Impact of manufactured sand in concrete

In the first of this series of articles on manufactured sand and aggregates for concrete, I touched on the importance of particle shape, as well as the material gradation and surface texture. The article concluded with an illustration of the minus 100 mesh material (-150 micron) having very little impact on the water demand of a concrete mix. Following on the same lines, this article is an introduction to the properties of manufactured sand that will allow higher percentages of materials passing the 200 mesh sieve (75 micron). By Barry Hudson.

Quarry Waste

It is not an unusual sight to see ever growing piles of waste product build up in a quarry site. Typically, the waste product is crusher or fracture fines. These materials are usually lacking in certain size fractions, and are of a flaky or elongated nature.

Huge stockpiles of this unsaleable or low value material are obviously a problem. Sometimes measured by the hundreds of thousands of cubic metres, these mountains occupy valuable quarry space and are an environmental headache.

The major markets for the particle size range that crusher dust or fracture fines fall into, are the concrete or asphalt industries. What makes this fine material undesirable for use in asphalt or concrete is not just that the materials are usually deficient in certain areas of a gradation, but typically the particle shape is very poor.

Particle Size Range

Under the right conditions, one of the largest industry groups that may be able to take this fine material, or manufactured sand, is the concrete industry. As part of our ongoing research program, we have been studying the properties required from manufactured or crushed rock fines, so that instead of producing a low value material, a highly sought-after premium manufactured sand can be delivered.

As environmental pressures increase, available natural sand resources are becoming less economic or totally out of reach to the concrete producer. The necessity of using manufactured sand is fast becoming a fact of life. There is however, an undoubted prejudice in the concrete industry towards the use of fine crushed rock products. Typically, when a concrete plant trials or tests the new concrete batch with these materials, they experience problems with compressive strength results, the concrete usually has excessive bleeding characteristics and the concrete placers find the material unworkable and hard to finish.

All of these problems are well documented, and anyone who has had experience with the substitution of manufactured sand for a natural product will have no doubt encountered these and more. There is a real resistance in the concrete industry to swap to manufactured sands for the reasons listed. The challenge to the aggregate industry is to handle the situation properly, and to understand that manufactured sands are completely different from natural sands, and so must be treated accordingly. The last thing that a manufactured sand user should do is use manufactured sand as a natural sand substitute and specify it to be at the same gradation, and the same quantity in a concrete mix.

Treat Manufactured Sands Differently

Most natural sands have spherical particles, with some having more cubical particles. The majority of manufactured fine aggregates or sands are extremely angular, flaky or elongated with only a few processes producing a cubical product. The characteristics of the fine aggregate significantly influence water requirement, workability, finishability, bleeding, segregation, strength and durability properties of the concrete.

It is accepted that as a general rule, the lower the water / cement ratio for a given concrete, the higher its quality. In a concrete mix therefore, the ratio of water to that of cement is extremely important. There are many factors that can influence the water demand, but when we consider the effect that aggregate has on this area of concrete mix design, the critical physical properties can be narrowed down to particle shape, angularity and surface texture. The overall effect of these various properties will alter with the way in which the aggregate grading is constructed as well.

Aggregate Specific Surface

All of these properties have an effect on a particle's specific surface. Specific surface is the relationship between surface area of a particle and its volume. The higher the surface area to volume ratio, the greater the specific surface. This is very important when considering that in a concrete mix every surface of every particle has to be coated by the cement paste in order to be 'glued' together. The relationship between particle size, the volume it occupies, and the surface area of the particles, is an important consideration. This relationship is shown in Table 1.

Particle Size mm	Particle Volume (mm^3)	Number of particles in 8200 mm^3	Surface area in 8200 mm^3 (m^2)
25	8200	1	0.002
0.075	$2x10^{-4}$	$4x10^{7}$	0.7
0.002	$4x10^{-9}$	$2x10^{12}$	24

Table 1: Source, R.H. Brown, Vulcan Materials Company. - Mineral Fines, Today's Opportunity, Tomorrow's Success. Paper presented at Center for Aggregate Research March 2-4, 1995.

As illustrated, one 25mm particle has a volume of 8200 mm^3, if assumed to be a sphere (The most efficient specific surface shape), but has a small surface area, 0.002m^2. A spherical clay size particle, 2 microns, has a volume of 4 x 10^{-9} mm^3 and it would take 2000,000,000,000 of these particles to occupy the same solid volume of space. These ultra-fine particles would

Sieve Size	ASTM C-33 Specification	Talbot Grading for n= 0.5	Talbot Grading for n= 0.4	Talbot Grading for n= 0.3
9.5mm	100	100	100	100
4.75mm	95-100	70.7	75.8	81.2
2.36mm	80-100	49.8	57.3	65.8
1.18mm	50-85	35.2	43.4	53.5
600um	25-60	25.1	33.1	43.6
300um	10-30	17.8	25.1	35.5
150um	2-10	12.6	19.0	28.8
75um	0-5	8.9	14.4	23.4

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

however have a surface area of 24 m^2. The ratio of surface area to volume ratio becomes even more extreme the less equidimensional or spherical a particle gets.

Bulk Voids Contents

Differences in particle shape affect bulk voids contents of the aggregates, and in turn, the ingredient proportions, mechanical properties, and the economy of concrete mixtures. Cubical particles are preferred to flat or elongated particles for use as concrete aggregates because they present less surface area per unit volume and generally produce tighter packing when compacted. To assist with cement paste-aggregate particle bond, it is desirable to have a 'roughened' particle surface.

It is important that this surface is not too rough or honeycombed, as this will greatly influence the amount of water required to get the concrete workable in its plastic state. Spherical particles in most cases are 'polished' and offer little for the cement paste to bond with, and can produce concrete with reduced strengths, particularly flexural strength.

When proportioning aggregates for a concrete mix, one of the basic considerations is that you are trying to achieve the maximum aggregate packing effect by having the minimum volume of voids between individual aggregate particles.

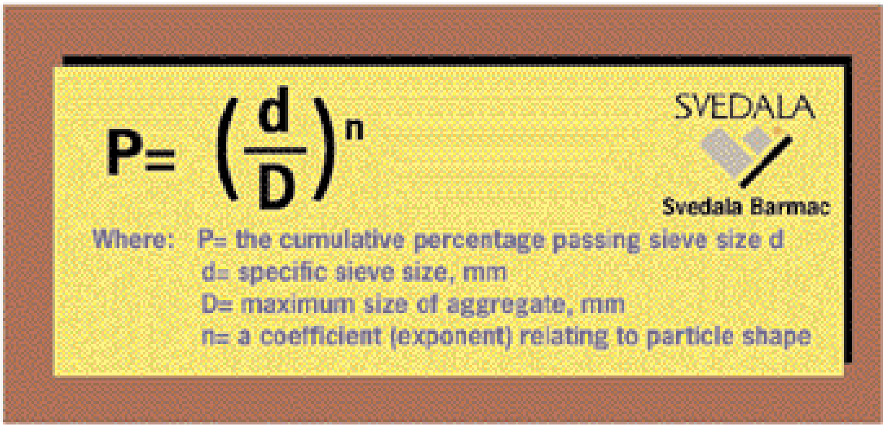
The grading of fine aggregate required to produce workable concrete is a function of the aggregate properties. The ideal grading for fine aggregate is frequently calculated by Talbot's formula. The grading curves from Talbot's formula give the percentages of materials that are required to fill the voids left by the particle size directly above, taking into account the particle shape.

Theoretical Manufactured Sand

Gradings

Mather [1] reported that a coefficient, n, of 0.3 to 0.38 is appropriate for angular crushed fine aggregate, and 0.5 is appropriate for spherically shaped natural sands and gravels. Further, if a grading suitable for relatively spherical particles is employed with particles that are highly non-spherical, the results may be expected to be less satisfactory than if a more appropriate grading had been employed.

The gradings of fine aggregate calculated using an exponent of 0.3, 0.4 and 0.5 are given in Table 2. Also shown in this table is the grading specification for fine aggregate for use in Portland cement concrete as contained in ASTM C-33. Angular crushed aggregates with a coefficient of 0.3 to 0.4 result in a greater proportion of the finer particle sizes to reduce the voids in the mixture. These particles also provide mixture workability, as demonstrated later.



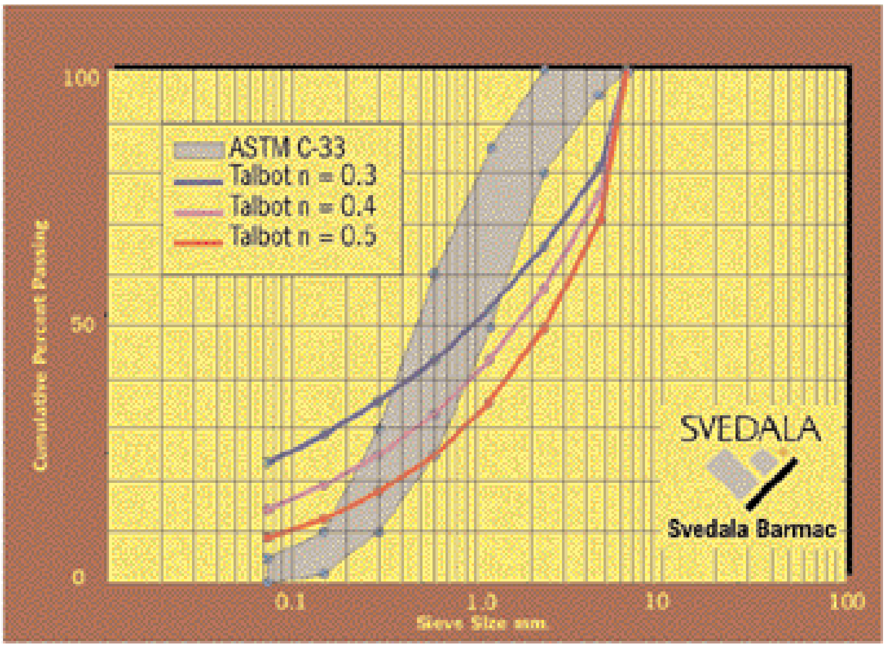
Graphic 1: Talbot's formula for calculating the theoretical gradation for minimum voids contents in sand.

You will note that the gradings get further away from the ASTM C-33 specification as the fine materials shape deteriorates. (The value of 'n' decreases) The total quantity of fine materials obviously has a dramatic effect on the total surface area of the concrete mix due to the excessively high surface area to volume ratio of the particles. It can be concluded therefore, that the particle shape of the fine aggregate has to be as close as possible to being cubical for an acceptable level of specific surface of the particles for a given size.

If the particles are not cubical or equidimensional the problem of requiring more finer material in the sand gradation will compound with the higher specific surface of the poorly shaped sand, further reducing the concrete quality. There will also be an increase in the cement and water requirement of the mix. A well shaped crushed or manufactured sand is likely to have an exponent (n) of approximately 4.0. This of course will depend on the method of crushing and the parent rock.

Manufactured sand gradation

The mathematical model does not reflect the overall gradation of the ASTM C-33 limits. It is frequently assumed that, among comparable aggregates, the aggregate that has the smallest percentage of voids is the most suitable for use in concrete. Experience with gradation curves, especially for manufactured sands in concrete tell us that the theoretical curves from Talbot's equation usually produce a workable concrete, but the percentage of material retained in the 3.0 to 4.75 mm size range can be too high to yield a workable mix. It should be remembered that Talbot's formula assumes that all of the particles are of the same shape regardless of particle size, and this is the factor that Talbot



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

uses for calculating the best gradation curves for void filling.

If you take the theory of Talbot's formula, and add the practical limits of both the British and American Standard grading curves, which limits the particle size range between 3.0 and 4.75 mm, you start getting 'workable' particle size distribution curves that bear little resemblance to the successful grading curves for a natural sand.

The very interesting feature of the Talbot grading curves is the increase in the amount of fine material required when the manufactured sand coefficient drops in value. The more angular characteristic of crushed or manufactured sand compared to the more spherical nature of most natural sands indicates that a higher percentage of minus 150 micron material is required to fill any voids. However, the increase in percentage of such fine particles will in theory dramatically increase the specific surface of the total manufactured sand product and hence have an extra demand on both the water and cement requirement. Interestingly though, this is not always the case.

Research has proven over the years that the minus 150 micron material in manufactured sand does not increase the water demand of a concrete, and, furthermore, an increase in the volume of the minus 150 micron material can actually increase the workability of a concrete mix, or further increase its compressive strength, assuming the particles are of a cubical or equidimensional shape.

Minus 75 micron material

Of particular interest is perhaps the most dreaded size fraction in a quarry product, the minus 75 micron material, the 'flour' or 'mud'. In traditional concrete technology and thinking, the quantities of ultra fine material have been kept to an absolute minimum. The reason for limiting the amounts of this material in a concrete mix has been due to the experience of natural sands, and the fact that deleterious materials such as clays, silt and other chemicals are typically in this size range. All of these materials have an extremely damaging effect on concrete performance in both the plastic and hardened states.

However, the presence of harmful substances is not the only reason that specifications have been tight in the minus 75 micron size range. Test work completed by Ahmed E. Ahmed [2] on the effects of the increase of minus 75 micron material in the total aggregate grading for both natural and manufactured sands highlights many other reasons.

The results from this study indicate that the water demand increases rapidly when the minus 75 micron fraction of the natural sand gradation is reached (minus 75 micron material is all from the same natural source), but a similar increase in water demand is not experienced in manufactured sand until the percentage of minus 75 micron material exceeds 15 per cent.

Water bleeding data indicates a beneficial effect from the incorporation of more minus 75 micron material in manufactured sand. Compressive strength results for constant water cement ratio concrete increase with the addition of minus 75 micron material in the manufactured sand and not in the natural sand.

Concrete strength with high fines

% replacement of sand with - 75 micron	mixing water kg	- 75 micron material kg	Fine aggregate kg	Manufactured Sand mixing water kg	- 75 micron material kg	Fine aggregate kg
0	245.0	0	720.0	245.0	0	720.0
3	245.0	21.6	698.4	245.0	21.6	698.4
5	245.0	36.0	684.0	245.0	36.0	684.0
7	245.0	50.4	669.6	245.0	50.4	669.6
10	245.0	72.0	684.6	245.0	72.0	648.0
15	245.0	108.0	612.0	245.0	108.0	612.0
	-			245.0		576.0

Table 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.

In the concrete tests, a comparison between natural and crushed sands was made by keeping the water/cement ratio constant at 0.70. Concrete mixtures made using natural sand incorporated 3, 5, 7, 10 and 15 per cent of natural minus 75 micron material by weight of fine aggregate. Mixtures made using manufactured sand incorporated between 3 and 20 per cent of minus 75 micron dust.

The minus 75 micron material was incorporated in the mixes as a direct replacement of an equivalent weight of sand. A control mix without minus 75 micron material was included in each series. The mix proportions are given in Table 3.

The performance of the concrete with the varying percentages of minus 75 micron material were measured by the compressive strength of the concrete. The results are listed in Table 4 and graphically illustrated in Graph 2.

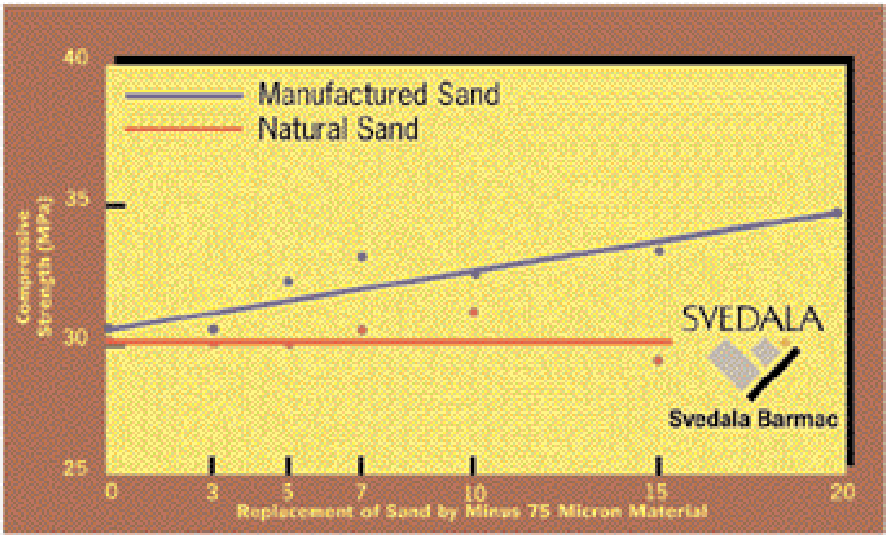
As you will note from the test results, there is a remarkable increase in compressive strength in the concrete manufactured with higher amounts of minus 75 micron material in the manufactured sand and virtually no difference to the compressive strength of the concrete manufactured using natural sands with higher percentages of minus 75 micron material.

As illustrated, current specifications for fine aggregates or sands for concrete are overly restrictive for many concrete applications. Increasing the minus 75 micron content of manufactured sand, assuming that the ultra fine fraction is dust of fracture, to levels exceeding 10 to 15 per cent will have beneficial effect on concrete. Use of high fines manufactured sand will produce concrete with superior compressive strength to that of normal natural sands. ■

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 second part of a continuing series of articles examining manufactured sand and concrete.*

	Natural Sand		Manufactured Sand	
Replacement of sand by - 75 micron material	water/cement ratio by weight	compressive strength mPa (28 day)	water/cement ratio by weight	compressive strength mPa (28 day)
0	0.70	30.0	0.70	30.3
3	0.70	29.9	0.70	30.2
5	0.70	29.8	0.70	31.8
7	0.70	30.2	0.70	32.8
10	0.70	31.1	0.70	32.0
15	0.70	29.7	0.70	33.0
20	0.70		0.70	34.7

Table 4: Source, Ahmed E Ahmed and Ahmed A. El-Kourd. - Properties of Concrete Incorporating Natural



Graph 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.