Chapter 4

Classification of Abrasion Tests

4.0 Scope and Purpose

In chapter 3 various mechanisms of abrasion were considered from the literature. Consolidating and building on this a number of models for abrasion-wear were proposed. In this chapter these ideas are, inter alia, applied to numerous abrasion tests. It was shown in chapter 2 that understanding of the various mechanisms of abrasion-wear (both in practice and in a test) is important in interpreting abrasion wear. Clearly it is equally important when selecting the best test for a given application.

A total of 66 abrasion tests are reviewed. These tests are those that could be extracted from the literature that was available to the author. The list is extensive but not exhaustive in that no attempt was made to explore publications in German, French, Spanish, Russian etc.

Table 4.1 classifies the 66 abrasion tests according to various criteria, and these are frequently referred to in the course of this chapter. Each test has a ‘Short name’ and is briefly described under the heading of ‘principle of the test’.

A more detailed explanation of each test is given in appendices U.1.1 through U.8.3. The ‘ID’ of each test is the same as that of the corresponding appendix, where each test is considered in terms of the history of its development, test apparatus and method, and the associated abrasion wear mechanisms. This latter aspect is the primary focus of appendix U, and is also considered an important consideration in the classification of the abrasion tests. The various abrasion wear mechanisms were given in chapter 3 and reference is made to the appropriate sections in that chapter as required.

The ‘abrading medium’ in contact with the concrete that causes the abrasion is not the same for all the tests. The 66 abrasion tests are logically divided into eight different test types or *sub-types*, according to the various types of abrading medium. They are grouped as follows:

U.1 steel drums
U.2 steels balls (includes tumbling and bouncing steel balls in addition to the more usual rolling/sliding-under-load)
U.3 special wheels (caterpillar tracks, chained tyres, studded tyres, dressing wheels)
U.4 steel wheels
U.5 fine abrasive (usually sand or silicon carbide granules)
U.6 abrasives that shear tangentially (steel pads, wire brushes, hardness scratchers)
U.7 steel hammers
U.8 non-damaging abrasives (water, sound)

Of these the most commonly used are various types of steel balls (U.2 tests), steel wheels (U.4 tests), and fine abrasives (U.5 tests).

Interestingly, it may be shown that the abrasive actions of these various abrasive media may be reduced to one or more of three actions:

- rolling
- sliding
- impact

The corresponding abrasion wear will depend on the severity of the action, and this is considered in two categories:

- mild
- severe

It is shown that 'mild' abrasion results in the cracking/crushing/shearing of the microscopic surface asperities, whereas 'severe' abrasion results in cracking/crushing/shearing effects that may extend some tenths of a millimetre into the sub-asperity zone, or even a few millimetres in cases of very severe rolling and impact.

Based on the type of 'abrasive action' and its 'severity', each of the 66 tests are classified in terms of an 'Abrasion Wear Code', shown in table 4.1 and explained more fully in section 4.2.4. This code serves as a useful quantitative means for comparing the various abrasion tests, and helps in selecting a test of the desired abrasion action and severity to match a practical application.

There are however other selection criteria that must also be taken into account when selecting an abrasion test, such as cost of equipment, repeatability, obtainability of abrasives etc, and these aspects are also factored in section 4.4.

It may be concluded that the ultimate purpose of this chapter is to recommend one or more suitable abrasion tests for testing concrete surfaces, and concrete pavers in particular.

Table 4.1

Table 4.1

Notes on Table 4.1

There are eight ‘test types’, U.1 through U.8. Generally there will be several variations within a particular test type. Some of these variations may be very minor. The exact nature of the variations may be ascertained from the appendices. For example there are ten tests that all operate on the Bohme principle (U.5.1 through U.5.10), although the test method of each test differs slightly in each case. The differences represent the different preferences of the specifying authorities of the various countries.

Some explanation is warranted of some frequently used terms in the column ‘Principle of Test’, used to describe the abrading mechanisms:

- tumbling : this implies a falling, rolling and sliding action, and it is likely that most of the abrasion will take place from the initial impact following the fall
- revolving or rotating : this generally refers to the spinning of a disc, brush, or drum about its axis
- orbiting : this generally applies to abrading wheels or balls moving in a circular circuit, as the moon does around the earth
- planetary motion : this generally applies to revolving discs that also move in a larger circuit, much as the spinning earth moves around the sun

Note that some ‘severe’ tests can be converted to ‘mild’ simply by reducing the applied load, or by reducing the quantity and/or mass of the abrasives, or by reducing the duration of the test. Thus an apparatus can often be upgraded or downgraded in terms of severity by relatively simple adjustments.

Prefixes

Prefix 1: These tests are done submerged in water, which is mostly flowing

Prefix 2: All the ‘rolling’ tests have a normally applied force, and this applies to both steel balls and steel wheels. The one exception is the U.2.08 (P.E.I) test, a very mild test consisting of small steel balls freely rolling on the surface with *no* applied normal force. Note that there are other ‘steel ball’ tests that do not have an applied normal load, but in this case the balls tumble in a rotating drum, and hence these tests are not described as ‘rolling’ tests, rather as ‘impact’ tests.

Prefix 3: This test may be regarded as severe depending on the sharpness of the scratching-tip and the applied pressure.

Prefix 4: The BRE-Screed test is classified as ‘severe’ because it results in substantial indentations typically 3mm. However, this is relative to the strength of the material. In a hard structural concrete there would be no indentation.

Prefix 5: The impact action of the plunger striking the surface will result in varying degrees of abrasion wear, depending on the hardness of the surface. For hard concrete it may be limited to I2, while for weaker surfaces the damage is more likely to be I3 or even I4.

4.1 Abrasive Actions

Above it was stated that the abrasive actions of the various abrasion tests may be reduced to one or more of three actions; rolling, sliding and impact. Sometimes the term 'tumbling' is used to imply a combination of impact, rolling and sliding. Alternatively the term 'bouncing' implies a repeating impact action.

Only three tests in Table 4.1 do not involve either impact, rolling or sliding. These are non-destructive tests involving water absorption or sound propagation, and are not therefore abrasion tests in the true sense. They are however included in the table, as in certain circumstances they are good indicators of abrasion resistance.

4.1.1 Rolling

Rolling is a very common abrasive action. It occurs on the many surfaces that must accommodate wheeled traffic. It also occurs in the form of fine abrasive particles rolling beneath footwear or tyres. It may be identified in as many as 50 of the 66 tests listed in Table 4.1, although it is considered as the predominant wear mechanism in only 26 of these tests.

Rolling is considered to be the dominant abrasive action in tests where various types of steel wheels or balls roll under load. The contact pressures vary from test to test. Examples of such tests include:

- DIN 51951, MA20 (steel balls rolling under a load)
- ASTM C799 Proc B, ASTM C944 (dressing wheels rolling under a load)
- C&CA, NT BUILD 044 (steel wheels rolling under a load)

The 'C&CA' rolling wheels may be considered a mild abrasion test, typically abrading 0,2 mm after 15 minutes in a surface made hard by power finishing. Conversely other tests may be categorised as severe. For example, the very highly concentrated pressures beneath the balls of the 'DIN 51951' apparatus are capable of penetrations of 2mm for a 40 MPa concrete, in 17,5 minutes.

The abrasive actions of rolling wheels/balls will be increasingly 'mild' with:

- increasing softness of abrasive material (e.g.rubber lined wheels)
- decreasing contact pressure (related to large diameters of the wheel/ball)
- decreasing load.

Conversely 'severe' abrasion corresponds to:

- hard wheels/balls that have high contact pressures (e.g. steel wheels with small diameters, are narrow widths)
- heavy loads.

It should be noted that the influence of the load extends beyond that of merely influencing the contact pressure. A lightly loaded small diameter wheel may have the same contact pressure as a more heavily loaded large diameter steel wheel, but the stress field of the large-wheel/high-load will extend deeper into the concrete resulting in an increased rate of abrasion wear, according to Siro(1991). [For a given critical stress this means that larger aggregate particles may be debonded from the paste in the case of the large-wheel/greater-load, resulting in the loss of more aggregate particles, including some coarse aggregate. As it is the aggregate particles that generally resist abrasive forces, a substantially increased rate of wear may be expected].

The mechanism of wear in the case of rolling ball/wheels/hard-abrasive is predominantly one of crushing. However, the related cracks, be they Hertzian cone cracks, lateral cracks or axial cracks will occur in the surface *asperities* and be truly microscopic in scale in the case of 'mild' rolling abrasion. These same cracks will occur on a much larger scale, *penetrating* some tenths of a millimetre in the case of severe abrasion, or even a few mm in the case of some very severe tests.

Cracking effects from crushing of surface asperities corresponding to 'mild' rolling abrasion will be similar to items (d), (e) and (f) of figure 3.3, whereas cracking effects occurring at greater depth, corresponding to 'severe' rolling abrasion may be explained from figures 3.8, 3.9 and 3.11 respectively. A consideration of these figures together with the theory discussed in section '3.3 Wear Induced by Normal Compression' indicates that compression induced abrasion wear is relatively complex, and no simple expression for the check 3.3 corresponding abrasion wear is given. However, it seems reasonable to conclude that this abrasion wear will be proportional to some exponential of the applied normal force, W, i.e. $Q \propto W^n$, (or more correctly Q is related to the normal stress on each asperity).

4.1.2 Sliding

When a body subject to a normal load slides tangentially over a concrete surface, then that surface will experience tangential shear stresses, that in turn lead to some degree of 'sliding abrasion'.

Sliding abrasion is used throughout this text in a generic sense to represent various frictional related actions such as slewing, cutting, scraping, scratching, skidding, slipping, rubbing, polishing etc. These terms variously appear in the literature, but in essence result in different forms of abrasion induced by tangential shear stresses acting on the surface. There can also be a vertical dimension to sliding, such as occurs when the tooth of a dressing wheel slides down a protruding aggregate particle, resulting in scraping and cutting effects in the process.

Some sliding abrasion is also present even where rolling is the dominant action. For example in the case of steel balls/wheels rolling under load, sliding abrasion is a secondary abrasive action relative to rolling abrasion. On the other hand, it is probably the dominant action in the case where fine abrasives are used as the abrading medium. In practice this translates to fine abrasive particles sliding beneath footwear, or sliding abrasion occurring in vehicular traffic where vehicles accelerate, brake or corner on dust/sand covered surfaces. Sliding abrasion may be identified in as many as 57 of the 66 tests of Table 4.1, and is considered as the dominant wear mechanism in as many as 21 of these tests. In some of these cases, as in U.6.02 through U6.05, sliding abrasion *completely* drives the abrasion process. In other tests such as U.5.01 through U.5.17, where a fine abrasive slides/rolls under load across the face of the specimen, sliding abrasion is likely to be the dominant though not exclusive action.

Generally the average vertical stress beneath the 'abrasive' of a sliding-abrasion test is significantly less than for a rolling abrasion test. The rolling-abrasion test relies on making relatively deep indentations resulting in crushing effects. Were the penetrations of the sliding-abrasion test to be as deep, it would take a great deal of force to plough/slide/cut the abrasive through the concrete, i.e. the abrasion equipment would need to be massive.

Thus sliding-abrasion tests mostly work on the principle of making tens of thousands of very shallow scratches via the abrasive, (see U.5.0.1 through U.5.17 and U.6.01 through 6.05)

In true ‘sliding-abrasion’ the static/dynamic coefficient of friction will determine the lateral resistance, whereas if there is an element of rolling the ratio of lateral resistance to normal force will be less.

As in ‘mild’ rolling abrasion, ‘mild’ sliding abrasion may be related to the removal of the surface asperities. This may be as the result of direct *shear* failure of an asperity in the face of the advancing horizontal force. Alternatively, if the force is applied near the top of the asperity and if the asperity is relatively tall and thin (i.e. it has a large aspect ratio) then it is possible for the asperity to fail in *flexure* and snap off at its base.

Sliding abrasion will occur at a substantially increased rate if there are already cracks present in the asperities as a result of vertical crushing effects (see (d), (e) and (f) of figure 3.3). However, providing these cracks are microscopic in scale, the resultant abrasion wear from such sliding abrasion is likely to remain ‘mild’. Furthermore, if the rate of this abrasion is proportional to the load W, and inversely proportional to the hardness, H, i.e. $Q \propto W/H$, then it seems reasonable to consider the concrete as behaving as a *plastic* material, since these are the criteria that apply to Archard’s equation [see expression (3-1)] for *plastic*-deformation wear.

On the other hand ‘severe’ sliding abrasion will occur where a hard object is pressed a few tenths of a millimetre or more into the surface and made to slide (e.g. a protruding nail beneath a pallet that is made to skid through the surface). ‘Lateral cracks’ of corresponding depth will occur, as was illustrated in figure 3.19. Relationship (3.19) as given in 3.4.6, indicates that severe sliding abrasion in a brittle material is proportional to some exponential of the load and the square root of the material’s hardness, while it is inversely proportional to the square of the toughness.

4.1.2.1 Special Cases of Sliding

Hutchings(1992) explains that whereas under zero load a cylinder or sphere [i.e. a steel ball or a steel wheel in the context of the abrasion tests under review] will roll over an elastic plane surface without slipping, when it supports a load some local slippage occurs in the following ways.

(a) Reynolds slip

Cylindrical rollers and spheres will both experience Reynolds slip due to the progressive stretching of the surface within the contact region. Figure 4.1 illustrates a cross section through a cylinder, rolling over an originally plane surface under load. The surface between B and D has been stretched to accommodate the cylinder. Reynolds envisaged that the strain in the surface would be greater at points C than at B or D, and that there would therefore have to be some differential movement between the surface of the plane and the surface of the cylinder as the cylinder rolled.

However, given the relative stiffness of both concrete and steel, the degree of elastic deformation is likely to be so small that this abrasive action will contribute very little to the actual abrasion that occurs. Hutchings states: ‘It is now clear, however, the Reynolds slip is of minimal importance, even in the rolling of steel spheres on rubber where the surface strains can be quite high’. This is exactly what happens when a car tire rolls over a concrete surface where the coarse aggregate is prominent relative to the mortar constituent. This amounts to turning figure 4.1 upside down and seeing the sphere as the aggregate particle, so that the rubber tire progressively stretches over the aggregate particle. According to Hutchings there is only a small degree of abrasion from the resultant slip. However, any fine dust particles that are likely to be resting on the protruding aggregate particle at the time, being much harder than rubber, will result in a substantially greater shearing effect, as they are made to slip relative to the coarse aggregate particle

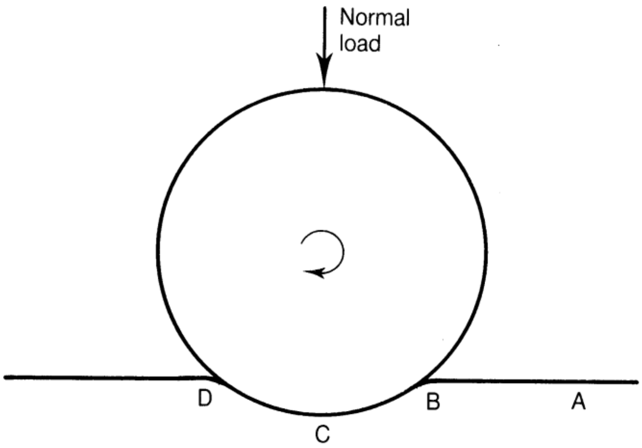

Figure 4.1 Cross section through a sphere or cylinder rolling over an elastic surface, illustrating the origin of Reynolds slip. [Hutchings(1992)].

by the action of the rubber stretching over the protruding particle. This type of sliding/rolling action is simulated by most of the U5 series of abrasion tests of Table 4.1.

(b) Heathcote slip

A second type of slip occurs with spherical rolling elements and not with cylindrical rollers. Figure 4.2 shows in plan view and in section a sphere rolling under load in a cylindrical grove. This is precisely what occurs in abrasion tests where a bearing is made to orbit under load in a ball-race (e.g. U2.12 through U2.16). Given that the ball/concrete contact zone is elliptical, if the sphere rotates through one complete revolution, the point A on the surface will have traveled a distance $2\pi r$ while point B has traveled the smaller distance $2\pi r'$. Since the sphere moves as a rigid body, slip must therefore have occurred within the contact region in order to accommodate this difference; this differential slippage is called *Heathcote* slip. (Figure 4.1 assumes that the grooved track is straight, but the effect also applies in a circular track).

Hutchings states that Heathcote slip makes a considerably greater contribution to rolling resistance than does Reynolds slip. In bearings this slip will cause surface damage that can lead to ‘severe wear or early failure’ in unlubricated bearings. This is most relevant to the abrasion tests under consideration as the abrading media are either non-lubricated or only water lubricated. (Water is not effective in preventing surface contact between ball/wheel and concrete).

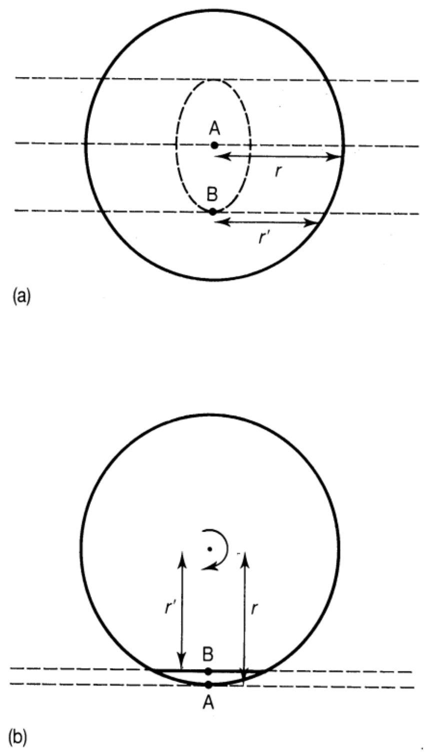

Figure 4.2 (a) Plan view and (b) section through a sphere rolling over a bearing track, to illustrate the origin of Heathcote slip. [Hutchings(1992)].

(c) Wheel slip

Finally, a third type of slip occurs with cylindrical rollers rolling in a planetary circuit, as occurs in all the U4 series of abrasion tests of Table 4.1. Tangential shear is the result of sliding caused by a continuous change in direction of the wheels. The degree of slip is related to the width of the wheels and the circumference of the circular track, since these factors determine the extent that the outside edge of the wheel has a proportionally greater path to travel around the circle than the inside edge.

The net effect of the three sliding mechanisms described in the preceding paragraphs must be superimposed on other sliding mechanisms described at the beginning of this section, such as slewing, braking, acceleration, frictional drag etc., leading to increased sliding and hence increased sliding abrasion.

4.1.3 Impact

The term impact implies the collision of one body against another. This may equally apply to abrasion or erosion. In the case of *erosion* the colliding particles are generally wind driven or water borne. On the other hand *abrasion* loads may include ore falling down concrete lined ore passes, or concrete floors in a heavy engineering environment where hard and heavy objects are dropped.

Fourteen of the 66 abrasion tests listed in Table 5.1 may be considered to operate on the principle of impact. These range from very severe tests such as Abram's tumbling heavy steel balls (U.2.01) or Fwa's tumbling cubes (U.1.01), to tests of intermediate severity such as SABS 541 (U.2.04) and AS/NZS 4456.9 (U.2.03), which also operate on the principle of tumbling balls, but in this case the balls are much lighter and tumble from a much lower height. At the other end of the scale are impact tests that may be classified as mild in that any cracking effects will be limited to the surface asperities. The ASTM C418 sandblast test (U.5.21) is an example of this.

A feature of impact tests is that the abrasion wear is caused by the kinetic energy of the abrasive particle, expressed as $½.m.U^2$, where U is the velocity of the particle just prior to impact, and m is its mass. In this respect impact tests differ from 'rolling abrasion' and 'sliding abrasion' where the abrasion wear is caused by a normal load from an abrasive medium that is relatively static. Even in the MA20 test, where the balls orbit at 1000rpm, their velocity in the vertical direction is almost nil, and is limited to whatever bounce/vibration may be in the system.

Notwithstanding these differences, the resultant damage and abrasion wear from impact is similar to that occurring in either '4.2.1 Rolling' or '4.2.2 Sliding', or a combination of the two. Clearly and impacting particle will either result in crushing or shearing effect – both involve the development of cracks, the nature of which are related to the severity of the impact. For mild forms of impact, abrasion wear is limited to crushing and shearing of asperities (illustrated in figure 3.3), while various forms of cracking at sub-asperity depth are the outcome of severe forms of impact (illustrated in figures 3.8, 3.9, 3.11, 3.18 and 3.19).

The degree to which impact abrasion emulates rolling as opposed to sliding depends on the angle of attack, and this may vary as the test proceeds. For example, in the initial stages of a sandblast test the impact angle, θ, will be 90°. The corresponding mechanism of wear will be that of crushing. As a crater forms, this angle will be reduced. Hutchings(1992) reports that for brittle materials wear is at a maximum when this angle is 90°, decreasing to zero as the angle of attack approaches 0°, whereupon the abrasive barely glances against the surface. Clearly, for smaller angles of θ, the mechanism of wear will shift to that of shearing.

The influence of the angle of attack on abrasion wear is illustrated in figure 4.3.

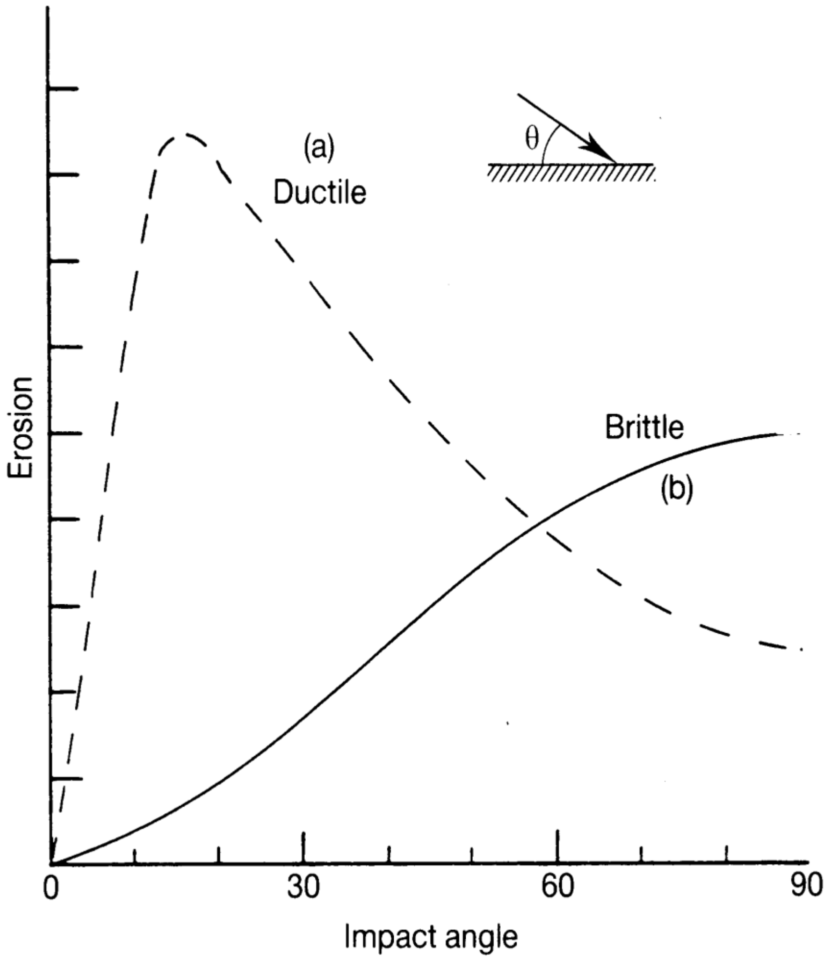

Figure 4.3 Influence of angle of attack on abrasion wear. [Hutchings(1992)].

Other than the angle of attack and the general principle of kinetic energy, there are other factors influencing the rate of abrasion. These differ depending on the severity of attack, i.e. 'mild' or 'severe' impact abrasion, and are considered below for the two cases:

(a) Mild Impact Abrasion

In this mode of wear the impacting particle does not impart a significant amount of kinetic-energy to the concrete, limiting shock. Therefore any cracking is confined to crushing or shearing effects of the surface asperities, illustrated in figure 4.4 (a) and (b).

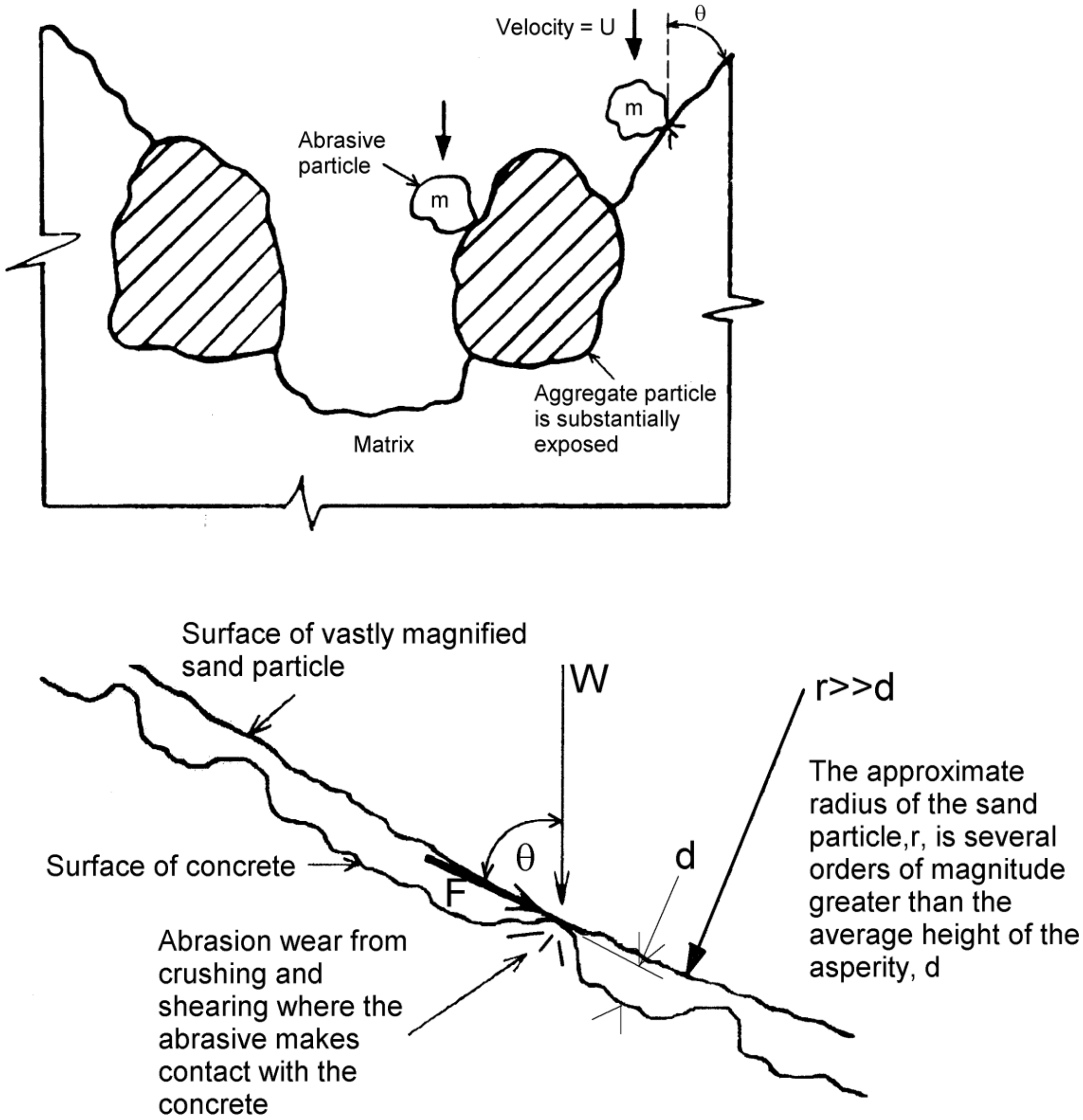

Figure 4.4 (a) The abrasive sand is seen to impact against the surface at an angle θ, causing microscopic crushing and shearing effects of the surface asperities, as seen in (b).

The corresponding abrasion wear, Q, may be described by:

$Q = K.\ f(\theta).(\ m.U^n/2)/H.$ ……. (4.1)

where:
Q = volume of material being removed (mm^3)
m = mass of impacting particle
U = velocity of particle immediately before impact
n = velocity exponential (note that in some more advanced models n>2, i.e. 2<n<2,5)
K = a constant that implies that only some fraction of the material attacked is displaced
f(θ) = a factor related to the angle of attack, θ, that indicates the mass of material removed relative to the mass of the attacking particles (e.g. see figure 4.3)
H = indentation hardness

This expression is derived for materials that behave plastically, and concrete only exhibits a form of plastic behaviour where the severity of the abrasion force is below a certain threshold, i.e. where Q of (4.1) is below a certain critical value. For a given angle of attack on a concrete of a given hardness it is the level of kinetic energy imparted that determines whether the concrete has a plastic or brittle response. The heavier the abrasive particle, the slower must be the velocity if the mode of attack is to remain 'mild', and vice versa, although clearly U is the dominant factor in the relationship. This explains why the SABS 541 tumbling ball abrasion test may be considered 'mild'. The rotating impact box revolves at a relatively slow 60 rpm, and the steel balls have a diameter of only 13,2 mm. Thus 'U' and 'm' are sufficiently small to limit the kinetic energy imparted by the tumbling balls. (Doulgerous(1996) considered the 13,2 mm steel balls too light and yielding too mild an abrasion wear, and increased the size to 25mm in a modified PCI test). On the other hand the sand particles associated with the ASTM C418 sandblast test has a very much greater 'U', but the 'm' of a 0,6 mm silica particle is of the order of $[(13{,}2^3 \,.\, 7{,}8) / (0{,}6^3 \,.\, 2{,}6) =]$ 32000 lighter. This allows its velocity to increase by a ratio of $\sqrt{32000} = 178$ (unlikely!) for the equivalent impartation of kinetic energy. However, even though the kinetic energy of each particle in the sandblast test is slight, there are a very substantial number of 'blows', concentrated on a small area, resulting in considerable rate of abrasion in that area.

(b) Severe Impact Abrasion

In contrast to the mild abrasion tests mentioned above, other abrasion tests such as 'Abram's tumbling balls' and 'Fwa's tumbling cubes' may be considered 'severe' impact abrasion tests. The severe impact tests are the most abrasive of all the 66 abrasion tests listed in Table 4.1. The internal working diameter of the Talbot Jones Rattler after the fastening of Abrams' specimens is approximately 1m. Contrast this to the 0,3m of the SABS 541 impact box. This means that the balls inside the Talbot Jones Rattler had much further to fall and hence had a greater 'U'. However, the increase in 'm' was even greater, since at least 10 of Abram's balls were 95mm in diameter. This implies an increase in mass ('m') of $95^3 / 13{,}2^3 = 373$.

It is therefore not surprising that Abrams obtained abrasion depths varying between 13mm through 50mm. Similarly Fwa's tumbling cube test may also be described as very severe, resulting in mass reductions in excess of 70%.

In section 3.3.5 and 3.4.6 expressions were given that showed that cracking is reduced by increasing 'fracture toughness' and reducing 'indentation hardness'.

Hutchings(1992) also gives a relationship that predicts wear in brittle materials subject to *impact* as follows:

$$Q \propto m \,.\, r^{0,7} \,.\, U^{2,4} \,.\, \sigma^{0,2} \,.\, H^{0,1} / K_c^{1,3} \quad \ldots\ldots. (4.2)$$

where:

Q = abrasion wear in mm^3
m = mass of abrasive particle
r = radius of particle
U = velocity of particle prior to impact
σ = density of abrasive particle
H = indentation hardness of concrete
K = fracture toughness of concrete

From this expression it may be said that *severe* impact abrasion:

- is improved only very slightly by increasing the hardness. (This therefore differs from 'mild impact abrasion' where abrasion wear was shown to follow an inverse relationship with hardness).

- reduces significantly with increasing toughness
- increases slightly with increasing density of abrasive particle
- increases very markedly with increasing velocity of abrasive particle
- increases with increase in ‘radius’ of abrasive particle
- increases with mass of abrasive particle

By comparing (4.1) with (4.2) it is immediately apparent that there are more factors governing severe impact abrasion relative to mild impact abrasion (r, σ, and K are not a consideration in mild impact abrasion), and that those that are common to both do not necessarily behave in the same way.

4.1.4 Abrasion Wear Code

It has already been postulated that all abrasive actions may be reduced to either rolling, sliding or impact, and these have been considered in the three preceding sections.

It has also been shown that abrasion may either be ‘mild’ or ‘severe’, where the former results in the crushing or shearing of the surface asperities, while the latter is accompanied by various forms of cracking in the sub-asperity zone.

In this section therefore the 66 abrasion tests are codified in terms of the type of abrasive mechanism (rolling, sliding, impact) as well as the severity of abrasion (mild or severe). In doing this it is necessary to further divide both mild and severe abrasion wear into two further categories. Accordingly mild abrasion may result in either *minor* crushing of the asperities, or *major* crushing. Similarly, severe abrasion will result either in *shallow* sub-asperity cracking, generally a few tenths of a millimetre in depth, or alternately the cracks will penetrate one or more millimetres below the surface, referred to as *core* cracking.

Thus it is possible to have a code with abbreviations that imply:

R = rolling abrasion
S = sliding abrasion
I = Impact abrasion
1 = mild abrasion that results in minor crushing of the asperities
2 = mild abrasion that results in major crushing of the asperities
3 = severe abrasion that results in shallow sub-asperity cracking
4 = severe abrasion that results in ‘core’ cracking

Clearly this notation allows each of the three abrasive actions four possible outcomes in terms of abrasion wear. The scope of this classification is illustrated in figure 4.6.

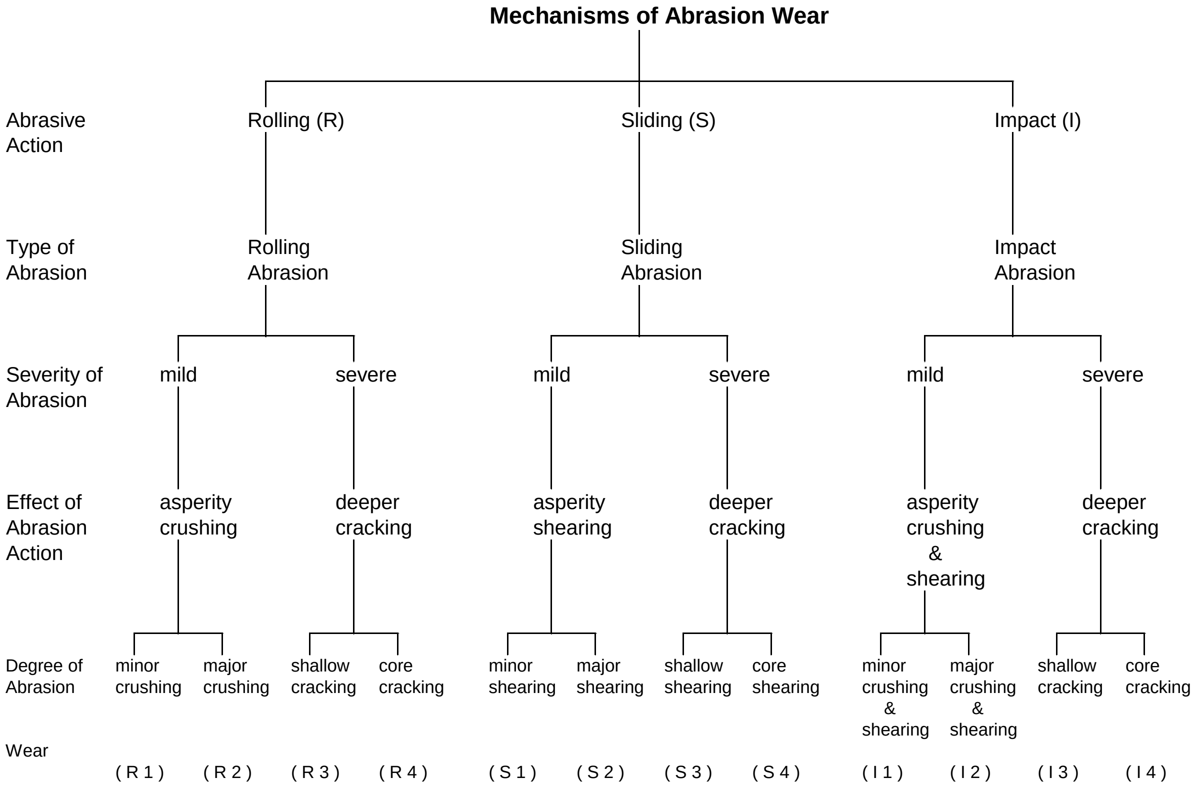

Figure 4.5 Elements that make up the abrasion wear code

There is also the additional possibility of an abrasion test having a zero intensity for a particular abrasive action, i.e:

0 = no abrasion

The *abrasion wear code* is a most useful way of classifying the various abrasion tests in terms of the abrasive actions and the severity of those actions. For example 'Abrams' tumbling balls' (U.2.1) will clearly have elements of rolling, sliding, and impact abrasion and furthermore the impact effects from 95mm steel balls falling from a possible height of 1m is clearly likely to cause more damage than if the balls were merely rolling or sliding along the surface.

The abrasion code R2S2I4 therefore implies that the abrasion wear corresponding to the impact (I) of this test is judged to be very severe (4), resulting in cracking of a millimetre or more, and this is borne out by eventual abrasion wear depths of up to 25 mm in Abrams' tests. On the other hand the rolling abrasion (R) and sliding abrasion (S) is respectively restricted to asperity crushing and shearing, albeit on an extensive or 'major' (2) scale. (The heavy steel balls have no externally applied load while rolling or sliding, and these actions are not therefore expected to result in any form of cracking, unless they bounce, but bouncing is an impact effect, and is therefore considered under 'I').

To further illustrate how the abrasion wear code may be applied to an abrasion test, the ASTM C418 abrasion test is now considered. Here the abrasion code R0S0I3 implies that there is no rolling abrasion or sliding abrasion, since a grain of sand rolling or sliding would result in negligible rolling or sliding abrasion. Clearly its ability in abrading the surface lies in its high velocity, but given its low mass, the impact damage is judged to be only mildly sub-asperity, i.e (3). However given the intensity of the attack (the huge number of sand-grains and their high velocity) on a relatively concentrated area, these abrasions add up to give an average depth of wear that generally exceeds 1mm, even for concrete with compressive strengths in the region of 60 MPa.

This raises the question: ‘Should the test not be classified as I4, seeing that the overall penetration exceeds 1mm?’

To answer this question, it is the individual effect of a single encounter that determines the severity of a test, since it is a simple matter to increase or reduce the duration of a test. In the case of the ASTM C418 test the penetration of the high velocity sand is likely to be just sub-asperity, hence I3, whereas the impact of a 95mm ball in Abrams’ test is likely to cause cracking at a depth of a few millimetres, hence I4.

In table 4.1, all 66 tests have been allocated an abrasion wear code based on the above stated criteria. Clearly this has involved a considerable degree of subjective ‘engineering judgement’ on the part of the writer. It is based on the understanding and ‘feel’ he has developed on the subject, from his own experimental work, his reading on the subject of abrasion resistance, and many years of mental ‘incubation’.

4.1.5 Recurrence of Wear Mechanisms

The ‘abrasion wear code’ discussed above has the ability to give the reader a quantitative grasp of the three abrasion actions, each with five possible outcomes of severity. However, although this allows 5x5x5=125 different ways of categorising an abrasion test, it does not mean that the essential wear mechanisms are so varied. In fact, qualitatively, the wear mechanisms of the tests are very similar.

Figure 4.6 shows, pictorially, the abrasion wear mechanisms of 11 different abrasion tests. It may be seen that regardless of the abrasion test or abrasive action, abrasion wear may generally be classified into two broad categories:

1. crushing or shearing of asperities – mild abrasion. Note that the vertical aspect of the asperities has been magnified to emphasise this effect. Normally the slope of even microscopic asperities is less than 10^0 [Hutchings (1992)].

2. sub-asperity crushing – severe abrasion. Note that in both cases (1) and (2), cracking may take the form of Hertzian cone cracks, lateral cracks, or axial cracks. Clearly the size of the cracks in (1) are limited to the height of the asperities and will therefore be very much less than in (2).

The selection criteria used to choose the eleven tests of figure 4.6 were:

1. that the test must be a current test method in use

2. that it should if possible represent a different generic block of tests (see U1 through U8 in table 4.1) in order to demonstrate commonality across generic boundaries

It may therefore be concluded that while there are many different tests, each with its own abrasion wear code, there are in reality only two abrasion wear mechanisms.

From this it would appear that most abrasion tests do more or less the same things to the concrete surface. Certainly this understanding does take a lot of the mystery and ‘black art’ out of abrasion testing. It also appears to validate many of the tests. But it should be remembered that within the two broad categories cited above the tests differ in intensity, which is not quantitatively reflected in the visuals of figure 4.6, but *is* defined by the ‘abrasion wear code’. With a proper understanding of the ‘abrasion wear code’ it may be possible to apply the findings of a particular test to several applications. Alternatively, where applications require very specialized testing, the ‘abrasion wear code’ will help to locate the correct abrasion test.

Figure 4.6 Selected Key Abrasion Tests and Corresponding Abrasion Wear Mechanisms

4.3 Shortcomings of Abrasion Tests

In the previous section the abrasive actions of the various abrasion tests were considered.

However, when deciding on an abrasion test, there are many other factors that should also be considered along with the mechanism of wear (especially seeing that the wear mechanism of nearly all abrasion tests, qualitatively, are very similar).

Some of these ‘other factors’ have not been properly understood in the past. This has resulted in investigators at times using tests that were not ideally suited to their ends, even leading to incorrect conclusions being drawn.

In this section the various abrasion tests of Table 4.1 will be considered in the light of their suitability for testing concrete pavers.

The approach will be to start by identifying the shortcomings of the various abrasion tests, and these are listed in Table 4.2 under the headings ‘primary problem’ and ‘secondary problem’. Where a problem is considered insurmountable in that it is caused by a particular intrinsic characteristic of the test that cannot be modified, then the lettering in the column in question (in Table 4.2) will be in *italics*. For example, if the abrasion is too severe, such that each individual contact causes deep cracks, then in this case *italics* will be used to show that the test may involve ‘severe rolling’ and therefore does not reflect the steady gradual abrasion process that is usual in an application involving, say, pedestrian traffic. (On the other hand, other tests that have a relatively deep final abrasion may be converted from a ‘core’ to a ‘surface’ abrasion test, simply by reducing the duration of the test, and where this is possible, the test is not marked down as too severe)

Having surveyed the various ‘problems’, those with the fewest *serious* flaws are put forward in a shortlist, for further consideration in section 4.4.

The ‘primary problems’ and ‘secondary problems’ mentioned in table 4.2 are discussed in greater detail hereafter under a number of headings. The general approach will be to review the 16 ‘problems’ listed in Table 4.2, with special reference to those tests that are affected by them.

4.3.1 ‘Severe Impact’

Generally concrete pavers are subject to vehicular and pedestrian traffic, resulting in gradual abrasion, and thus a suitable abrasion test should not be too severe, and in particular should not result in fracturing of the surface and especially not the surface aggregate.

The two tests that make up the U1 series of tests consist of specimens tumbling in a concrete drum. Similarly the first two of the U2 tests also involve tumbling onto the concrete specimens by means of heavy steel balls (95mm and 25mm in diameter respectively). The falling balls possess a substantial degree of kinetic energy resulting in severe impact, deep cracking and rapid loss of material. While not suited as a paving abrasion test they will be ideal for checking concrete destined for stilling basins and workshops for heavy engineering, etc.

4.3.2 ‘Slow’

Whereas the heavy tumbler tests result in rapid abrasion loss, those with small steel balls tend to be slow, as those detailed in U.2.04 through U.2.06. This means that tests need to run for several hours, during which time the balls gradually crush and shear the surface asperities. However from the standpoint of regular abrasion-wear this is preferable to having heavy balls that cause the aggregate to fracture.

4.3.3 'Too mild'

Certain tests result in minimal abrasion wear, such as the very small rolling balls (5mm) of U.2.08 and the revolving pads of U.6.01. These tests will barely produce a measurable result, except in the most inferior of concretes.

4.3.4 'Severe Rolling'

'Severe rolling' generally occurs from steel balls or steel wheels with relatively small diameters, made to roll under load. The 'wheels' may also have irregular surfaces, such as dressing wheels, steel chained tyres, steel studded tyres or even caterpillar tracks. The small contact areas in the case of steel balls, especially in the initial stages of the test translates into high tensile stresses, and hence various forms of cracking are possible, including Hertzian cone cracks, lateral cracks and axial cracks. There are many tests of this kind and these are detailed in appendices U.2.09 through U.4.03.

4.3.5 'Can't Measure Aggregate/paste Bond'

A weak paste bonds weakly to the aggregate, so that the aggregate is easily plucked out. Since the aggregate forms the bulk of the concrete, and since it is generally substantially harder than the paste, any test that prevents the loss of aggregate after the aggregate/paste bond has failed, gives a false impression of the abrasion resistance. Many tests have this failing, and are listed in Table 4.2 as U.5.01 through U.5.12 as well as U 5.16. Invariably the tests involve a fine abrasive that grinds the specimen under load. However the fineness of the aggregate also ensures that there is only a small gap between the specimen and the grinding disc, and this is so small that the aggregate is usually trapped in position, even though it may no longer be bonded to the aggregate. Thus the relatively hard aggregate continues to resist abrasion, whereas in practice it would be removed by abrasive forces. This can be particularly misleading in abrasion tests where a very hard aggregate is used with a relatively soft paste.

4.3.6 'Aggregate does not Contribute'

The shortcoming of the tests discussed under the previous heading is that they are unable to discriminate between the stronger and weaker constituents of the concrete. On the other hand, there are also problems associated with tests that discriminate too well. Although these tests attack the full surface, the weaker paste constituent will abrade at a far greater rate, since it is not protected in any way. The abrasive material steadily picks its way through the weaker paste until an aggregate particle is sufficiently exposed so that it can be dislodged. Such tests mostly have abrasive material consisting of pneumatically blasted fine sand or fine wire bristles, and are listed as U5.19 through U5.22 and U6.02 through U6.03 in Table 4.2. It is by virtue of the fineness of these abrasive materials that they are able to get in between even relatively small fine aggregate particles and scratch out the weaker paste. (Other tests such as small tumbling steel balls also attack the surface indiscriminately, but clearly a ball that is 13,2 mm will have a certain 'span' that prevents it from penetrating between fine aggregate particles, or even from going much between the coarse aggregate particles. The aggregate particles in this case 'contribute' to abrasion resistance, and this is the general case in practice under vehicular or pedestrian traffic. Even if the surface is covered with a substantial degree of fine abrasive and is trafficked, there is a limit to how far the fine aggregate can penetrate). Therefore tests that can scratch or blast their way deep into the core concrete, and so erode the aggregate

Table 4.2

Table 4.2

out, do not measure the ‘contribution’ that the aggregate *makes in practice*. In this regard it may be said that sand-blast tests are the most misleading, since there is a limit to how deep the wire bristles of the wire-brush test can penetrate without a general penetration, whereas the sand, given its size and velocity is capable of penetrating as much as 15mm or more.

On the other hand, where a significant percentage of large coarse aggregate has been used, say 26mm, the rate of penetration of both the wirebrush and sandblast tests will soon slow down and reflect the abrasion resistance of the coarse aggregate. Instead of removing the large particles, these virtually arrest further penetration, whilst remaining firmly embedded at their base ends. Olorunsogo(1999)’s results showed that where a high proportion of large aggregate particles are used, the wire-brush test becomes meaningless. The penetration of the brush is brought to a virtual halt on reaching the coarse aggregate. The bristles that do scratch in between and around these particles are unable to penetrate far enough to sufficiently expose enough of the aggregate to materially increase the aggregate/paste bond stress. The same effect may be expected from sand-blast tests. Furthermore, the comparatively small aperture size of the shield (that is placed over the specimen), relative to the size of the coarse aggregate, means that at times it is only this aggregate that is exposed to the abrasive.

To conclude it may be said that for fine aggregate and relatively fine coarse aggregate (less than 9,6mm), the aggregate contributes minimally to abrasion resistance as determined by the wire-brush and sand-blast tests, as it is simply eroded. Since concrete pavers are typically made precisely from such relatively fine aggregates, the wire-brush and sand-blast tests do not measure the contribution of the aggregates, and thus do not reflect what happens in traffic, except where excessive grit and sand is present on the surface. On the other hand, in conventional concretes where the coarse aggregate size is typically 19mm or more, after a settling in period, the hardness of the coarse aggregate will contribute almost 100% towards the ‘abrasion resistance’ of the concrete, and this *will* be reflected by these tests.

Initial surface absorption tests (ISAT), e.g U.8.01 and U.8.02, are very sensitive to the strength and density of the surface concrete, and in this respect are good indicators of abrasion resistance. However they are unable to gauge the hardness of the aggregate, a serious shortcoming given the important contribution of aggregate hardness to abrasion resistance.

4.3.7 ‘Skill and Interpretation Required’

The ‘diamond tip scratcher’ and the ‘Mohs hardness scratcher’ (see U6.04 and 6.05 in Table 4.2) are not conventional abrasion tests, but do give a good indication of the hardness of the surface, and this in turn *is* related to abrasion resistance. Both tests require a level of understanding. In the case of the Mohs hardness test, the correct minerals must be identified, and a consistent sharpness of crystal should be used to scratch with. In both tests it is important to apply a consistent pressure and angle. The scratch depths should be interpreted in the light of comparable depths obtained in concrete of known or acceptable abrasion resistance.

4.3.8 ‘Only for Screeds’

The limitation of U.7.01 is that it should only be used to test screeds (which are relatively soft compared to hard concrete). In this case the test may be considered as a deep abrasion test, and results in various kinds of cracks to some depth into the screed.

4.3.9 'Repeatability Poor'

The rebound hammer (see U7.02 in Table 4.2) is a direct measure of the hardness of the surface and should therefore be a good indicator of abrasion resistance. According to BS 1881:Par202:1986 the characteristics of a concrete surface which govern abrasion resistance have been shown to correlate reasonably well with those characteristics which determine rebound hammer readings.
However, rebound hammer readings in paving is complicated by the fact that the paving is the topmost layer of a *flexible* pavement. Each paving unit is not necessarily supported to the same extent by the bedding sand, which may also be variable in thickness and compaction from one area of the site to another. The jointing sand between pavers may also vary in density, allowing different degrees of load transfer from one unit to the next. All these influences are likely to effect the rebound hammer readings. Where paving is tested in a laboratory, special care is required in clamping the blocks if the rebound is to be consistent.

4.3.10 'Measures Core Qualities'

Ultrasonic pulse velocity, see U.8.03, requires a minimum specimen thickness of 150mm, whereas virtually all pavers are 80mm or less in thickness. Moreover the test is a measure of the average density of the concrete, and is therefore only an indication of abrasion resistance where the surface and core concrete have the same density.

4.3.11 'Expensive Equipment'

Appendices U.2.01, U.2.09, U.3.01, U.3.03 through U.3.05, U.5.01 through U5.05, U5.07 through U.5.09, U.5.17, U.6.03 show photographs or diagrams of abrasion testing equipment that is relatively elaborate and costly. Although the purchasing of such items may be within the grasp of a large commercial concrete laboratory, it will be a major financial burden to a small or medium size producer of concrete pavers, who wishes to do routine quality control testing. On the other hand, some of this equipment, such as that used for testing according to the Bohme principle, may be modified to something slightly smaller and more affordable. For example the equipment specified in BS 812 : Part 113 (see appendix U.5.06) is a simplification of the 'Bohme' test equipment. The reciprocating table shown in U.5.17 could equally well be made much simpler and would then be affordable.

4.3.12 'Water'

ASTM C1138 (see appendix U.2.07) is an abrasion /erosion test that consists of steel balls tumbling in a circular orbit in swirling water. The water will assist in plucking out aggregate that has become unbonded. Similarly there are a number of tests modelled after ASTM C779 Proc C (which in turn was modelled after the Davis test) that use water to flush out abraded particles (see U.2.10 through U.2.16). In addition the effect of water being forced into minute cracks as the loaded balls roll over on top has the potential to cause very high momentary hydraulic pressure in these cracks and surrounding pores that is potentially destructive. Sukandar(1993) showed that paving that is soaked prior to testing using the ASTM C779 Proc C apparatus has a substantially lower abrasion resistance relative to dry tested pavers.

Far from being a shortcoming, it may be argued that concrete surfaces subject to tired traffic will in fact experience just this kind of cyclical hydraulic pressure during rain, and that the use of water in the test is therefore justified.

4.3.13 'Odd Sized Specimens'

The apparatus of U.2.07 requires that the test specimens be cast as a circular disc of a certain size to fit into the apparatus. This is clearly a disadvantage when it comes to testing pre-formed concrete pavers. In this case it will be necessary to substantially modify the apparatus so that it can take rectangular or square specimens.

Generally the tumbler test apparatuses of U.2.01 through U.2.05 also require special adaptation to mount the pavers. This has been done in the case of U.2.03.

On the other hand, the grinding tests operating on the Bohme principle require that the sample be sawn to the plan area of 70mm x 70mm. This shortcoming is more of a nuisance than a serious problem.

4.3.14 'Large Track Diameter'

Many abrasion tests consist of steel wheels moving in a circular orbit with a diameter that is greater than the least dimension of the paver. This diameter may vary from 225mm in the case of the C&CA steel wheel test (see U.4.06) to 60,6 m in the case of the track shown in appendix U.3.2. The Norcem studded wheel apparatus runs on a track of 6m in diameter.

Overcoming this difficulty for relatively small diameter tracks of up to 500mm is not insurmountable. It will require a sawing operation to give the pavers a trapezoidal shape. The bases of these blocks may then be set into a circular mould using a grout or resin with their upper faces clamped to a perfectly horizontal plate during the setting period. A similar process can be followed with the larger diameter tracks of the studded wheel machines (see U3.03 through 3.05), up to 6m in diameter, but the shaping and levelling processes clearly requires skilful workmanship.

4.3.15 'Outdated Test

In selecting an abrasion test, it is always preferable to decide on one that is in use at the current time, and preferably one that already appears in a recognised national standard, e.g. ASTM, BS, EN etc. Therefore a test that was used many years ago and that is no longer in use, and moreover may have been used on only a few occasions, is not ideal. However, this does not *necessarily* mean that the test is flawed from a materials engineer's point of view, and could still be considered if other tests do not yield a satisfactory result. The reciprocating table test (U.5.17) is a good example. The test seems to have all the correct abrasion mechanisms, but is no longer used. It would not be difficult to build a simplified cost effective version of that apparatus, that would be ideal for testing concrete pavers.

4.3.16 'Abrasives Difficult to Obtain, or Expensive.'

This would apply to a test such as Mohs scratch hardness test (U.6.05), where the minerals corresponding to Mohs scale may not be readily available. On the other hand the cost of the abrasives used in various tests should also be considered, particularly if the test is to be useful for daily checks on the quality of the previous days production and later for final verification prior to dispatch. Consideration should therefore variously be given to the cost of ball bearings; dressing wheels; hardened steel wheels; accessing a fine abrasive of consistent hardness/size/shape; wire-brushes etc.

4.4 Abrasion Test for Concrete Pavers

4.4.1 Shortlist

South Africa does not have a formal abrasion test for concrete pavers. This has led to serious and unacceptable abrasion wear in the past, and continues to be a problem.

In section 4.3 the main weaknesses of the various abrasion tests were highlighted in an attempt to isolate the most suitable abrasion test for adoption into the national standard. It may be seen from Table 4.2 that only a few of these tests emerge relatively unscathed. Accordingly the following three tests are judged to be worthy of further consideration for inclusion into the national standard SABS 1085 as a recommended abrasion test:

- C&CA – steel wheels (appendix U.4.06)
- AS/NZS 4459.9 (appendix U.2.03)
- ASTM C779 Proc A (appendix U.5.15)

None of these tests are currently in use in this country. However two tumbler tests, similar to AS/NZS do exist locally and are described in appendices U.2.02 and U2.04. It is also possible to conduct tests locally at two institutions (SABS and C&CI) that are similar in principle to ASTM C779 Proc A. Like ASTM C779 Proc A they use an abrasive as a grinding agent, and these tests are respectively described in U.5.02 and U.5.16. However, a serious flaw in these two tests is their inability to correctly predict aggregate/paste bond (explained in the previous section), and for this reason these tests have been passed over.

The test selected quite recently as the current European standard test for testing the abrasion resistance of concrete pavers, discussed in appendix U5.12, is also considered not able to correctly predict aggregate/paste bond (it does not allow debonded aggregate to fall out), and has therefore not been selected for further consideration.

Other tests that have been conducted in this country (or are still current), notably MA20SA, ASTM C418, and the C&CI wirebrush test (described respectively in appendices U.2.15, U.5.21 and U.6.02) are also not included in the recommended list, for reasons given in section 4.3. A special point of interest in this regard is that Papenfus (1994), in comparing the C&CI wirebrush, MA20SA and ASTM C418 abrasion tests, concluded that the MA20SA was the best of the three and recommended it be adopted into the national specification for the manufacture of concrete pavers. However, the scope of the testing done at that stage was limited to those three tests, and only a precursory consideration had been given to *some* of the other tests listed in table 4.1. Nor were the principles and mechanisms of abrasion wear well understood.

In the following section the three selected tests (from the list of 66) will be scrutinised relative to the criteria considered important for an abrasion test.

4.4.2 Important criteria of an Abrasion Test

(a) Mild Impact

Mostly paving is used for pedestrian or vehicular traffic. Stones trapped in the tread of tires and heels will impart a *mild* degree of impact. (In both cases the stone has minimal velocity in the downward direction at the time of impact and hence the corresponding abrasion action is considered ‘mild’).

The steel wheels of the C&CA test may impart a degree of impact from vibration and minor surface unevenness, and especially once some coarse aggregate particles begin to become prominent, but generally this test has a low level of vibration/bounce, although possibly less than what would occur in practice. On the other hand, the impact of the tumbling steel balls of the AS/NZS 4459.9 test may be considered realistic, although the impact in this test is probably more than what would occur in practice. Finally the grinding sand of the ASTM C779 test has no impact to speak of, and this may be seen as a shortcoming in this test. The corresponding abrasion wear codes are respectively judged as:

C&CA = I2 (or I1 for HSC that is well finished)
AS/NZS = I2
ASTM C779A = I0

(b) Mild Rolling

Tests that have a ‘severe rolling’ action, such as the ‘loaded steel ball tests’ and ‘loaded steel wheel tests’, do not realistically model contact stresses and mechanisms of abrasion that occur in practice. On the other hand the three tests under consideration here are all judged to be suitably ‘mild’ in their respective ‘rolling abrasion’ wear mechanisms (explained in appendices U.4.06, U2.03 and U.5.15). Of the three the AS/NZS is likely to be the mildest, with an abrasion wear code of R1, while the C&CA and ASTM may be considered to have a code of R2.

(c) Test Duration

The respective test durations are 15 - 30 minutes (C&CA), 60 minutes (AS/NZS), 30 - 60 minutes (ASTM C779 A). This may be regarded as slow relative to tests such as U.2.12 (ASTM C779 Proc C) that achieve relatively deep penetrations after 5 minutes owing to high contact stresses from ‘severe rolling’, but it is precisely this rapid abrasion wear process that makes such tests too severe. On the other hand some tests have duration cycles of 24 hours such as U.2.04 (SABS 541), or 72 hours in the case of U.2.7, and this clearly excludes these tests from being used to test specimens that are 24 hours old as a means of detecting bad quality prior to commencing the next days production.

It appears that the three tests have the correct balance between fast/severe and slow/mild.

(d) Positive Result

A test such as EN 154 (see U.2.8) is so mild that it merely changes the degree of gloss on the surface of a tile. Similarly the C&CI wirebrush test (U.6.02) does not yield a positive result for concretes with a high abrasion resistance; the wire bristles are not able to make any significant penetration. Contrariwise, the selected tests are all capable of producing measurable abrasion wear within their test periods.

(e) Affordable Equipment

The equipment in all three tests involves relatively simple turning mechanisms powered by a small geared motor. In each case the equipment may be lifted and moved by two persons if required.

(f) Assessment of Aggregate/Paste Bond

By this is meant that the abrasion test is capable of removing an aggregate particle that is no longer bonded to the paste.

This certainly will be the case with the AS/NZS test; the impact has the ability to slowly chip away at the aggregate particle and at the same time make it even looser until it falls out in one piece or in small fractured pieces. The ability of the ASTM to remove loose aggregate particles has been argued in some detail in appendix U.5.15.

The ability of the C&CA test to do this is not known with certainty. However, a similar test but with much greater wheel loadings, the 'Finnish steel wheel' test does have this ability, as is demonstrated in appendix U.4.1, figure U.4.1.3. According to Chaplin(1990), the C&CA test is known to have a degree of impact once the steel wheels reach the level of the slower wearing coarse aggregate. This impact will conceivably fracture and break up the hard protruding aggregate particles, or/and make them even looser in the matrix. Thereafter the wheels rumbling around the circumference at a rate of 3 revolutions per second may result in a suction effect that sucks these loose particles out.

(g) Assessment of Aggregate Hardness

Assuming that aggregate/paste bond is sufficiently strong, then the rate of abrasion wear will largely be determined by the hardness of the aggregate. Therefore abrasion tests should measure this quality. The three selected tests all abrade the aggregate and the paste at approximately the same rate, and it is therefore true to say that these tests all measure the contribution of the aggregate towards abrasion resistance.

(h) Test Current

The three selected tests are more than current tests; they all form parts of national tests/specifications:

(i) The C&CA test has been adopted as the abrasion test in the specification BS 8204:Part2 (1999)
(ii) The AS/NZS test is described in the joint national specification AS/NZS 4459.9 : Masonry units and segmental pavers
(iii) The ASTM test is an accepted abrasion test in the US, i.e ASTM C779 Proc A : Test Method for Abrasion Resistance of Horizontal Concrete Surfaces

(j) Repeatability

Results published by Kettle(1984) show an average coefficient of variation of 8.8%, for the C&CA test which is relatively low. Experimental work reported by Shackel(1993a) indicates that the coefficient for the SCC test, the forerunner of AS/NZS, is in the region of 8.5%. The repeatability of the ASTM test is unknown to the writer at this point in time. It may be judged to be even lower than the other two, owing to the impact free steady grinding action of this test.

(k) Skill and interpretation

The AS/NZS test is likely to be the easiest to set up in the apparatus. The others methods require that the surface of the pavers are carefully set up in a horizontal plane. This can however be simplified with use of jigs.

The abrasion wear of the ASTM and C&CA tests is easily understood as the depth of penetration and may be measured at various points around the circumferential wear-path and averaged. This is more difficult in the AS/NZS test, where the loss in volume is determined by mass loss, and then converted to volume by dividing by the SG of the specimens, (determined by the mass in water versus mass in air method), from which an average depth may be calculated.

However none of the tests will be beyond the reach of a trained laboratory operator.

(l) Water

No water is used in any of these tests, although the specimens may be pre-soaked for 24 hours prior to the test.

(m) Track Diameter

As previously explained, this poses a problem in the case of the ASTM and C&CA tests, requiring (1) careful levelling of the top faces of the paving units in a horizontal plane, ideally with the use of jigs, and (2) butting the sides of the specimens against each other. This done, the bases of the pavers may be set in a grout or more conveniently in a fast setting resin – after which the jigs may be removed and the testing preformed.

(n) Availability of Abrasives

The steel wheels of the C&CA test, the balls of the AS/NZS test and the silicon carbide abrasive of the ASTM test may readily be sourced locally.

4.4.3 Comparison of six tests using the above stated criteria

In table 12.1 of volume 1 the three abrasion tests used in this thesis were compared against 24 criteria. This approach is again used in table 4.3 below, considering the 13 criteria discussed above. Although the latter criteria are fewer in number, they are considered the most important and reflect a degree of refining in the writer’s thinking in the interleading years between 1994 and 2001.

Once again the relative importance of the various criteria are ‘weighted’, allowing a ‘weighted performance’ for each criteria. In principle the test with the highest weighted performance is the ideal abrasion test.

It may be seen that table 4.3 compares six different tests. The first three are those of volume 1, while the latter three are those chosen after considering the arguments presented in sections 4.3 and 4.4.2 above. Although the writer is able to speak with greater authority on the first three tests, he considers that he is also in a position to make an assessment on the latter three as well, given the study made on the many different abrasion tests and their various abrasion mechanisms. Clearly in all of these comparisons there is an element of subjectivity.

Table 12.3 shows that the three proposed tests have very similar totals and that they clearly exceed those of the abrasion tests used in volume 1.

Sectional Conclusion

From the above analysis it appears that the three tests generally meet most of the criteria deemed important for an abrasion test. Further investigations are therefore justified to confirm their supposed superiority over the volume 1 tests, and to determine which test is the *most* suitable

TABLE 4.3 CRITICAL COMPARISON OF 6 ABRASION TESTS

ATTRIBUTES	PERFORMANCE OF TEST						WEIGHT	WEIGHTED PERFORMANCE					
	MA20	WIRE	C418	C&CA	AS/NZ	C779A		MA20	WIRE	C418	C&CA	AS/NZ	C779A
(a) MILD IMPACT	3	4	3	4	2	5	4	12	16	12	16	8	20
(b) MILD ROLLING	1	5	4	4	5	4	5	5	25	20	20	25	20
(c) TEST DURATION	5	5	4	3	3	3	4	20	20	16	12	12	12
(d) POSITIVE RESULTS	4	3	5	5	5	5	10	40	30	50	50	50	50
(e) AFFORDABLE EQUIPMENT	4	3	4	3	3	3	5	20	15	20	15	15	15
(f) ASSESSMENT OF AGREGATE/PASTE BOND	5	1	1	5	4	4	10	50	10	10	50	40	40
(g) ASSESSMENT OF AGGREGATE HARDNESS	5	2	2	4	4	4	10	50	20	20	40	40	40
(h) TEST CURRENT	3	2	5	5	5	5	5	15	10	25	25	25	25
(j) REPEATABILITY	1	3	5	4	4	5	10	10	30	50	40	40	50
(k) SKILL AND INTERPRETATION	3	3	3	3	3	3	3	9	9	9	9	9	9
(l) WATER IN TEST	5	1	5	5	5	5	1	5	1	5	5	5	5
(m) TRACK DIAMETER	5	5	5	1	5	1	3	15	15	15	3	15	3
(n) AVAILABILITY OF ABRASIVES	5	5	3	5	5	5	3	15	15	9	15	15	15
Affordability of abrasives							TOTAL	266	216	261	300	299	304

PERFORMANCE OF TEST
1 = POOR
2 = FAIR
3 = ACCEPTABLE
4 = GOOD
5 = VERY GOOD

WEIGHTS - RELATIVE IMPORTANCE OF ATTRIBUTES
1 = MINOR, NOT IMPORTANT
2 = SECONDARY
3 = INTERMEDIATE
4 = IMPORTANT
5 = VERY IMPORTANT
10 = CARDINAL

4.4.4 Recommended Test Program

It is recommended that an experimental programme be carried out with the following aims:

(a) to establish the extent that the three tests in fact possess the necessary attributes to meet the criteria outlined in the preceding section
(b) to determine the sensitivity of the tests to mix design variables that have an important bearing on abrasion resistance, such as aggregate hardness, water content, w/c, and aggregate/paste bond
(c) to examine the microscopic abrasion wear characteristics of the various abrasion tests
(d) based on the results of the above points, to recommend a single abrasion test for the concrete industry, and particularly the concrete paving industry

4.5 Summary and Conclusion

This chapter builds on the theory set out in chapter three, going on to propose a logical systematic method of understanding and classifying abrasion wear.

Sixty six abrasion tests have been considered, and the salient features of each test, particularly pertaining to the abrasion wear mechanisms, are presented in appendix U.

The abrasion tests may be placed into eight groups according to the applied abrading medium causing the abrasion wear.

Almost every abrasion test will cause either a 'mild' form of crushing or shearing of the surface asperities, or a more 'severe' form of abrasion, resulting in cracking to a deeper sub-asperity level. Often both types of abrasion will take place in a test.

An abrasion wear code has been developed to describe the mechanism of wear for each of the 66 tests considered. The code categorises the tests by their abrasive actions:

- rolling
- sliding
- impact

and also indicates the severity of the actions. Clearly this assists in giving an appreciation of the abrasion wear characteristics of the test, particularly for engineers not experienced in the field of abrasion testing. The abrasion code allows tests to be compared quickly and easily in regard to their abrasion wear characteristics. Furthermore if the mode of abrasion is understood in the proposed application, a suitable test/s can be recommended.

A consideration of the actual abrasion process in 'mild abrasion', for the various tests, shows a great degree of similarity (see figure 4.6). The same may be said of 'severe' abrasion. Therefore it may be said that the many abrasion tests actually have a lot in common, in terms of the end effect, so that the discerning materials engineer may be in a position to apply the results of a particular test to a wider spectrum of applications.

On the other hand there are several other important criteria that are also important when deciding on an abrasion test. Does it 'see' the aggregate? Does it measure the aggregate/paste bond? etc. Therefore the various tests have also been examined in the light of these 'other criteria'.

Three tests that generally meet the many requirements that may be regarded as important for an abrasion test of surfaces trafficked by pedestrian and vehicular traffic have been short listed for a focussed experimental programme, with the ultimate aim of recommending the best one as an abrasion test for the concrete paving industry in South Africa.

Finally it is hoped that the concepts of:

- identifying an abrasion test according to the abrading medium
- using an abrasion code to signify the abrasive action and the severity of the abrasion process
- appreciating the many other factors that affect abrasion wear in an abrasion test and in practice

will lead to a better understanding of abrasion wear and result in surfaces with improved.