2.8 Moisture Conditioning

There appears to be universal agreement that concrete tested in a dry state has greater abrasion resistance relative to the equivalent concrete tested in a saturated condition. This tendency is greater for relatively porous, lean, low strength concretes, whereas dense, rich and strong concretes are not nearly as sensitive to moisture conditioning. The same observations have been made for compressive strength and flexural strength, although it appears that abrasion resistance is far more affected by moisture conditioning than is compressive strength. Following are the findings of a number of investigators:

Dry Surfaces have Improved Abrasion Resistance ……

Shackel(1985) did abrasion tests using MA20 [=*rolling steel balls*, see appendix 2.13] on both dry and wet specimens. He found that the penetration of the balls was greater in the case of the wet specimens.

Nanni(1989) studied roller compacted concrete and found that while dry testing relative to soaked testing resulted in 12% higher compressive strength, the difference in the case of abrasion resistance [MA20,=*rolling steel balls*, see appendix 2.13] was 50%.

Pickel(1997) did tests on the DIN 52108 abrasion apparatus [=sliding fine-abrasive, see appendix U.5.02] and found that dry test specimens had greater resistance to wear relative to soaked specimens.

Sawyer(1957) did tests according to DIN 51951 [*rolling steel balls*, see appendix U.2.09] and found that abrasion resistance was greater on dry surfaces relative to wet surfaces. The depth of wear after two weeks of moist curing reduced from 3,8mm to 2,4mm when a specimen was allowed to dry for 24 hours.

Helland(1991) reported on abrasion tests made by Gjorv O E and Baerland T on high strength concrete using the NORCEM's road tester, 'a full scale accelerated road-wear simulator' [=*rolling studded tyres*, see appendix U.3.03*]*. Penetration rates of 0.47mm/10000 revolutions-of-four-studded-truck-tyres-at-63km/hr were obtained when tested dry, and 1.04mm/10000 revolutions for wet conditions. This is comparable to massive granite, with the dry concrete being slightly better than the granite, while the wet concrete was slightly worse.

Tveter(1994) similarly did abrasion testing using rolling studded tyres. An analysis of his results shows that wet pavers had approximately 70% more abrasion wear relative to dry.

Webb(1996) used the C&CA rolling steel wheels to test, amongst other things, the abrasion resistance under wet conditions of concretes made of various coarse and fine magnesian limestone aggregates, and found that water on the test surface considerably increased the abrasion wear. He considers that this may be the result of 'the hydraulic effect of the water entering microcracks under pressure'.

….. but this effect is minimised for richer mixes

Sukandar(1993 did abrasion tests according to ASTM C779 Proc [=*rolling steel balls, see appendix U.2.12]* to do abrasion tests on concrete paves with a:c ratios varying from 3 to 9. Pavers tested in a wet condition had lower abrasion resistance than those tested dry. However this difference depended on the cement quantity of the specimens; at a cement content of 223 kg/m^3 the difference was 111.2% while at 594 kg/m^3 it was 15.2%. Strength reductions experienced with compression testing and tensile splitting tests, on companion samples, were much less. For compression testing the dry blocks tested 18.3% stronger than the wet blocks for the lean mix, and 5.4% stronger for the rich mix. For tensile splitting the dry blocks tested 21.8% stronger for the lean mix and 1.5% stronger for the rich mix.

Sukandar refers to the literature and offers three possible explanations to explain why blocks tested wet have lower strength:

1. Mills(1960) suggests that the loss in strength due to wetting of a compression test specimen is caused by dilation of the cement gel by absorbed water: the forces of cohesion of solid particles are then decreased.
2. Powers(1959) explains that beneficial effect due to the Van der Waals attraction forces between water molecules and solid matter, which contributes to the total cohesive force, is overcome by the weakening effect due to swelling.
3. Neville(1981) states that the change in structure of the C-S-H (calcium silicate hydrate), on drying, is the reason for the higher strength of the dry specimen.

Komonen(1998) did abrasion tests on concrete pavers using *rolling studded tyres [see appendix U.3.05]*, and found that the rate of abrasion of wet pavers was substantially greater than when they were tested dry. However, the mixes with the highest flexural strengths (related to block density) were insensitive to testing condition at greater depths where the strongly bonded course aggregate afforded a measure of protection from the studs.

Gjorv(1990) found that the abrasion wear (rolling studded tyres, see appendix U.3.3.03) in high strength concretes between 50MPa and 100MPa was substantially less for the dry testing condition relative to the wet condition. However, at strengths of 150MPa this difference was much reduced, and that at this level abrasion wear in the wet or dry concrete matched that of massive granite.

Discussion and Conclusion

The findings of the various investigators may be summarised as follows:

1. *Dry concrete has a higher abrasion resistance relative to wet concrete*.
Sukandar offered three explanations, but has not considered the effect of change in pore pressure. An applied load on the surface of concrete, say a ball rolling on the surface under load, will compress the surface structure, thus creating hydraulic pressures in the pores/capillaries if they are saturated. These increased hydraulic pressures have an expansive/rupturing effect on the surrounding/confining gel structure. Clearly the degree of capillary saturation in dry specimens would be substantially less, leading to less rupturing in the gel structure from hydraulic effects and hence improved abrasion resistance. Webb(1996) quoted earlier seems to support this view.

2. *Abrasion resistance is more sensitive to moisture conditioning than is compressive strength*
It is well known that compression test results are negatively affected by a rapid rate of loading, and this aspect is therefore carefully controlled in specifications. The fact that abrasion resistance appears to be more sensitive to these hydraulic affects may be related to a substantially increased rate and intensity of loading, in the immediate zone of the abrasive load. Accordingly, in abrasion tests where the loading is very fast, there simply is insufficient time for high localised hydraulic pressures to dissipate. Logically therefore these effects will lead to accelerated deterioration if repeated many times, and this is often the case. For example, Sukandar's tests involving a number of ball bearings moving along a circumferential track for a few thousand revolutions. (see appendix U.2.12)

3. Dense/binder-rich concrete is not nearly as sensitive to moisture conditioning relative to porous/binder-lean concrete.

Binder rich concretes are far less sensitive to the moisture content in the capillaries and pores because they have a far more refined pore structure, combined with a higher proportion of gel and dense CSH structures within that gel. The analogy of stresses in the wall of a pipe is useful here. The smaller the diameter of the pipe, and the thicker its wall, the smaller the induced stresses in the wall for any given rise in pressure. Thus a refined pore structure translates into smaller rupturing forces, which are better contained by thicker/denser surrounding CSH structures.

2.9 Surface Cracks

A detailed discussion of *all* the various types of cracks that occur in concrete, and their effect on abrasion wear is beyond the scope of this investigation. This section is therefore included merely to give the reader some awareness of the many different types of cracks and to show ‘abrasion wear cracks’ in the context of a ‘family tree of cracks in concrete’, as illustrated in figure 2.10.

Virtually all the cracks mentioned in figure 2.10 also occur at the surface, and indeed in many cases they are at their worst at the surface (e.g. drying shrinkage cracks, crazing, freeze/thaw etc.).

Cracks represent breaks across which tensile stresses cannot be transmitted. They therefore necessitate the distribution or redistribution of the load elsewhere, thereby increasing the stress on other components of the structure, and increasing the likelihood of failure there.

An abrasive load that applies a very concentrated though localised compressive or shear stress to an existing crack showing at the surface, may therefore result in further cracking or spalling. Therefore abrasion wear in surfaces that already have surface cracks will occur at an increased rate.

On the other hand ‘abrasion wear cracks’ may occur as new cracks on previously uncracked surfaces. They are classified in figure 2.10 as Hertzian cone cracks, lateral cracks, and axial cracks. They occur when an abrasive load applies excessive localised compression and/or shear forces to the face of the concrete. However they are even present in the mildest forms of attrition. In this event, these cracks (in a very diminutive form) are responsible for limited crushing and shearing at perhaps just a few surface asperities.

The various wear mechanisms relating to abrasion wear, including ‘abrasion wear cracks’, are discussed in some detail in chapter three and four.

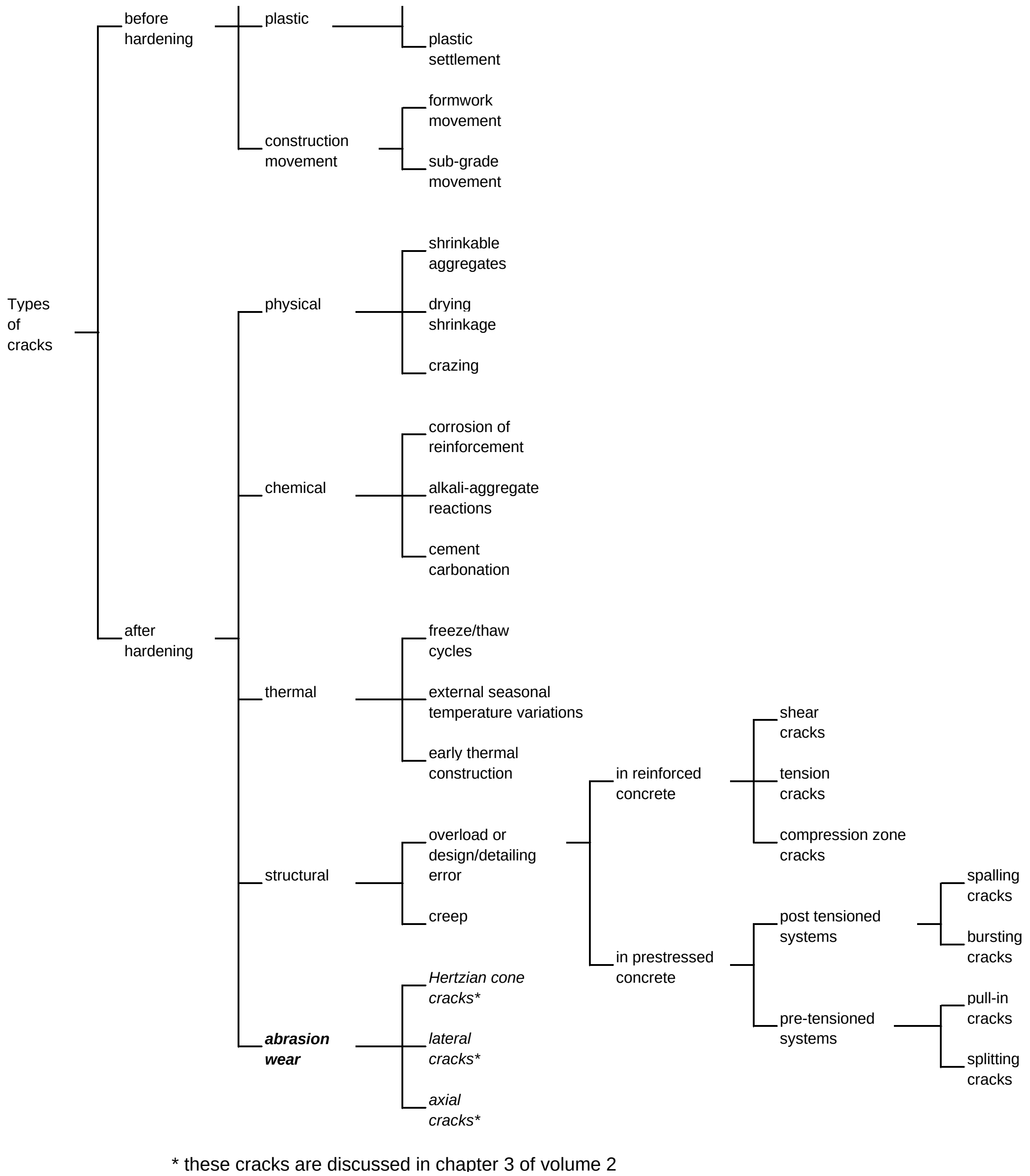

Figure 2.10 Family tree of cracks in concrete, showing where cracks related to abrasion wear fit in

2.10 Temperature

The only person who seems to have investigated the effect of temperature on the abrasion resistance of concrete is Horiguchi(1995). It is nevertheless possible to make some further predictions, based on numerous investigations [Khoury(1992) has a bibliography of 60 authors] into structural concrete's performance in high temperatures. (This requires the assumption that there is a relationship between abrasion resistance and compressive strength).

2.10.1 Low Temperatures

The abrasion resistance of concrete at low sub-zero temperatures is significantly greater than that of concrete at ordinary temperatures.

Horiguchi(1995) showed a very distinct increase in the 'surface fatigue wear' (*impacting steel balls* in liquid, see appendix 2.06) of cement paste between -25^{o}C and 0^{o}C. (In other words paste is substantially more abrasion resistant below 25° C). On the other hand increasing the temperature further between 0 and 85^{o}C resulted in no change in the rate of wear.

In other words, above freezing point the abrasion resistance of paste may be considered to be constant, for most normal uses. This is the essential situation in South Africa. Seldom does the temperature drop below zero, and only in very special industrial applications associated with handling hot materials, will it rise above 85° C.

2.10.2 High temperatures

Figure 2.11 indicates that when a concrete slab is exposed to intense heat such as may occur in an industrial fire, the temperature of the concrete at a depth of 5mm will reach 600 degrees centigrade within half an hour (and clearly the surface concrete will be substantially hotter). This applies to a 'dense concrete'. It appears that, in its hydraulic state of binding, the upper critical limit of Portland cement concrete is about 600°C. This would be for a concrete ideally designed for resisting heat, with aggregate that is thermally stable at high temperatures, and that produces a strong temperature bond with the cement paste. The cement paste should also have certain characteristics, such as a low C/S ratio and low calcium hydroxide content. Commonly used concretes, where aggregate and paste do not have these special attributes start losing considerable strength at temperatures as low as 300°C
[Khoury(1992)].

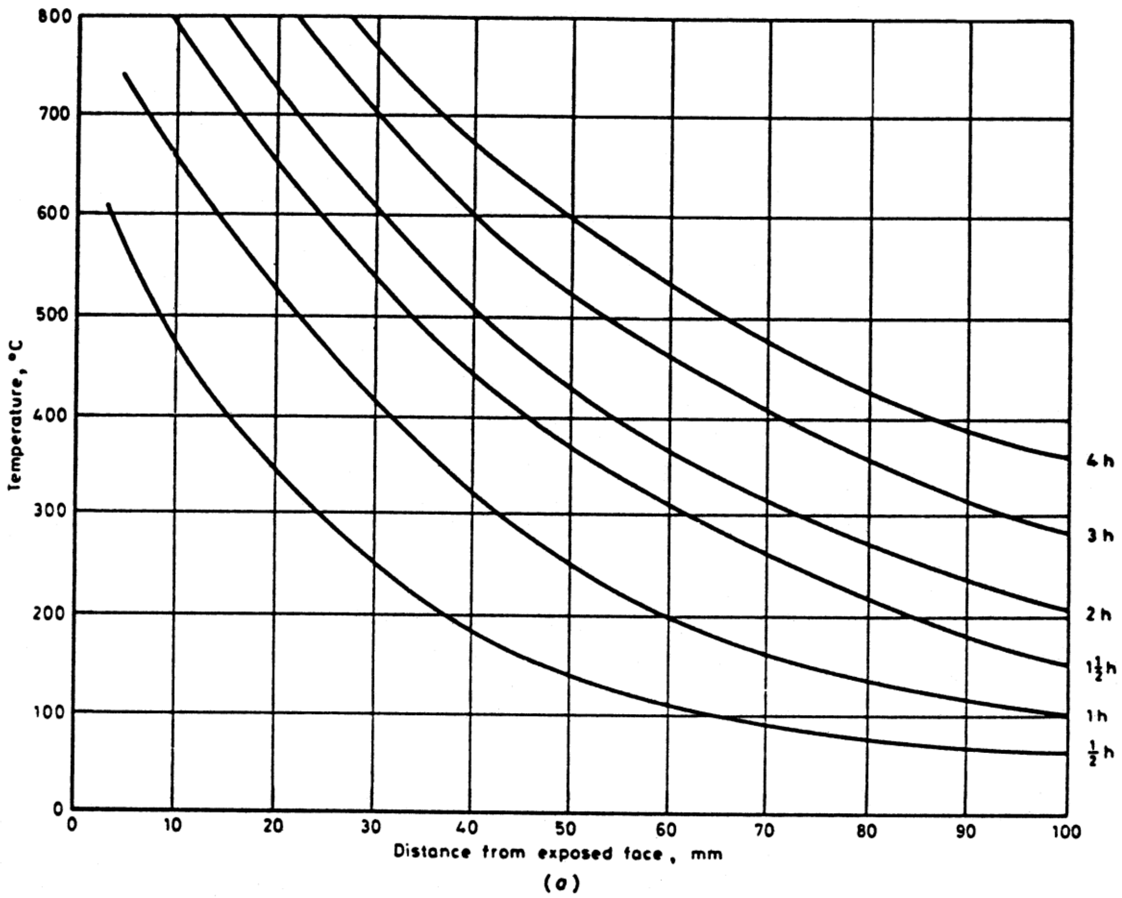

Figure 2.11 Temperature distribution in a concrete slab for dense concrete [ISE(1978)]

Conclusion: Given the above considerations, and that generally materials for concretes are not carefully selected for their fire resistance properties, and that the abrasion surface may be considered to be the top mm where exposure to high temperatures will be extreme, it seems reasonable to say that a serious fire, even if it lasts just half an hour, will significantly weaken the surface and substantially reduce abrasion resistance.

2.11 Influence of Test Method

Many investigators have commented on the effect that the test method has on 'abrasion resistance'. For example:

Alexander(1984) considers that the 'most difficult part of an abrasion test is the correct interpretation of the results'. As an example he cites Smith(1958) who found that limestone was abraded more rapidly by the crushing effects of *steel balls* compared to harder aggregates, whereas it abraded slower than the harder aggregates when subjected to the relatively light impinging effects of the *shot-blast* test. The softer limestone seems to be more resilient and is more capable of absorbing and dissipating the relatively light attack of the No 20 broken steel shot'.

Hilsdorf(1995) concluded that correlations between abrasion resistance and compressive strength are markedly influenced by the type of abrasive action or the test method employed.

Smith(1958) investigated the influence of various coarse and fine aggregates on the abrasion resistance of the corresponding concretes using three abrasion tests (rolling steel balls, impacting fine-abrasive , rolling dressing wheels). While showing the same general trend, the three tests had distinctly different wear (grams) vs compressive strength (MPa) characteristics. The degree to which the data correlated with a best fit curve also differed widely for the different abrasion tests.

From the above it is clear that an abrasion test should be carefully selected according to its ability to correctly assess the abrasion resistance for a given application. This has been confirmed over and over in the preceding sections of this chapter, where seemingly contradictory results can often be explained by the pecularities of the different test methods.

In recognition of the effect that an abrasion test has on the corresponding 'abrasion resistance', a full chapter, chapter 4, is devoted to the characteristics of the various abrasion tests, and these characteristics are comprehensively catalogued in appendix U.

The tests are grouped together according to the abrading medium applicable to each grouping. Included is a description of the test and a sketch/photograph (see appendix U).

Specifically chapter 4 considers the various abrasive actions are considered, as well as the severity of those actions. These two criteria form the basis of an abrasion code, giving the reader has an immediate appreciation of the wear characteristics of the test. In this way the code assists with the correct selection of an abrasion test for a given application, although other criteria must also be considered in this process, such as the limitations and weaknesses of the different tests.

Suffice it here to say that the correct selection of an abrasion test may profoundly 'influence' the abrasion resistance.

2.12 Conclusion

In the introduction to this chapter, it was stated that 'The purpose of this chapter is to consider the factors affecting the abrasion resistance of concrete floors and concrete paving'. This has been done by *reviewing the literature* on abrasion resistance, *analysing the various viewpoints* presented by the many authors (sometimes conflicting), *synthesising and formulating theory* from the various extracts where applicable, relating personal experience where appropriate, and considering how it all relates to generally accepted *principles of concrete technology'.*

The extent that these objectives were achieved is now considered.

The '*review of the literature'* may be described as very comprehensive. It may be the most comprehensive survey of abrasion resistance in concrete ever undertaken. Over 300 publications have been cited, dating from 1920 (Crepps) through 2000 (Ramezanianpour).

The subject matter of each author was dissected into various segments, which were posted to relevant headings, as indicated in the wiring diagram (figure 2.2). By grouping together in this way like statements made by the different authors, it was possible to establish and '*analyse the various viewpoints'*, including those that were contradictory.

By introducing a number of concepts such as 'hard' and 'soft' concrete, 'surface' and 'core' concrete, 'deep' and 'shallow' wear, 'mild' and 'severe' abrasion, it was often possible to reconcile the positions that initially seemed contradictory. This was also achieved by considering differences in the concrete, i.e. paste, aggregate, aggregate/paste bond, etc. Finally, conflicting views could also be shown to stem from differences in abrasive actions. The discussions around these topics inevitably often led to '*synthesising and formulating of theory '.*

The wiring diagram shows how the various materials and processes that relate to abrasion resistance are inter-related. The associated text, consisting of the findings of the various investigators, together with comments and arguments by the writer, goes beyond merely illustrating the factors that affect abrasion resistance, indeed the related *'principles of concrete technology'* are also presented*.*

A simple philosophy arises out of the information presented in this chapter.

2.12.1 Simple Philosophy of Abrasion Resistance

The abrasion resistance of concrete is primarily a function of two characteristics, its *hardness*, and the strength of the *paste/aggregate bond*.

The <u>hardness</u> of concrete is a function of the:

(a) hardness of the aggregate = f (aggregate type including special 'dry-shake' aggregates)
(b) hardness of the paste = f (w/b, % air, binder type, curing, liquid surface treatments, finishing techniques, weathering, moisture condition)
(c) resultant hardness of the concrete = f (relative proportions of aggregate and paste, degree of impact in abrasive action)

(In certain situations where abrasive loads have a substantial impact aspect, some hardness should be sacrifices in favour of toughness – this is fully explained in chapter 3).

The bond between paste and aggregate is a function of the:

(a) quality of the paste = f (w/b, % air, binder type, curing, liquid surface treatments, finishing techniques, weathering, moisture condition)
(b) aggregate texture = f (aggregate type, aggregate source, preparation, weathering)

Stating that abrasion resistance is primarily a function of these two components does at first seem to be an oversimplification, but clearly both these components are dependant on factors that may be found in virtually every facet of the wiring diagram and these have been discussed in great detail under the respective headings. Finally, assuming that it *is* the *hardness* of the surface that governs the rate of abrasion, this hardness will be assured providing the paste has sufficient strength to *bond* the harder more wear resistant aggregate particles.

Accordingly the major role that hardness plays in abrasion resistance is thoroughly demonstrated in the next chapter, chapter 3.