APPLYING CONCRETE TECHNOLOGY TO ABRASION RESISTANCE

Papenfus, N.

Dams for Africa Pty (Ltd), Private Bag X 09, Suite 499, Weltevreden Park, 1715
Tel: (011) 475 2764. Fax: (011) 475 9381 Cell: (082) 4168958.
E-mail: damsforafrica@worldonline.co.za

ABSTRACT

The many factors that contribute towards abrasion resistance in concrete (with special reference to concrete pavers) are considered. These include the various raw materials, their specific characteristics, and some manufacturing processes that contribute to abrasion resistance. They are also arranged in a flowchart to show how each relates to the other and ultimately to abrasion resistance. All along, attention is given to explaining fundamental principles of concrete technology, albeit briefly, given the constraints of limiting the presentation to 10 pages.

Finally, recommendations are made that will assist the industry in producing pavers with enhanced abrasion resistance.

1. APPLYING CONCRETE TECHNOLOGY TO ABRASION RESISTANCE

1.1 Overview

There are many factors that influence abrasion resistance. The diagram in figure 1 shows how the specific characteristics of the various raw materials and the different manufacturing processes all contribute. It is evident that the two major attributes of abrasion resistance are (a) hardness and (b) aggregate/paste bond. These attributes complement each other - the hard aggregate protects the softer paste, providing that for a given aggregate the strength of the paste is such that there is an adequate aggregate/paste bond, strong enough to hold the aggregate securely in the face of the attacking abrasion load.

The bulk of the principles discussed here apply both to conventional concrete and semi-dry concrete – where there is a discrepancy special mention will be made. Much of the material has been extracted from chapter 2, volume 2 of Papenfus(2002). The reader is referred to this document (also available in CD) for a fuller discussion.

To facilitate the ensuing discussion, numerical values have been assigned to the various factors affecting abrasion resistance, in consecutive order as they first appear in the text, and these numbers are replicated in figure 1 in order to assist the reader to appreciate each factor in its proper context.

Proceedings of the 7th International Conference on Concrete Block Paving (PAVE AFRICA 2003) 12th – 15th October 2003
ISBN Number: 0-958-46091-4 Sun City, South Africa
Proceedings produced by: Document Transformation Technologies Conference Organised by: Conference Planners

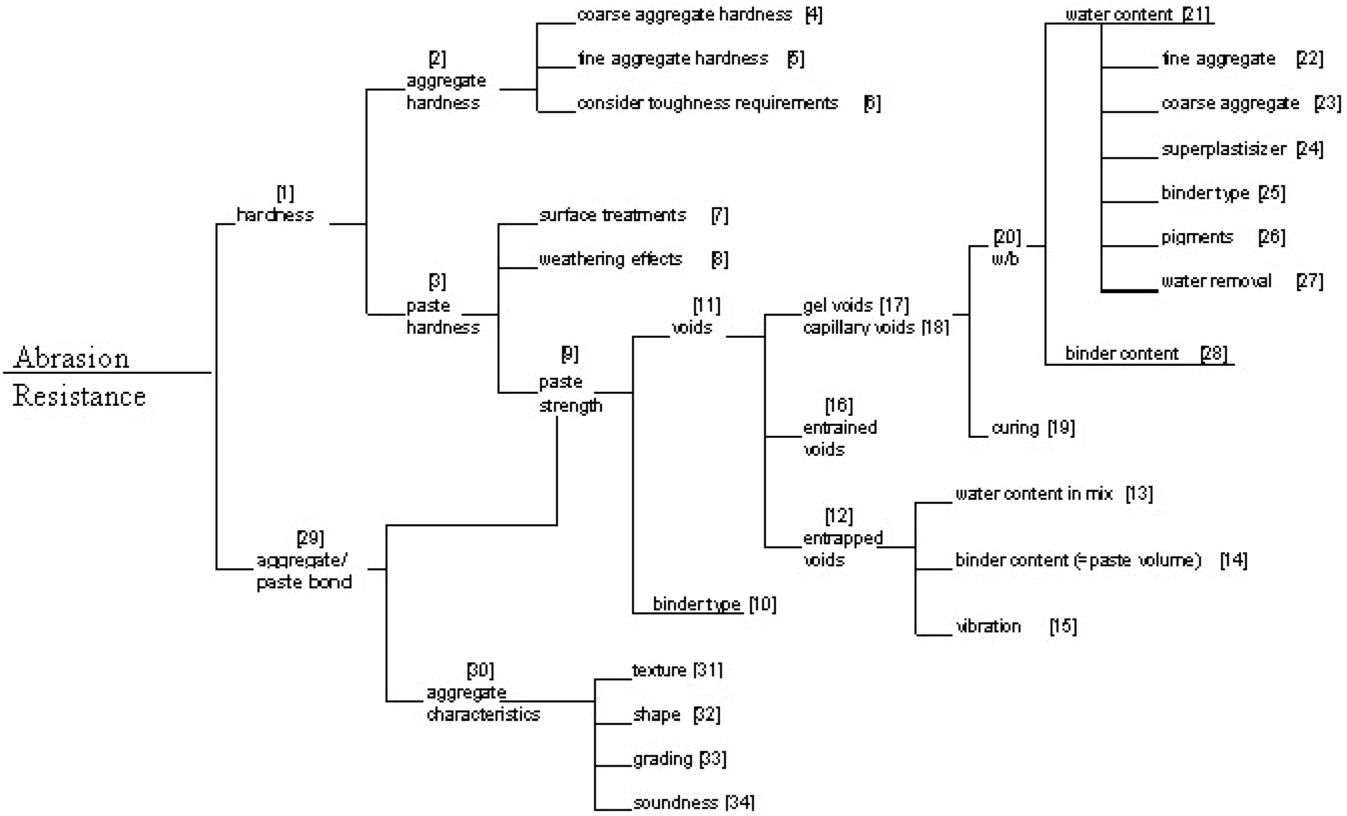

Figure 1. The concrete technology of abrasion resistance in schematic form; it shows how the various factors affecting abrasion resistance relate to hardness and aggregate/paste bond

2. DISCUSSION

Figure 1 shows that **hardness** [1] is a function of the hardness of the two major constituents of the mix, the **aggregate hardness** [2] and the **paste hardness** [3].

The aggregate plays a far more important role than the paste, firstly because aggregate generally makes up for upwards of 80% of the bulk and mass of concrete, and secondly, most commercial aggregates are much harder and more abrasion resistant than hardened binder paste (hbp).

Logically, 'aggregate hardness' is a composite of **coarse aggregate hardness** [4] and **fine aggregate hardness** [5]. Hardness may be understood as the ability of the concrete to resist indentations from applied normal loads, or scratches in the case where there is also a tangential component that makes the abrasive slide over the concrete. [See Papenfus(2002) for a fuller discussion on hardness]. Although hard aggregates have excellent abrasion resistance, they are generally very brittle. There are instances where the **toughness** [6] of the aggregate is more important than its hardness. Tough aggregates are less brittle, and hence more resilient against impact type loads.

The hardness of the paste [3] may be increased by applying various surface **treatments** [7], usually after the concrete has hardened. Some treatments have the ability to substantially increase abrasion resistance, and various epoxies, polyurethanes, acrylics and rubber based solvents are available on the market.

Weathering effects [8] can either harden the surface, making it more abrasion resistant as with carbonation, or attack the constituents of the binder, making the surface less abrasion resistant, as in the case of acid rain, or soft water attack.

Finally the hardness of the paste is affected by the **paste strength** [9]. Addis(1989) showed that the greater the crushing strength of the hardened cement paste, the greater its abrasion resistance, but that at all levels of strength, the paste was very substantially softer than an equivalent mortar made with commercial aggregates such as dolerite, andesite, granite, quartzite etc.

Logically it follows that paste strength is governed by its microstructure.

Firstly the morphology of the paste's microstructure is affected by the **binder type** [10] i.e. its physical properties and chemical composition. Increasingly cement is being 'extended' by partial substitution with materials which also have hydraulic properties e.g. ground granulated blast furnace slag, and/or alternatively by materials which have pozzolanic properties such as fly ash and silica fume. These materials all have mechanisms that improve/refine the microstructure of the paste, and studies [see Papenfus(2002)] have shown increases in strength and abrasion resistance when favourable substitution proportions are made (e.g. 30% for GGBS, 20% for fly ash, 2% for silica fume).

Secondly the morphology of the microstructure is affected by **voids** [11]. Many studies [see Papenfus(2002)] have shown that, regardless of the source of the voids, they have a detrimental effect on the strength of the concrete. Generally for every one percent of voids there is a five percent loss in strength/abrasion resistance.

Four types of voids may be identified in concrete:

(a) **Entrapped voids** [12] These are cavities in the concrete that came about as a result of trapped *air* that was introduced during the mixing and placing operation. On a microscopic scale air may be trapped between binder particles, while on a macroscopic scale the voids can be as much as 10mm in diameter. For a given workability, the presence of these voids will decrease with increasing compactive effort. Entrapped voids result in pavers having inferior abrasion resistance and compressive strength, and their existence in concrete may generally be traced to three factors.

- The first and most common reason for entrapped voids is inadequate **water content** [13] in the mix, since the water acts as a lubricant, facilitating compaction. This aspect will be discussed more fully in [21].
- Secondly, **binder content** [14] also has a bearing on the ease of the compaction process (=elimination of entrapped voids). Sukandar(1993) stated that high cement content 'enhances the workability and compactability of the matrix'. An increase in cement content increases the thickness of the coating of paste around the aggregate particles. This thicker layer has greater mobility and lubricating ability in the presence of vibration. Accordingly it is possible to reduce the w/b ratio of the thicker pastes and still achieve adequate compactability. It may therefore be postulated that the volume of paste contributes more to the rheology of semi-dry concretes than the w/c of the paste. Or put another way, more of a viscous paste is better able to reduce voids than less of a more fluid paste (within limits). The greater quantity of the viscous paste is able to 'bed-in' the aggregate particles more easily with fewer voids. Although it is less fluid, the relative movements of adjacent cement particles can be less, as there are more of them at any given section, and cumulatively their capacity for shear related displacements is better.
- Thirdly, for any given water content and cement content, the proportion of entrapped voids depends on the magnitude and duration of the **vibration** [15]. Clearly mixes that are relatively dry and/or have lower cement contents require increased vibration.

(b) **Entrained voids** [16]. Sometimes air is deliberately entrained into paste for such purposes as frost resistance, improved workability, decreased density etc. In this case the air bubbles are not so small that they occupy the spaces between the cement particles, such as in (c) and (d) below. Rather entrained voids are surrounded by the paste. In fact their stable existence in the matrix is dependant on having a shell of hardened paste, making them an order of magnitude greater than capillary voids (see (d)).

(c) **gel voids** [17] The gel structure is made up of sub-microscopic particles called hydrates (the products of the process of hydration), separated by sub-microscopic interstices i.e. gel voids (also called gel pores). In appearance hydrates are fibrous particles with straight edges and bundles of these fibres form a cross-linked network, and the open water filled spaces around these structures are the gel voids . (The hydrates and the gel voids/pores together make up the 'gel'.)

(d) **Capillary voids**[18] exist in the hardened paste as microscopic interconnected channels called capillary pores, or if the paste structure is dense enough, as capillary cavities interconnected only by sub microscopic gel-pores. These two structures may be grouped together under the heading 'capillary voids'. They represent space not filled by gel or solid components of the system. They are residues of the original water filled spaces from the fresh paste, and may be filled with water or air, depending on such factors as the curing regime, the presence or absence of external water etc.

The morphology of the gel voids and capillary voids defines the microstructure of hardened paste (hp). The larger and more numerous they are, the weaker is the hp. Two factors play an important role in the formation of hp:

The first is **curing** [19]. It is well established that proper curing has a significant effect on the strength of concrete and even more so on abrasion resistance, as hydration can only proceed in the presence of water, or water vapour with a relative humidity exceeding 90%. Therefore premature surface drying suspends the hydration of the binder in the affected zone, which arrests further gain in abrasion resistance.

The factors that are known to impact negatively on the rate at which newly cast concrete loses its free water through evaporation, are low relative humidity, high wind speed, high ambient temperature and hot fresh concrete (resulting from sun warmed aggregates, warm water etc).

Curing at increased temperatures accelerates the rate of hydration, but results in a coarser gel/pore structure, with a corresponding reduction in potential strength.

Importance of curing: Curing affects abrasion resistance far more than it affects compressive strength. An uncured surface will dry out quickly, bringing hydration to a halt, while drying out of the bulk concrete takes much longer.

Sukandar(1993) did abrasion tests according to ASTM C779 Proc C [=*rolling steel balls*] on concrete pavers with a/c ratios varying from 3 (25% cement) to 9 (10% cement). Abrasion testing on pavers revealed that at age 24 hours sealed pavers had 75,5% more abrasion resistance than air-cured specimens.

The second factor that largely determines the nature of the paste's microstructure (especially the volume of gel voids and capillary voids) is the relative distance between the individual cement grains dispersed in the paste and separated by water. This may be gauged by the ratio of the mass of the water to the mass of the cement making up the paste, i.e. **w/b** [20]. This ratio is commonly used throughout the industry as an indicator of paste quality, concrete strength, abrasion resistance, etc., with low w/b ratios superior to high ratios.

For low w/b ratios the resultant cementitious gel structure will be dense and the pore structures more refined. For *very* low w/b ratios [(Sukander(1993) went as low as 0,21 for his experimental pavers] it is possible to have the cement particles so closely packed that there is insufficient water in the spaces between the cement grains to fully convert each individual grain of cement into gel. Therefore the inner cores of the cement particles remain unhydrated, but this is not detrimental to strength, as the unconverted inner cores may be likened to aggregate (expensive aggregate!) that is very well bonded to the surrounding paste. The important thing is that the cement grains are close to each other to begin with which greatly increases the density of the microstructure, and consequently abrasion resistance.

Clearly the w/b ratio is simply a function of two factors: the quantity of water, and the quantity of binder:

It follows that the first way to reduce w/b is to reduce the **water content** [21]. [However water should not be reduced below its optimum level, i.e. to a point where the mix is insufficiently lubricated to expel entrapped voids. A feature of semi-dry mixes is that they have no slump (essential for immediate demoulding/extrusion) and therefore have high internal friction. This makes compaction difficult, requiring specialized equipment. The author agrees with Lane(1986) that the optimum water content is the maximum water content that can be used that will not adversely affect the manufacturing process (i.e. water should be maximised but not to the extent that the blocks slump). Papenfus(2002) showed that in semi-dry concrete the increase in abrasion resistance (from reducing voids by having improved lubrication from increased water content) far outweigh the reduction in abrasion resistance from the corresponding higher w/b].

Certain processes of the manufacturing operation and characteristics in concrete materials have a bearing on the amount of water that is required in the mix.

(a) **Fine aggregate** [22] has an important bearing on the water requirement of the mix – such aspects as grading, particle shape, surface texture, and proportioning all have an influence. Well <u>graded</u> fine aggregates that result in workable mixes at low water requirements will result in lower w/b ratios. Round or cubical *shaped* particles with smooth *surface textures* further promote workability and w/b reduction. Finally the mix should ideally be *proportioned* to maximise the coarse aggregate component relative to the fine aggregate, as this also lowers w/b.

(b) **Coarse aggregate** [23] also affects the water requirement of the mix, but to a much lesser degree, owing to a very much reduced surface area per unit mass. As was the case with fine aggregate, round or cubical *shaped* particles with smooth *surface textures* promote workability and w/b reduction. Generally the topmost surface of concrete pavers is made with minimal coarse aggregate, and is limited to 6,7mm in size. This is because aesthetic considerations often dictate that the upper surface of the pavers should be relatively smooth. On the other hand the base layer, where aesthetics is unimportant, can have a much higher proportion of coarse aggregate.

(c) **Superplasticizers** [24] are powerful water reducing admixtures and are widely used. They have the effect of substantially increasing the fluidity of the paste, with a corresponding increase in the lubrication of the mix. Generally this allows either (1) a reduction in the binder content (without sacrificing strength), or (2) an increase in strength (without increasing binder content), or (3) increased workability (without increasing water content). Respectively the superplasticizer achieves this by (1) reducing both the binder and water contents without altering the w/b ratio, (2) decreasing the w/b ratio by reducing the water content while leaving the binder content unaltered, and (3) by leaving both the binder and water contents unaltered. It should be said that pavers are made from semi-dry mixes, and there is therefore not as much scope for water reduction as is the case with conventional concrete.

(d) **Binder type** [25] also influences water requirement. The binder in the mix constitutes the finest material, and therefore has the greatest surface area per unit mass, and thus the greatest water requirement per unit mass. It follows that more water is required where cement is very finely ground, but even though this represents a potential increase in the w/b ratio, strength and abrasion resistance are significantly increased for fine cements, as the greater surface area allows for increased hydration.

The high water requirement of the binder is also moderated by the much lower water requirement of the aggregate, as typically most paving mixes have aggregate: binder ratios ranging between 5 and 7.

Three commonly used cement extenders are ground granulated blastfurnace slag (GGBS), fly ash, and silica fume:

The physical characteristics (size and shape) of GGBS are similar to those in Portland cement, and it follows that the water requirement will be similar.

Fly ash particles are generally spherical in shape. This improves the lubricating properties of the paste towards ease of placement and consolidation during vibration. If this increased workability is not required, a reduction in the water and total binder content can be made whilst maintaining the same w/b. It is largely by virtue of this reduction in water that equivalent 28-day strengths are achievable for fly ash mixes with up to 30% replacement, relative to mixes consisting entirely of Portland cement.

Silica fume particles are extremely fine, resulting in the material having a specific surface area of 20000m^2/kg. At replacement levels of approximately 2%, the material acts as a very effective void filler, increasing density and strength. The silica fume particles are so fine (of the order of one hundredth of a cement particle) that they easily occupy the voids between other binder particles, whether particles of cement, fly ash or GGBS, and even penetrate the voids within floccs of these particles.

However, ACI committee 234(1995) report that above 5% by mass of cement the water demand of concrete containing silica fume increases with increasing amounts of silica fume (even when the beneficial pozzolanic effects are taken into account). This increase is due primarily to the high surface area of the silica fume, and is usually offset by use of a superplasticizer. Nevertheless Papenfus(2002) achieved significantly improved 28 day abrasion resistance with both 5% and 10% replacement levels. This work was done on concrete pavers, and it therefore seems that the 5% rule does not apply to semi-dry concrete.

(e) For aesthetic reasons, concrete pavers are frequently coloured. It appears that providing dosage levels are not excessive, the void filler effect of incorporating **pigments** [26] such as iron oxides and carbon black more than compensates for the corresponding increase in surface area. Oxides may be considered as inert very fine fine-aggregate. Puttbach(1987) explains that their diameters lie in the order of the wavelength of light, i.e. well below 1 micron. The different colours are obtained by variations in shape and diameter. It is the binder paste that is coloured by the finely particulate colour pigments. The aggregate itself cannot be coloured, its particles being merely surrounded by the coloured cement paste.

Buchner(1987) showed that additions up to 10% of the weight of the cement had practically no adverse effect on strength. In fact, in his tests there was a well defined increase in compressive strength for red, black and brown pigments, peaking at 6% by mass of cement.

Generally the point of colour 'saturation' (the point at which colour intensity approaches a maximum) is reached at between three to five percent by mass of binder, and therefore iron oxide pigments, when proportioned in this way will if anything increase the compressive strength and abrasion resistance.

(f) Above a number of methods have been considered that have the effect of reducing the amount of water that is added to the mix, thus reducing w/b and increasing abrasion resistance. Another approach is **'water-removal'** [27], i.e. removing the water after the concrete has been placed.

Different techniques are possible:

- In 'vacuum dewatering' a vacuum blanket is placed over the surface of the concrete. The material in contact with the surface is a fine filter sheet that allows water to pass through it but prevents cement, additions, or fine aggregate to enter under the action of a vacuum pump. This process both reduces the water/binder ratio and by virtue of the pressure on the surface of the concrete closes the bleed channels and capillaries, resulting in a dense surface.
- With 're-vibration' the cast concrete is re-vibrated after some hours. This results in a disruption of early gel structure, releasing water trapped in gel cavities, as well as facilitating a measure of settlement of the solid components of the mix. Revibration is not specifically a surface densifying process, rather it improves the density of the core concrete.
- However, the simplest way of extracting water from the surface is delayed and repeated power trowelling. The action of power trowelling (due to the application of high uniform pressure) tends to bring the binder enriched surface matrix (a positive consequence of segregation and bleeding) into more intimate contact, thus closing up surface pores and microcracks. Although this technique only densifies the top few millimetres of the slab, the resultant surface is so hard that it easily withstands the intended traffic.

  While vacuum dewatering and re-vibration have no application to concrete paving, a form of power trowelling does occur, chiefly on that part of the paver that was in contact with the vertical walls of the mould, as there is a degree of densification at the contact zone as the mould moves up and down during the vibration process, rubbing against the concrete in the process. In this way concrete pavers formed with their wearing surfaces in a vertical orientation have increased surface density and abrasion resistance. [see Papenfus(2002) for a fuller discussion].

The second way to reduce w/b is to increase the **binder content** [28]. Clearly if the binder content increases relative to the water, the distance between the individual cement grains will decrease, resulting in a reduction in gel voids and capillary voids, and a corresponding increase in microstructure density, and this in turn translates to increased abrasion resistance.

In the foregoing sections the many factors affecting the hardness of the surface have been considered. Ranking alongside hardness in importance is **aggregate/paste bond** [29], as clearly the hardness of the aggregate is immaterial if it not securely bonded to the paste. The various factors that affect this attribute are shown in figure 1, and are discussed below.

Certain physical **aggregate characteristics** [30] will affect the quality of this bond:

(a) First and foremost is its **surface texture** [31]. Clearly rough aggregate will have many nooks and crannies that increase the contact area between aggregate and paste, reducing bond stresses. This however does not mean to say that aggregate that appears smooth to the eye is inferior, as it is the micro-texture of the aggregate as much as the macro-texture that affects bond.

(b) The **shape** [32] of the aggregate also affects aggregate/paste bond. For example angular aggregate will have superior inter-particle interlocking compared to rounded aggregate.

It is evident that what may be favourable in (a) and (b) described here may have a negative effect on the water requirement – see [22] and [23].

(c) **Grading** [33] also affects aggregate/paste bond. It may be shown mathematically that the tangential interfacial stresses at the interface between paste and aggregate are inversely proportional to the square of the aggregate particle's size. Thus the coarser is the grading the lower the aggregate/paste bond stresses.

(d) Finally the **soundness** [34] of the aggregate has a bearing on its ability to bond with the aggregate. Aggregate that has many micro-fractures, or has a crumbly surface, or that has many impurities, will experience micro-crushing and micro-shearing effects in the face of normal and tangential stresses that will ultimately lead to its demise at the paste/aggregate interface.

It is also evident that even if aggregate has the most favourable attributes in regard to surface texture, shape, grading, and soundness - if there is insufficient **paste strength** [9], this will still lead to the aggregate being plucked out of the paste matrix. A strong paste is thus vitally important for good abrasion resistance.

3. RECOMMENDATIONS FOR IMPROVED ABRASION RESISTANCE

The most important and relevant aspects of the above discussion (relating to figure 1) may now be grouped into a number of recommendations. For those well versed in concrete technology, most of them will merely confirm well established principles, while to less aquainted producers, specifiers and end users, the recommendations will serve as useful guidelines. Note that it is assumed that the concrete is normal concrete in the sense that it consists predominantly of aggregate, and that this aggregate is harder wearing than the paste component.

Concrete surfaces can be made more abrasion resistant by:

1. Increasing **binder content**. This increases the mobility/rheology of the mix for any given moisture content. The result is that there is a reduction in both entrapped and capillary voids. Increased binder content relative to the water content means that the individual cement grains are in closer proximity to each other, resulting in a denser microstructure in the hardened paste. These aspects result in a stronger paste that is at the same time harder, but more importantly has an increased ability to bond to aggregate.

2. Optimizing the **water content**. For any given binder content there is an optimal water content. This amounts to finding the happy middle road between two evils. Using more water in the mix assists in reducing *macroscopic* entrapped voids, but too much water increases

microscopic capillary voids. Conversely using less water has the potential to allow a closer packing of binder particles, but makes it so much more difficult to expel the air voids, as clearly less water means reduced lubrication/mobility.

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

It should be stated that in semi-dry mixes, the danger of too little water is far greater than too much. (This is because the mix already has a low w/b, consistent with zero slump, and thus increasing water improves compactability, reducing entrapped voids. Papenfus(2002) showed that the optimum water content is very close to the point at which the blocks will begin to slump).

3. Using **superplasticizers**. Powerful water reducing agents are available and are very effective in reducing the water in the mix without sacrificing mobility and compactability. Reducing water in this way translates into a reduction of both ‘capillary’ and ‘entrapped’ voids. Again this results in a stronger paste with increased hardness and bonding ability, and so increased abrasion resistance. However, superplasticisers are not as effective in semi-dry concrete as these mixes already have significantly reduced water contents.

4. Using **hard aggregates**. The harder the aggregate, the slower it will abrade, and hence the better it will protect the softer paste component. If both the fine and coarse aggregate are bound in a strong paste, the surface of the concrete should retain a relatively smooth surface, with minimal loss of paste. On the other hand a weak paste has inferior bonding capability, and consequently, the fine aggregate is lost to abrasive forces. In very weak pastes, subjected to significant gouging effects, the paste/mortar constituent may be abraded to a depth where even coarse aggregate can be dislodged.

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

   In concretes that will be subjected to significant impact loads, it may be advisable to substitute a hard aggregate for one that has increased ‘toughness’. Hard aggregates are generally brittle, and tend to shatter more easily under impact than tough aggregates that have more resilience. Hard aggregates such as granite, basalt and quartz did not perform as well as softer limestone aggregates in the high impact environment of a Los Angeles testing machine [see Smith(1958).

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

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

concrete is far more prone to the ills of inadequate curing than is rich concrete.

7. Using **power finishing**. If done correctly this has the effect of collapsing the capillaries and voids near the surface after bleeding stops. Again this void reduction represents an increase in the strength of the paste, and so its hardness and aggregate bonding capabilities, and so its abrasion resistance. In concrete pavers made with their wearing surfaces in an upright position, there is a degree of densification at the contact zone as the mould moves up and down during the vibration process, rubbing against the concrete in the process.

8. While most modern paving machines have powerful vibrators capable of producing high density blocks in a matter of seconds, it is equally true that careful maintenance and skilful fine tuning is required on a weekly or even daily basis to ensure **optimum compaction.**

9. Applying **surface treatments**. There are various surface treatments that may be used to increase abrasion resistance. These include dry shakes, fresh on fresh toppings, concrete overlays, liquid applied surface treatments, coatings, polymer impregnation, and grinding. With some modifications/additions to the production process it is possible to apply most of these techniques to concrete pavers, and very abrasion resistant surfaces are thus achievable for special applications.

4. REFERENCES

ACI (1995); ACI Committee 234 : Abstract of guide for the use of silica fume in concrete ; ACI Materials Journal, Title No. 92-M47, July-August 1995, pp. 437-440.

Addis(1989) ; Addis, B.J. & Doulgeris, N.P. ; The development of a method for determining the abrasion resistance of concrete ; Proceedings : Annual Transportation Convention, Pretoria, South Africa, Aug 1989.

Büchner(1987) ; Bücher, G. Experience in the production of coloured concrete paving blocks ; Bayer Technical Publication no. PK 13850 DE, 1987 ; Bauverlag GmbH, Wiesbaden, 1987.

Hutchings(1992) ; Hutchings, I.M. ; Tribology : Friction and wear of engineering materials ; Edward Arnold, London, 1992.

Lane(1986) ; Lane, J. ; Semi-dry mixes for precasting ; Fultons Concrete Technology, pp 875-876 ; Portland Cement Institute, Midrand, 1986.

Papenfus(2002) ; Papenfus, N.J. ; Abrasion Resistance, abrasion wear, and related strength properties in concrete, with special reference ot concrete pavers ; PhD thesis, Faculty of Engineering, University of the Witwatersrand, Johannesburg, Feb 2002.

Puttbach(1987) ; Puttbach, E. ; The most important pigments – packaging – physiological aspects – disposal, Bayer Technical Publication no. PK 13850 DE, 1987 ; Bauverlag GmbH, Wiesbaden, 1987.

Smith(1958) ; Smith, F.L. ; Effect of aggregate quality on resistance of concrete to abrasion ; Cement and Concrete, ASTM STP 205, pp91-105 ; American Society for Testing and Materials, Philadelphia, 1956.

Sukandar(1993) ; Sukandar, B. M. ; Abrasion Resistance of Concrete Paving Blocks : A Thesis submitted in Partial Fulfillment of the requirements for the Master of Science Degree ; Department of Civil Engineering & Mechanics, Graduate School Southern Illinois University, Jan 1993.

APPLYING CONCRETE TECHNOLOGY TO ABRASION RESISTANCE

Papenfus, N.

Dams for Africa Pty (Ltd), Private Bag X 09, Suite 499, Weltevreden Park, 1715
Tel: (011) 475 2764. Fax: (011) 475 9381 Cell: (082) 4168958.
E-mail: damsforafrica@worldonline.co.za

Biography

Nicholas Papenfus qualified as a civil engineer in 1975 and has spent much of his working life in the concrete manufacturing environment, making prestressed concrete products, conventional precast concrete products and semi-dry concrete products such as building blocks and pavers.

Specifically he has fourteen years experience in the manufacture of concrete pavers, and in 2002 he was awarded a PhD for his studies in abrasion resistance of concrete, with special reference to abrasion in concrete pavers. In 2000 he left the corporate world to pioneer the company 'Dams for Africa', which focusses on providing water related infrastructure for farmers in disadvantaged rural communities.