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# Flow analysis of water–powder mixtures: Application to specific surface area and shape factor

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ABSTRACT

This paper addresses the characterization of powder materials with respect to their application in concrete. Given that powders provide by far highest percentage of specific surface area in a concrete mix, their packing behavior and water demand is of vital interest for the design of concrete. They dominate physical properties like workability or strength and durability in hardened state.

Regarding the granular properties of powders, different states of packing are analyzed and compared. In reference to water demands, this paper compares and analyzes four different methods, including the spread-flow test. It is shown that linear relations can be derived in order to correlate the methods. Besides comments and modifications to individual tests, the spread-flow test is analyzed in more detail. In this way new measures are derived which contribute to a deeper understanding of wet granular mixtures at the onset of flowing.

Furthermore, the deformation coefficient which is derived by the spread-flow test is confirmed to correlate with the product of Blaine surface and intrinsic density of the individual powders when the mixture is flowing only under its own weight. Similarly, correlations with equal accuracy are found with a computed specific surface, based on measured particle size distributions. Using the flow experiments it is possible to derive an overall factor for assessing the non-spherical shape of the powder particles. It is shown that the computed surface area and the Blaine value have a constant ratio (of about 1.7).

Finally, the value of a constant water layer thickness around the powder particles is computed for all powders at the onset of flowing. This implies the possibility to predict flow behavior of paste only based on the knowledge of their specific surface area, either determined by computation or Blaine measurements.



## 1. Introduction

Powder analysis is considered to be an important part of industry and research. The knowledge of powder properties is necessary to control product attributes and the way of processing powders. This holds for all sectors of industry such as the paint, ceramic or rubber industry. In many cases emphasis is put on the packing of different powders within each other or in coarser granular fractions. This also holds for concrete industry. Because of the nature of concrete, here emphasis is placed on wet powders [1].

The macroscopic properties of concrete such as strength or durability are guided by the properties of the matrix, the aggregates, and the bond behavior of matrix and aggregates. Cement, mixing water, air, the fines content of the aggregate, and possibly admixtures and additions are considered to form the matrix. In other words, the matrix is composed of water, air and powder [2]. The latter is in concrete technology usually defined as any particle being smaller than 125 μm. This boundary value appears to be a suitable measure, at least for the metric unit system. Though it is less appropriate for the interests of powder technology which usually is using smaller particles sizes, it is rather important for concrete industry as the majority of cements are included in this size range and standard sieve lines stop at this size.

The characteristic of the matrix and the bond behavior between aggregate and matrix are dependent on a number of factors, of which the effective water/cement ratio (or water/powder ratio), and the reactivity, particle shape and particle size distribution of the powders are the most important ones. Furthermore, for a dense grain packing in the matrix not only an optimized granular build-up of the solids is necessary [1] but also the water content will influence the state of packing [3]. This concept has been successfully applied by Hunger and Brouwers [4] for the production of self-compacting concretes (SCC). During a stepwise saturation of a granular mixture, first all voids are filled with water. This process is accompanied by the generation of water films around the particles. Having a filled void fraction, i.e. saturated or supersaturated conditions, the present ratio of total specific surface area to the remaining

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**Nomenclature**

| | |
|---|---|
| BET | Brunauer–Emmet–Teller method |
| GCC | ground calcium carbonate |
| OPC | ordinary Portland cement |
| RCP | random close packing |
| RLP | random loose packing |
| sc | simple cubic |
| SCC | self-compacting concrete |
| SSA | specific surface area |
| *Romans* | |
| $A$ | surface area ($m^2$) |
| $a$ | specific surface area, mass-based ($m^2$/kg) |
| $a_{Blaine}$ | specific surface area according to the Blaine method ($cm^2$/g) |
| $E_p$ | deformation coefficient (–) |
| $d$ | diameter (m) |
| $P$ | packing (–) |
| $S$ | specific surface area, volume based ($m^2/m^3$) |
| $u$ | diameter ratio of subsequent fractions (–) |
| $V$ | volume ($m^3$) |
| *Greeks* | |
| $\beta_p$ | water/powder percentage (vol.%) for $\Gamma_p = 0$ |
| $\Gamma_p$ | relative slump of powder suspensions |
| $\delta$ | water layer thickness (m) |
| $\xi$ | shape factor |
| $\rho$ | density (kg/$m^3$) |
| $\Phi$ | void fraction |
| $\omega$ | mass fraction |
| *Subscript* | |
| agg | aggregate |
| app | apparent |
| arith | arithmetic |
| comp | compacted |
| geo | geometric |
| loose | loose |
| marq | modified Marquardt test |
| p | powder |
| s | specific |
| sph | spherical, based on spheres |
| spread | spread-flow test |
| sur | surface |
| vibr | vibrated |
| w | water |

amount of water determines significantly the workability of a mixture. Based on this assumption, a water layer thickness can be derived, as shown later on. The increasing thickness of water layers determines the location of particles in the system relative to each other. With further rise of the water content, there is an increase in mean interparticle distance. Then, densest possible packing is not given anymore. Furthermore, depending on the specific density of powders, an increasing tendency to segregation is noticed, since the surplus water can no longer be adsorbed at the particle surfaces. On this account, an accurate determination of the water demand is of importance for the success of a mortar or concrete mixture, in particular if it should provide self-compactibility.

In the following Chapter a number of powders are introduced and characterized regarding their density, void fraction in different modes of packing, and particle size distribution. The introduced powders cover the broad range of powders used in concrete technology. These are for example different cements, non-reactive powders such as limestone powder or reactive powders such as fly ash. In addition fine mineral quarry waste such as marble or granite powder is characterized as well. Based on the particle size distribution a calculation algorithm is derived in order to compute the specific surface area of powders. In another chapter these powders are analyzed regarding their water demand using four different tests methods and comparing these results. Based on the data obtained with the spread-flow test a deeper analysis has been carried out which resulted in a number of new hypotheses. These are for example the concept of constant water layer thickness and the derivation of shape factors based on flow experiments. The latter has been verified by SEM analysis in addition.

## 2. Characterization of powders

In regard to the large specific surface area which is provided by small particles, characterization of powders is essential for the ability to control physical properties, such as workability of self-compacting concrete. Furthermore, strength development and durability of concrete is effected by the type and amount of applied powder. In the following all applied powder materials are introduced.

### 2.1. Selected powder materials

#### 2.1.1. Cements

Since blast-furnace cements gain importance in the construction sector (e.g. [5]) a multitude of tests for this research has been performed using two types of a CEM III/B 42.5 N (A and B), being a typical representative of blast-furnace cements. The second blast-furnace cement, type B ($d_{median} \approx 6.5$ μm), shows a finer size distribution than type A ($d_{median} \approx 15$ μm). These cements are known, in contrast to ordinary Portland cements (OPC), to show a slower hydration development but to exhibit later, in particular after 28 days, a denser microstructure, which contributes to the durability of concrete made from these cements. Besides a low effective alkali content (LA) and low hydration heat release (LH), the applied cements offer a high sulfate resistance (HS) as well. OPC CEM I 52.5 N was also tested. Since the significance of ultra fine cements is increasingly recognized in recent years, a micro-cement CEM I 52.5 R was included. Ultra fine powders are of interest for the improvement of packing. Due to their high specific surface area they are also supposed to yield key results in respect to water demands and flow behavior of pastes.

A scheme with the composition of the applied cements can be found in Table 1. Furthermore, Table 2 shows the basic cement characterization according to EN 196. These tests were partly done in the own lab, otherwise data from the respective cement producer is given.

#### 2.1.2. Non-reactive rock flour

Limestone powder, one of the standard filler materials in concrete production, was included in the test series. The deployed limestone powder is a ground calcium carbonate (GCC) originating from natural limestone. In Table 3 the used limestone powder is characterized with regard to its chemical composition.