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# Modeling the relationship between the shape and flowing characteristics of processed sands

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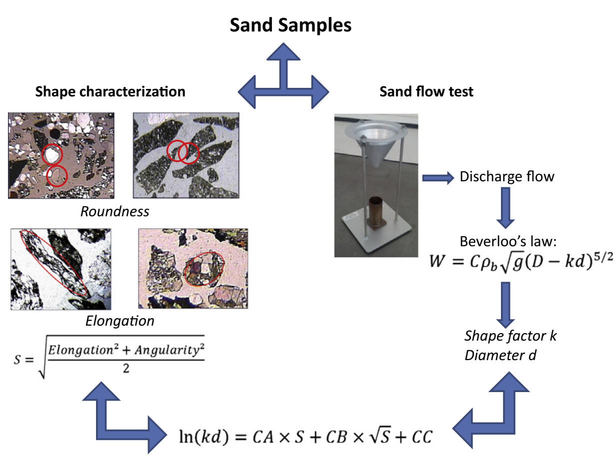
## HIGHLIGHTS

- The quality of processed sands is important for many construction applications.
- High accuracy video equipment can be used to characterize the shape of sand.
- A simple shape factor describing the shape of sand particles has been proposed.
- A simple relationship between shape factor and actual shape has been proposed.
- The empirical relationship has been validated using the ASTM 1252 flow test.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The quality of processed sands is a critical issue for several construction applications (asphalt mixes, concrete, granular layers). The sand flow test is commonly used to control this quality. High accuracy video-capturing equipment is now also used to characterize the shape of aggregates. The objective of this study is to model the relationship between the actual shape of sand particles, measured using a video-capturing equipment, to the sand's flowing time in a hopper, in order to eliminate the need for sand flow laboratory measurements.

Several samples of processed and natural sands were tested using on the sand flow test equipment used in the European standards. The shape of the particles was then analyzed using a video-capturing equipment. A simple empirical relation was found between the shape factor of particles by Beverloo's law and the actual shape of particles, characterized by a shape index defined in this study. The results were then confronted with the sand test equipment specified in the ASTM standards, to validate this empirical relation.

The coefficients in this new relation had to be experimentally determined according to definition of the particle's diameter, the video system, and the sand flow test equipment. The discharge coefficient was also taken into consideration. This is mainly experimental work; the physical explanation of this relation would have to be analyzed in greater depth in the future.



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**Nomenclature**

| | |
|---|---|
| $\varepsilon_d$ | bulk porosity of the material |
| $\eta_d$ | flowing packing density |
| $\mu_g$ | dynamic air viscosity, kg/ms |
| $\rho_b$ | bulk density of the material, kg/m$^3$ |
| $\rho_d$ | flowing density of the material, kg/m$^3$ |
| $\rho_g$ | air density, kg/m$^3$ |
| $\rho_p$ | solid mass density of the material, kg/m$^3$ |
| $\rho_{mix}$ | bulk density of a mix of different materials, kg/m$^3$ |
| $C$ | discharge coefficient |
| $d$ | diameter of the particles, m |
| $\bar{d}_{coarse}$ | mean diameter of coarse particles, m |
| $\bar{d}_{fines}$ | mean diameter of fines particles, m |
| $\bar{d}_{mix}$ | mean diameter of the mixed particles, m |
| $d_{50}$ | diameter at 50% of the distribution, in volume, m |
| $d_{eff}$ | effective diameter of powder mixture, m |
| $d_m$ | mean diameter, m |
| $d_{vm}$ | "moment volume mean" diameter, m |
| $D$ | output diameter of the conical hopper, m |
| $g$ | gravity, m$^2$/s |
| $k$ | shape factor |
| $P$ | gas (air) pressure, Pa |
| $S$ | shape index |
| $St$ | Sutherland's temperature, K |
| $U_{mf}$ | minimum fluidization velocity, m/s |
| $W$ | material flow, kg/s |
| $X_f$ | weight fraction of fines, % |
| $Z'$ | modified empty annulus, m |
| $Z$ | empty annulus width, m |
| $z$ | height or vertical direction of the system, m |

## 1. Introduction

Processed sands are widely used throughout the world in many construction materials for several applications. In the road industry, sand represents a major part of the granular skeleton of the materials used in the bound and unbound layers. Sand characteristics, for instance, have a significant impact on rutting and the compaction ability of asphalt mixes. The rheology of cement concrete is also greatly influenced by the quality of the sand used. Sand is also used in the granular foundation layers of a road; its quality has a significant impact on the stiffness and stability of these layers. The physical parameters of sands are therefore extremely important regarding the final mechanical properties of the final structure.

Shape characterization equipment has significantly improved over the last decades, using the latest video-capture technologies. Various types of equipment are available today to define the shape of a particle of sand, for very small sizes (a few micrometers), and for all shapes of particles. The capabilities of the equipment vary and each type of equipment has its own advantages and inconveniences. This precise control of a particle's shape is very useful to study the mechanical properties of the final applications, for example, concrete or asphalt. Nevertheless, this equipment is still very expensive and requires strict environmental conditions. These constraints are usually not suitable for such a production site as a quarry or a road construction site.

Thus, control of the shape of particles of sand is usually carried out by a *Sand Flow test* in sand production sites. The shape of the sand is empirically correlated in this test to the flowing time for a determined mass of sand, through the orifice of a hopper. This equipment is very simple and can be used in any quarry quality control laboratory. The sand flow test is often required to comprise specific limits to control the quality of sand used in the road construction business.

The relationship in this sand flow test between the shape parameters of the particles, accurately defined by video captures, and the flowing time has not yet been identified or modeled. This study aims therefore to link the shape parameters related to certain specific 2D video equipment to the sand flow test results, defined in the EN933-6 Standard [5] or the ASTM 1252 standard [2], for various sizes of different sands. In this way, when it is possible to measure the shape of the particles of sand, i.e. with a video system or by the sand flow test, the result for the flowing time could be deduced.

## 2. Background

### 2.1. Granular discharge history

Prediction of the flow rate for the discharge of dry granular materials from a conical hopper has been widely studied over the last decades. Most studies were carried out in ordinary gravity and atmospheric conditions.

The most broadly-accepted equation for prediction of the granular flow through an orifice was first proposed by Beverloo et al. [4], and can be expressed:

$$W = C\rho_b\sqrt{g}(D - kd)^{5/2} \tag{1}$$

where $W$ is the flow rate, $C$ is a discharge coefficient, $\rho_b$ is the bulk density of the material, $g$ is the gravity, $D$ is the diameter of the orifice, $k$ is a shape factor, and $d$ is the diameter of the flowing particles. The flowing particles were first considered to be monogranular, i.e. with one single diameter in all the samples.

The value of the discharge coefficient $C$ was determined experimentally. Beverloo et al. found that this coefficient depended on the bulk density of the flowing material. The value of $C$ ranged from 0.55 to 0.65 [4]. Several authors have discussed this coefficient [1,4,7,9,11]. According to what is generally accepted, this coefficient is related to internal friction in the powder, the geometry of the discharge, and the sand's bulk density. Hungtington and Rooney [10] claimed that this $C$ coefficient was very much related to the consolidation time required to compact the powder in a bed. They determined the value of $C$ more accurately (between 0.575 and 0.59). The value increased for very smooth and spherical particles. This was later confirmed by other authors [7,8,11]. The value 0.58 is now considered to be an acceptable value for most experiments [1,7–9].

Additionally, the shape factor $k$ was also determined experimentally. This parameter was widely discussed in literature. Beverloo et al. [4] found that the value of $k$ ranged from 1.5 to 2.9 for sands. Literature provided certain values of $k$, from 1 to 3 [1,4,7,8,11].

The term $kd$, noted as the function of $Z(d)$ by Beverloo et al. was interpreted by Brown and Richards [1,7,9] as the empty annulus effect, arguing that no particle center can approach within a distance of $kd/2$ of the orifice's edge. This $Z$ function, initially determined for mono granular mixtures, was reconsidered for polydisperse materials by Arteaga and Tüzün [1], and then changed