3.4 Wear Induced by Lateral Sliding

When a body is made to slide laterally, the rate of wear is likely to be increased quite substantially relative to that occurring under stationary compression. Clearly if a normal load causes damage when at rest, this damage will be replicated wherever the body is moved. Frictional forces resist such lateral movement, the degree of resistance being determined by the characteristics of both surfaces.

Section 3.4 discusses the effects of lateral sliding, as section 3.3 did for normal compression. Accordingly these two sections present a number of theoretical models for abrasion wear, establishing a suitable platform for section 3.5, where some common applications are considered.

3.4.1 Friction

Friction may be defined as the resistance encountered by one surface as it moves over another. There are two important classes of relative motion: sliding and rolling, and in both cases, a tangential force, F, is needed to move the upper body over the stationary counterface. This force is both equal in magnitude and opposite in direction to the frictional resistance, and is illustrated in Figure 3.17.

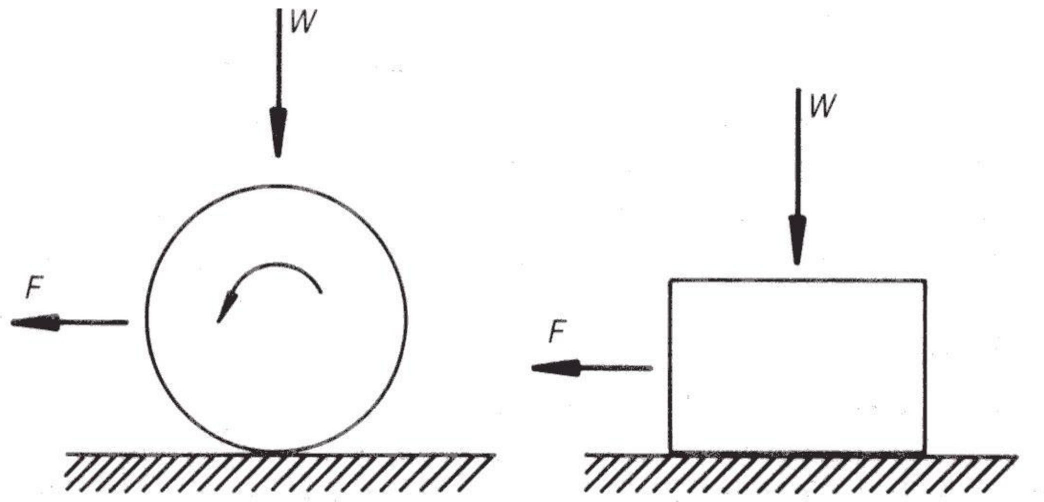

Figure 3.17 A lateral force, F, is needed to cause motion by (a) rolling or (b) sliding.

Friction is generally directly proportional to the normal load, W, given by the expression:

$F = \mu W$ ……. (3.15)

Where

μ = coefficient of friction. Its value is determined by the characteristics of both surfaces, particularly its roughness. It is usually constant once the body is in motion. The coefficient of friction for *initial* sliding may however be higher.

Rolling wheels that have well lubricated bearings will have very low frictional resistance. Crushing under the influence of W, rather than sliding, will be the predominant mode of abrasion wear. However, if the wheels lock from a braking action, and consequently skid over the surface, then a substantial degree of wear is possible, since F is focussed on a relatively small contact area, resulting in high shear stresses. Similarly wheels sliding relative to the surface when a vehicle turns, also cause increased rates of abrasion wear.

The coefficient of friction readily gives an idea of 'ease of sliding' and allows for comparison of different surfaces. Although friction is responsible for sliding wear, this does not mean that a high coefficient of friction necessarily causes a rapid rate of wear, since the sliding body in question may have a high wear resistance. An example of this would be a brake pad in a motor vehicle. Concrete/rubber interfaces also need to have high coefficients of friction for good road holding in vehicles. This however does not imply that the concrete surface will wear rapidly; it often has excellent wearing properties.

Although concrete will generally undergo *elastic* deformation from the mild abrasive actions of rubber tyres or footwear, this is not necessarily the case where tyres skid and slew over the surface, from the actions of sudden braking and turning respectively. In such cases *plastic* deformation is possible, particularly in the presence of grit/sand, resulting in a degree of material being deformed and/or densified. If the particles are large, sharp and heavily loaded, then localised fracturing is likely, but the point to make here is that there is a middle road of plastic deformation between elastic deformation and brittle fracture.

According to Archard, the wear, Q, in a *given* material, subjected to plastic deformations, will be proportional to the normal load, W (see equation 3.18 further on). As friction is also proportional to the normal load (equation 3.15) it follows that wear is proportional to friction.

Friction stems from two surfaces either tending to *adhere* to each other at their real areas of contact (asperity junctions), or from the harder asperities *deforming* the softer, or from the effort involved in the load *fracturing* the wearing surface, and may therefore be expressed as:

$F = F_{adhesion} + F_{deformation} + F_{fracture}$ ……. (3-16)

Note that as in 3.3, deformation may either be elastic (recoverable) and/or plastic (non-recoverable), while 'fracture' may involve cone cracks, lateral cracks and/or axial cracks.

The seven mechanisms of wear shown in Figure 3.3 (adhesion, elastic deformation, plastic deformation, cone cracks, lateral cracks, axial cracks and hard particle effect) also occur when one surface slides relative to the other. The difference is that the compression related adhesive/deformation/fracturing wear will 'travel', and accordingly will be greater. As for pure compression, the effects indicated in equasion (3-16) will quite realistically occur simultaneously at different asperities.

Note to the reader: In spite of the apparent similarity in the wear mechanisms associated with 'pure compression' and 'compression + lateral movement', there is in fact minimal replication in this section of the information presented in section 3.3. Only the main headings and some essential information to set the scene is replicated, prior to the presentation of the new material. The alternative would have been to combine section 3.4 with 3.3, but introducing the two concepts of 'pure compression' and 'compression + sliding' together would be like trying to take two steps at once, and would therefore complicate the presentation.

As in 3.3 it will be convenient to separately discuss the seven mechanisms of wear.

3.4.2 Sliding Adhesion

Abrasion wear associated with sliding adhesion may be described as the transfer of material from one surface to another by means of atomic bonding as one surface slides over the other [Hutchings(1992)]. In metals these adhesive forces may be so great in ideal conditions (atomically clean surfaces) that the *coefficient of friction* may be as high as 10, or more. The corresponding value of μ for ceramic-ceramic contacts is much lower, and lies typically in the range from 0,25 to 0,80.

It is probable that some covalent bonds also develop between a concrete surface and an abrasive particle that is calcareous or siliceous in nature. So long as two surfaces are in atomically clean contact, no pressure across the interface is required for adhesion to take place. That is to say that 'sliding adhesion wear' *does not* require any physical deformation related to mechanical stresses between the surfaces before wear can proceed. However, the abrasive actions associated with sliding *coupled with high normal stresses* conceivably brings minerals and compounds into 'atomically clean contact' i.e. free of barrier layers of oxygen, water vapour, and oxidised compounds. Thus although sliding *adhesive* wear does not theoretically require normal stresses to operate on the respective surfaces, they do assist in the preparation of the surfaces.

The adhesive component of the of the frictional force between two surfaces, whether metallic, ceramic or concrete may be stated as:

$F_{adhesion} = A.s$ ……. (3.17)

Where:

A = true area of contact (at the asperities)
s = shear strength

The following sections will be devoted to frictional forces and/or wear that *do* require deformation between the surfaces.

3.4.3 Elastic Deformation from Sliding

For a given load and given smoothness of surface texture (discussed earlier in 3.3.2), elastic contact rather than plastic contact is much more likely in ceramics and concrete than in metals, since for these materials E/H is typically one tenth that of metals, leading to a proportionate reduction in the plasticity index, ψ (see figure 3.7).

Elastic deformation in the context of sliding wear occurs when the extreme fibres of both materials are strained less than their respective elastic limits by the imposed shear stresses, resulting in no wear. This can come about in three ways:

- It is clear from equation (3.15) that *limiting the normal force/stress* will limit the friction, and this in turn limits the shear stress, which then limits the deformation at the surface to a level below the elastic limit. This may occur when a light passenger vehicle with pneumatic tyres skids.

- On the other hand it is possible to have a substantial normal stress but with a very *slight lateral motion* action, such that the shear strains on the asperities are still within their respective elastic limits. This may occur when a large capacity forklift with solid hard compound rubber tyres carrying a heavy load gently brakes or accelerates without skidding. In this case there is some lateral elastic deformation in the concrete asperities, but the corresponding strains are in the elastic zone.

- A third means of limiting the shear stress is to reduce friction by means of a very low coefficient of friction, as in highly polished surfaces, or lubricated surfaces, etc.

Elastic deformation is particularly prevalent in concrete roads subjected to ordinary pneumatic tyre traffic, where the pressure typically varies between 200 and 800 kPa. This is well below the yield strength of even average concretes. Furthermore because rubber is so compliant, the load distribution on a microscopic level makes contact not just with the asperities, but goes some way towards filling the valleys as well. If it is assumed that the polymer compound of the tyre is sufficiently compliant to make contact with half of the gross surface area, then the real pressure on the contact areas of the concrete surface will be 0.4 MPa. If it is further assumed that the coefficient of friction between tyre and concrete is 0,5 (μ for polymers generally ranges between 0,1 and 0,5), then the shear stress will not be more than 0,5 x 0,4 =0.2 MPa. This is less than the recommendation of $4p_q$ = 4 x 0,8 = 3,2 given in Reynolds(1972) for a *permissible* working shear stress of a nominal 1:1,5:3 concrete, where the equivalent direct compression (permissible working stress) is limited to 6,5 MPa. Thus even for concretes which may by today's standards be considered very ordinary, it appears that the integrity of concrete is such that it is capable of easily withstanding the shear stresses applied by sliding/skidding pneumatic tyres. This is confirmed by the ever present sign of black skid marks on our concrete freeways from brake-lockup in heavy trucks, accompanied by no visible sign of damage to the concrete.

Similar compressive and shear pressures relate to pedestrian traffic, where relatively soft elastomeric polymers or leather soles also impart relatively gentle compressive and shear stresses compared to say a heavy duty storage bin on skids. The fact that mild stresses from tyres and footwear constitute a major percentage of the applications where concrete is used would render many a substandard surface undetected were it not for the presence of hard particles (see 3.4.8) that result in plastic deformation and brittle fracture.

Suffice it to say that elastic deformation, is a common response to traffic. On its own, it is associated with very low rates of sliding wear.

3.4.4 Plastic Deformation from Sliding

When two surfaces slide over one another, plastic deformation generally occurs. As indicated in figure 3.3 (c) a deeper level of interaction occurs relative to elastic deformation. In effect the shear stresses consequent of the frictional forces exceed the yield strength of the softer material, resulting in either permanent distortion/densification or loss of material associated with eventual fatigue.

In metals plastic deformation is the major means of deformation and wear (for all but the most finely polished, conformal and lightly loaded surfaces, where deformation may be confined to its elastic limits, see figure 3.7).

On the other hand brittle materials such as ceramics and concrete also deform plastically, the corresponding load lying between that for elastic deformation and brittle failure within a relatively narrow band.

Archard's well known equation for wear, based on the plastic deformation that occurs as a hard surface *scrapes over* a softer counterface, is a good predictor of plastic wear in both metals and ceramics (and probably concrete as well). It is defined as:

$Q = K.W/H$ ……. (3.18)

Where

Q = volume of material removed per unit length of sliding
W = applied normal load
H = indentation hardness of the material (explained in 3.2.3).
K = a dimensionless wear coefficient, of fundamental importance, and indicates the severity of the wear process in different systems. For example K may be considered as the probability of each asperity interaction resulting in the production of a wear particle. Alternatively it may also be taken to reflect the number of cycles of deformation required on each asperity before a fragment of material is removed by a fatigue process, or it can also be correlated with the size of the wear particle produced by every asperity contact.

The identical expression obtained by Archard for scraping wear can also be developed by assuming a hard protuberance *cutting through* the counterface. In both cases the surface is assumed to behave plastically. However, whereas Archard derived his expression by considering the removal by lateral sliding of surface asperities reduced to a state of plastic deformation by the load, the latter derivation assumes a relatively deep groove made by a particle tearing/cutting its way through. The value of K to a large degree depends on the severity of this wear process. Accordingly wear may be classified as 'mild' or 'severe'. In the former wear is superficial, affecting only the surface asperities, while in the latter, wear takes place to some depth below the surface. Frequently the value of K undergoes a quantum leap, by as much as two orders of magnitude, as wear changes form 'mild' to 'severe'. This implies that when the load increases to a certain critical point, W, the mechanism of wear changes from shallow scraping to deep cutting. A good analogy is a farmer's plough. The plough must have a certain critical mass to assist the discs down into the soil; if it is too light the discs will merely scratch the surface. Finally it is not difficult to understand the need for a much higher K value for 'severe' wear if the same equation is to satisfy both 'mild' and 'severe' wear.

Both derivations of equation 3.18 are simple and easy to interpret, i.e. wear is proportional to the normal load and wear coefficient, and inversely proportional to indentation hardness. But clearly the value of the wear coefficient, which is strongly influenced by the magnitude of the load, largely determines the magnitude of the wear.

Finally it should be said that not all materials will remain plastic over a wide range of load. Brittle materials, concrete included, will tend to fracture rather than deform plastically as the load increases to a critical value.

Transition from Elastic/plastic Deformation to Brittle Fracture - Sliding

If sliding of very smooth brittle surfaces over each other under light loads results in elastic deformation, and sliding of slightly rougher surfaces over each other under moderate loads results in plastic deformation, then it may be generalised that frictional forces/stresses accompanying sliding of heavy loads over standard engineering surfaces will exceed the shear strength of the surface, resulting in cracking, either of the surface asperities, or to deeper levels.

This is because ceramics have coefficients of friction generally varying between 0,25 and 0,80, so that sliding under high stress results in significant tangential forces/shear stresses.

The three forms of cracking illustrated in figure 3.3 (d) through (f), will also occur in sliding abrasion, except that these effects will ‘travel’ with sliding, as mentioned earlier. They are considered in 3.4.5 through 3.4.7.

3.4.5 Semi-Cone Cracks from Sliding

In 3.3.4 it was explained that hard blunt objects pressed down on a brittle counterface result in Hertzian cone cracks. However when an additional tangential force is applied to this load, such that it is dragged along the surface, the cracks will appear at about W/10, if W represents the stationary load at which Hertzian cracks would appear in a stationary load. Clearly the 'Hertzian' tensile stress, associated with the normal load, will be increased at the back side of the object by the additional tension created by dragging. Conversely, at the front end the effect of drag will tend to compress the concrete and thus reduce the Hertzian tensile stresses in this area. Thus semi-circular cracks may be expected rather than classical Hertzian circular cracks, and this is illustrated in figure 3.18.

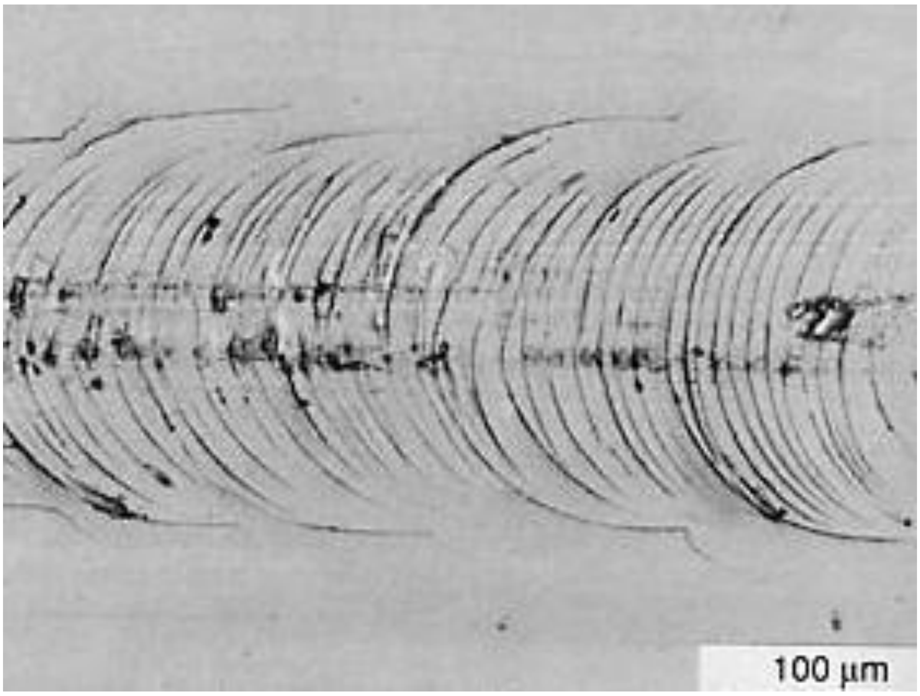

Figure 3.18 Series of arc-shaped fractures caused by sliding a sphere over a brittle solid under normal load. This example shows the damage due to a tungsten carbide sphere on a soda-lime glass plane. The sphere slid from left to right [Hutchings(1992)]

The effect described above is very sensitive to the prevailing coefficient of friction between the two materials. The W/10 quoted above applies to a μ = 0,2. If μ is increased to 0,9 then the sliding load will induce semicircular cracks at a load as little as W/500.

These cracks represent the surface of truncated cones that terminate deeper in, and do not as such result in any loss of material. However, it follows that subsequent loads applied to the surface, whether predominantly normal or horizontal in character, will produce similar cracks, and the intersection of these various cracks will result in loose blocks of material that may be removed relatively easily.

This principle has direct application to the MA20 test, where steel spheres in the form of ball bearings apply both compressive stresses and a tangential sliding in the form of 'Heathcote slip' (discussed in chapter 4).

3.4.6 Lateral cracks from Sliding

The lateral cracking described earlier (in 3.3.5) that is caused by a stationery sharp point, e.g. a V shaped object, is clearly more destructive when this point moves. It leaves in its path a wake of delaminated material, similar in section to figure 3.19 and extending along the full length of its travel.

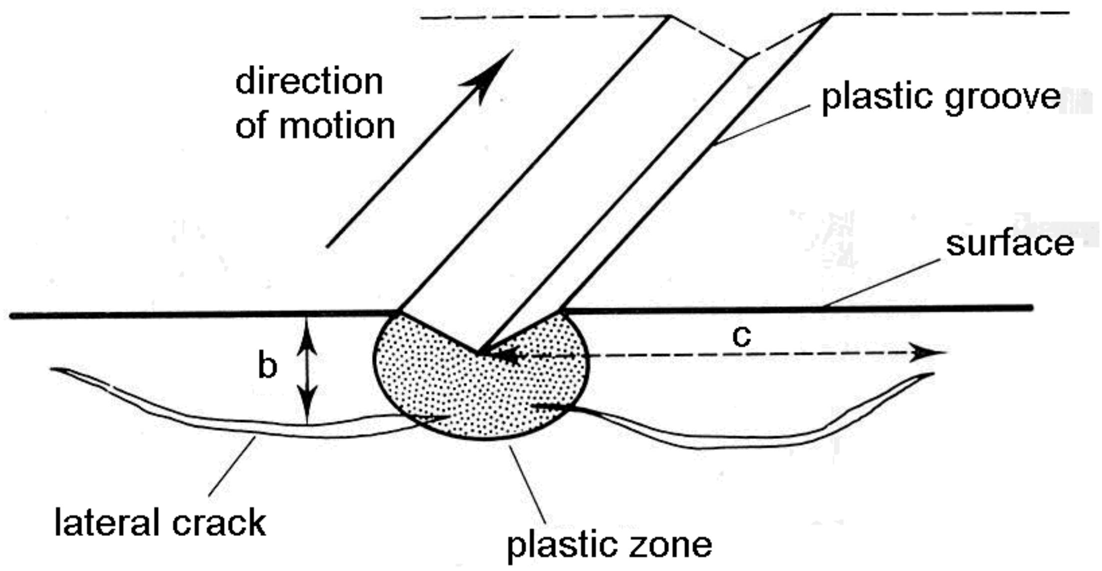

Figure 3.19 Schematic illustration of material removal in a brittle material by the extension of lateral cracks from beneath a plastic groove.

Experiments have been done on ceramics containing microcracks and brittle grain boundaries (similar in this respect to concrete) and a relationship for wear has been found such that:

$Q = \alpha_6 . N . w^{3/2} . H^{½} / Kc^2$ ……. (3.19)

Where
Q = the wear per unit of lateral movement
N = the number of asperity contact points
w = the average load at an asperity
H = indentation hardness
Kc = fracture toughness
α_6 = constant

From this model it is evident that:

a. wear by brittle fracture increases exponentially with the magnitude of w. Therefore wear increases rapidly as the number of contact points decrease, given that w = W / N, where W = the total load. Conversely for many contact points, w is small. As soon as w < w* (see equation 3.8), the failure mechanism reverts to plastic deformation as defined by equation 3.18.
b. Harder materials fracture more easily than softer materials, although hardness is not a very crucial factor in the equation.

c. The strong dependence on Kc, representing the fracture toughness, shows how sensitive brittle materials are to this property.

In practice lateral cracks as described above may be expected from mobile bins being placed onto the surface while still moving. This happens when drivers lower the bin onto the surface while the forklift is still in motion, thus using the frictional resistance of the legs of the bins to stop the forklift rather than apply their brakes. Lateral cracks are also likely to occur when a vehicle skids to a halt on a surface with some loose grit.

3.4.7 Axial Cracks from Sliding

As reported in 3.4.5 and 3.4.6 the wear associated with cone cracks and lateral cracks is proportional to the sliding distance. This may also be expected of axial cracks. (See 3.3.6 for a full discussion on axial cracks at a single point, as well as figure 3.3 f). As the load makes contact with the asperities of the counterface, axial cracking may occur at these contact points. The severity of the cracking (crack initiation vs stable crack propagation vs unstable crack propagation) will be a function of the intensity of the stress at these asperities, or in the case of severe abrasion these cracks will appear at sub-asperity depths.

On the other hand a degree of lateral compression is induced by the vertical stress, particularly in concrete slabs that have a large lateral aspect, and this will tend to limit axial cracking.

As was concluded in 3.3.6, further research into the extent of axial cracking in concrete slabs is recommended.

Sectional Summary

From the information presented in the literature thus far, it appears that axial cracking is most likely when the load has a flat surface whereas cone cracking occurs under a spherical load, while lateral cracking occurs as a result of a sharp object. This generalisation applies both to stationary and moving loads. Lateral cracking accompanied by sliding is clearly the most abrasive condition, and involves removal of material by means of the primary gouging/scratching action, see figure 3.19. It may be preceded by a degree of ‘densification’, that renders the counterface more susceptible to material loss from ongoing abrasion.

3.4.8 Sliding Hard Particles

The more severe forms of wear resulting from plastic deformation and the various forms of cracking mentioned above, are most often brought about as a result of hard particles acting as stress multipliers. This may take the form of a piece of sand/grit trapped between the tyre/shoe and the concrete surface. The particle is made to move laterally over the surface under pressure when the vehicle brakes heavily or slews during turning. It is not difficult to imagine such a particle gouging out a groove in the concrete’s surface, similar to figure 3.19, which depicts a combination of plastic deformation (labelled ‘plastic zone’) and lateral cracking. Similarly a hard rounded pebble made to roll over the surface in similar circumstances could quiet easily lead to the semi-circular cone cracks shown in figure 3.18.

The abrasive nature of hard particles emphasizes the need for regular sweeping of surfaces subject to either pedestrian or vehicular traffic.

3.4.9 Shear Failure in Concrete

From the arguments presented in the foregoing sections, it is evident that a body sliding under a normal load is opposed by a tangential frictional resistance, that in turn is made up of adhesion, deformation and cracking effects. Clearly the severity of these effects determines the degree of both the shear stress and abrasion wear at the points of contact. The average shear stress acting at the interface is the quotient of this frictional resistance and the apparent (i.e. gross) contact area of the load.

i.e. s = F / A ……. (3.20)

a. Pure and Simple Shear

A high degree of mechanical interlock may occur where a rough surface is subjected to a load that is also rough. For example a steel studded tire may be considered rough. If such a load slides/skids across a rough surface, *shear* failure may occur even under relatively light normal loads. In the extreme, the applied normal force may be considered negligible relative to the applied shear stress, in which case the distribution of shear stresses on an element at the surface will take on the form of figure 3.20.

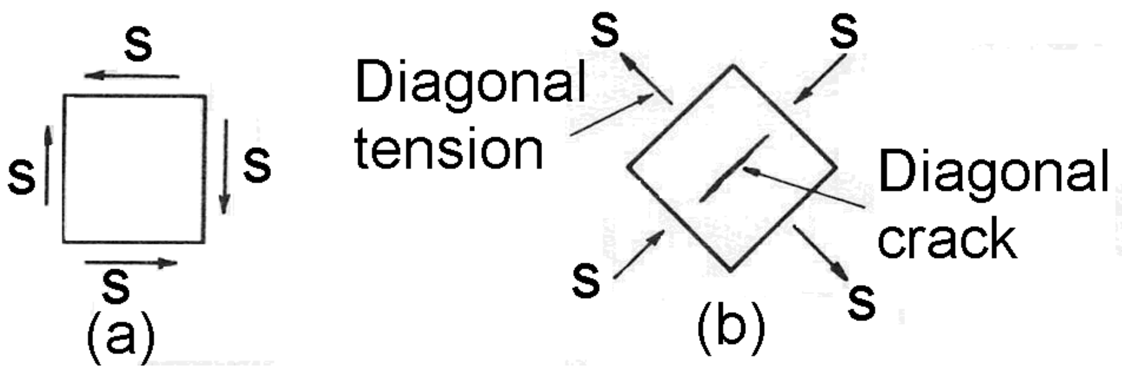

Figure 3.20 Traditional concepts of shear and diagonal tension.

In figure 3.20(a), the applied stress at the surface is resisted by an equal and opposite shear stress at the base of the element. Together they form a couple, resulting in a tendency for the element to strain in a clockwise fashion. The adjoining elements resist this rotation, resulting in vertical shear stresses of equal magnitude but at right angles as shown, thus establishing rotational equilibrium.

These shear stresses may be converted to normal stresses by resolving them into their respective components displaced by 45 degrees. In figure 20 (b) they are shown to act on an element that is also rotated by 45 degrees. Since fracture occurs *either* in the direction of the maximum principle *compressive* stress, or orthogonal to the maximum principle *tensile* stress (**Newman(1997a**), and since *both* these conditions are seen to exist in figure 3.20(b), it follows that 'diagonal cracking' is highly likely to occur as the stress, s, reaches a critical value. Clearly the point at which cracking occurs is related to the tensile strength of the concrete. When such cracks occur at or near the surface, this will accelerate abrasion wear.

b. Combined shear and compression

The more general case of abrasion occurs when there is *both* shear and compression.

In section 3.3.6.7(b) it was argued that the lateral compression on a concrete element at the surface near the center of a superimposed uniformly distributed load is $\sigma_x = \nu \cdot q$ (i.e. equation 3.14) where μ is Poisson's ratio, and q is the udl. Clearly this horizontal compression in the concrete retards the development of axial cracks, *and* thereby increases abrasion resistance. However it has also been shown that horizontal compression increases shear strength, as shown in figure 3.21 [Kong(1980)]. This applies except where the compressive stress is almost at ultimate. If for example, the level of compression is in the region of 0,6 f 'c, the ultimate shear strength may be as much as 0,25 f 'c, which is substantially more than the tensile strength of concrete, generally approximated as 0,1 f 'c. Thus for example, a 40MPa concrete with a lateral compressive stress of 24MPa will have an ultimate shear strength of 10MPa, whereas the shear stress would only be about 4MPa without lateral compression.

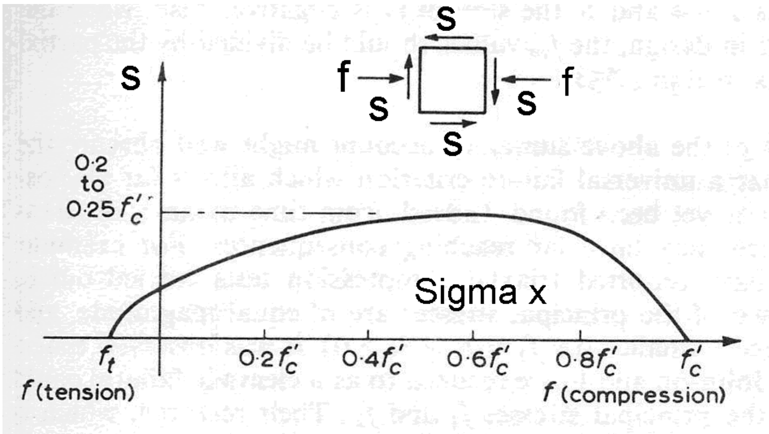

Figure 3.21 Failure of concrete under combined direct and shear stresses

The principle established here is that a vertical udl induces a lateral stress in the underlying concrete that in turn increases its shear strength. The increased shear strength will be related to fewer deformation and cracking effects and hence less abrasion wear.

However, in terms of expression 3.15 (F=λW), increasing the normal load also increases the frictional force, and thus *shear stress*. It may therefore be said that *both* the shear stress and the shear strength are increased by an increased udl. It follows that if the applied shear stress is greater than the shear strength, abrasion wear will occur at a substantially greater rate compared to vice versa. It is not immediately obvious whether the increased *shear strength* will keep pace with the increased *shear stress*. The former follows the parabolic shape of figure 3.21, with an ever decreasing gradient as lateral compression increases, while the latter increases linearly with increasing vertical compression. Once again this aspect will be illustrated in terms of specific examples, see table 3.2 in section '3.5 Common Applications'.

c. Bending Stresses

When a reinforced concrete slab sags in bending under an applied load, the top fibres are compressed. Clearly this also will have the effect of increasing 'f (compression)' and thereby 's', and thus abrasion resistance. If it is assumed that the level of compression is generally limited to 1/3 of the crushing strength, then based on figure 3.21, the shear strength corresponding to such a load sliding would result in a shear strength of approximately 0,22, a substantial improvement.

3.4.10 Other Wear Mechanisms

Before proceeding to section 3.5, it will be useful to establish two wear mechanisms related to the strength and integrity of the surface:

- *Interfacial wear mechanisms* affect only the topmost fibres of the concrete. This occurs in relatively strong concretes, where the cohesive shear strength of the material is greater than the shear stress at the interface of the two surfaces (induced by adhesion, elastic deformation, plastic deformation etc). The load therefore slides/skids/scrapes over the surface and although the degree of wear will depend on the magnitude of the load as well as the coefficient of friction between the two surfaces, only the topmost surface material in contact with the load is removed in this mode of abrasion. On the scale of asperity abrasion wear, interfacial wear represents the loss of the very topmost material in contact with the load (see figure 3.22), and the contact area, A_{net}, representing the contact at the asperities remains essentially constant and is clearly less than the total A_{total} .

- *Cohesive wear mechanisms* affect the concrete at a greater depth. In its most severe form, the asperities are levelled, and the area A_{total} is the full area of the load. These wear mechanisms apply to inferior types of concrete or alternately to sliding under high normal loads. Here the adhesion and mechanical interaction between the applied load and the surface is greater than the cohesive strength of the material, so that the concrete fails at a deeper level. Brittle fracture leading to lateral cracking may also be considered a form of cohesive wear, in that the lateral cracking takes place at some depth into the material. Conversely the very small strains associated with elastic deformation do not result in sub-surface wear, or any wear for that matter.

Note that plastic deformation/densification may be classified either as interfacial or cohesive wear, depending on the severity of the load and the strength of the material

Interfacial and cohesive wear are illustrated in figure 3.22

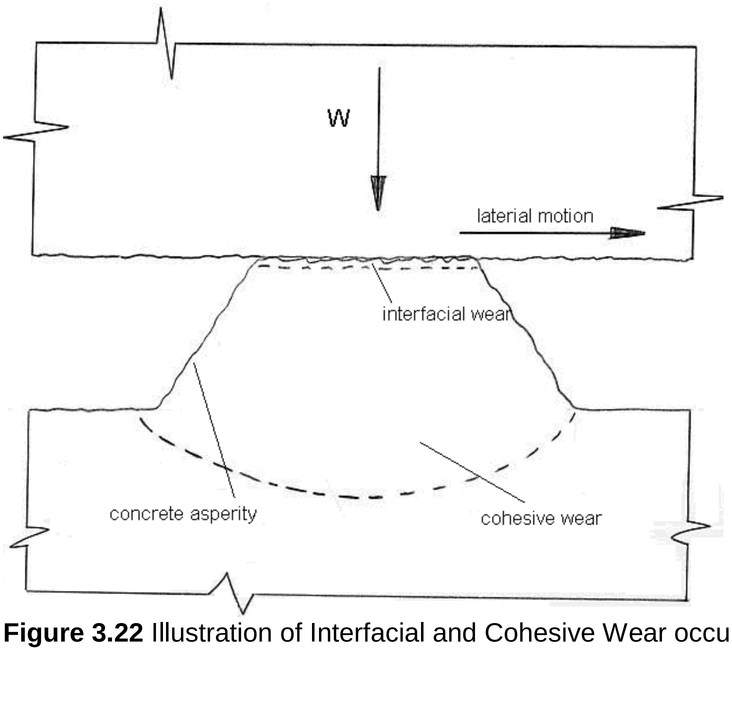

Figure 3.22 Illustration of Interfacial and Cohesive Wear occurring at an asperity contact.

3.4.11 Other Factors Affecting Shear Strength, Abrasion Resistance, and Abrasion Wear

It has been shown that horizontal compression in concrete increases its shear strength [e.g. see 3.4.9 (b)].
If it is assumed that the same factors that increase abrasion resistance also increase shear strength, then, from the discussions in chapter 2, and figure 2.2, it is evident that there are many other factors that increase shear strength, including a low w/c ratio, a strong aggregate/paste interfacial zone, liquid surface treatments that harden and toughen the surface matrix, etc.

One aspect that was not discussed that has a definite influence on shear strength, particularly in the post crack zone, is aggregate particle interlock. According to Kong(1980) the mechanisms of shear transfer in a cracked concrete beam may be apportioned as follows:

- Aggregate interlock = $V_{a\ (50\%)}$
- Dowell action = $V_{d\ (20\%)}$
- Compression zone shear = $V_{cz\ (30\%)}$

It is not difficult to visualise how a surface that is already cracked owing to severe shear-stress/abrasive-effects will resist loss of further material where the aggregate particles are substantially '*interlocked*'. On the other hand dowel action refers to the contribution to shear strength from the longitudinal tensile reinforcing of a reinforced concrete beam, and has no relevance to abrasion resistance. Finally the contribution of '*compression zone shear'* is noted and ties in with the discussions and general conclusions of 3.4.9.(b).

3.4.12 Sectional Summary and Conclusion

The normal load may adhere to the surface, deform the surface, or even crack the surface, and it is these physical effects that contribute towards a resistance to lateral motion, referred to as friction. The effect of lateral sliding is to 'export' and 'multiply' whatever abrasive effects occur as a result of direct compression. Deformation may be elastic or plastic, while cracking may take the form of semi-circular cone cracks, lateral cracks or axial cracks. The resulting sliding wear may be confined to the immediate vicinity of the contact asperities, in which case it is 'interfacial'. Alternatively the effects of friction may be relatively deep, resulting in 'cohesive' wear. In concrete floors the application of a vertical stress induces lateral compressive stresses that tend to limit the development of axial cracks and increase the shear strength. However, it the frictional force associated with the sliding load is too great, the shear stress will exceed even the 'enhanced' shear strength and cracks will appear. In the following section the various common applications of stationary compression as well as sliding abrasion will be considered, and the 'enhanced' shear strength will be compared with the applied shear stress.

3.5 Common Applications

The various modes of physical attack on concrete surfaces have been listed in figure 2.1 as abrasion, erosion, cavitation, and freeze-thaw, while dissolution, leaching, expansion, and alteration are given as a means of chemical attack. Of these, abrasion induced wear may be regarded as the primary source of wear in most industrial floors, concrete roads, and paved areas. The other physical wear mechanisms listed are more applicable to hydraulic applications or cold climates, while the chemical mechanisms listed are not normally a major concern, and are discussed in 2.2.2.3 and 2.2.2.4.

In this context four of the most commonly occurring situations that lead to abrasion will be considered, and each case shall be considered in the light of a ‘motionless’ load and a ‘sliding’ load, applying the theory of sections 3.3 and 3.4. The relative severities of the different cases will be evaluated by calculating the applied compression and shear stresses relating to these examples, and comparing them to generally accepted values.

This exercise is finally summarised in table 3.2 which serves as a means of grading the relative severity of the various applications relative to shear stress and consequently abrasion resistance. The outcome of the grading will be considered against generally observed levels of abrasion wear in practice, although this will be according to the writer’s subjective point of view. It does nevertheless give some indication of relative severities of various abrasive situations, and the extent that they can be assessed by a combination of theory, calculation and judgement.

The eight cases are illustrated in figure 3.23, and may be summarised as:

1 Tyre – motionless
2 Heel – motionless
3 Baseplate – motionless
4 Hard particle – motionless
5 Tyre – sliding
6 Heel – sliding
7 Baseplate – sliding
8 Hard particle - sliding

Note: The calculations generally assume a concrete with a compressive strength of 40MPa.

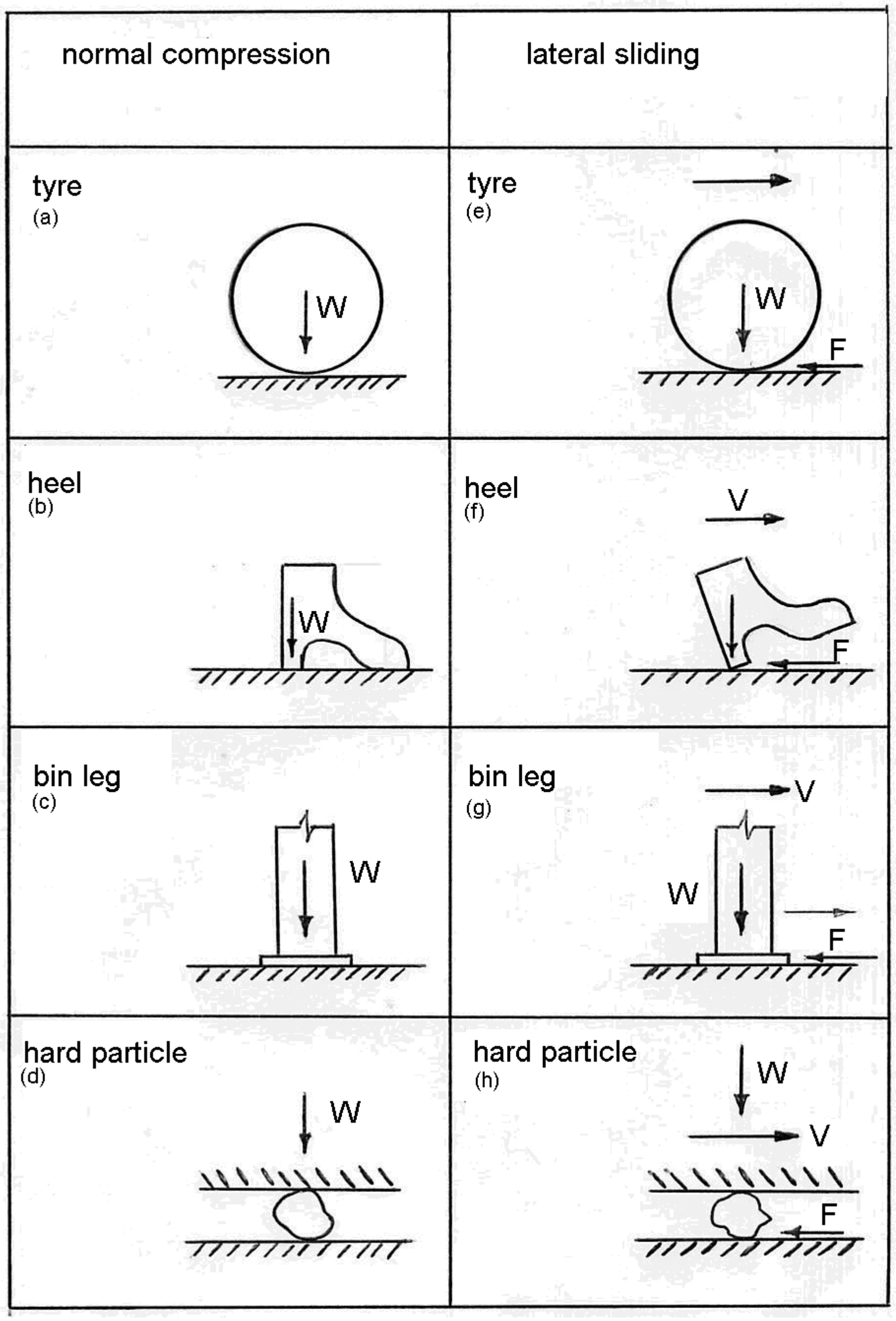

Figure 3.23 Common modes of abrasion wear

3.5.1 Applied Loads Consisting of Pure Compression

1 Tyre - Motionless

Most concrete surfaces are trafficked by vehicles with pneumatic tyres. This includes major intercity freeways that are heavily trafficked both in terms of number of vehicles per hour and in tonnes per axle. It also includes paved areas in industrial parks, garage forecourts, and on the other end of the scale domestic driveways and garden footpaths, etc.

If the maximum permissible axle load in a truck is 8 tonnes, and there are four tyres on the vehicle, each 200mm in width, inflated to a pressure of 800kPa, then to satisfy vertical equilibrium:

W_{mean} = pressure x area
i.e. 80000N = 0.8N/mm2 x (4 x 200mm x L)
i.e. L = 125 mm
where L is the contact length between tyre and road.

Clearly a surface stress of 0,8 MPa is a very low level of compression, even for an average concrete of say 25MPa, and the surface fibres of the concrete will remain well within their elastic limit. Furthermore given that concrete is very much harder than rubber, it is the concrete that will cause wear on the rubber (although very slowly), not vice versa. Concrete freeways around the world, in service for many years, testify to the excellent performance of concrete surfaces subject to pure compression from rolling wheels.

Wheeled traffic however is not confined to pneumatic rubber tyres. Concrete surfaces are also the first choice in most industrial warehouses, where some forklifts are fitted with 'solid' tyres made from a relatively hard synthetic polymer. To obtain an idea of the pressures in this instance it will be assumed that the axle load is 10 tonnes, there are two tyres, each 150mm wide, making apparent contact over a length of 50 mm.

Mean Pressure = Force / area

i.e. Mean Pressure = 100000N / (2 x 150mm x 50mm) = 6,7N/mm2.

Although not excessive, this is clearly a considerably higher stress than that applied by pneumatic tyres, and the compressive strength and abrasion resistance of warehouse floors carrying heavy forklifts with 'solid' rubber tyres should be designed with this in mind.

Steel wheeled traffic, which will have a very small contact length, especially where small diameter wheels are used, should be avoided at all costs, unless very lightly loaded.

2 Heel – Motionless

As in the case of a wheel of a truck, it is possible to estimate the pressures beneath the heel of a 60 kg lady wearing stiletto shoes. Assuming that the nominal area of the heel is 9mm x 9mm, and that all her weight is on the heel of one of her legs at a given point in time, then the nominal pressure on the surface is:

Pressure = Force/area

i.e. Pressure = 600N / (9mm x 9mm) = 7,4 N/mm2.

Clearly this is considerably more than the pressure beneath a pneumatic tyre, and is comparable with the pressure beneath a ‘solid’ rubber compound tyre. Neither should it be considered an extreme case, as the initial angle of contact of the heel of an ordinary shoe is such that the area of contact is also very small, and moreover is accompanied by an element of impact. It may be concluded that compressive stresses beneath footwear are not insignificant.

The following discussion serves to show that compressive stresses beneath pedestrian footwear as highlighted above, approaches the crushing strengths of pavers that may even comply with the lower limits of the SABS paving standards. If 10MPa concrete (as determined in a standard 100mm cube crushing test) is moulded into a 50mm high paver of plan area 200mm x 100mm, and is furthermore made with a shallow 10mm wide bevel on the outer circumference of the wearing surface, it will appear to have a compressive strength of 20MPa, and thus still ‘conform’ to the requirements of the SABS 1058 specification for ‘individual’ results on concrete pavers. (The average must be ‘25MPa’). This is the effect of not applying an aspect ratio correction factor and using the net area rather than full plan area of the surface in the calculation. It is hoped that this 1985 specification will be revised by the industry (they are aware of the problem) to ensure that sub-standard concrete, with poor abrasion resistance (see chapter 8 in volume 1 for evidence of 3rd and 4th degree abrasion), is eradicated. Ultimately the additional cost of using a stronger mix and well-controlled processes will improve the image of the industry and increase market share.

3 Baseplate – Motionless

Warehouses typically have racks for storage of goods. The trend over the last few decades has been to increase the height of the racks resulting in greater mass and therefore high contact loads at the bases. It is essential that these bases are soundly grouted to the concrete floor to prevent excessive pressures. However, some factories have mobile free standing storage bins that are moved by forklift or crane from one area to another. These bins will not have *very* heavy loads, but the possibility of poor baseplate/surface-contact is also much greater. The potential exists for Hertzian cone cracks (see figure 3.8) or alternatively lateral cracks leading to spalling (see figure 3.9). This may occur if the slab is not very even so that contact is made only at a few ‘hills’, or alternatively where baseplate alignment is poor such that the mass is transferred as a single point load at one corner of the baseplate.

If for example the load at one of the four baseplates is 1 tonne, and if there is poor alignment between the baseplate and surface such that the contact area is 16mm x 16mm, then:

Contact pressure = Force / Area

i.e. p = 10000N / (16mm x 16mm) = 39N/mm2

In these situations even 40MPa concrete is likely to undergo a degree of plastic-deformation/densification/lateral cracking as illustrated in figure 3.9, although the effect of lateral confinement will enhance the load carrying capabilities of the slab.

4 Hard Particle – Motionless

Even if there is good base plate alignment and surfaces are level, the presence of grit beneath movable storage bins allows for extremely severe abrasion wear on surfaces.

This may be illustrated by considering a hard particle of contact area 5mm x 5mm beneath a load of 1000kg. Once again:

Contact pressure = Force / Area

i.e. i.e. P_{mean} = 10000N / (5mm x 5mm) = 400N/mm2

Localised compression at this level will result in severe localised crushing and loss of material.

Similarly large pressures and crushing effects are possible with grit beneath a vehicles tyre.

What may not be so apparent is that a grain of sand on a pedestrian sidewalk can be equally abrasive. If the area of contact is 4mm^2, and a person of mass 70kg steps on this particle, then:

P_{mean} = Force / Area = 700 / (2x2) = 175 N/mm^2

This clearly exceeds the compressive strength of the concrete, and loss of material by means of the plastic-deformation/densification/lateral-cracking process (illustrated in figure 3.9) is virtually assured.

Alternatively, assuming loading conditions that are not quite as severe, so that the surface responds elastically, Herzian cone cracks may appear if $\sigma_{\text{Hertz cone crack}}$ > tensile strength of the concrete.

To demonstrate this the foregoing illustration may be slightly modified, such that a small child of mass 7.5 kg steps on a spherical piece of hard grit that has a radius of 2mm. By applying expressions (3-1) and (3-2) and making the assumptions $E_{concrete}$ = 40 GPa, E_{grit} = 120 GPa, $\nu_{concrete}$ = 0,22 and ν_{grit} = 0.15, then the radius representing the contact circle between the spherical grit particle and the concrete counterface is, a = 1,0 mm.

i.e. $\frac{1}{E} = \frac{1-0{,}22^2}{40} + \frac{1-0{,}15^2}{120}$

i.e. E = 31,3 GPa

and

a = $\left(\frac{3.75.2}{4.31300}\right)^{1/3}$ = 1,0 mm

Now applying expression (3-3), and (3-7) the compressive stress P_{mean} is 24MPa, while the Hertzian tensile stress acting at the radius a is 13,4 MPa. As this exceeds the tensile strength of most commercial concretes, Hertzian cone cracks may be expected.

i.e. p_{mean} = $\left(\frac{75}{\pi.\{1\}^2}\right)$ = 24 MPa

and $\sigma_{\text{max Hertzian tensile stress}}$ = (1-2.0,22)24 = 13,4 MPa.

However these cracks do not generally lead to loss of material [Hutchings(1992)], and the concrete directly beneath the particle will still be in a state of *elastic* compression (for P_{mean} =24 MPa and assuming say a 50 MPa concrete).

It may be concluded that a hard particle under a relatively *light* load can easily lead to Hertzian cone crack development, which is not generally associated with wear, whereas

the very high compressive stresses associated with concentrated *moderate* loads will lead to localised crushing (associated with various forms of cracking, such as lateral and axial lateral cracking, and this *is* associated with loss of material.
The high stresses associated with concentrated loads explain why inferior quality paving blocks degenerate very quickly. Once loose particles of aggregate are free of the matrix, they act as stress accelerators, and the demise of the surface thereafter is rapid.

3.5.2 Applied Loads Consisting of Lateral Sliding

Having considered the effects of pure compression on motionless objects, attention is now focussed on situations where the element of lateral sliding is introduced. The corresponding frictional resistance will stem from a combination of adhesive effects, elastic deformation, plastic deformation, and various forms of cracking. In fact all the mechanisms of wear resistance indicated in figure 3.3 (with lateral sliding added) are likely to apply to a greater or lesser measure. At the same time it should be expected that the shear strength of the surface will be enhanced by lateral compressive stresses that are induced by the normal stresses associated with the applied shear stress (explained in section 3.4.9.(b)). This and other effects are summarised in the next section, 3.5.3.

5 Tyre – Sliding

Tyres slide/skid on the surface during:

- deceleration, especially rapid deceleration accompanied by classical skidding
- acceleration, especially rapid acceleration where tyres are made to spin
- turning/slewing movements during parking and cornering

The affects of this sliding is considered here under clean-surface condition where ‘hard particle effect’ does not play a part (this is dealt with in ‘8 Hard particles – skidding’.

(a) Pneumatic tyre

Figure 3.23 (e) shows a rubber tyre under normal load W skidding over a concrete surface. It is resisted by a tangential frictional force, F equal to the $W.\mu$. The frictional force imparts an average shear stress, s_{mean} to the concrete, such that:

$s_{mean} = W.\mu / A$ where s is the shear stress, and A is the gross area. Using the example given in ‘1 Tyre - Motionless’, and assuming μ is 0,4 for a rubber/concrete interface, this shear stress may be calculated as:

s_{mean} = (80000 N) x 0,4 / (4 x 200mm x 125mm) = 0,32 N/mm2.

Reynolds(1972) tables a *permissible* shear stress of 0,7 MPa for a nominal mix of 1:2:4. The stress level of 0,32 MPa is thus below the ‘cohesive’ shear strength of the concrete. Therefore, whatever wear effects do occur will be ‘interfacial’.

(b) Solid rubber tyre

Concrete surfaces subjected to skidding *solid* rubber tyres are still likely to experience only interfacial wear. Again using the example for solid tyres from section ‘1 Tyre – motionless’, the maximum shear stress may be calculated as:

s_{mean} = (100000 N) x 0,4 / (2tyresx 150mm x 50mm) = 2.67 MPa. This is clearly an order of magnitude higher than that of pneumatic tyres and raises some concern in terms of failure. It is however a classical case of the simultaneous application of shear and compression working, and therefore improved shear strength may be expected. It was shown in ‘1Tyre – motionless’ above that the equivalent compressive strength was 6.7

N/mm2, and therefore for a 40 MPa concrete the relevant ratio is 6.7/40 = 0.17 f'c. Figure 3.21 indicates that at this level the shear strength, s, is approximately 0,16 f’c , or 6,4 MPa. This demonstrates the benefits of compression-enhanced shear strength, since without it the shear strength would be of the order of 4 MPa.

The absence of damage to clean concrete floors in warehouses across the country that are typically trafficked by forklifts fitted either with pneumatic tyres or ‘solid’ tyres is thus accounted for.

6 Heel – Sliding

A slight amount of tangential sliding or ‘skid’ occurs when a heel of a shoe is placed on the surface during walking. Figure 2.23 (f) indicates that as it slides, it is resisted by a tangential frictional force, F, equal to the W x μ. This imparts a shear stress, s, to the concrete, such that:

s = μ W / A where A is the gross area. Using the example given in ‘2 Heel - Motionless’, and assuming μ is 0,4 for concrete/polymer surface interaction, then the shear stress may be calculated as:

s = (600 N) x 0,4 / (9mm x 9mm) = 3 N/mm2

Once again the simultaneous application of shear and lateral compression applies in this example, and improved shear strength can be expected. It was shown in ‘2 Heel – motionless’ that the equivalent compressive strength was 7,4 MPa, and therefore for 45 MPa strength concrete pavers, formally specified in Australia in MA20(1986) prior to the introduction of AS/NZS 4456(1997) (which specifies flexural strength), the ‘enhanced’ shear strength can be determined by the ratio 7,4/45 = 0,164 f'c. Figure 3.21 indicates that at this level the shear strength, s, is approximately 0,16 f'c or 7 MPa. The MA20 paver specification is meaningful to use here as an illustration since it allows the full plan area, and makes correction for aspect ratio.

(On the other hand, if the equivalent ‘10 MPa’ concrete of SABS 1058 is used, the enhanced shear strength will be determined by the ratio of approximately 7MPa/10MPa = 0,7 f’c. Figure 3.21 indicates a corresponding shear strength 0,24 f’c = 2,4 MPa).

Clearly the applied shear stress of 2.8 MPa is significantly lower than the shear strength of 7 MPa for pavers made to the former Australian standards, but it is higher than the shear strength of 2,4 MPa for pavers that only just comply to SABS. An obvious but very important conclusion arising out of this is that shear-strength/abrasion-wear in pavers subjected to footwear may or may not be excessive depending on the quality of the pavers.

Although the example may be regarded as extreme (60kg lady walking in stiletto heeled shoes), excessive wear in paving blocks in shopping malls and sidewalks, particularly where traffic is funnelled, has resulted in excessive wear. This was one of the primary motivations for the Australians including an abrasion test in their national standard.

7 Baseplate – Sliding

Some forklift drivers have a braking technique that involves lowering the movable storage bin onto the ground before at a standstill. The baseplates scrape on the surface under their full load, propelled by the combined momentum of the bin and coasting forklift. It was shown in ‘3 Baseplate – motionless’ that contact compression of up to 39 MPa is possible resulting in deformation/cracking effects, and clearly these effects will be duplicated wherever the load goes, with the potential for rapid abrasion wear, both in terms of light scratches related to plastic deformation/densification and deep gouging related to cracking. Cracking may take the form of semicircular cracking as illustrated in figure 3.18 or lateral cracking as illustrated in figure 3.19, the former associated with blunt contacts, the latter with concentrated contacts. Axial cracking may also occur from the high compression.

Figure 2.23 (g) indicates that as the baseplate skids, the normal load W is once again resisted by a tangential frictional force, F, equal to W x μ, resulting in a shear stress s = μ W / A, where and A is the gross area of the baseplate. Adapting the case '3 Baseplate - Motionless' to sliding, and assuming μ is 0,3 for concrete/steel surface interaction, then the shear stress may be calculated as:

s_{mean} = (10000 N) x 0,3 / (16mm x 16mm) = 11.7 N/mm2

In this case the ratio of actual compressive stress to compressive strength is 39/40 $\not\subset$ 1f 'c and figure 3.21 shows that in this zone the shear strength arising out of the horizontal compression is virtually zero. (Qualitatively his makes sense, as concrete that is failing in compression will have minimal shear strength).

Thus it may be expected that a shear stress of 11.7 MPa will plough/scrape a significant groove into a concrete that is locally at a point where it has virtually no shear strength. The example is extreme but does illustrate the need for care in manufacturing equipment, and ensuring smooth surfaces.

8 Hard Particle – Sliding

(a) Grit under base-plate

The presence of a hard particle below the baseplate will have very severe gouging effects if the load is made to slide. Assuming a contact area of 5mm x 5mm beneath a load of 1000kg (see '4 – Hard Particle – motionless') vertical compression was shown to be 400 MPa. This translates to a shear stress of 160 MPa (λ = 0,4). The expected mode of failure will likely resemble 3.19, and lateral cracks are likely to be extensive. Interfacial wear will be insignificant relative to cohesive wear.

(b) Grit under man

Similarly grit or sand beneath tyres or footwear is also very abrasive. In an earlier example ('4b') for a motionless pedestrian weighing 70 kg who is standing on a particle of sand of contact area 2mm x 2mm the contact pressure was shown to be 175 N/mm^2. Figure 2.23 (h) indicates that as the sand particle skids, the normal load W is again resisted by a tangential frictional force, F, equal to W x μ, resulting in a corresponding shear stress s_{mean} = μ W / A, where A is the contact area between sand particle and concrete. Assuming μ is 0,4 for concrete/grit interaction, the maximum shear stress may be calculated as:

s_{max} = (700 N) x 0,4 / (2mm x 2mm) = 70 N/mm^2

Once again no shear strength enhancement will be achieved under a regime such as this where localized crushing effects are so severe. The example is not extreme.

(c) Grit under child

Even if the person stepping on the grit was half the weight, i.e. 35kg, shear effects would still meet with virtually no resistance from the locally crushed concrete. This again illustrates the need to keep concrete surfaces well swept.

3.5.3 Effectiveness of Lateral Compression

Remarks on Table 3.2: Table 3.2 considers the vertical stress at a defined distance, z, beneath the center of the rectangular loads described in 5(a) through 8(c). The distance z is arbitrarily taken as the depth beneath the surface where the vertical stress is equal to 98% of the surface pressure, q. The analysis is based on Bousinesq's equation [see expression (3-9)], and is adapted to expression (3-21) for a uniformly distributed load, q, applied to a rectangular area with sides a and b, see figure 3.24.

$$\sigma_z = \frac{3qz^3}{2\pi}\int_0^a\int_0^b \frac{dydx}{\left(x^2+y^2+z^2\right)^{5/2}} \quad \ldots\ldots. \ (3\text{-}21)$$

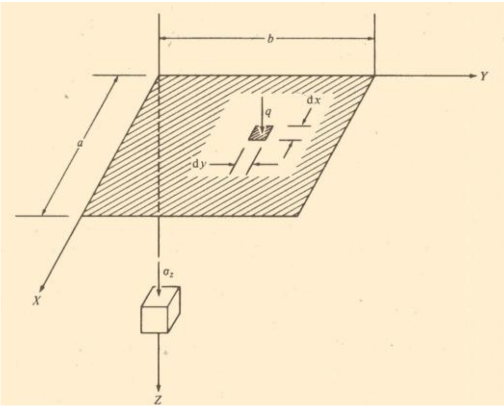

Figure 3.24 Stresses on an element beneath the corner of a quadrant having sides a and b, which subject to a uniformly distributed load, q. [Cernica(1982), pg181]

Note that the application of expression (3-21) has been simplified by relating σ_z to the ratios m=a/z, n=b/z, such that σ_z = q.f_z(m,n), where f_z(m,n) may be obtained from tables set out in Cernica(1982). Note that q is obtained by dividing the load acting on the quadrant by that area, i.e. q = W/(a.b).

However, this expression applies to only one quadrant of the rectangles of 5(a) through 8(c), and furthermore the stress pertains to the vertical line beneath the corners. Therefore to obtain the vertical stress at the center of rectangles which in effect have sides of 2.a and 2.b, the stress given by expression (3-21) must be quadrupled.

No formulae are given for σ_Y,and σ_X ,but logically these values may be assumed to be equal to the product of Poisson's ratio and the vertical stress at that depth, i.e.:

$\sigma_Y = \sigma_X = \nu . \sigma_Z$……. (3.14)

for elements that are more to the centre of the applied load and relatively close to the surface.

Table 3-2 shows the influence of the area of the applied load on the depth of the vertical stress. The smaller a or b is, the smaller z is. It is logical that the vertical stress for an applied load with a small surface contact area is only at a level of 98% at depths very close to the surface. Nevertheless, even for the grain of sand of dimensions 2mm x 2mm (see cases '4 and 8 - grit under man'), the 98% level is 0,3mm, and in terms of the slow rate of wear that is typical with say 'mild' abrasion, this may be considered reasonably *deep*. Furthermore horizontal compression operating in this zone would have a positive effect on increasing the shear strength.

The following may be concluded from Table 3.2:

(a) The shear strength is generally enhanced (see $s_{enhanced}$) by horizontal compression, to a level above the nominal shear strength of 0,1 f 'c (no horizontal compression), and this increases abrasion resistance. For example the enhanced shear strength of '6 ladies heel' may be seen to be 5MPa rather than the nominal un-enhanced 4MPa.The level of enhancement is somewhat limited by a relatively low Poisson's ratio, which was taken as 0,22 in Table 3.2, which is a typical value for concrete.
(b) Abrasive loads and stresses can vary very substantially in magnitude (i.e. from 0,8MPa to 400 MPa). Generally the high stresses apply to the loads that have small contact areas. In such cases there is no benefit from lateral compression, since clearly lateral compression cannot build up where concrete is already crushed.
(c) Attaining stresses as high as 400MPa is based on the assumption that the abrasive will itself not break down under these high compressive stresses, and furthermore that it is significantly harder than the concrete counterface. In practice however, the grit is generally no harder than the aggregate, and may even be softer, if the concrete is made from andesite aggregate. In such cases abrasion-wear related crushing will be limited to areas where paste is exposed.
(d) The rate at which the vertical stress on an element dissipates is a function of the area of the udl. In the examples cited the depth at which the stress on an element is 98%-of-the-vertical-surface-stress varies from 0,3mm for '8 – grit under a man' to 20mm for '5- pneumatic tyre of a truck', the difference clearly being related to the area of the applied load.
(e) The order of severity of the applied shear stresses, s_{mean}, is as follows:

- 8(a) grit under baseplate
- 8(b) grit under man
- 8(c) grit under child
- 7 baseplate
- 6 ladies heel
- 5(b) solid rubber
- 5(a) pneumatic rubber

Correlation between observed abrasion and above stated 'order of severity'.

Since $s_{mean} = \nu .q$, it is evident that the greater the applied stress at the surface the greater is the shear stress. Furthermore it is also evident that s_{mean} generally decreases with increasing softness of 'abrasive'. The slight wear witnessed on concrete freeways that are free of grit and that have been subjected to heavy traffic over many years confirms that 5(a) should be at the bottom of the 'severity' list given above. On the other hand rapid abrasion may be seen on concrete surfaces where grit has accumulated. This is very evident in the 'fourth degree abrasion' grit-covered-pavers outside the factory entrance, subjected to heavy vehicles braking and slewing, see figure 8-44 of volume 1.

Although both the freeway and the factory entrance are traversed by the some heavy trucks, the latter has a very high q relative to the former as a result of the grit's stress multiplier effect (discussed in 3.3.7).

The shear stress corresponding to sliding solid tyres and sliding ladies stiletto heels falls within the shear strength of 40MPa concrete, particularly where it is 'enhanced', as shown in table 3-2. On the other hand, where inferior concrete is used, these abrading mediums have been known to cause significant abrasion.

Table 3.2

Sectional Summary and Conclusion

This section has focussed on four different types of abrasion loading each being subject to two loading cases, first that corresponding to pure compression, followed by lateral sliding under load.

Both these loadings are capable of causing serious abrasion wear, depending on the value of q as tabled in Table 3.2.

It is also shown that the vertical strain caused by normal surface stresses results in lateral compression that enhances the shear resistance of the concrete, and hereby its abrasion resistance.

Table 3.2 has shown that providing the surface under traffic is free from grit, the corresponding compressive strength and shear strength will exceed the applied compressive stress and shear stress applied by most sliding loads, and wear is therefore not expected to be excessive.

The general order of severity shown in the table is a confirmation of what the writer has observed in many concrete surfaces in the field.

3.6 Summary and Conclusion to Chapter 3

The discussions in this chapter have been largely theoretical, although much of the material used is based on the experimental findings of many researchers, whose findings have variously been reported on by Hutchings(1992), Newman(1997a), Kong(1980), and Cernica(1982). From these sources, as well as from the writer’s own experience and observations, an attempt has been made to formulate a theory on the ‘mechanisms of abrasion wear’ in concrete.

Abrasion wear takes place when two surfaces come into contact with each other, whereby the harder surface causes the softer to suffer material loss. It appears that ‘indentation hardness’ is *the* most desirable property for abrasion resistant surfaces, unless significant impact forces are present, and in this case some hardness should be sacrificed for increased toughness (i.e. less brittle, more ‘ductile’, softer) in order to prevent excessive abrasion related to cracking.

There are three principle mechanisms of abrasion wear, adhesion, deformation, and cracking. Deformation may be either elastic or plastic, whereas cracking may take the form of Hertzian cone cracks, lateral cracks or axial cracks. In concrete, adhesion is unlikely to account for much wear. Contrariwise the various kinds of cracking are associated with the greatest abrasion rates.

These mechanisms of wear occur either in a state of pure compression or may include the element of sliding. Generally the damage that occurs in sliding wear will be the same as that in pure compression multiplied by the sliding distance.

Concrete is known to fail by the initiation and propagation of ‘axial’ cracks (in the direction of the applied load). In the process the concrete dilates laterally, the vertical shortening being related to the horizontal widening by Poisson’s ratio.

In a rigid concrete slab the vertical strain following the application of a vertical stress results in horizontal compression, since lateral dilation is restrained. The more central the elements are in relation to the centre of the uniformly distributed load and nearer they are to the surface, the more perfect is this restraint (see table 3.2), and thus the greater is the horizontal compression for a given vertical stress. Furthermore, where a concrete slab sags in bending beneath an applied load, the top fibres will be subject to further lateral compression.

Clearly lateral compression limits axial cracking in brittle materials. Similarly, by applying horizontal compression to the various components that make up concrete (the aggregate, the paste, the aggregate /paste interface), it will be more difficult to pluck these components out of the matrix by means of abrasive shearing actions. It has been shown that a lateral compression of 60% of the crushing strength, can raise the shear strength to 25% of the crushing strength. This has relevance in regard to all forms of sliding abrasion.

Wear may either be 'mild' and 'interfacial', involving a slight amount of material sheared off at the asperity/abrasive interface, or alternatively 'severe', whereby the depth of abrasion extends to a sub-asperity depth. This may also be referred to as 'cohesive' wear.

Figure 3.25 below shows a hierarchy of the mechanisms of abrasion and that there are 11 possible levels. The mechanism that applies will depend on (1) the characteristics of the abrasion-load / abrading-media, and (2) the abrasion resistance of the surface.

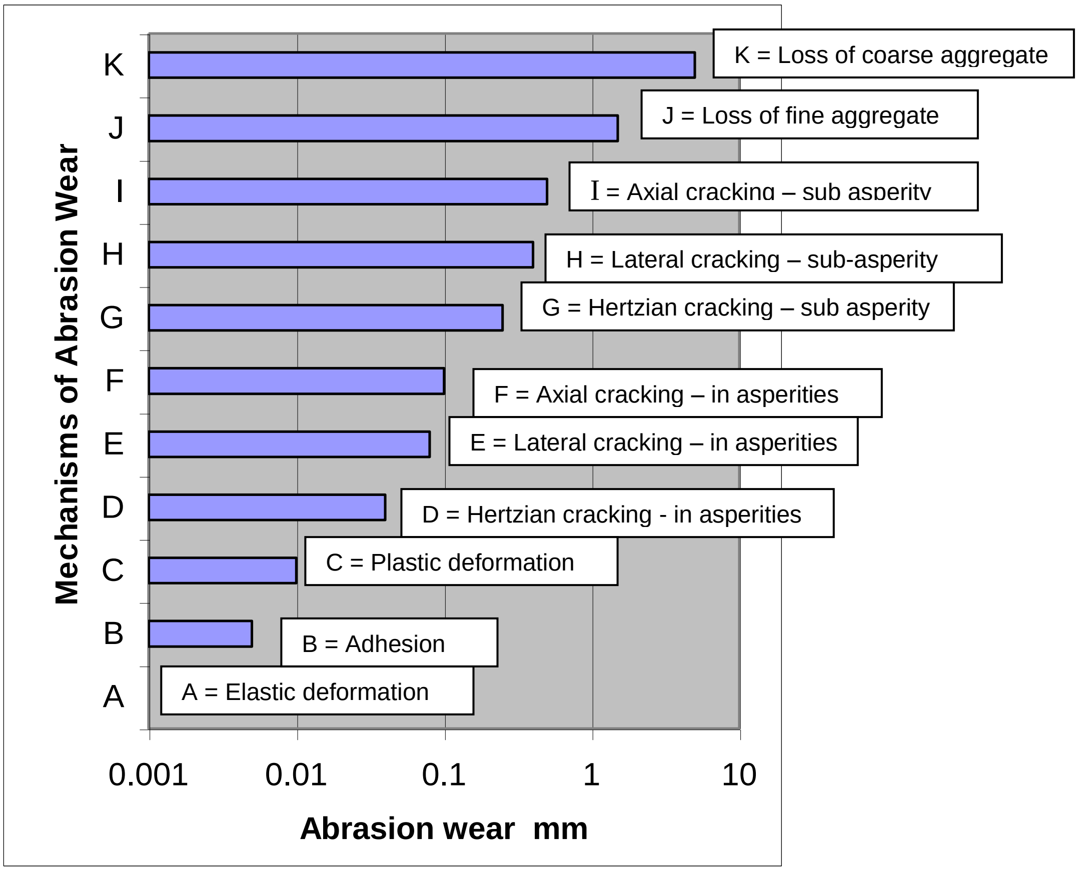

Figure 3.25 Hierarchy of the 'mechanisms of abrasion wear' in terms of 'abrasion wear'

The first nine mechanisms of abrasion wear have already been discussed in preceding paragraphs, and the abrasion wear may be seen to vary from zero for elastic deformation, to almost 1mm for sub-asperity cracking. (Note that the values in figure 3.25 are not based on any specific experimental data, and serve merely to indicate typical values for the different types of wear). The last two responses, corresponding to the loss of fine and coarse aggregate respectively, are equivalent to 3rd and 4th degree abrasion-wear as described in chapter 8 of volume 1. Clearly these responses represent the greatest wear, showing the relative danger of a weak aggregate/paste bond.

A consideration of the most common applications of abrasion has shown that abrasion is most unlikely to occur beneath pneumatic wheels, and will only be slight under pedestrian traffic and even solid rubber tyres, even where they carry heavy loads. A proviso is that the surface is clean. However, the presence of grit/loose-sand entirely changes this - the small contact area between grit and surface greatly magnifies the compressive stress, leading to rapid abrasion even where the load on top of the grit is pedestrian footwear or the pneumatic tyres of vehicles.

Finally, this chapter serves as a useful introduction to chapter 4, where the various mechanisms of abrasion wear of sixty six abrasion tests will be considered.