Effet de la taille d'hétérogénéité et effet d'échelle : une approche combinée pour des matériaux quasi-fragiles

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RÉSUMÉ. *Expérimentalement, l'effet d'échelle sur le béton est très souvent étudié à l'aide des corps d'épreuves homothétiques entaillés où l'on cherche à relier la résistance nominale estimée à partir de la charge de rupture en flexion à une dimension caractéristique D. L'objectif de cette étude est d'étudier expérimentalement l'impact de l'hétérogénéité (taille maximum de granulat d_{max}) sur l'effet d'échelle. Celui-ci a été réalisé en considérant le rapport D/d_{max} comme facteur fondamental de l'effet d'échelle. Trois coupures granulaires ont été testées sur trois tailles de poutres similaires. Les résultats mettent en évidence une grande influence de la taille du granulat sur le comportement à la rupture du béton. Il existe une relation directe entre les paramètres de l'effet d'échelle obtenus par la loi de Bazant et la taille du granulat. Le traitement des résultats d'une même taille avec bétons de différentes granulométries dans le même diagramme conduit à la même loi d'effet d'échelle structurelle classique avec une valeur de transition identique.*

ABSTRACT. *Experimentally, size effect in concrete is commonly studied by using geometrically similar notched beams where the nominal strength obtained from the bending failure load is related to the characteristic dimension (D).The objective of this research is to study experimentally the effect of heterogeneity (maximum aggregate size d_{max}) on the size effect. This is done by considering the ratio D/d_{max} as a fundamental factor causing the size effect. Three aggregate grading where complete grading curve was scaled were tested on three different sizes of beams. The results demonstrate a significant influence of the aggregate size on the fracture behaviour of concrete. There is a direct relationship between the size effect parameters obtained by Bazant's law and maximum aggregate size. The results obtained from the specimen having the same size but made of concretes with different aggregate sizes produced the same classical size effect with identical transitional between LEFM and strength based laws.*

MOTS-CLÉS: *béton, effet d'échelle, effet de granulat, fissuration, énergie de fissuration, longueur caractéristique.*

KEY WORDS: *concrete, size effect, aggregate size, cracking, fracture energy, characteristic length.*

1. Introduction

It is known that the mechanical behaviour of quasi-brittle composites such as concrete, coarse grained ceramics and fibre-reinforced composites, is manifested by mechanisms like strain localization and progressive fracture in the material. This is an intrinsic property of quasi-brittle materials due to sizeable heterogeneity of the material microstructure [ALA 17]. The heterogeneity in concrete material is generally defined by the size of the coarse aggregate. Generally, aggregate accounts for 60% – 80% of the volume and 70% – 85% of the weight of concrete, of which, coarse aggregate occupies about 45% of the volume of concrete. Thus the properties of coarse aggregate have a significant effect on the performance of concrete. Coarse aggregate properties, such as grading, surface area, particle size and shape, angularity, surface texture, mineralogy, water absorption and strength have been investigated [NEV 95]. Among these properties, maximum aggregate size (d_{max}) is one of the important parameters that affect the properties of fresh and hardened concrete.

By scaling the aggregate size (d_{max}) (or the heterogeneity size of concrete), not only the local properties of concrete changes but the impact is significant on the macroscopic behaviour of the structure. When the size of the structure (D) is sufficiently small with respect to the size of the heterogeneity, the overall mechanical behaviour approaches strength criterion, however, when the size of the structure (D) is sufficiently large as compared to the size of heterogeneity, the mechanical behaviour approaches Linear Elastic Fracture Mechanics (LEFM). By keeping the heterogeneity size (or aggregate size) constant and varying d_{max}, one arrives at the well-known size effect problem [BAZ 99]. Here, the strength of the structure decreases by increasing D. However, by scaling the heterogeneity size (or aggregate size) and keeping D constant, one can observe the aggregate size effect [WAL 60]. In this case, literature shows both increase and decrease of the strength of structure by increasing D. However, in these studies only the maximum aggregate is used as the scaling parameter (which is usually only 10% of the complete aggregate content), without considering the complete grading curve.

In this paper, an experimental and analytical study is presented where both the characteristic structural dimension (D) and the aggregate size (d) are considered as scaling factors. The size effect is investigated by taking the ratio of the characteristic structural dimension (D) and the maximum aggregate size (d) as a key parameter. While scaling the aggregate size (d) complete grading curve is scaled with the same factor. The objective of the study is to investigate experimentally the role of the ratio D/d as the cause of size effect. Three methods are presented: Method 1 by scaling D, Method 2 by scaling d . In order to scale d_{max}, three types of concrete mix are designed (C05, C10, and C20) with the same aggregate to mortar volumetric ratio and same mortar properties, only the aggregate sizes are changed. Aggregate sizes were up-scaled in C05, C10 and C20 concretes such that the volumetric fraction for each class of aggregate with respect to maximum aggregate size in each concrete remains same. Method 1 is the typical size effect; this study however shows how the size effect parameters are influenced by changing the aggregate size. It will be demonstrated that up-scaling D by keeping d_{max} constant or down-scaling d_{max} by keeping D constant shows similar effects on the size effect plot. Here, we propose a new approach to study size effect by scaling aggregate size. In this case, the parameters governing the size effect and material properties independent of D are discussed in detail.

2. Materials and specimens

Ordinary Portland cement (CEM I 52.5 N) was used as a binder. Water-cement ratio (W/C) was maintained to 0.4 for all the mixes. Fine aggregate was crushed fine sand of maximum size not greater than 2 mm. Coarse aggregate was crushed limestone. Three concrete mixes were designed namely C05, C10 and C20, in which the coarse aggregate sizes was varied, the maximum size of coarse aggregate was 5.25, 10.5 and 21 mm respectively. The maximum aggregate size is taken as 90 % passing on the sieve analysis. Thanks to the availability of different classes of aggregates which make it possible to achieve the reference grading curve for each aggregate mix such that the volumetric fraction for each class of aggregate is the same as shown in Figure 1.

Three point bending tests are performed on beam width (b) equal to 100 mm. In order to analyse size effect, three sizes of beams were considered in accordance with RILEM-TC 89 recommendation where the ratio of length to depth (L/D) and span to depth (S/D) are maintained constant. Also the ratio of vertical notch depth to the depth of beam in all cases is equal to 0.2 ($a_0 = D/5$). The general size effect analysis was performed on series C05, C10 and C20 using beams with depth varying from 100 mm to 400 mm. It gives insight on how size effect parameters vary if heterogeneity is scaled. The three-point bending tests were performed with a controlled crack mouth opening displacement ($CMOD$) rate of 0.2 µm/sec.

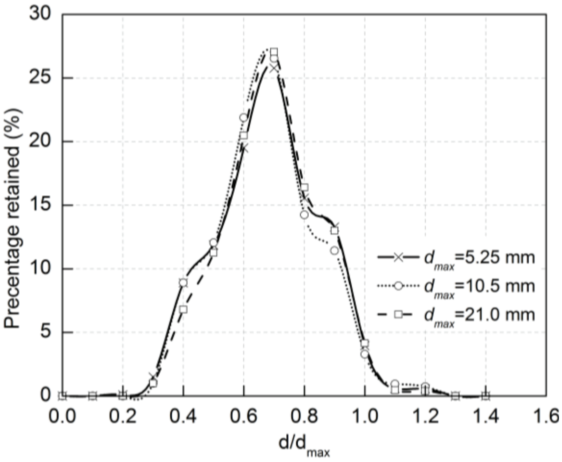

Figure 1. *Coarse aggregate grading curve for each concrete.*

3. Results and Discussion

Size effect is the one of the most important physical phenomena which impacts critically the mechanical and fracture behaviour of quasi-brittle materials like concrete. As explained in Section 1, size effect is related to the heterogeneity size in the material. Therefore, it is worthwhile to relate the size effect with the aggregate size. Bažant [BAZ 84] proposed energetic description of size effect based on the ductile-brittle transition of the failure modes in geometrically similar specimens. According to linear elastic fracture mechanics (LEFM), the normal stress (σ_N) decreases in proportion to the square root of depth of specimen (D). However, in concrete structures, the size effect is transitional between the strength criterion representing horizontal line and the size effect of LEFM represented by the inclined line. Bažant's size effect law can be described by Equation 1.

[1]

where Bf_t and are empirical constants obtained by the fitting plot. is also considered as the transitional structural dimension between the plasticity and LEFM.

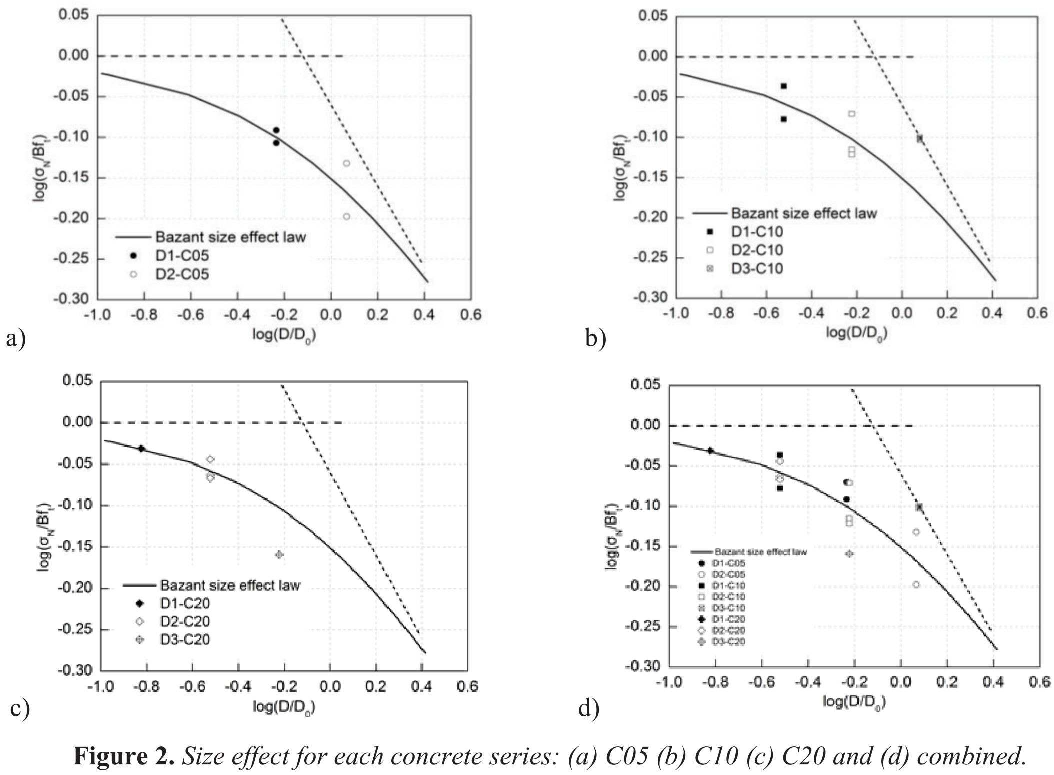

Figure 2. *Size effect for each concrete series: (a) C05 (b) C10 (c) C20 and (d) combined.*

The nominal stress for each beam is presented on the size effect plot for each concrete as shown in Figure 2 a, b and c. The results show a transitional behaviour well described by Bazant size effect law curve. Although the parameters are different for each series of concrete, the obtained size effect plot is unique. All the size effect plots of Figure 2 a, b, and c are transferred to a single curve in Figure 2 d, where one can analyse the effect of aggregate size. It can be seen that with the increase of aggregate size, the behaviour of specimens approaches the hypotheses of strength criterion and when the decrease of aggregate size the behaviour approaches the LEFM. It means that when the heterogeneity size in a quasi-brittle material like concrete is smaller enough as compared to the size of the structure, the material behaviour becomes brittle and can be described with fracture mechanics principles. Since the maximum aggregate size (d_{max}) directly affects the characteristic length (l_{ch}) and fracture process zone length (c_f), it can be inferred that it the ratio between the characteristic structural dimension and aggregate size (D/d_{max}) which affects the strength of the structure when the size effect tests are performed. However, if both structural size and aggregate size increases at the same time so as to keep the ratio D/d same, there is no effect on the nominal strength. It can be seen in Figure 2 d by observing the results of D1-C10 beams and D2-C20 beams. Similar observation can be made on the results of D1-C05 beams and D2-C10 beams.

4. Conclusions

The results indicate a significant influence of the aggregate size on the fracture behaviour of concrete. There is a direct relationship between the size effect parameters obtained by Bazant's law and maximum aggregate size. The results obtained from the specimen having the same size but made of concretes with different aggregate sizes produced the same classical size effect with identical transitional between LEFM and strength based laws. Thus size effect can be studied by scaling of aggregates on the same size of the specimen which is equivalent to the scaling of specimen size on the same concrete.

5. References

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