Chapter 3

Mechanisms of Abrasion Wear

3.1 Introduction

Chapter 1 concludes with a very perceptive view of Volume 2: 'In essence Volume 2 is a mammoth literature study on abrasion resistance (chapter 2) that sprouted two additional chapters (chapter 3 and 4) to explain how the use of different tests could at times explain the apparently contradictory conclusions made by different investigators'.

Accordingly the focus in *chapter 4* is the many abrasion tests used by the various authors of chapter 2, including the apparatuses, the various test methodologies, and most importantly their abrading actions and abrading mediums.

However, in describing the abrading actions of the various abrasion tests the writer became aware of the need for a greater depth of understanding of the various processes and mechanisms of wear. This then explains the *purpose* of chapter 3; to explore various theories on the wear/failure mechanisms in some engineering materials and finally propose a suitable theory to explain abrasion wear in *concrete*, and use this in chapters 2 and 4 where appropriate.

A considerable review of the literature on abrasion wear and abrasion resistance has revealed that no in depth study has been made of fundamental abrasion-wear mechanisms of *concrete* surfaces. On the other hand, friction and wear has been the subject of careful study in metals, alloys, ceramics and polymers for many decades. In this regard polymers and ceramics are indeed of interest, the former because of their use in rubber tyres/footwear and the second because it is brittle and may therefore be compared to concrete in many respects.

The writer has found in Hutchings(1992) a fresh approach to the study of wear. His book is in itself a summary of the work of many researchers on the subject of 'tribology' (the study of friction, lubrication and wear). Although the findings of this book are based on work done on metals, alloys, ceramics and polymers, it is believed that many of the principles are universal. This chapter therefore has borrowed from his experience, and seeks to apply it to abrasion wear in concrete.

Other authors that have also been a source of ideas in this chapter are Newman(1997a), Kong(1980) and Cernica(1982).

3.2 Background

Before proceeding with the discussion on the main mechanisms of wear, an understanding of some fundamental concepts is necessary.

3.2.1 Surface Topography

When studied on a sufficiently fine scale, all solid surfaces are found to be uneven. In the limit, the surface irregularities will be on the scale of individual atoms or molecules. The surfaces of even the most highly polished engineering components, show irregularities appreciably larger than atomic dimensions.

Many methods are used to measure the topography of surfaces; optical methods, electron or light microscopy, electrical or thermal measurements, leakage of a fluid between surfaces, scanning tunnelling microscopy, atomic forces microscopy etc.

Perhaps the most commonly used method is the stylus profilometer, capable of magnifications of 10^6.

Using this instrument, it may be shown that even polished engineering surfaces in fact have ‘hills and valleys’. However their slopes are generally limited to ten degrees, and usually much less.

The relative roughness of surfaces may be classified in many ways. The most commonly used term is the *Average roughness*, $R_a = 1/L \, {}_0\int^L |y(x)|.dx$ where y is the height of the surface above the mean line at a distance x from the origin. (Note that the area above the mean line is equal to the area below it).

Other expressions for defining surface topography, in order of sophistication, include:

Root mean square deviation $R_q^2 = 1/L \, {}_0\int^L y^2(x).dx$

Bearing ratio, the ratio of the contact length to the total length in a given length.

Amplitude density function p(y), the probability of finding a point on the surface at height y above the mean line. Effectively it describes the distribution of surface heights. The plot of p(y) for the surface heights ranging between $-\equiv$ to $+\equiv$ of a given topography gives the ‘*amplitude density curve’*.

Skewness of amplitude density curve, $S_k = 1/R_q^3 = {}_{-\infty}\int^{+\infty} y^3.P(y).dy$

Kurtosis (sharpness of the peak of the amplitude density curve), $K = 1/R_q^4 \, {}_{-\infty}\int^{+\infty} y^4.P(y).dy$

The distribution of the hills and valleys across a surface are given by the expressions:

Autocorrelation function, $C(\beta) = 1/L \, {}_0\int^L y(x).y(x+\beta)dx$, where β is some displacement along the surface.

Power spectral density, $P(\omega) = 2/\pi \, {}_0\int^X C(\beta).\cos(\omega\beta)d\beta$, the Fourier transform of the autocorrelation function.
The above expressions will not be referred to again and are given purely to illustrate that quantifying surface topography is complex, and is considered important in engineering. Instead, such qualitative expressions as ‘hills and valleys’, ‘asperities’ (high areas) etc. will be used.

In metals, the topography of machined surfaces depends on the machining process and the nature of the material/alloy. Typical average roughnesses, Ra, for various machining processes are: milling 1 to 6μm; grinding 0,1 to 2μm; polishing 0,1 to 0,4μm. This does have some relevance to concrete pavers, as their surfaces will be influenced by the roughness of the tamper shoes. These are sometimes machined, and sometimes pressed in a die from standard plate.

Typically however the roughness of concrete surfaces will exceed that of engineered steel surfaces, sometimes by a few orders of magnitude, particularly in the case of a non-slip screeded concrete road. Even a power trowelled surface is considerably rougher. Furthermore, the asperities will vary in height and be randomly distributed, and the implications of this are discussed below.

3.2.2 Contact Between Surfaces

When two nominally plane and parallel surfaces are brought together, contact will initially occur at only a few points, depending on the rigidity of the surfaces. As the normal load is increased, a larger number of higher areas (asperities) come into contact. Therefore the asperities support the normal load, and are responsible for generating any frictional forces which act between them. It also means that the compressive and shear stresses that ultimately lead to wear will be concentrated at these points. (However, where one surface is relatively flexible, e.g. the tyre of a car, the number of contact points will be much greater, with corresponding reductions in compression and shear stresses and hence a lesser rate of wear).

3.2.3 Hardness

There are several standard methods for measuring the 'hardness' of various engineering materials. Accordingly hardness may variously be quantified in terms of standard units, such as Vickers hardness (HV), Brinell hardness, shore hardness, rebound hammer number, etc. These different ways of determining hardness will be examined in 3.2.3.1 through 3.2.3.4 with a view to arriving at an acceptable generic explanation for 'hardness'.

3.2.3.1 Indentation hardness

In metals hardness is generally measured by applying a load via a hard indentor to the surface, and then measuring either the diagonal or diameter of the opening. The three most common hardnesses and associated tests are briefly described below:

(a) Vickers hardness

The Vickers indenter has a diamond tip, a square-based 'pyramid' that has included angles of 136° between opposing faces. The tips come in two sizes, the larger size is capable of deeper penetrations and can give an indication of the average or core hardness of the material, while the smaller tip measures the microhardness of the outer surface. The load may be varied from 1 to 120 kg. The result is reported in units of HV and based on the formula:

$HV = 1{,}854 \times \text{load (kg)} / d^2$

where d is the average length in mm of the two diagonals at the opening of the indentation. The units are kg/mm^2 (=9,81 MPa).

(b) Brinell hardness

The Brinell indenter consists of a hardened 10mm (=D) steel ball that is pressed into the material at a given load for a given duration. For example, for ferrous materials it is stipulated that a load of 3000 kg be applied for 10 seconds, while non-ferrous metals the load is reduced to 500 kg for 30 seconds. For a given material the Brinell hardness (HB) is a function of the size of the diameter of the indentation at the surface of the crater so formed (d), and is given by the formula:

$HB = \text{load (kg)} / [\pi D/2(D-\sqrt{(D^2-d^2)})]$.

The units are kg/mm^2 (=9,81 MPa).

For testing very hard materials a tungsten carbide ball is used.

(c) **Rockwell hardness**

This test has a number of suffixes, A though to L, denoting the test tip (composition of material and size), and load; depending on the type of material being tested. For example a 'Rockwell A' test is made with a diamond cone under an applied load of 60kg, used for testing very hard materials such as tungsten carbide, while a 'Rockwell L' test uses a ¼" hardened steel ball under a load of 60 kg, used for testing very soft materials such as lead. Altogether there are four different size balls to supplement the diamond cone tip, and considerable variation in the applied load depending on which test is being done. Similar to the Brinell test the diameter of the indentation (at the surface) is measured.

Of the three tests the Vickers hardness has the advantage of using the same tip for all materials (discounting the tip for microhardness, which is really a different study), and thus prior knowledge of the test material is not required. The test also has the simplest and most uniform test procedure.

Correlation charts exist for converting an indentation hardness from say Rockwell to Vickers hardness or Brinell hardness, and vice versa.

Indentation hardness

Regardless of the test being used and thus type of indentation being made, in materials that have a significant plastic phase, such as metals, a point is reached where significant penetration occurs for a given stress, and this is referred to as the 'indentation hardness', H. The indentation hardness is generally equal to three times its uniaxial yield stress, i.e. H = 3Y.

Brittle materials, on the other hand, have a very limited capacity for plastic flow. Plastic flow may go hand in hand with densification in these materials. Brittle materials lack toughness and fracture follows soon after yield, well before 3Y. In spite of this, indentation tests have been successfully used to quantify the hardness of various ceramics. Other brittle materials such as quartz, corundum, and even diamond may also be classified in terms of HV [Hutchings(1992)].

It appears that the only attempts to explore the possibility of a relationship between hardness and the abrasion resistance was made by Sadegzadeh(1987). He did microhardness determinations using a 'Model 12' microhardness tester to determine the 'Vickers hardness' of concrete surfaces made with various cement contents and finished by different processes. He found good correlation with abrasion depths (rolling steel wheels).

(d) Shore Hardness

Interestingly the hardness of flexible polymers such as rubber, is also quantified in terms of indentation hardness, referred to as 'shore hardness'. In this test the spring-loaded plunger of a 'shoremeter' is pressed against the face of the rubber. The plunger is free to move axially inside a tube type housing. The exterior of the tube/housing is hand held and is pressed with sufficient force against the rubber such that the front face of the tube/housing maintains contact. The shore hardness is proportional to the length that the plunger moves into the tube housing against the force of the spring. For perfectly soft rubber (eg a liquid rubber compound), the plunger does not move at all, and this corresponds to a shore hardness of zero, while for a perfectly stiff 'rubber', corresponding to a shore hardness of 100, the front face of the plunger moves to a position flush with the front face of the tube/housing. The plunger is also connected to a calibrated dial gauge, and this allows the operator to determine the degree of travel, representing the shore hardness.(Tyres of vehicles are made to a shore hardness ranging between 68 through 75).

3.2.3.2 Sliding hardness

Some hardness tests operate on the basis of a hard material scratching a softer material. A scratch is in effect a downward indentation that has the added dimension of sliding or lateral movement. This is the modus operandi of the *Mohs* hardness number.

In 1824 Mohs, an Austrian mineralogist, assigned integer hardness numbers to a sequence of 10 minerals, each of which would scratch all those, but only those, below it in the scale. This scale is based on the observation that a certain minimum ratio of hardness is needed for one material to be able to scratch another. This ratio in Mohs scale it is about 1,6, rather higher than the minimum of 1,2 necessary to cause scratching [according to Hutchings (1992)].

A noticeable relationship exists between 'HV' and 'Mohs number', illustrated in figure 3.0.

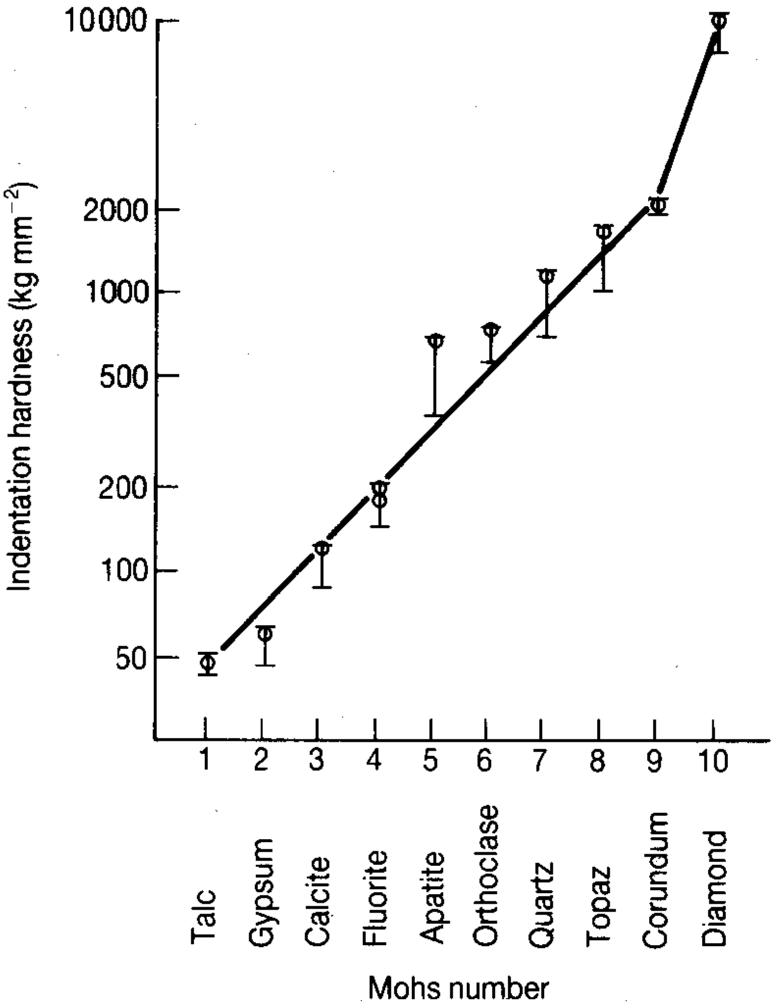

Figure 3.0 Comparison of indentation hardness (Vickers method) with Mohs hardness number for ten standard minerals [Hutchings(1992) from Bowden F P and Tabor D, The Friction and Lubrication of Solids, Part II, Claredon Press, Oxford, 1964]

3.2.3.3 Impact hardness

If sliding hardness may be considered as indentation hardness coupled with resistance to lateral movement, then 'impact hardness' is the response of a material to an indentation made by a moving object. Some of the object's kinetic energy will be absorbed via various dynamic or plastic effects, and some of it will be reflected/transmitted back into the object, causing it to bounce back such as occurs when the plunger of a rebound hammer strikes a surface. Accordingly the 'hardness' of concrete has frequently been assessed using a *rebound hammer*, and various authors Kettle(1986), Chaplin(1991), have found good correlation between the rebound number and the factors that are known to influence the abrasion resistance (rolling steel wheels).

Hard surfaces will yield higher rebound numbers than soft surfaces. Clearly soft surfaces are slightly crushed in the process (see figure U.7.2.3 in appendix U), and act as energy absorbers damping the rebound effect, whereas hard surfaces have more of an *elastic* response, where the greater the elastic modulus the greater is the spring effect. This may lead to some inaccuracy in the test, since although the elastic modulus of concrete is related to compressive strength, and by extension the density-of-the-surface/abrasion-resistance, it will also be affected by the elastic modulus of the aggregate near the surface of the concrete. Clearly the elastic modulus of the aggregate is not necessarily correlated with its abrasion resistance.

Sectional Conclusion: Interestingly the three forms of hardness mentioned above, (indentation, sliding, and impact) may be compared to the three primary forms of abrasion mentioned in chapter 4, i.e. rolling abrasion, sliding abrasion, and impact abrasion. Clearly a surface with good indentation hardness has the ability to withstand crushing effects, and will therefore also have excellent rolling abrasion. This has been shown by Sadegzadeh(1987). Likewise a surface with good impact hardness should also have good impact abrasion resistance, and in this regard it would be interesting to do parallel testing with the rebound hammer (impact hardness) and an ‘impacting steel balls’ abrasion test, e.g. as described in AS/NZS 4456.9 (see appendix U.2.03).

3.2.3.4 Influence of Hardness on Abrasion Resistance in Different Materials

From the foregoing it appears that the ‘hardness’ of a material strongly influences it’s wear characteristic. Figure 3.1 (based on indentation hardness, HV) shows that this holds true for a number of different materials, even though the different materials have very different characteristics. The following is immediately apparent:

(a) **Ceramics**: Abrasion wear is directly proportional to hardness.
(b) **Metals**: As for ceramics a direct relationship (see top diagonal) between hardness and abrasion resistance is also evident for pure metals, such as lead, cadmium, aluminium, zinc, copper, nickel, iron, cobalt, chromium, titanium, molybdenum, beryllium, and tungsten. However, at any given hardness metals have superior abrasion resistance relative to ceramics.
(c) **Steel alloys**: At a certain point, alloys depart from the ‘pure metal’ line, such that for a given increase in hardness there is a diminishing return in abrasion resistance, and in some cases e.g. white cast iron, there is a decrease. Clearly the different alloys have their own unique characteristics.
(d) **Polymers**: The relationship between hardness and abrasion resistance will depend on the specific properties of the polymer under consideration, which differ widely. For this reason no clear relationship exists between abrasion resistance and hardness as indicated in figure 3.1. It is evident however, that they have limited hardness (and abrasion resistance) relative to ceramics, and especially metals.

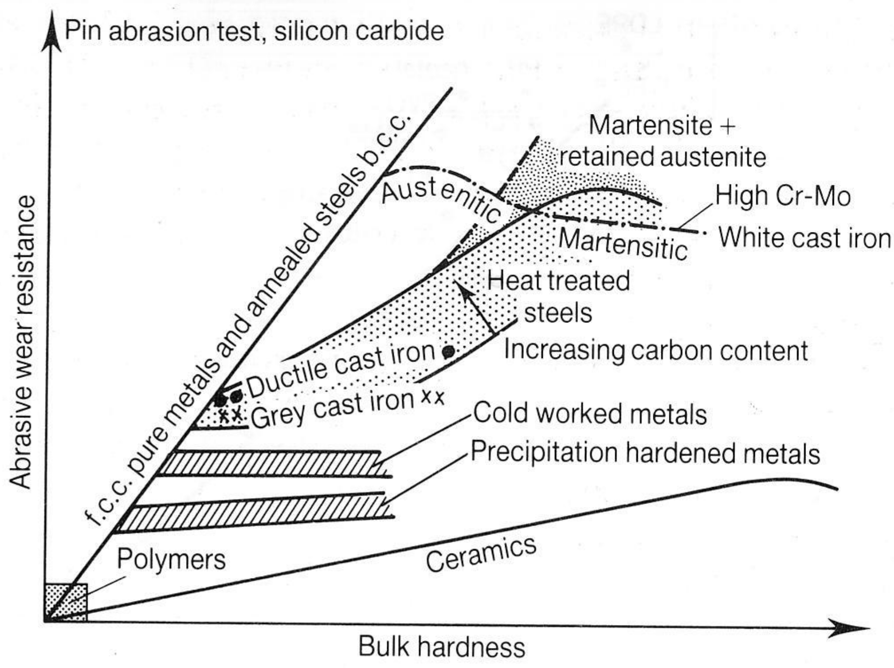

Figure 3.1 Abrasion resistance (1/volume of wear rate) of various materials plotted against bulk hardness. [Hutchings(1992) from Zum Gahr K-H, Microstructure and Wear of Materials, Elsevier, 1987)]. Note that the abrasion resistance is defined here as the reciprocal of the volume wear rate in a 'pin abrasion test'. This test involves a small cylinder (i.e. the specimen) being pressed against a large revolving disc with silicon carbide in between as the abrading medium.

The hardness of the applied load relative to that of the counterface largely influences the rate of abrasion. The 'applied load' may be very hard as in the diamond tip of a Vickers indenter, or very soft as in a pneumatic rubber tyre, or intermediate as in steel wheels. The applied load may also be an abrasive such as grains of silica sand beneath traffic or silicon carbide in an abrasion test. As inferred earlier, if the hardness of the applied-load/abrasive relative to the counterface exceeds 1,2, then plastic scratching occurs in the surface. This is sometimes referred to as hard abrasion. Where this ratio is less than 1,2, the abrasive will be blunted, permitting only 'soft abrasion'. The rate of wear of soft abrasion can be a few orders of magnitude less than hard abrasion, particularly if the abrasive hardness is less than that of the counterface. From figure 3.1 it may be understood that the relative softness of rubber, a type of polymer, leads to negligible wear on metals and ceramics, and indeed on concrete. This was proven by **Jackson(1924)**, who found negligible wear from a rubber tired 'truck' traversing the various concrete test surfaces.

3.2.4 Toughness

Where materials are subject to impact, particularly if they tend to be brittle, toughness rather than hardness may govern the rate of wear.

Toughness may be defined as the ability of a material to resist fracture, as determined in tests involving either direct tension or bending.

Figure 3.2 shows that initially abrasion resistance increases with increasing fracture toughness, that there is an optimum toughness where abrasion resistance is a maximum, and that therefore any further increase in toughness results in a reduction in abrasion resistance. This comes about as there is a general tendency for a material's hardness to diminish as fracture toughness increases. Conversely, a very hard but very brittle material will fracture easily, and excessive cracking leads to loss of material, particularly where cracks intersect to form loose isolated blocks, or where cracks form below and parallel to the surface, e.g. lateral cracks. Therefore where the abrasive load involves impact, increasing the risk of fracturing, it is prudent to reduce hardness in favour of toughness. For example Smith(1958) found that concrete incorporating softer but more resilient aggregates had improved abrasion resistance compared to harder more brittle aggregates, when subject to the 'impact' action of a shot-blast test, whereas the harder aggregate was superior for 'rolling' abrasion. On the other end of the 'hardness' scale ductile materials with inherently high toughness, such as metals, tend to be softer, and suffer abrasive wear by plastic deformation (explained in the next section) rather than brittle fracture. For these materials, wear resistance increases with increasing hardness and diminishing toughness again to a point.

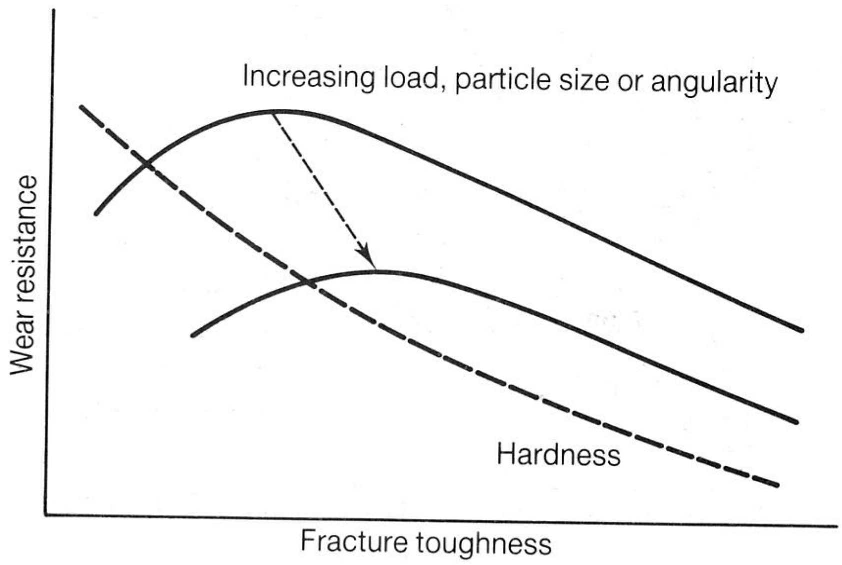

Figure 3.2 Relation between fracture toughness and resistance to 'hard' abrasive wear for metallic and ceramic materials. [Hutchings(1992) from Zum Gahr K-H, Microstructure and Wear of Materials, Elsevier, 1987)].

3.2.5 Particle Size

Figure 3.2 shows that the greater the size of the abrasive particle, the greater must be the toughness of the surface to effectively resist the attack. In these situations hardness is less important. Clearly large abrasive particles have more kinetic energy when in flight, and are heavier when rolling or sliding, resulting in deeper cracking/crushing/shearing effects. On the other hand it is evident that very small particles will merely scratch a brittle surface. In this process cracking/crushing/shearing effects are still involved, but only the level of the microscopic asperities. In concrete, small abrasive particles do not have the potential to impact against the aggregate particles to the extent that the paste/aggregate bond is disrupted, which would hasten the loss of aggregate particles. This allows the much harder aggregate particles to remain in the matrix to effectively resist wear.

For abrasive particles less than 100μm in size there is an accelerating tendency towards zero wear in metallic surfaces. This is because there is an increase in the local flow stress (in the counterface material) as the scale of deformation is diminished which leads to a reduction in wear rates by plastic processes.

3.2.6 A Final Word on Hardness

From the foregoing discussions of the various forms of hardness, together with a consideration of the way toughness influences hardness, it is possible to extract some general statements that should lead to a clearer understanding of hardness:

(a) From 3.2.3.1 through 3.2.3.3 it may be inferred that hard surfaces are not easily indented or scratched, and that they have a high elastic modulus.
(b) From figure 3.1 it is evident that:
- polymers are soft (the opposite of hard)
- the various metals range in hardness
- steel alloys can be formulated to be very hard
- ceramics can be made with an even greater hardness

(c) From figure 3.2 it was shown that as hardness increases, fracture toughness decreases. This in effect means that very hard materials are brittle (prone to cracking), and this has a detrimental effect on abrasion resistance where the applied load has a significant impact component. Therefore while abrasion resistance clearly increases with hardness, it does so only as long as the toughness of the material is not unduly compromised.

From the above observations it may be said that scratch and indentation resistance increases with hardness, but so does brittleness. The former attributes increase abrasion resistance, while the latter is detrimental. It was shown from figure 3.2 that the ideal hardness for a concrete surface is a compromise between indentation hardness and fracture toughness (the opposite brittleness). The point of compromise will naturally depend on the nature of the abrasive action. If impact is a major element, then some hardness should be sacrificed for toughness, while in tests and applications where there is virtually no impact, indentation hardness may be maximised.

Summing up it seems that hardness is best considered as indentation hardness, meaning of course resistance to indentation by abrasive loads. (Scratch resistance is embodied in this concept. Also the negative side effect of increased brittleness should always be kept in mind).

3.2.7 Sectional Summary and Conclusion

The purpose of this section was to give some insight into surface topography, and particularly to highlight that abrasion wear occurs at the topmost asperities of the surface, in the case of mild abrasion. On the other hand deeper abrasion involves a great number more asperities or may even occur within the sub-asperity zone depending on the severity of the load.

Different types of hardness were considered including indentation hardness, sliding hardness and impact hardness, and various ways of measuring and quantifying these hardnesses were described. The relationship between indentation hardness and abrasion resistance was briefly considered for various materials such as ceramics, metals, steel alloys and polymers.

It was shown that in very hard brittle materials, abrasion resistance may be improved by sacrificing some hardness for increased fracture toughness.

The next two sections of this chapter form the essential body of the chapter, and build on these concepts. They specifically refer to the wear that results from normal compression (section 3.3) and lateral sliding (section 3.4).