Elements for effective design of abrasion resistant concretes

by D. van Heerden*, H. Fryda†, and F. Saucier†

Synopsis

In the mining industry abrasion caused by both sliding and impact have over the years resulted in costly damage to installations such as ore passes and silos. Good geotechnical practices combined with the use of a high quality abrasion resistant concrete can prolong the life of such an installation and minimize problems associated with abrasion. In order to maximize the life of an abrasion resistant concrete, the choice and combination of the correct raw materials (cement, aggregate and fibre) and overall mix design needed to make up such a concrete are important. This paper presents technical data and practical experience showing that concrete formulated with calcium aluminate cement resists severe abrasion conditions better than similar OPC-based concretes.

Introduction

Most hard rock mines in South Africa use a system of ore passes as part of their mined rock transport system. Due to adverse geological conditions and at times high stresses, some mines have experienced major problems with these ore pass systems. These problems have resulted in costly disruptions to production and, at times, high rehabilitation costs.

Based on historic data and knowledge of the local conditions, mines that anticipate problems with their ore pass systems will usually adequately support these ore passes using a combination of rock bolts, cable bolts and mesh and then line them with an abrasion resistant concrete. The function of the abrasion resistant concrete is to protect the rock support units as well as the rock surrounding such an ore pass. There are many types of abrasion resistant concretes available on the market today, varying in price and performance. The choice of this concrete should be based on life expectancy as well as on cost effectiveness of the product.

An abrasion resistant concrete alone is not enough to provide long-term stability of an ore pass; this concrete must be combined with adequate rock reinforcement as well as solid geotechnical design principles.

In this paper, the evolution of calcium aluminate cement (CAC) based ore pass linings, test methods, concrete mix designs, and cost effectiveness of the various concretes as well as methods of application, will be covered.

History and evolution of CAC based ore pass linings in South Africa

The first ore passes lined with a Calcium Aluminate Cement (CAC) based concrete were in 1982 at the Free State Geduld (FSG) Mine's no. 5 shaft in Welkom. The mix proportions for this project were the following, this mixture being applied by dry guniting (shotcrete) (Van Der Westhuizen, 1986).

Corundum aggregate	100 kg
Alag® aggregate	100 kg
Cement Fondu Lafarge® (CFL)	50 kg

Figure 1 shows the FSG ore passes after lining. twenty-five million tons of rockpassed through these ore passes with only one minor repair to a Y-leg in one pass (Spies 1984). Various other sections of ore passes were lined up until 1985 using the same mix design as described above. During the period 1985 to 1995, very little CAC based concretes were supplied into the mining industry.

In 1995 Lafarge Aluminates decided to try and re-establish a market in the mining industry for abrasion resistant concretes. At that time, the alluvial corundum, which was used to line the ore passes, as described above was no longer available. Lafarge Aluminates had to develop new abrasion resistant concretes based on different combinations of CFL®, Alag® and natural aggregate.

* *Lafarge Alluminates, South Africa.*

† *LafargeAluminates, France.*

© *The South African Institute of Mining and Metallurgy, 2005. SA ISSN 0038–223X/3.00 + 0.00. This paper was first published at the SAIMM Colloquium,* Design, Development and Operation of Rockpasses, *16–17 November 2004.*

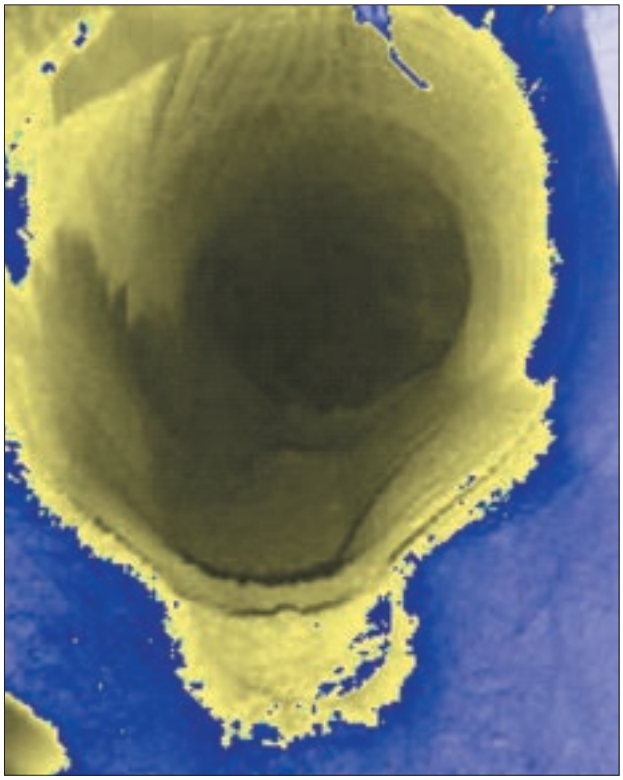


Figure 1—FSG ore pass lined with CAC based concrete in1982

These concretes had to be designed to be placed by either casting or shotcreting (see section below on placing).

A new range of abrasion resistant concretes based on CAC was developed for ore pass lining. These products have been continually improved in response to market needs, test programmes and practical experienced gained.

Definition of abrasion and test methods to evaluate abrasion resistance

Two types of abrasion within an ore pass structure

The wear caused by rock and ore flow within an ore pass is related to several parameters: grading, size of larger blocks, specific gravity of rock, hardness of ore, angle of chute and type of circulation within the ore pass (free flow or 'silo feed'). For instance, magnetite ore has a specific gravity greater than 5, and, being hard, it is a very aggressive material, while lighter or more friable ore will impose less damage for the same volume circulated in a given ore pass.

The term 'abrasion' is often used as a generic term to describe the cause of concrete wear, but it covers various mechanisms of degradation. Globally, 'abrasion' designates the wear mechanism resulting from two solids moving against each other, the harder creating damage on the softer. The way these solids come into contact with each other is of importance. For concrete wear in ore passes, two different type of abrasion should be distinguished: abrasion by friction (or sliding abrasion), and abrasion by impact. It is important to distinguish between these mechanisms because the appropriate design and choice of materials will vary according to the actual conditions at a given location.

Abrasion by friction

Abrasion by friction designates the case where several particles are circulated over a surface with a more or less parallel movement and some normal force. For instance, sand paper relies on the mechanism of abrasion by friction to polish wood.

In the case of an ore pass, the friction between the downward moving particles of rock creates abrasion on the sides of the ore pass, as illustrated in Figure 2. The size of these moving particles varies from rock dust (some µm) up to raw material (20-200 mm) and even large rock boulders (>200 mm). The hardness of moving particles determines how damaging they are for the concrete surface.

Abrasion by impact

The deterioration by impact happens when a moving solid hits a surface locally. In this case, the impact energy is applied to a point rather than to a large friction surface (Figure 3). Description of crack propagation principles is beyond the scope of this paper, but briefly it can be said that crack initiation and propagation depends on intrinsic properties of a given material and on the level of stress at the tip of cracks. Under impact, a lot of energy is imposed suddenly on the material and this favours the creation and propagation of cracks. Under repeated impact, cracks grow and join together, allowing pieces of concrete to dislodge from the main concrete mass.

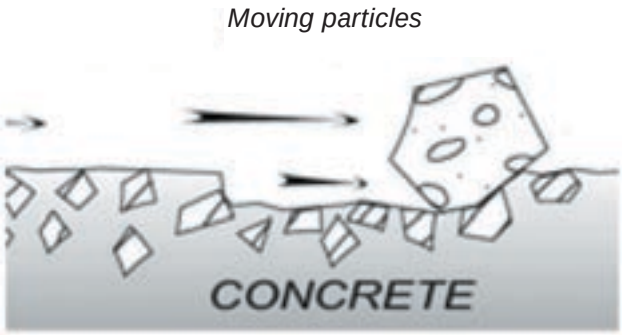


Figure 2—Mechanism of abrasion by friction

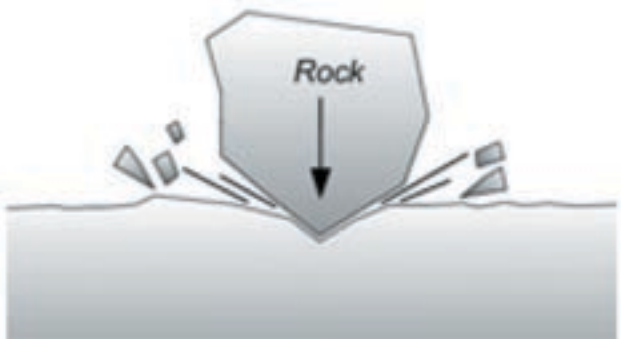


Figure 3—Mechanism of abrasion by impact

In an ore pass, impact is caused not only by rock free falling under gravity but also when the material is moving in a 'silo-type' feed. The larger the blocks, and the more angular they are, the higher the 'punching stress' applied to the surface.

Methods for testing abrasion resistance of concretes

Quantitative evaluation of abrasion resistance of concrete is a difficult task because concrete constructions are subjected to a large variety of conditions that cannot be assessed by a unique laboratory testing procedure. In a recent review of literature, Hu (2002) identified 19 different laboratory procedures utilized to assess the potential 'wear resistance' of concrete. These various tests can be split into the 6 different categories listed in Table I.

In the case of an ore pass, the mechanism of wear is a combination of abrasion caused by both impact and friction. None of the existing testing techniques appeared representative enough of the real conditions in an ore pass, so it was decided to develop a method specific for this case.

Development of the 'LASA modified tumbling test'

An ore pass concrete lining will, during its life, be subjected to extremely aggressive abrasion caused by both impact and friction. No laboratory test method had been developed for the specific case of ore passes. Considering the average size of material circulating within an ore pass, the goal cannot be to reproduce such conditions with a laboratory test method, but rather to evaluate the concrete's capacity to withstand the abrasion mechanisms similar to those found in an ore pass, i.e. abrasion caused by impact and friction.

To try and simulate at laboratory scale the specific conditions encountered in an ore pass, Lafarge Aluminates developed in 2000 a modified testing procedure designated as the 'LASA modified tumbling test'. It is based on the existing SABS 541 South African standard test method utilized for precast concrete pavement slabs. This existing testing method for pavement slabs induces both impact and friction abrasion on concrete specimens tested, but at a moderate level using small sized steel ball-bearings. Because this method is described in a Standard, it was decided to rely on it, but with simple modifications in order to better represent the very aggressive conditions encountered in an ore pass. The main modification has been to replace the charge of small 12 mm ball-bearings by larger and heavier 40 mm steel balls, and to add deflectors to increase the impact component of the test.

Figure 4 shows the 'LASA modified tumbling machine' utilized to test concretes that are used to line ore passes. Because impact abrasion is the cause of most damage to an ore pass lining, deflector plates (Figure 5) were incorporated into the testing unit to increase the impact energy (height of drop of balls). Some friction abrasion is still involved in this system.

The test method is as follows: four concrete panels are cast (Figure 6) and secured to the sides of the testing unit. The testing unit is then loaded with 12.5 kg of 40 mm steel balls (Figure 7). The concrete panels are then tumbled continuously for 24 hours at a rate of 60 rpm. After 24 hours, the volume of eroded concrete is measured by sand filling (Figure 8). Then, the same concrete panels are tumbled for an additional 24 hours and second measurements on the volume of concrete eroded are again taken. Results are reported as a volume of eroded material (in cm^3) after 24 and 48 hours, respectively. Based on 12 series of Fonducrete SL made with 4 identical slabs, the coefficient of variation is estimated to lie between 15% and 20%. Thus, a difference of eroded volume larger than 30%–40% can be considered significant from a statistical point of view. Differences of eroded volume reported below are often larger than 100%.

Mix design parameter related to abrasion resistance of concrete

To maximize the abrasion resistance of concrete, technical literature and field experience underlined the key importance of the following parameters that are, in order of importance:

- the cement type
- the aggregate type
- the fibre type
- the mechanical strength.

The following sections report various data on these parameters.

Contribution of mechanical strength

While there is a relationship between mechanical strength and abrasion resistance, it will be seen in the following sections that it is not the main parameter.

Over a wide range of compressive strengths, there is a general relationship between abrasion resistance and compressive strength: the higher the strength the better the abrasion resistance. This intuitive relation can be explained by the densification of the paste, which leads to a 'harder' matrix, which is more resistant to friction, and also by the higher resistance to crack initiation and propagation, hence giving a better resistance to impact.

However, above a certain level of compressive strength, the correlation is less significant and the compressive strength appears to become a second or third order parameter for abrasion resistance. Most of abrasion resistant concretes

Table I

Different categories of abrasion testing methods

Abrasion by polishing	A tool forces over the concrete surface a grinding media, either abrasive powder or balls.
Abrasion by cutting	A tool forces cutting surfaces ('teeth' or blade) over the concrete surface
Abrasion by impact	Concrete surface is exposed to repeated shock of a single mass or from a falling flow of several objects
Abrasion by water erosion	A stream of water charged with abrasive sand is projected onto concrete surface
Abrasion by gaz/particles	A stream of air charged with abrasive sand is projected onto concrete surface
Abrasion by cavitation	Very high velocity/pressure water flow condition induces cavitation phenomenon on concrete surface

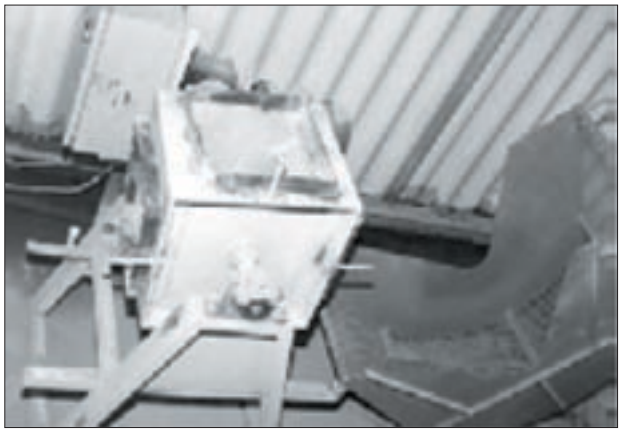


Figure 4—General view of LASA modified tumbling test device

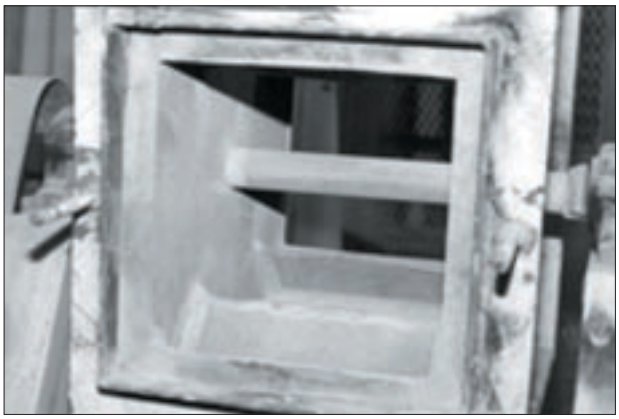


Figure 5—Inside view of testing unit with deflector plates

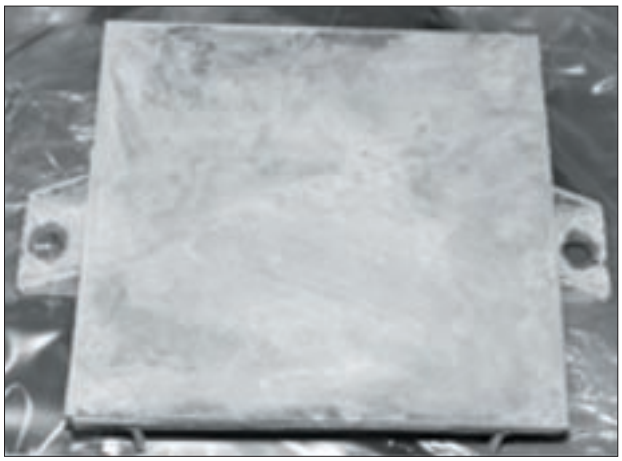


Figure 6—Cast test panel

Figure 7—12.50 kg x 40 mm ball charges

Figure 8—Measurement of volume of eroded concrete by sand filling

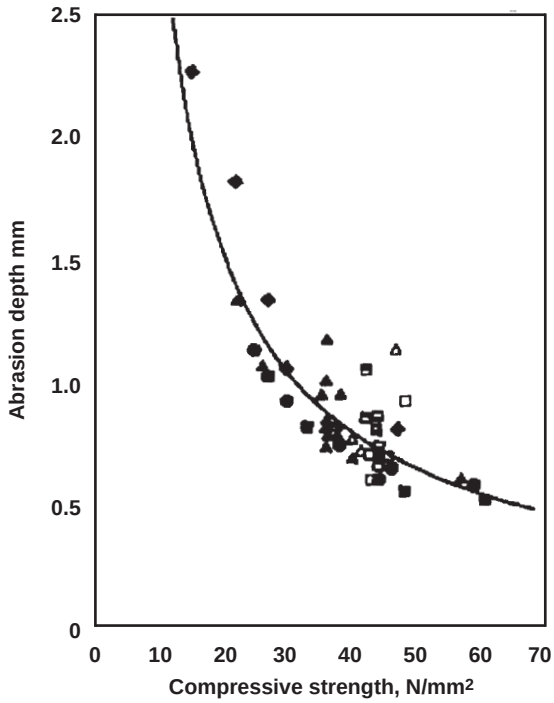


Figure 9—Relationship between the wear resistance (BCA method) and the compressive strength of OPC concrete with silica-limestone aggregates with W/C ratio ranging form 0.4 to 0.7 (Dhir *et al.* 1991)

compared in this paper are characterized by compressive strengths in excess of 80 MPa. The following examples illustrate that, for this level of strength, cement and aggregate nature are more important parameters than mechanical strength.

Contribution of calcium aluminates cement to abrasion resistance

Benefit brought by CAC to abrasion resistance

Calcium aluminate cement (CAC) is different from ordinary Portland cement (OPC) in many aspects, including abrasion resistance. Different tests series carried out at Lafarge Aluminates over the years, for a wide range of projects, always show that a CAC paste exhibits much better performance than a similar OPC paste when submitted to abrasion. The main reason proposed to explain this fact is that CAC clinker is a much harder material than OPC clinker, and thus CAC cement particles are more resistant to abrasion.

A second hypothesis, which would require more study to be confirmed, is linked to differences in the microstructure of hydrated CAC and OPC paste. OPC hydration leads to the formation of free Portlandite that favours the formation of a 'transition zone' at the aggregate grain interface, which locally reduces the mechanical characteristics. On the other hand, CAC hydration does not produces free Portlandite and there is no transition zone. Moreover, when CAC is utilized with calcium aluminate aggregates (ALAG,), the quality of the bond obtained between hydrated paste and aluminous aggregates is very monolithic and this probably contributes to a higher toughness. More research would be needed to better understand the importance of the microstructure difference over abrasion resistance.

Figure 10 compares various mixes of OPC and CAC based concrete. The general trend is clear, i.e. the eroded volume is reduced as the strength increases up to about 80 MPa. However, above 80 MPa, there is no similar correlation between compressive strength and abrasion resistance. It should be noted that the erosion is reported on a logarithmic scale, and that the best OPC mixture has shown erosion three times larger than the best CAC mixture.

Figure 11 shows the volume of eroded concrete for mixtures made with the same aggregates, but with either CAC or OPC. It is seen that using CAC leads to significantly reduced eroded volume. The difference of the strength observed between the two types of binder is not considered to be significant, as shown in Figure 10. Also, the higher abrasion resistance with CAC concurs with other field observations and practical experience

Conversion phenomenon influence on CAC concrete properties

One useful feature of CAC concrete is its rapid strength development, a value over 60 MPa being normal at 24 hours. Such high early strength should always be considered in relation to the conversion phenomenon described hereafter.

CAC concrete is subject to a specific behaviour called conversion; over time, the transient high early strength decreases to stable lower long-term strength. Converted strength can be predicted by rapid laboratory tests (5 to 7 days at 38°C wet curing) and only converted strength should be considered for design purpose. More detailed information about conversion can be found in Scrivener and Capmas (1998).

In field conditions, the time needed for hydrates to fully convert ranges from a few hours to several years, depending on moisture and heat. For instance, a large element of CAC concrete (thickness of 300–400 mm such as an ore pass lining) undergoes high initial self-heating, which induces conversion within the first hours of concrete life. In comparison, thinner elements exposed to a low temperature environment would take years for the hydrates to complete conversion. Thus, at the time of assessing the long-term properties of a CAC concrete, the conversion influence should not be ignored.

For mining applications such as those presented hereafter, a long-term track record demonstrates that CAC based concretes fit these purposes satisfactorily, despite the fact that conversion occurs over time. In order to correctly interpret the data presented below, two cases should be distinguished:

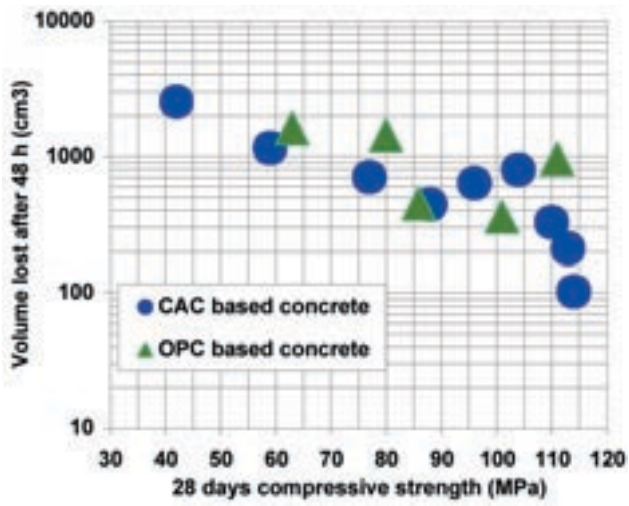


Figure 10—Infuence of cement type on the relationship between compressive strength and abrasion resistance, various aggregates and mix proportions (source: AATS report compilation of data from phase 1 and 2)

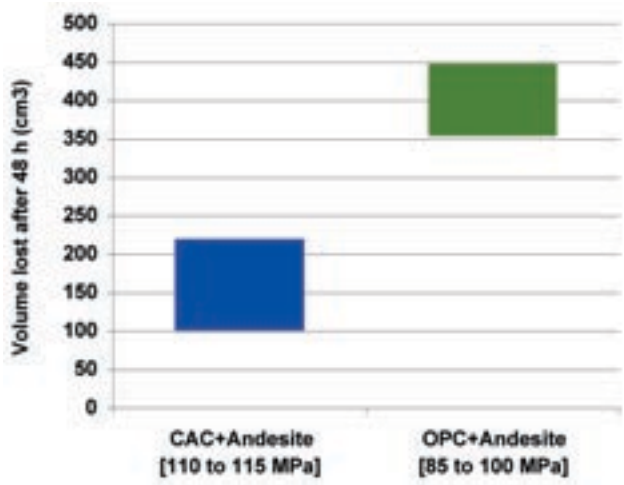


Figure 11—Comparison of abrasion resistance of CAC and OPC concrete mixture made with the same aggregates

Field track records—CAC abrasion resistant concretes have shown good track records in some deep mines in South Africa where ambient temperatures are high. Such temperature conditions accelerate the conversion phenomenon, and it can be assumed that conversion took place within a few days or weeks of concrete casting, depending on the installed thickness and self-heating conditions. Thus, the good track records reported for this CAC concrete over the years indicate that even when converted, CAC concrete gives satisfactory abrasion resistance

Laboratory results—most of abrasion data presented in this paper were obtained from specimens cured for at least 28 days at 35°C and 80–100% R.H, and these curing conditions favour conversion over a few days or weeks. Thus, it is correct to assume that specimens tested for abrasion resistance were converted (fully or almost fully) and that results obtained describe the long-term potential of the material.

In summary, conversion is inevitable with CAC concrete, but it does not prevent the achievement of satisfactory performance with abrasion resistance concretes, as shown by appropriate laboratory tests and moreover, by good industrial references over years in South Africa and elsewhere.

Contribution of aggregate type to abrasion resistance

The aggregate properties play a major role for both friction and impact abrasion resistance. For friction abrasion, the higher the aggregate hardness, the better the concrete resistance. For impact abrasion, the concrete performance is rather related to the aggregate toughness, i.e. its capacity to absorb energy without being fractured.

Aggregate hardness can be directly related to the friction abrasion resistance of concrete. There are several laboratory methods available to evaluate aggregate hardness, and thereby friction resistance, as this is an important parameter to obtain durable concretes when these are subject to this type of abrasion. Mohs scale of hardness is one such method used to rank hardness of an aggregate.

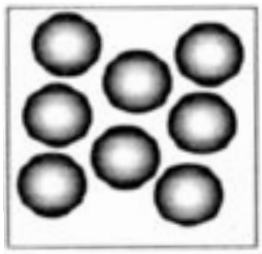
Aggregate toughness cannot be directly determined by a simple test. However, it can be evaluated or compared with usual testing methods such as the Los Angeles tests (ASTM C535 and C131) or Micro-Deval test (ASTM D6928), where a load of large or small aggregates with given grading is tumbled with a load of steel balls in a rotary drum for a given time. The higher the toughness, the less the particle will be fractured during the test.

Aggregate potential toughness is related to their geological nature. Rocks such as flint, chert or schist are often friable, whereas igneous rocks such as basalt or andesite are expected to be very sound. Because of their heating history, grains are bonded to form a very coherent matrix. Thus, when searching for naturally occurring aggregates with the best toughness, these types should be preferred when available.

Another important parameter is the maximum size of the aggregate, or D_{max}. As long as D_{max} remains under the 'critical diameter' of a given aggregate type, the higher the D_{max}, the better the abrasion resistance. This trend is explained by the fact that, for a given aggregate volume, an increase in D_{max} leads to a decrease in the interfacial paste-aggregate surface, which is a weak part of the material. The 'critical diameter' corresponds to the size where larger particles are most likely to present a significant weak plane, making them more fragile (reduction of toughness). When quarried rock is crushed to produce aggregates, fracture takes place preferentially along existing flaws and weak planes, removing them, while particle size is reduced. Best aggregates for impact abrasion resistance do not contain flaws, which mean that they are below their critical diameter.

Various aggregates have over the past 20 years been used with CAC based abrasion resistant concretes. Table II compares some properties of these aggregates.

Past experience indicates that the best abrasion resistance was obtained with natural corundum of D_{max} = 20 mm, but unfortunately the supply of this specific corundum in South Africa is no longer available. Concretes using alternative aggregate have been developed; the best combination to date has been a blend of fine Alag® and andesite of D_{max} =20 mm, as shown in Figure 12. In this example, the mix proportions are the same, with only the aggregate being changed. While andesite aggregate already gives good results, the use of fine ALAG reduces the abrasion by half, which is a significant difference.



8 spheres of radius = R

1 sphere of radius = 2R

$$Volume = 8 \times \frac{4\prod R^3}{3} \qquad Volume = 8 \times \frac{4\prod R^3}{3}$$

$$Surface = 8 \times 4\prod R^2 \qquad Surface = 4 \times 4\prod R^2$$

Table II

Some properties of various aggregate utilized within CAC concrete

Aggregate	Type	Main chemical analysis	Hardness (Mohs scale)	Specific Gravity
Corundum	Aluminum-oxide	Al_2O_3	9.00	4.00
Corrundum-siliminite	Aluminum-silicate	$Al_2O_3SiO_2$	8.50	3.25
Alag®	CAC aggregate	$Al_2O_3CaOSiO_2Fe_2O_3$+FeO	7.50	3.25
Andesite	Hornblende & plagioclase	$SiO_2Al_2O_3Fe_2O_3$	6.50	2.92

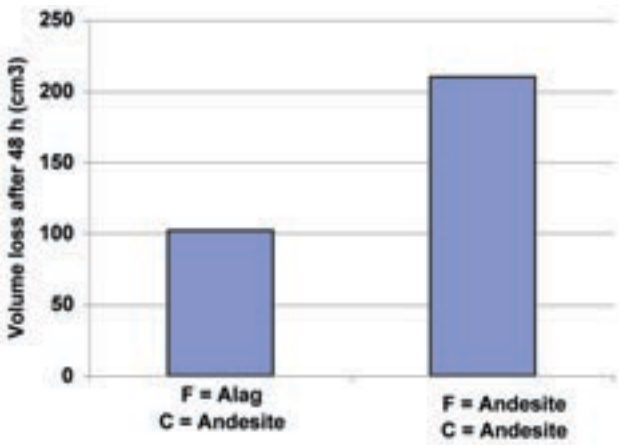


Figure 12—Influence of the type of aggregate on abrasion resistance of CAC based concrete, F: Fine aggregate. C: Coarse aggregate

Figure 13—One type of steel fibres

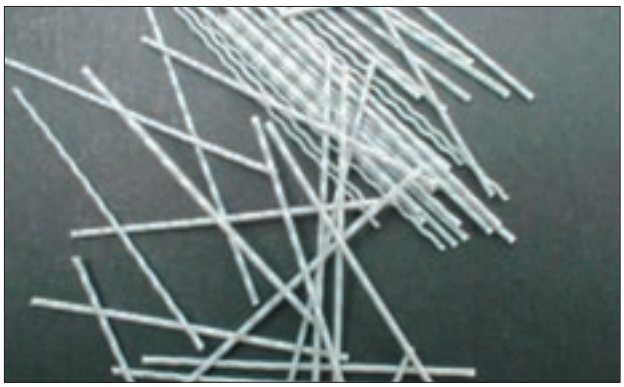


Figure 14—One type of polypropylene fibres

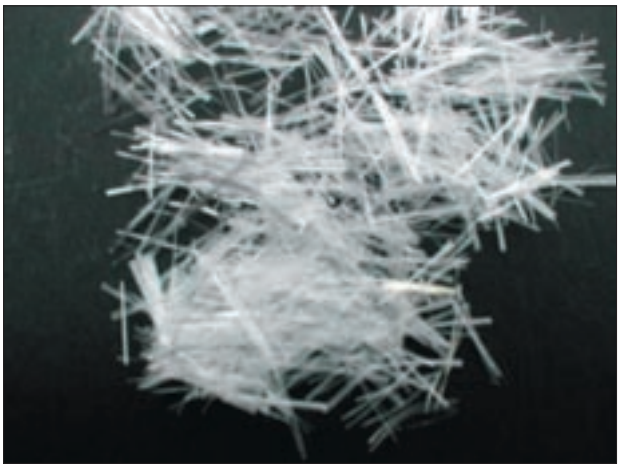


Figure 15—One type of synthetic micro fibres

Contribution of fibres to abrasion resistance

Over the past 25 years, fibres have become a common addition to concrete due to the fact that they can improve some of the concrete's properties, including resistance to impact. Fibre contribution can be explained in two ways: it can absorb and dissipate energy, reducing crack initiation and propagation, and it can maintain a fractured piece of concrete within the main body, slowing down the deterioration process. However, the presence of fibres is not expected to modify the friction abrasion resistance of a concrete.

In the field, fibres have proved to increase the durability of concretes subjected to impact abrasion. Three types of fibres are used in concretes that are subject to abrasion. These are steel fibres (Figure 13), polypropylene fibres (Figure 14) and micro synthetic fibres (Figure 15). Steel fibres are usually dosed at 30 to 40 kg/m^3 in concretes designed to resist impact abrasion, whereas polypropylene fibres are usually dosed at 9.0 kg/m^3 and micro synthetic fibres at 0.9 kg/m^3, respectively, in similar concretes.

In order to rank the benefit brought by various fibres, a test programme is currently in progress at Lafarge Aluminates. A single CAC based concrete mixture, namely Fonducrete SL (the product used to line the South Deep ore passes) is adjusted with different dosages and type of fibres. Steel fibre content is 40 kg/m^3, and the polypropylene fibre content is at 9.0 kg/m^3 in combination with micro synthetic fibres at 0.9 kg/m^3. The tests use the LASA modified tumbling apparatus as described previously. Each test point shown in Figure 16 is the average result of four test panels.

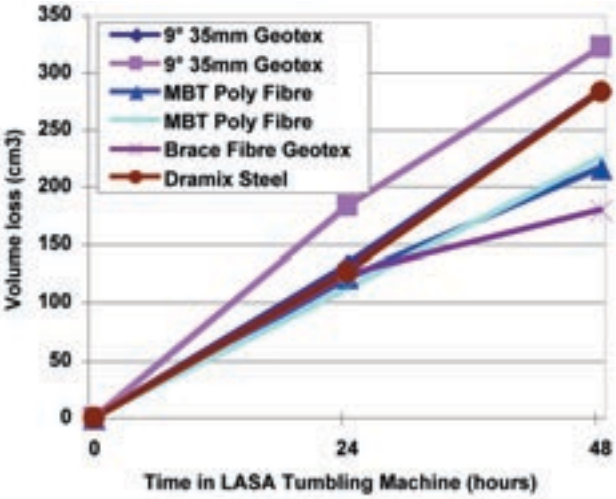


Figure 16—Comparison of fibres type influence on abrasion with LASA tumbling test

Table III

Comparison of classic and high strength Fondu/ALAG mixtures

	Usual Fondu/ALAG	High strength Fondu/ALAG
Cement nature	CAC	CAC
Aggregate nature	CA synthetic	CA Synthetic
Silica fume	0%	10%
Volume of aggregates	64%	64%
W/C	0.40	0.25
28 days' strength	69.1 MPa	133.7 MPa

In this test series, it is noted that 24 hour results are not as varied as the 48 hour results, when the relative difference becomes more apparent. At this point of the programme, it can be said that some synthetic fibre combinations are outperforming steel fibres at the selected dosages. However, more work is needed in order to better define the cost/benefit ratio of various dosages and types of fibres.

Contribution of admixtures to abrasion resistance

It has already been shown that cement type and aggregate nature are the primary levers for abrasion resistance in concretes. Apart from this, mechanical strength is also a contributing factor, but not the most important. In this regard, chemical admixtures for concrete are an indirect lever to improve abrasion resistance as they permit the lowering of the water content in concretes and this improves the mechanical strength of such concretes. Most mixes that were compared in this paper show a compressive strength in excess of 100 MPa, which was made possible only by the use of proper admixtures.

Production of high strength and very high strength OPC concrete is possible today because of the powerful super plasticizers that have been developed, allowing engineers to obtain acceptable rheology with very low water/cement (W/C) ratio mixtures. In the past, OPC super plasticizers were not efficient with calcium aluminate cements and CAC concretes were produced without admixtures, except occasionally retardants, which were used to extend the working time if this was required. However, in the last few years, new super plasticizing molecules have been developed and have proven to be very effective with CAC to reduce water and disperse CAC particles (Fryda *et al*, 2000). This development permitted the application of the modern approach of concrete add-mixturization to CAC based concrete. For abrasion resistant CAC based concrete, the use of adapted super plasticizers allowed the reduction of the W/C ratio, resulting in an increase in the final compressive strength of the concrete. Most of the test results reported in this paper have been obtained with CAC based concrete produced with some super plasticizer allowing low W/C and high mechanical strength. Table III compares the compressive strength obtained with a 'classical' Fondu/ALAG mixture, and a 'high strength Fondu/ALAG' mixture made possible with the use of new generation admixtures. Such reductions of water contribute to a denser and tougher concrete matrix.

Learning from the South Deeps abrasion test campaign (AATS report 2000)

In 2000 South Deep mine commissioned Anglo American Technical Services (AATS) to evaluate the various abrasion resistant concretes available in the market. A large testing programme was realized over 12 months to quantify and rank the potential service life of various concrete mixtures when these were subject to abrasion caused by both impact and friction. One key parameter of this study was to compare OPC based mixtures and CAC based mixtures, in order to determine if the proven abrasion resistance of CAC solutions could be matched to a lower cost mix design.

The main parameters involved in this campaign were the following:

Mixes were based on either OPC or CAC.
Some mixes contained micro silica or ultra fine flyash adapted to CAC concrete (low alkali content)
Aggregate used was andesite, Alag®, and corundum-siliminite in various combinations
Some mixes were tested with fibre (synthetic and steel) and some mixes without fibre
Some mixes contained polymer.

Figure 17—Example of test panels from South Deep test campaign: Left—a panel that failed during testing. Right—a panel presenting good abrasion resistance after 48 hours

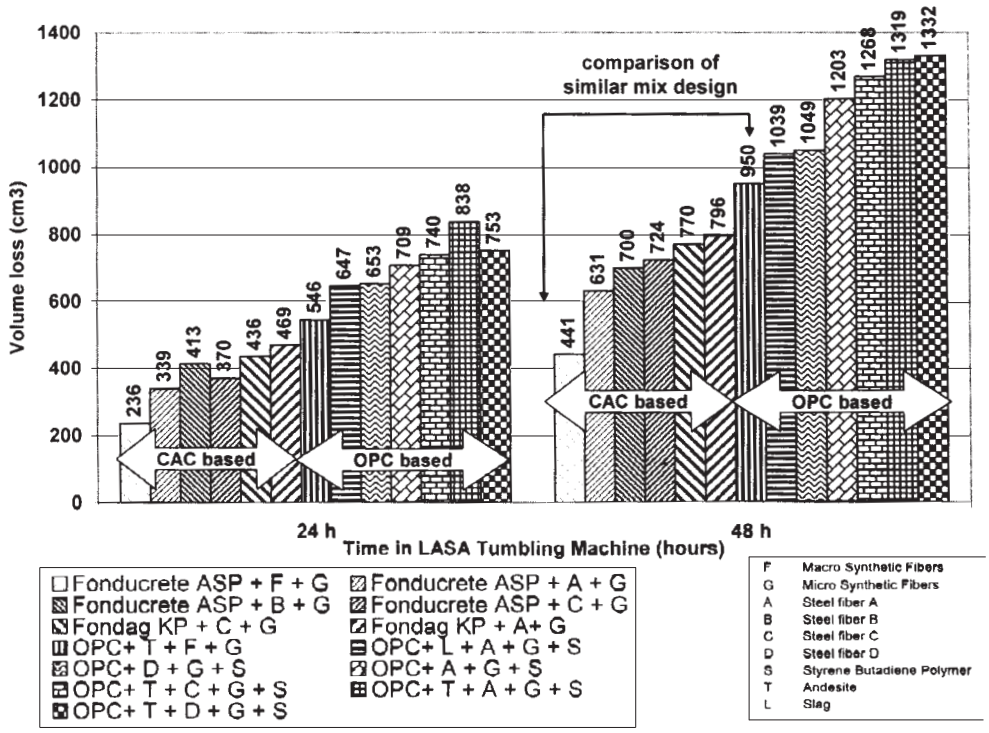


Figure 18—South Deep test campaign: abrasion resistance for the 13 concrete mixes that did not fail during the 48 hours of LASA modified tumbling testing

Table IV

Initial cost of installing an ore passes lining in an ore pass with a diameter of 2.70 m and length of 100 m

Item	Cost (Rand)
Raise boring	R2 500 000
Installation of support and lining.	R1 800 000
16.0 mm shepherd's crooks	R6 652
Cement capsules	R4 384
Grouted cable anchors	R11 500
Welded mesh	R6 786
CAC lining 300 mm thickness	R954 000
OPC based lining 300 mm thickness	R318 000

Total CAC based	R5 283 322
Total OPC based	R4 647 322

All candidate mixes were fabricated in a laboratory and cured for a minimum of 28 days at 35°C at a relative humidity of 80%–100%. These mixes were then tested using the LASA modified tumbling test. The main results of this study can be summarized as follows:

28 of the 41 mixes failed either due to cracking or complete destruction (Figure 17)

All 13 mixes that were not destroyed contained fibre (Figure 18)

The best 6 mixes were based on CAC

The best OPC and CAC mixes contained polypropylene fibre

For comparable mixtures, the volume of eroded material has been up to 3.50 times lower with CAC mixes.

Cost comparison of cementation options for ore pass linings (Van Heerden, 2004)

All costs indicated in this section are based on raise boring an ore pass 100 m long with a diameter of 2.70 m.

Table IV indicates that the total cost of an installation using CAC based concrete is 13.7% more expensive than the equivalent OPC based concrete. If the OPC based lining lasts for the entire life of the ore pass, this is the option to use.

If the ore pass has to be rehabilitated at any time during its life span, the CAC option now becomes more cost effective because of the high cost of rehabilitation. Parrish (2000) indicated a life expectancy of 12 years for the best OPC mix design tested. The CAC mix designs will outperform this OPC product by at least a factor of 2, although second phase testing indicates a factor of 3.50.

Table V

Cost to reline a failed ore pass after 12 years in operation (based on current costs)

Item	Cost
Relining and supporting	R3 000 000
16 mm shepherd's crooks	R6 652
Cement capsules	R4 384
Grouted cable anchors	R11 500
Welded mesh.	R6 786
OPC based lining 300 mm thickness.	R318 000
Total	R3 347 322
Original & rehabilitation cost.	R7 994 644

To evaluate the cost of rehabilitation, it is assumed that the dimensions of the ore pass remain the same. This is a very conservative assumption, since an ore pass that has to be rehabilitated has usually scaled to at least twice its original diameter.

The cost of using an OPC option now becomes 52% more expensive than if the mine had decided on a CAC option originally. This excludes any additional cost such as loss of production due to ore pass problems and items that are difficult to quantify, such as dilution of ore caused by scaling in the ore pass.

If the CAC based lining last three times as long as the OPC option, this saving becomes even greater.

Application methods

The method of applying an ore pass lining is often a result of on-site conditions or personal choice. There is no wrong method of applying such a lining, but each method has its own advantages and disadvantages. Lafarge Aluminates have developed products that can be applied by any of the methods described in the following sections.

Application by dry shotcrete

For many years, this has been the most popular method of applying an ore pass lining.

Advantages

Ideal for a stop-start type of operation
There is a lot of knowledge within the industry about the dry shotcrete process.

Disadvantages

Dusty
Loss of material caused by the high rebound inherent with this method
Water-cement ratio and quality of applied product is controlled by the nozzle man.

Figure 19—Example of local wet shotcrete unit

Application by wet shotcrete

Advantages

Lower loss of material due to lower rebound than dry shotcrete
Use of plasticizers allows low water-cement ratios
Less dust than dry shotcrete
Quality control not the sole responsibility of the nozzle man
Lower cost local shotcrete units now available (Figure 19).

Disadvantages

Not suited for stop-start operations, as mixed material must be used before it sets.

Applications by castable ore pass lining

Lafarge Aluminates have developed concrete mixes suitable for standard casting and slick casting (Figure 21). Casting can be either behind a disposable shutter (Figure 20) or a sliding shutter.

Figure 20—Disposable shutters

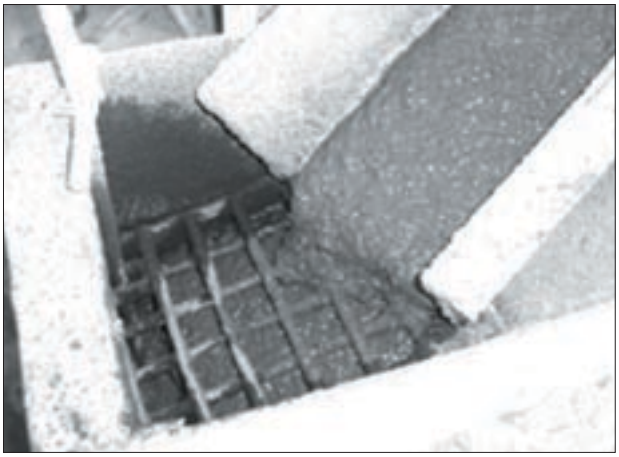


Figure 21—Feeding of a slick line with Fonducrete SL

Figure 22—Cast ore pass segments

Advantages

Very low material wastage
Low water-cement ratios are achieved with the use of admixtures
Better compaction compared to shotcrete
Easier quality control than with shotcretes.

Disadvantages

Cost of shuttering
Transportation underground of shutters.

Application by precast units

Although this method of lining an ore pass is no longer in use, the option to use this method is still available.

Advantages

Quality control of segments is at the manufacturing plant.
Controlled segment thickness.

Disadvantages

Segments are bulky to transport
Special winching required to install these segments down the ore pass.

Conclusion

In conclusion, the data presented above can be summarized as follows:

Improved resistance to harsh abrasion conditions can be attained with appropriate concrete mixture design. The key design parameters, in order of importance, are the cement type, the nature of aggregates and the presence of the correct fibres
Both sliding and direct impact of particles on ore pass linings cause the abrasive conditions in ore passes. Laboratory testing to evaluate potential abrasion resistance must simulate as realistically as possibly these two mechanisms. The LASA modified tumbling test appears to be a good method for laboratory evaluation and has proven its ability in different test campaigns to discriminate between various concrete mixtures
Different test campaigns demonstrate that using CAC as the primary binder of an abrasion resistant concrete results in a large increase in abrasion resistance. The ratio is in the range of 2 to 3.5 times better than comparable OPC mixes
The economic gain of using a CAC based abrasion resistant concrete is demonstrated when an ore pass is evaluated over its expected life cycle. The improved abrasion resistance of a CAC concrete will delay or even eliminate the usual maintenance that would be required when using an OPC based concrete.

Acknowledgements

Lafarge Aluminates thanks the management of South Deep Mine for allowing the use of data from the AATS report.

References

DHIR *et al.*, 1991, Near-surface characteristics of concrete: abrasion resistance, Mat. and Stru., vol. 24, pp. 122–128.

HU, C. State-of-the-art on the mechanical wear resistance of ALAG concrete (in French), Lafarge internal report. 2002. 50 p.

FRYDA *et al*, 'Interaction of Superplasticizers with Calcium Aluminate Cements', in Superplasticizers and Other Chemical Admixtures in Concrete, *6th CANMET conference*, Nice, France. 2000.

PARRISH. AATS Engineering report, June 2000, Placer Dome Western Areas JV: Report on the investigation of the most appropriate material system for durable ore pass linings. 2000.

SCRIVENER, K. and CAPMAS, A. Calcium Aluminate Cements, Chapter 13 of *Lea's Chemistry of Cement and Concrete*, Fourth Edition, Peter C. Hewlett (ed.), Arnold Publisher, 1998. pp. 709–778.

SPIES, J.D. Follow Up Report On Corundum Based rock passes. 1984.

VAN DER WESTERHUIZEN, A.B. Corundum-based Shotcrete Lining of Rockpasses, Association of Mine Mangers Of South Africa Circular No. 3/86 November. 1986.

VAN HEERDEN D. The use of cementitious linings to protect ore passes in the mining industry. *Ground Support in Mining & Underground Construction*, Perth 2004. u