Concrete optimisation with regard to packing density and rheology

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CONCRETE OPTIMISATION WITH REGARD TO PACKING DENSITY AND RHEOLOGY

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CONCRETE OPTIMISATION WITH REGARD TO PACKING DENSITY AND RHEOLOGY

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Abstract

In Civil Engineering granular materials, mixtures of particles with a wide grading span are used commonly. At the dry state, the sake of a minimum porosity – or the maximum packing density – is generally considered as a good strategy to get an optimised mix. However, modern concrete technology is now offering a variety of mixes suitable for different applications, that should match complex sets of specifications. These specifications ensure the ease of placement, the attainment of sufficient mechanical properties at the hardened state and a satisfactory durability in a certain environment. Rheology becomes a key issue in some mix categories, like Self-Compacting Concrete (SCC). In such a case, how the optimal aggregate gradation compares with the one of a dry mixture ? The paper discusses this old question through an example where a dry aggregate mix (in bulk or confined conditions), a Roller-Compacted Concrete, a Normal-Strength Concrete and a Self-Compacting Concrete are optimised with the same constituents. The effect of granular interactions, as wall effect and loosening effect, is highlighted.

1. INTRODUCTION

A concrete mixture can be viewed as a dry packing of aggregate particles, filled up with cement paste. Since this matrix is both more expensive and less strong and durable than the natural rock, the basic proportioning strategy is to design the granular mix with the sake of a minimum porosity. Then, the composition of the matrix is fixed with regard to final strength and durability, the water-cement ratio being the key parameter.

However, such an approach does not provide any flowing capacity to the mixture. To permit an easy shear motion within the fresh mix, it is thus necessary to decrease the aggregate content, or to increase the paste content. In this case, are the proportions of aggregate fractions which led to the minimal dry mix porosity still the best possible? Also, should these proportions account for the congestion brought by a dense reinforcement or a close distance between form walls ? This paper intends to clarify this old question, based upon the global mix-design theory developed by the author and his colleagues [1].

2. PACKING DENSITY OF DRY MIXTURES

The problem of aggregate fraction combination which gives the lowest porosity, or the highest packing density is as old as construction materials, and was already investigated by the ancient Greek Appolonios de Perga. A number of authors [2-4] provided literature reviews of packing models related to concrete mix-design. In the modern physics production, many recent papers can be found where aggregate packings are geometrically and numerically simulated with an explicit description of each grain. However, the very wide grading span of civil engineering mixes – commonly from 10^3 to 10^5 – makes impossible to use this approach for realistic materials. Then come the analytical models, where mathematical equations are derived to predict the packing density of a grain mixture. The Compressive Packing Model [1] pertains to this category.

This model is the third generation of packing models developed at LCPC. The aim is to predict the packing density of a polydisperse mix, from the knowledge of three types of parameters:

i) packing density of monosize classes;
ii) size distribution of the mix; and
iii) compaction energy.

It is based upon the concepts of virtual packing density and compaction index.

2.1 Virtual packing density of an assembly of particles

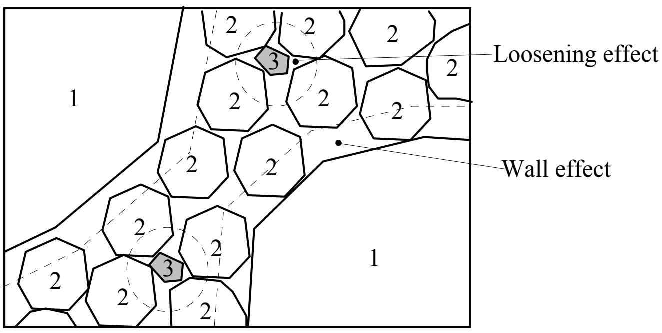

Figure 1. Wall effect and loosening effect in a binary mixture.

For a given population of grains, it is well known that the packing density, which is the ratio of the solid volume by the total volume of the container, depends on the placing process. The virtual packing density is, by convention, the maximum value which is attainable by placing the grains one by one, without altering their shape. Industrial mixtures are always randomly placed, with a finite energy, so that the experimental packing density is lower than the virtual one.

Let us consider a mix of particles of any shape, divided into n classes of monosize particles (with respect to conventional sieving process). In any mix, one may define the *dominant class i*, which forms itself a packing in the voids of the coarser particles (see Fig. 1). Let β_i be its residual packing density, that is the virtual packing density displayed when the class is isolated and fully packed. The packing density of the overall mixture is computed by noting that the bulk volume of the i class fills the space around the coarser grains; moreover, the volume of finer classes inserted in the voids of i class must be added. Two interaction effects must be accounted for in this calculation: the *wall effect*, exerted by the coarser grains, and the *loosening effect* exerted by the finer particles (see Fig. 1). In the model, it is assumed that those interactions are additive, which means that a possible intersection between the perturbed zones is neglected.

2.2 Actual packing density: the concept of compaction index

The previous idea, when applied to a n-class mixture of particles leads to the calculation of n equations of the virtual packing density, each one being valid when the corresponding class is dominant. The 'real' virtual packing density is the lowest of these n values. Another parameter, called the compaction index K, is necessary to compute the actual packing density. It expresses to which extent the actual packing is close to the virtual one. Therefore, K appears as a characteristic of the placing process. Mathematically, it is defined as the sum of partial compaction indexes K_i corresponding to each class i. K_i is governed by the actual volume of i grains in the mix Φ_i, and by Φ_i*, the maximal value of Φ_i if the mix were fully packed by an excess of i grains, all the remaining classes having a constant volume. The equation is

$$K = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{\dfrac{\Phi_i}{\Phi_i^*}}{1 - \dfrac{\Phi_i}{\Phi_i^*}} \qquad (1)$$

When the solid concentration increases from zero up to the virtual packing density, the packing index grows from zero to infinity. For a given mixture, fixing a K value provides an implicit equation that has only one solution: the actual packing density predicted by the model. When properly calibrated, the accuracy in the prediction of packing density of mixtures is better than one percent (mean value for a set of experimental data).

2.3 Packing density in a congested medium

When a mixture is placed in a volume, the dimensions of which are not great when compared to the maximum size of particles, it is in confined conditions. In such a case, the packing density is lower, because of supplementary voids appearing in the vicinity of obstacles and walls (see Fig. 2). The CPM can account for this fact, by decreasing the β_i parameters according to Ben Aïm's model [1].

3. FLOWING CAPACITY AND SEGREGATION ABILITY

3.1 How to describe scientifically the flow and placement of fresh concrete

Between the mixer and the form, fresh concrete may undergo two types of elementary deformations: it may be sheared and/or compacted. For very dry, bulking concretes, compaction is the critical step. On the contrary, for very fluid mixtures like self-compacting concretes, the important phenomenon is the shear deformation (since gravity alone ensures the mixture compaction).

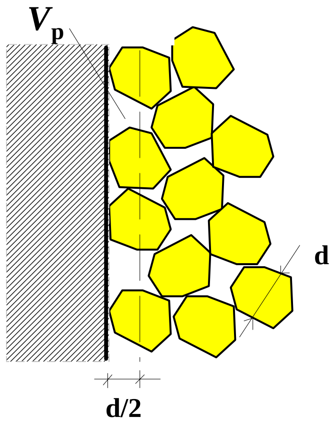

Figure 2. Wall effect at the mix boundaries. In the perturbed zone V_p, the mean packing density is lower than in bulk conditions.

Compactability is directly described by the compaction index, that we will call K' in the case of fresh concrete, to make a distinction with that of the corresponding dry mixture. K' is a major mix-design parameter. Unfortunately, there is today no way to measure it, to the best of the author's knowledge. As for the shear behavior, it is well known that, in the range of soft-to-dry consistency, fresh concrete may be viewed as a Bingham material; in other words, its rheological behavior is described by a straight line in a diagram giving the shear stress vs. strain gradient. The intercept of the line is the yield stress, and the slope is called plastic viscosity. Within these two parameters, the former is closely related to the slump. The latter makes the difference between a 'worker-friendly' high-performance concrete from those having a 'sticky' behavior, being hard to pump and displaying coarse bubbling at the form removal.

3.2 Prediction of plastic viscosity, yield stress and slump

The yield stress is a common feature of fresh concrete and dry granular materials (like soils), while plastic viscosity tends to relate fresh concrete to viscous bodies like oils or water. Therefore, one may assume that the yield stress is the result of intergranular friction during concrete shear, while plastic viscosity is the macroscopic signature of the flow of water in the porosity of the granular system. As for the viscosity of newtonian materials, plastic viscosity is governed by the relative concentration of the mixture, defined as the ratio between the proportion of solid materials (in volume) and its packing density. This last parameter can be viewed as the maximum solid proportion corresponding to a non-workable, water-saturated fresh concrete. From this assumption, it can be concluded that the contribution of the various grain fractions contribute to the plastic viscosity only to the extent to which they contribute to the packing density of the corresponding dry mixture.

The pattern is different if the yield stress is considered. As a matter of fact, a small particle assembly contains more interparticle contacts than a large particle packing. Thus, the friction generated is higher, for a given compaction index. In order to predict the yield stress of fresh concrete, one must add the contributions of the various grain fractions, which depend on their partial compaction index, weighed by a coefficient. This 'friction' coefficient increases when the particle size decreases. The cement friction coefficient may decrease in a 5 to 1 ratio when a superplasticizer is added: this is the lubricating effect of the admixture. Moreover, superplasticizer exerts also a deflocculating effect, which can be measured through the decrease of water-demand, giving a higher residual packing density in the frame of the packing model. Finally, the yield stress model may be converted into a slump model, having a mean precision of about 4-5 cm.

3.3 Case of self-compacting concrete: flow in congested medium and avoidance of static segregation

Self-compacting concrete is supposed to flow under the only action of gravity. In bulk conditions, this condition can be translated in terms of yield stress, which must be lower than a certain threshold. However, any blockage should be avoided when the mix is flowing in congested area. Sedran [5] shown that this condition is satisfied if the amount of coarse aggregate is low enough with regard to the maximum amount which can be placed in confined conditions. Mathematically, it corresponds to a limitation of the coarse aggregate partial compaction index K'_{gg}. After SCC has been placed, coarse aggregate may sink in the mix if the cement paste is not thick enough. According to Sedran, this phenomenon can be overcome by observing a minimal value for the fine, cementitious material partial index K'_f.

4. APPLICATION: OPTIMISATION OF VARIOUS TYPES OF MIXTURES

Table 1. Specifications of concrete mixtures.

Properties or parameter		RCC	NSC	SCC
Durability constraints	Equivalent* cement content (kg/m^3)		≥ 280	≥ 280
	Equivalent* water/cement ratio		≤ 0.60	≤ 0.60
Fresh concrete constraints	Slump (mm)		∈ [100, 150]	
	Yield stress (Pa)			≤ 400 Pa
	Plastic viscosity (Pa.s)			≤ 200 Pa.s
	Compaction index K' (unconfined conditions)	≤ 14	≤ 6.5	
	Compaction index K'_{conf} (confined conditions**)			≤ 7
	K'_{GG} (partial compaction index of coarse particles in confined conditions**)			≤ 1.4
	K'_f (partial compaction index of fine particles)			≥ 3.3
Hardening concrete constraint	Adiabatic temperature rise (K)	Minimum		
Hardened concrete constraint	Compressive strength at 28 d. (MPa, mean value measured on cylinder)		≥ 40	≥ 40
	Compressive strength at 90 d. (MPa, mean value measured on cylinder)	≥ 15		
Economical constraint	Cost (€/m^3)		Minimum	Minimum

*according to EN 206, with a XF1 environment category - **35 mm distance between rebars

After this brief overview of our mix-design method, an application is presented in this section. Dry aggregate mixtures and concretes are designed based on different specifications, given in Table 1. All mixtures are optimised using the BetonlabPro 3 software [6] and its generic constituents: two fractions of crushed coarse aggregate (12.5/20 and 5/12.5 mm), two types of fine aggregate (a 0/4 alluvial and a 0/0.5 mm eolian sand). For the concrete mixes, a Portland cement, a Class C fly ash, a melamin-type superplasticizer and water are also used.

For the dry aggregate mix (DA), a K value of 9 is taken, corresponding to a mode of placement where grains are vibrated and compacted under a pressure of 10 kPa. The proportions of the four fractions are optimised in order to minimize the porosity of the mix. After automatic optimisation of the five mixtures, the concrete recipes appear in Table 2, and the whole grading curves (including cementitious materials, if any) are plotted in Fig. 3.

Table 2. Proportions of concrete mixtures.

	RCC	NSC	SCC
12.5/20mm coarse aggregate (G1, kg/m^3)	972	742	392
5/12.5mm coarse aggregate (G2, kg/m^3)	519	230	618
0/4mm coarse sand (S1, kg/m^3)	504	637	614
0/0.5 fine sand (S2, kg/m^3)	147	136	46
Cement (kg/m^3)	36	205	165
Fly ash (kg/m^3)	192	215	330
Superplasticizer (kg/m^3)	0	1,09	4,6
Water	93	170	163

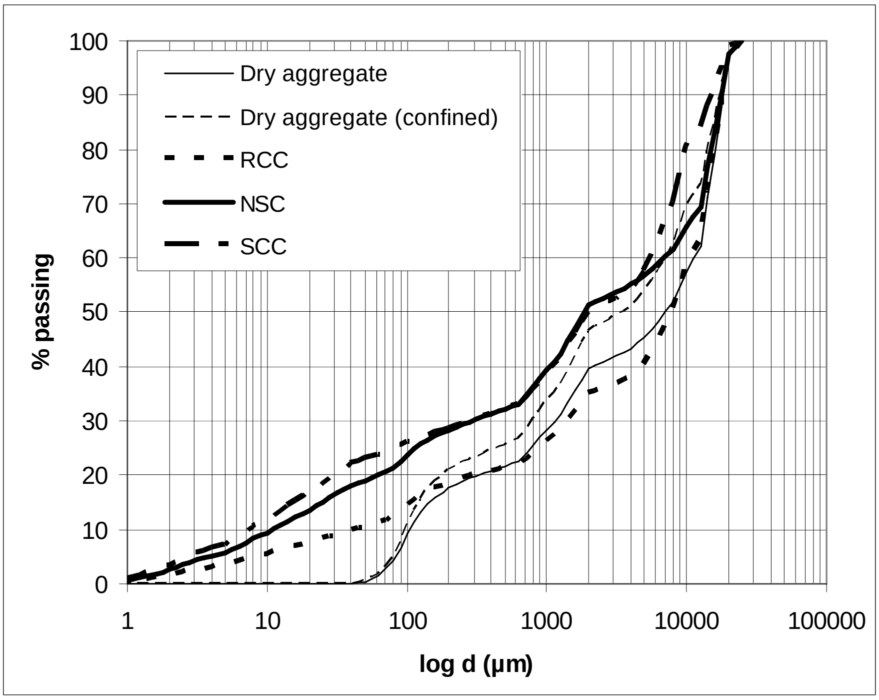

Figure 3. Comparison between optimum grading curves.

Let us focus on the aggregate proportions displayed in Fig. 4:

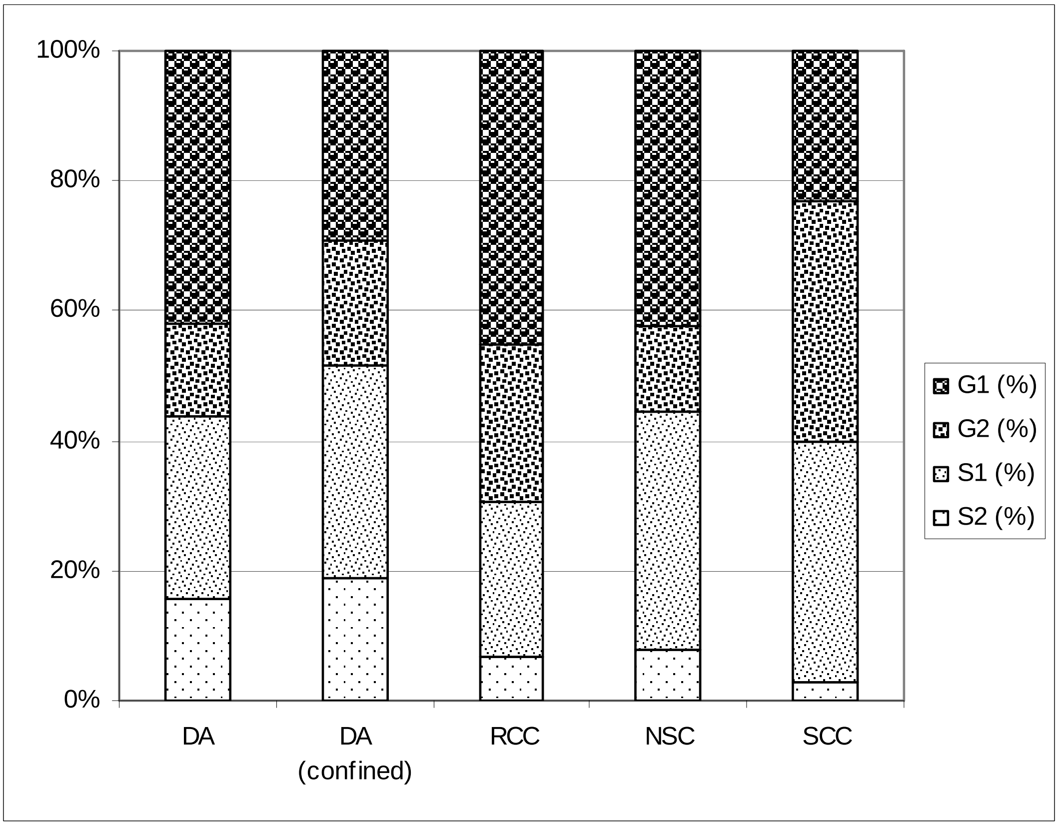

Figure 4. Comparison between optimum proportions of aggregate fractions. DA : Dry Aggregate, RCC : Roller Compacted Concrete, NSC: Normal-Strength Concrete, SCC: Self-Compacting Concrete.

- as compared to the DA (dry aggregate) mix, the DA in confined conditions contains less materials of the coarsest class, and more fine aggregate. This is a direct consequence of the wall effect exerted by the form;
- in the roller-compacted concrete (RCC), the mutual aggregate proportions are close to those of the DA mix, with a slightly higher amount of coarse materials. This is only due to the fact that the compaction index is higher (14 instead of 9); therefore less space is let for the fine particles that should fill the voids of the coarsest ones;
- in the normal-strength concrete (NSC), the percentages of the two highest fractions are about the same as in the DA mix. As for the sand fractions, the presence of binders decrease the volume of eolian sand, which is compensated by the alluvial sand. Here, it is an illustration of the loosening effect;
- finally, in the self-compacting concrete (SCC), both effects are presented: the confinement exerted by the close rebars decreases the amount of the coarsest gravel; the high amount of binders creates a strong loosening effect which decreases the proportion of eolian sand.

5. CONCLUSION

In this paper, the question of concrete optimisation was addressed, by using the Compressible Packing Model and other related models dealing with fresh concrete properties. Through an example of numerical optimisation, the following facts were shown (or recalled) :

1. in a dry packing of particles, all granular fraction play a certain role, leading to certain optimum mix-proportions;
2. in confined conditions, the amount of coarse particles is limited to a greater extent, which tends to favour the finer particles;
3. when water is added to the mix, the rheological properties have to be considered. For plastic viscosity, the packing density of dry mix is still the key parameter, while, for yield stress, the role of fine particles is more important (but is highly influenced by the presence of superplasticizer);
4. the mutual proportions of aggregate fractions in an optimised concrete mixture are strongly influenced by the set of specifications governing the concrete design. More specifically, the amount of fine sand is decreased by the presence of binder. At the other side of the grading span, the confinement leads to a decrease of the volume of coarsest grains;
5. these facts show the limited value of so-called universal grading curves, and the need of optimising modern concretes using sophisticated tools which may account for a wide variety of specified properties.

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