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DISCRETE ELEMENT MODELING OF HIGH PERFORMANCE CONCRETES: EFFECT OF AGGREGATES PROPERTIES

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Abstract. We analyse the interaction between aggregate properties and concrete strength. A discrete model is used, allowing to decorrelate the effect of aggregate stiffness and aggregate strength. Based on the numerical results, we show that the performance classification of aggregates based on inverse analysis of concrete properties cannot be directly used from one concrete to an other one. For example, a bad aggregate for an ordinary concrete can be a good one for a high performance one. The results drawn from this numerical study are in agreement with experimental observation.

1 INTRODUCTION

High performance concrete (HPC) strength depends on several factors like binder content, water-cement ratio, but also on aggregates performance. Usually, high strength aggregates are preferred in HPC mix design. But the "performance" of an aggregate can be estimated in different ways, starting from mineralogical properties to inverse analysis of concrete strength using homogenisation procedure. The last is largely used based on experimental results, but a conclusion obtained on a concrete cannot be extrapolated to a different one.

We propose in this study to use a discrete element model to evaluate concrete failure modes related to different types of aggregates, with a focus on HPC. The concrete is represented by an assembly of particles linked by brittle beams. Three different phases are considered: the cement paste, the aggregates and the aggregate-paste interface. The size of each aggregate is picked from an imposed size distribution, and the aggregates are placed randomly in the model. Beam properties depend on the phase assigned to its location. A parametric study will be performed to assess the relationship between the aggregate properties and the concrete strength.

2 DISCRETE MODEL

A discrete model is used to study the response of a concrete-like material, *i.e.* a two-phase brittle heterogeneous material. The first phase φ_1 relies to the cement paste/mortar, the second phase φ_2 relies to coarse aggregates. The interface between both phases will have phase φ_1 properties. For obvious reason, it is not possible to represent explicitly all the aggregates in the model. For the sake of simplicity, we assume next that all particles below 5 mm belong to the homogeneous phase φ_1 as aggregates above 5 mm are represented explicitly and belong to phase φ_2.

2.1 Principle of the model

The model is based on a Voronoi tessellation of the material. The Voronoi particles must have a size much lower than the coarse aggregates of the concrete in order to avoid any mesh dependency [3]. A 0.5 mm-size for the Voronoi particles is chosen. Each particles are linked together by a brittle Euler-Bernoulli beam. The breaking threshold P_{ij} between two particles i and j is defined as:

$$P_{ij} = \left(\frac{\varepsilon_{ij}}{\varepsilon_{ij}^{cr}}\right)^2 + \left(\frac{\bar{\ell}|\theta_i - \theta_j|}{\ell_{ij}\theta_{ij}^{cr}}\right) \qquad (1)$$

with ε_{ij} the longitudinal deformation of the beam, θ_i and θ_j respectively the rotations of particle i and j, ℓ_{ij} the beam length (Figure 1). $\bar{\ell}$ is the average beam length in the model. ε_{ij}^{cr} and θ_{ij}^{cr} are two model parameters picked from a Weibull distribution (see [4, 5] for details on identification process).

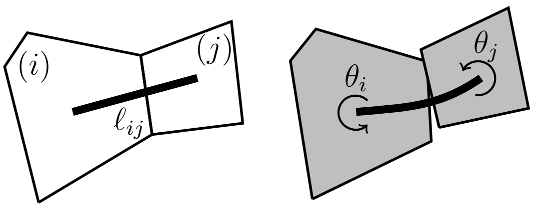

Figure 1: Link between two particles: initial state (left), deformed configuration (right).

2.2 Aggregate distribution

We consider a fixed coarse aggregate size distribution in this study. Circular shape is considered for simplicity, and 5 different sizes are considered (5 mm, 8 mm, 13 mm, 16 mm, 20 mm). A packing density of 0.7 is imposed [6,7], with an imposed cumulative size distribution (Figure 2). The largest aggregates are first randomly placed in the sample as long as space is available, then this operation is repeated for the decreasing sizes of the aggregates.

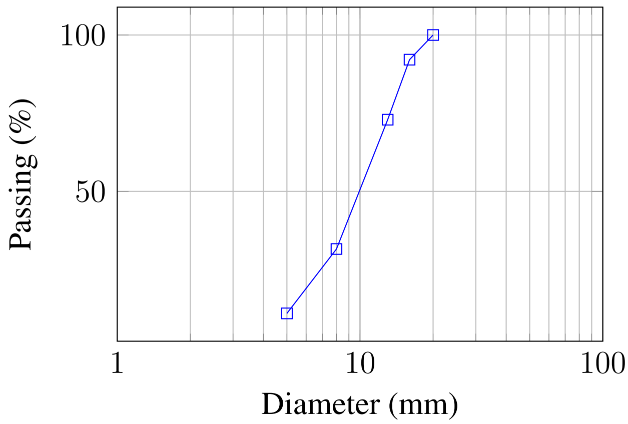

Figure 2: Aggregate cumulative size distribution.

A example of generated material is shown on Figure 3, with a zoom showing the corresponding Voronoi particles.

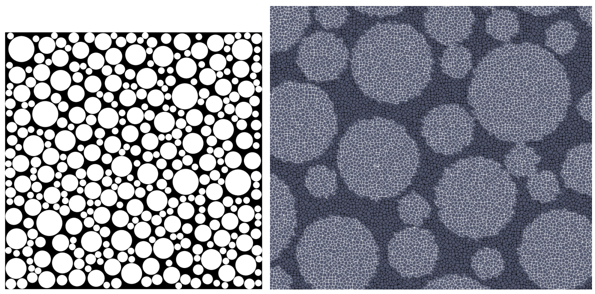

Figure 3: Packing density of circular aggregates with cumulative size distribution given in Figure 2 (left) and zoom showing the Voronoi particles (right).

3 APPLICATION

We focus this study on the influence of aggregate properties on material strength. Two types of material are considered: an ordinary concrete (OC) and a high performance one (HPC). The only difference between these two materials will be the properties of phase 1 (cement paste/mortar) properties. Then, different types of aggregates are used in both concretes and their global mechanical properties are analysed.

3.1 Mortar properties

Table 1 gives the Young modulus and tensile strength properties of the mortar corresponding respectively to the ordinary concrete and the high performance one. These values, and in particular the tensile strength, are chosen in order to exemplify the conclusion of the study. They can be changed without affecting this conclusion. These properties are fixed for all the study.

Table 1: Phase 1 properties for the two concretes

	Young modulus (GPa)	Tensile strength (MPa)
OC	21	2.6
HPC	31	12

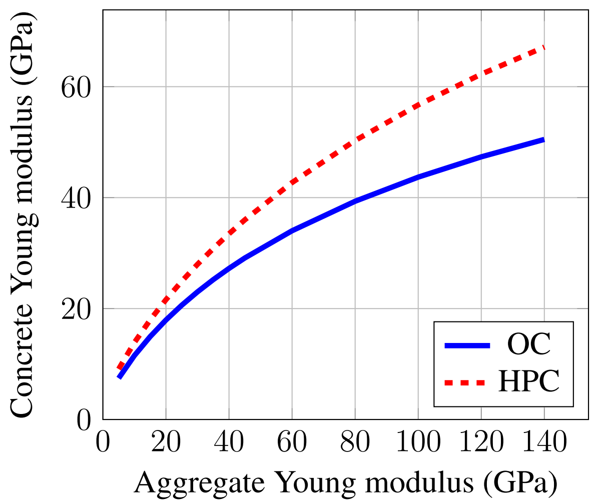

Figure 4: Concrete Young modulus *vs.* aggregate modulus

3.2 Aggregates properties

This study focuses on the analysis of aggregate strength and modulus on concrete properties. Such analysis is tricky to realize experimentally because aggregate properties are strongly coupled and it's almost impossible to evaluate just the effect of aggregate strength keeping the elastic modulus constant. Furthermore, the interfacial transition zone (ITZ) properties depends also on aggregates ones. Even if the discrete model used in this study is far from a real concrete, it allows easily to analyse the effect of aggregate properties.

Next, the aggregate modulus and aggregate strength will range respectively between [40, 140] GPa and [3,15] MPa.

3.3 Effect of aggregate modulus

Evaluating the elastic modulus for a two-phase composite with circular inclusions is straightforward and a simple homogenisation approach gives the exact solution [10]. We use here the discrete model to get this relationship. Figure 4 shows the Young modulus evolution for OC and HPC.

3.4 Effect of aggregate strength

Usually, analysing the cracking pattern of a concrete can be split in two types: either the main crack is running around aggregates, either the main crack propagates through aggregates. This crack propagation depends on the loading type as well as aggregates and ITZ properties. We limit here the analysis to the effect of aggregate strength. Figures 5 and 6 show the evolution of concrete tensile strength *vs.* aggregate tensile threshold for different aggregate modulus E_{agg}.

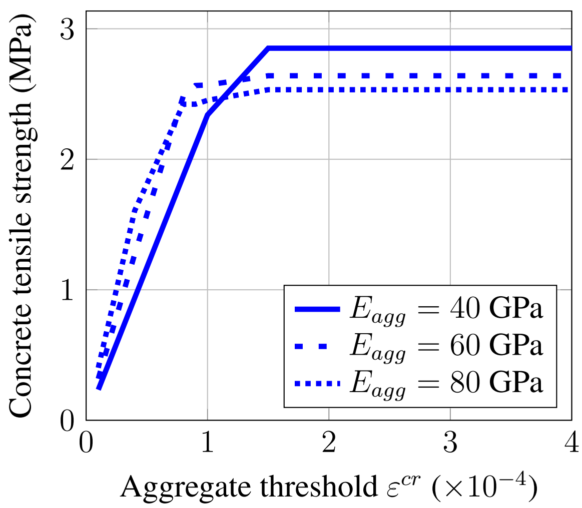

Figure 5: OC tensile strength *vs.* aggregate strength

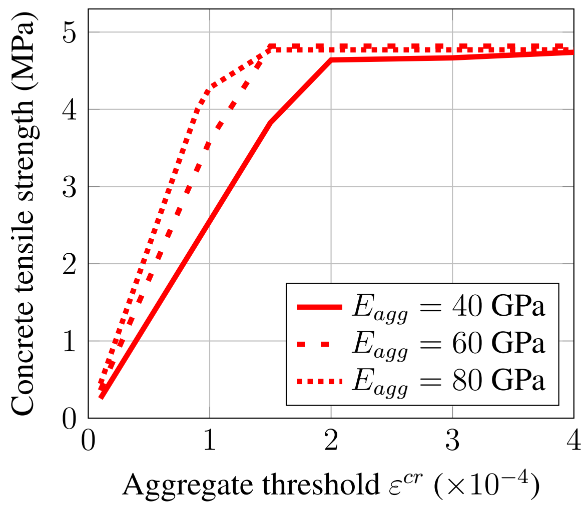

Figure 6: HPC tensile strength *vs.* aggregate strength

The evolution is linear with aggregate threshold as long as the crack pattern crosses the aggregates (Figure 7).

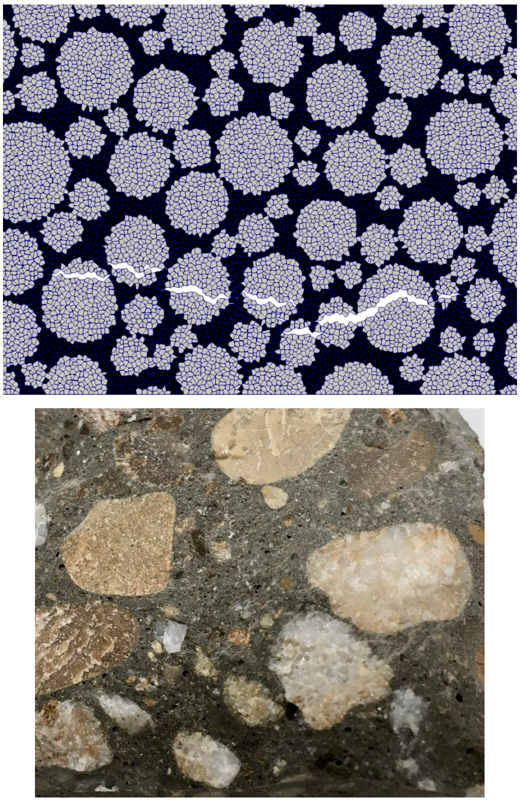

Figure 7: Crack propagation through aggregates: numerical model (top), experimental observation (bottom).

Once the aggregate strength is greater than the paste strength (and its interface strength which is considered as similar to the paste strength in this approach), a maximum value of concrete tensile strength, which is independent of the aggregate one, is reached. In that case, crack propagates around aggregates (Figure 8). One can note that on Figures 5 and 6, the maximum concrete tensile strength decreases slightly as the aggregate Young modulus increases. This effect is analysed next.

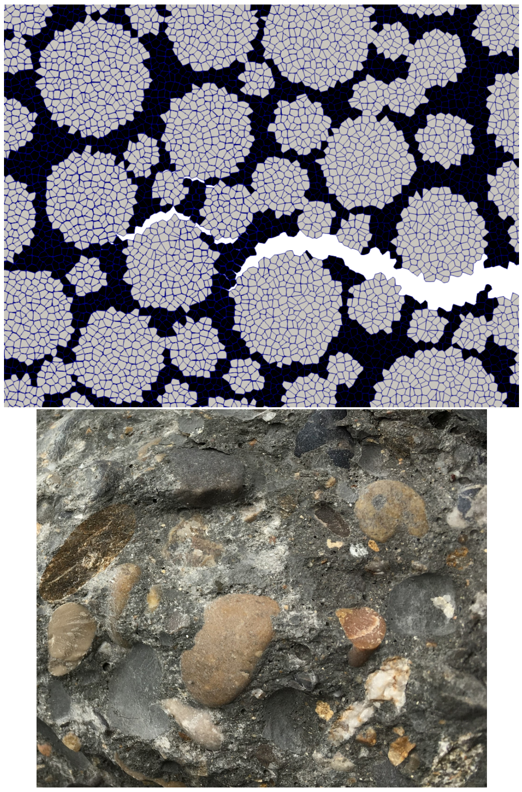

Figure 8: Crack propagation around aggregates: numerical model (top), experimental observation (bottom).

3.5 Effect of aggregate modulus on concrete strength

In a two-phase material, stress localisation leads usually to the initiation and propagation of a crack until material failure. The level of the stress value depends among others on the modulus ratio between the two phases: the greater the ratio is, the sooner the crack initiates.

Figure 9 shows the evolution of concrete tensile strength *vs.* the aggregate stiffness.

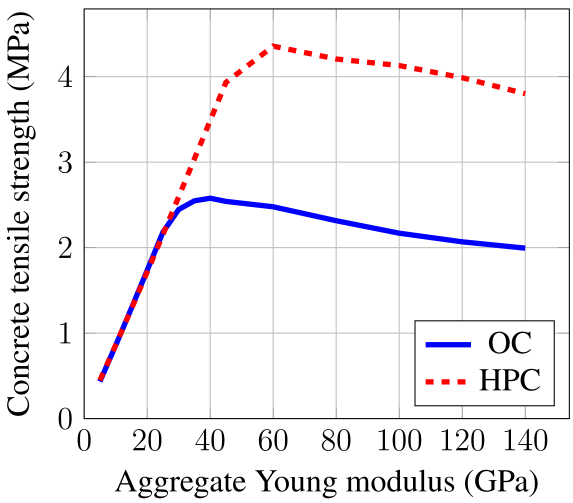

Figure 9: Concrete tensile strength *vs.* aggregate modulus

As expected, the concrete strength is decreasing for large aggregate stiffnesses. Even if this result is quite obvious, it can lead to not so intuitive outcome. Let's consider two different types of aggregate with respective elastic modulus of 35 and 50 GPa. The second aggregate can be considered as a *premium* one as its stiffness is higher than the first one. In fact, following the evolution of concrete strength shown on Figure 9, HPC strength is higher using the premium aggregate (4.1 MPa *vs.* 3.1 MPa). But this result is different for the OC as its strength is lower using the premium strength (2.5 MPa *vs.* 2.7 MPa).

A different interpretation can be drawn if the aggregate properties are not known, that is quite frequent in ready-mix industry. Considering only the result obtained with OC, one can reject the use of the premium aggregate for HPC because it leads to a lower strength for the OC. But because the stiffness of HPC paste is closer to the aggregate one, the HPC strength is effectively higher using the second aggregate.

Even if such effect (a contradictory conclusion using two types of aggregate in an OC and a HPC) is difficult to reproduce experimentally, different experimental studies have shown a different dependence of aggregate properties between an OC and a HPC. Hence, a higher aggregate strength leads to higher strength for HPCs but to almost no effect for OCs [11]. In the same way, the lower the water/cement ratio is, the greater the concrete tensile strength is correlated with aggregate strength [2].

4 CONCLUSIONS

Experimental study of the effect of aggregate properties on concrete strength is not so easy to perform. The main reason is that it's difficult to decorrelate the aggregate stiffness and the aggregate strength. Furthermore, there is also a high correlation between aggregates and ITZ properties. It can lead to a misinterpretation of experimental results and a bad usage of aggregates depending of the concrete type.

We use a simple discrete model to emphasize this non obvious type of result. Hence, we show that the classification of aggregate performance can not be transposed from a concrete to an other one, that is in agreement with experimental results [12]. In our study, we focus the analysis to the aggregate/cement paste modulus ratio without considering specifically the interface properties. We show that an aggregate with a higher modulus can lead to a lower strength for an ordinary concrete class and on the other hand higher strength for a high performance concrete. This result can be verified experimentally, even if the real strength of an aggregate is correlated to its Young modulus. A perspective of the study will be to consider the interface properties independent of the paste one, but with a correlation with aggregate types.

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