**In the first in a series of articles discussing the impact and properties of manufactured sand, Barry Hudson explores the properties of aggregates and how they influence concrete performance and cost.**

# AGGREGATE SHAPE AFFECTS CONCRETE COST

While the shape difference between a bolt and a marble is obvious, they may have an identical cross section. Likewise, distinct particle shapes behave differently in a concrete or asphalt mix, but the sieve analysis may get the same result.

For the aggregate producer, one of the largest potential clients for crushed or natural stone and sand has to be the concrete producer.

It is to the benefit of aggregate producers therefore, that they understand exactly what the concrete producer requires from the aggregates, and to utilise the resources of both operations in the most efficient manner. The aggregate producer, or quarry operation, needs to understand just how their materials influence the operations of the concrete manufacturer. The same can be said for the relationship between the quarries and asphalt producers. The implementation of the Superpave specifications in the United States and the subsequent impact on the entire aggregate industry is testimony to that.

### Aggregates occupy volume

Typically, in a mix of concrete, the aggregate and sand will occupy in the vicinity of 80 per cent of the total volume of the finished mix. Obviously, the most expensive component in the concrete mix is cement. A typical value of the cement for the same volume of concrete is 60 per cent of the cost of all of the raw materials.

At 80 per cent of the volume of the concrete mix, it is easy to understand that the aggregate properties can, and do, have a major impact on the concrete performance, both in its plastic and hardened states. Also, as I will demonstrate, aggregate properties have an impact on the overall cost effectiveness of the concrete.

Assuming that the aggregates, either natural or crushed, are inert or neutral type particles, the three basic properties that the individual particles possess are: particle shape, surface texture, and particle size.

In the past, the usual way to characterise a particle, or a sample of particles was to perform a sieve analysis. From this sieve analysis, a gradation curve is generated and the sample of aggregate is deemed to be of suitable quality or not by whether or not the gradation curve fits inside the prescribed envelope.

However, this method of testing for the quality of a sample of aggregate tells us little about the shape of the particles, or the surface texture. For example, if you were to perform a sieve analysis on some marbles with a diameter of 25 mm, and compare the results to a sample of bolts, with a cross sectional measurement of 25 mm, you would get the same result. Obviously, these two particle shapes will behave in a different fashion in a concrete or asphalt mix, but the sieve analysis is the same.

The equidimensionality and angularity of coarse and fine aggregate particles; the degree and shape of the relief on their surfaces; the amount of surface area caused by the degree of relief, and the chemical and physical nature of coatings, if present, are all characteristics that significantly affect the properties of both fresh and hardened concrete.

Differences in particle shape and surface texture between aggregates will affect their bulk voids contents and frictional properties and, in turn, the ingredient proportions, mechanical properties, and economy of the concrete mixtures made from them.

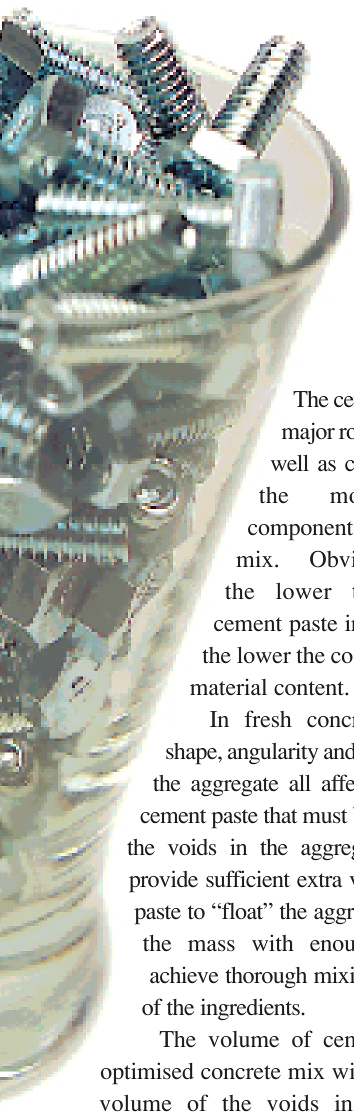
### Water/Cement ratio

It is accepted that as a general rule, the lower the water/cement ratio for a given concrete, the higher its quality. (The quality being measured by compressive strength, durability, resistance to abrasion and chemical attack and impermeability etc.) The use of cubical or equidimensional aggregates can be a major factor in the reduction in the water cement ratio, and therefore the use of these well shaped aggregates has the ability to:

- Decrease the cost of production and placement of concrete,
- Increase the workability without having a detrimental effect on the quality or cost, or
- Alternatively simply enhance the overall quality of the concrete.

### Aggregate shape and cement paste volume

There are two major states in which a concrete mix can exist. The first is its plastic or workable state, the second its hardened state.



The cement paste plays a major role in both states as well as collectively being the most expensive component of the concrete mix. Obviously therefore, the lower the volume of cement paste in a concrete mix, the lower the cost of the total raw material content.

In fresh concrete the particle shape, angularity and surface texture of the aggregate all affect the volume of cement paste that must be used first to fill the voids in the aggregate and then to provide sufficient extra volume of cement paste to "float" the aggregate and provide the mass with enough plasticity to achieve thorough mixing and dispersion of the ingredients.

The volume of cement paste in an optimised concrete mix will be equal to the volume of the voids in the compacted aggregate, as well as having sufficient extra volume of paste needed for workability. Powers[1] has noted that the volume of concrete exceeds the volume of the compacted aggregate by three to 10 per cent, and not usually by more than four per cent when air entraining agents are not used.

Concretes manufactured with aggregates that are angular, rough, and irregularly shaped require a higher volume of cement paste. This is because fewer coarse aggregate particles can be packed, without interference, in concrete where the shape is irregular rather than cubical.

From the point of view of the contribution of aggregate shape to that of the total volume of cement paste, and therefore cement quantity, it is physically very easy to demonstrate a direct relationship between the packed aggregate voids content and cement paste volume in an optimised concrete mix.

From data in Wills[2], Shergold[3] and Kaplan [4,5], it may be estimated that, at a given grading of combined aggregate, the maximum ranges in voids content at dense compaction between aggregates at the extremes of the shape and texture spectrum may be around 10 to 11 per cent. In practice the average difference should be less because it is unlikely that two aggregates being compared would be at opposite extremes of the shape and texture spectrum. A typical value for the percentage voids difference between cubical aggregates and elongated or flaky aggregates will usually be four to five per cent.

The extra volume of cement paste required to produce an acceptable quality of concrete with a specified workability factor is obviously significantly less for coarse aggregates with a cubical shape rather than those of flaky or elongated aggregate shape.

From the data above, it is reasonable to expect that the total saving in cement paste, and therefore cement volume, by using a cubical shaped aggregate rather than a poorly shaped aggregate, will be about four to five per cent.

One can conclude therefore that a good particle shape in the coarse aggregate fraction of a concrete mix can permit production of concrete at a given workability using a smaller volume of cement paste, and hence a smaller volume of cement and a lower total cost.

## Coarse aggregate particle size in concrete

The strength of concrete of given mix proportions is very seriously affected by the degree of its compaction. It is vital therefore, that the consistency of the mix be such that the concrete can be transported, placed and finished easily and without segregation.

The role of aggregate in a concrete mix differs relative to the nominal size of the particle. For example, the maximum particle size in a given concrete mix design is usually dictated by some form of physical constraint such as spacing between reinforcing bars, the size or spacing of formwork. The normal practice in designing a concrete mix is to have the largest possible maximum particle size, so to capitalise on the decreasing surface area-to-volume ratio as a particle size increases. In other words, the larger the aggregate particle, the less surface area present in relation to that particle's total volume. The lower the surface area, the less cement paste required to coat and lubricate the particle, and hence the total volume of cement paste is minimised.

The proportioning of aggregate in a concrete mix usually begins with selecting the maximum particle size. The coarse aggregate portion of a concrete mix is usually defined as the material with a particle size greater than 4.75 mm. Typically, graded concrete aggregates will be produced in size ranges that double their nominal bottom size particle, ie. the finest concrete "coarse aggregate" is graded 5 mm to a nominal top size of 10 mm. The next grade of aggregate would be 10 mm bottom size to a top size of 20 mm. The next 20 mm to 40 mm and so forth. The reason for separating the particle size fractions is to keep the aggregate portion of the concrete mix as evenly graded as possible, as well as minimising the effects of segregation. It should be mentioned at this point however, that the incidence or degree of segregation is significantly diminished with well shaped aggregates

In the majority of concrete mix designs, an even gradation of the total coarse aggregate fraction is desirable. Having the coarse aggregate sizes split as above, the best particle size distribution can be obtained resulting in optimisation of the voids content by having smaller aggregate particles fitting between the larger particles. It is highly desirable to be able to combine the coarse aggregates in differing ratios so that the individual characteristics of each size range can be maximised for different concrete applications. For example, the aggregate proportions for pumping concrete are different from those of a concrete building block mix.

## Fine aggregate in concrete

The impact that the physical characteristics of sand (or minus 5 mm aggregate), exhibits on the concrete mix properties, in both the plastic and hardened states, is significantly greater than with the coarse aggregate fraction. The same principles of total internal friction and void content also apply to the fine aggregate. Due to the vastly smaller particle size however, and hence the greatly increased surface area to volume ratio, any detrimental or undesirable shape or texture properties that the fine aggregates particle have will be greatly amplified in both the plastic and hardened states of concrete.

With the ever-increasing environmental pressures and the diminishing resources of natural sands throughout the world, viable alternatives to natural sands are necessary. The obvious alternative to natural sands is to utilise manufactured sands derived from crushed rock.

When investigating the use of such sand, it is virtually impossible to compare the normal practices and test results to those for naturally occurring sands. One of the main reasons why naturally occurring and manufactured sand products cannot be compared is the nature of the minus 75 micron (minus #200) size fraction.

This very fine particle size in naturally occurring sands often contains undesirable minerals and clays. The effect of these materials on both the fresh and hardened states of concrete can be extremely harmful. For fresh concrete, the effect of clay particles is not obvious, as the particles absorb disproportionate volumes of water and hence swell to many times their original size. This swelling occupies a volume in the cement paste in the fresh state of the concrete. When the concrete hardens, the clay particles contract and leave minute voids, which in turn increase the shrinkage, and permeability, and hence, reduce chemical resistance, and, of course, the concrete's compressive strength. Other undesirable materials can exist in this fine material fraction and range from basic chlorides through to more harmful chemicals.

Because of diminished risk of impurities in manufactured sand, the incidence of impurity contamination is significantly reduced if not totally eliminated. With this reduction of the risk of undesirable material, "traditional" particle size distribution curves can be altered to allow a higher percentage of minus 75 (minus #200) micron material.

## Aggregate specific surface

The relationship between surface area and volume is known as specific surface. Taking for simplicity a sphere of diameter D as representative of the shape of the aggregate we have the ratio of surface area to volume of 6/D. For particles of a different shape, a coefficient other than 6/D would be obtained but the surface area is still inversely proportional to the particle size.

In the case of graded aggregate, the grading and the overall specific surface are related to one another, although, of course, there are many grading curves corresponding to the same specific surface.

It can be seen that, having chosen the maximum size of aggregate and its grading, we can express the total surface area of the particles using the specific surface as a parameter, and it is the total surface area of the aggregate that determines the water requirement or the workability of a concrete mix (Voids content is directly proportional to specific surface).

Mix design on the basis of specific surface of the aggregate was first suggested by Edwards[6] as far back as 1918, and interest in this method was renewed 40 years later. Specific surface can be determined using the water permeability method[7] but no simple field test is available, and a mathematical approach is made difficult by the variability in the shape of aggregate particles. This, however, is not the only reason why the design of mixes on the basis of specific surface of aggregate is not recommended.

## Manufactured fine aggregate in concrete

The application of surface area calculations was found to break down with aggregate particles smaller than 150 microns, (#100) and for cement. These particles, and also some larger sand particles, appear to act as a lubricant in the mix, and as long as the particle shape is rounded or cubical they do not require wetting in quite the same way as coarse particles. An indication of this can be obtained from some results of tests by Glanville, Collins and Matthews[8], reproduced in part in the following table.

The majority of mix design methods try to optimise the cost of the raw materials whilst achieving a desired concrete quality. To do this, the mix design attempts to fill any voids in the aggregate with other aggregate particles, hence reducing the total volume of paste required.

Ignoring the chemical contribution to the concrete that a cement particle makes, and taking into consideration the cement particle size (varying between 5 and 90 microns), the physical cement fraction of a concrete mix must be considered along with the minus 150 micron (minus #100) portion of a manufactured sand.

As illustrated in Table 1, the manufactured sand particles of less than 150 micron do not have the same function in a concrete mix as larger particles above 150 microns, in regard to mixing water demand. The particles less than 150 micron, including the cement, act in the fresh concrete as a lubricant.

Assuming that in various grades of concrete mix using a constant source of aggregate you require the same volume of minus 150 micron paste for lubrication to achieve a given workability, the presence of a relatively high percentage of minus 150 micron (minus #100) aggregate can be beneficial.

This is the case especially in concretes that have a target strength of less than 20 Mpa (3000 psi). The volume of cement that that, say, a design 35 Mpa (5000 psi) mix may have could be in the vicinity of 100 kg/m$^3$ greater than that of a 20 Mpa (3000psi) concrete, hence the 100 kg of cement or lubricating volume can be replaced by minus 150 micron crushed aggregate (of cubical shape) without significantly increasing the mixing water demand.

The presence of minus 150 micron (minus #100) combined aggregate and cement material also assists in the finishability of concrete. Assuming that the amount of this material is not so great as to induce shrinkage and/or bleeding, the fine material is usually more receptive to trowel finishing, and because there is a cost-effective volume of minus 150 micron (minus #100) (the aggregate fraction),

| Grading Curve | -150 Micron as percentage of total aggregate | Low workability | Medium workability | High workability |
|---|---|---|---|---|
| 1 | 0 | 0.612 | - | - |
| | 3.0 | 0.618 | - | - |
| | 6.0 | 0.634 | - | - |
| | 9.0 | - | 0.700 | 0.750 |
| | 12.0 | - | 0.730 | 0.760 |
| 2 | 0 | 0.630 | - | - |
| | 3.5 | 0.635 | 0.715 | - |
| | 7.0 | 0.648 | 0.715 | 0.750 |
| | 10.5 | 0.653 | 0.720 | 0.745 |
| | 14.0 | - | 0.720 | 0.750 |
| 3 | 0 | 0.665 | 0.735 | 0.780 |
| | 4.2 | 0.665 | 0.725 | 0.758 |
| | 8.4 | 0.682 | 0.735 | 0.766 |
| | 12.6 | 0.695 | 0.740 | 0.770 |
| | 16.8 | 0.740 | 0.775 | 0.790 |
| 4 | 0 | 0.713 | 0.780 | 0.820 |
| | 4.8 | 0.720 | 0.787 | 0.825 |
| | 9.6 | 0.732 | 0.787 | 0.825 |
| | 14.4 | 0.765 | 0.805 | 0.830 |
| | 19.2 | 0.807 | 0.835 | 0.850 |

**Table 1**

the incidence of surface blemishing can be significantly reduced.

However, the quality of the sand (as it relates to particle shape, surface texture and gradation) dictates the workable amount of fines (minus #75 or minus #200) that can be in sand product. In the next article in this series, we will discuss the various properties of a good manufactured sand that make it possible to have higher fines present.

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