CHARACTERIZATION OF FINE AGGREGATES IN CONCRETE BY DIFFERENT EXPERIMENTAL APPROACHES

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ABSTRACT

Being its major component, aggregate can occupy up to three-quarter of the volume of concrete. The structure of aggregate formed in hardened state impacts largely on mechanical and durability properties of concrete. On another hand, physical characteristics of aggregate are primarily assumed to be relevant to granular behavior of aggregate. Therefore, characterization of aggregate is of high relevance to concrete studies. In this study, different types of fine aggregate used in concrete, namely river sand and crushed limestone, are selected for morphological characterization. Traditional sieve analysis and laser diffraction method are employed for separation and size analysis of specimens. Different types of fine aggregate samples with comparable size ranges are then analyzed by two advanced dry (static) and wet (dynamic) image analysers. These new analysers are especially suitable for characterization of fine particles, which is difficult by traditional image analysis equipments. Size and shape characteristics of different fine aggregates will be revealed by different experimental methods. The results on different parameters for shape characterization will be compared and discussed.

KEYWORDS: fine aggregate; image analysis; concrete; laser diffraction; particle size; particle shape.

INTRODUCTION

As a basic component, aggregate can occupy over three-quarter volume of concrete. It is used based on both economic and engineering considerations. Aggregate is packed into a mould to form the skeleton structure of concrete. High packing density of aggregate can reduce the amount of binder and so the cost of concrete. Hence, a good selection of aggregate is important for having a good workability and matured performance of concrete.

Compared with size, shape of aggregate is a complex feature to identify and characterize. Manual measurement was firstly developed for the simple shape acquisition. Due to the limitation in measurement tools, Feret diameters and their ratios are frequently assessed by this method. For instance, BS 812-105.1 and BS 812-105.2 specify the manual methods of measuring elongation and flakiness of aggregate. Image analysis (IA) method was developed to replace the laborious and time-consuming manual method. From 2D projections, IA can provide more accurate and elaborate shape information of particles. Different test approaches were developed to image orthogonal profiles for the characterization of Feret diameters, on a holder [1], on a conveyor belt [2], on a rotating cylinder [3]. Kwan *et al.* [4] assumed aggregate from the same resource would have similar shape characteristics and then estimated the thickness and volume of a particle with 2D IA. For the detailed shape information, a mathematical method, called Fourier analysis, was applied on the digital images. By this method, surface texture can be quantitatively assessed [5-7]. More recently, real 3D shape imaging and analysis was attempted on basis of improvement of optical and computer technology. X-ray computer tomography ((micro-tomography) (CT or μCT) is the most popular technology [8-11]. It can even reveal the internal structure of an arbitrary particle without destroying it [8]. μCT can even be used for characterization of fine particles like cement grains [9]. Some other technologies were also applied to 3D shape imaging, *e.g.* the laser detection and ranging (LADAR) [12-13], the focused ion beam nanotomography (FIB-NT) [14], laser triangulation [15], stereological imaging [16].

Although various experimental methods have been developed for shape characterization, IA is still the conventional most canvassed and effective method. It allows imaging and analyzing tens of thousands of particles per minute with a suitable equipment and software. Furthermore, most previous studies focus on characterization of coarse aggregate (from several millimeters to several centimeters) due to the limitations of equipments and software [1-8,10-13,15-16]. Only recent comprehensive X-ray tomography methods go into details of the size level below 1 millimeter or even in the cement-size level [9,14]. Fine aggregate used in concrete is closely relevant to properties of concrete. Granular behavior and packed structure of fine aggregate can directly influence the fresh properties and hardened strength properties. Elastic properties and fracture behavior are also affected by the particle packing of fine aggregate [17-18]. In this study, some advanced IA methods are used for size and shape characterization of fine aggregate.

MATERIALS AND EQUIPMENTS

Two types of typical aggregate used in Belgium for concrete, *i.e.* a fine natural river sand (RS) and a crushed (intrusive) rock (CR), with the same nominal range 0~2 mm are selected in this study. The samples are analyzed by the sieve tests. The relatively large particles (>0.315 mm) are separated by the sieve analysis and then tested by a dry packing method. This part of the work will not be discussed in this paper. Particles of the two selected

aggregate materials passing through the sieve of 0.315 mm are retained as the experimental material and analyzed by different methods.

Sieve analysis is an effective way to evaluate the size and separate the samples. But it is labor intensive and limited by available sieve meshes. Hence, some other experimental approaches are referred to in this study. Optical microscopy is firstly used for the general morphological characterization of two fine aggregates The specimens are then analyzed by two types of IA equipments, *i.e.* 500 Nano and Flowcell (Occhio SA, Belgium). The major difference between the two systems is the method of image acquisition. 500 Nano is a static IA system and acquires images of dry powders. As particle dispersion is essential for accurate analysis of particle size and shape, a vacuum dispersion device is used by this system. It can effectively reduce the agglomeration phenomenon of fine particles. The maximum resolution of this system is around 0.5 µm/pixel. Flowcell is a dynamic IA system and analyzes particles in a liquid environment. A pump is used by this system for a transport of particles in the liquid. The maximum resolution of this system is similar as the 500 Nano system. Based on the combination of high-quality optical components and sophisticated IA software, these two systems are all suitable for fine powder materials. Both size and shape of two type of fine aggregate are characterized by these two IA systems. Laser diffraction (LD) is a conventional popular method for size identification of particulate materials and thus used in this study for a comparison purpose.

RESULTS AND DISCUSSION

On microscopy observation

Optical microscopy observation can give the first impression of the size and shape of two materials. Example images of the two types of fine aggregate are shown in Fig. 1. Some phenomena may be directly observed from these images. Many RS Particles are white and crystal under an optical microscope. Compared with CR, less fine RS particles can be found in the sample. Some particles are quite rounded and worn. Some CR particles are white and others are quite dark in Fig. 1(b). The surface texture of CR particles seems relatively rougher than RS particles. A lot of CR particles are quite angular. Since microscopy observation can only give some qualitative features of aggregate, some quantitative analysis methods, *e.g.* IA, are then referred for the more detailed size and shape comparisons.

On size characterization

PSDs of two types of aggregate are evaluated by different methods. The static IA system, *i.e.* 500 Nano, is firstly used for size analysis. It is logically assumed that particles are lying on the most stable position on the glass plate after dispersion. The inner diameter is defined as the diameter of the maximum inscribed circle of a particle profile. It has been proved that the inner diameter can precisely estimate the sieve size of a particle [19]. The resolution is set to 2.71µm/pixel in the tests. Flowcell is then used in the wet environment for the same purpose. The resolution is set to 1.74 µm/pixel in the tests. The inner diameter is also used to represent the sieve size. Furthermore, LD is used for the comparison purpose. Due to space limitation, only results of RS are discussed in this paper. The final PSDs of two fine aggregate by different methods are plotted in Fig. 2.

Although on the same materials, PSDs by different methods are quite different. The static IA by 500 Nano can reasonably estimate the PSDs of two aggregates. The upper bounds of PSDs comply with sieve test results. However, the results by the dynamic IA method underestimate the PSDs of two aggregates. Large particles are missed by this method. It may due to the serious sedimentation phenomenon of aggregate in the system. Large particles are rarely pumped and passed through the chamber. It indicates further improvements

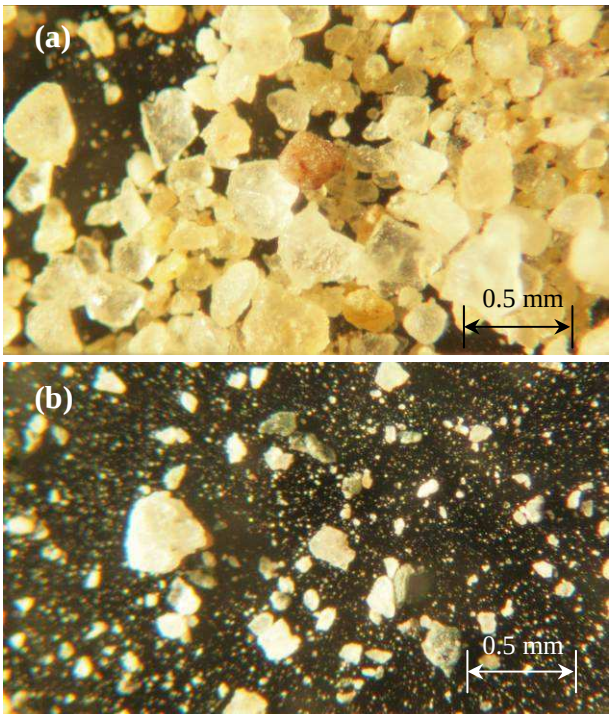

Fig. 1 Microscopic images of two types of fine aggregate: (a) RS and (b) CR

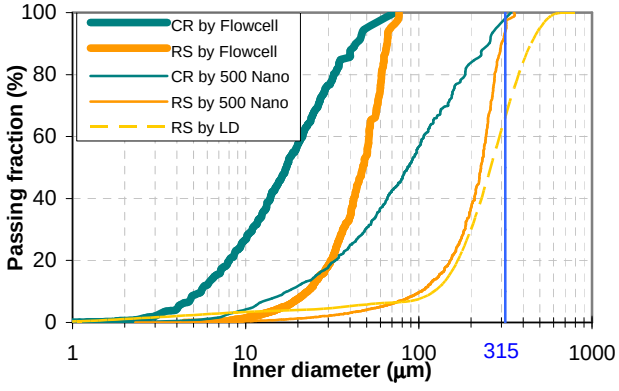

Fig.2 PSDs of two types of aggregate by different measurement methods

are necessary for this dynamic wet IA system for analysis of fine aggregate. Although LD is the most popular method used for PSD analysis, results of RS in this test by LD do not fit properly with the upper bound of PSD by the sieve test. Sizes of some particles are overestimated by LD. This may be due to the sensitivity of LD to geometrical and optical properties of particles. Particle size can be irrelevantly estimated by LD either from maximum distance, length, width, thickness or area of a particle. It is unmatched with the principles of particle size in a sieve test. Therefore, results of PSDs by the static IA are more accurate and reliable. Similar to the estimation from the aforementioned microscopy observation, PSD results by static IA show CR contains a larger proportion of smaller sized particles compared with RS. The PSD curve of CR is more linear in the log-chart than RS.

On shape characterization

Based on the aforementioned size analysis, the static IA is selected for shape characterization of two fine aggregates. Compared with size identification, shape characterization requests higher amount of pixels to represent a particle. Therefore, only particles containing more than 500 pixels are selected in the analysis. The size of selected particles ranges approximately 30 μm and above. As shape evaluation is sensitive to the number of pixels of a single particle, wide size distributed particles are classified into several size ranges, *e.g.* 30~50 μm, 50~70 μm, 70~90 μm, *etc.* The comparison of shape characteristics is more meaningful within a narrow size range.

Some traditional shape parameters are then used for the evaluation. Elongation is one of the most popular parameters used in the shape analysis: it describes the relationship between width (b) and length (a), as shown in Fig. 3(a) (Eq. 1):

$$Elongation = 1 - \frac{b}{a} \quad (1)$$

A more elongated particle has a higher value of elongation (≤1). Circularity is defined as the ratio of equivalent circle perimeter to perimeter of the particle (P) (Eq. 2):

$$Circularity = \sqrt{\frac{4\pi A}{P^2}} \quad (2)$$

in which A is the projected area of a particle. It indicates the similarity degree of a particle to a disc, considering the smoothness of the perimeter. Circularity and elongation distributions of two type of aggregate are plotted in Fig. 3(b). These two types of aggregate have similar elongations in all size ranges. The particles in the smallest size range have a slightly high elongation. It may be due to a bit higher crushing degree of smaller particles than larger particles. Two aggregates have quite different circularities in all size ranges. RS has a higher circularity than CR in a same size range.

Two other shape parameters, *i.e.* solidity and roundness, are also used for the shape evaluations. Solidity is defined as ratio of particle area (A) to the area of the corresponding convex hull bounded particle (A_c, shown in Fig. 4(a)). It measures the overall concavity of a particle. A similar parameter called convexity ratio was used by Mora and Kwan [20] for shape characterization of coarse aggregates. It was found that convexity is one of the most important parameters affecting the packing density of aggregates [20]. Roundness is also a useful parameter for describing the similarity degree of a particle to a circle. Unlike circularity, roundness considers the maximum Feret diameter (χ_{Fmax}, shown in Fig. 3(a)) in the equation:

$$Roundness = \frac{4A}{\pi \chi_{F\max}^2} \quad (3)$$

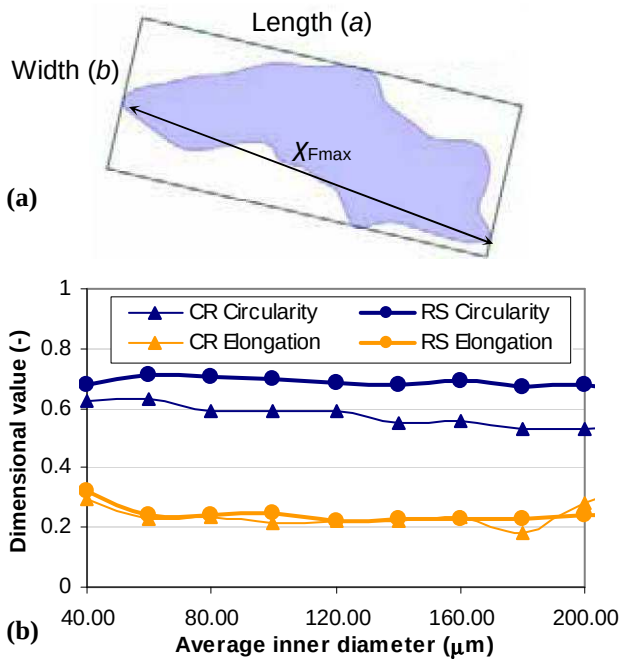

Fig. 3(a) Length and width of an arbitrary shape, (b) distribution of circularity and elongation of particles within each size range for both samples

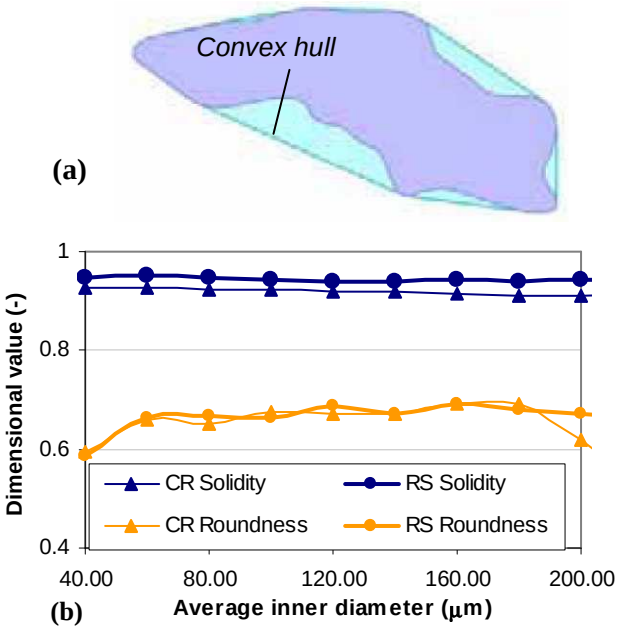

Fig. 4(a) A convex hull bounding particle and (b) distribution of solidity and roundness of particles within each size range for both samples.

The distributions of solidity and roundness of two aggregates with different size ranges are shown in Fig. 4. Solidity of RS is a bit higher than that of CR in the same size range. It indicates RS particles have higher convexity than CR particles. CR particle may also have rougher surface textures than RS particles. However, there is no much difference of roundness between two aggregates within a same size range. Compared with definition of circularity, roundness describes the similarity of a particle to a disc only from Feret diameter. As difference of elongation between two materials is low, roundness of two aggregates is logically similar. As another result, roundness of particles in the smallest size range is lower than that of larger particles.

From results on the above shape parameters, it can be concluded that fine RS particles have a similar dimensional ratio as CR particles. But CR particles have a much rougher surface texture than RS particles. Shape comparisons for these two types of materials need including the information on surface details, e.g. circularity.

CONCLUSIONS

In this study, PSDs of two typical fine aggregate are characterized by different experimental methods. The results show the inner diameter used in the IA systems can perfectly represent the sieve size of a particle. Due to sedimentation phenomenon, large particle are missed in PSDs of fine aggregate by the current wet dynamic IA system. It is recommended to further improve instrument of this system for a better size and shape characterization. Although as one of the most popular method for size characterization, LD may provide a biased estimation of PSD shown in this study. This may be due to sensitivity of LD to geometrical and optical properties of particles. The static IA method has a good estimation of PSDs of two types of aggregate and thus is used for shape characterization. Results show two fine aggregates have similar dimensional shape characteristics. There are no significant differences of elongation and roundness between two materials. However, circularity, estimated from smoothness of perimeter, of a RS particle is higher than a CR particle. It also indicates CR particles have rougher surface and higher angularity than RS particles.

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