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Microstructural Origins of Wave Modulus of Elasticity of Concrete

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Abstract: Nondestructive ultrasound-based methods have been applied to evaluate the elastic properties of concrete materials. While the wave modulus of elasticity of concrete is frequently reported higher than the static counterpart, the microstructural and physical mechanisms are not well understood. In this study, a computational micromechanics is conducted to investigate the effects of aggregates and voids on both the effective wave modulus of elasticity and static modulus of elasticity, based on concrete microstructures resolved with X-ray microtomography. It is demonstrated that the existence of void defects plays a significant role in the elastic properties of concrete when compared with the aggregates. It is shown that the wave modulus of elasticity of concrete is higher than the static one because of the existence of crack-like voids with small aspect ratios.

Keywords: concrete, micromechanics, void, wave modulus of elasticity, finite-element method.

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Introduction

Ultrasound-based methods have been widely used to evaluate the mechanical properties of concrete materials. For example, the elastic modulus can be assessed according to the measured velocity of wave propagation (Philleo 1955; Nwokoye 1974; Popovics et al. 1990; Song et al. 2008; Qiao and Chen 2013). The estimation of elastic modulus or modulus of elasticity comes from a well-known relationship:

$$V_s = \sqrt{\frac{E_w}{2(1+\upsilon)\rho}} \quad (1)$$

where V_s is the propagation velocity of shear wave used, ρ is the material density, E_w is the wave modulus (WM) of elasticity, and υ is the Poisson's ratio. In practice, the time of flight (TOF) of wave is measured through the input and transmitted signals (Qiao et al. 2011; Qiao and Chen 2013). For homogeneous materials, E_w is equal to the elastic modulus, i.e., the Young's modulus. In contrast with the static uniaxial compression testing, the distinct advantage of the pulse velocity test is nondestructive and easy to perform in-situ. There are a few terminologies regarding wave-velocity-based modulus estimation, such as pulse modulus, dynamic modulus, and wave modulus. In this study, the term of wave modulus (WM) of elasticity is used.

When either the direct transmission or surface transmission is currently performed practically, WM relies on the wave velocity estimation while avoiding the material heterogeneity on the propagation path (Qixian and Bungey 1996; Sun et al. 2008; Qiao et al. 2011). Due to the composite nature of concrete materials even with exiting voids, the heterogeneity takes effect in both microscale and macroscale. So far, investigations have been conducted, using the analytical micromechanics principles and experiments to reveal the effect of heterogeneity not only on the static modulus of elasticity (Li et al. 1999; Zheng et al. 2016; Rezakhani et al. 2017), but on the wave propagation (Yang 2003; Chaix et al. 2012; Planès and Larose 2013; Kohlhauser and Hellmich 2013). It needs to be pointed out that current discussion is under the requirement of separation-of-scales, namely, $d \ll \Re \ll \lambda$ (where $\Re$ is the characteristic length of the representative volume element (RVE), d is the characteristic length of heterogeneities in RVE and λ is the wavelength) (Zaoui 2002; Kohlhauser and Hellmich 2013). While those analytical explorations are limited to inclusions of regular shape, some fundamental conclusions have been reached. First, the influence of inclusions on the propagation path is coupled with wavelength or frequency. Second, the product of the wave number and the inclusion radius, ka (where k is the wave number equal to $2\pi/\lambda$ and a is the inclusion radius), is a useful parameter to better understand their coupling mechanisms. If the wavelength is much greater than the characteristic length of inclusions, it has limited sensitivity to the inclusions scale. When $ka \to 0$, WM tends to be the corresponding static modulus of elasticity. If the wave frequency makes $ka \to 1$, i.e., the inclusion size is in the same order as the wavelength, the propagation starts showing wavelength-dependent. With increase of ka, when $\lambda < d$, the wave can have multiple interaction with a single inclusion during propagation, which is beyond the scope of current discussion. Third, for the cases of stiffer inclusions, WM is less than the static modulus of elasticity in relatively low ultrasound frequencies because of wave scattering, in which the wavelength is larger than the aggregate scale. In WM testing, with considering the frequency dependent attenuation, the required frequency is set on the order of 100 kHz (Qixian and Bungey 1996; Sun et al. 2008; Qiao et al. 2011; Planès and Larose 2013; Qiao and Chen 2013). In the range of such frequency, the wavelength of concrete is $\sim 10^1$ mm that is larger than fine aggregates. Therefore, mortar that is the mixture of fine aggregate and cement can be treated as homogeneity (Smolarkiewicz et al. 2000). For coarse aggregates and voids, the frequency causes $ka \sim 1$ that is approved to affect wave motion. It has been reported that WM of concrete is up to 30% higher than its corresponding static modulus of elasticity based on both longitudinal and shear wave excitations (Philleo 1955; Qiao 2010; Qiao and Chen 2013), which seems to contradict with the aforementioned third conclusion.

Because aggregates and voids of concrete are of irregular shapes, there are no analytical solutions available to predict their effects on the overall elastic properties of concrete. The analytical analysis with the assumption of regular shapes could only present some basic ideas, but not the full picture. Numerical solutions through finite-element method (FEM) is anticipated to provide more insight because FEM is free of the inclusion shape restriction and sheds light on studying complex heterogeneous multi-phase concrete (Smolarkiewicz et al. 2000; Kim et al. 2008; Acciani et al. 2010). Furthermore, realistic microstructures of concrete can be resolved by utilizing the state-of-the-art imaging technologies such as X-ray microscopic computerized tomography (micro-CT) (Leite and Monteiro 2016; Dong et al. 2018, Luo et al. 2018). The integration of FEM and the micro-CT imaging technology helps bridge the microstructural features of concrete and its macroscopic mechanical performance. The current study is among the first efforts to investigate the microstructural origins of WM of concrete by combining the computational micromechanics and micro-CT technology.

In the article, with the treatment of concrete as a three-phase composite material (aggregates, mortar and voids), effect of aggregates on WM is first studied using FEM to simulate shear-wave motion. In this part, the aggregate with $ka \sim 1$ is analyzed and approved that its presence is not the reason causing higher WM. In addition, different ka values, i.e. different λ/d, are disused. Second, the effect of voids is investigated and approved that crack-like voids are the reason causing higher WM. In this part, aspect ratio is specially analyzed and concluded that smaller aspect ratio makes faster drop of static modulus than of WM. Finally, the wave velocity analysis is performed on the real concrete structures resolved with micro-CT.

Effect of aggregates

In this section, the role of aggregates in wave motion is analyzed using the microstructure-based FEM. To ensure the simulation accuracy, at least ten nodes are introduced with a wavelength in developing finite-element mesh. Further, the incremental time step is less than the propagation time passing through a single element (Serón et al. 1990; Kim et al. 2008). A commercial FEM package, *Marc Mentat* 2017 (64 bit) (MSC Software Corporation), is used to conduct all simulations. The input signal is the acceleration excitation of a half-sine pulse of 100 kHz. In an idealized homogeneous material with no consideration of microstructures, WM depends on the time of flight (TOF) between two points that one serves as the source (e.g., transmitter) and the other as the detection (e.g., receiver). The velocity evaluated from the TOF between any two points is simply a constant. However, for heterogeneous concrete, the wave velocity can locally be path-dependent because of the aggregate variation. To demonstrate the local path-dependence of aggregates, three plane-strain cases are modeled. The first two are a triangular aggregate of 6.7 mm size as shown in Fig. 1 (a) and a circular aggregate (area unchanged) embedded in a matrix of 102 mm × 120 mm, respectively, while the third one is a homogeneous matrix-only case as a reference. The three models are meshed with 11332 triangular elements with the maximum edge of 1.5 mm that is 1/10 (or finer) of wavelength. The triangle is represented by 28 elements and the circle by 36 elements. The basic property input includes the elastic modulus of 14 GPa, density of 2200 kg/m^3, and Poisson's ratio of 0.17 for the matrix, and the elastic modulus of 45 GPa, density of 2690 kg/m^3, and Poisson's ratio of 0.17 for aggregates. The excitation of the half-sine pulse is set near the left end as denoted by arrows in Fig. 1. The time increment per step is 0.25 μs (which is about 27% of time traveling within a matrix element and 42% within an aggregate element). Upon the completion of simulation, the typical acceleration contours are illustrated at the moment of 25 μs in Fig. 1 from which the wave front and the reflection of boundaries can be observed. The model size can allow the front to reach the right boundary first without interfering with the boundary reflections. To reveal the difference among the three cases, the accelerations normalized by the maximum absolute value are plotted in Fig. 1 (b) along the wave propagation centerline. It shows that the difference emerges and presents the shape effect apparently. In relation to the WM evaluation, the first peak head is the only interest used to estimate the TOF between the two peaks of the input and the transmitted signal. Specifically, TOF is estimated by subtracting the quarter period of the input signal from the first peak moment of the transmitted signal, followed by the determination of the wave velocity by dividing the distance between the excitation source and the receiver by TOF. Thus, WM is obtained through Eq. (1). Estimated from Fig. 1 (b), the normalized WMs are 1.00, 1.08 and 1.13 for the no-aggregate (matrix-only) case, the circular one and the triangular one, respectively. Although the areas of the triangle and the circle are same, i.e. the same volume fraction, the triangular aggregate delivers a faster motion because of more occupation on the wave path and has larger effective ka. WM of the triangular case is 4.6% higher than WM of the circular one, showing that the triangular orientation affects the WM estimation. If the wave propagates right along one triangular side, it reaches 5.0% higher than WM of the circular particle. The difference may exist in their corresponding static moduli. Even if their static moduli of elasticity are the same, the 5.0% cannot eliminate the large 30% gap between WM and the static counterpart.

Real concrete materials contain many aggregates. In fact, the existence of aggregates causes lower WM than the static counterpart. If a 30% volume fraction of 5 mm diameter aggregates is embedded in the matrix as shown in Fig. 2 (a), the simulation results show that the WM is lower than the static as shown in Fig. 2 (b). Boundary conditions of Fig. 2 (a) are set free, except that the two end points of the left boundary are fixed. The half-sine excitation is set at the center on the left boundary. In the simulation, the time increment of 0.25 μs is determined through comparison with other increments as shown in Fig. 3 (a). It is shown that the increment starts to converge below 0.4 μs although the time passing through an element is ~ 1 μs. For all simulations in the current study, the time step is chosen as 1/4 of the time length passing the element. The loading position of excitation is set at the center of the left boundary. To demonstrate the chosen model satisfying RVE requirement, the loading is also applied with different positions within $\pm 5a$ (a is the radius of the inclusion) around the center of the boundary. The results illustrated in Fig. 3 (b) indicate that the times having the peak front are consistent, only causing WM errors within 1%, although the amplitudes are variable due to scattering. Furthermore, the position change leads to the wave path different which can be understood on different random generalizations of the inclusion distribution. Up to 50% volume fraction of aggregates, normalized by the elastic modulus of the matrix, the tendencies of WM and the static modulus are plotted in Fig. 2 (b). It is shown that WM becomes smaller than the static modulus of elasticity with the increase of the volume fraction of aggregates. For the sake of demonstrating the effect of changing frequency, Fig. 4 shows the normalized WM by the static modulus with different λ/d and demonstrates that the WM variation is subtle in the frequency range of WM; yet the WM is always lower than the static modulus. To further demonstrate the aggregate irregularity in concrete, an X-ray microscopy slice of the natural aggregate concrete (details will be introduced in Section 4) is segmented and meshed as shown in Fig. 5. The simulation of wave motion and comparison are conducted on two directions, which reports the static modulus of 19.68 GPa and WM of 15.27 GPa on the horizontal direction, and the static modulus of 19.29 GPa and WM of 17.59 GPa on the vertical direction. The two static moduli are consistent. WM values reflect the path dependence, but lower than related static moduli. Based on the analysis, the aggregate existence is not the reason causing higher WM.

Lower WM due to the presence of aggregates can be interpreted by the wave refraction. Known from wave's characteristics (Graff 1991), if the wave incidence is not on the direction of the interface normal of two media, the refraction occurs and its angle is not equal to the incidence angle. From this point of view, refraction tends to change the propagation direction and makes the travel path not in a straight line between two points, but in polylines. Because the length of polylines is longer than that of a straight line, the propagating velocity under the assumption of the straight line thus leads to an underestimation of wave modulus of elasticity. This also concludes that the higher WM does not result from its sensitivity to aggregates.

Effect of voids

Different from aggregates, micro-voids reduce elastic modulus of material. If voids are spherical and evenly distributed, the similar analysis process can be conducted as done for aggregates, and the similar conclusions can be drawn that spherical voids are not the reason causing higher WM.

For example, if the volume fraction of 2-mm-diameter void is 5% in a 2D model (with the RVE of 102 mm by 120 mm), the normalized static modulus of elasticity is 1, whereas the WM is 0.88 under both 10kHz and 50kHz, corresponding to $\lambda/d{\sim}8$ and $\lambda/d{\sim}16$, respectively. Within RVEs, the propagation path is the presentative of cross-section based on which the static modulus is determined. The tendency in 2D simulations may be applied to 3D cases.

Based on the above analysis, both aggregates and spherical voids are not the reasons causing higher WM. They make WM and static modulus of elasticity varying synchronically. Furthermore, WM is smaller than the corresponding static modulus of elasticity. In real concrete, all voids are not possible in spherical shape. There is a need to investigate the effect of non-spherical voids such as crack-like voids. For a cracked solid (Budiansky and O'connell 1976; Dormieux and Kondo 2009), the elastic modulus is the function of the crack density that can be defined as,

$$c_d = \frac{2N}{\pi} < \frac{A^2}{P} > \tag{2}$$

where c_d is the crack density, N is the number of cracks per unit volume, A is the area of crack, P is the perimeter of crack, and $<\ >$ denotes the volume average of the quantity. For 2D cracks, the crack density is computed accordingly as,

$$c_d = \frac{8}{\pi^3} M < l >^2 \tag{3}$$

where M is the number of cracks per unit area, and $< l >$ is the average trajectory of the cracks (Budiansky and O'connell 1976; Pan et al. 2009). It is noticed that the effect of cracks on the static modulus of elasticity is associated with the order of the third power of the crack size for 3D and the second power for 2D. However, WM is just associated with the first power of the crack length, i.e., ka, which implies higher WM. In addition, both c_d and ka are directly linked to the length a, instead of the porosity. High crack density can reduce the elastic modulus severely (Budiansky and O'connell 1976; Pan et al. 2009; Nguyen 2017). For concrete, the crack density depends on the compression stress level because higher stress will induce more microcracks and initiate existing cracks to propagate. At the initial status of zero stress, the crack density of cementitious materials is above 0.2 (Pan et al. 2009). Based on Eq. (3), the crack density of 0.2 is modeled with the 8 mm long cracks of random distribution, as shown in Fig. 6. Through FEM simulation, the normalized WM by the corresponding static modulus of elasticity is 1.49, which is 49% higher than the static modulus. In this simulation, the boundary conditions are set as the same as those in Fig. 2. It seems clearly that crack results in the larger decrease of the static modulus of elasticity. In other words, the existence of crack leads to higher WM. It needs to be pointed out that the volume fraction of crack-like voids is only 1.5% in the model as shown in Fig. 6. If the 1.5% volume fraction counts on spherical voids, the conclusion is totally different, being lower WM.

However, spherical voids and cracks are the two extreme ends. One end presents higher static modulus and the other does higher WM. Even if the crack density is constant, the wave velocity will decrease with respect to the extent of crack opening (Shuai et al. 2016). This phenomenon is anticipated because wider crack gives higher volume fraction. Obviously, the aspect ratio of a void, being the scenario between crack and spherical void, plays the role manipulating the difference of WM and its static counterpart, which can be illustrated in Fig. 7 with the void volume fraction (porosity) of 5%. The void shape is elliptical. It can be seen that the static modulus drops dramatically with the smaller aspect ratios. Although WM has the same tendency, it has the same value as the static modulus at about 0.2 aspect ratio and starts being larger below 0.2. It is noted that WM does not change smoothly, which may be because of the strong nonlinear interactions among wave motion, aspect ratio and the number of voids. The discussion about this is beyond the scope of current study. However, one thing is confirmed that WM is always lower than its static counterpart above a specific aspect ratio, and higher than the static counterpart below the specific ratio. The voids with aspect ratios smaller than a specific value are identified as crack-like voids because they cause higher WM. The voids above the specific aspect ratio are called as round voids because they cause lower WM like ideally spherical voids.

In reality, however, the void configuration is commonly irregular and cannot be simply delineated by an ellipse and an ellipsoid. For example, as shown in Fig. 8, it is difficult to use the aspect ratio to quantify the real void that is detected by X-ray micro-CT. Another parameter, sphericity, is thus suggested to deal with the irregular void (Wang et al. 2016). Sphericity, s, is defined as,

$$s = 6\sqrt{\pi}\frac{V_s}{\sqrt{A_s^3}} \tag{4}$$

where V_s is the void volume and A_s the surface area. For the ideal sphere, $s = 1$, and for the ideal penny, $s = 0$. Accordingly, for 2D problems, the roundness can be defined as,

$$r = 4\pi\frac{A}{C^2} \tag{5}$$

where r is the roundness, A is the area and C is the circumference. For the ideal circle, $r = 1$, and for the ideal crack, $r = 0$. If Eq. (5) is applied to the case with the specific aspect ratio 0.2 as shown in Fig. 7, $r = 0.45$, meaning that roundness below 0.45 tends to generate higher WM.

Simulation on real concrete structures

In order to strengthen the conclusion that higher WM is attributed to crack-like voids, two concrete samples are imaged by X-ray micro-CT, followed by FEM simulations. The CT scanner is *Xradia*

410 Versa (Carl Zeiss X-ray Microscopy, Inc.) that has the best spatial resolution of 0.9 μm. In the present study, the resolution is 25 μm. The two samples are the recycled aggregate concrete (RAC) and the natural aggregate concrete (NAC) (Qiao 2010). For each concrete, the cubic specimen with approximate edge-length of 15 mm and prismatic specimen with dimensions of 50 mm by 50 mm by 100 mm are cut from the same laboratory-cast beam with dimensions of 75 mm by 100 mm by 400 mm. Cubic specimens are used in micro-CT scan and prismatic specimens in uniaxial compression testing. The X-ray CT images are shown in Fig. 9, showing internal structures of concrete. ScanIP®, a professional image processing product of *Simpleware LTD*, is employed to segment, measure and mesh all components of 3D concrete images.

According to these CT images, the difference between RAC and NAC cannot be visually identified. It has been characterized that RAC has less elastic modulus, lower density, and greater water absorption than NAC (Qiao 2010). Scales of voids below 0.1 mm are not counted, and the measured volume fraction of voids is 5.6% for NAC and 5.2% for RAC as shown in Fig. 10. During segmentation, only is the aggregate above 1.5 mm picked out, which shows the volume fraction of aggregate of 28.2% in NAC and 33.9% in RAC. Smaller aggregate is merged into mortar treated as a part of the matrix because they are not expected to affect WM under current wavelength. The size of aggregates ranges from 1.5 mm to 8 mm, which is less than the wavelength amounting to ~20 mm. Although the requirement of separation-of-scales is not strictly satisfied (Zaoui 2002; Kohlhauser and Hellmich 2013), the expected error is less than 1.8% as shown in Fig. 4. This level of accuracy is sufficient for the present study. Because of microstructural features inside concrete, the final mesh is reasonably dense as shown in Fig. 10.

Before FEM simulation, the two kinds of concrete properties are measured by uniaxial compression testing. The corresponding elastic static moduli are tested on the prismatic specimens using a MTS machine (ASTM (American Society for Testing and Materials) 2014). Two LVDTs with 2-inch gauge length are oppositely mounted on specimen surface to measure the compressive strain. To enable compression under quasi-static state, a very low loading rate (i.e., 0.1 mm/min.) is chosen. The measured elastic static moduli are 20.36 GPa and 16.85 GPa for NAC and RAC, respectively, extrapolated from compressive stress–strain curves as shown in Fig. 11. Although cement paste is viscoelastic in nature, identification of the elastic Young's modulus from quasi-static tests on cement pastes (by accounting for both elastic and creep deformation during loading) delivers virtually the same stiffness values as ultrasonic testing (Irfan-ul-Hassan et al. 2016). With added aggregates, the WM will be below the static modulus as discussed in aforementioned analysis, indicating that viscoelastic nature is not the reason causing higher WM. In addition, the creep evolution of concrete is significantly slower than its stiffness (Ausweger et al. 2019). However, there is no apparent relaxation in Fig. 11, which shows that the samples are nearly mature in creep evolution. Then, the material properties' input of FEM can be estimated based on the measured elastic static moduli. Initial rough estimations follow the rule of mixtures (Alger 2017) and, then, use the trial-and-error method to match with the measured elastic static moduli. Input of material parameters are listed in Table 1. The final resultant homogenization moduli are listed in Table 2 in which errors compared with experiments are shown in parentheses. During the simulation, the symmetric boundary conditions are assigned to each model.

For RAC and NAC, the wave speed is around 2,000 m/s which results in a wavelength of around 20 mm with 100 kHz frequency. For FEM models shown in Fig. 10, the wavelength is larger than the boundary scale, which influences the wave velocity (Sun et al. 2008). Therefore, three dimensions of both RAC and NAC models are doubled by symmetric duplication. With applying symmetric boundary conditions, four original images are piled up together. Totally, the RAC FEM model contains 8,069,700 tetrahedral elements and 1,547,822 nodes, while the NAC model contains 7,130,676 elements and 1,348,910 nodes. The time step is 0.25 μs which satisfies the accuracy requirement of numerical simulation. Both computations take more than 48 hours per job for WM estimation, running in a 4-core i7 CPU and 16 GB memory PC. Wave pulse is applied at the center of an outer surface and the transmitted data acquired on the opposite surface. The propagation velocity is estimated by comparing the input signals with its transmitted signals. Thereafter, WM is calculated based on Eq. (1).

Except the simulation on real concrete, the simulation with all voids removed and merged into the matrix is performed as the comparison origin. All simulation results and the static measurement are tabled in Table 2 and graphed in Fig. 12. The experimental WMs are obtained from Qiao 2010 that reported how to measure WMs in detail. It can be seen that the simulated WMs agree well with the experimental ones and are larger than corresponding elastic static moduli by 13.1% for NAC and by 7.3% for RAC. Taking the results without voids as the origin, the simulated WM is reduced by 3.2%, and the static modulus of elasticity by 14.0% for NAC, and by 7.0% and 11.1% for RAC. Both NAC and RAC results verify that the static modulus of elasticity decreases larger. To verify whether or not these higher WMs of NAC and RAC are attributed to crack-like voids, the probability density functions of sphericity of NAC and RAC are computed in terms of the micro-CT images and Eq. (4) as shown in Fig. 13. It can be seen that all voids are not ideal spheres and have sphericity mostly in range of 0.2 to 0.6. It is further validated that higher WM must be caused by non-spherical pores.

Conclusions

With the aid of computational micromechanics and finite-element method, factors associated with the wave modulus (WM) of elasticity evaluation are analyzed to investigate the microstructural origins on why WM is higher than its corresponding static modulus of elasticity. Possible factors (aggregate and void) are analyzed and discussed. While higher aggregate concentration results in an increase of both WM and static modulus of elasticity, it does not indicate that WM is more sensitive to aggregates than static modulus of elasticity. It is also noted that the presence of wave scattering and refraction around aggregates tends to result in lower WM when compared with the static cases. Microstructural porosity due to spherical voids leads to lower WM than the static modulus of elasticity of concrete. However, the crack-like voids prove to be the critical factor causing the higher WM. The crack-like voids are identified with a specific roundness or sphericity.

Data Availability Statement: Some or all data, models, or code generated or used during the study are available from the corresponding author by request (finite-element simulation data of dynamic wave propagation for single aggregate cases; finite-element simulation data of dynamic wave propagation for concrete with various volume fractions of aggregates; micro-CT experimental data of microstructures of concrete; finite-element simulation data of dynamic wave propagation for concrete with randomly distributed cracks; and finite-element simulation data of dynamic wave propagation for NAC and RAC concrete materials.

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Figure Captions

Fig. 1. Acceleration (mm/s^2) contour bands at 25 μs with (a) a single triangular aggregate and (b) the propagation comprison of three cases along the propagation centerline at 25 μs

Fig. 2. (a) Concrete microstructure with 30% volume fraction of aggregates and (b) the comparison between the WM and static modulus of elasticity of concrete as a function of volume fraction of aggregates

Fig. 3. Comparison of (a) different time increments and (b) loading positions

Fig. 4. WM with different λ/d values

Fig. 5. An X-ray CT resolved concrete slice (17.2 mm × 18.9 mm), segmented aggregate (30% volume fraction), and finite-element mesh with no consideration of voids.

Fig. 6. FEM model of concrete with randomly distributed cracks

Fig. 7. Comparison of WM and its static counterpart with different aspect ratios

Fig. 8. A real void detected by X-Ray micro-CT that can be characterized by sphericity rather than aspect ratio

Fig. 9. Micro-CT images of RAC and NAC: (a) a typical slice of 15.8 mm × 13.9 mm and 3D image of NAC, and (b) a typical slice of 13.1 mm × 14.8 mm and 3D image of RAC

Fig. 10. Microstructural voids and FEM mesh of (a) NAC and (b) RAC concrete materials

Fig. 11. Stress–strain curves of compression test of NAC and RAC samples

Fig. 12. Experimental and FEM results of NAC and RAC

Fig. 13. Probability density functions (PDF) of sphericity of NAC and RAC

Table 1. Material parameters of NAC and RAC

Parameter	NAC		RAC	
	Aggregate	Mortar	Aggregate	Mortar
Elastic modulus (GPa)	33.0	19.3	25.6	16.4
Density (kg/m^3)	2337	2337	2262	2262
Poisson's ratio	0.15	0.15	0.15	0.15

Table 2. Simulation results of RAC and NAC

Concrete	Static modulus of elasticity (GPa)			Wave modulus of elasticity (GPa)		
	Experiment	FEM		Experiment	FEM	
		With voids	Without voids		With voids	Without voids
NAC	20.36	20.41 (-0.25%)	23.74	23.11	23.08 (0.13%)	23.85
RAC	16.85	16.98 (-0.77%)	19.10	18.81	18.22 (3.1%)	19.60