

QUANTIFICATION OF THE SHAPE OF PARTICLES FOR CALCULATING SPECIFIC SURFACE AREA OF POWDERS

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Abstract

The concepts of particle packing and water/paste layer theories are commonly used for basis of concrete mix design models. While particle packing insists on achieving fewer voids in aggregate matrix by e.g. adding fine aggregates, water/paste layer theories state that increasing the amount of fines will lead to higher water demand since the specific surface area of particles will increase. In order to calculate the thickness of excess paste in water/paste layer theories, it is essential to have an estimation of specific surface area of the particles. However, the complexity of the instruments required to measure specific surface area makes the methods costly and also causes an issue regarding the availability of the instruments leading to less popularity of water/paste layer theories compared to mix design approaches based on the particle packing theory. Introducing a model that can roughly estimate the specific surface area of particles may eliminate the need for measuring specific surface area which in turn contributes to cost reduction and also laying a foundation for calculation of water layer thickness.

The paper aimed to study calculated specific surface area by replacing regular convex polyhedrons with actual particle shapes based on the size distribution curves of the samples and to compare the results with data obtained by Blaine test.

The conducted study suggests that in most cases, assumption of spherical shape for the particles leads to an acceptable estimation of SSA. However, SSA of powders with more angular particles can be calculated more accurately with the assumption of Polyhedron shape rather than spheres

1. Introduction

1.1. Background

During past decades, several attempts were made on formulating the mix design of concrete. Most of these models are based on the assumption that the properties of concrete in fresh state namely; flow properties and workability are chiefly governed by the particle size distribution (PSD) and the particle packing [1-3]. According to the above-mentioned models, particle packing can be increased by modifying PSD which in turn usually leads to increasing the share of fines. Packing theory assumes that adding fine particles to a particle structure helps fill up the voids in the particle structure leaving only minimum space for water. In this way adding fine particles will reduce the water requirement [1,4,5]. However, the packing of aggregate is dependent also on the shape of the aggregate particles. The effect of particle shape is more difficult to comprehend and it is indirectly accounted for by measuring the packing of mono-sized fractions.

Another approach to compiling a mix design model is based on excess paste/water layer theories first introduced by [6]. A major hypothesis by [7] states that the relative slump of a water-powder mixture becomes a function of the specific surface area (SSA) when sufficient water is present to flow. Based on the hypothesis, a thin layer of adsorbed water molecules around the particles is necessary to assure the flow characteristics of the hydrating system. It is reported that the thickness of this water layer is related to sensitivity of the mix on changes in the water content and also the specific surface area of the material used [7], as later confirmed by [8]. Moreover, the water layer theory assumes that the water demand of a mixture depends on the surface area of the particles in that mixture. Increasing the surface area by adding small particles will increase the water requirement [9-13].

Both approaches (Particle packing and Water/paste layer theories) strongly depend on the shape of the aggregate in one way or another, that is especially more essential when it comes to water/paste layer theories which requires the specific surface area as an input for the model. While it is possible to directly measure SSA, the complexity of instrument required for the measurement imposes issues namely; the availability of the testing instruments and the cost. It is also possible to estimate the SSA based on the assumption that particles have ideal spherical shapes using the PSD data [14].

The paper aims at defining an alternative way to improve the accuracy of calculated SSA by assuming ideal polyhedron shapes for the particles in addition to the previously mentioned spherical shapes and by comparing the calculated SSA to the measurements obtained by Blaine test. Accurate estimation of SSA can provide a tool for calculating water demand of the powders at the on-set of flow and also can be used in water/paste layer theories.

1.2. Specific surface area (SSA)

The specific surface area is the quotient of the absolute available surface excluding all open inner surfaces (pore walls) divided by the mass [m^2/g]. For concrete mix design, only the outer surface being in contact with water is of interest. With the consideration of the specific density, the specific surface area could also be expressed as area per volume [m^2/m^3]. Besides mass and solid volume, the SSA can also be related to a bulk volume (taking account for the void fraction) or a cross-sectional area [8].

There are several ways of determining SSA based on direct and indirect measurements, e.g. Blaine test, Lea and Nurse method. Both tests give closely similar results but are not

applicable to fine and ultra-fine powders. Another method that has been used to determine SSA is the volumetric static multi-point method better known as the BET method [15]. However, determining the SSA value using the mentioned tests is associated with a highly device-related complexity. An indirect possibility for determining the SSA can be its deviation from the particle size distribution [14]. Assuming that all the particles are spheres, total SSA for spherical particles can be calculated by Eq. (1).

$$a_{sph} = 6 \sum_{i=1}^n \frac{\omega_i}{\bar{d}_{i,arith} \cdot \rho_s} \quad (1)$$

where:

ω_i is the mass of a grain fraction i , being the mass percentage of the fraction between d_i and d_{i+1} .

$\bar{d}_{i,arith}$ is the arithmetic mean diameter of fraction i and $i+1$.

ρ_s is the specific density of the particles.

1.3. Water/Paste layer theories

The paste layer theory originates in the design of self-compacting concrete. It is known that cement paste should not only fill the voids among the aggregates but surround all particles with a thin layer of paste to fulfill workability requirements [16]. The required amount of paste for this layer depends on the specific surface area of the particles. The larger the surface area of the particles, the smaller the thickness of the surrounding paste layer and the larger the available surface for cement matrix-aggregate bond. The theory has proven useful in self-compacting concrete [9,17].

In paste layer theory approach, the packing density of the aggregate is measured in order to determine the amount of cement paste required to fill up the voids, the ramming paste added in the mixture is considered as excess paste, Water layer theory follows a similar principle as paste layer theory. Based on the excess water layer theory, the thickness of water layer can be calculated by dividing the amount of water by available specific surface area of all the particles including cement and other micro fines. see Figure 1.

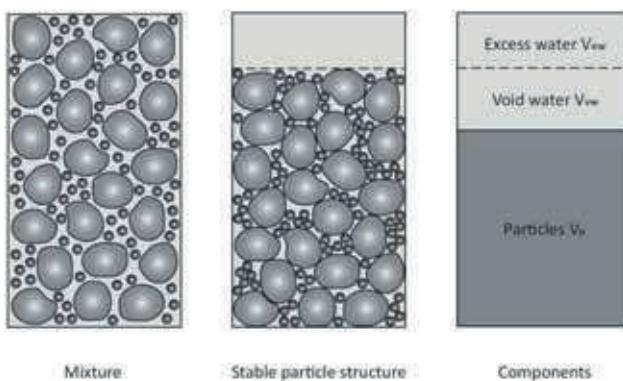


Figure 1. Volume of water, divided into excess water and void filling water, within a concrete mixture in a unit volume [12].

Estimation of specific surface area of particles plays a major role in calculation of thickness of both paste and the water that surrounds the particles.

2. Materials

In order to examine the accuracy of SSA calculation, the data needs to be compared to actual measurements of SSA; for this purpose, four powders were chosen and their properties namely specific density, bulk density, Blaine value and their particle size distribution curves were extracted from [10] and [18] and are represented in Table. 1.

Table 1: Densities and SSA of the powders.[10][18]

Material	Specific density (g/cm ³)	Loose packing density	Bulk density (g/cm ³)	SSA based on Blaine (cm ² /g)
CEM III/B 42.5 N	2.96	0.72	2.13	4500
Marble Powder	2.80	0.64	1.79	4580
Limestone	2.21	0.69	1.87	4040
Quartz Powder	2.60	0.64	1.66	2600

Particle size distribution of the materials is an important factor in calculation of the specific surface area, there are several methods for determining the PSD. The size distribution curve was obtained by deploying low angle laser light scattering technique (LALLS) conducted by [10]. See the particle size distribution curves of the selected powders in Figure 2.

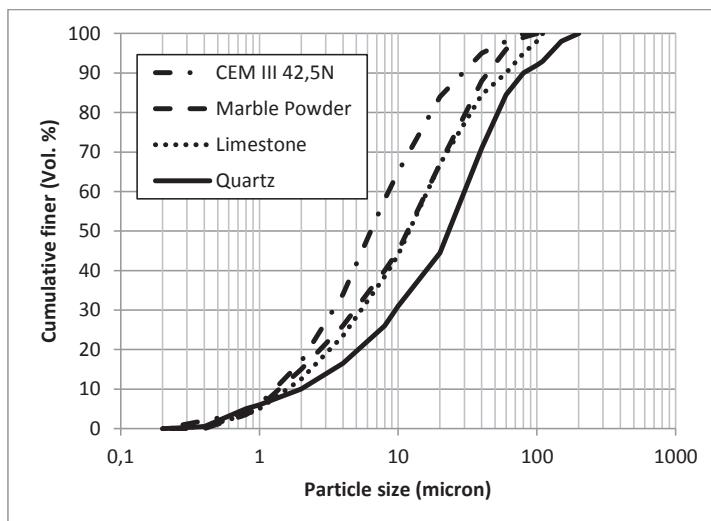


Figure 2. Particle size distribution of the powders.[10][18]

Additionally, in order to further validate the relation between polyhedrons and the particle shape and to be able to distinguish the difference in particle geometry, SEM micrographs have been prepared by [10] and shown in Figure 3.

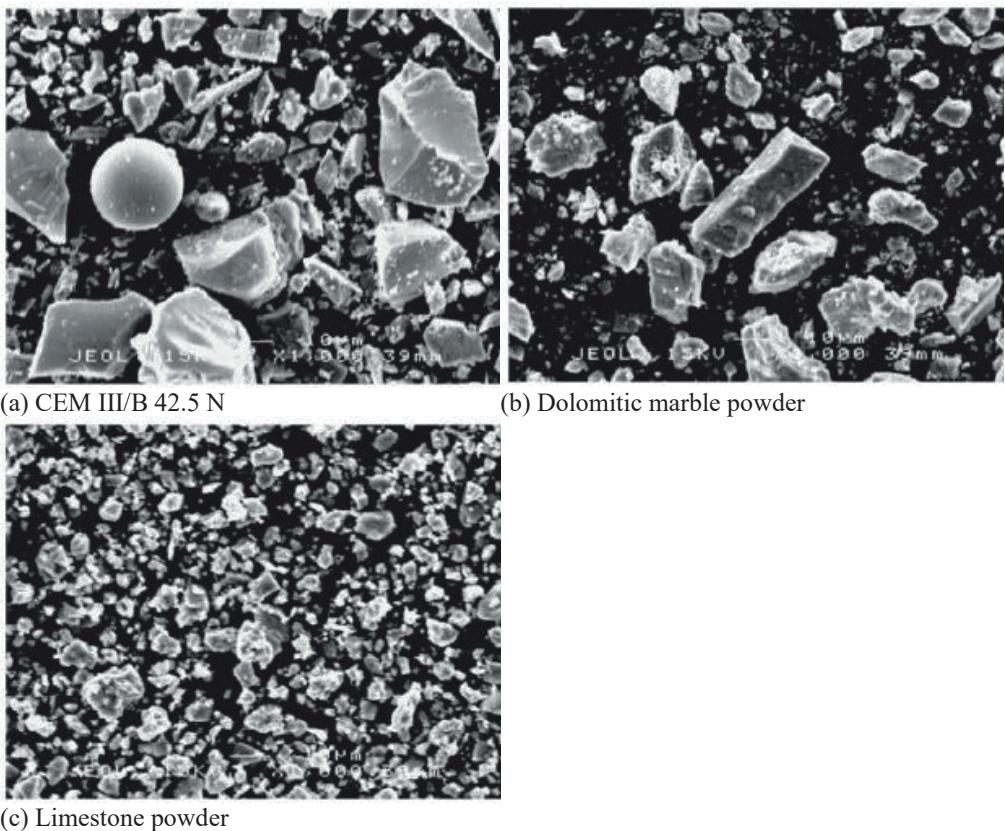


Figure 3. SEM micrographs of the investigated powders, 1000X magnified.[10]

3. Computation of SSA based on particle size distribution

As mentioned before, using Eq. (1) it is possible to calculate SSA based on the particle size distribution for spheres. In addition to sphere-based calculation of SSA, other polyhedrons were examined to re-calculate the SSA. Table 2. shows the selected polyhedrons and their geometrical properties.

Table 2: Polyhedrons used in the calculation of SSA.

Shape	Surface Area	Volume	SSA/V
Tetrahedron		$\sqrt{3}a^2$	$\frac{\sqrt{2}a^3}{12}$
Cube		$6a^2$	a^3
Octahedron		$2\sqrt{3}a^2$	$\frac{1}{3}\sqrt{2}a^3$
Dodecahedron		$\sqrt[3]{25 + 10\sqrt{5}}a^2$	$\frac{1}{4}(15 + 7\sqrt{5})a^3$
Icosahedron		$5\sqrt{3}a^2$	$\frac{5}{12}(3 + \sqrt{5})a^3$
Sphere		$4\pi a^2$	$\frac{4\pi a^3}{3}$

Replacing spheres with other polyhedrons will not only change the calculated volume and specific surface area but also affects the pace of growth in SSA/Volume ratio according to square-cube law.

3.1. Square-Cube law

The square-cube law was first introduced by Galileo [19] and it defines a mathematical principle which describes the relationship between the volume and the area in accordance to changes in size. According to the principle, as a shape grows in size, its volume grows faster than its surface area. Consequently, as the size decreases its surface area grows faster than its volume. The effect of square-cube law becomes especially significant for calculation of specific surface area of finer particles namely powders and cement. Figure 4 illustrates the difference in growth of SSA/Vol ratio of polyhedrons according to square-cube law.

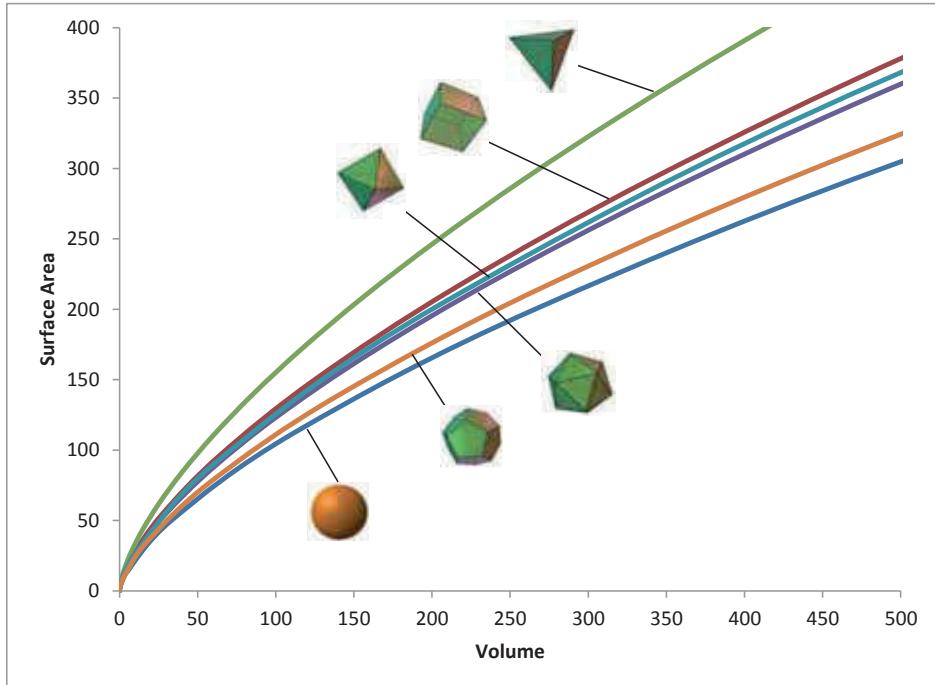


Figure 4. Surface area against volume of the platonic solids and a sphere.

By writing Eq. (1) in its general form, the square-cube law effect can be implemented in the equation.

$$a_{poly} = \sum_{i=1}^n \frac{SSA_i \cdot \omega_i}{V_i \cdot \rho_s} \quad (2)$$

where:

SSA_i/V_i is the specific surface area to volume ratio of fraction i and is related to the shape as shown in table 2.

To define the equivalent polyhedron to the spheres, it was assumed that the polyhedrons have the same volume as the retained spheres on each fraction. The length of the sides of polyhedrons is calculated based on the mentioned assumption. The average diameter of the spheres in each fraction is determined based on the arithmetic mean approach.

4. Results and discussion

Calculated specific surface area according to Eq (2) and their corresponding Blaine values from laboratory tests [10][18] are presented in Table 3.

Table3: Surface area of the powders and the deviation from the calculated SSA

Material	Blaine	Specific surface area (cm^2/g)					
							
CEMIII/B42.5	4500	6892	5737	5469	5078	4927	4625
Marble	4580	4766	3968	3784	3515	3406	3199
Limestone	4040	7689	6401	6103	5668	5495	5160
Quartz	2600	4031	3355	3200	2964	2881	2705

Calculated values of SSA in case of CEMIII/B42.5, Limestone powder, and Quartz powder were overestimated by 2.7%, 27% and 4%, respectively, in comparison to their corresponding Blaine values. The high margin of error for Limestone powder can be related to the principles of the Blaine method as it is a relative test which depends on the shape of the particles and the compaction level or porosity of their compacted bed [20][21].

It should be noted that the model overestimated SSA in most of the studied materials. For the case of Marble powder, calculations based on Tetrahedron shape for particles give a closer estimation of SSA compared to the other platonic solids.

5. Conclusion

5.1. Analysis of the model

While it is shown that using the water layer theory can be a helpful tool for prediction of flowability of concrete [9], the complexity of instruments required for measuring the SSA as an essential input in the water layer theory model makes this approach less favoured by the industry comparing to the mix design models based on particle packing. Thus formulating an equation that can predict SSA using simple input data, the water layer theory can be used with more simplicity and efficiency as a tool for anticipating the workability of the concrete.

The conducted study suggests that in most cases, assumption of spherical shape for the particles leads to an acceptable estimation of SSA. However, SSA of powders with more angular particles can be calculated more accurately with the assumption of Polyhedron shape rather than spheres as it was the case for the Marble powder. See Figure 3 and Table 3.

5.2. Future work

More data is required in order to categorize the shape of particles based on the suggested polyhedrons. In addition, since the Blaine test will result in relative values for powders other than cement, an accurate method of measuring SSA of particles is necessary to calibrate the

model, e.g. microtomography. As a next step in the study, the actual SSA can be measured using 3D models of the particle structure generated by microtomography scanning and can be compared with the results obtained from the model. Moreover, the effect of changes in PSD can be studied by modifying the distribution curves of the particle to a target curve.

References

ESTIMATION OF SPECIFIC SURFACE AREA OF PARTICLES BASED ON SIZE DISTRIBUTION CURVE

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Abstract

Workability at fresh state is one of the most important factors in design and production of concrete and can be related to the water demand of the mixture, which in addition to other factors, is a function of particle shape of aggregates and binders and their specific surface area. While it is known that the shape of fine particles have a significant effect on the water demand, there are uncertainties regarding how the various shape parameters would affect the specific surface area, mainly because up to now many of the shape parameters are not yet clearly defined and there are no commonly accepted methods for their measurement and/or estimation.

In this research the actual particle shapes was replaced with regular convex polyhedrons to calculate the total specific surface area using size distribution curves of the samples.

The obtained results indicate that while in some cases, assumption of spherical shape of particles leads to an acceptable estimation of the specific surface area when compared with Blaine tests results, the specific surface area of powders with more angular particles could be calculated more accurately with the assumption of Polyhedron shape rather than spheres.

1. Introduction

Concrete in the plastic state can be characterized by several parameters among which workability is probably the most important one and is influenced by the water requirement, which in turn is a function of aggregates' shape, size, and fine content. Thus, understanding the role of aggregates is fundamental for the production of high performance concrete (Alexander and Mindess, 2010).

Aggregates have a large variability in mineral composition, shape, surface roughness and surface texture and their specific surface area. One major parameter influencing the water demand is a comprehensive measurement of size, shape and roughness (Wang and Lai, 1998).

The shape of particles is a complex function of their formation conditions, the mineralogical composition, and particle size and not only refers to basic shape of aggregates, but also to other measures such as angularity, flakiness, etc. There is a considerable confusion on how various shape parameters are defined. There are also no commonly accepted methods for their measurement (Kwan and Mora, 2001). Particle shape can be classified by measuring the length, width and thickness of particles. Estimation is easier for larger particles. The specific surface area can be used as an indicator of size, shape and surface roughness of particles.

In asphalt mixtures, the specific surface area of the aggregate can be directly related to the asphalt concrete binder thickness and therefore related to the rutting and fatigue performance of asphalt concrete, (Alexander and Mindess, 2010). Furthermore, Hunger (2010) concluded that in the case of a self-compacting concrete, a certain thickness of water layer surrounding the particles in water-powder dispersion will put the mixture at the on-set of flow. In other words, the relative slump of a water-powder mixture becomes a function of the specific surface area when sufficient water is present to enable the flow (Brouwers and Radix, 2005).

It is also possible to estimate the specific surface area using particle size distribution data based on the assumption that particles have spherical shape. However, particle shapes are far from being spherical due to 3D randomness in their dimensions, related to the origin of the aggregates, and their production method. This is particularly true for example in the case of crushed aggregate.

The specific surface area is the quotient of the absolute available surface inclusive all open inner surfaces (pore walls) divided by the mass [m^2/g]. For concrete mix design, only the outer surface being in contact with water is of interest. With the consideration of the specific density, the specific surface area could also be expressed as area per volume [m^2/m^3]. The total surface area of a set of aggregates is governed by the fine aggregate fraction according to the square-cube law. Assuming that all particles were spherical in shape, the Specific Surface Area (SSA), a_{sph} , would be easy to calculate based on the particle size distribution and grading curves,(McCabe et. al., 1993) :

$$a_{sph} = 6 \sum_{i=1}^n \frac{\omega_i}{\bar{d}_i \cdot \rho_s} \quad (1)$$

where

ω_i is the mass of a grain fraction i , being the mass percentage of the fraction between d_i and d_{i+1} .

\bar{d}_i is the mean diameter of fraction i and $i+1$.

ρ_s is the specific density of the particles.

Since the solid constituents of concrete mixtures seldom have spherical particle shape, some error should be expected in the results from Eq (1). It has been found that the specific surface area of the aggregate can be much larger than that of spheres of equivalent size (Wang and Frost, 2003).

There are several ways of determination of SSA based on direct and indirect measurements, e.g. Blaine test (ASTM C204, 2016), Lea and Nurse Method (Lea and Nurse, 1939). Both tests give similar results but are not applicable to fine and ultra-fine powders. The Blaine test method was developed exclusively for measurement of the specific surface area of cement and is based on the assumption of spherical particle shape which leads to relative measures for materials other than cement.

Another method that has been used to determine SSA is the volumetric static multi-point method, better known as the BET method (Brunauer et. al., 1938). Results from BET test include the measure of surface area of internal pores, which is not of interest for calculation of water demand in concrete mixtures.

Determination of the SSA value using these three test methods includes complex measuring devices. As a result developing a cheaper and easier to use method for estimation of SSA is necessary. The main aim of this research was to verify the effect of the assumption of the ideal polyhedron shapes of the particles instead of spheres on calculation of the SSA. For this purpose, the specific surface areas of the particles were mathematically calculated based on the size distribution curve and the assumption that particles have a uniform shape. The particle shapes were substituted with the shape of standard platonic solids. The calculated values were compared to the specific surface area of the samples measured using Blaine method.

2. Materials

Four types of powders were used in this study and all required input data were extracted from earlier test results. Characteristics of the first three materials shown in Table 1 were extracted from Hunger & Brouwers, (2009) and included specific density, bulk density, grading curve, Blaine values, and Scanning Electron Microscope (SEM) images. The information on the Quartz powder was obtained from Jennings et. al., (2013).

Table 1: Densities and SSA of the powders, from.(Hunger and Brouwers,(2009) and Jennings et. al.,(2013)

Material	Specific density (g/cm ³)	Loose packing density	Bulk density (g/cm ³)	SSA based on Blaine (cm ² /g)
CEM III/B 42.5N	2.96	0.72	2.13	4500
Marble Powder	2.80	0.64	1.79	4580
Limestone	2.21	0.69	1.87	4040
Quartz Powder	2.60	0.64	1.66	2600

Particle size distribution curve of the materials was obtained by deploying low angle laser light scattering technique (LALLS) conducted by (Hunger and Brouwers, 2009), Figure 2.

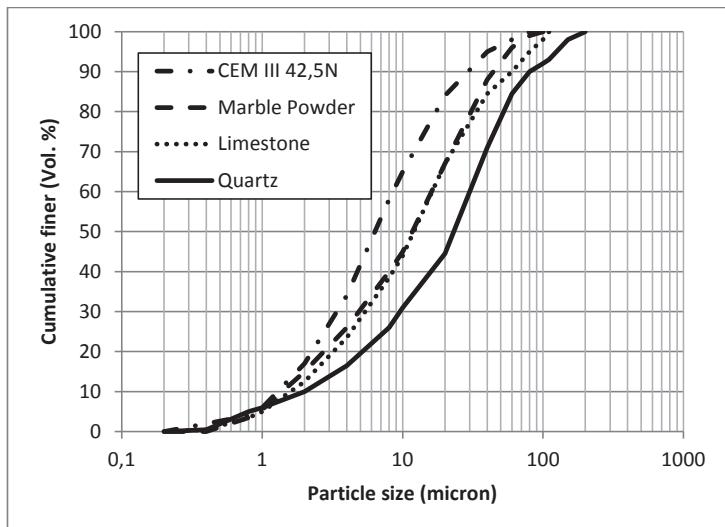
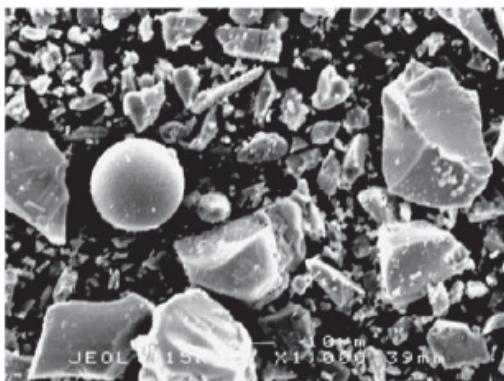
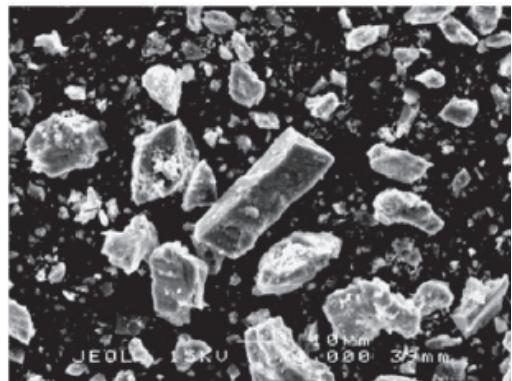


Figure 2. Particle size distribution curves. (Hunger and Brouwers, 2009)(Jennings et. al., 2013).

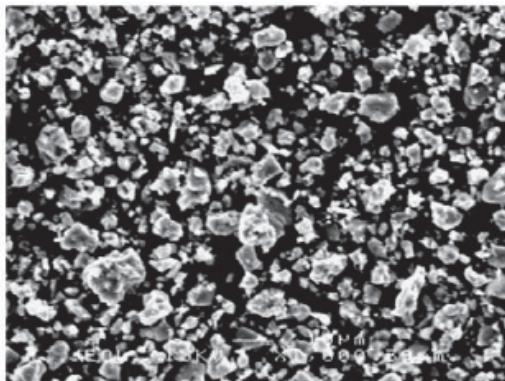
Additionally, in order to further validate the relation between polyhedrons and the particle shape and to be able to distinguish the difference in particle geometry, SEM images from Hunger and Brouwers (2009) Figure 3.



(a) CEM III/B 42.5 N



(b) Dolomitic marble powder



(c) Limestone powder

Figure 3. SEM-SE images of studied powders, 1000X magnification. (Hunger and Brouwers, 2009).

3. Computation of SSA

3.1. Square-Cube law

The square-cube law defines a mathematical principle describing the relationship between the volume and the area related to changes in size and was first introduced by Galilei and Drake, (1946). According to the principle, as a shape grows in size, its volume grows faster than its surface area. Consequently, as the size decreases its surface area grows faster than its volume. The effect of the square-cube law becomes especially significant for calculation of specific surface area of finer particles namely powders and cement i.e. for a given mass of aggregate, the surface area increases with reducing particle size. The specific surface area can be calculated mathematically by assumption of spherical shapes for the particle. In case when spheres were replaced by another shape, the difference in calculations is caused the fact that different shapes have different volumes and also the ratio between specific surface area and volume changes based on the chosen shape according to square-cube law. Figure 4 shows the difference in pace of growth of SSA/Volume ratio of so called Platonic solids - a set of five 3D regular convex polyhedrons - obeying the square-cube law.

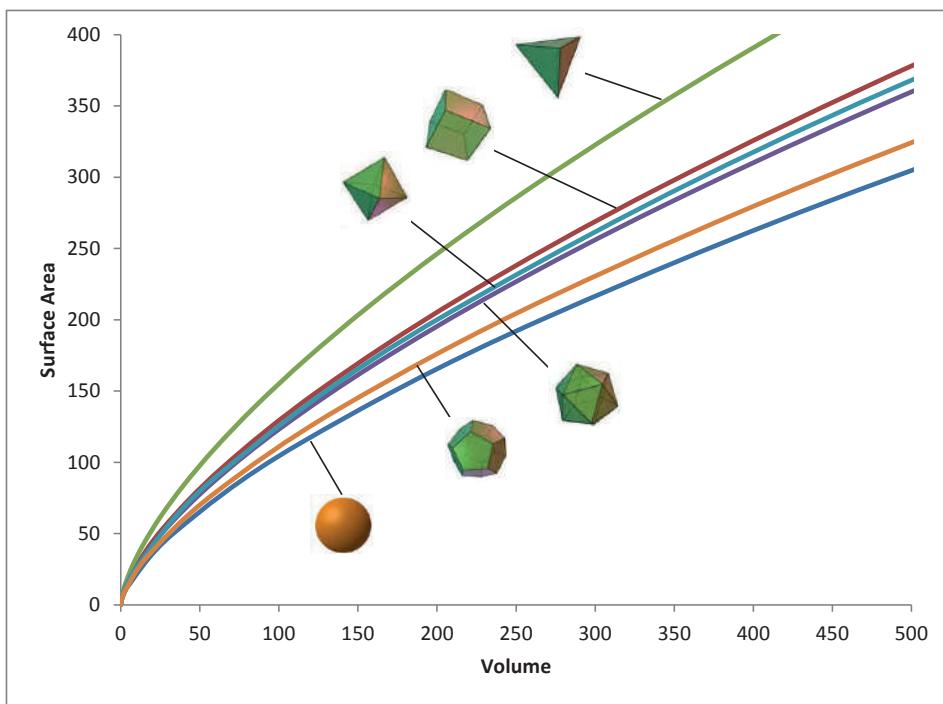


Figure 4. Surface area versus volume of the platonic solids and a sphere. (Ghasemi et. al,2016)

The formula presented in Eq. (1) deals with a special case of calculating the SSA for spherical particles, the equation can be written in its general form where the ratio of SSA/V implements the square-cube law in the formula:

$$a_{poly} = \sum_{i=1}^n \frac{SSA_i \cdot \omega_i}{V_i \cdot \rho_s} \quad (2)$$

where:

SSA_i/V_i is the specific surface area to volume ratio of fraction i and is related to the shape as shown in Table 2.

As mentioned before, it is possible to calculate SSA based on particle size distribution curves and with the assumption of mono-shaped particles. The Platonic solids that were examined to re-calculate the SSA are shown in Table 2. Substituting spheres with the platonic solids will not only change the calculated volume and specific surface area but also affect the rate of growth in SSA/Volume ratio according to the square-cube law.

Table 2: Platonic solids used in the calculation of SSA and their volumes.

Shape		Surface Area	Volume	SSA/V
Tetrahedron		$\sqrt{3}a^2$	$\frac{\sqrt{2}a^3}{12}$	$\frac{14.697}{a}$
Cube		$6a^2$	a^3	$\frac{6}{a}$
Octahedron		$2\sqrt{3}a^2$	$\frac{1}{3}\sqrt{2}a^3$	$\frac{7.348}{a}$
Dodecahedron		$\sqrt[3]{25 + 10\sqrt{5}}a^2$	$\frac{1}{4}(15 + 7\sqrt{5})a^3$	$\frac{2.694}{a}$
Icosahedron		$5\sqrt{3}a^2$	$\frac{5}{12}(3 + \sqrt{5})a^3$	$\frac{3.970}{a}$
Sphere		$4\pi a^2$	$\frac{4\pi a^3}{3}$	$\frac{3}{a}$

3.2. Equivalent polyhedron shape

The spherical surface area of each fraction can be calculated using Eq (1). To do so, the mean diameter of the particle sizes d_i and d_{i+1} of a fraction i as the characteristic particle size, is required. The mean diameter d_i can be calculated using either arithmetic mean or geometric mean, see . Eq (3) and Eq (4) respectively:

$$d_{i,arith} = \frac{d_i + d_{i+1}}{2} \quad (3)$$

$$d_{i,geo} = \sqrt{d_i^2 + d_{i+1}^2} \quad (4)$$

For the corresponding calculations for the polyhedrons, the length of the sides is needed since the Platonic solids should be defined in relation to the spheres. This relation can be conditioned based on geometric properties of the spheres using the concepts of circumsphere and midsphere or by equivalent volume (mass) to the spheres. In geometry, a circumscribed sphere or circumsphere of a polyhedron is a sphere that contains the polyhedron and touches each of the polyhedron's vertices. Midsphere is defined as a sphere that touches all of the polyhedron edges.

The midsphere does not necessarily pass through the midpoints of the edges, but is rather only tangent to the edges at same point along their lengths (Cundy and Rollett, 1989). The length of edges of platonic solids are smaller for the circumsphere approach comparing to midsphere.

For volumetric equivalency the sides of the polyhedrons can be back-calculated by replacing the volume of the polyhedrons by the volume of spheres assumed for each fraction, see Figure 4.

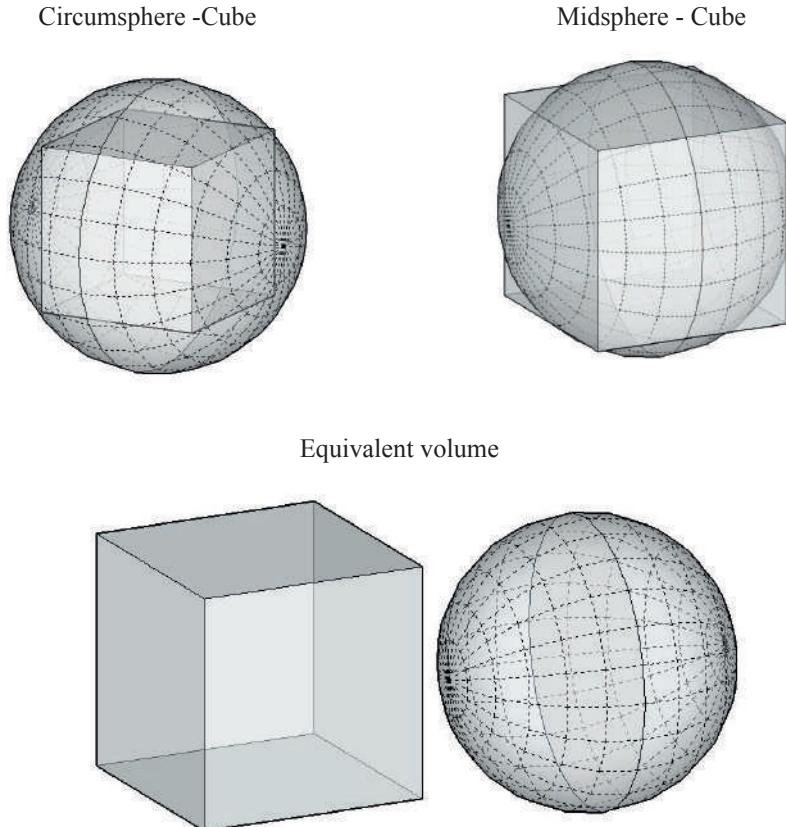


Figure 4. Circumsphere, Midsphere and volume equivalency of a cube.

It is also possible to define the equivalency based on the concept of Insphere. Insphere is a sphere that is contained within the polyhedron and is tangent to each of the polyhedron's faces. The issue with calculation based on Insphere is for some polyhedrons e.g. Tetrahedron, only a relatively small sphere can be contained in comparison with other shapes. This would affect the calculation of SSA and therefore calculation based on Insphere was ignored.

In this study different approaches have been examined to define the equivalent polyhedrons to the spheres by utilizing the concepts of circumsphere, midsphere, and volume equivalency. The computation was done based on both arithmetic and geometric means.

The lengths of sides of the polyhedrons were calculated for different assumptions:

- The polyhedrons are contained in spheres (circumsphere) with diameter calculation based on arithmetic mean.
- The polyhedrons are contained in spheres (circumsphere) with diameter calculation based on geometric mean.
- The sphere touches all of the polyhedron edges (midsphere) with diameter calculation based on arithmetic mean.
- The sphere touches all of the polyhedron edges (midsphere) with diameter calculation based on geometric mean.
- The polyhedrons have the same volume as the spheres (volumetric) with diameter calculation based on arithmetic mean.
- The polyhedrons have the same volume as the spheres (volumetric) with diameter calculation based on geometric mean.

The edge lengths of the polyhedrons, a , were calculated by equations listed in Table 3. Median radius of equivalent spheres, r , can be calculated by either Eq (3) or (4).

Table 3: Edge lengths of polyhedron.

Shape		Circumsphered edge length (a_c)	Midsphered edge length (a_m)
Tetrahedron		$\frac{4r}{\sqrt{6}}$	$\frac{4r}{\sqrt{2}}$
Cube		$\frac{2r}{\sqrt{3}}$	$\frac{2r}{\sqrt{2}}$
Octahedron		$\frac{2r}{\sqrt{2}}$	$2r$
Dodecahedron		$\frac{4r}{\sqrt{3}(1 + \sqrt{5})}$	$\frac{4r}{(3 + \sqrt{5})}$
Icosahedron		$\frac{4r}{\sqrt{10 + 2 \times \sqrt{5}}}$	$\frac{4r}{(1 + \sqrt{5})}$

4. Results and discussion

Calculated specific surface areas according to Eq (2) and their corresponding Blaine values obtained from laboratory tests of the referred previous studies are presented in Table 4 where specific surface was calculated based on the size distribution curve assuming different platonic solids.

In the case of most of the studied powders, the calculated spherical values of SSA were close to the Blaine value. The marble powder showed the largest deviation and thus its calculation should be conducted with the assumption of a different shape rather than spheres. This result corresponds well to the observed elongated, flaky particle shape of that material, Figure 3.

Moreover, in case of CEMIII/B42.5, Limestone powder, and Quartz powder, the calculation based on the assumption of spherical shape for the particles led to an overestimation of the SSA. It should be noted that the less spherical is a particle, the greater is its specific surface area. Since the particle shapes of powders are normally anything but spherical, therefore, the SSA of the actual particles should be higher than the calculated one based on the assumption of spherical shapes. Slight overestimation of spherical SSA can be related to the approach that is taken for determining the mean diameter of a particle.

In the case of the Marble powder, the calculated spherical SSA has a more noticeable difference to the Blaine value and is also the least spherical in terms of particle shape, Figure 3. It should also be mentioned that the Blaine test is a relative test designed for measuring SSA of cement and not necessarily any non-spherical powder, in other words Blaine value is a relative value and not absolute.

To sum up, among the studied scenarios used for defining the equivalent shape and mean diameter, The assumption of midsphere equivalency and arithmetic mean results in less error comparing to other approaches. See a compilation made in Figure 5.

As it can be seen in Figure 5, the assumption of spherical shape agrees with the Blaine values for CEM III and Quartz. While cement particles usually have round shape, the same cannot be said about Quartz. The reason that calculated SSA for quartz agrees with the spherical shape could be related to the fact that the source of information for Quartz comes from a different research (Jennings et. al., 2013).

In the case of Marble powder, assumption of cubical shape leads to a better estimation of specific surface area, which this can be directly related to angularity of Marble grains. Moreover, it should be noted that for the finer particles, there is a larger difference in the calculated specific surface area for different shapes which can be related to the principle of square-cube law.

It should also be mentioned that each column of data in Figure 5 shows the difference in calculated specific surface area based on different shape for a given size distribution curve. The difference in SSA for different shapes becomes more significant as the fine content of studied materials increases as a result of the square-cube law, e.g. see the difference in SSA for Limestone comparing to Quartz.

Table4: Calculated specific surface area of the powders

Calculation based on Circumsphere and Arithmetic mean							
Material	Specific surface area (cm^2/g)						
	Blaine						
CEMIII/B42.5	4500	13874	8014	8014	5822	5833	4625
Marble	4580	9596	5542	5543	4027	4036	3199
Limestone	4040	15478	8940	8940	6495	6512	5160
Quartz	2600	8116	4689	4688	3397	3415	2705
Calculation based on Circumsphere and Geometric mean							
Material	Specific surface area (cm^2/g)						
	Blaine						
CEMIII/B42.5	4500	14642	8458	8454	6140	6143	4881
Marble	4580	10112	5838	5838	4240	4245	3371
Limestone	4040	16325	9426	9426	6846	6851	5441
Quartz	2600	8562	4944	4944	3581	3594	2854
Calculation based on Midsphere and Arithmetic mean							
Material	Specific surface area (cm^2/g)						
	Blaine						
CEMIII/B42.5	4500	8011	6543	5664	5433	5215	4625
Marble	4580	5540	4525	3917	3761	3644	3199
Limestone	4040	8936	7300	6319	6064	5812	5160
Quartz	2600	4685	3828	3313	3005	2995	2705

Calculation based on Midsphere and Geometric mean							
Material	Specific surface area (cm ² /g)						
	Blaine						
CEMIII/B42.5	4500	7625	6904	5978	5743	5224	4881
Marble	4580	5164	4767	4128	3969	3608	3371
Limestone	4040	8534	7696	6665	6404	5824	5442
Quartz	2600	4656	4037	3495	3354	3054	2584

Calculation based on equivalent volume and Arithmetic mean							
Material	Specific surface area (cm ² /g)						
	Blaine						
CEMIII/B42.5	4500	6892	5737	5469	5078	4927	4625
Marble	4580	4766	3968	3784	3515	3406	3199
Limestone	4040	7689	6401	6103	5668	5495	5160
Quartz	2600	4031	3355	3200	2964	2881	2705

Calculation based on equivalent volume and Geometric mean							
Material	Specific surface area (cm ² /g)						
	Blaine						
CEMIII/B42.5	4500	7273	6056	5772	5358	5195	4881
Marble	4580	5022	4182	3986	3703	3588	3371
Limestone	4040	8109	6751	6434	5977	5791	5442
Quartz	2600	4253	3541	3375	3128	3037	2584

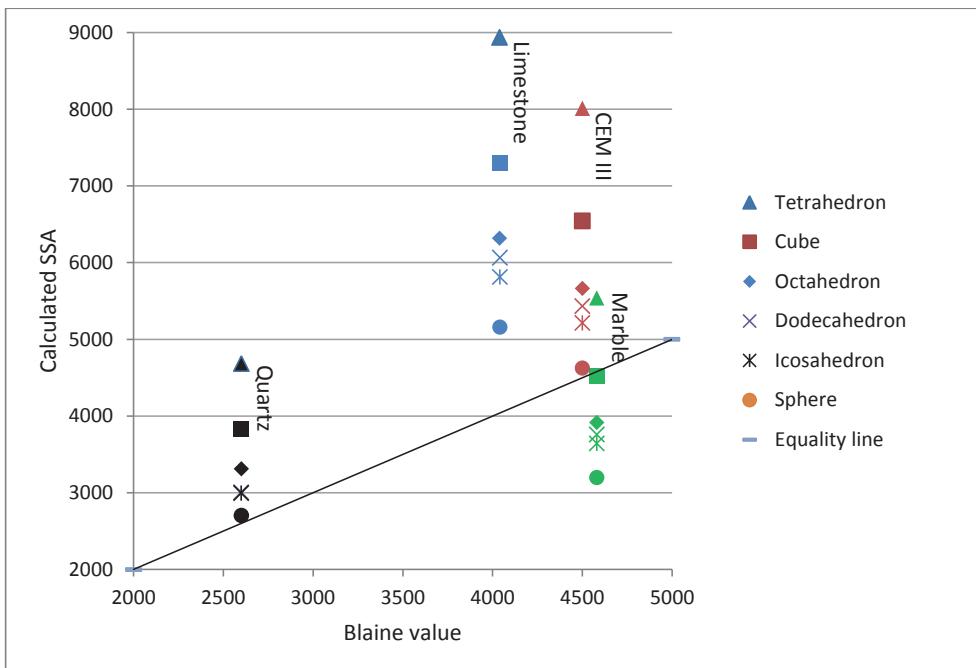


Figure 5. Blaine values vs. calculated SSA based on Midsphere-arithmetic mean assumption.

5. Conclusion

The specific surface area of aggregates, fillers and binders affects the fresh and hardened concrete properties. The water layer theory is a potentially useful tool for prediction of fresh concrete flow ability. However, the complexity of the analytical instruments required to measure the specific surface area limits a wider usage of that approach for e.g. concrete mix design. An alternative is to formulate an equation enabling theoretical prediction of the specific surface area using only simple input data. The results of the present study showed that while assumption of spherical shape for particles leads to an acceptable estimation of the specific surface area for round particles, in case of more angular flaky particles, substituting polyhedrons with sphere improves the accuracy of specific surface area estimation.

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