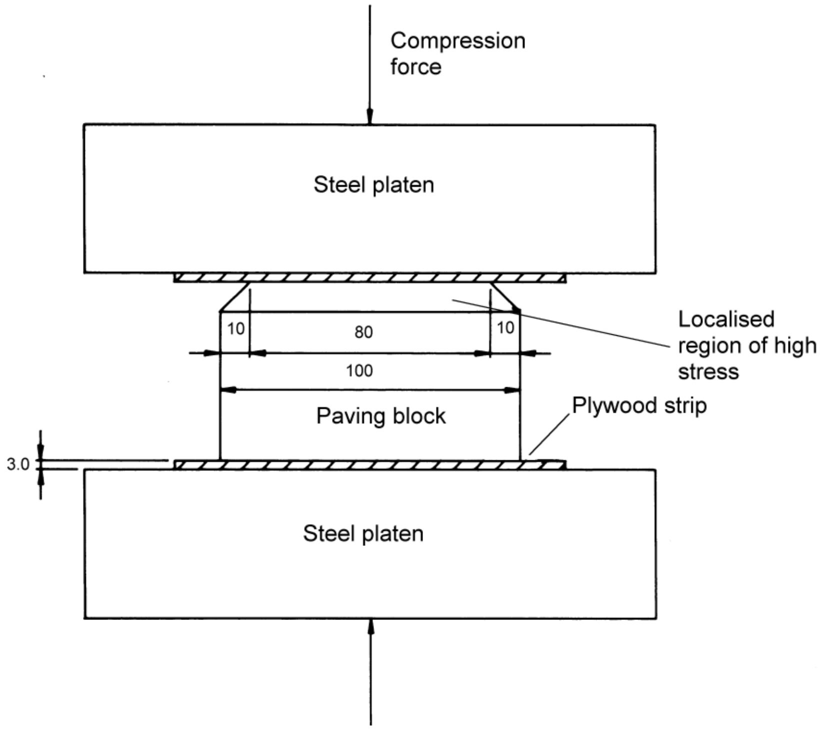

Figure 7.6 Frontal view of block in testing press

The effect on the results of using the net surface area of the block can be illustrated by a simple example. If the strength of the block mentioned earlier (and shown in the diagram above) can be calculated as 25 MPa when using the net surface area (as in SABS 1058), then its 'real' strength based on the plan area of the block would be less by a factor of 180x80 / 200x100 = 0,72. Thus the actual strength of the block is 25 x 0,72 = 18 MPa. The engineer on site thinks he is getting 25 MPa quality, but in actual fact the block fails at 18 MPa.

7.3.3 Specified compressive strength

The specified compressive strength requirements in table 7.2 show that South Africa's are the lowest. This can be explained by certain historical developments.

Between 1980 and 1984 extensive experimentation [Shackel(1979), Shackel(1981), Clifford(1984] on cbp was carried out by the CSIR at the Silverton test site. It was found that cbp that had a compressive strength value of 25 MPa was adequate for it to act as an effective structural layer in the design of a pavement. Consequently when the SABS paving specification came out in 1985 the nominated strength was 25 MPa, as an average for 12 test specimens, with 20 MPa as a minimum for an individual result. The thinking at the time in South Africa may be understood from Lane(1988): 'The specifying of an unnecessarily high minimum strength will therefore only increase the cost of the paving without improving its performance'. Although the lower cement content required to make 25 MPa blocks would indeed result in a marginal saving (of the order of 3% to 6% of the installed cost of the units), the direct relationship between *abrasion resistance* and cement content (see 6.4.3) was not fully appreciated. A number of sites installed with blocks that conformed to the SABS requirements started manifesting alarming signs of wear. An example of this would be the Van Wyk street shopping mall, Roodepoort. At the time of installation the blocks complied with SABS 1058. (The blocks were made at Brickor Precast's Roodepoort factory, where the writer was the factory manager). Nevertheless, after seven years of pedestrian traffic, several areas manifested fourth degree abrasion. (For photographs of this site and a discussion on 'degrees of abrasion' refer to chapter 8). Other sites around the country manifesting excessive wear were also identified and the CMA embarked on a research programme. This investigation was part of that initiative.

The very high compressive strength requirements of the USA and European countries (e.g. see Table 7.3) no doubt reflect the need for protection against freeze/thaw cycles experienced in these countries. They also explain why abrasion-wear is not a major problem there.

7.3.4 Soaking

The SABS blocks are soaked for 24 hours prior to crushing, whereas in the MA20 and ASTM C140 tests the blocks are crushed in a dry state. Blocks tested in a wet condition always have a lower result compared to similar blocks tested dry. (Hydraulic pressures set up in the pores of the wet blocks by the compression process lower the shear strength. Also, according to MacKechnie (see correction 7.3.4 at the end of BOOK 1) drying of concrete also reduces the distance between adjacent layers of CSH, which increases bonding energies and therefore strength of the material. This together with the different areas used in the calculation (see 7.3.2) as well as the aspect ratio correction (7.3.1) are the only material differences between the MA20 and SABS tests.

As explained earlier the 'mean quality' (or inherent average strength) of all the blocks subjected to the MA20 test can be considered identical to that of the SABS test, since in both cases 288 blocks from the same 48 mixes were subjected to either test.

This may be expressed as an equation:

mean quality SABS blocks = mean quality MA20 blocks ……. (7-2)

Therefore any difference between the two averages of 288 tests must be the result of differences in the method of preparation and testing.

If the differences between the two tests can be identified, then it is possible to equate the 'average' totals of table 7.1, using coefficients to represent the said differences. Equation (7-2) thus becomes:

$C_{SABS} \times B \times R \times Z = C_{MA20}$ ……. (7-3)

i.e. 21,73 x 0,7644 x 1,516 x Z = 28,20

Where:

C_{SABS}	=	average compressive strength result to SABS 1058
	=	21,73 MPa (see table 7.1)
B	=	Bevel correction factor, equivalent to the net surface area divided by the gross plan surface area, i.e. 15600 mm² / 20408 mm² for the blocks in this work
	=	0,7644
R	=	Aspect ratio correction factor varies depending on thickness and area of blocks. It is 1,516 for 100mm blocks of plan area 20408 mm². (See7.2.1).
Z	=	Soaking correction factor (to be determined)
C_{MA20}	=	average MA20 compressive strength (see table 7.1)
	=	28,20 MPa

Substituting the various values into the equation, and solving: Z = 1,120. The inverse of this number i.e., 0,893, represents the factor by which soaking reduced the strength of the blocks. i.e. on average soaking reduced the strength of the blocks by 10,7%, say 11%.

Ghafoori(1992) found that the air-dry strength of concrete pavers was on average 14,2 % higher than the individual samples tested under wet conditions. However this value depended on the cement content, with weak mixes being 29,6 % stronger in the dry state, while strong blocks were only 4,7 % stronger.

Shackel(1985) found that soaked blocks have a greater standard deviation than blocks tested dry. This is confirmed here by the ASTM and MA20 tests having a lower coefficient of variation than the soaked SABS test. (I.e. 9,2% and 8,7% vs 10,4% respectively, based on 3 x 288 blocks tested, see table 7.1).

7.3.5 Capping

In the SABS test the block is crushed between two 3 mm thick plywood strips. The MA20 test calls for 6 mm thick strips, while the ASTM test calls for the blocks to be capped with either granulated sulphur or gypsum plaster. This difference in capping together with the aspect ratio correction is the only difference between the ASTM and MA20 test. As before the 'mean quality' of the blocks subjected to either test is the same. Again, the averages of the two tests (ASTM and MA20) can be equated if the differences between them can be factored out:

$C_{ASTM} \times R \times Y = C_{MA20}$ ……. (7-4)

i.e. 21,37 x 1,516 x Y = 28,20

Where:

C_{ASTM}	=	average compressive strength result to ASTM C140
	=	21,37 MPa (see table 7.1)
R	=	Aspect ratio correction factor varies depending on thickness and area of blocks. It is 1,516 for 100 mm blocks of plan area 20408 mm². (See 7.3.1)
Y	=	'capping' correction factor (to be determined)
C_{MA20}	=	average compressive strength result to MA20
	=	28,20 MPa

Substituting the various values into the equation, and solving, Y = 0,870. The inverse of this figure, 1,149, represents the factor by which capping increases the strength of a block. I.e. capping increases the result by 14,9%, say 15%.

The most likely reason why capping has a positive effect on the compressive strength is that in effect it brings the upper and lower surfaces of the blocks in direct contact with the very stiff steel platens, inhibiting lateral dilation to a considerable depth. Conversely the relatively low modulus plywood packing does allow some lateral dilation at its interface with the block.

Secondly, capping contributes towards higher crushing results by eliminating any irregularities on the upper and lower faces of the blocks. The blocks used in these tests were made directly on wooden pallets and therefore had the imprint of the wood-grain on their lower surface. In some severe cases this may result in ridges as high as 3 mm.

The upper surface of the block assumes the smooth texture the steel shoes of the machine's press, unless the mix is too wet. In this case a rippled effect on the upper surface is created by the pulling effects as the shoes of the press are lifted away from the wet upper surface. Also noticeable craters (about 1 cm²) could be seen on the surface of the wettest mixes, a characteristic of *very* wet mixes, e.g. see appendix Y.7.

Such irregularities on the upper and/or lower surfaces would act as points of high stress which could cause premature failure. Capping reduces this problem. (The 6 mm plywood packing used in the MA 20 test would more easily cushion such point loads and is therefore preferable to the 3 mm plywood as used in the SABS test).

7.3.6 Summary of differences

The differences between the three compression tests are summarised in table 7.3 below, and in addition details of the British standard have been included [Chryssafis(1988)].

TABLE 7.3 SUMMARY OF VARIATIONS IN COMPRESSION TESTS				
VARIABLES	SOUTH AFRICA	U.S.A.	AUSTRALIA	BRITAIN
	SABS 1058	ASTM C140	MA20	BS 6717:PART 1
MOISTURE PREPARATION CONDITION	24 HOUR SOAKING	DRY	DRY	24 HOUR SOAKING
SURFACE PREPARATION	3mm PLYWOOD	CAPPING	6mm PLYWOOD	4mm PLYWOOD
COMPRESSIVE STRENGTH, MPa NORMAL/SEVERE	25/35	55	30/45	49
AREA USED IN STRENGTH CALCULATION	NET AREA OF WEARING SURFACE	GROSS PLAN AREA	GROSS PLAN AREA	GROSS PLAN AREA
ASPECT RATIO CORRECTION	NO	NO	YES	NO

In determining the equivalent MA20 compressive strength of a paving block the following general formula can be applied to the ASTM C140 and SABS 1058 results:

$C_{EQMA20} = F / A \times Y \times Z \times R \times B$ .... (7-5)

Where:

C_{EQMA20} = the ‘equivalent MA20’ result applied to either the ASTM C140 or SABS1058 compression test to yield the equivalent MA20 result
F = failing force in newtons
A = area in mm²
Y = capping factor (from expression 7-4) to apply when converting results of capped blocks to the equivalent ‘plywood’ capping (use 0,870 for converting ASTM test)
Z = Soaking factor (from 7-3) to apply when converting results of soaked specimens to the equivalent ‘dry’ results (use 1,120 for converting SABS test)
R = Aspect ratio correction factor, (see equation 7-1), varies depending on the thickness and area of blocks. It is 1,516 for 100 mm blocks of plan area 20408 mm² and should be used to convert the ASTM and SABS results to MA20
B = Bevel correction factor, (see expression 7-2), to be used to convert results where the net area is used in the calculation, as in the SABS test, (15600/20408) = 0,7644 for the blocks in this work)

Where a factor does not apply unity should be substituted.

As an example this formula is applied to the averages of table 7.1.

For the ASTM result:
C_{EQMA20} = 21,37 x 0,87 x 1 x 1,516 x 1 = 28,2 MPa = MA20

For the SABS result:
C_{EQMA20} = 21,73 x 1 x 1,12 x 1,516 x 0,7644 = 28,2 MPa

The effect of soaking vs. testing dry, capping vs. plywood packing, no aspect ratio correction vs. aspect ratio correction, and net surface area vs. gross surface area are apparent from expression (7-5). This formula is useful when converting SABS and ASTM tests to equivalent MA20 results. Since the MA20 results are used in the remainder of these chapters when compression testing is referred to (because they are considered the most realistic), such a conversion may prove useful to the reader.

Similarly the formula may be manipulated to change MA20 results into equivalent SABS (or ASTM) results.

7.4 Coefficients of variation

From table 7.1 the following average coefficients of variation are reproduced below:

SABS - 1058	= 10,4 %
ASTM - C140	= 9,2 %
MA20	= 8,7 %

These coefficients are the average of 48 coefficients obtained on a sample size of six blocks in each case. The coefficients are low in relation to most of the other tests done in this investigation (e.g. tensile splitting strength test, MA20 abrasion test – see table 12.4.), and confirm that the compression test is an excellent means of assessing the overall quality of concrete. The blocks were made and tested under carefully controlled conditions. In practice higher coefficients are likely for factory made concrete pavers.

7.5 Revision of SABS 1058

The writer is persuaded that the clauses governing the compression test in the existing SABS 1058 paving specification are in urgent need of revision. The MA20 compression test (with some possible modifications) should be adopted for the following reasons:

7.5.1 Aspect ratio correction

It contains an aspect ratio correction factor whereby blocks with a given quality of concrete will register the same strength regardless of their thickness. This will eliminate the current situation whereby blocks that are 80 mm and 100 mm thick need significantly more cement than blocks that are 50 mm or 60 mm thick to comply with the strength requirements. It will mean that regardless of thickness, the pavers will have a similar cement content and hence similar abrasion resistance.

7.5.2 Gross plan area

It uses the gross plan area of the block, not the net surface area, to measure the compressive strength. This also simulates the real stresses, which occur in the main body of the block.

Furthermore, using the gross plan area will alleviate the situation whereby blocks that are not chamfered need significantly more cement to achieve the specified target strength.

7.5.3 Dry testing

It tests the blocks dry. This has three advantages. Firstly it will compensate for the lower compressive strength calculated from using the gross rather than the net surface area. Secondly, blocks tested dry have a slightly lower coefficient of variation (confirmed in this investigation), making the compression test even more repeatable. Thirdly, it allows a manufacturer or end user to obtain an immediate ‘pass’ or ‘fail’ result, without having to wait for a 24 hour soaking delay. In a mass production manufacturing environment, or a construction site where suspect blocks that are being installed require verification, such delays can be most inconvenient.

On the other hand, soaking the blocks ensures a consistent moisture content. It also ensures that the blocks are being tested in their weakest state, thus providing something of a factor of safety.

7.5.4 Higher limits

It calls for a higher compressive strength. Although this may not be necessary from a structural point of view, it is nevertheless advisable for improved abrasion resistance.

However this argument would not be correct for blocks made in a process whereby a thin layer of face concrete is bonded to the underlying concrete. In this case it is possible to have a block with a relatively low compressive strength while achieving a high abrasion resistance, from face or topping concrete that is made from a relatively rich mix.

A look at the problem

At the Delft and Rome conferences, Marais(1984) and Lane(1988) both reported on SABS-1058. (The views of these highly respected authors carried considerable weight in drafting the national paving specification).

They stated that blocks with a low compressive strength of 25 MPa would be less brittle and would therefore be subject to less chipping.

However they did not foresee that:

- using the ‘wearing area of the block’ for calculating the compressive strength
- omitting an aspect ratio

would lead to inferior surfaces, particularly in pavers that are 50mm or 60mm thick. This may be demonstrated with an example:

If expression (7-1) is applied to two pavers, one of dimensions 200x100x100 high, (block A), the other of dimensions 200x100x50 high (block B), then it may be shown that block B has 43% more crushing strength. Furthermore if block B is now given a 10mm wide bevel on its upper face then according to the method of calculating strength in SABS 1058, its crushing strength is effectively increased by the factor:

$$\frac{200\text{mm} \times 100\text{mm}}{180\text{mm} \times 80\text{mm}} = 1.39$$

When these two effects are combined, it is evident that if block B is moulded from 10 MPa concrete (cube crushing strength), it will appear to have a strength of 10 x 1.43 x1.39 = 19.9 MPa, say 20 MPa. This paver would just ‘pass’ the SABS 1058 minimum criteria for an individual block.

With the wisdom of hindsight these views have resulted in paved surfaces in South Africa with inferior abrasion resistance. Clearly concrete with an equivalent cube strength of 10 MPa (but that passes the 20 MPa minimum requirement if moulded as a 50mm high x 100mm x 200mm paver with a 10mm wide bevel) will have inferior abrasion resistance.

The recommendations in this section should therefore be seen as an attempt to correct the flaws in the current specification.

Corrective action

This should take the form of higher limits for compression testing, or the introduction of an abrasion testing. Furthermore strength should always be calculated based on the gross plan area.

7.6 Summary, Conclusion and Recommendations

Houben(1984) reported that 12 of 16 countries surveyed used compression testing for quality control. (Austria and France used a tensile splitting strength, while Finland and the Netherlands did flexural testing).

1. Given the universally important role that compression testing plays in quality control, the correlation between compressive strength and abrasion resistance was examined for the blocks tested in this investigation. R^2 values of approximately 0.8 for all the abrasion tests indicate a relatively good correlation. However, there are many factors that can result in a significant difference between the surface and core concrete, leading to a poor correlation. These factors were briefly stated.

2. The SABS 1058 specification should be revised in the direction of a more scientific specification such as the MA20, which allows for aspect ratio correction and uses the base area of the block.

3. A higher compressive strength should be specified to ensure better abrasion resistance. Alternatively the 25MPa strength requirement may be retained providing an abrasion test is implemented to supplement compression testing. This will allow '25MPa structural' quality concrete for the base concrete and a special hardwearing topping.

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

The focus in the remaining chapters is to define the various degrees of abrasion-wear that occur in pavers (chapter 8), evaluate various abrasion/surface tests (chapters 9, 10, 11, 12, 13), and correlate these laboratory tests as well as a number of mix designs with actual wear recorded after six years of traffic (chapters 14, 15).