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Stiffness of a recycled composite aggregate

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A B S T R A C T

Recycled concrete aggregate (RCA) is a promising substitute for natural aggregates and the reuse of this demolished material would benefit the construction projects both economically and environmentally. A difficulty associated with the prediction of the behavior of RCA is because of its multi-composition which is linked to the grain size in consideration. In this study, a comprehensive laboratory testing program is conducted on different fractions of RCA for which the ratio of silicon over calcium increases for the coarser fractions due to the limitation of the cement mortar inclusion as the mean size increases. The study incorporates bender/extender element tests capturing small-strain constrained moduli, Young's moduli and Poisson's ratio of RCA fractions with different mean grain size and grain size distribution. For the uniform RCA fractions, the results showed that during isotropic compression, the specimens had a clear dependency of their dynamic properties on mean grain size. For the better graded specimens, it was shown that their behavior was dominated to some extend by the finer fraction they were composed rather than being affected equally by the different fractions they consisted of. The results also highlighted the sensitivity of the behavior of the samples to the over-consolidation stress history. For RCA, a multi-composition material, the grain size has a dominant role on the modulus – pressure relationship as well as the sensitivity of material behavior to stress history and these observations must be considered in the analysis of geo-structures where RCA is used as construction material.

1. Introduction

The amount of concrete aggregate recycled from demolished buildings or structures has risen rapidly in recent years (e.g. [29]). Facing the increasing need of aggregates in engineering construction and the rising cost of natural aggregates, recycled concrete aggregate (RCA) has become a promising and economic substitution. Benefitting from extensive research on RCA, the material is starting to be used as a non-structural construction element in practical projects, including geotechnical engineering and pavement geotechnics applications (e.g. [31,32,11,29,30,40,13,14]). This replacement of the natural aggregates releases, partly, the pressure from both the demand of quarry sites and the cost of land-fill disposal.

In modeling the behavior of RCA when used as a geotechnical material, stiffness at small strains is a key property. Material small-strain stiffness is a critical parameter for the prediction of the deformations of geo-structures and soil-structure interaction problems. The stiffness of geo-materials, including the shear modulus (G), constrained modulus (M) and Young's modulus (E), reaches its maximum value in the elastic range of behavior (generally less than 10^{-3}% strain). The bender element test (BE) [38], which is a high-frequency dynamic testing technique that uses a pair of piezo-element inserts, is widely adopted to capture the shear wave velocity (V_s) for the purpose of deriving the small-strain soil shear modulus (G_{max}) (e.g. [41,18,22,45,23,1], Airey and Mohsin, [10]). The same pair of bender elements can also be configured to send primary waves (P-waves) and measure their propagation velocity (V_p), denoted as extender element mode (EE) (used by [24,23,19,20,13], among others). The small-strain constrained modulus (M_{max}), Young's modulus (E_{max}) and Poisson's ratio (ν) can be thereafter derived from the knowledge of V_s, V_p and the specimen density, thus the complete characterization of the small-strain behavior of geo-materials can be implemented based on measurements from bender/extender element tests.

In the light of examining in this study sand-sized recycled concrete aggregate, particular focus has been paid on the associated literature on granular materials. Based on published works on the dynamic properties of sand-sized materials, it can be concluded that the major properties that affect their dynamic behavior at small strains at a given isotropic confining pressure are the void ratio, the coefficient of uniformity, the particle shape and overall morphology as well as the

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mineral composition (e.g. [12,7,4,17,33,25,6,42,43,35,27,28], among others). Although work on other materials, for example natural sands of single mineralogy or reference granular materials such as glass beads, has not reported any significant effect on G_{max} when changing the mean grain size of the material (e.g. [25,42,35,44]), a recent study on recycled concrete aggregate by He and Senetakis [13] reported a clear dependency of the sensitivity of G_{max} to pressure on the mean grain size (D_{50}), which sensitivity must be captured for accurate predictions of geo-structures deformations [8]. He and Senetakis [14] conducted a characterization of the material through consolidated-drained triaxial shearing tests, breakage analysis after one-dimensional compression tests and the shear and primary wave velocities as well as the Poisson's ratio (ν) measurements of two fractions of RCA, 0.60–1.18 mm and 1.18–2.36 mm. That study highlighted the significant stress history influence on the dynamic properties of the aforementioned fractions. He and Senetakis [14] also reported on the small to medium strain stiffness degradation and damping characteristics throughout the conduction of resonant column tests. Although He and Senetakis [14] reported on the shear and Young's moduli of RCA, that study focused only on two uniform fractions, while in another study, He and Senetakis [13] investigated the effect of mean grain size on G_{max}, covering a wide range of sizes but of uniform fractions with no information for constrained modulus, Young's modulus and Poisson's ratio which would be necessary to capture completely the small-strain properties of RCA.

For the complete modeling of the small-strain behavior of geo-materials, it is necessary to quantify, apart from the shear modulus, the constrained modulus or Young's modulus as well as the Poisson's ratio. However, in the literature, there has been a relatively limited amount of work examining both shear and primary wave velocities (or shear and Young's modulus) as well as material Poisson's ratio of sands (e.g. [34,20,43,5,28]). Even though in many research works and practical applications, Poisson's ratio is considered as a constant, recent laboratory works have highlighted that Poisson's ratio (ν) is notably affected by the effective confining pressure in the range of small strains, while, Kumar and Madhusudhan [20] found an additional effect of material porosity. An effort to explain the micromechanics behind the pressure dependency of Poisson's ratio was presented in their study by Gu et al. [10] through numerical simulations. Given that the Poisson's ratio is affected by the confining pressure, the necessity of the knowledge of both shear and Young's moduli of the material is stressed.

In this study, the constrained modulus, Young's modulus and Poisson's ratio of a range of uniform fractions (from 0.15–0.30 mm to 2.36–4.75 mm) and poorly graded recycled concrete aggregate (RCA) specimens are investigated with a set of bender/extender element tests. The small-strain constants of different uniform fractions were measured and compared through an array of dynamic tests to study whether there is an effect of mean grain size on the dynamic behavior of the RCA, particularly in correlating the different small-strain properties (i.e. constrained modulus and Poisson's ratio) with the size and size distribution of RCA grains. This is particularly important for this type of geo-material since SEM-EDS analysis from He and Senetakis [13] has shown that RCA is a multi-compositional material and this composition varies with the fraction (i.e. grain size). The Young's modulus constants during the isotropic swelling stages are also examined for a limited number of specimens. In practice, it is possible that RCA will be used in a relatively better graded form rather than a single size fraction. Thus, apart from the study of uniform fractions of RCA, which provides some fundamental insights into the behavior of those complex materials, additional experiments on better graded specimens (denoted in the study as poorly graded samples) were conducted to study the effect of grading. Thus, the major contributions of this work are:

(i) The complete characterization of the small-strain properties of RCA fractions providing some insights into the role of their multi-compositional nature (exploring constraint modulus, Young's modulus and Poisson's ratio). A detailed analysis of the loading and unloading small-strain constants and the comparison with a Young's modulus literature model are given;
(ii) Compare the dynamic properties of the poorly graded RCA specimens with the uniform fractions and explain the different observed trends from a fundamental point of view;
(iii) Provide empirical expressions, based on the experiments, to correlate small-strain properties to important factors (e.g. pressure and grain size) which comprise simple but useful tools in modeling the behavior of geo-materials. This could provide practical but also some theoretical aspects of the dynamic behavior of recycled concrete aggregate with many potential applications in geotechnical engineering.

2. Materials and methods

2.1. Material properties

The recycled concrete aggregate tested in the current study was demolished, crushed and supplied by an Australian supplier (New South Wales). After the crushing process, the recycled concrete consisted of a well-graded aggregate which includes gravel, sand and silt sized grains. Therefore, sieving was conducted before testing and sand sized aggregates are focused on in this study. Five uniform fractions (with coefficient of uniformity, $C_u \approx 1.4$) together with three better graded materials, denoted as poorly-graded fractions ($C_u \approx 2.8$), which are mixtures of three successive single fractions, were studied and the grading curves for all the materials are given in Fig. 1. The particle sizes

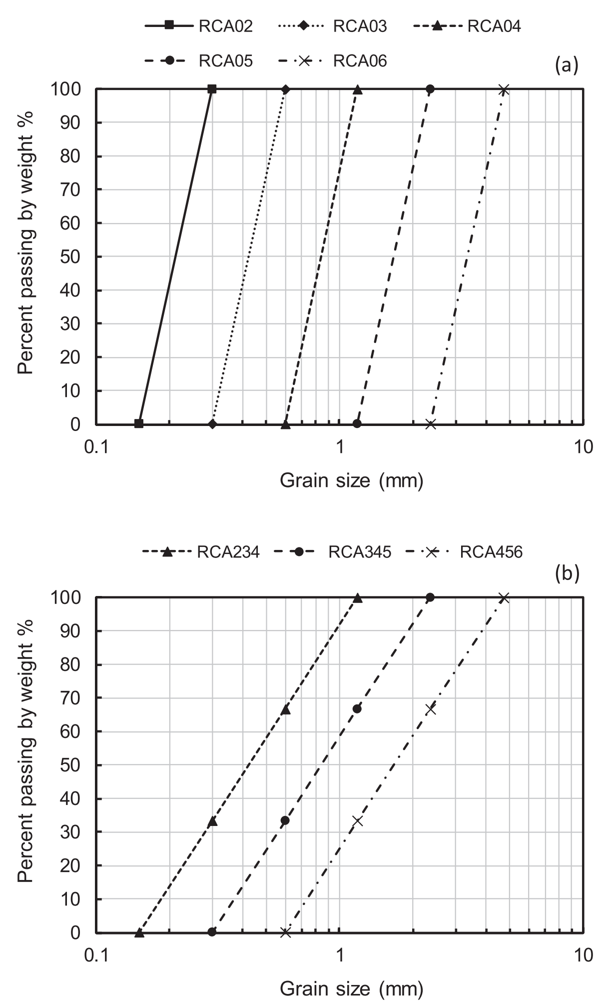

Fig. 1. Grading curves of recycled concrete aggregate (RCA) specimens tested: (a) uniform fractions ($C_u \approx 1.4$) (b) poorly graded fractions ($C_u \approx 2.8$).