Chapter - 5

Summary and Conclusion of Volume 2

Chapter 5 – Summary and Conclusion

A brief summary of some of the more salient aspects of volume 2 follows, together with some conclusions.

Chapter 2: The many factors affecting the abrasion resistance of concrete floors and concrete paving were studied very widely. This was done by *reviewing virtually all the available 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 numerous factors relating to abrasion resistance were arranged into an extensive ‘wiring-diagram’, showing their various contributions. Thereafter each of these factors were individually reviewed. Some of the factors only affect the ‘surface zone’ while others also influence the ‘core concrete’. Abrasion may be considered ‘mild’ when confined to the surface zone, and ‘severe’ when extending into the core concrete.

The abrasion test used by each investigator was cited, and this often proved the key in reconciling apparent contradictions between the findings of different authors. (Readers unfamiliar with the various tests are referred to appendix U, where the apparatus, test method, and abrasion wear mechanisms for each test are explained).

Arising out of the analysis of the literature is a simple philosophy: abrasion resistance is a function of the *hardness* of the surface, and the strength of the *aggregate/paste bond*.

Chapter 3: This chapter seeks to formulate a theory on the ‘mechanisms of abrasion wear’ in concrete. The discussions are largely theoretical, although much of the material considered is based on the experimental findings of several researchers, and the writer’s own experience and observations

Confirming the ‘philosophy’ proposed in chapter two, ‘indentation hardness’ is a 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.

The three principle mechanisms of abrasion wear are explained as 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.

These mechanisms of wear occur either in a state of pure compression or may include the element of sliding.

The application of a horizontal compressive stress to the concrete’s surface zone (either by restraining lateral dilation, or by ‘sagging bending’) increases the shear strength and consequently the abrasion resistance.

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

A consideration of the most common applications, has shown that abrasion related to pedestrian and vehicular traffic is only severe in the presence of grit.

Chapter 4: This chapter presents a systematic method of classifying abrasion wear.

Sixty six surface tests are considered. The abrasion tests are placed into eight groups according to the applied abrading media causing the abrasion wear.

An abrasion wear code categorizes each test by its abrasive actions, (consisting of rolling, sliding and impact) and also indicates the severity of the actions, either a 'mild' form of crushing or shearing of the surface asperities, or a more 'severe' form of abrasion, resulting in cracking to a deeper sub-asperity level.

It is shown that the various 'mild abrasion' tests, which may appear quite different from one another, result in very similar wear mechanisms. Likewise the 'severe abrasion' tests, though quite diverse, result in virtually identical wear processes.

However, there are also several other important criteria other than 'wear mechanisms' that are very important when deciding on an abrasion test, e.g. does it 'see' the aggregate, does it 'measure' the aggregate/paste bond? etc. Therefore the various tests have also been examined in the light of these 'other criteria'.

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

Philosophy of Abrasion Resistance – Revisited and Reinforced

In the conclusion to chapter 2 of volume 2, a simple philosophy for abrasion resistance was proposed. It was stated that abrasion resistance is principally a function of the hardness of the concrete and the strength of the aggregate/paste bond.

The important role of hardness in abrasion resistance was further discussed in some detail in chapter 3, where Hutchings(1992) was a valuable source. In addition, the many photographs of appendix Z reveal that the aggregate, as the harder component of the mix, soon becomes prominent as abrasion proceeds, and thereafter governs the rate of abrasion. Clearly this presupposes a hard aggregate, and furthermore, that the aggregate is sufficiently strongly bonded to the aggregate. In the weaker mixes, it is once again clear from the photographs that some of the aggregate has been plucked out (e.g. see appendix Z.131/132). On the other hand, in the stronger mixes, the aggregate is less prominent, indicating that the hardness of the binder also makes a contribution to abrasion resistance in these instances (e.g. see appendix Z.101/102). More significantly, the stronger paste holds even the very fine aggregate particles, allowing them in turn to 'protect' it.

The principle role of hardness and aggregate/paste bond in abrasion resistance is not made adequately clear in the three models given thus far (two models in chapter two and a further model in chapter 3). In the first model that takes the form of a comprehensive 'wiring diagram', see figure 2.2 through 2.2(c), the effect on abrasion resistance of a number of factors are discussed at length; factors such as the paste, voids, aggregates, aggregate/paste bond, and surface treatments. However, the discussions tend to be compartmentalized under these headings, and the inter-dependencies of the factors, and their respective contributions to abrasion resistance relative to each other is not clear.

The second model, i.e. that shown in figure 2.3, has a much stronger emphasis on the inter-relationships of the various factors, and even shows how these all lead up to hardness and aggregate/paste bond, which according to the proposed philosophy, ultimately determines abrasion resistance. However, this model tends to understate the important role of voids, and does not indicate that the influence of w/b on abrasion resistance is chiefly as a result of its influence on microscopic voids and capillaries (referred to as ‘capillary voids’). On the other hand, the third model, that shown in section 2.3.6, adequately distinguishes between ‘entrapped voids’ and ‘capillary voids’, and clearly shows that abrasion resistance is directly linked to voids and only indirectly to binder and water content (and hence w/b). However, this model is limited to a discussion of voids, and ignores other important contributors to abrasion resistance such as aggregate hardness, surface treatments, curing, etc.

In order to bring these various concepts together, and to redress the shortcomings of the earlier models, a final model is set out in figure 5.1. Most importantly it shows how the many factors affecting abrasion resistance are related to hardness (especially aggregate hardness) and aggregate/paste bond. The model shows in bold those factors that have been emphasized above. Note that the ‘binder content’ has also been made bold to accentuate its dual function in reducing both ‘entrapped voids’ and ‘capillary voids’, respectively by improving the rheology of the mix and by producing a lower w/b.

Although the model does not boast the detail of figure 2.2, it is referenced to chapter 2, (and in some cases to chapter 3 and 4), using the same numbering system as figure 2.2, thus allowing access to the comprehensive discussion in chapter 2 on any particular aspect to be investigated in greater depth.

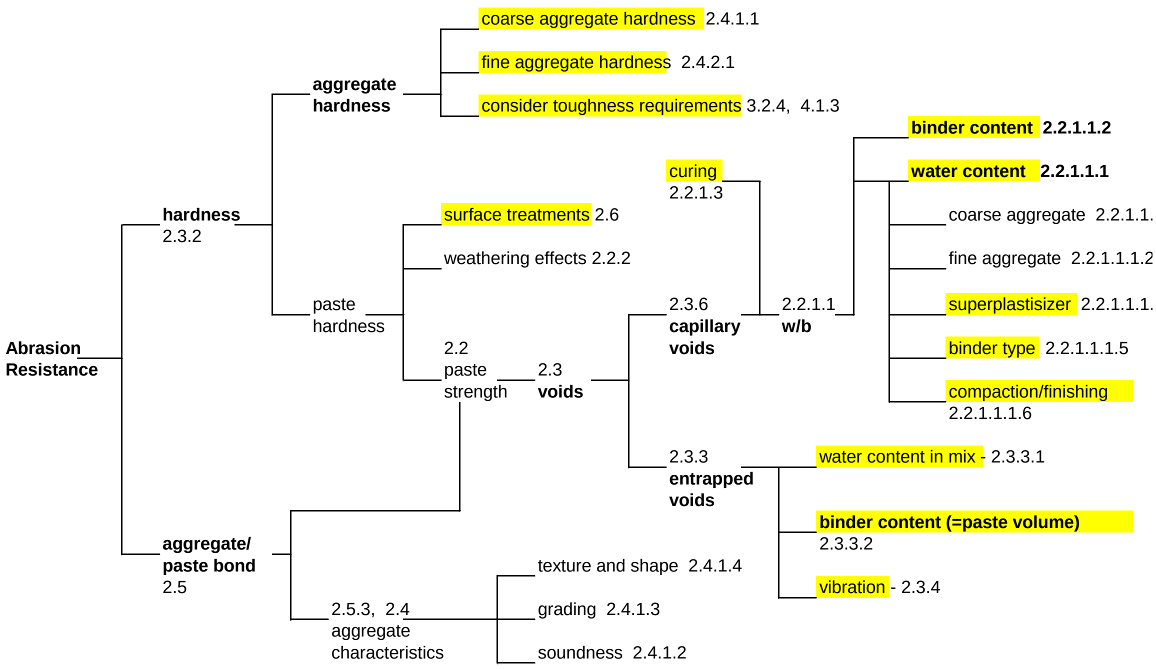

Figure 5.1 A simple philosophy of abrasion resistance in schematic form; it shows how the various factors affecting abrasion resistance relate to hardness and aggregate/paste bond.

Relevance to Abrasion Testing

The importance of the concrete’s hardness (which is mainly a function of the aggregate), and the aggregate/paste bond (which is mainly a function of the paste strength), means that only *abrasion tests* that can discern these qualities should be considered. For example, the wire-brush test (see appendix U.6.02), gouges out the paste component, thereby hastening aggregate removal, and is therefore a good measure of paste hardness, and even aggregate/paste bond, but does not ‘measure’ the hardness of the aggregate. The test is therefore only relevant where paste strength is inferior, i.e. where aggregate will be scraped out before it can contribute to abrasion resistance. On the other hand the NBRI test (see appendix U.5.16) adequately measures the aggregate hardness, but not the aggregate paste bond, since aggregate that is unbonded in the course of the test is not readily extracted, and continues to resist abrasion, whereas in practice it would be dislodged. The test is thus unable to discern a major potential flaw in concrete and should only be used in special applications by discerning persons.

Recommendations for Improved Abrasion Resistance

In chapter 1 of volume 1, the aim of this investigation was stated as, 'to provide a knowledge base that will lead to improved abrasion resistance in concrete surfaces and in concrete block paving in particular'. It therefore seems appropriate at the end of this document to make certain recommendations from the main findings, both from the experimental work reported on in volume 1, and the findings of other authors (and the writer's synthesizing thereof) reported in volume 2. The recommendations that follow all have a place in figure 5.1, and the items mentioned in the recommendations are highlighted in the figure.

For those well versed in the principles of concrete technology, most of the findings will merely confirm well established principles, while to producers, specifiers and end users that are less acquainted with abrasion resistance, the recommendations will serve as useful guidelines. Note that it is assumed that the concrete is normal concrete in the sense that it consists predominantly of aggregate, and that this aggregate is harder wearing than the paste component.

Concrete surfaces can be made more abrasion resistant by:

1. Increasing **binder content**. This increases the mobility/rheology of the mix for any given moisture content. The result is that there is a reduction in *both* entrapped and capillary voids. This results in a stronger paste that is both harder and has an increased ability to bond to aggregate, the two main requirements for increased abrasion resistance.

2. Optimizing the **water content**. For any given binder content there is an optimal water content. This amounts to finding the happy middle road between two evils. Using more water in the mix assists in reducing macroscopic entrapped voids, but to much water increases microscopic voids and capillaries. Conversely using less water has the potential to allow a closer packing of binder particles, but makes it so much more difficult to expel the air voids, as clearly less water means reduced lubrication/mobility.

   Thus optimizing the water content optimizes the overall strength of the concrete, striking the right balance between minimizing both macroscopic *and* microscopic voids.

   It should be stated that in semi-dry mixes, the danger of too little water is far greater than too much. (This is because the mix already has a low w/b, consistent with zero slump, and thus increasing water improves compactability, reducing entrapped voids. In fact the optimum water content is very close to the point at which the blocks will begin to slump).

3. Using **superplasticizers**. Powerful water reducing agents are available and are very effective in reducing the water in the mix without sacrificing mobility and compactability. Reducing water in this way translates into a reduction of both 'capillary' and 'entrapped' voids. Again this results in a stronger paste with increased hardness and bonding ability, and so increased abrasion resistance.

4. Using **hard aggregates**. The harder the aggregate, the slower it will abrade, and hence the better it will protect the softer paste component. If both the fine and coarse aggregate are bound in a strong paste, the surface of the concrete should retain a relatively smooth surface, with minimal loss of paste. But as the paste becomes weaker and its hardness and bonding capabilities deteriorate, more and more fine aggregate will be lost to abrasive forces. In very weak pastes, subjected to significant gouging effects, the paste/mortar constituent may be abraded to a depth where even coarse aggregate can be dislodged.

   It may be said that providing the paste has adequate bonding ability, abrasion wear in concrete is primarily related to the hardness of the *aggregate*. On the other hand the smoothness of a surface subjected to ongoing abrasion, for a given aggregate, will be related to the strength of the *paste*. As paste strength increases, so the particle size of non-dislodged fine aggregate - exposed to abrasive effects - reduces. Clearly this has implications with regard to both aesthetics and serviceability.

   In concretes that will be subjected to significant impact loads, it may be advisable to substitute a very hard aggregate for one that has increased ‘toughness’. Hard aggregates are generally brittle, and tend to shatter more easily under impact than tough aggregates that have more resilience.

5. Using a **fly ash** based binder. In this investigation, and for a given binder content, pavers incorporating fly ash substitutions of up to 28% had the least abrasion wear after 6 years of traffic (compared to 50:50 MGBS:OPC binders, and even binders with up to 10% silica fume). The ongoing pozzolanic related strength of fly ash over time has thus been shown to be ideally suited to resisting abrasion wear that proceeds equally slowly over many years. Thus if fly ash has economic benefits it should be used.

6. Ensuring good **curing**. The beneficial effects of curing on paste strength/hardness are well known. This is an important aspect, given that the surface will dry out very soon if not cured, and that it is the surface that must withstand abrasion.

   Studies have shown that lean concrete is far more prone to the ills of inadequate curing than is rich concrete.

7. Using **power finishing**. If done correctly this has the effect of collapsing the capillaries and voids near the surface after bleeding stops. Again this void reduction represents an increase in the strength of the paste, and so its hardness and aggregate bonding capabilities, and so its abrasion resistance. Clearly this is not applicable to paving blocks made with semi-dry concrete, where it is the level of vibration power that determines the degree of void reduction for a given consistency.

8. Applying **surface treatments**. There are various surface treatments that may be used to increase abrasion resistance. These include dry shakes, fresh on fresh toppings, concrete overlays, liquid applied surface treatments, coatings, polymer impregnation, and grinding. Not all of these options apply to cbp.

Abrasion Load

Much has been said thus far about abrasion resistance and abrasion wear. Less has been said about the various abrading media that cause abrasion, and what has been said is fragmented and dispersed, mostly in chapters 2, 3 and 4 of volume 2. The aim of this section therefore is to consolidate this material into a coherent unit as no thesis on abrasion would be complete without a consideration of the abrading media.

The *abrasion load* may be defined as the application of an abrading medium to a concrete's surface. In practice abrasion loads consist of the soles of pedestrian footwear, or the rubber tires of vehicles, or steel wheels in certain industrial situations, and the abrasive effect of all of these loads is significantly magnified when they press down on a particle of grit/sand/dust.

Accelerated abrasion tests make use of a number of hard materials to simulate in a few minutes what takes years in practice. Often the abrading medium is attached to the test apparatus; at other times it is the interface between apparatus and specimen.

It may be said that the abrasion load (i.e. the abrading medium and its correct application) is the most important aspect of an abrasion test, since it is, quite literally, the 'cutting edge'. For this reason the 66 abrasion tests of appendix U have classified according to their various abrading media. These include steel drums, steel balls, steel tracks, chained tyres, dressing wheels, steel wheels, fine abrasive, steel pads, wire bristles, scratching tools, steel hammers. Moreover, since many tests have the same media, this has provided a basis for grouping tests together.

The success/relevance of an abrasion test in a particular application often hinges on using an abrasion load that correct simulates field conditions. Clearly abrasion loads will vary considerably according to their respective abrading media, as well as certain other criteria.

Table 5.1 : The abrasion load may be described according to seven characteristics; the abrasive action, the applied force, the abrasive's size, its shape, its hardness, the rate of application of abrasive, and finally duration of abrasive application. The material in the table has been extracted from the various chapters and concisely defines the abrasion load in terms of its various characteristics and their effects on abrasion wear.

Table 5.1 – Characteristics of the Abrasion Load

	Character-istics of abrasion load	Element	Implication on abrasion wear
1	Abrasive action	Rolling	Adhesion and/or deformation and/or cracking effects occur from the application of a force normal to the surface
		Sliding	Adhesion and/or deformation and/or cracking effects occur from the application of a tangential force in conjunction with a normal load
		Impact	Deformation and/or cracking (shattering) occurs
2	Applied force	Light	↓ Abrasion wear. Wear is restricted to asperities/surface-zone. This is termed mild/interfacial wear.
		Heavy	↑ Abrasion wear. Wear extends to sub-asperity zone/core concrete. This is termed severe/cohesive wear.
3	Abrasive size	Large	↓ Abrasion wear. Abrasive spans across the paste, effectively resting on aggregate abutments on either side
		Small	↑ Abrasion wear. Abrasive gouges out softer paste between aggregate particles
4	Abrasive shape	Sharp	↑ Abrasion wear Extreme stress multiplication
		Blunt	↓ Abrasion wear Mild stress multiplication
5	Abrasive Hardness	Hard	↑ Abrasion wear Abrasive penetrates into surface
		Soft	↓ Abrasion wear Abrasive does not penetrate
6	Rate of application of abrasive	Rapid application	↑ Abrasion wear
		Slow application	↓ Abrasion wear
7	Duration of abrasive application	Short	↓ Abrasion wear
		Long	↑ Abrasion wear

Abrasion System

The concept of an *abrasion system* is proposed here. It consists of three elements that have all been adequately described :

(1) abrasion resistance
(2) abrasion wear
(3) abrasion load

These three components are inter-related, whereby abrasion wear increases as the abrasion load increases, and decreases as the abrasion resistance decreases, and vice versa. These relationships are illustrated in expressions (5-1) and (5-2):

↑ abrasion load + ↓ abrasion resistance = ↑ abrasion wear ……. (5-1)

↓ abrasion load + ↑ abrasion resistance = ↓ abrasion wear ……. (5-2)

Linking the three elements of the abrasion system in this simple way seems a fitting ending to this document.

Final remarks on volume 2

It is hoped that the contents of volume 2 will lead to a better understanding of abrasion wear and result in surfaces with improved abrasion resistance. The reader is referred back to the conclusions at the end of chapters 2, 3 and 4 for a more comprehensive summary of the subject matter covered in them.

Some of the more notable contributions may be re-stated in point form as:

- a compartmentalized *wiring diagram* to show the contributions of the many factors that affect abrasion resistance
- an in depth *literature study* of virtually every part of the wiring diagram, recognizing the characteristics that increase abrasion resistance, with special reference to concrete pavers
- a simple *philosophy* that relates abrasion resistance to the important attributes of hardness and aggregate/paste bond, and shows how these properties are inter-related with the many factors governing abrasion resistance
- a statement of the *mechanisms of abrasion* in terms of adhesion, deformation and cracking, both for stationary and sliding loads
- an appreciation of the relative severities of typical *abrasion applications* , and the stress multiplication effect that grit/sand has
- a *classification of 66 abrasion tests* according to several characteristics, including the abrading medium, and abrasive action. A correct understanding of the abrasion tests used by different authors has made it possible to explain contradictory conclusions.
- an *abrasion code* that defines the abrasive action and its severity.
- *recommendations for further study* by future investigators of abrasion resistance
- eight *practical recommendations* for improved abrasion resistance
- establishing the concept of an *abrasion system* that relates abrasion wear to abrasion resistance and the abrasion load