Concrete Workability With High

In this, the fourth article in the series exploring manufactured sands and aggregates, Barry Hudson looks into the importance of having high fines contents in the manufactured sand gradation.

The surface texture, particle angularity and particle shape all have an impact on the workability of concrete in its plastic state. If you can imagine that the surface condition of a particle will exert a frictional force to resist the movement within the cement paste, you will understand that the sharp, angular edges, or flaky, elongated particles will resist such transportation. However, if the particles are of a cubical or equidimensional nature, the resistance to movement in the cement paste will not be as great.

The water required for a given degree of concrete workability (slump) is directly related to the void space in the aggregate. When the void space is high, the water requirement necessary for a given workability will also be high, and the strength of the concrete after curing will be low unless additional cement is added to the mix.

The void content of manufactured sand (when identically graded by weight) is generally greater than that of natural sands. These voids must be filled with water, cement, fly ash, or fines to produce concrete having the desired workability and strength. In fresh concrete, the particle shape, angularity and surface texture of the aggregate 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 all of the ingredients.

Graph 1 illustrates the water required for constant mortar flow in relation to the percentage of minus 75 micron material in the manufactured sand. The graph adequately demonstrates that for the material fraction below 150 micron, as long as the particles are of a equidimensional shape, these finer particles actually act as a lubricant in the concrete mix.

In most cases, a concrete manufactured with a high percentage of minus 75 micron material will yield a more cohesive mix than that of a concrete made with a typical natural sand.

Graph 1 illustrates the typical relationship between the amount of minus 75 micron material in a manufactured sand and the water required to produce mortars having constant workability. These particular relationships are for manufactured sand from a constant source having a cubical particle shape. The relationship indicates that water demand is fairly constant over the range of minus 75 micron material evaluated up to 10 per cent and appears to decrease at higher percentages, due to the lubricating effect of the minus 150 micron material.

Because of the lubrication effects of the minus 150 micron material, the specific surface gives a somewhat misleading picture as to the workability that can be expected from a concrete mix. An empirical surface index was suggested by Murdock [1] and its values as well as those of the specific surface are given in Table 1. The overall effect of the surface area of an aggregate of a given grading is obtained by multiplying the percentage mass of any size fraction by the coefficient corresponding to that fraction, and summing the products. According to Murdock, the surface index (modified by an angularity index) should be used, and in fact the values of this index are based on empirical results.

You will note that the apparent specific surface according to Murdock is at its highest in the coarse end of the sand gradation, this may well explain why "normal" sand gradations tend to produce concrete that is harsh, where the reduction of the population of these size particles seem to let the concrete flow efficiently. Murdock's surface index also reinforces the minus 150 micron lubrication theory.

Particle Size mm	Relative Surface Area	Murdock's Surface Index fraction
76 - 38	0.5	0.5
38 - 19	1	1
19 - 9.5	2	2
9.5 - 4.75	4	4
4.75 - 2.36	8	8
2.36 - 1.18	16	12
1.18 - .600	32	15
.600 - .300	64	12
.300 - .150	128	10
< .150	256+	1

Table 1: Source, L.J. Murdock, The Workability of concrete, Magazine for Concrete Research. No. 36 pp. 135-144 (November 1960).

Concrete Finishability With High Fines Content Sands

As long as the particle shape of the manufactured sand is cubical, throughout the entire gradation, and a gradation that is suited to manufactured sand is employed, it has been shown that the compressive strength and workability properties can be superior to those of natural sands in concrete. However, one of the main detractions from using manufactured sands

Fines Content Sands

in the past has been the difficulty in finishing the concrete. (See graphic 1)

Durability/Permeability and High Fines Content Sands

With the rapid increase in technology in the cement and concrete industries over the last decade, the total mass of cement required to attain the nominal or minimal compressive strengths has progressively diminished. Specifications for minimal cement contents have got to an all time low. However, as stated earlier, the quality of a concrete mix is not just measured by its compressive strength.

The chemical reaction that occurs when cement and water are added together creates complex matrices of capillaries and other products of hydration. To ensure that a concrete is durable at a given cement content, it is important that the water / cement ratio is as low as possible. The inclusion of a high percentage of minus 75 micron in a suitably graded form, with a cubical particle shape, allows for efficient aggregate packing and results in a denser concrete mix. The denser concrete will be more durable and less permeable than that of concrete produced without these manufactured fine particles.

The inclusion of a higher percentage of minus 75 micron material and the effect on the concrete permeability is illustrated in Graph 2. This increased efficiency in void filling in the ultra fine particle size range of the cement paste can actually force capillaries to close, thereby stopping the passage of liquids, decreasing permeability and increasing the durability by preventing chemical or liquid ingress into the concrete mass.

Concrete Bleeding Properties with High Fines Contents

As demonstrated, given the correct conditions and product specifications, manufactured sands can not only adequately replace natural sands, they can offer distinct performance advantages in compressive strength, durability and placement characteristics. There is however one potential downside point that needs to be recognised and planned for if high fines concrete is going to be used.

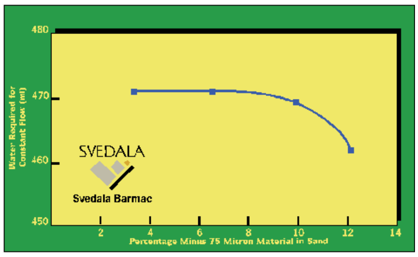
Bleeding, also known as water gain, is a form of segregation in which some of the water in the mix tends to rise to the surface of freshly placed concrete. This is caused by the inability of the solid constituents of the mix to hold all of the mixing water when they settle downwards. We are therefore dealing with subsidence or sedimentation. Bleeding can be expressed quantitatively as the total sedimentation per unit height of concrete. The bleeding capacity as well as the rate of bleeding can be determined experimentally using various test methods.

As a result of bleeding the top of every lift may become too wet and non durable concrete will result due to the surface having a high water / cement ratio. On the other hand, if evaporation from the surface of the concrete is faster than the bleeding rate, plastic shrinkage will occur.

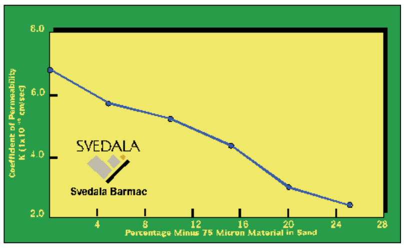
The higher the percentage of minus 75 micron material in a manufactured sand, the lower the typical bleed rate for the concrete will be. It is crucial to the performance of hardened concrete that plastic shrinkage is controlled. Concrete made with sands with minus 75 micron content in the 12 to 15 percent range when used in areas with climates of low humidity and dry winds often demonstrates plastic shrinkage problems. Table 2 illustrates the effect of wind velocity on concrete shrinkage. Graph 3 shows the shrinkage characteristics of concrete made with different quantities of minus 75 micron material in the manufactured sand.

There is no noticeable difference in the shrinkage of the concrete between similar quantities of minus 75 micron material in both natural and manufactured sands for concrete. The point must be stressed though, that when higher fines concrete is being produced, the plastic shrinkage properties have to be closely monitored.

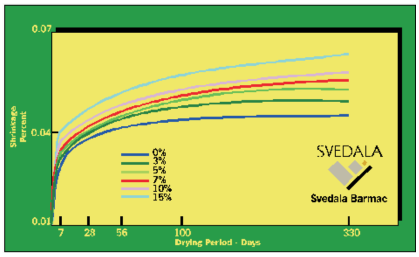
Once again, a critical area of the controllability of the shrinkage and bleeding is the quality of the particle shape. If particles are not cubical, they will tend to produce concrete that has excessive bleeding due to a high initial water demand



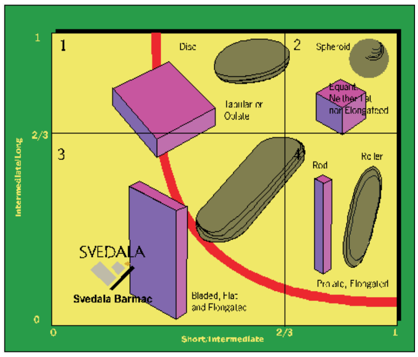
Graph 1: Source, C.R. Marek, Vulcan Materials Company - Importance of Fine Aggregate Shape and Grading on Properties of Concrete, Paper presented at Centre for Aggregate Research March 2-4, 1995.



Graph 2: Source, Tahir Celik and Khaled Marar. Effects of Crushed Stone Dust on Some Properties of Concrete. Cement and Concrete Research, Vol. 26, No. 7, pp. 1121 - 1130. 1996.



Graph 3: Source, Ahmed E Ahmed and Ahmed A. El-Kourd. - Properties of Concrete Incorporating Natural and Crushed Stone Very Fine Sand. ACI Materials Journal, Vol. 86, No 4, July 1989. pp 417 - 424



Graphic 2: Source, Ozol, M.A., Chapter 35 - "Shape, Surface texture, Surface Area, and Coatings." ASTM Special Technical Publication No. 169-B, pp. 584-625. Philadelphia, PA, 1978.

to achieve a desired workability.

The plastic shrinkage of the concrete, or the surface protection that may be required if the shrinkage becomes a problem, will be overcome by proper concrete curing practices that should already be in place on a construction site. The concrete should be protected from drying forces by being kept moist or the application of curing membranes or concrete covers.

Particle Shape

The concept of particle shape incorporates three geometrical ideas; sphericity, roundness and form. "Sphericity" is a measure of how nearly equal are the three axes or dimensions of a particle. "Roundness" is the measure of the sharpness of the edges and corners of a particle. "Form" is a measure of the relation between the three dimensions of a particle based on ratios between the proportions of the long, (a), medium, (b), and the short, (c), axes of the particle. Form, also referred to as "shape factor," is used to distinguish between particles of the same numerical sphericity, but having different axial proportions. Shape is described in terms of ratios as follows:

When the shape factor is greater than one, the intermediate length is the closest to the shortest in length, and prolateness is indicated. When the shape factor is less than one, the intermediate length is closest to the longest length, and oblateness is indicated. A graphical representation of various shape categories is given in the Graphic 2.

Wind Velocity m/s	Percentage Shrinkage 8 hours after placing 10-6
0	1 700
0.6	6 000
1.0	7 300

Table 2: Source, Ahmed E Ahmed and Ahmed A. El-Kourd. - Properties of Concrete Incorporating Natural and Crushed Stone Very Fine Sand. ACI Materials Journal, Vol. 86, No 4, July 1989. pp 417 - 424

The roundability of a natural sand particle depends on the particles hardness and toughness, as well as geological factors such as abrasion, attrition, chipping, rubbing and solution that occur during transport to the site of deposition.

The most useful test to determine the shape of a sand particle is to determine the voids content of the material in a loose pour state. The lower the voids content, the more equidimensional the particles. As with the previous table, in a manufactured sand, the cubical particle will yield the lowest voids content, especially if the cubical particle has had its sharp edges and corners removed.

The voids content is a good representation of particle shape right across the particle size range, from the top size aggregate in a mix through to the finest of sand particles.

Mortar Volume

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 [2] has noted that the volume of concrete exceeds the volume of the compacted aggregate by 3 to 10 per cent, and not usually by more than 4 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.

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.

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

The major problem that most manufactured sands have is that because the sand material is so fine, the particle shape is usually not cubical. Kojovic [3] conducted tests to determine particle shape at the extremes from the crusher setting. The tests indicated that the further a particle size was from this setting, the higher the probability that it would be flaky or elongated.

When you combine the effect of flaky and elongated material with the small particle size, you will appreciate that the relationship between total surface area and volume of the particle is considerably greater, hence the use of manufactured sands that do not have a cubical shape should be avoided. Poorly shaped sands in concrete have a much greater total effect on concrete quality and workability than coarse aggregates of bad shape, because of the relationship between particle size and surface area-to-volume ratio.

Working to the same water/cement ratio, it may be calculated from quantities reported by Blanks [4] that there was approximately an eight percentage point difference in paste volume required - the undifferentiated amount for both void filling and workability - between two concretes with the same maximum size coarse aggregate 38 mm, but one made with a "cubical" sand and the other with a "harsh and angular" type sand. The first concrete needed 99.8 kg of water and 261.6 kg/m^3 of cement, the second 136.1 kg of water and 356.4 kg of cement.

Not varying anything but allowing the effect of particle shape and surface texture on the plasticity of a mortar mix at constant sand gradation and mix proportions to be expressed, Malhotra [5], using the time index of Rex and Peck [6] as a measure of the particle shape and surface texture of seven crushed sands, found the flow of mortars (of exactly the same mix proportions) was related inversely to the time indices of the sands. He concluded that the water requirement for constant flow would vary as the time index varied, and that the index is a satisfactory method for determining shape and water demand for fine aggregates.

Allowing the water/cement ratio to change, Wills [7] showed the

To a large extent, the problems of finishability can be attributed to:
(a) The poor particle shape of the manufactured sands that have been trailed
(b) The gradations have typically been deficient in the minus 150 micron size range
(c) There has been a tendency to have an over abundance of coarse manufactured sand particles

Graphic 1: Common problems with the finishability of concrete produced with manufactured sand. Note: Concrete finishability can be enhanced by the use of various concrete admixtures, such as air entraining agents and plasticisers.

direct influence of particle shape on the void content of the aggregate and, in turn, on the concrete mixing water demand at constant cement content, and, through the mixing water demand, on the strength of the concrete.

The effect that fine aggregates have on the concrete compared with the coarse aggregates can be quantified in the following example. A four percent increase in voids of the fine aggregate caused a 14.9 litre/m^3 increase in water demand, which lowered the compressive strength by 6.9 MPa, while a 3.8 - 5.7 litre/m^3 increase was associated with a similar increase in voids content of the coarse aggregate.

Fine aggregates influenced compressive strength almost entirely through their effect on mixing water demand, whereas, for the coarse aggregates, other factors such as elasticity or bond strength had a contributing influence on the strength decline.

In the next article in this series, we will look closer at Murdock's Surface Index and how this holds the key as to what properties and gradations a manufactured sand needs to have to be utilised in concrete. ■

Barry Hudson is with Svedala USA and is currently undertaking collaborative research trials with manufactured sand with Vulcan Materials Company in the United States. This is the fourth part of a continuing series of articles examining manufactured sand and concrete.

Elongation Ration	= q = b/a
Flatness Ratio	= p = c/b
Shape Factor	= f = p/q =ac/b2

Table 3: Source, Ozol, M.A., Chapter 35 - "Shape, Surface texture, Surface Area, and Coatings." ASTM Special Technical Publication No. 169-B, pp. 584-625. Philadelphia, PA, 1978.