Chapter 2

Factors Affecting the Abrasion Resistance of Concrete Floors and Concrete Pavers – A Review of the Literature

2.0 Introduction

2.0.1 Purpose

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, considering how it all relates to generally accepted principles of concrete technology, and relating personal experience where appropriate.

Accordingly this chapter lays a suitable foundation for the rest of this thesis. It creates a framework for seeing the limited experimental work done in this investigation (see volume 1) in the wider context of the larger body of concrete technology relating to abrasion resistance.

2.0.2 Significance

Abrasion resistance is a most important characteristic of concrete floors and paved surfaces. Many industrial surfaces are required to remain in a smooth and dust free state even in the face of severely abrasive loads. These may include rolling steel wheels, scratching by pallet and stillage legs, forklift truck tines, or even impact from falling objects. Concrete pavers on the other hand must be able to resist a degree of grinding from sand trapped beneath vehicle wheels, or the continual rubbing and mild impact from pedestrian footwear.

2.0.3 Durability

Abrasion resistance may be grouped with the ‘durability’ family of attributes and its position in this hierarchy is shown in bold type in figure 2.1, from Ballim(1997).

In terms of physical attack from abrasive forces a concrete surface may be said to be durable if it has a level of abrasion resistance such that the depth of abrasion induced wear does not exceed the allowable depth for the intended service period. Ideally the acceptable level of wear can be correlated to a depth of wear induced by an accelerated abrasion test, making it possible to predict the eventual wear and thus verify durability with respect to abrasion resistance. (This was done in Chapter 14 of volume 1)

2.0.4 Definitions and Conventions

The following terminology will apply throughout the document:

2.0.4.1 Definitions

(a) **Wear** is the loss of surface material as a result of weathering (exposure to the elements e.g. O_2, CO_2, H_2O, temperature), chemicals or abrasion. The term is also loosely used to describe ‘abrasion wear’.

(b) **Wear resistance** is the ability of a surface to resist wear.

(c) **Abrasion wear** is a sub form of wear. It implies the steady systematic loss of surface material by some mechanical means or load. The load may be in the form of direct compression or pure shear, but generally both these actions will apply simultaneously, such as occurs in rubbing, scratching, scraping, gouging etc. (In chapter three it will be shown that the movement of the load is opposed by a frictional resistance in consequence of the load either adhering to the surface, deforming the surface or cracking the surface. The frictional resistance divided by the contact area is the shear stress, while the normal component of the load divided by contact area is the compressive stress).

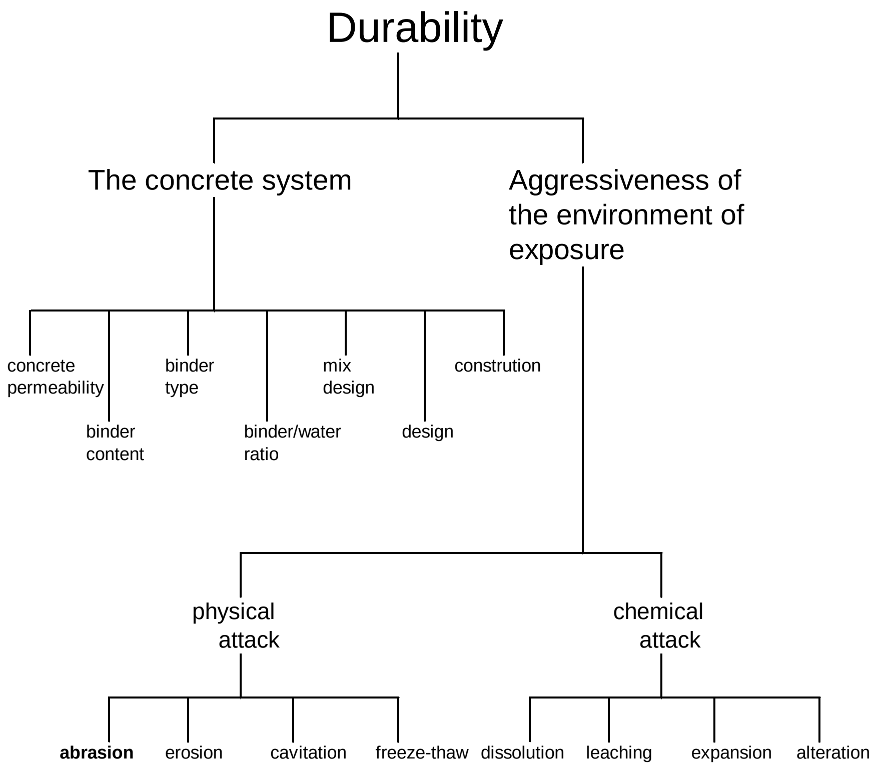

Figure 2.1 Factors influencing the durability of concrete

(d) **Abrasion** is the mechanical means, process or load that causes abrasion wear.

(e) **Abrasion resistance** is the ability to resist abrasion. Accordingly a material with a high abrasion resistance will suffer minimal loss of material when subjected to abrasive actions such as rubbing, scratching etc.

Other definitions for abrasion resistance exist and these are supplied in '2.3.5 Abrasion Resistance' of volume 1.

(f) **Shallow, Intermediate and Deep Abrasion Wear:** Abrasion wear that is limited to 1mm is referred to as 'shallow abrasion', above 5mm it is called 'deep abrasion', while in-between values are 'intermediate abrasion'.

Note: These six definitions will be consistently applied to the above stated terms throughout this thesis. Given their relevance, the reader is advised to become well acquainted with them.

(g) **Authors:** When quoting investigators who have published material relevant to this thesis, the system of identification used is 'first author's name(year of publication)' e.g. Addis(1989), is used to represent Addis B J and Doulgeris N P who co-authored the paper 'The development of a method for determining the abrasion resistance of concrete' in 1989. The decision to name only the first author, even excluding his initials, streamlines the presentation, since a great many references are made. The full details of *all* the authors for the various publications are given in the 'Reference'. Frequently, when reporting an author's contribution to a topic, a full paragraph will be devoted to his findings, and the convention of Author's name (date) as described above, will be used to start the paragraph, and it will appear in bold. This serves as a sub heading and allows for fast identification when searching for a particular author's contribution.

(h) **Writer:** The author of this thesis is referred to as the 'writer'.

(i) **Investigator:** This may refer either to the author or the writer, as inferred by the context.

(j) **Volume 1:** This refers to the document containing the experimental phase of the thesis, initially compiled in 1994, and revised in 2001.

(k) **Volume 2:** This refers this document, completed in 2001.

(l) **Thesis:** This amounts to 'volume 1' plus 'volume 2'.

2.0.4.2 Conventions

(a) **Underlining and *Italics:*** In certain places in the text underlining or italics have been used for emphasis. Sometimes both are used at different places in the same paragraph to emphasize different aspects; e.g. a key word, a phrase, or even a complete sentence. This technique is especially useful when a number of authors are considering a particular point; underlining highlights commonality of the main thought at a glance.

(b) **[Square brackets] :** These are sometimes used to differentiate between the author's statements and the writer's view and comments, which are bracketed. Without this demarcation the reader, in many instances, would not be aware of the source of the text.

2.0.5 Early Work

Research into the abrasion resistance of concrete floors and pavements has a long history; Chaplin (1972a) mentions that testing with accelerated abrasion machines was carried out in Germany as long ago as 1844 (Bauschinger) and in the USA since about 1915 (Shoop). Many of the findings of the early investigators are still applicable today. For example Crepps(1920) reports on some early research which is interesting in that all his findings are essentially correct and have in fact been confirmed by numerous researchers subsequently. He found that:

1. Abrasion wear decreased with decrease in the 'water ratio'.
2. Abrasion wear decreased with increase in compressive strength.
3. Abrasion wear decreased with increase in fineness modulus (defined as 1/100 x sum of the percents retained on the sieves, including coarse aggregate). This amounted to a reduction in wear with increase in coarse aggregate proportion relative to fine aggregate.
4. Abrasion wear decreased with increasing curing duration
5. Abrasion wear decreased when the specimens were tested in a dry state.

Crepps's tests were done using a modified Talbot-Jones rattler, powered with equipment from a brick rattler abrasion tester (used in 1889 for testing paving bricks).

Since this early work several studies have been conducted, some of them quite extensive, and reference will be made to them in the course of this chapter. It will be shown that there is agreement in the findings of most researchers, and where there appear to be conflicting conclusions these can usually be explained.

2.0.6 Concrete Pavers

Most of the work reported in the literature has been carried out on conventional cast-on-site concrete, with only a few publications relating to the abrasion resistance of concrete pavers. Some fundamental differences exist in the manufacturing process of pavers, and it will be shown that this sometimes brings into play other laws governing abrasion resistance. For example %air in pavers is often the most crucial variable, rather than w/c. This is because pavers are mass-produced by large machines with very rapid cycle times in pre-cast factories, and are made from semi-dry concrete with relatively small coarse aggregate. Most concrete floors on the other hand are cast in-situ using a relatively plasticised mix, and are routinely subjected to elaborate finishing regimes which can take up to nine hours, excluding the curing processes or application of surface hardeners or sealers.

2.0.7 Abrasion tests

In analysing the various factors that affect abrasion resistance, it is essential to have some understanding of the abrasion test that was used. Results taken at face value without due consideration to the test used may be meaningless! Furthermore the writer has been able to reconcile many of the apparently contradictory findings of different authors by a consideration of the tests they used. Clearly there is a difference between deep abrasion relative to shallow, or uniform grinding relative to indiscriminate attack, or high crushing/impact relative to light rubbing

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.

Therefore, whenever appropriate, in citing the work undertaken by an investigator, reference will be made to the test that was used by the author. This may take the form of citing the abbreviated name of the test, e.g. ‘ASTM C418 is used to represent ‘ASTM C418 - 1990 : Test method for abrasion resisting by sand blasting’. Alternatively a test may be referred to by a ‘generic name’, e.g. the generic name used for ASTM C418 is ‘ impacting fine abrasive’. Other typical generic names for other tests include ‘impacting steel balls’, ‘rolling steel balls’, ‘sliding fine abrasive’, etc. The first word of the test’s generic name indicates the abrasive action (either impact, rolling or sliding), while the rest of the name indicates the abrasive medium. Quite often the abbreviated name and the generic name are both given in the text. This nomenclature streamlines the presentation, yet still gives the reader an appreciation of the mechanism of wear.

Finally, the abbreviated and/or generic names are often referenced to appendix U, (which describes 66 surface/abrasion tests in some detail). For example, the text may say: ‘ Holland(1991) did abrasion tests using ASTM C418 (=impacting fine abrasive, see appendix U.5.21), and concluded that …’.

Accordingly appendix U serves as a useful catalogue for the many abrasion tests, and also comments on the various mechanisms of abrasion wear, including ‘severe’ versus ‘mild’ wear, the various abrasive actions such as impact, rolling and sliding, etc. This appendix is a most useful source for reference purposes when interpreting ‘abrasion resistance’ as inferred by one or other abrasion test.

A useful summary of the various abrasion tests with their abbreviated/generic/appendix-U names is given in Table 4.1.

2.0.8 Organization of Chapter

A full presentation of the organization of the chapter is given in figure 2.2, in the form of a ‘ *wiring diagram* ‘. This diagram shows the many factors that influence abrasion resistance and how they are related to each other. There are eleven major headings, numbered as 2.1 through 2.11. Under each heading are sub headings, sometimes with numerous layers, indicated by a numbering system that is important for identification and classification. For example, the number 2.2.1.1.1.6(a) may be classified with its ‘ancestors’ as follows:

2	= chapter 2
2.2	= paste
2.2.1	= paste micro structure
2.2.1.1	= w/b ratio
2.2.1.1.1	= water quantity
2.2.1.1.1.6	= water extraction
2.2.1.1.1.6(a)	= power finishing

When read in the correct context in the chapter it will be seen that 2.2.1.1.1.6 (a) is an abbreviated way of saying that ‘power finishing’ has the effect of ‘extracting water’ to the surface, and the extent that this occurs depends inter-alia on the original ‘water quantity’, which in turn effects the ‘w/b ratio’, which impacts on the ‘paste micro structure’, an aspect of the ‘paste’, which is one of the factors discussed in ‘chapter 2’ that determines abrasion resistance.

The wiring diagram is in effect the indispensable map that guides the reader through the body of this chapter that would otherwise be a very confusing maze.

The variables selected for investigation in the experimental section of this thesis (volume 1) are indicated in the wiring diagram under the headings 2.2.1.1.1 ‘water quantity’, 2.2.1.1.2 ‘binder quantity’, and 2.2.1.2 ‘binder type’, and 2.11 ‘influence of test method’ (i.e. the abrasion test). It is immediately apparent that the scope of the experimental work was relatively narrow compared to the many topics covered in the wiring diagram.

The relevant extracts taken from the literature are arranged under various main and sub headings, using the same numbering system as given in the wiring diagram. Pieced together, the extracts make up the bulk of the text of this chapter, to give the reader a thorough insight of what the various researchers have to say on abrasion resistance. Following the findings of a particular author on a particular subject, the writer has made his own comments as appropriate. In this he has allowed himself the liberty to interject his own thinking, to synthesize, and to formulate theory.

The various topics covered in the wiring diagram also include a brief overview of the supporting concrete technology. This serves as a useful background and sometimes adds clarity to the statements made in the literature.

Summarising, the following aspects will generally be reviewed for each element of figure 2.2:

- some backgound of the concrete technology relating to that topic
- the findings of the various authors that investigated the topic
- the personal observations, analyses and thoughts of the writer on the topic
- a summary and/or conclusion

On several topics different authors arrived at different conclusions. Sometimes their views appeared to be quite contradictory, hence the need for careful consideration and analysis. In doing this the writer generally found that the experimental data of the respective authors was valid, and that it was not a question of one investigator being right and the other wrong. Usually the differences in their conclusions could be accounted for by considering the differences in material properties, test methods and procedures.

In reporting the findings of the various authors under the many headings indicated in figure 2.2 the writer faced a dilemma, in that certain findings applied to more than one topic. For example Helland(1991) reported on the use of high strength concrete (HSC) for concrete road and bridge surfaces in Norway, which must have exceptionally good abrasion resistance to resist the very abrasive action of steel studded tyres on vehicles. This is generally achieved by means of using *silica fume*, together with a *superplasticized* very low *w/b* ratio mix.

The writer's dilemma here is: Should he on the one hand report Helland's findings under 2.2.1.1(a) Water Binder Ratio, or under 2.2.1.1.1.3 Superplasticizer, or under 2.2.1.2.3(a) Silica Fume, since all three contributed to the performance of the HSC, or on the other hand should he report the findings under all three headings. The first option involves a brief presentation of the background followed by a discussion of the findings relevant to the first topic (i.e. 2.2.1.1(a) in this case), and then referring back to this first reference rather than re-sketching the background again each time the author's work has relevance under another heading/s (i.e. 2.2.1.1.1.3 and 2.2.1.2.3(a) in our example). Although this has the advantage of preventing repetition, it is disadvantageous in that the reader would constantly be referring forwards and backwards. In the case where a reader was interested in only one specific subject or topic and had not read the full document this option would not be user friendly and could even be confusing.

The alternative would be to re-sketch the background each time it applied to a different heading/topic. All things considered the writer decided on this second approach. Although repeating some information makes a systematic reading of the chapter more tedious, this disadvantage is outweighed by the advantage of allowing some minor changes of emphasis in reporting the background to fit in with the particular aspect under discussion, and the need to refer back is eliminated. This makes the presentation user friendly when information is desired on the influence of a particular material or process on abrasion resistance. By consulting figure 2.2 the address/location of the desired section is easily located. Then by turning up that section the views of the various authors (and writer) may be ascertained.

The reader should be forewarned on one further point. In order to demonstrate the extent that a particular topic has been investigated, the writer has tried to quote every available author. The advantage of this approach is that it allows all the divergent views of the various authors to be expressed. It also gives a clear indication of the degree of agreement, in the case where many authors come up with the same finding. The reader should see it in this light rather than repetition that is unnecessary/tedious.

Chapter 2 - Factors Affecting Abrasion Resistance

- **2.1 Compressive Strength**
- **2.2 Paste**
- **2.3 Voids**
- **2.4 Aggregates**
- **2.5 Aggregate/Paste Bond**
- **2.6 Surface treatments**
- **2.7 Fibres**
- **2.8 Moisture Conditioning**
- **2.9 Surface Cracks**
- **2.10 Temperature**
- **2.11 Influence of Test Method**

2.1 Compressive Strength

- 2.1.1 factors affecting the relationship between compressive strength and and abrasion resistance
- 2.1.2 comparison of failure mechanisms
- 2.1.3 choice of abrasion test influences relationship with compressive strength
- 2.1.4 'core' and 'surface' abrasion resistance
- 2.1.5 conflicting views on the relationship
  - (a) view 1 - good relationship

Figure 2.2 Factors affecting the abrasion resistance of concrete

- **2.2 Paste**
  - 2.2.1 microstructure of hardened paste
    - 2.2.1.1 w/b
      - 2.2.1.1.1 water quantity
        - 2.2.1.1.1.1 fine aggregate
          - (a) grading
          - (b) particle shape
          - (c) surface texture
          - (d) proportioning
        - 2.2.1.1.1.2 coarse aggregate
          - (a) grading
          - (b) size
          - (c) shape
          - (d) surface texture
          - (e) proportions
        - 2.2.1.1.1.3 superplasticizer
        - 2.2.1.1.1.4 pigment
        - 2.2.1.1.1.5 binder type
          - (a) fly ash
          - (b) silica fume
        - 2.2.1.1.1.6 water extraction
          - (a) finishing
          - (b) vacuum de-watering
          - (c) re-vibration
      - 2.2.1.1.2 binder quantity
    - 2.2.1.2 binder type
      - 2.2.1.2.1 fly ash
      - 2.2.1.2.2 ggbs
      - 2.2.1.2.3 silica fume
      - 2.2.1.2.4 opc
      - 2.2.1.2.5 rhpc
      - 2.2.1.2.6 polymers
      - 2.2.1.2.7 hydrated lime
      - 2.2.1.2.8 CAC
    - 2.2.1.3 curing
      - 2.2.1.3.1 curing systems
        - (a) polythene sheeting
        - (b) wet burlap
        - (c) ponding/water
        - (d) curing compounds
        - (e) air
        - (f) heat and steam
        - (g) comparisons of systems
      - 2.2.1.3.2 binder content
      - 2.2.1.3.3 binder type
      - 2.2.1.3.4 age
        - (a) duration
        - (b) early
        - (c) delayed
  - 2.2.2 weathering and corrosion
    - 2.2.2.1 freeze/thaw damage
    - 2.2.2.2 early frost damage
    - 2.2.2.3 water corrosion
    - 2.2.2.4 chemical attack
    - 2.2.2.5 carbonation
    - 2.2.2.6 wetting and drying
    - 2.2.2.7 Influence of abrasion resistance on weathering
      - (a) acid attack
      - (b) water
      - (c) freeze/thaw
      - (d) carbonation
      - (e) wetting and drying

Figure 2.2(a) Factors (paste) affecting the abrasion resistance of concrete

- **2.3 Voids**
  - 2.3.1 introduction
  - 2.3.2 an expression for strength including influence of air voids
  - 2.3.3 the influence of paste on entrapped voids
    - 2.3.3.1 effect of consistency on entrapped voids
    - 2.3.3.2 effect of relative proportion of paste on entrapped voids
  - 2.3.4 influence of compactive effort on entrapped voids
  - 2.3.5 entrained voids
- **2.4 aggregate**
  - 2.4.1 fine aggregate
    - 2.4.1.1 hardness & type
    - 2.4.1.2 soundness
    - 2.4.1.3 grading and particle size
    - 2.4.1.4 shape and texture
    - 2.4.1.5 volume fraction relative to paste
  - 2.4.2 coarse aggregate
    - 2.4.2.1 hardness and type
    - 2.4.2.2 Grading
    - 2.4.2.3 size
    - 2.4.2.4 volume fraction relative to sand
- **2.5 aggregate/ paste bond**
  - 2.5.1 failure mechanisms
    - (a) failure mechanism in compression
    - (b) proposed failure mechanism in abrasion wear
    - (c) relative contribution of the transition zone
    - (d) consideration of abrasion forces
  - 2.5.2 quality of paste
    - (a) improved paste porosity
    - (b) summary
  - 2.5.3 aggregate

Figure 2.2 (b) Factors (voids, aggregate, bond) affecting the abrasion resistance of concrete

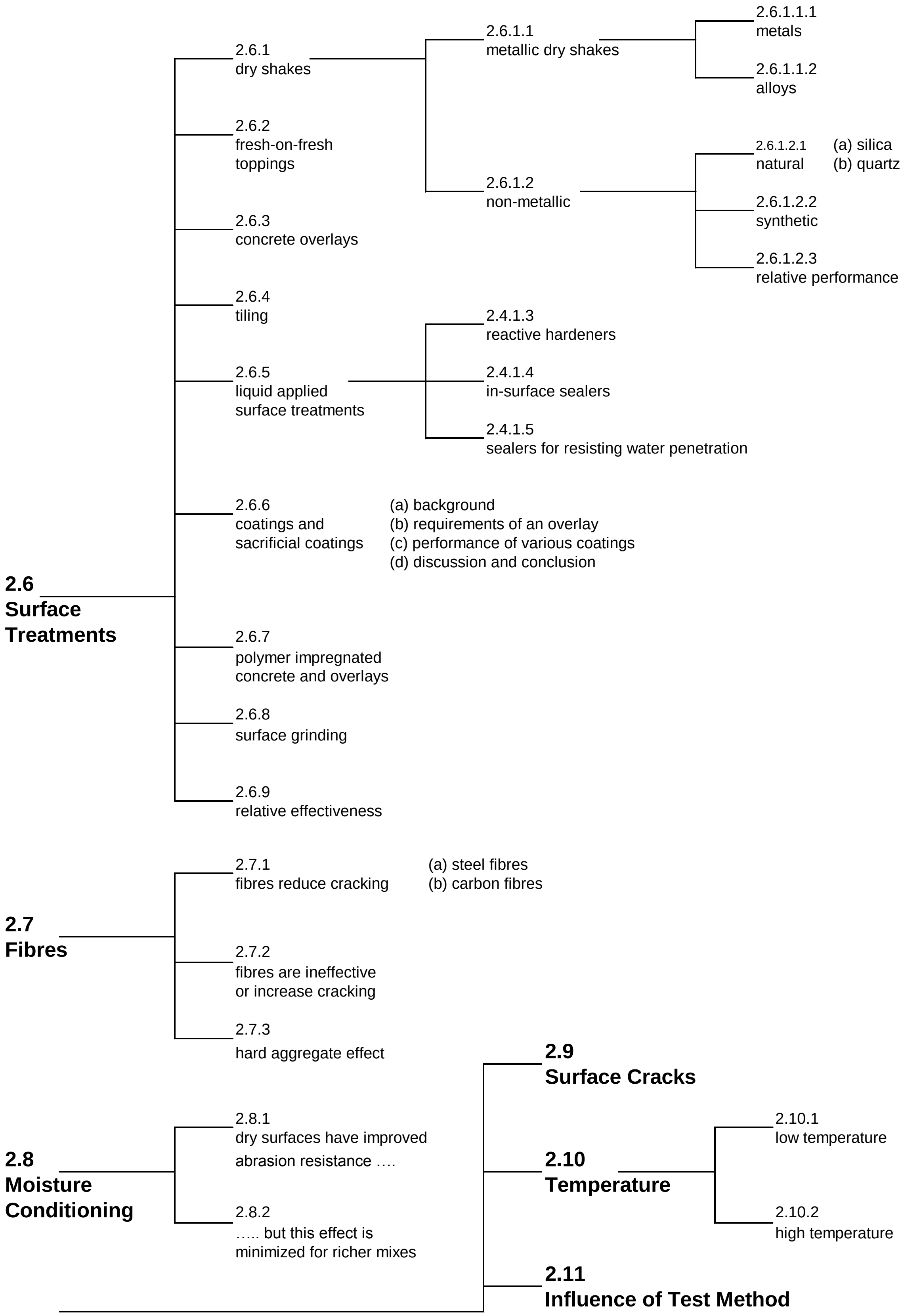

Figure 2.2 (c) Factors (surface treatments, moisture conditioning, surface cracks, fibres, temperature, influence of test method) affecting the abrasion resistance of concrete

2.0.9 Preview of Chapter

According to Fulton(1986) ‘concrete may be viewed as a composite material consisting of different phases which are mechanically and chemically distinct and are separated by definite interfaces’. In effect the wiring diagram, in splitting up the many aspects that have a bearing on abrasion resistance, takes cognisance of this.

The major headings of the wiring diagram describe the main materials, characteristics and processes that govern abrasion resistance. A preview is given below:

2.1 Compressive strength
2.2 Paste
2.3 Voids
2.4 Aggregates
2.5 Aggregate/Paste Bond
2.6 Surface Treatments
2.7 Fibres
2.8 Moisture Conditioning
2.9 Surface Cracks
2.10 Temperature
2.11 Influence of Test Method

Item 2.1: Compressive strength is the most common method of assessing concrete quality, and many investigators have reported a direct relationship with abrasion resistance. On the other hand others have found a very poor correlation. This apparent contradiction is explored.

Items 2.2 through 2.4: These aspects focus on the physical components of the concrete and therefore deserve careful attention. There are many permutations and these are considered, as well as the processes that have a bearing on them, e.g. curing, finishing etc.

Item 2.5: The quality of the bond between paste and aggregate in concrete is normally the weakest link in compression and tensile strength testing, and its effect on abrasion resistance is therefore given special attention.

Item 2.6: Surface treatments have an important bearing on abrasion resistance and are given some consideration.

Item 2.7: The contribution of fibres is considered.

Item 2.8: The percentage of moisture in concrete at the time of testing affects its abrasion resistance, and this is considered here.

Items 2.9 and 2.10: The effect of surface cracks and temperature on abrasion resistance are covered very briefly, and are included mainly to raise a certain level of awareness in the reader.

Item 2.11 Each of the many abrasion tests are in actual fact merely measures of the particular dynamic of that test. Therefore the ‘abrasion resistance’ so determined must be interpreted in that light. Clearly, some tests are better suited than others to measuring a particular aspect of abrasion resistance, and for this reason this item is briefly considered here. It is dealt with more fully in chapter 4.

The rest of the chapter is devoted to a systematic review of these eleven areas relative to their influence on abrasion resistance.