

# EFFECT OF THE MIX COMPOSITION ON RHEOLOGICAL BEHAVIOR OF A FRESH GRANULAR-CEMENT PASTE MATERIAL

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## ABSTRACT

*In this paper, the effect of the mix composition on rheological behavior of a mixture is studied by considering a two-phase model for a mixture. A mixture is decomposed into a granular and a paste phase. Paste itself is divided into the void paste and the excess paste. The slump test is used for evaluation of rheological behavior of a mixture. The results show that the granular-cement paste mixtures can be split into three main classes viz Granular-High Paste, Granular-Intermediate Paste and Granular-Low Paste. In Granular-High Paste class, the behavior is governed by the excess paste and the capacity of deformation of mixtures is maximal. In Granular-Low Paste class, the behavior is governed by the void paste and the capacity of deformation of mixtures is minimal. In Granular-Intermediate Paste class, the behavior is determined by both the excess paste and the void paste, and the deformability is in between that of the two other extreme cases.*

**Keywords:** Fresh granular-cement paste material; consistency of the paste; void paste; excess paste

## INTRODUCTION

The response of fresh granular-cement paste material to any imposed action, such as mixing, transportation, placement and compaction, depends on the rheological behavior of this material. Besides, the mechanical properties and durability of this type of material can be influenced by the early age behavior as well [1]. Therefore, understanding this particular early age period of a granular-cement paste system is crucial for achieving an optimum workability.

From a rheological perspective, a fresh granular-cement paste material can be considered as a heterogeneous system that in its early state can perform either closer to a paste or to a granular system, depending on the properties and proportion of the components [2]. For a low amount of the aggregates, it can be considered that there is no continuous network of aggregates that are in direct contact and the paste phase dominates the behavior. If the volume fraction of grains is close to its maximum, i.e. when the volume of the mixture is equal to the bulk volume of the compacted particles, the granular phase governs the behavior.

In order to describe this complex behavior, first a mixture is characterized by means of a two-phase model. Then the effect of the paste consistency, the paste volume fraction and the aggregate grading on deformability of a mixture is studied [3]. The slump test is used for evaluation of the rheological behavior of a mixture.

### MIX CHARACTERIZATION BY TWO-PHASE MODEL

In a two-phase model, the mixture is divided into two parts viz. aggregates and paste (see Fig. 1(a)). Paste itself is a dispersion of powder particles in water. 0.125 mm is recommended for the boundary size between the aggregates and the powder particles [4]. The granular phase is characterized by its packing density ( $\zeta$ ). The packing density is expressed as follows:

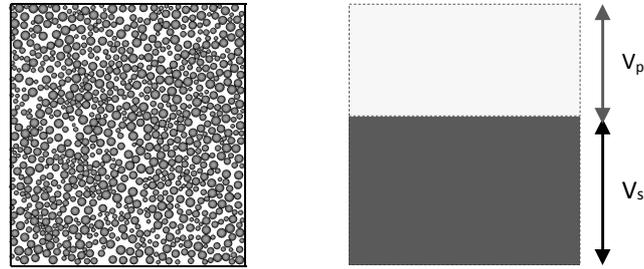
$$\zeta = \frac{\rho_b}{\rho_s} \quad (1)$$

where  $\rho_b$  and  $\rho_s$  are the bulk density of aggregates [5] and the specific density of the aggregates [6, 7], respectively. The packing density of aggregates depends on four main factors viz. grading, shape of the aggregate particles, surface roughness of the grains and packing method of the aggregate particles [8]. The paste phase is divided into two parts: 1) void paste and 2) excess paste. The void paste is the part of the paste filling the void space between the aggregates in compacted state (see Fig. 1(b)). The excess paste is the part of the paste used to form a layer with constant thickness around each individual aggregate particle ( $\delta_{pex}$ ) (Fig. 1(c)). The volume fraction of void paste ( $V_{pv}$ ) can be calculated with Eq. 2:

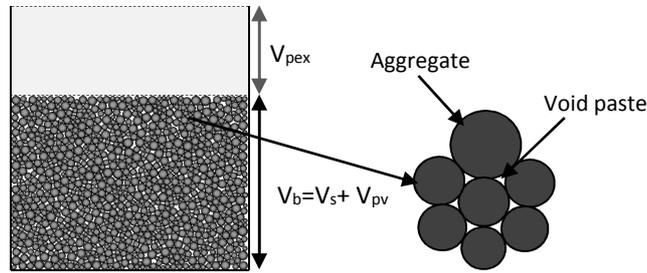
$$V_{pv} = \left(\frac{1}{\zeta} - 1\right) \cdot V_s \quad (2)$$

where  $V_s$  represents the solid volume (aggregate volume) in a unit volume of granular material. The volume of the excess paste ( $V_{pex}$ ) is calculated by subtracting the volume of the void paste ( $V_{pv}$ ) from the total volume of the paste ( $V_p$ ).

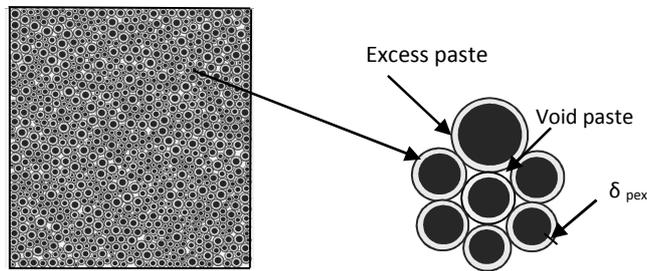
Figure 1. Two-phase model.  $V_b$ ,  $V_p$ ,  $V_{pv}$ ,  $V_{pex}$ ,  $V_s$  and  $\delta_{pex}$  stand for bulk volume of aggregates in compacted state, total paste volume, void paste volume, excess paste volume, volume of the aggregates and thickness of the excess paste layer, respectively.



(a) Loosely packed aggregates



(b) aggregates in compacted state



(c) Packing of aggregates corresponding to two-phase model

In the calculation procedure for the thickness of the excess paste it is presumed that the shape of the grain particles is spherical and the thickness of the excess paste around the particles is the same for all particle sizes. Under these considerations, the solid volume of the granular skeleton ( $V_s$ ) and the excess paste volume ( $V_{pex}$ ) can be calculated with Eq. 3 and Eq. 4, where  $R_i$  and  $N_i$  represent the radius of particles of class  $i$  and the number of particles per class  $i$ , respectively.

For  $V_s$  we have:

$$V_s = 4/3.\pi. \sum N_i R_i^3 \quad (3)$$

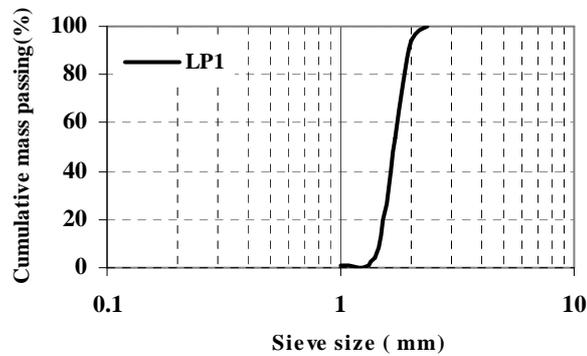
and for  $V_{pex}$ :

$$V_{\text{pex}} = 4/3 \cdot \pi \cdot \sum N_i ((R_i + \delta_{\text{pex}})^3 - R_i^3) \quad (4)$$

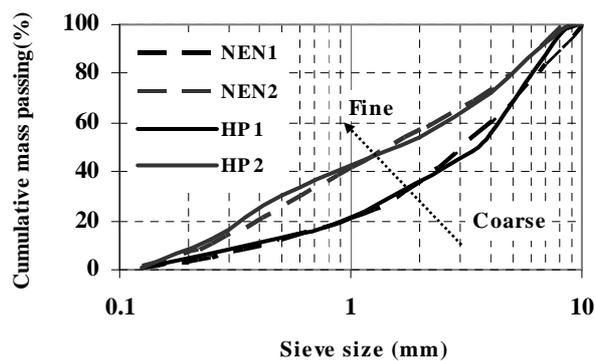
## MIX COMPOSITION

Granular materials used in this study consist of natural aggregate particles with specific density ( $\rho_s$ ) of 2.56 g/cm<sup>3</sup>. With respect to the particle size distribution, the granular materials are divided into the two main groups as shown in Fig. 2.

Figure 2. Mass grading of granular materials. The criteria recommended by NEN 5905 for a dense aggregate grading with maximum aggregate size of 8 mm [9] are shown by dashed lines in Fig. 2(b).



(a) Low poly size aggregate material with the bulk density ( $\rho_b$ ) of 1.69 g/cm<sup>3</sup>.



(b) High poly size aggregate materials (well graded samples),  
i.e. HP1 ( $\rho_b = 2.05$  g/cm<sup>3</sup>) and HP2 ( $\rho_b = 2.08$  g/cm<sup>3</sup>).

Table 1. Volumetric proportions of super-plasticizer and other paste components.

Ingredients	Cement I 52.5		Limestone powder		Water	W/C
Volume proportion	0.365		0.214		0.413	0.36
Paste N.	N1	N2	N3	N4	N5	
Glenium 51 [%]	0.56	0.64	0.71	0.87	0.98	
Cs (Pa)	57	48	37	29	22	

Five paste mixtures are prepared with Portland cement CEM I 52.5 ( $\rho_s=3.15 \text{ g/cm}^3$ ), limestone powder ( $\rho_s=2.64 \text{ g/cm}^3$ ), water and superplasticizer (see Table 1). The consistency of each mixture is characterized by characteristic (yield) strength (Cs) [3]. The mix proportions are given in Table 2.

Table 2. Mix proportions for high poly size (HP) and low poly size (LP) mixtures for one liter sample. The aggregate gradings are given in Fig. 2.

Mix type	Excess paste volume fraction (%)	Calculated ratio of void paste volume to total paste volume (%)	Calculated thickness of excess paste layer ( $\mu\text{m}$ )	Total paste volume fraction (%)
HP1- N1	0	100	0	20
HP2- N1	0	100	0	19
LP1- N1	0	100	0	34
HP1- N2	5	79	10	24
HP2- N2	5	78	6	23
LP1- N2	5	86	20	37
HP1- N3	10	64	21	28
HP2- N3	10	63	12	27
LP1- N3	10	75	41	41
HP1- N4	14	55	28	31
HP2- N4	14	53	17	30
LP1- N4	14	68	58	43
HP1- N5	17	50	33	34
HP2- N5	17	48	20	33
LP1- N5	17	62	72	45
HP1- N6	20	44	40	36
HP2- N6	20	43	24	35
LP1- N6	20	58	88	47
HP1- N7	24	39	47	39
HP2- N7	24	37	30	38
LP1- N7	24	52	105	50

## EXPERIMENTS AND DISCUSSION

The rheological behavior of a mixture is evaluated by the slump test. The cone which is used in this study is selected according to (NEN-EN 12350-5)[10]. The slump test results are indicated in Fig. 3.

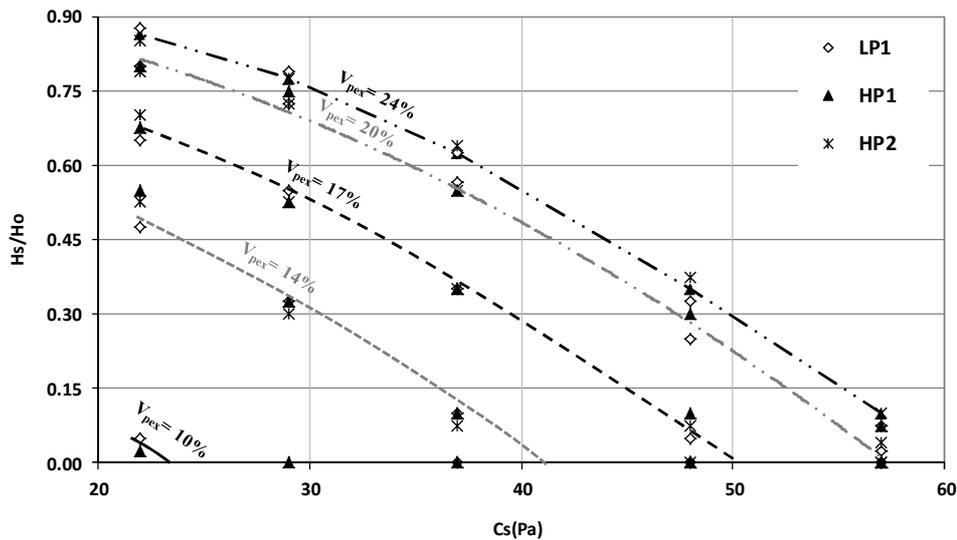


Figure 3. Relative slump ( $H_s/H_o$ ) vs. characteristic strength of paste ( $C_s$ ) for various mixes given in Table 2. A mixture is represented by its aggregate grading, i.e. LP1, HP1 and HP2, and its volume fraction of the excess paste ( $V_{pex}$ ).  $H_o=200$  mm. As the mixtures with excess paste volume less than 10% showed no deformation after demolding, they are not presented.

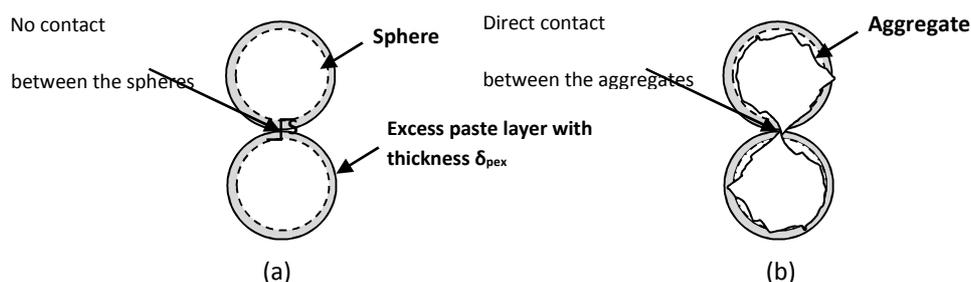
The graphs show that all mixtures with the same volume fraction of the excess paste ( $V_{pex}$ ) and the same type of the paste (same  $C_s$ ) show almost the same relative slump value ( $H_s/H_o$ ), irrespective of the aggregate grading of the granular phase. With increasing excess paste volume and decreasing characteristic strength  $C_s$  of the paste, the relative slump  $H_s/H_o$  increases. However, the change of the slump by changing the excess paste volume is not linear and increases with decreasing the excess paste volume fraction. For example for  $C_s=22$ Pa, for the first 4% decrease of the excess paste volume (24% to 20%),  $\Delta H_s/H_o=0.05$  while for the second and third decrease,  $\Delta H_s/H_o$  is about 0.15 and 0.20, respectively. For the last one (14% to 10%),  $\Delta H_s/H_o$  is about 0.45. For  $V_{pex} \leq 10\%$ , the change of the excess paste volume fraction  $V_{pex}$  does not have significant effect on rheological behavior anymore and mixtures show almost no deformation.

This difference can be related to the effect of the void paste on rheological behavior of a mixture. Contrary to the excess paste, which tries to push the aggregates apart and facilitate their mobility, void paste behaves like a bond and tries to keep the aggregates in their position. Three classes are distinguished for the mixtures as follows:

1. Granular-High Paste class,  $V_{pex} \geq 20\%$ , where the excess paste governs the rheological behavior and the void paste does not significantly influence the rheological. This criterion is usually recommended for self-compacting concrete [11].
2. Granular-Intermediate Paste class,  $V_{pex} < 20\%$ , where the effect of the void paste on rheological behavior becomes significant and increases with decreasing the excess paste volume fraction (the effect of the granule phase gradually increases). Under influence of the void paste, the capacity of deformation of a mixture decreases.
3. Granular-Low Paste class, where the void paste dominates the effect of the excess paste ( $V_{pex} = 0$ ) and a mixture shows almost no deformation. In this case, a mixture behaves like a pile of aggregate particles in which particles are almost in direct contact and are stuck together by the void paste.

In our cases mixtures with  $V_{pex} \leq 10\%$  show almost no deformation. This behavior can be related to the effect of the irregularity of the shape of aggregate particles on the interlocking distance between the aggregates. As the aggregate particles in the mixture are not exactly spherical, the irregularity of shape of aggregates can cause contact between them while the inter-particle distance  $S > 0$  ( $\delta_{pex} > 0$ ) (see Fig. 4). In this case the interaction between aggregate particles becomes independent of the thickness of the excess paste layers and changing the excess paste thickness is not effective anymore on deformability of a mixture.

Figure 4. Effect of the irregularity of shape of aggregate particles on inter-particle interaction, a) Interaction through the excess paste layers; b) Direct contact between the aggregates.



## CONCLUSIONS

In this paper, the effect of the mix composition on rheological behavior of a mixture was studied by considering a two-phase model for a mixture where a mixture consists of aggregates, void paste and excess paste. It was found that the aggregate grading

does not significantly affect rheological behavior if the volume fraction of the excess paste and the consistency of the paste are kept constant. Three classes were distinguished for the mixtures viz. Granular-High Paste, Granular-Intermediate Paste and Granular-Low Paste. In Granular-High Paste class, the excess paste dominates the rheological behavior and the capacity of deformation of mixtures is maximal. In Granular-Intermediate Paste class ( $V_{\text{pex}} < 20\%$ ), the excess paste and void paste work in harmony together. The capacity of deformation of the Granular-Intermediate Paste class mixtures is lower than the Granular-High Paste class mixtures. Finally in Granular-Low Paste class, the aggregate particles are almost in direct contact and the capacity of deformation of a mixture is minimal.

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