Influence of the Particle Shape on the Packing Density and Pumpability of UHPC

Jolien Van Der Putten, Karel Lesage, Geert De Schutter
Magnel Laboratory for Concrete Research, Ghent University, Belgium

The pumpability of a concrete mixture can not be described by one "single parameter". The mixture composition, the pump equipment, the pumping pressure,.. all these parameters affect whether a mixture is pumpable or not. In this research, only the effect of the particle shape will be investigated. For that reason two types of aggregates are used: crushed (basalt and porphyry) and rounded (gravel). The effect of the particle shape on the packing density of the mixture was evaluated using centrifugal consolidation. The pumpability was tested with the sliding pipe rheometer. Although basalt and porphyry are most commonly used in an UHPC-mixture, gravel gives the best results. The packing density of the mixture is higher and the yield stress and plastic viscosity are lower so the lubrication layer will be formed in an easier way.

Keywords: UHPC, particle shape, packing density, pumpability

1 Introduction

Concrete pumping is the most common technique that has been widely used to transport fresh concrete on construction sites. Pumping operations are often based on an engineer's experience or on simplified design charts or qualtitative estimation of the pumpability through slump testing or bleeding testing [2]. However, a quantitative prediction such as predictions of pumping height and pressure are necessary to control the total duration of the construction period and the related construction cost [2, 3]. Different investigations [4-7] showed that the dominant factor to facilitate the pipe flow of pumped concrete is the formation of the lubrication layer, formed at the interface between the concrete and the pipe wall. This layer is formed due to the fact that coarse aggregates move towards the centre of the pipe and form a core, while the fine materials move towards the pipe wall in order to form an easily deformable layer. A very important factor here is the ability of the materials to form this lubrication layer. In case of UHPC, where the high amount of powders, the optimal gradation of the granular constituents and the low water-to-binder ratio is necessary to obtain a compressive strength higher than 150 MPa [8], the formation of the lubrication layer is not evident, this due to a couple of reasons. First of all, the high packing density of the components and the low water amount leads to a denser structure, decreasing the ability to form a lubrication layer. Most UHPC-mixtures use as granular components a combination of fine quartz sand with strong aggregates, such as basalt or porphyry [8]. These two types of crushed aggregates have a high strength and a rough surface texture. But to investigate the influence of the particle shape also rounded aggregates, such as gravel are taken into account.
Secondly, also the rheological properties (yield stress and plastic viscosity) affect the flow behaviour of fresh concrete. These properties are higher in case of UHPC compared to traditional concrete, which implies that not only the shear stress required to initiate flow but also the material resistance of UHPC are higher, affecting the pumpability in a negative way [9].

2 Materials and methods

Materials

The three types of aggregates are combined with cement, silica fume, quartz flower and quartz sand. A more detailed identification of the particles is given in Table 1. This table gives an indication whether the aggregates are crushed (CA) or rounded (RA) and indicates also the maximum size of the particles (MSA) and the packing density (PD) of the individual fractions. Quartz sand had a density of 2650 kg/m³ and a mean particle size of 370 µm The chemical composition of all aggregates, except gravel, can be found in Table 2. CEM I 52.5 N (HSR/LA) had a particle size distribution with a d_{50} of 11.87 µm and a Blaine finess of 3975 cm²/g. A cement with a low C_3A content was used due to their low water demand [10]. In order to decrease the amount of cement, quartz filler (M400) is used. It has a 99.5 wt.% SiO_2, a N_2-BET specific surface of 1.9 m²/g and a d_{50} equal to 12 µm. In order to optimize the paste matrix, also silica fume is applied to decrease the porosity. The silica fume is a densified type (DSF) with a N_2-BET specific surface equals to 15.51 m²/g and a d_{50} of 12.60 µm. The chemical and mineralogical composition of cement and silica fume, used in this research, is given in Table 2.

Table 1: Identification of the different types of aggregates

Parameter	Basalt	Porphyry	Gravel
Codification	CAB	CAP	RA
MSA [mm]	4	4	4
Specific gravity [kg/m³]	2930	2960	2660
Scale of Mohs	7	6.5	5.5
PD	0.534	0.582	0.623

Table 2: Chemical and mineralogical composition of cement, silica fume and M400

Chemical composition [%]	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**K_2O**	**MgO**	**Na_2o**	**SO_3**	**Alkali**
Basalt	44.58	11.50	4.30	10.77	0.65	12.98	2.11	-	-
Porphyry	64.83	14.93	5.74	2.99	2.36	2.87	2.50	0.45	-
Quartz sand	99.50	0.20	0.04	0.01	0.03	-	-	-	-
Cement	20.90	3.64	5.19	63.68	0.63	0.77	0.17	3.03	-
DSF	94.73	0.36	0.71	0.20	0.90	0.39	0.20	0.27	0.79
Mineralogical composition [%]	**C_3S**	**C_2S**	**C_3A**	**C_4AF**					
Cement	59.82	14.88	0.88	15.78					

A polycarboxylic ether was used as superplasticizer with a molecular weight of approximately 40000 g/mol and 35% solids. The composition of the different mixtures with a water to binder ratio of 0.18 is given in Table 3. The particle size distribution of the materials can be seen in Figure 1.

Table 3: Composition of the different mixtures

Materials	MIX CAB		MIX CAP		MIX RA	
	[kg/m³]	[volume%]	[kg/m³]	[volume%]	[kg/m³]	[volume%]
CEM I 52.5 N HS/LA	632	20,15	632	20,15	632	20,15
DSF	198	8,93	198	8,93	198	8,93
M400	158	5,93	158	5,93	158	5,93
Quartz sand M31	434	16,32	434	16,32	434	16,32
Basalt	870	29,62	-	-	-	-
Porphyry	-	-	870	32,34	-	-
Gravel	-	-	-	-	870	32,71
Superplasticizer	27	13,30	27	13,30	27	13,30
Water	133	2,45	133	2,45	133	2,45

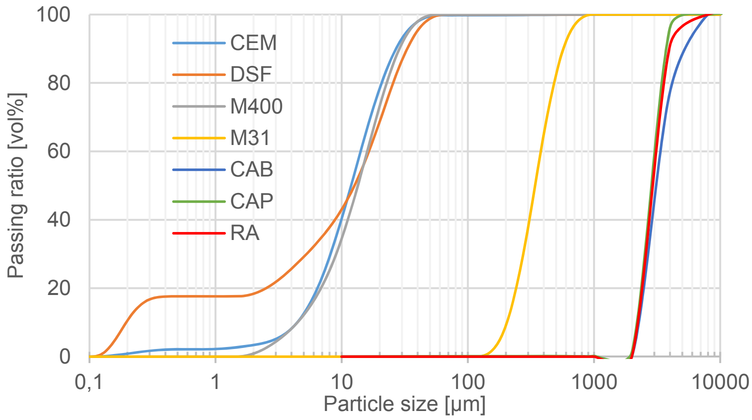

Figure 1: Particle size distribution

Mixing procedure

The mixing procedure is determined based on previous investigations [11, 12] and is kept the same for each mixture. First, binders, fillers, fine and coarse aggregates were weighed in a mobile scale and then introduced in the intensive mixer simultaneously while it was rotating. The dry material was premixed during 15 s. In the next 20 s, the water was automatically added and the superplasticizer was manually poured into the mixture at a mixing speed of 1.6 m/s. In case of ultra-high performance concrete, this is followed by an intensive mixing period of 150 s at a mixing speed of 6 m/s. Finally, a slow mixing phase for 120 s at a speed of 1.6 m/s is applied. The specifications of the mixer are given in Table 4.

Table 4: Specifications of the intensive mixer (75 liter and 5 liter)

Eirich R-type mixer (75 liter)		Eirich R-type mixer (5 liter)
Maximum weight [kg]	120	8
Speed mixing pan [rpm]	8-41	42-83
Speed rotor [rpm]	175-520	70-4535
Diameter mixing pan [mm]	750	235
Height mixing pan [mm]	380	230
Diameter rotor [cm]	30.9	13.32
Filling volume [l]	30	3

Centrifugal consolidation

To obtain the packing density of the complete mixture, centrifugal consolidation was used. The mixing procedure is the same as mentioned before, but the mixtures are made in a smaller intensive mixer of 5 liter. The specifications are given in Table 4. After mixing, the paste is poured into four test tubes with an internal diameter of 27 mm and a length of 115 mm. The test tubes are weighted and afterwards centrifuged for 15 min at 3500 rpm. By centrifuging the tubes, the components are compacted and a smaller amount of water is necessary to fill the voids. Therefore, the test sample will possess an excess amount of water, which leads to a water layer on top of the compacted paste. This water is removed with a pipette. Based on the amount of removed water the particle packing density can be calculated, using the following equation (1):

$$\mathrm{PD} = \frac{1000}{1000 + \rho_{\mathrm{average}} \cdot \frac{m_{\mathrm{water}}}{m_{\mathrm{solids}}}} \tag{1}$$

where $\rho_{average}$ [kg/m³] is the average density of the mixture, m_{water} [g] the excess water amount and m_{solids} [g] the amount of powder.

Sliding Pipe Rheometer

The pumpability is tested by using the Sliding Pipe Rheometer (SLIPER) [13]. By combining the actual geometry of the pipe and the testing procedure used on construction sites, the physical conditions in the concrete pumping process can be efficiently reproduced. Different parameters are measured, in particular the speed of the pipe, measured by a distance sensor, the pressure P of the concrete when the pipe is sliding downwards and the flow rate Q. From the pressure and the flow rate, two parameters a and b are calculated. Parameter a is directly related to the yield stress of the concrete, parameter b is a function of the slope of the P-Q curve and is related to the plastic viscosity in the same region. Due to the high viscosity of the mixtures, it was necessary in this research to apply from the beginning a weight of 4.728 kg. Without this mass, the pipe was not able to slide downwards.

3 Results and discussion

Influence of the type of coarse aggregate on the packing density

In order to investigate the influence of the particle shape, crushed and rounded aggregates are used. As mentioned before, the size of the particles is kept constant, no particles larger than 4 mm are used. The three different aggregates have similar particle size-distributions but different surface textures and shapes. Also the composition of the reference mix is unchanged. The amount of powders, sand, water and superplasticizer is similar.

At first instance, the packing density of the mixtures is obtained using centrifugal consolidation and the results are shown in Table 5. The mixture consisting of RA has a higher packing density compared to the mixtures with CAB and CAP. These results are in accordance with the individual packing densities mentioned in Table 1. The angularity of the crushed particles affects the packing and the amount of voids in the mixture. The interstitial volumes between the crushed aggregates are more concave, and they are generally more difficult to fill up [14].

From the packing density, it becomes possible to derive two important parameters, the water film thickness (WFT) and the plastic viscosity (η). The WFT will be discussed in this section, the influence on the plastic viscosity will be discussed in the next paragraph. First of all, the WFT can be derived using equation (2) [1], where V_w [m³] is the volume of water in the mixture, V_p [m³] the volume of all the particles, PD [-] the measured packing density, A_p [m²/kg] the surface area of particles and m_p [kg] the mass of the particles.

$$\mathrm{WFT} = \left| \frac{V_W - V_P \cdot \left(\frac{1-\mathrm{PD}}{\mathrm{PD}}\right)}{A_P \cdot m_P} \right| \tag{2}$$

For the surface area of the particles, the Blaine value as reported by the material producers was used. In case of a BET-specific area, this value was transformed using equation (3).

$$S_{m,blaine} = \sqrt{\frac{S_{m,BET} - 3500}{3.89 \cdot 10^{-4}}} \tag{3}$$

According to Table 5, the WFT increases when the packing density increases. This can be explained by the packing density. Figure 2 shows a general concrete mixture, before and after centrifugal consolidation. After consolidation, the particles are more compacted and the voids are filled with water. The rest of the water forms a water layer on top of the mixture, and is called the excess amount of water. When the packing density is higher, e.g. in case of RA, the amount of voids is smaller because the particles have a denser structure and are more compacted. The amount of water is kept the same in the three mixtures. In case of RA, less water is needed to fill the smaller amount of voids, and the amount of excess water will increase.

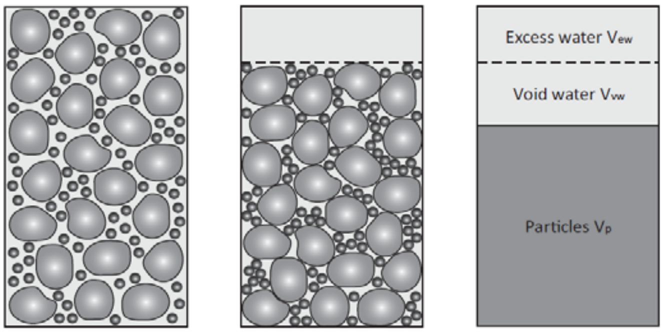

Figure 2: Volume of water, divided into excess water and void filling water, within a concrete mixture in a unit volume before and after centrifugal consolidation [1]

Table 5: Packing density and WFT for the different concrete mixtures

Parameter	CAB	CAP	RA
Packing density [-]	0.661	0.666	0.667
WFT [µm]	0.0363	0.0365	0.0375

Influence of the type of coarse aggregate on the performance of UHPC

Concrete flow in the pipeline can be characterised by plug flow and the formation of a lubricaton layer. In order to create real life conditions with the sliding pipe rheometer, it is necessary to apply 5 to 10 prestrokes before starting the measurements. This is very important because investigation [4, 6] showed that the pumping pressure, calculated with the lubrication layer can be significantly lower than when no lubrication layer is considered. For practice, this means that before the formation of the lubrication layer, very high discharge pressures are needed to be applied by the pump. However, as soon as the lubrication layer is formed, the required pressure decreases drastically. Based on previous research [4], the thickness of the formed lubrication layer is assumed equal to 2 mm. Figure 3 and Table 6 give an indication of the test results obtained by the SLIPER. M_1 and M_2 in Table 6 indicate whether one or respectively two masses of 4.728 kg are applied.

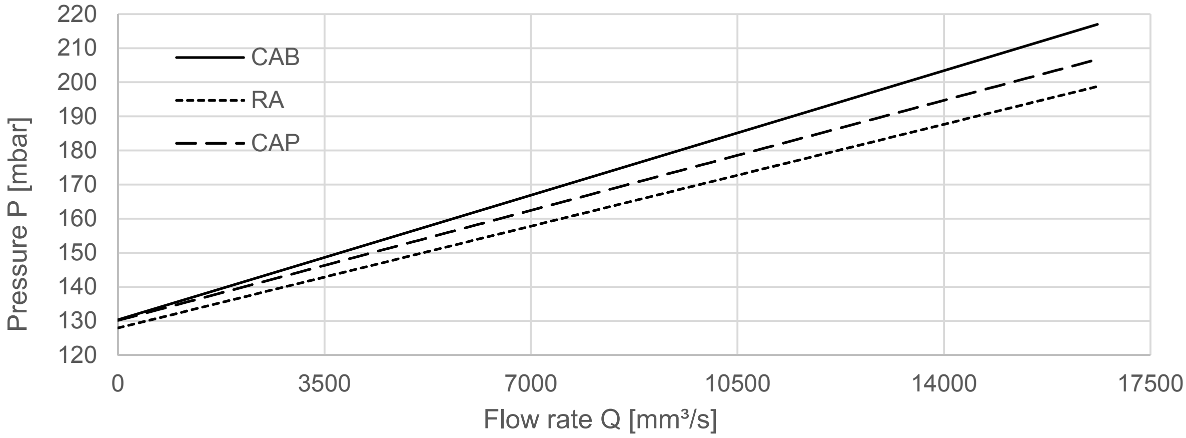

Figure 3: Pressure P vs. flow rate Q curves obtained from Sliper test

Table 6: Experimental results of Sliper

Parameter	CAB	CAP	RA
a	130.34	130.17	127.95
b	0.0052	0.0046	0.0043
Pressure (M_1) [mbar]	173	169	165
Flow rate (M_1) [mm³/s]	8172	8419	8681
Pressue (M_2) [mbar]	207	200	198
Flow rate (M_2) [mm³/s]	14685	15141	16413

As can be seen in Figure 3, the P-Q curve is quite similiar for all the different mixtures. Due to the fact that UHPC is considered as a Bingham fluid, the flow behaviour is described based on two different parameters: yield stress and plastic viscosity. In case of the experimental Sliper results, parameter a is directly correlated to the yield stress (τ_0) of the lubrication layer and parameter b, is related tot he plastic viscosity (η). These two values are both smaller in case of RA compared with the ones obtained for CAB and CAP. A lower b-value indicates a curve that is slightly flatter. As mentioned before, it is also possilbe to calculate a theoretical value of the plastic viscosity based on the packing density of the mixture, using the Krieger-Dougherty model. This model is given by equation (4), where ϕ [-] is the volume fraction of the solid, ϕ_{max} [-] the maximum packing density and [η] [-] the intrinsic viscosity of the suspension.

$$\eta = \left(1 - \frac{\phi}{\phi_{\max}}\right)^{-[\eta]\phi_{\max}} \qquad (4)$$

The maximum packing density is according to [15] the experimental packing density obtained by using centrifugal consolidation, the volume fraction of the solid is given in Table 3. The intrinsic viscosity is equal to 2.5 when the suspension consists of only spheres. In this case, the suspension consists of cement, silica fume and quartz flour. The value of 2.5 has to be adapted due tot he fact that the particles of cement and quartz flour cannot be assumed as spheres. For that reason, a shape factor [16], given in Table 7, is used and the value of the intrinsic viscosity becomes equal to 3.34.

Table 7: Shapefactor powders [16]

	CEM	DSF	M400
Shapefactor [-]	1.58	1.00	1.22

Table 8: Theoretical value of the plastic viscosity

Parameter	CAB	CAP	RA
ϕ	0.810	0.837	0.841
ϕ_{max}	0.661	0.666	0.667
$[\eta]$	3.34	3.34	3.34
η	**27.019**	**20.662**	**20.110**

The results, given in Table 8, are similar with the ones obtained by the sliper and indicate a flatter flow curve in case of RA. In other words, mixtures consisting of RA have a higher pumpability and can be pumped at higher flow rates at the given pumping pressure. This is related to the rounded aggregates facing less resistance from the mortar matrix during shear deformation of the concrete, as compared to those with crushed aggregates. Moreover, crushed aggregates interlock with each other and prevent the smooth flow of the concrete. The crushed aggregates also have a larger surface area per unit volume as compared to rounded aggregates, and thus require more mortar to coat the surface. More specifically, the formation of the slip layer will occur more easily in case of rounded aggregates [13]. The lower values of the rheological parameters in case of RA are also obtained by [17], as shown in Figure 4.

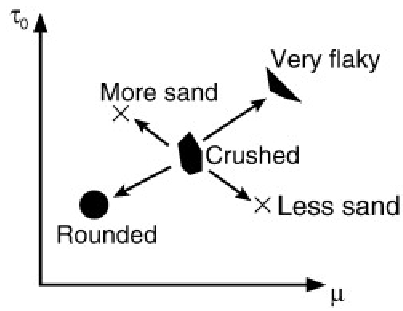

Figure 4: Effect of the particle shape on the rheological parameters of a concrete mixture [17]

4 Conclusion

In this study the effect of the particle shape on the packing density and the pumpability of an UHPC has been studied. The following conclusions have been obtained.

- The packing density of a mixture containing rounded aggregates is higher compared to mixtures consisting of crushed aggregates.
- The higher packing density results in a higher WFT because the water amount, necessary to fill the voids between the particles is smaller.
- The pumpability of a mixture containing rounded aggregates is better. The P-Q curve shows a lower slope, representing a lower yield stress and plastic viscosity. The shape of gravel is more appropriate to form the necessary lubrication layer.

References

[1] Fennis, S., *Design of ecological concrete by particle packing optimization*. 2011, PhD-dissertation, Delft University of Technology. p. 277.

[2] Choi, M.S., Y.J. Kim, and S.H. Kwon, *Prediction on pipe flow of pumped concrete based on shear-induced particle migration.* Cement and Concrete Research, 2013. **52**(0): p. 216-224.

[3] Choi, M., et al., *Lubrication layer properties during concrete pumping.* Cement and Concrete Research, 2013. **45**(0): p. 69-78.

[4] Le, H.-D., *Etude de l'effet de la couche limite sur les profils de vitesse du béton pompé*. 2014, University of Ghent and University of Cergy-Pontoise.

[5] Kaplan, D., *Pompage des bétons*. 2001: PhD-dissertation, Laboratoire Central des Ponts et Chaussées, Paris.

[6] Kaplan, D., F. de Larrard, and T. Sedran, *Design of Concrete Pumping Circuit.* Materials Journal, 2005. **102**(2).

[7] Feys, D., *Interactions between rheological properties and pumping of self-compacting concrete*. 2009, University of Ghent.

[8] Dils, J., *Influence of Vacuum Mixing, Air Entrainment or Heat Curing on the Properties of Hardened and Fresh (Ultra) High Performance Mortar*. 2015, Phd-dissertation, University of Ghent. p. 362.

[9] Mahmoodzadeh, F. and S.E. Chidiac, *Rheological models for predicting plastic viscosity and yield stress of fresh concrete.* Cement and Concrete Research, 2013. **49**: p. 1-9.

[10] Dils, J., V. Boel, and G. De Schutter, *Influence of cement type and mixing pressure on air content, rheology and mechanical properties of UHPC.* Construction and Building Materials, 2013. **41**(0): p. 455-463.

[11] Dils, J., G. De Schutter, and V. Boel, *Influence of mixing procedure and mixer type on fresh and hardened properties of concrete: a review.* Materials and structures, 2012. **45**(11): p. 1673-1683.

[12] Mazanec, O. and P. Schiessl. *Mixing time optimisation for UHPC*. in *Proceedings of the Second International Symposium on Ultra High Performance Concrete*. 2008b. Kassel, Germany.

[13] Mechtcherine, V., V.N. Nerella, and K. Kasten, *Testing pumpability of concrete using Sliding Pipe Rheometer.* Construction and Building Materials, 2014. **53**(0): p. 312-323.

[14] Mora, C.F. and A.K.H. Kwan, *Sphericity, shape factor, and convexity measurement of coarse aggregate for concrete using digital image processing.* Cement and Concrete Research, 2000.**30**(3): p. 351-358.

[15] Lowke, D., et al. *Control of Rheology, Strength and Fibre Bond of UHPC with Additions - Effect of Packing Density and Addition Type*. in *3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials*. 2012. Kassel.

[16] Hunger, M., *An integral design concept for ecological Self-Compacting Concrete*. 2010, PhD-dissertation, Technical University of Delft. p. 260.

[17] Wallevik, O.H. and J.E. Wallevik, *Rheology as a tool in concrete science: The use of rheographs and workability boxes.* Cement and Concrete Research, 2011. **41**(12): p. 1279-1288.