Properties of South African silica sand used for rapid filtration

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Abstract

The paper reports the findings of an investigation into the properties of silica sand for use in rapid sand filtration, as supplied by various South African producers. The properties that were investigated are grain size, uniformity coefficient, grain shape, porosity, density, durability, silica content and acid solubility. Each property is defined, its role and influence on the filtration process are pointed out, the method(s) of measurement is explained, and typical values for the property are finally presented. From the results, a general profile of the commercially available media is derived to guide filter designers towards media specifications that will guarantee consistent filter media of the highest quality, within the constraint of economic attainability.

In general, South African silica media, from all sources, are characterised by a high degree of chemical and mechanical stability, as evidenced by low values for attrition losses (median 0.149%) and acid solubility (median 0.11%), a high value for silica content (median 99.47%) and density (median 2 632 kg·m^{-3}) which is close to the generally accepted 2 650 kg·m^{-3} for pure silica. The aeolian deposits yield media grains that are rounder (median 0.82) than the other deposits (median 0.58). The porosity and sphericity relationship at minimum fluidisation closely agrees with correlations published by earlier workers. The measured effective sizes d_{10} conformed closely to the values claimed by the suppliers, but not so for the coefficient of non-uniformity, which emphasises the need to use a clear, unambiguous sieve analysis procedure.

Introduction

The most commonly used filter medium for water treatment, world-wide, is silica sand. This need has spawned a sophisticated industry in South Africa which supplies media to a wide range of specifications. At present, there is no clear and comparative picture of local silica sand in the general sense in terms of its physical properties. This study, as a result, was consequently directed at the following objectives:

- To sample a number of representative sources of silica sand in South Africa
- Determine those physical properties of each sample which are normally employed in filter sand specifications
- Present a typical profile of South African silica sand to guide designers towards strict, yet attainable tender specifications.

Media sources

There are three major silica producing areas, namely two northern deposits near Delmas (Mpumalanga) and Brits (Northwest Province) respectively, and a southern deposit on the Cape Flats. Suppliers to the filter industry also supply silica sand for use in the tile, foundry, fertiliser and glass industries amongst others. Due to the variation in requirements amongst the industries, suppliers concentrate on one or two industries depending on the characteristics of their silica sand. The glass industry, for example, requires an extremely pure silica with a small grain size whereas the filter industry is interested in larger grains than the glass industry but with a small variation in grain size. The purity of the silica is less critical for the filter industry.

The northern deposit is along the Magaliesberg range and mines are found from Delmas in the east to Brits in the west. The southern deposit has an aeolian origin and is found in the Cape Flats. Six media producers participated in this investigation, from all three major silica-producing areas in South Africa. The media producers extract the silica in a variety of ways. It is extracted either as a granular material which is only cleaned and graded, or it is extracted as unweathered sedimentary rock which has to be crushed first. Table 1 summarises the nature and processing of each of the samples tested in this study.

All but one of these mines were visited and samples were taken in accordance with the AWWA standard specification for filtering material (AWWA, 1989) as well as the SABS standard procedure 827 (SABS, 1976a). The samples from the last mine were taken by the producer and it is assumed that they are representative. All media gradings that were likely to be used as sand in rapid gravity filters were sampled for this investigation. The samples were taken to the laboratory where a number of tests were performed, which will be individually discussed further on.

The mines have been designated names A to F and individual samples are identified with the mine of origin. For example, Sample A5 would be the fifth media product from Mine A.

Grain size

The filter medium grain size is an important process parameter for any of the following reasons:

- Fine-grained media produce better filtrate quality than coarse-grained media (Conley and Pitman, 1960)
- Fine-grained media induce higher headloss than coarse-grained media (Conley and Pitman, 1960)
- Coarse-grained media, by allowing deeper penetration of particles, provide longer filter runs than fine-grained media (Anonymous, 1936; Baylis, 1937)
- Coarse-grained media are backwashed more effectively than fine-grained media mainly because of the higher backwash velocity required to fluidise the larger grains, which induce larger shear forces on the flocs attached to the grains (Armstrong, 1931).

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TABLE 1
SUMMARY OF MEDIA SAMPLES USED IN THIS INVESTIGATION

Source	Nature of deposit	Processing	Remarks
Mine A	Matrix of single silica grains. Well weathered with a brittle matrix.	Crushed to separate individual grains, which are washed and dry-sieved.	Compared with other sources, the deposit contains a large fraction of fines.
Mine B	Silica is mined from an old river bed as loose material which includes foreign material. No cementation has taken place in the deposit.	Washed and sieved out with a wet-sieving process.	Product contains the most fine material of all sources, with no conglomerates.
Mine C	Unweathered. Individual grains are discernible only in the upper strata of the mine.	Crushed to granular form, with dry-sieving following.	Due to the purity, the product is used mostly for the glass industry.
Mine D	Relatively little weathering has taken place in the rock.	Crushed to granular form followed by hydraulic sorting and dry-sieving.	Hydraulic sorting of the media ensures a relatively dust-free product.
Mine E	Mined as loose material from an aeolian deposit. Highest degree of weathering of all sources.	Material is dredged from below the water table. It is sorted hydraulically and with dry-sieving.	Grains are very round and smooth. Sample contains almost no dust.
Mine F	Weathering ranges from well-weathered to no weathering at all. The deposit has several layers of severely folded strata, and recrystallisation of the silica has occurred in places. Individual grains are discernible in places.	Crushed, washed and dry-sieved.	The medium is relatively clean.

There are numerous methods and definitions for measuring and expressing grain size. The first is the *sieve size*, where the grain size is stated as those sieve size openings that pass and retain the grains in a sieve analysis, for example 0.6 mm to 0.7 mm sand where the sand passes through a 0.7 mm sieve but is retained by a 0.6 mm sieve (De Lathouder, 1973). From this the geometric mean diameter d_g can be calculated using:

$$d_g = \sqrt{d^- . d^+} \quad (1)$$

with d^- = the aperture of the retaining sieve (mm)
d^+ = the aperture of the passing sieve (mm).

The equivalent diameter d_{eq} of a grain is the diameter of a sphere of equal volume and density to the grain. This parameter is used in certain mathematical models and is determined by counting and weighing at least 100 media grains. If the density of the media is known, the average d_{eq} can be calculated directly (Cleasby and Fan, 1981).

The hydraulic equivalent diameter d_h of a grain is defined as the diameter of a sphere, of equal density, that has the same settling velocity as the grain (Ives, 1975). It is determined from its hydraulic behaviour during settling. If the settling velocity of the grain is known, its corresponding hydraulic equivalent diameter can be determined by solving the following equations:

$$v_t = \sqrt{\frac{4g\,(\rho_s - \rho)d_h}{3C_D\rho}} \quad (2)$$

$$C_D = \frac{24}{Re_t} + \frac{3}{\sqrt{Re_t}} + 0.34 \quad (3)$$

$$Re_t = \frac{\rho v_t d_h}{\mu} \quad (4)$$

with v_t = terminal settling velocity ($m \cdot s^{-1}$)
g = gravitational acceleration (9.81 $m \cdot s^{-2}$)
ρ_s = density of medium ($kg \cdot m^{-3}$)
ρ = density of water ($kg \cdot m^{-3}$)
C_D = drag coefficient (-)
Re_t = Reynolds number at grain settling velocity (-)
μ = dynamic viscosity of water ($kg \cdot m^{-1} \cdot s^{-1}$).

Some of the above definitions are employed in filter medium specification, mostly those that are easily and directly measurable. The definitions such as d_g, d_{eq} and d_h are never used to specify grain size when buying media, but are essential for the theoretical prediction of the hydraulic behaviour, such as head loss, point of fluidisation and bed expansion.

Grain size distribution

Media of natural origin do not consist of identical uni-sized grains, but of a range of grain sizes. This non-uniformity of the grains leads to stratification of the bed during backwashing, the finest grains rising to the top. This is exactly the opposite of what the designer desires. To facilitate deep penetration of solids into a filter bed, the grains should be organised such that the coarse grains lie on top of the finer grains. From a process point of view, it is therefore important to limit the variation in grain size to the smallest practical value.

The variability in grain size is measured by passing a sample through a stack of sieves, from which a size distribution curve is calculated and plotted. For mathematical expression, the ratio between d_{60} and d_{10} (or coefficient of non-uniformity, traditionally abbreviated as UC) is selected as indicator of the steepness of the size distribution curve. For perfect mono-sized media, the UC will be 1. Designers want the UC as close as possible to 1, but have to temper this requirement for economic reasons. A practical compromise is usually reached at about 1.4 to 1.5. The UC effectively controls that section of the size distribution curve between d_{10} and d_{60}. To also limit the parts of the curve outside these boundaries (to avoid excessively fine or coarse material), maximum and minimum sieve sizes are specified beyond which only a very small fraction of the material may fall. A typical example would be that not more than 5% of the mass should pass an 0.6 mm sieve and not more than 3% of the mass should be retained on a 1.35 mm sieve (De Lathouder, 1973). An example of this type of specification is shown in Fig. 1.

Variation in media size can alternatively be specified by means of an envelope within which the size distribution curve must fall. An example of a typical grading envelope (De Lathouder, 1973) is given in Fig. 2.

The variability in grain size of the different sand samples used for this study was measured and compared with the specifications to which the material was purported to comply; the results are reported in Fig. 3. Although the measured and claimed values compare well in general, there are some very definite differences as well. These differences can be attributed to at least two factors. The first is the possible difference in testing apparatus and procedure. Sieving is a statistical process and it rests upon the possibility of a grain falling through a sieve or not and therefore there is no definite end to the process (Heywood, 1947). The end point of the analysis therefore has to be chosen arbitrarily by either a chosen sieving time or until the grains move through the sieves at a constant rate. To control this procedure, specifications similar to SABS Standard Method 829 are employed throughout the world. These standards unfortunately differ markedly from each other and could lead to incomparable results from the same media sample. Further reasons for non-repeatable results can be found in the differences in the equipment used as well as the natural variation in media from the same supplier. It is also unrealistic to expect that a supplier will produce material which has unchanging characteristics in the long term. This last point serves as motivation for continued vigilance and control; even for media from established, reputable suppliers.

The measured UC values were also compared to the UC claimed by the suppliers; this is shown in Fig. 4. The values for the sands vary widely from an impressive 1.24 to 1.62. The average values lie in the range of 1.40 to 1.50. There is, however, a wide discrepancy between the values quoted by the suppliers and those measured. This discrepancy can in part be attributed to the fact that the UC is a ratio and therefore sensitive to variations

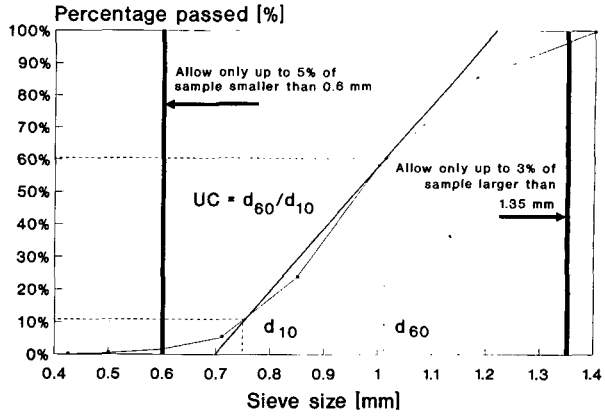

Figure 1
Specification of grain size variation by top and bottom limits

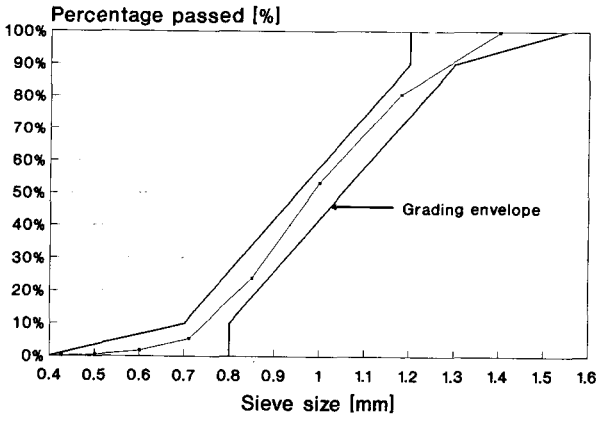

Figure 2
Specification of grain size variation by envelope grading

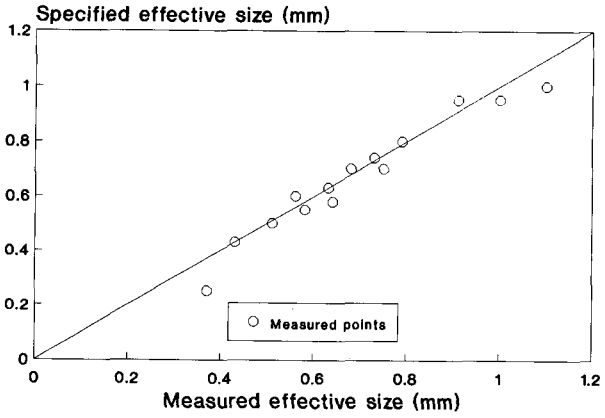

Figure 3
Comparison of measured values and values claimed by media suppliers: effective size (d_{10})

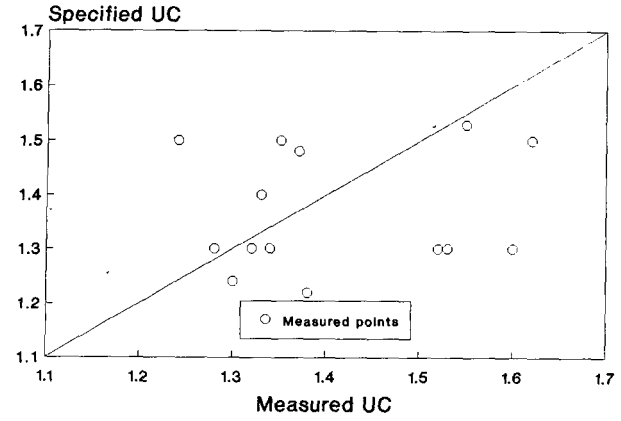

Figure 4
Comparison of measured values and values claimed by media suppliers: coefficient of non-uniformity (UC)

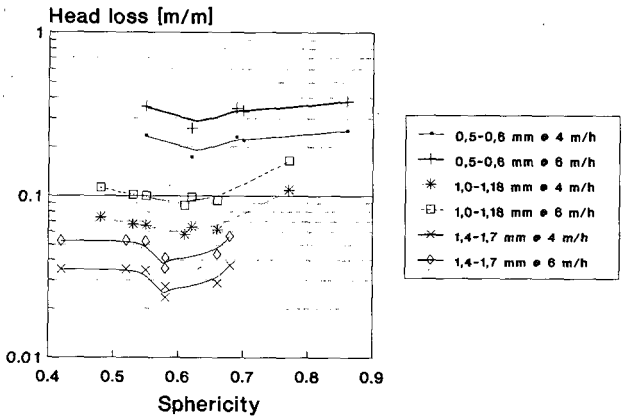

Figure 5
Variation of head loss as a function of grain shape (surface ratio sphericity)

in both d_{10} and d_{60}. Variations that would be acceptable in these two parameters could lead to an unacceptable variation in UC. This sensitivity suggests that it would be advisable to move away from the UC-type of specification and to adopt grading envelopes.

A preliminary visual inspection of the sands revealed that the samples from Mines A and B had significantly more dust than the other samples. One would therefore expect lower d_{10} and higher UC values for these samples. This did, however, not manifest itself in any significant way, except for sample B2. From this it can be concluded that dust in a media sample will have a minor effect on the d_{10} and UC of a sample, although it will have other detrimental effects.

Grain shape

Grain shape influences the backwash characteristics of a filter bed, the bed porosity, the energy loss through the bed during filtration, the effectiveness of the filtration process and the sieve analysis during grain size distribution analyses (AWWA, 1990).

Angular grains afford more effective filtration runs (Ives, 1975). The grain matrix creates a more tortuous path for the water to follow and this in turn provides more opportunity for the various transport mechanisms to act on the suspended material. Intuitively, this should translate into higher energy losses as the water passes through the bed; a view supported by Ives (1975). Morrison (1993), however, states that experiments done by The Cape Town City Engineers Department show that round grains actually have a higher head loss than angular grains; a finding supported by Degrémont (1979). Calculations done using data gathered for actual media samples show both these viewpoints to be true. This is due to the inherent relationship between sphericity and porosity. This will be expanded on later in this discussion; in short the inverted relationship between the two factors leads to increased head losses when the surface ratio sphericity increases or decreases from an optimum value of 0.60 to 0.65. Figure 5 shows the variation in head loss as a function of grain shape for three different grain sizes and two different filtration velocities.

The definition of grain shape is a complex matter which is complicated further by the extensive list of definitions used by various authors to describe it. Dharmarajah and Cleasby (1986) compiled a list of 15 such definitions, and even more may exist. The most useful definitions are based on the comparison of the actual grain shape with a sphere, which leads to the concept of sphericity (ψ). Two important definitions are the surface ratio sphericity (where the sphericity is equal to the ratio of the surface area of a perfect sphere to that of the grain if the equivalent diameter are equal (Dharmarajah and Cleasby, 1986)), and the hydraulic sphericity (where the sphericity is equal to the ratio of the hydraulic equivalent diameter and the geometric mean diameter (Ives, 1990)). For these definitions, the sphericity can only be equal to or smaller than 1, with 1 being a perfect sphere. The surface ratio sphericity is independent of grain size, while the hydraulic sphericity does depend on grain size. The surface ratio sphericity, therefore, is believed to be fundamentally the more correct definition (Dharmarajah and Cleasby, 1989). Models that predict the behaviour of filter media in the bed, have been formulated in terms of both sphericity definitions, but no mathematical relationship exists between these models (Dharmarajah and Cleasby, 1989).

Surface ratio sphericity

The surface ratio sphericity can be estimated by a visual method presented by Fair et al., 1968. This method entails the comparison of the actual roughness of the grain with published diagrams of grain silhouettes. Alternatively, the surface ratio sphericity can be quantitatively determined by solution of the Ergun equation:

$$\frac{h}{l} = 150 \frac{\mu}{\rho g} \frac{(1-\varepsilon)^2}{\varepsilon^3} \left(\frac{1}{\psi d_{eq}} \right)^2 v + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{v^2}{\psi d_{eq} g} \quad (5)$$

with
- h/l = hydraulic gradient through the filter medium (-)
- ε = bed porosity (-)
- μ = dynamic viscosity of water ($kg \cdot m^{-1} \cdot s^{-1}$)
- ρ = density of water ($kg \cdot m^{-3}$)
- v = filtration velocity ($m \cdot s^{-1}$)
- g = gravitational acceleration ($m \cdot s^{-2}$)
- d_{eq} = equivalent diameter (m)

The determination of the hydraulic sphericity follows directly from its definition. The most troublesome part is the tedious and time-consuming determination of the hydraulic equivalent

diameter.

The surface ratio sphericity (visual as well as with the Ergun equation) and the hydraulic sphericity were determined on all the media samples collected for this study. For the quantitative determinations, the samples were split into a fine, a medium and a coarse fraction.

The results for the visual determination of surface ratio sphericity are summarised in Table 2, with the grains of two samples shown in Fig. 6. From Table 2 it appears that the silica grains found in South Africa are generally fairly spherical, and that the sphericity does not differ very much from mine to mine, the exception being Mine E, which has substantially higher sphericities.

The results for the determination of the surface ratio sphericity and hydraulic sphericities, using the same size fractions as before, are shown in Table 3. For the hydraulic sphericities the general trend seems to be that the sphericity is higher for the smaller size fractions than the larger size fractions. This appears not to be the case with surface ratio sphericities. Close inspection of the samples showed that the *in situ* media matrix consisted in some cases of primary silica grains of a certain size, which were cemented into conglomerates or clusters of primary particles. The small size fractions consisted mostly of single primary particles crushed from the deposit, while the larger size fractions consisted of small conglomerates of primary particles. The surfaces of the conglomerates were more uneven than the more angular surface of the primary particles. This could partly explain the difference in sphericities but this could also be the result of the influence of size on the hydraulic sphericity. This has been pointed out as the largest fundamental problem with hydraulic sphericity (Dharmarajah and Cleasby, 1989).

In general the results for the hydraulic sphericities of the grains, shown in Table 3, show that grains that are crushed have the lowest sphericities. Mines C, D and F crush rock to produce the smaller grains required in filtration. The sand in Mine A has undergone some *in situ* weathering, that from Mine B was transported by water and as a result has undergone more weathering than the silica from Mine A. The silica from Mine E has undergone the most weathering. The hydraulic sphericity seems to keep to this order and grains have higher sphericity values as the level of weathering increases.

The complete data set from the test procedure for hydraulic sphericity was statistically analysed with the ANOVA and Tukey procedures (Box et al., 1978). The following were the main findings:

- Each mine has the same hydraulic sphericity in the same size fractions, regardless of which product is used ($\alpha = 0{,}75$). This indicates that the same degree of crushing is required to obtain a certain size, regardless of which product is produced.
- The hydraulic sphericity of different size fractions, from the same mine, differs significantly ($\alpha = 0.99$).
- When comparing products from different mines, the hydraulic sphericity of each size fraction is significantly different ($\alpha = 0.95$). This indicates that there are significant differences in the nature of the primary deposit being processed.

How do the different definitions and methods for sphericity compare? Figure 7 shows the average values determined for each mine, according to the three different methods. It is immediately obvious that the visual sphericity test substantially overestimates the sphericity in every case. The method advocated by Fair et al., 1968 assumes that grains have a similar "elevation" around at

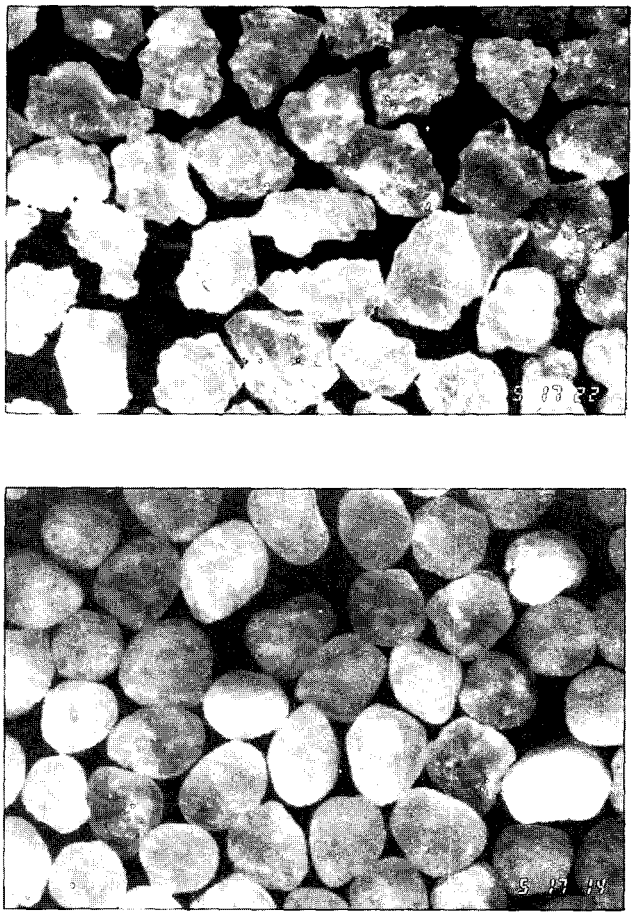

Figure 6

Photomicrographs of two samples used in this study. Sample A has surface ratio sphericity of 0.66 , a visual sphericity of 0.74 and a hydraulic sphericity of 0.66. Sample B has surface ratio sphericity of 0.77, a visual sphericity of 0.96 and a hydraulic sphericity of 0.79

TABLE 2
SURFACE RATIO SPHERICITY, DETERMINED VISUALLY FROM THE DIAGRAMS OF FAIR ET AL., 1968

Sand sample	Visual sphericity	Sand sample	Visual sphericity
A1	0.81		
A2	0.78	D1	0.78
A3	0.81	D2	0.81
A4	0.81	D3	0.78
A4	0.81	D4	0.78
A5	0.81	D5	0.78
A7	0.78	D6	0.78
B1	0.87	E1	0.94
B2	0.78	E2	0.98
C1	0.81	F1	0.70
C2	0.70	F2	0.78
C3	0.81		
C4	0.81		

TABLE 3
COMPARISON BETWEEN SURFACE RATIO SPHERICITY AND HYDRAULIC SPHERICITY

	500 to 600 µm		1 000 to 1 180 µm		1 400 to 1 700 µm	
	SRS	HS	SRS	HS	SRS	HS
MINE A						
Average	0.67	0.70	0.62	0.67	0.68	0.60
Standard deviation	0.036	0.078	0.024	0.082	0.028	0.078
MINE B						
Average	0.69	0.69	0.48	0.67	0.58	0.65
Standard deviation	0.048	0.079	0.024	0.064	0.027	0.085
MINE C						
Average	0.70	0.66	0.58	0.61	0.58	0.57
Standard deviation	0.027	0.074	0.007	0.087	0.013	0.092
MINE D						
Average	0.52	0.63	0.55	0.60	0.55	0.56
Standard deviation	0.016	0.075	0.020	0.087	0.013	0.081
MINE E						
Average	n/a	0.76	0.77	0.79	0.86	0.69
Standard deviation		0.071	0.073	0.064	0.014	0.088
MINE F						
Average	n/a	0.67	0.66	0.66	0.42	0.60
Standard deviation		0.065	0.025	0.078	0.020	0.072

SRS = surface ratio sphericity, HS = hydraulic sphericity

least major two axes. This is not the case for local media and it was found that the grains tended to be "flaky", *i.e.* the elevation of the grains around the three major axes differed markedly. If the measured sphericity is required for quantitative calculation of head loss, this method cannot be recommended.

In order to compare the hydraulic and the surface ratio sphericities, the comparative values in Table 3 are shown in Fig. 8. It is clear that there is no consistent difference between the two methods. It does, however, appear as though the hydraulic sphericity is a less sensitive parameter than surface ratio sphericity. Hydraulic sphericity ranged between 0.56 to 0.79 (a range of 0.23) compared to surface ratio sphericity between 0.42 to 0.86 (a range of 0.44).

The design engineer normally only requires the media sphericity for the calculation of clean bed head loss. For this purpose, it is clearly the best to use the surface ratio sphericity, which is calculated from an actual measurement of the head loss. The determination of the hydraulic sphericity is much simpler and would have been a useful and practical way of checking the surface ratio sphericity if they were closely correlated. From the data presented in this section, such a correlation does not exist and the surface ratio sphericity is recommended for use.

Porosity

The porosity (ε) of a filter bed is a function of the volume of the filter medium grains in the media bed and the total volume of the bed. Equation (6) describes this relationship with two alternative, but equivalent formulations:

$$\varepsilon = 1 - \frac{V_s}{V_t} \qquad (6)$$

$$\varepsilon = 1 - \frac{m}{\rho_s V_t}$$

where V_s = volume of the medium sample (m^3)
V_t = total bed volume (m^3)
m = the mass of the medium sample (kg)
ρ_s = density of the medium ($kg \cdot m^{-3}$)

The porosity influences the head loss through the media bed, its backwash requirements and its capacity for suspended solids retention (AWWA, 1990). The porosity, however, is not a variable that can be varied independently; it is a function of the shape of the media grains. Wen and Yu (1966) studied the relationship between the porosity of a bed and its surface ratio sphericity and found two mathematical relationships that both gave good correlations between porosity and surface ratio sphericity:

$$\frac{1 - \varepsilon_{mf}}{\psi^2 \varepsilon_{mf}^3} \cong 11 \qquad (7)$$

$$\frac{1}{\psi \varepsilon_{mf}^3} \cong 14 \qquad (8)$$

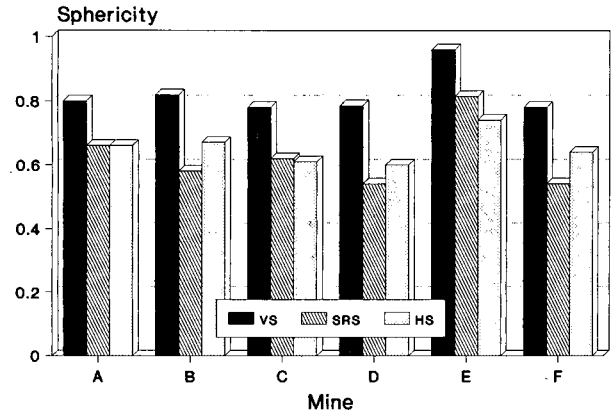

Figure 7

Comparison amongst the average sphericity for each mine. VS: a visual determination of the surface ratio sphericity; SRS: the surface ratio sphericity calculated from the head loss with the Ergun equation; HS; hydraulic sphericity.

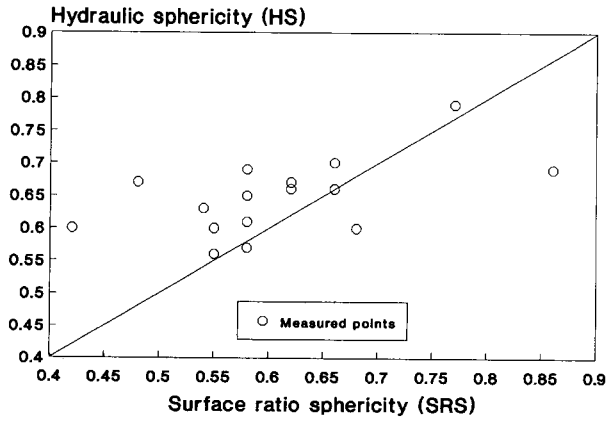

Figure 8

Comparison between the measured surface ratio sphericity (SRS) and hydraulic sphericity (HS)

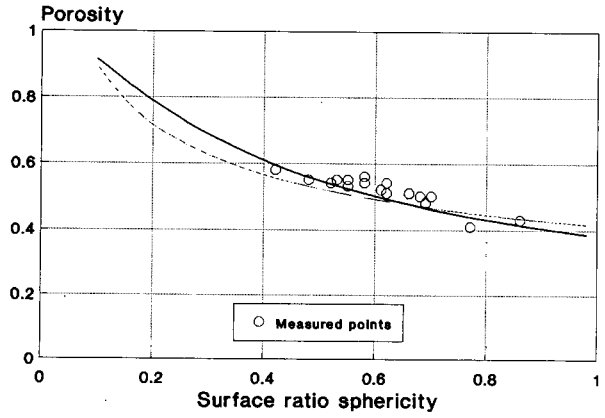

Figure 9

Measured relationship between porosity at minimum fluidisation and surface ratio sphericity, together with the correlations of Wen and Yu (1966)

The porosity is influenced by the degree of bed compaction. A bed that is allowed to settle slowly after fluidisation can have a porosity of up to 5% higher than one that settles rapidly. This effect is more noticeable with rounder grains (AWWA, 1990). Porosity is also affected by grain size; Ghosh (1958) found that porosity increased for uniformly shaped grains as they decreased in size. This was reported for both glass ballotini and sand grains.

The porosity of a filter bed in its loosest possible configuration, is called the porosity of minimum fluidisation ε_{mf} (Zenz and Othmer, 1960). This configuration is obtained by allowing the bed to settle very slowly after fluidisation. The porosity of minimum fluidisation is used to calculate the bed expansion of media beds during backwash.

The determination of the porosity of a filter bed is a relatively simple procedure although care should be taken to measure the porosity at the same degree of compaction. The simplest is to measure the porosity at minimum fluidisation. Cleasby and Woods (1975) suggested that a bed should be expanded to 150% of its rest depth and should only then be allowed to settle very slowly to ensure reproducible results. Ives (1990) warned that consolidation of media in a test column happens very easily when it is bumped or disturbed in any way.

The porosity of silica samples collected from the various mines was tested for ε_{mf} with the proper precautions mentioned above and the results are summarised in Fig. 9, which also shows the Wen and Yu (1966) correlations. One sand sample from the 500 to 600 µm, 1 000 to 1 180 µm and 1 400 to 1 700 µm size intervals for each mine was tested and each data point on the graph represents an average of six measurements.

Figure 9 shows that all the media samples conform very well to the correlations of Wen and Yu (1966). The agreement between the data and the model is so good that it could even be used as a quick approximate method to determine sphericity; it is much easier to determine porosity than sphericity.

Density

The density of a filter medium plays a role in:

- The backwash requirements of the filter bed
- Determining the relative position of a medium layer relative to other layers in a multi-media filter
- The degree to which a grain will be cleaned during backwash (the denser of two similarly sized grains will have a higher minimum fluidisation and will thus be subjected to higher hydrodynamic shear forces) (AWWA, 1990).

Media density can be expressed as either the absolute density (expressed as $kg \cdot m^{-3}$), or as the specific gravity SG (dimensionless). The SG of a medium is the mass ratio of a unit volume of medium and a unit volume of water at a given temperature. The American standard, ASTM C128-84, specifies 23°C. The density of media can be determined in various ways. All the methods are based on measuring the volume of water displaced by a known mass of medium. The mass of the dry material should obviously be tested at a constant moisture content. The easiest way of achieving this is to measure the mass after it has been dried to constant mass; a determination described in detail in SABS Standard Method 844.

The density of silica sand is commonly quoted as 2 650 $kg \cdot m^{-3}$ (Ives, 1990). The media obtained from local producers were subjected to extensive density determinations to see whether:

- the value of 2 650 kg·m^{-3} can be used for local silica sand, and
- if there are any meaningful differences in density amongst the silica from different mines.

Duplicate density determinations were made for each sample used in this study, resulting in 46 density tests. The samples from each respective mine did not show meaningful density differences, and the results from each mine could thus be pooled into an average density for the mine. The resultant average densities are compared in Table 4. The average density of all the silica samples tested was 2 632 kg·m^{-3}, a value only 0.7% different from the commonly accepted 2 650 kg·m^{-3}.

TABLE 4
COMPARISON OF MEDIA DENSITY BETWEEN DIFFERENT MINES

Media source	Density (kg·m^{-3})
Mine A	2 631
Mine B	2 627
Mine C	2 641
Mine D	2 629
Mine E	2 625
Mine F	2 623
Average	2 629
Standard deviation	6.4
Coefficient of variation	0.0024

Durability

The designer has not only to ensure that the correct medium is placed in the filter bed, but also that it will remain essentially unchanged in use to guarantee proper operation over the full design life of the filter. The specification and measurement of media durability does, however, present some difficulty. Some researchers and institutions correlate media durability with its ability to withstand impact, while others use the Moh hardness scale as an indicator of durability. The use of both these indices can be questioned. Cleasby (AWWA, 1990) states that the reduction in grain size of brittle media, which have poor impact resistance, has never presented itself as a problem and Ives (1990) reports the successful use of soft coal as filter medium, despite its low Moh hardness.

Media grains are generally not round and have sharp edges or an irregular surface. During the first few backwash cycles sharp points may break off. The presence of these fragments will not be a problem, as they will be washed out. If the media grains have a weak structure, however, the fragmentation and loss of media during backwash will continue and this could present a problem. To simulate the bed behaviour during backwash, an attrition test is proposed (Ives, 1990), which entails backwashing at minimum fluidisation for 100 h in a test column. This simulates the actual abrasion the grains will experience during three years in a filter bed.

One sample from each mine was tested. In order to evaluate the results on an equal basis for all the samples, the test sands were sieved to get samples with similar grain sizes, to ensure comparable surface to volume ratios for all the test samples. The test results are tabulated in Table 5.

TABLE 5
MEDIA LOSS DUE TO ATTRITION

Media source	Mass loss during backwash
Mine A	0.247 %
Mine B	0.374 %
Mine C	0.148 %
Mine D	0.149 %
Mine E	0.022 %
Mine F	0.064 %

The lowest attrition loss was measured for Mine E, which is an aeolian deposit with the highest surface ratio sphericity of all the mines tested. Although there are differences amongst the samples, their attrition losses are all way below the recommended limit of 1% (Ives, 1990). Media with an attrition loss of more than 1% have questionable application while an attrition loss of more than 3% is unacceptable.

Silica content

Ideally, filter sand should consist of pure silica (SiO_2), due to its hardness, durability and chemical stability. The silica content is, therefore, often specified for filter sand, as it gives a good indication of the stability of the sand under adverse conditions. The silica content, as well as the nature of the impurities, were determined for all the sand sources used in this study. One representative sample from each mine was selected for analysis. The results are shown in Table 6.

The silica content was high throughout, ranging from 98.43% in the worst case to 99.96%. The largest identifiable contaminants, in general, were the iron and aluminium compounds. This conforms to the most stringent requirements. A review of international specifications has shown that the highest standard required is 98% (De Lathouder, 1973).

Acid solubility

An alternative method of assessing chemical stability, other than measuring the silica content, is to measure the solubility of the media under acidic conditions. The maximum acid solubility is commonly employed in filter media specifications. Although the pH value to which the media are subjected during the test is much lower than would normally be experienced under filtration conditions, it stands to reason that if it passes this test, it will most probably not fail under normal conditions. The acid solubility test could indicate three potential media problems (Ives, 1990):

- Conglomerates will be revealed when the cementation between the particles is dissolved.
- The presence of excessive organic material or calcitic shell fragments will show up as a mass loss or as effervescence of the sample.
- Discolouration of the acid will indicate the presence of other acid-soluble materials, such as iron.

The test procedure is relatively simple and entails the determination of mass loss after the silica has been submerged in an acid of

TABLE 6
CHEMICAL ANALYSIS OF FILTER MEDIA

-	Mine A	Mine B	Mine C	Mine D	Mine E	Mine F
SiO_2	99.15%	98.43%	99.90%	99.55%	99.39%	99.96%
TiO_2	0.05%	0.08%	0.03%	0.04%	0.03%	0.02%
Al_2O_3	0.23%	0.29%	0.00%	0.16%	0.00%	0.00%
Fe_2O_3	0.08%	0.25%	0.00%	0.06%	0.02%	0.00%
MnO	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
MgO	0.07%	0.08%	0.00%	0.07%	0.06%	0.09%
CaO	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Na_2O	0.01%	0.02%	0.01%	0.03%	0.00%	0.00%
K_2O	0.08%	0.02%	0.00%	0.05%	0.00%	0.00%
P_2O_5	0.01%	0.01%	0.00%	0.00%	0.03%	0.00%
Cr_2o_3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
NiO	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
H_20-	0.05%	0.08%	0.03%	0.04%	0.02%	0.02%
LOI	0.25%	0.22%	0.11%	0.22%	0.19%	0.12%
Zr ppm	72	44	20	50	55	26
ZrO_2	-	-	-	-	-	-

TABLE 7
ACID SOLUBILITY OF FILTER MEDIA

Media source	Mass loss [%]
Mine A	0.15%
	0.18%
	0.21%
Mine B	0.24%
	0.25%
	0.26%
Mine C	0.10%
	0.10%
	0.13%
Mine D	0.10%
	0.11%
	0.11%
Mine E	0.05%
	0.05%
	0.05%
Mine F	0.06%
	0.07%
	0.11%

fixed strength for a fixed time. Colouration and effervescence should also be reported if present. For this investigation, a 20% (by mass) solution of hydrochloric acid was used and the sand was submerged for 24 h at room temperature. The test specified in other sources varies slightly in terms of acid strength, test temperature and duration. The procedure followed here is, however, considered to have an "average" methodology. The results obtained on three samples from each mine are shown in Table 7. The samples were sieved to ensure comparable surface to volume ratios.

The losses shown by the sand were all low and compare well with the generally accepted limit of 2% (De Lathouder, 1973; Ives, 1990; Degrémont, 1979). A slight yellow discolouration indicates the presence of iron in the silica (Ives, 1990) but from the chemical analysis it is clear that the iron was too low to be a real problem. Furthermore no effervescence was noticed. The media tested did not consist of unstable conglomerates, as no break-up of grains could be detected. All in all, the sand samples tested in this study, measured by their acid solubility, are of the highest quality.

Summary

- South Africa has a well-established and reputable industry for the supply of silica. By taking representative samples from six different silica mines, an attempt was made to derive a general profile of South African silica sand, specifically for use as a filter medium in rapid gravity filtration systems.
- The effective grain size (measured as d_{10}) is well controlled and corresponds closely to the specification claimed by the media producers.
- The grain size distribution (measured as the coefficient of non-uniformity), when measured in a consistent manner for all the sources, differed substantially in some cases from what was claimed, which emphasises the importance of not only specifying a maximum for the coefficient, but also the exact test procedure. This problem can also be avoided partly by using grading envelopes.
- The grain shape can be defined, and measured, in many different ways. The surface ratio sphericity, as calculated by the Ergun equation from a head loss measurement, is recommended as the most reliable and practical measure of grain shape. The surface ratio sphericity of the media supplied from the five northern producers has a median value of 0.58, while the median for the one southern supplier (which mines an aeolian deposit) is 0.82.
- The porosity of the media at minimum fluidisation is well described by the correlations of Wen and Yu (1966). As it is

faster and simpler to determine porosity than sphericity, it could even be used as a short-cut method for the preliminary estimation of surface ratio sphericity.

- There is very little variation in the density of the media. The density varied between 2 623 and 2 641 $kg \cdot m^{-3}$, with a median value of 2 628 $kg \cdot m^{-3}$.
- The media all had low attrition losses upon an extended backwash test. The mass losses varied between 0.022% and 0.37%, with a median value of 0.15%.
- The silica content of the media was exceptionally high. The silica content varied between 98.43% and 99.96%, with a median value of 99.47%. The contaminants were mainly iron and aluminium compounds.
- The acid solubility, another measure of media purity, was low. It varied between 0.05% and 0.26%, with a median value of 0.11%.

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