2.6 Surface Treatments

The merits of power finishing have been discussed in 2.2.1.1.1.6(a). This system is very widely used today for industrial floors and results in a hard surface with negligible abrasion wear when traffic loadings are limited to rubber wheeled traffic and/or pedestrian traffic.

TR34(1994) classifies the abrasion loadings on concrete floors into four categories i.e. severe abrasion, very high, high and moderate. The corresponding depths of wear permitted after testing with ‘small-steel-wheels’ is 0,05mm , 0,1mm , 0,2mm , 0,4mm. Wear to any appreciable depth results in undesirable dust, and makes it difficult to manoeuvre laden pallets with hand operated tines. Accordingly TR34 considers that a surface in an industrial warehouse that has worn as much as one millimetre has failed.

Surface treatments such as dry shakes and liquid treatments, which generally focus solely on improving the abrasion resistance of the top one or two millimetres are therefore most relevant in a consideration of abrasion resistance.

There are however applications calling for both hard and tough surfaces (i.e. surfaces that can resist heavy impact loads). An example would be some engineering workshops where heavy steel objects are dropped onto the floor, or tracks meant to convey tanks or bulldozers, or buckets of front end loaders and tines of forklifts scraping the surface. In these situations improving the top one or two millimetres may not suffice, and the use of a thicker layer may be required, applied either monolithically as a ‘fresh-on-fresh’ topping, or the following day as a ‘fresh-on-hard’ topping.

In the following sections a number of surface treatments will be considered including dry shakes, fresh-on-fresh toppings, concrete overlays, tiling, liquid applied surface treatments, sacrificial coatings, polymer impregnation, and surface grinding.

Such products are commercially available in South Africa and a typical product range of a company that supplies a wide range of surface treatments is included in appendix S.

Finally, in section 2.6.9, the various systems are compared, in terms of application and effectiveness.

2.6.1 Dry Shakes

Background

Speers(1999) explains that dry shakes enhance concrete surfaces not least of which is increased abrasion resistance. They have an established track record of fifty years, are cost effective, and are specified world-wide. Typically dry shakes consist of one part cement (with or without an extender), and two parts aggregate, which may be metallic or non metallic.

Today's dry shake topping is a complete 'concrete mix' in a kiln dry state, applied to the surface of freshly laid concrete to form a monolithic finish. Application rate is generally between 5 kg/m^2 to 7 kg / m^2, by automatic telescope spreaders or by hand. The topping absorbs a proportion of the free water from the concrete mix in the slab to lower the w/b of the surface. Power floating and or power trowelling follows and results in a wearing surface, typically 2mm to 4mm thick, with excellent abrasion resistance, where the aggregate used in the dry shake mostly determines performance.

TR34(1994) explains that timing is critical in applying dry shakes. It should be applied while there is still some bleed water, to assist in moistening the cement/aggregate, but too much water will at a later stage lead to 'crazing' cracks. On the other hand, too little water results in inferior bonding of the dry shake leading to delamination. Delamination can also take place where water becomes trapped below the dry shake layer as a result of delayed bleeding.

Dry shakes have various benefits. The surface is finished monolithically with the slab, ensuring *good bonding* and *economy* from the fast track all-in-one-visitation operation. Economy is also achieved by using a base concrete of average grade, and this does not compromise the hard abrasion resistant surface achieved by the application of the dry shake. Further economy is achieved by low maintenance costs.

Performance is enhanced in many ways; they are *non dusting*; can be made *slip resistant* and easy to clean; increased surface density results in *reduced permeability*; malleable iron dry shakes result in improved *impact resistance; aesthetics* can be improved in terms of quality smooth finishes and various colours. Iron oxide pigments are ideal for colouring and are both light stable and are cost effective in reds, browns, charcoal and yellows. Green and blue chromium based oxides are far more expensive. For maximum light reflectance white oxides with white cement can be used.

Two parameters generally used to assess the potential performance of a dry shake aggregate relative to abrasion resistance are aggregate abrasion value, and Mohs hardness. The former indicates loss of material from a steady grinding-with-abrasive process, while the latter essentially relates to scratch-resistance/hardness. The two attributes are generally, but not always related. For example, ferro-silica may be judged to be a very wear resistant material as it has a very low aggregate abrasion value, and also judged a very hard material as it has a high Mohs value. Quartz on the other hand has a much higher aggregate abrasion value of 18, and therefore appears to be inferior to ferro-silicon in terms of abrasion resistance, but its Mohs hardness is a relatively high seven. Conversely, an iron alloy may be 'abrasion resistant' with an aggregate abrasion value of three, but may be relatively soft in terms of having a Mohs value of five. It is highly wear/grind resistant but is not very hard, so that its has a resilient/shock-absorbing response to impact loads.

[For impact loads, aggregates should be tough/malleable rather than brittle. In addition to the Mohs hardness scratch test, the LA abrasion test for aggregate should also be used. The former distinguishes between hard and soft, the latter between tough/malleable and brittle. Ideally aggregates subject to abrasion with an element of impact should be both hard and tough/malleable].

The aggregate component of metallic dry shakes may either be a pure metal or an alloy. On the other hand the aggregate used for non-metallic dry shakes may be a natural mineral such as silica or quartz, or synthetic. These aggregate types are considered below.

2.6.1.1 Metalic Dry Shakes

In this section the various metallic dry shakes are considered under separate headings.

2.6.1.1.1 Metals

Speers(1999) states that iron (and steel) chippings have excellent abrasion and impact resistance, but are susceptible to corrosion in exposed areas, evidenced by brown spots.

Ahlers(1928) speaks of 'metallic hardeners' that could be applied as part of a topping, or directly to the final surface level with no other treatments. The latter would be referred to as a 'metallic monolithic surface' and is both simple and cost effective. Typical Ahlers dosed at 30 lbs per 100 square feet (or 1,5kg/m^2).

Schuman(1939) applied an abrasive between a loaded spinning disc and the specimen [=*sliding fine-abrasive*, see appendix U.5.14] and found reduced abrasion resistance for specimens finished off with a top coat of oily metallic aggregate. This was evidenced by excessive pitting. On the other hand a top coat of cement and metallic aggregate [presumably free of oil] greatly enhanced abrasion resistance.

Scripture(1954) found that malleable iron aggregate increased abrasion resistance (sliding fine-abrasive) by approximately 400% relative to mineral aggregates.

Samson(2000) ***Ferroshield*** (see appendix S) is an example of a commercially available 'iron aggregate dry-shake floor hardener '.

2.6.1.1.2 Alloys

Speers(1999) reports that high density ferrous alloys (e.g. high density ferro-silicon alloy with some titanium) and also non ferrous alloys have very high abrasion resistance and do not oxidise. 'Soft' alloys with relatively low Mohs values, such as iron alloys, still have very good abrasion resistance (as well as impact resistance).

2.6.1.2 Non-Metalic Dry Shakes

2.6.1.2.1 Natural

Natural dry shakes generally consist of one part binder to two parts fine aggregate, pre-blended and packaged in bags.

(a) Silica

Speers(1999) reports that these aggregates are generally made of common, cheap sands, which are typically no harder than the concrete aggregate resulting in minimal benefit.

Schuman(1939) did abrasion tests using revolving rotating spinning discs (sliding fine-abrasive) and found increased abrasion resistance for specimens finished off with sand top coats.

Samson(2000) Samtech Floor Screed (see appendix S) is an example of a commercially available ‘silica aggregate hardener and conditioner for concrete floors’.

(b) Quartz

Speers(1999) reports that these aggregates come in various forms with various degrees of hardness.

Ahlers(1928) did abrasion tests using *rolling steel wheels* (see appendix U.4.04) to determine the abrasion resistance of natural non-metalic dry shakes consisting of cement with various combinations of grit and sand, invariably with a/c = 2 (by volume). The results were on a par with the metallic hardeners tested at the same time.

2.6.1.2.2 Synthetic

Speers(1999) states that synthetic dry shakes are generally made with slag aggregates, which can be extremely hard. They do however require careful crushing and blending to obtain the desired grading.

2.6.1.2.3 Pure Cement

Schuman(1939) applied an abrasive between a loaded spinning disc and the specimen [=*sliding fine-abrasive*, see appendix U.5.14] and found improved abrasion resistance for specimens finished off with a top coat of cement.

[Normally cement by itself is softer than concrete, since generally aggregates are harder than cement. Abrasion tests done by Addis(1989) confirmed this. However where a binder is applied as a dry shake, and worked into the surface, it will have the effect of reducing the w/b ratio of the paste and at the same time increase its plasticity and subsequent density. Thus the hard aggregate component will be strongly bonded in the matrix, which accounts for the increase in abrasion resistance].

2.6.1.2.4 Relative Performance

An attempt is made in this section to compare the relative effectiveness of various dryshakes in increasing abrasion resistance.

Kettle(1986) did abrasion tests using the C&CA apparatus [=rolling steel wheels, see appendix U.4.06] on different dry shakes and found that both the natural aggregate and cement dry shakes did not produce significant improvements in the abrasion resistance of slabs which had already benefited from repeated power trowelling.

Fentress(1973) did abrasion tests according to DIN52108 [=(sliding fine-abrasive), see appendix U.5.02] and found that the abrasion resistance of iron / cement shakes were the best, pure cement was second, a red [aggregate] shake was third, while a sand/cement blend was the worst.

[The good performance of the cement paste may probably be ascribed to an increased paste/aggregate bond from a lower w/b and increased density].

From all the statements made in 2.6.1.1 through 2.6.1.4 it is possible to construct a hierarchy of performance of the abrasion resistance for the various dry shakes as follows:

1 Cement/strong steel alloy
2 Cement/steel or iron shot
3 Cement/synthetic aggregate
4 Cement/quartz aggregate
5 Cement/silica

6 Cement (This may be higher up if it improves the w/c and density of the existing mortar where a hard aggregate is used).
7 Alloy or steel without additional cement
8 Quartz of silica without additional cement

Note that the position shown for silica and quartz is not very clear from the literature. Some authors have reported a great improvement in abrasion resistance, while others say that these materials contribute minimally. Clearly the hardness of quartz will vary depending on its exact mineral composition. It is further evident that both materials will appear to make a large improvement when added to a concrete that was made with a relatively soft limestone aggregate, and conversely their performance in say an andesite mortar may even appear to be detrimental to abrasion resistance.

Sectional Summary and Conclusion on 'Dry Shakes'

Metallic dry shakes are able to enhance abrasion resistance very substantially, particularly in the form of malleable iron aggregate. They may be applied directly to the surface, but preferably with additional cement. They should be free of oil. Unfortunately they do create stains on the concrete in areas that receive water.

Metallic alloy dry shakes on the other hand may not be corrosive, but may be much more expensive with no addition performance benefits.

'Soft' alloys have excellent impact abrasion resistance, the resilience of the material absorbing some of the shock.

Non metallic dry shakes appear to have variable performance, from almost as good as metallic shakes on the one hand, to virtually no improvement on the other. Clearly the hardness of the dry shake material relative the hardness of the aggregate in the host mortar is important. Extremely hard synthetic materials such as silicon carbide should yield very hard surfaces.

Finally, the additional expense of dry shakes may not always be justified where power trowelling is capable of yielding a very hard abrasion resistant surface by itself. Furthermore the depth of a dry shake surface is generally limited to a few millimetres, and this may be unsuitable for certain applications.

2.6.2 Fresh-on-fresh Toppings

As the title implies, fresh-on-fresh toppings, also called monolithic toppings, are placed on the base concrete within a few hours resulting in an excellent bond to the base concrete. This ensures that even where the surface is as little as 10mm thick, it will not debond if properly constructed. It also means that superior materials may be used without adding too much to the overall cost. Being thicker than a dry shake surface it will withstand greater impact forces as well as ‘deep abrasion’:

It is clear from **Ahlers(1928)** that various special toppings have been in use or under consideration for many decades. Ahlers describes nine different topping surfaces tested by rolling steel wheels (see appendix U.4.04) moving circumferentially under load. The 16 hour test was considered to equate to 11 years of traffic that included steel wheeled traffic.

He considered both metallic and non-metallic materials, which were generally applied monolithically in specially blended ‘toppings’ that were typically one inch thick. All the results were considered to be very good with average depths of wear ranging between 0,3mm and 1,6mm. Of special interest is that a non metallic topping consisting of one part cement and two parts ‘grits’ and that was steel trowelled ‘until it was impossible to make any further impression with a steel tool’ had almost as good an abrasion resistance as the best of the metallic toppings.

Siro(1991) pointed out that while the practice of strewing cement on the surface (followed by power finishing) was effective in absorbing water and so lowering the w/b ratio and producing a hard outer skin, this skin tended to be much thinner than would be the case if a rich topping mix of 10mm to 20mm had been applied fresh-on-fresh.

Siro makes reference to the Finnish Concrete Floors Classification. A class 1 surface is to have a 10mm to 20mm fresh-on-fresh special concrete layer of either quartz, metal, silicon carbide, or electro corundum, and must have less than 1mm of wear according to the Finnish abrasion test (=*rolling steel wheels*, see appendix U4.01). With quartz as aggregate it was possible ‘to attain the highest wear resistance grade’, comparable with a metallic aggregate (although toppings with metallic aggregates were ideal where vehicles with steel tracks were used).

A class 2 surface may consist of a dry shake incorporated into a 50MPa surface layer. In this case up to 3 mm of wear is permissible. Class 3 and 4 are progressively more lenient. The point to note here is that the Finns consider a special topping layer to be superior to a dry shake.

TR34(1994) refers to monolithic toppings (formally referred to as granolithic toppings) as special layers of concrete which are placed onto the base concrete slab when it is between one to three hours old. In nearly all cases the long strip construction method is used. Monolithic toppings are generally rich in binder, typically 500kg/m^3 with w/c = 0,4 or less, one part natural sand and two parts 10mm coarse aggregate. Final finishing is done with a power float and power trowel, resulting in a surface with excellent abrasion resistance.

Samson(2000) Ferroshield Screed and Floroguard Screed (see appendix S) are examples of commercially available ‘monolithic toppings’ for concrete floors. The former incorporates iron aggregate and the latter silica.

Paving typically uses a base concrete and a fresh-on-fresh topping of surface concrete, which may be pigmented. As the latter is generally only about 6mm to 8mm thick, the possibility exists for incorporating into this layer materials that are known to improve abrasion resistance. This may include hard aggregates, metallic aggregates, high percentages of cement etc.

Pesch(1980) reports that highly wear resistant paving blocks, with abrasion values of below $3cm^3/50cm^2$ for the DIN52108 abrasion test (=*sliding fine-abrasive*, see appendix U.5.02) have been used in Germany where impact is present or in the case of vehicle traffic with steel tyres. Note that the acceptable limit is normally $15cm^3/50cm^2$.

Dreijer(1980) reported that paving blocks that had been provided with a top layer of 'face concrete' suffered very badly in the very severe winter of 1962/63 experienced in the Netherlands. This layer was lost to the rest of the block. Later much care was placed on maximising the plasticity of the mix, in order to improve abrasion resistance, but the measures taken had the useful side effect of dramatically improving the inter-layer bond as well. (Increased plasticity is generally achieved with more fines in the form of a higher cement content and more water. This has the effect of reducing voids as well as promoting good bonding between 'face' concrete and 'heart' concrete, and of course also increases abrasion resistance). At any rate these measures proved effective as very few problems were experienced in the equally severe winter of 1978/79 in product supplied by producers who had implemented the recommendations of maximum plasticity and 48 hour curing.

[Maximising the moisture in both the base and surface concrete is the surest way of improving bond between the two layers. In addition, increasing cement content will have the added benefits of increasing plasticity and supplying added cementing material, thus improving bond further. However there is a limit to how far the *surface* concrete can be plasticised in this way, since this also increases its adhesion to the tamper shoes, resulting in 'tamper stick'. It follows that the adhesion of the surface layer to the tamper must be less than its adhesion to the base or 'heart' concrete. Furthermore the internal cohesion in the base concrete must exceed tamper/surface-concrete adhesion. In practice a relatively dry surface mix, with a high cement content to ensure good abrasion resistance, will bond well to a relatively moist base, neither will it adhere to the tamper. However care must be taken to ensure that the surface concrete is not so dry that entrapped air cannot be expelled during the vibration process. On the other hand the degree of plasticity/moisture that the *base* concrete can tolerate is limited by the onset of slump].

Sectional Conclusion

Fresh-on-fresh toppings are cast monolithically with the base slab after a delay of a few hours. They have a high cement content together with special hard wearing aggregates, resulting in a hard and tough surface. They are generally between 10mm and 40mm thick, and consequently are better able to resist severe abrasion and impact effects than floors finished with dry shakes.

As with dry shakes timing is crucial. Fresh-on-fresh toppings should only be applied after bleeding in the base concrete has ceased, in order to prevent the possibility of a weak interface with subsequent delamination. It the delay period is too long, bonding with the base concrete will once again be compromised, and again, delamination may occur. Finally the moisture content in the topping is most important to ensure adequate compaction.

2.6.3 Concrete Overlays

PCA(1996) Concrete overlays are an obvious method of resurfacing existing surfaces, and in so doing create a new-like appearance and improve abrasion resistance. These may be fully bonded, partially bonded or unbonded to the existing surface.

[A fully bonded surface is generally achieved by roughing up the base surface followed by a vigorous rubbing with a cement slurry. In a partially bonded surface no surface preparation is made, other than some sweeping, while an unbonded surface is achieved by applying placing a membrane between the two surfaces (e.g. plastic sheeting) which will allow relative movement between the two surfaces. The mix proportions, curing, finishing procedure etc. may be tailored to achieve excellent abrasion resistance].

Helland(1991) reported on the use of a 80mm thick overlay made from high strength concrete (HSC), for use on a bridge in Norway, which had to have exceptionally good abrasion resistance to resist the very abrasive action of steel studded tyres on vehicles. A crucial element in this type of overlay is the bonding with the base concrete, which in this case was a relatively impermeable high grade structural concrete. To this end a latex-cement slurry was applied to the sandblasted deck of the bridge. However insufficient time was allowed for the slurry to bond adequately, given the impermeable nature of the structural concrete in the deck. A drop in temperature of 10 to 15 ^{o}C from midday to midnight in Norway (in South Africa this could be as much as 25 degrees on the highveld in winter) resulted in stains of 0,15% to 0,25% in the overlay concrete, leading to debonding and cracks developing.

Helland(1995) reports on 130 MPa concrete (cylinder compressive strength!) being used as a 35 mm deep inlay to repair an existing 55MPa concrete road in Norway that had been severely rutted by steel studded tyres. The road was milled out to a depth of 35mm in two 800mm wide tracks. These were primed with an epoxy prior to concreting. Sawn sections representing both the old and new surface were subjected to accelerated abrasion testing (a machine consisting of four studded wheels, each attached to an arm which allows them to go along a circular track, see appendix U.3.03). The abrasion results for the high strength concrete were comparable to those normally obtained in massive granite. Following the tests it was possible to predict that the new surface would have four times the life of the old. After six years of service, the pavement was performing as expected and no debonding had been observed.

Sectional Conclusion

Concrete overlays are an economical method of repairing rutted concrete roads and surfaces. Because they are relatively thin (examples of 35mm and 80mm have been cited), they can be made with a relatively high cement content and special hardwearing aggregates. They utilise the structural strength of the existing slab, merely having to provide a hardwearing surface.

Preparation is crucial to ensure adequate bonding with the base concrete.

2.6.4 Tiling

Shopping malls make extensive use of tiling in heavily trafficked pedestrian areas. Tiles may be of natural stone, concrete or ceramics, and may have excellent abrasion resistance. These surfaces in effect become the overlay to the supporting concrete slab, and are periodically replaced once worn. It is however probably more correct to say that the concrete base is the subservient partner in the synergistic relationship, and that it is primarily there as a convenient support for the aesthetically pleasing tiles.

Suda(1990) used an abrasion machine with ‘spiked’ tyres (rolling studded tyres, see appendix U.3.05) and found that the abrasion resistance of specially tiled concrete pavers was vastly improved, with about one fortieth of the wear of equivalent untiled pavers. (It is not stated if the spikes are a hard rubber protrusion or made of steel). Using tiles as an overlay to concrete pavers to significantly improve abrasion resistance, or using paving as a support for tiles to enhance aesthetics? Either way a novel idea!

Inuzuka(1995) reports on the problem of asphalt surfaces in Japan that become unserviceable as a result of scratching from anti-skidding devices on tires in winter, and that melt in extreme heat in summer. One solution is to remove the asphalt and replace it with conventional concrete blocks on a bed of sand. The concrete is reported to be much more wear resistant. A second solution, which reduces the closure period of the road, involves some grinding of the asphalt by way of surface preparation, followed by an adhesive 3mm to 10mm thick bituminous material to ‘glue’ tiles to the asphalt. The tiles are generally 20mm to 40mm thick and typically 400mm square in plan area. They are made of an acrylic resin mixture with carbonic calcium, and fine aggregates mainly of roll mill slag. These tiles are extremely wear resistant, even more so than concrete paving. Wear tests (presumably with a studded wheel tyre apparatus) have shown that a wear depth of 80mm in asphalt is reduced to 23mm in concrete and 8mm with resin/slag tiles.

Horiguchi(1995) did abrasion testing (using rolling dressing wheels) on steel tiles that were grouted to concrete pavers. The steel tiles also had a rubber layer bonded to them as a wearing course. The rate of wear of the tiled pavers was 1/3 that of the ‘plain concrete’ and one tenth of ‘bituminous concrete’.

Sectional Conclusion

Tiles can be specifically manufactured to be very hard-wearing. Even though relatively thin they can have excellent flexural strength and may be ideal for resurfacing roads, asphalt and concrete etc.

On the other hand tiles may crack easily when subject to impact from hard objects.

2.6.5 Liquid Applied Surface Treatments

Background

Liquid surface treatments influence the 'micro surface texture' of concrete by filling pores/capillaries and valleys to give a smoother surface. The blocking of these pores will reduce the permeability and increase the density of the surface microstructure with corresponding reductions in initial surface absorption (ISA) and abrasion resistance respectively.

Sadegzadeh(1986) did parallel testing on various concrete surfaces using an initial surface absorption test (ISAT, see appendix U.8.01), the Impact rebound hammer, and an abrasion test (rolling steel wheels). He concluded that there was a very thin surface zone, the 'micro surface zone', the texture of which could be improved by liquid surface treatments, to varying extends, depending on the choice of the liquid treatment. He found that the ISAT and small steel wheel abrasion test were sufficiently sensitive to distinguish between liquid treatments of varying effectiveness, whereas the rebound hammer was not. This is because the influence of the rebound hammer goes deeper than the micro-surface zone, indeed it penetrates down into a zone which has a 'macro-surface texture'.

The macro-surface zone is affected by processes that influence the microstructure of the surface at a greater depth than do surface treatments. These processes include power trowelling, the application of dry shakes, and curing. The rebound hammer is in this instance found to be sensitive to variations in this somewhat deeper zone. This is because the rebound hammer measures the loss of energy due to local crushing of the cement paste, and the loss of energy due to the absorption of the stress wave set up in the material by the impact hammer, effects that extend beyond the zone of the micro-surface texture.

The limited penetration of the liquid surface treatments is thus demonstrated by the inability of the rebound hammer to differentiate between the various liquid surface treatments.

Two groups are generally used; reactive hardeners of various kinds (2.6.5.1), and in-surface sealers (2.6.5.2).

2.6.5.1 Reactive Hardeners

Gill(1996) states that when hardeners are applied to a concrete surface a chemical reaction takes place with the lime (whether hydrated or unhydrated) in the pores of the concrete matrix, resulting in a mixture of dicalcium or tricalcium silicate compounds, which hydrate even further to produce calcium silicate hydrates. Therefore liquid hardeners increase the strength of concrete by increasing the concentration of CSHs. It stands to reason that this crystalline growth in the pores reduces the permeability of the concrete. Penetration is in the region of ⅛ ' to ¼', so that they do not wear away like surface sealers.

The effectiveness of the product is implied by the 10 year guarantee that 'many' manufactures offer. However, the following quote does seem to place a question in the mind of the reader (italics mine). 'Liquid hardeners *can* improve the abrasion resistance and reduce the dusting of a lower quality concrete floor. On higher quality concrete surfaces the need for a chemical floor hardener diminishes.'

Chaplin(1991) explains that sodium silicate or magnesium or zinc silico-flouride as dilute solutions react with CaO within the pore structure near the surface converting this to calcium silicate glass, or calcium fluoride. The pores are thus blocked with a glass like material. These substances are not known to greatly enhance abrasion resistance, as they are brittle and break down under wheel traffic, although Chaplin achieved quite good abrasion results (rolling steel wheels) with silico-fluoride. Hardeners are effective in reducing dusting in lighter applications. They are more effective on medium quality floors, but are unable to redeem poor quality finishes, and add little to good quality finishes.

Lane(1978) stated that surface hardeners densify and harden the surface of concrete and therefore improve the abrasion resistance. Tests with a revolving disc (sliding fine-abrasive) showed that magnesium-fluosilicate had good abrasion resistance against rubbing action, while zinc-fluosilicate was better against the impact action of rolling dressing wheels.

Liu(1991) stated that magnesium fluorosilica and zinc fluorosilica were a means of increasing the abrasion resistance of defective floors, with the former chemical more effective in rubbing abrasion and the latter more effective in impact abrasion.

Schuman(1939) found hardeners were beneficial in improving the abrasion resistance of surfaces which had not been cured, but did not add much to cured surfaces. (Curing therefore was more important than treating with a surface hardener).
Magnesium fluorosilicate was superior to silica water glass. (His test applied an abrasive between a loaded spinning disc and the specimen, i.e *sliding fine-abrasive*, see appendix U.5.13).

C&CAofNZ(1997) have produced a guide based on abrasion tests done using the *rolling steel wheels* (see appendix U.4.06). The document states that 'surface hardeners' improve the abrasion resistance of industrial concrete floors initially, but once the hardener layer is penetrated, the abrasion resistance reverts to that of an untreated concrete.

Kettle(1986) found that the application of concrete surface hardeners (e.g. sodium silicate, magnesium fluorosilicate) increased the abrasion resistance (=*rolling steel wheels*, see appendix U.4.06) of concrete only very slightly. They were more effective on lower w/c ratios than on mixes with higher ratios. Adequate curing appeared to be more effective in improving abrasion resistance than the application of surface hardeners.

Samson(2000) 'Converseal 200'S' & 400' (see appendix S) is an example of a commercially available 'silicaonate sealer and densifier' for concrete floors.

Sectional Conclusion

Apart from Gill(1996), who has a very positive view, the other investigators highlight various limitations (i.e. reactive hardeners only enhance abrasion resistance in certain applications).

Their findings (excluding Gill) may be collated as follows:

- Reactive hardeners consist of diluted solutions of sodium silicate or magnesium or zinc silico-flouride
- They react with CaO within the pore structure near the surface converting this to calcium silicate glass, or calcium fluoride. The pores are thus blocked with a glass like material.
- Hardeners are effective in light applications in reducing dusting, but are brittle and break down under concentrated loads
- Their effectiveness is limited to the very topmost surface, so that once this has been penetrated, the rate of abrasion wear proceeds as if no hardener had been applied.
- They must be carefully selected to suit the abrasive load. For example magnesium-fluosilicate had good abrasion resistance against rubbing action, while zinc-fluosilicate is better against impact action.
- They improve the abrasion resistance of medium quality floors, but add little to hard and well cured floors, and are unable to redeem poor quality surfaces.

2.6.5.2 In-Surface Sealers

Low molecular weight sealers, which may be based on polyurethane, acrylic or epoxy resins, are capable of penetrating the pore structure of the surface mortar layer, so effectively sealing and strengthening the surface. The sealer materials are also resilient in nature and therefore provide support to the more brittle mortar structure. This resilience has a cushioning effect, resisting crushing breakdown [(Chaplin(1990)] that would otherwise translate into abrasion wear.

Kettle(1986) did abrasion tests using the C&CA apparatus [=rolling steel wheels, see appendix U.4.06] and found that in-surface sealers based on polymers in aromatic solvents, produced significant increases in abrasion resistance.

Chaplin(1991) found that in-surface sealers make a very substantial improvement to abrasion resistance (C&CA rolling steel wheels). Epoxy or polyurethane sealers are also used to upgrade defective surfaces. These are generally first prepared by a surface grinding operation to remove the soft, crazed or uneven material.

Sadegzadeh(1986) did abrasion tests using the C&CA rolling steel wheels and found very substantial reductions in wear for specimens treated with various in-surface sealers. The abrasion wear corresponding to a 20% solution of 'low molecular weight aliphatic isocyanate pre polymer based moisture curing polyurethane resin in aromatic solvents' was down to approximately 20% of that of the untreated surface. Similarly a 30% solution of a 'bisphenol A/F resin and blended polyamine hardener in aromatic solvents' performed almost as well, as did a '10% solution of fully reacted methyl methacrylate/ethyl acrylate copolymer in aromatic solvents'.

TR34(1994) recognises that resins such as polyurethane, acrylic or epoxy, in dilute form, penetrate the surface pore structure to toughen the mortar matrix. This improves resistance to crushing breakdown, but should not be considered as a substitute to an inherently strong mortar surface.

Samson(2000) 'Aqueous Sealer' (see appendix S) is an example of a commercially available 'acrylic polymer' sealer for concrete floors.

Sectional Conclusion

Resin based sealers of polyurethane, acrylic, or epoxy that are capable of penetrating the pore structure of the mortar surface substantially increase abrasion resistance. They toughen the mortar matrix and improve resistance to crushing breakdown from abrasive loads. It may be that they act as a secondary type of binder, so that even after the paste surrounding an aggregate particle has fatigued from repeated attack by an abrasive, the more flexible sealer within the pores still binds the particle.

2.6.5.3 Sealers for Resisting Water Penetration

A third category of liquid applied treatments exists, developed primarily for resisting the penetration of water into structures. Although these sealers in themselves have no abrasion resistance, they may reduce abrasion wear indirectly by preventing or limiting rebar corrosion, freeze-thaw deterioration, etc. For example, it is sometimes desirable to seal concrete decks that are subject to both de-icing salts and abrasion wear, to keep the salt from the reinforcing. Many surface-protection options are available to prevent water from entering concrete. Waterproofing coatings or membranes can provide a complete barrier to water, but their impermeability can be a drawback because they trap within the concrete water that would otherwise evaporate. This leads to a build up in water vapour pressure that leads to debonding or even a breach of the sealer.

Another option is to provide a sealer or clear water repellent that does not render the concrete impermeable. Such sealers resist water penetration while allowing the concrete to breathe.

McGovern(2000) Sealers can be broadly grouped into two categories: *film formers* and *penetrants*. This is an important distinction when choosing a sealer for concrete structures exposed to abrasion, such as bridge and parking decks, because film formers, in forming a barrier on the concrete *surface*, wear off under abrasion and can reduce skid resistance, and may be vulnerable to UV light. They are however capable of spanning small cracks, which penetrants are unable to owing to their small molecular size. Common film formers include acrylics, silicones, stearates and epoxies. (Epoxies offer excellent water resistance, but often have much lower-water vapour permeability relative to the other film formers, and should possibly therefore be classified as waterproofers).

Of the several generic classes of penetrants, only silanes, siloxanes, silicates, and siliconates can accurately be described as penerating sealers, and only silanes and siloxanes achieve significant penetration. (Silanes and siloxanes are part of the broad family of silicone-based water repellents).

Silanes and siloxanes are reactive penetrants. Instead of simply plugging the pores of concrete, they react and bond with the concrete to form a hydrophobic layer that repels water effectively while providing excellent breathability. Those containing an octyl or butyl alkyl group perform much better than those with methyl of ethyl groups.

Although silanes and siloxanes have similar water repellent abilities, silane molecules are smaller than siloxane molecules, so they penetrate deeper into the concrete, generally at least 2,5mm. Therefore they provide longer lasting protection to concrete exposed to abrasion. The higher the solid contents of silanes, the deeper the penetration and the better the performance.

Tsur(1996) describes a water based acrylic sealer which prevents absorption of stains, thus facilitation easy and low cost cleaning of the sealed surfaces. He explains that the sealing capability of the surface is maintained even with a degree of abrasion, since only the peaks of the protruding aggregate particles (together with any sealer covering the peaks) are abraded. This exposed aggregate is relatively impermeable, while the more permeable ‘valleys’ remain filled with sealer.

Tsur explains that a good surface sealer requires a combination of properties in order to function properly:

- very low viscosity in order to flow and spread on the surface, and get easily absorbed
- chemical and water resistance
- hard and durable
- UV and weather resistant
- Low cost

Various surface sealers have been classified in terms of these properties in table 2.2:

Table 2.2 Relative Performance of Various Surface Treatments

	PROPERTY				
MATERIAL	Low viscosity	Chemical and water resistance	Hard and durable	UV and weather resistant	Low cost
Epoxy (2 component)	---	++	++	-	--
Polyurethane (2 component)	+ -	+	++	+ -	--
Acrylic (mono methyl methacrylate)	+	++	++	++	--
Chlorinated rubber solvents	+	+-	++	+	-
Acrylic solvent based	+	+	+	+	-
Polyurethane water based	+	+-	+	+-	-
Acrylic Emulsion water based	+	+	+	++	+

Samson(2000) 'Siloxane Sealer' (see appendix S) is an example of a commercially available penetrating treatment for 'waterproofing' concrete surfaces.

2.6.5.4 Conclusion

Liquid applied surface treatments vary considerably in performance according to type. Reactive hardeners are not as effective as in-surface sealers in improving the abrasion resistance of concrete surfaces, while the main use of sealers that resist water penetration is in limiting freeze/thaw deterioration.

2.6.6 Coatings and Sacrificial Coatings

(a) Background

White(1997) explains that of the 500,000 concrete bridge structures in the USA, some 200,000 are now classified as structurally or functionally deficient. This crumbling of the nation's infrastructure has necessitated cost effective methods of extending the lifespan of bridges, including various polymer overlays as sacrificial coatings.

Polymer concrete overlay systems have been used in the USA since the 1950s. The first systems were coal tar epoxies heavily broadcast with fine aggregates. These overlays had poor abrasion resistance to traffic and were relatively porous. Polyester resins, epoxy resins and methyl methacrylates were first used in the 1960s. While these systems had improved abrasion resistance, the early formations proved very brittle, especially at low temperatures, and therefore were susceptible to cracking. Moisture tolerant epoxies were introduced in the 1970s, offering much needed, long-term performance.

Abrasion resistance to traffic was the primary performance requirement for the early epoxy resins. Lower modulus, higher elongation, and 'flexibilized' epoxy resins were later developed for improved overall performance on bridge decks. These low modulus systems have proven to be very useful and forgiving in both application and performance in harsh conditions.

(b) Requirements of an overlay

Chaplin(1991) In its simplest form this may consist of a 3mm to 4mm self levelling epoxy resin applied to a surface prepared by shotblasting. Although this type of system gives the concrete full protection against abrasion wear, an epoxy resin on its own, without the inclusion of a hard wearing aggregate, is likely to wear excessively in more abrasive conditions.

Samson(2000) 'Samtech High-Build Coating' (see appendix S) is an example of a commercially available epoxy floor coating' for concrete floors.

A successful overlay is dependant upon many factors. The resin binder and graded aggregate must be formulated to meet the abrasive loads of high traffic volumes, remain flexible in cold temperatures, not soften excessively at elevated temperatures, be impermeable to de-icing salts, and absorb a minimum of water.

McGovern(1997) Some sacrificial coatings are multi-layered. The lowest layer is a primer layer for adhesion to concrete, followed by a flexible base coat which serves as a waterproofing base capable of bridging and sealing small cracks and in so doing protect the concrete against aggressive chemicals or the near-surface reinforcing against de-icing salts. Next follows a wear coat consisting of a solution with a high solids content consisting of silica sand or equivalent. This may also serve as an anti-slip mechanism. Finally a top coating is applied.

Generally these multi-layered coatings are polymer systems consisting of polyurethane, epoxies, epoxy urethanes, polyureas. The solids used to resist abrasive forces are either silica sand, aluminium oxide (or silicon carbide) granules, or even rubber granules. It is important to achieve a relatively high solids content to minimize shrinkage effects. The requirements for these specifications are conveniently set out in ASTM C957 'Standard Specification for High Solids Content, Cold Liquid Applied Elastomeric Waterproofing Membrane with Integral Wearing Surface' and six areas are catered for:

- retension of flexibility in cold conditions
- retension of bond even where the concrete surface becomes saturated

- retension of tensile strength after exposure to aggressive chemicals
- U V Resistance
- abrasion resistance
- solids content – a minimum of 60% is specified to limit shrinkage effects

Abrasion resistance is determined in terms of a modified ASTM C501, and the membrane system must not loose more than 500 mg when subjected to 1000 cycles of the CS-17 abrasion wheel using a 100kg weight.

(c) Performance of Various Coatings

Omata(1997) did abrasion tests with pneumatic rolling studded tyres (see appendix 3.05) made to roll over specimens, and found that *methyl methacrylate (MMA)* resin mortar experienced approximately two thirds of the wear of a conventional 50MPa concrete specimen, and about one third of the wear of a fine gap graded asphalt specimen (to represent a high wearing asphalt pavement). Field test measurements at a site subject to chain tires and studded wheels revealed a wear of 0,67mm for the MMA surface compared to a wear of 4,5mm for the parallel Portland cement concrete section. (This work was initiated because flexible epoxy mortars used as overlays had failed to yield satisfactory results).

Liu(1981) found that mortars consisting of three or four parts of Ottawa sand mixed with different *resins (epoxy, furim, acrylic*) demonstrated excellent abrasion resistance according to (the forerunner of) ASTM C1138 [=*impacting steel balls* (mild), see appendix U.2.07]. They had an even better resistance than iron aggregate topping, but not quite as good as the *resilient polyurethane coats*, which showed virtually no wear. The polyurethane coats did however require very good surface preparation to prevent debonding. All coatings given above were far superior to vacuum treated concrete.

Liu(1991) reported that *paints* and coatings used to seal concrete surfaces and to protect the concrete from the attack of the environment of chemicals possess only limited abrasion resistance.

Some coatings, among them *vinyl and heavy rubber*, if properly bonded remain fairly resilient and effective in protecting concrete from abrasive actions.

Several types of surface coatings including *polyurethane, epoxy resin mortar, furan-resin mortar, acrylic mortar* have exhibited good abrasion resistance in laboratory tests.

Siro(1991) explains how a polymer impregnated surface can be further improved by applying additional coatings to form an exterior top coat of a desired thickness. The strength of the surface will then be a function of the depth and quality of the impregnated polymer in conjunction with the thickness, strength and deformation properties of the top coating.

He found, to illustrate the above, that a 3 component commercial polymer material applied to a final thickness of 2mm was very effective in reducing abrasion wear. After 700 revolutions of a three steel-wheel apparatus at 3kN/wheel (rolling steel wheels, see appendix 4.01), wear was measured at 0,05mm. Wear increased to 0,4mm when the thickness of the coating was reduced to 1mm. Without any coating the wear on the equivalent test surface was 2,5mm.

Siro explains that part of the reason why polymer coated surfaces perform so well is that the friction between a steel wheel and a polymer coating is much reduced relative to a concrete finish without the polymer. The abrasive forces that would normally apply from acceleration, deceleration and especially slewing and scraping are thus much lower.

Discussion and Conclusion

Sacrificial coatings are a useful way of upgrading concrete surfaces. They may be formulated to have excellent abrasion resistance. In the past polyester resins, epoxy resins and methyl methacrylates were widely used. The more recent emphasis on lower modulus, higher elongation, and 'flexibilized' epoxy resins are reported as being 'very useful and forgiving in both application and performance in harsh conditions by White(1997), but Omata(1997) found that flexible epoxy mortars used as overlays had failed to yield satisfactory results, and reverted back to the older methyl methacrylate technology, achieving very good results.

Perhaps the reason for their different views is that there are so many demands made on these coatings that compromises are inevitable in certain areas, which may not always be acceptable. For example it is expected of these coatings that the resin binder and graded aggregate must be formulated to meet the abrasive loads of high traffic volumes, remain flexible in cold temperatures, not soften excessively at elevated temperatures, be impermeable to de-icing salts, absorb a minimum of water, retain bond even where the concrete surface becomes saturated, retain tensile strength after exposure to aggressive chemicals, be U V resistant.

These coatings may either be in the form a single layer, a multi-coating, or a resin based mortar. Generally they are made from polyurethanes, epoxies, epoxy urethanes, polyureas, furims or acrylics.

Polyurethane coats are known to be resilient, and this makes them far superior in certain applications. Vinyl and heavy rubber, are also fairly resilient and effective. On the other hand paints and coatings used to protect the concrete from chemicals possesses only have limited abrasion resistance.

The old adage 'prevention is better than cure' applies to concrete surfaces as well. This can be achieved by ensuring that the concrete has a low w/b, a low air voids content, is made with hard aggregates, receives good curing, etc. However, if these 'preventative' steps were not taken, then the application of a suitable sacrificial coating may be a practical 'cure'.

2.6.7 Polymer Impregnated Concrete and Coatings

The mechanisms whereby polymers improve abrasion resistance in polymer modified concrete were discussed in 2.2.1.2.6. Polymer impregnated concrete (PIC) will also assume some of these benefits. For example polymer impregnation will reduce capillary pores by means of a secondary polymer-matrix within the primary cementitious system, and in so doing densify and improve the paste microstructure. However, other benefits of polymer modified concrete will not be imparted to polymer impregnated concrete, since the mortar is generally hard by the time the impregnation process is done. These include such aspects as improved compaction, a more even dispersion of the cement particles, and a great reduction in the size of the crystals formed throughout the polymer cement matrix, such as calcium hydroxide crystals, allowing a more dense microstucture than that of the conventional concrete.

It seems logical that polymer modified concrete will benefit a relatively porous medium quality concrete more than a high strength concrete with a very refined pore structure. (Poor quality very porous concretes are probably beyond redemption). Its main use, it seems, is therefore corrective, i.e. improving the abrasion resistance and toughness of marginal surfaces.

Lane(1978) reported that polymer impregnated concrete had improved abrasion resistance.

Fukuda(1984) did abrasion tests using a chain fitted wheel (same as seen in appendix U3.05 except that chains are fitted to the tyres). He found that abrasion wear in polymer impregnated paving was 1/5th that of asphalt, and ½ that of conventional cbp concrete. Similar ratios were obtained in field trials. The PIC blocks had only abraded 0,6mm after one winter.

A word of caution is that even the best impregnating agents will not penetrate adequately or adhere to the surface if the surface has not been properly prepared. Clean and open capillary pore passages enable the polymers to infiltrate to some depth beneath the surface.

Horiguchi(1994) did abrasion testing using several different methods, including rolling dressing wheels, rolling steel balls, and bouncing steel balls in water. He found that in all cases PIC had improved abrasion resistance, but that the degree of improvement largely depended on the type of abrasion test; respectively the PIC samples had improved abrasion relative to the untreated concrete by a factor of 31%, 119%, and 740%.

The magnitude of this range in improvement indicates that PIC will be very affective in certain applications, and only make marginal improvements in others. Therefore it is important to correctly assess the expected or prevailing abrasive conditions and choose an abrasive test that will correctly simulate such conditions.

2.6.8 Surface Grinding

The concept of surface grinding, evolved in Scandinavia, is used as an alternative to power finishing. This means that the construction crew do not need to spend many hours after casting with power floating and power finishing. Instead the surface is merely covered with polythene sheeting, or suitable cured in some or other way for several days. Surface grinding of the top few millimetres commences when the concrete has matured sufficiently to withstand the plucking out forces of the grinder's carborundum pads. Thus the relatively soft surface layer is removed, exposing the new ground surface consisting of hard aggregate interspersed in a paste which itself has much improved abrasion resistance.

Chaplin(1990) reports that, compared to power finishing, surface grinding yields an equivalent hardness in low or high grade concretes, but is not as good in medium grades.

Siro(1991) found that grinding improved the abrasion resistance of a floor beyond what could be expected merely from removing the inferior surface layer. He states that it is the smoothness of the newly ground surface which causes significantly reduced friction relative to an otherwise worn or unground surface. This is borne out by the fact that the newly ground surface is slow to wear at *first*. [Siro used an abrasion test consisting of rolling steel wheels revolving in planetary motion, each with a load of 3 kN (see appendix U.4.01). As the wheels penetrated the softer mortar component would have been abraded preferentially, resulting in an undulating surface with increased impact effects. This explains the increased rate of wear at increased depth].

Surface grinding may also be seen as an ideal first step in the preparation of a surface for a liquid applied surface treatment or a sacrificial coating.

2.6.9 Relative Effectiveness of Various Surface Treatments

From the literature reviewed here it is possible to make some limited and generalised judgements of the relative effectiveness of certain surface treatments, within a particular group. For example, it is possible to rank the various different types of dry shake, but it is not possible to say if they are superior to sacrificial coatings, or grinding, or polymer impregnation.

A tentative ranking is set out below using the findings of the foregoing investigators:

2.6.9.1 Ranking of Surface Treatments

(a) Dry shakes: Metalic shakes may be considered superior to non-metalic, although the difference is sometimes minimal, depending on the formulations and finishing processes. Of the non-metalic shakes, synthetic shakes are superior to natural aggregates, and in this grouping quartz is harder than natural sand/silica. Cement shakes come last.

(b) Fresh on fresh toppings: The same comments made for dry shakes apply here, in that the ranking will depend on the hardness of the materials selected. However it may be said that fresh on fresh toppings can withstand greater impact and abrasion loads relative to dry shakes, given their extra thickness.

(c) Conventional overlays: Ranking will go according to material selection, as well as construction process.

(d) Tiling: Very variable depending on the tile used. However a hard-wearing tile is probably comparable to a metallic dry shake, while concrete tiles may perform no better than a ‘cement shake’ floor, or worse.

(e) Liquid applied surface treatments: Clearly in-surface sealers (e.g. polyurethane, acrylic or epoxy resins) are superior to reactive hardeners. Amongst the hardeners, zinc or magnesium silico-fluorides appear to perform better than sodium silicates.

(f) Sacrificial coatings: Coatings incorporating hard wearing aggregates will have superior abrasion resistance, particularly when combined with some hardwearing epoxy resins. On the other hand a polyurethane coating can be made so resilient that it clearly outperforms all other coatings in certain applications.

(g) Polymer impregnated concrete: This is generally done to correct a problematic surface. Not much information was found in the literature.

(h) Grinding: The abrasion resistance achieved will depend on the hardness of the aggregate and cement paste at the corresponding depth. Grinding is capable of rendering hardnesses similar to repeated power trowelling.

Chisholm(1994) used the *rolling steel wheels* of a test developed at the C&CA (see appendix U.4.06) to do abrasion tests on surfaces incorporating various dry shakes, some liquid surface treatments, and some additives. The results are comparable as the same finishing technique and curing was applied. Relative to the untreated control slab, the performances of the various treatments are ranked in table 2.6.

It would be most useful to have a performance index of *all* the various surface treatments mentioned in this section, together with an indication of their relative costs. This would be a substantial undertaking, given that a range of abrasion tests should be used, and that there are many processes and materials available. Nevertheless Chisholm’s data, although limited, does give some indication of the relative performances across group boundaries.

Comment: Broadly speaking it may be said that in-surface sealers perform better than dry shakes. It appears from the above that epoxy and polyurethane in-surface sealers perform best, even better than metallic dry shakes. However, while this may be the case for the relatively mild action of the steel wheel abrasion test used by Chisholm, an entirely different result may emerge for a more severe loading, which may include a degree of impact. Metallic dry shakes and toppings are known to perform very well in these situations.

Table 2.6 % Abrasion of Various Surface Treatments relative to Untreated Concrete

Epoxy	1.5 %	In-surface sealer
Polyurethane	1.5 %	In-surface sealer
Metalic aggregate dryshake	14.3 %	Dryshake
Metallic aggregate topping	21.4 %	Topping
Natural aggregate dryshake	42.8 %	Dryshake
Ethyl acrylate	50 %	In-surface sealer
Sodium silicate	50 %	Reactive hardener
Silica fume concrete	57.1 %	Cement extender
Polymer modified concrete	71.4 %	Additive
Steel fibre	71.4 %	Additive

Polyurethane sealers, while seen to perform very well here, are generally not UV stable.

As expected the natural aggregate dry shakes do not perform as well as the metallic shakes.

Reactive hardeners perform well for a short period, but soon fatigue and break down under the action of the rolling steel wheels.

Additives such as silica fume and polymers show relatively minor improvements in abrasion resistance.

2.7 Fibres

Severe forms of abrasion result in cracking. It therefore seems logical that the inclusion of tensile reinforcement in the form of steel and other fibres in the mix may prevent or reduce such cracking. The investigations of various authors who studied the effect of fibre addition on abrasion resistance are now considered under two headings that represent different points of view:

2.7.1 Fibres Reduce Cracking

According to Newman(1997a) the mode of compressive strength failure is by crack initiation followed by progressive crack propagation as strains increase. Generally this process of crushing is accompanied by lateral dilation.

Fibres (of significant tensile strength) spanning the potential zones of crack initiation and development will slow down the rate of crack-widening, and consequent crack-lengthening. In particular the post-cracking behaviour of fibre reinforced concrete (depending on the ductility of the fibre) is vastly superior to that of normal concrete, which rapidly loses the ability to support load after the peak crushing stress has been reached.

Severe forms of abrasion involving impact and high local compressive stresses will experience various degrees of cracking. These may include Hertzian cone cracks, lateral cracks, and axial cracks; these various crack types are discussed in chapter 3, but clearly the tensile strength of the concrete which may be enhanced with fibres plays an important role in severe abrasion.

The effectiveness of various fibres in a number of applications is now considered.

(a) Steel fibres

Fwa(1990) did abrasion tests by loading 100mm cubes into a LA abrasion machine (=*impacting steel drum*, see appendix U.1.01), resulting in deep wear from impact, sliding, rubbing. Keeping w/c and a/c constant, he found that after 2000 revolutions the cubes made with 0,5 % steel fibre had a 2% less wear, whereas those made with 1 % fibre had 9% less wear. [The LA abrasion test imparts a high degree of impact upon the tumbling cubes resulting in considerable cracking and loss of material. Steel fibres serve to limit the growth of these cracks, and also keep the cracked material connected to the uncracked material for some time. Steel fibres are known to improve the post-failure characteristics of concrete, in effect transforming a brittle material into one that has a degree of ductility].

Malhotra(2000) used the *rolling steel balls* of the ASTM C779 Proc C test (see appendix U.2.12) to determine the seven year abrasion resistance of concrete slabs in arctic tidal zones. He found that concretes made with steel fibres; (50mmx0,5mm low carbon cold drawn steel fibres with hooked ends) had **superior abrasion resistance** relative to companion test specimens without fibre. The same trend was generally observable with compressive strength.

Nanni(1989)'s conclusions were mixed. On the one hand he observed that roller compacted pavement surfaces subject to vehicular traffic appeared to manifest *less scaling* when steel fibres were present. On the other hand *abrasion testing* (=*rolling steel balls* to ASTM C779 Proc C) *did not discriminate between plain and fibre concrete.* Fibres used in his programme included 30mmx0,5mm hooked end drawn wire; 25mmx0,2mm straight slit sheet; 25mm x 0,42mm crimped slit sheet; and 19mm long fibrillated polypropylene bundles.

[A possible explanation for the negligible contribution of the fibres in Nanni's abrasion is:

Brittle surfaces subject to loads beneath spherical steel balls undergo 'Hertzian core cracks'. (see figure 3.8 in chapter 3). This type of cracking is likely in the early stages of the ASTM C779 Proc C test. However, the tensile strains leading to these cracks are relatively low, so that the corresponding tensile force developed in the fibres is relatively insignificant, and therefore does not make a material difference].

It is interesting to note that Malhotra and Nanni both used the same abrasion test, but came to different conclusions. Possible reasons for this are differences in:

- the bond strength of the paste
- length of the fibres
- diameter of fibre
- special anchorage effects
- material of fibre
- proportion of fibre used

(b) Carbon fibres

Carbon fibres have also been shown to improve abrasion resistance. They have exceptionally high tensile strength, which allows them to be made to a very small diameter, and this allows a very high aspect ratio that in turn translates into a good non pull-out characteristic. Therefore those fibres spanning the zone of potential or actual cracking will inhibit crack development and consequent loss of material, and this is borne out by Shi.

Shi(1997) found that the addition of carbon fibres to a latex mortar reduced the abrasion wear from 0,161mm to 0,096mm (ASTM C944, *rolling dressing wheels*, see appendix U.3.09].

Above, limited evidence was presented to show that fibres improve abrasion resistance. Some equally limited evidence is now considered that comes to the opposite conclusion.

2.7.2 Fibres are Ineffective or Increase Cracking

Where fibres have a low *aspect ratio*, and therefore have a tendency to slip or pull-out, their inclusion into concrete, far from inhibiting crack development, may actually provide sites for additional crack initiation once the concrete-to-fibre bond has been broken. Some investigators have concluded that steel fibres either make no improvement, or accelerate deterioration from abrasive effects.

Doulgeris(1996) found that steel fibres generally made no difference to abrasion resistance, unless they had a low aspect ratio, in which case they reduced abrasion resistance.

Liu(1991) stated that steel fibres in mixes tended to reduce abrasion resistance.

In 1992 the writer conducted a number of impact experiments on cubes of lightweight concrete that were reinforced with steel and polypropylene fibres. Invariably there was similar or more mass loss for the fibre reinforced cubes compared to the equivalent unreinforced cubes. There was a marked loss of material as the % of fibre was increased beyond a certain threshold.

Another handicap that fibres will have in inhibiting cracking is that only those fibres that are normal to the plane of the crack work efficiently in preventing crack growth. Fibres that are in the same plane as the crack (representing the other two directions), contribute nothing towards inhibiting crack propagation, and may well provide sites for crack initiation. It may therefore be stated that approximately only one third of fibres will contribute to crack prevention, and then only if there is sufficient bond length on either side of the crack to prevent slip/pull-out.

2.7.3 Hard Aggregate Effect

Some abrasion tests subject the specimen to minimal impact/crushing/cracking effects, such as the Bohme test, which is essentially a horizontal grinding table with a very fine abrasive. In this test the hardness of the material will determine the rate of abrasion wear. Therefore if the steel fibre is harder than the aggregate, some improvement in abrasion resistance can be expected.

Sustesic(1996) did abrasion testing using the Bohme method (=*sliding fine-abrasive*, described in appendix U.5.02) on concretes with steel fibres and carbure slag aggregate as well as natural aggregate. Whereas the inclusion of up to 1,5% of steel fibre made no difference in the case of the slag aggregate mixes, it resulted in substantial improvements for the natural aggregate mixes. No explanation for this is offered by the author. [It is possible that the relatively high resistance to wear of the steel relative to natural aggregate resulted in the improvement. Similarly it may be argued that the hardness of the slag was comparable with that of the steel, and hence no improvement was detected in this case].

2.7.4 Conclusion

The inclusion of fibres into concrete will be beneficial relative to severe abrasion if they inhibit crack initiation and propagation, and in so doing enhance the post-failure characteristics of the material. On the other hand if they tend to slip or pull out this may accelerate crack development, which may be detrimental to abrasion resistance. In the case of mild abrasion, such that the concrete does not crack, the inclusion of fibre will make no improvement. However, their inclusion may increase the average hardness of the concrete, and in certain instances (e.g. where abrasion effects amounts to a gentle grinding) this will enhance abrasion resistance.

Clearly the contribution of fibres in any particular application will depend on the their physical dimensions (aspect ratio, hooked ends etc.), the type of material (steel or carbon etc.), and the type of abrasion loading (impact or grinding etc.).