Damping properties of metaconcrete structures under transverse excitation

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Abstract

Metaconcrete made of engineered aggregates (EAs) as an alternative for mitigating vibration and shock waves has been intensively investigated in recent years. The resonant behaviours of EAs enable the metaconcrete structure to exhibit negative effective properties (i.e., negative effective mass and negative effective stiffness) interacting with stress waves induced by dynamic loadings, and thereby resulting in wave propagation attenuation. These properties are being relatively intensively investigated in recent years for using metaconcrete to mitigate stress wave propagations induced by blast and impact loads. Investigations of vibration properties of structures made of metaconcrete are very limited. Some studies found it is very difficult to make the frequency bandgap of EAs to coincide with the predominant frequency band of earthquake ground motions for structural protection against seismic excitations and it is also very costly, therefore the concept of metaconcrete is not necessarily applicable to earthquake resistant designs. Damping properties of metaconcrete structure, however, have never been studied yet. As local resonations of EAs would attract a significant amount of vibration energy, which can be equivalent to structural damping for vibration mitigation, metaconcrete structure may be effective in seismic resistant in terms of its high damping property, besides frequency bandgap for resisting wave propagations. This study investigated the equivalent damping properties of cementitious-based metaconcrete with engineered aggregates made of rubber-coated steel balls (RCSB) subjected to transverse excitations. Laboratory tests were carried out to investigate the influences of volume fractions of RCSBs (i.e., 9.2%, 18.4% and 22.9%), different sizes of RCSBs (i.e., 22 mm, 18 mm and 15 mm) and periodic/ non-periodic distributions of RCSB on equivalent damping properties of metaconcrete structures. The implications on seismic resistance performance of structures constructed with metaconcrete are discussed.

Keywords: Damping, Metaconcrete, Engineered aggregate, Transverse loading

1 Introduction

Over the past two decades or so, metamaterial defined as artificial materials that exhibits an exotic behavior has elicited the curiosity of many researchers. It has been developed and employed for various applications such as seismic isolator/barrier (Li et al., 2020) and mechanical energy absorber (Li et al., 2021), etc. In particular, recent development in the fields of locally resonant metamaterials (LRMs) with the feature of manipulating wave propagation brings new way of developing multifunction materials based on the concept of Bragg scattering (Yuan et al., 2013) and/or local resonance mechanism (Liu et al., 2000). Besides, a newly developed concrete-based metamaterial named metaconcrete provides a new concept of protecting concrete structures from vibration and impulsive waves by its favourable wave filtering capacity (Briccola et al., 2020; Briccola et al., 2016; Briccola et al., 2019; Jin et al., 2021a, b; Jin et al., 2020; Kettenbeil and Ravichandran, 2018; Liu et al., 2021; Mitchell et al., 2014, 2015; Xu et al., 2020). Metaconcrete is manufactured by mixing engineered aggregates with cementitious material, and the engineered aggregates can be tuned to trigger negative effective mass of overall system and hence attenuate stress wave propagation (Mitchell et al., 2014). The previous experimental studies (Briccola et al., 2020; Briccola et al., 2016; Briccola et al., 2019; Kettenbeil and Ravichandran, 2018; Liu et al., 2021) demonstrated that adding resonant inclusions into the concrete matrix could improve attenuation capacity of axial wave propagation and longitudinal vibration of the structural component by converting the loading energy to kinetic energy through local resonance of engineered aggregates. In addition, several numerical studies showed that concrete with local resonators coated by viscoelastic compliant layer could have higher energy dissipation capacity (Cheng and Shi, 2013). Therefore, metaconcrete with superior wave attenuation and energy dissipation capacity could be potentially used in constructions for multi-dynamic hazards protections.

Most of the previous studies focused on investigating the frequency bandgaps of metaconcrete for mitigating stress wave propagations induced by blast and impact loads. Limited studies have also been reported to investigate the acoustic performance and dynamic response in the longitudinal direction (i.e., in-plane and 1-dimensional structure) have been reported by different researchers (Briccola et al., 2020; Briccola et al., 2016; Briccola et al., 2019; Kettenbeil and Ravichandran, 2018; Liu et al., 2021), the vibration characteristics and damping properties associated with transverse dynamic response of metaconcrete structure, which are important for seismic resistance, have not been reported yet. This study firstly investigated the damping properties of metaconcrete beam specimens composed of cementitious mortar and resonant aggregates (i.e., RCSBs) subjected to transverse loading. Various embedded resonant RCSBs were considered. The influences of volume fraction of RCSBs and aggregate size on the vibration characteristics and equivalent damping properties of metaconcrete beams were assessed. It is worth mentioning that this study focused on damping properties of metaconcrete with different configurations of engineered aggregates, the wave attenuation characteristics associated with negative effective properties were not specifically discussed herein.

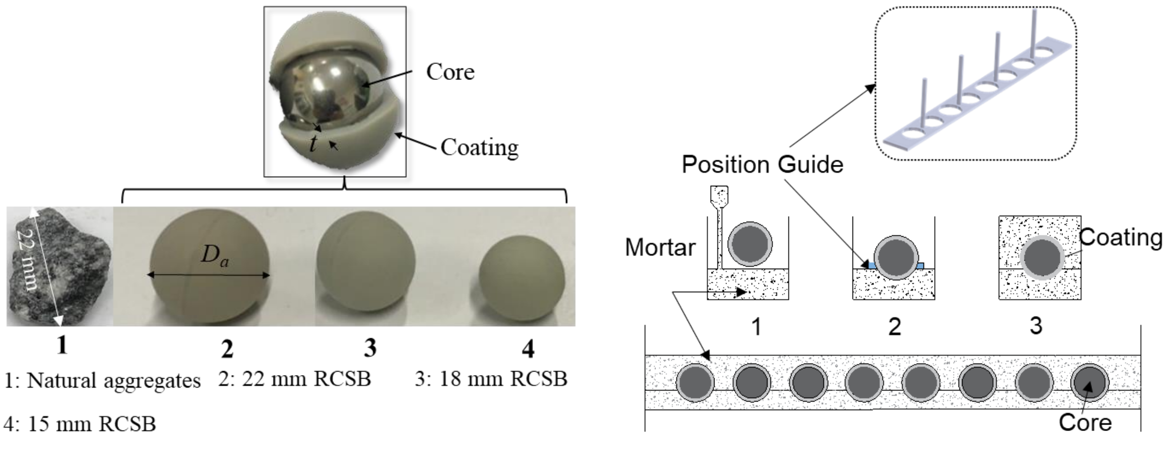
2 Experimental study

2.1 Specimen preparation

The present study was aimed to investigate the damping properties of metaconcrete beam with different RCSBs subjected to transverse load. High strength mortar was used as the matrix of metaconcrete to avoid damage during the test. The mortar was made by using dry-mix Davco Lanko 701 duragrout produced by Sika Australia Pty Ltd with the designated compressive strength of 73 MPa after 28 days (Davco Australia, 2020). The mix ratio of cement/sand/water/additives was 1/2/0.5/0.33. Four different types of silicone rubber coated steel balls (RCSBs) as shown in Figure. 1 (a) were fabricated by encapsulating steel ball with rubber coating, followed by curing process. In addition, the casting method for specimens with periodically placed RCSBs in mortar matrix is schematically depicted in Figure. 1(b).

Detailed information on the specimens and the configuration of inclusions are listed in Table 1. As shown, a total of eight specimens (i.e., S1-S8) with a length of 270 mm and a cross-sectional area of 30×30 mm were prepared. A plain mortar beam (S1) without aggregate was prepared as a reference specimen. Besides, S2 and S3 were fabricated by respectively adding regular distributed natural aggregates and RCSBs to evaluate the effect of inclusion type. Three specimens labelled as S3, S4 and S5 were designed to periodically mix different numbers of 22 mm-diameter RCSBs in metaconcrete, giving the respective RCSB volume fraction of 18.4%, 9.2%, and 22.9% in metaconcrete to explore the influence of volume fraction of engineered aggregates on the damping properties. S7 has the same number of aggregates as S3, but the aggregates were randomly distributed in mortar matrix to study the influences of randomly distributed vs periodically distributed engineered aggregates on the damping properties of metaconcrete beam structure. RCSBs with different sizes, namely, 22 mm, 18 mm and 15 mm in diameter as illustrated in Figure. 1(b), were used to fabricate the S6, S7 and S8 with randomly distributed aggregates to study the effect of aggregate size on the damping properties.

To ensure the periodic position of S3, S4 and S5, 3D-printed position guides were prepared for the specimen fabrications. During the fabrication process as illustrated in Figure. 1(b), the first step was to place the bottom layer of mortar in the mould to provide the initial cover. After that, the position guide was used for placing aggregates and then the position guide was removed. For S6, S7 and S8, the RCSBSs were randomly placed on top of the initial layer. Sequentially, the remaining mortar was poured. Finally, a steel rod was used to ram the specimen to minimize the voids.



(a) (b)

Figure. 1: Illustration of: (a) configuration of different RSCBs; (b) fabrication of specimen. Note: D_a and t are the aggregate size and coating thickness, respectively.

Table 1: Summary of specimen configuration and parameters.

Specimens No.	Type	Distribution	D_a (mm)	t (mm)	V_a (%)	f_n (Hz)
S1	-	-	-	-	-	66.2
S2	Natural aggregates	Periodic	22	-	18.4	68.8

S3	RCSB	Periodic	22	1.5	18.4	53.6
S4	RCSB	Periodic	22	1.5	9.2	58.5
S5	RCSB	Periodic	22	1.5	22.9	47.4
S6	RCSB	Random	18	1.2	18.9	52.8
S7	RCSB	Random	22	1.5	18.4	54.6
S8	RCSB	Random	15	1.2	18.6	56.5

Note: D_a is the dimeter of the RCSB; t is the thickness of rubber in RCSB; V_a (%) is the volume fraction of RCSB to the overall beam structure. '-' means not applicable. f_n is the fundamental vibration frequency of specimen in Hz.

2.2 *Laboratory testing set-up*

The hammer excitation technique has been commonly used to study the damping properties, which is also used in this study to determine the vibration properties of metaconcrete beam. For the test setup, two accelerometers (i.e., accelerometer #1 (a_1)) adhered underneath the impact location and accelerometer #2 (a_2) near the support) were used to record the acceleration responses via a Quantum X universal data acquisition system (DAQ) with a sampling rate of 19.2 kHz. A Dytran® 5800B3 impulse hammer equipped with a soft polyurethane tip (6250PS) was used to impact the specimen at the prescribed location and the hammer force was also recorded by DAQ. All specimens were fixed at one support and excited at its free end to evaluate the damping properties. The actual experimental setup is illustrated in Figure. 2.

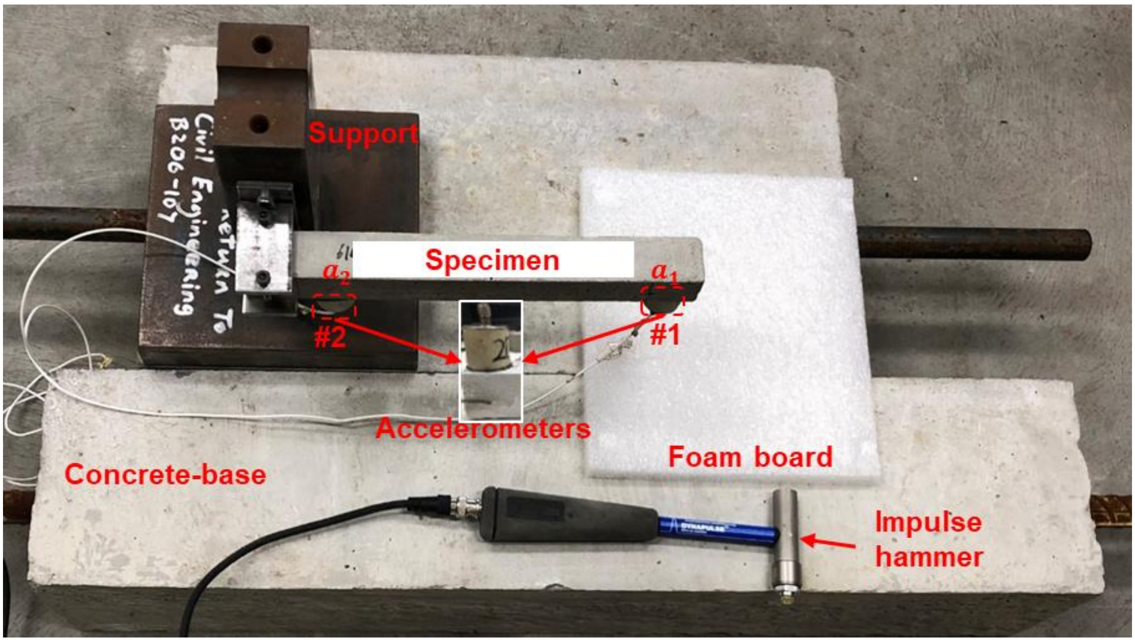


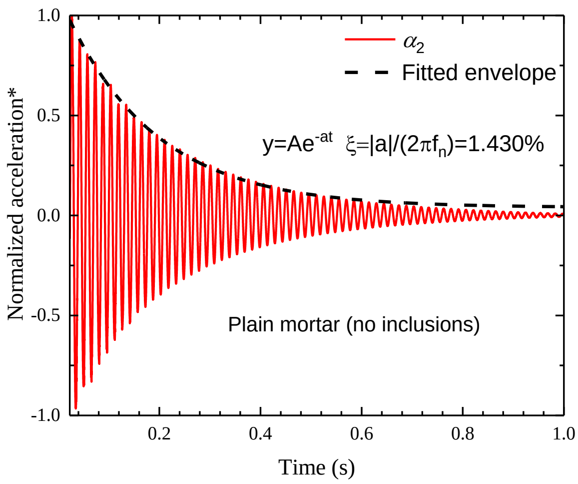
Figure. 2: Illustration of testing set-up.

3 Results and discussion

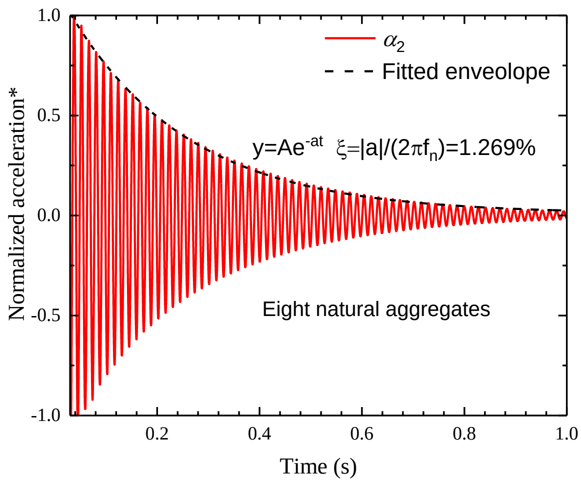
In this study, eight cantilevered specimens were studied by conducting forced vibration test with an instrumented impact hammer. For the forced-vibrated specimens, the specimen started vibrating freely at the end of the impulse induced by hammer impact. The free vibration phase of the structures was used to evaluate the equivalent damping ratio. The equivalent damping ratio, which was used to characterize damping properties of concrete specimens, can be determined by using the exponential fitting method (Cui et al., 2020; Pan et al., 2013; Song et al., 2019). Acceleration response recorded at accelerometer #2 was selected for analysis. The fundamental frequency can be calculated through taking fast Fourier transform (FFT) of the recorded acceleration response. Figure. 3(a) and (b) respectively depicts the evaluation of equivalent damping ratio (ξ) of plain mortar and mortar with natural aggregates via exponential fitting and the value of damping ratio was calculated by using the equation shown in the figure. Besides, Figure. 3(c)-(h) exemplifies the exponentially fitted curves as well as the corresponded equivalent damping ratio for S3-S8 (i.e., mortar with RCSBs in different configurations). It is worth mentioning that each specimen was impacted by the hammer at least three times, and a total of 21 acceleration-time histories were analysed to derive the equivalent damping ratio. The results and average equivalent damping ratio for each specimen from the test are summarized in Table 2.

Table 2: Summary of equivalent damping ratio of cantilevered specimens.

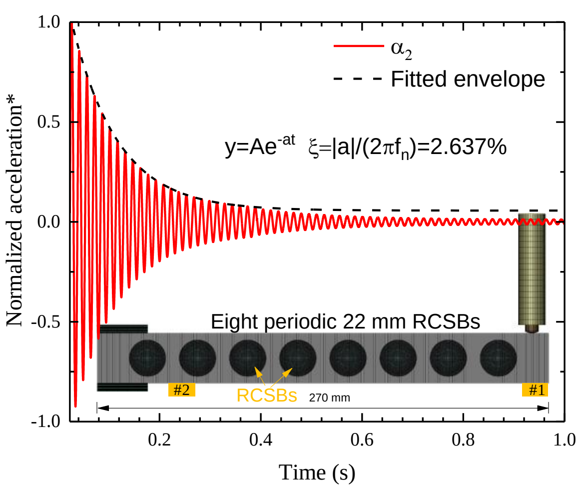
ξ (%) / Specimens No.	Test no.			Average value	Standard derivation
	T1	T2	T3		
S1	1.430	1.370	1.204	1.335	0.166
S2	1.269	1.461	1.369	1.366	0.136
S3	2.739	2.637	2.672	2.683	0.073
S4	2.506	2.450	2.615	2.524	0.119
S5	2.989	3.215	2.953	3.052	0.201
S6	2.757	2.952	2.994	2.901	0.179
S7	2.647	2.847	3.039	2.844	0.277
S8	2.708	2.913	3.109	2.910	0.284



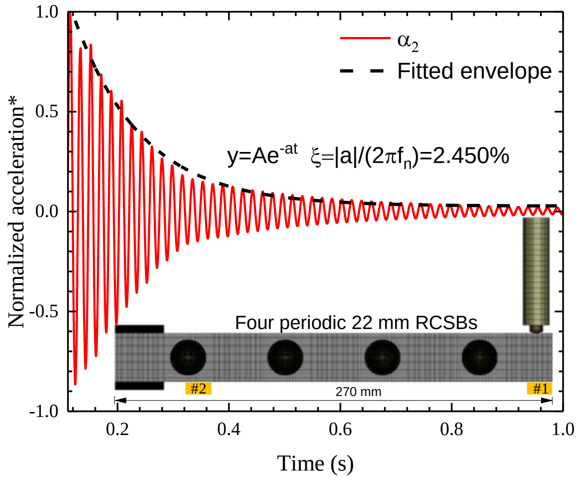
(a) *equivalent damping ratio of S1*



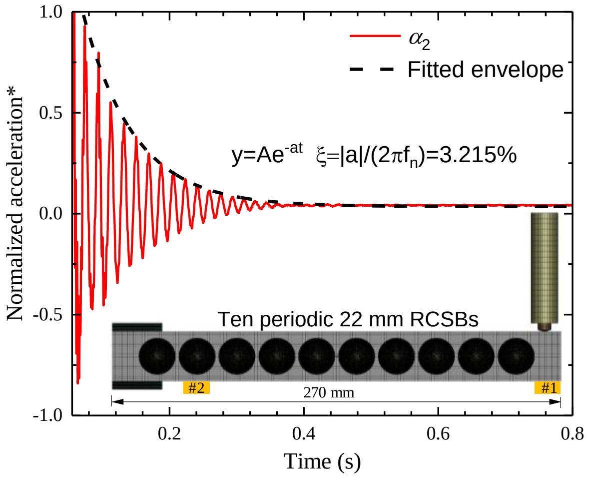
(b) *equivalent damping ratio of S2*



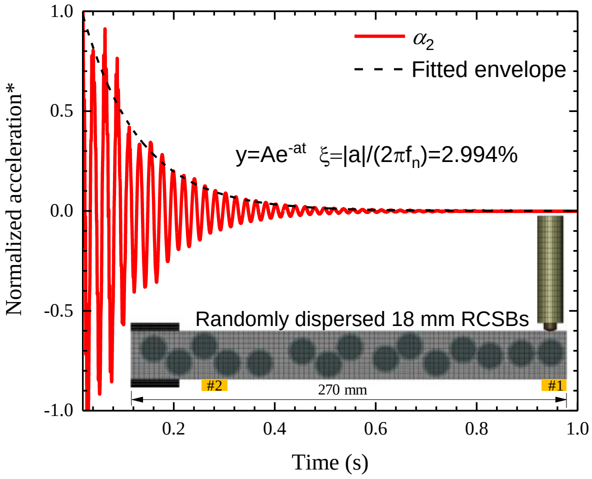
(c) *equivalent damping ratio of S3*



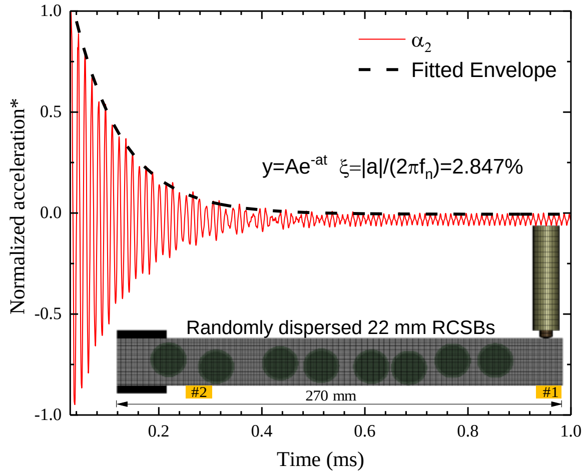
(d) *equivalent damping ratio of S4*



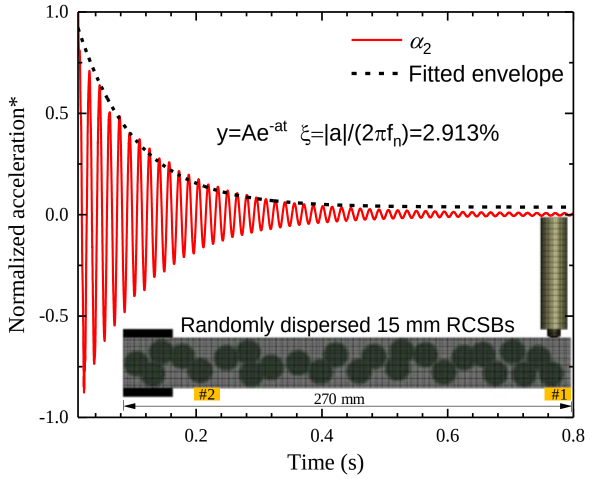
(e) *equivalent damping ratio of S5*



(f) *equivalent damping ratio of S6*



(g) *equivalent damping ratio of S7*



(h) *equivalent damping ratio of S8*

Figure. 3: Evaluation of equivalent damping ratio.

As given in Table 1, increasing contents of RCSBs resulted in the reduction of fundamental vibrational frequencies of metaconcrete specimens. The reduction in the fundamental frequencies was attributed to the following reasons: a) the increased total weight of specimen with higher contents of RCSBs; b) the reduced bending stiffness of beam structure due to the low stiffness of soft coating outside the RCSB. Using a modified design of engineered aggregates with a stiff coating layer can mitigate the problem of structural stiffness reduction.

Figure. 4 shows the average equivalent damping ratios of S1-S8. The specimens with RCSBs (i.e., S3-S8) had much higher equivalent damping ratio than the specimens without RCSBs (i.e., S1 and S2). For instance, the equivalent damping ratio for the beam with eight RCSBs (i.e., S3) had an average equivalent damping ratio of 2.683%, which was 98% higher than S1 of 1.355% and 96% higher than that of S2. The enhancement of equivalent damping ratio was attributed to the existence of RCSBs because vibration energy was partially absorbed by local vibrations of steel cores and RCSBs provide the favourable effect on the equivalent damping ratio. It was found that the average equivalent damping ratio increased from 2.524% in S4 (9.2% volume fraction) to 3.052% in S5 (22.9% volume fraction). This is because larger amount of viscoelastic rubber coating and more local vibrations could enhance the vibrational energy dissipation. Thus, the damping ratios of the metaconcrete specimen were positively correlated to the volume fraction or the number of RCSBs in the metaconcrete mix. Besides, the average equivalent damping ratio changed marginally for the specimens with different aggregate sizes (S6, S7, S8) but similar volume fraction of RCSBs. Given similar volume fraction of RCSBs, S6 with 18 mm RCSBs had the average equivalent damping ratio of 2.901%, and S8 with 15 mm RCSBs presented an average equivalent damping ratio of 2.910%, which was slightly different from that of S7 with 22 mm engineered aggregates. Furthermore, the distribution of EAs had no significant effect on the damping properties by comparing the equivalent damping ratios of S3 and S7. It can be concluded that the metaconcrete specimens with RCSBs can achieve a much higher equivalent damping ratio than the normal concrete specimen, indicating energy can be dissipated more effectively and efficiently.

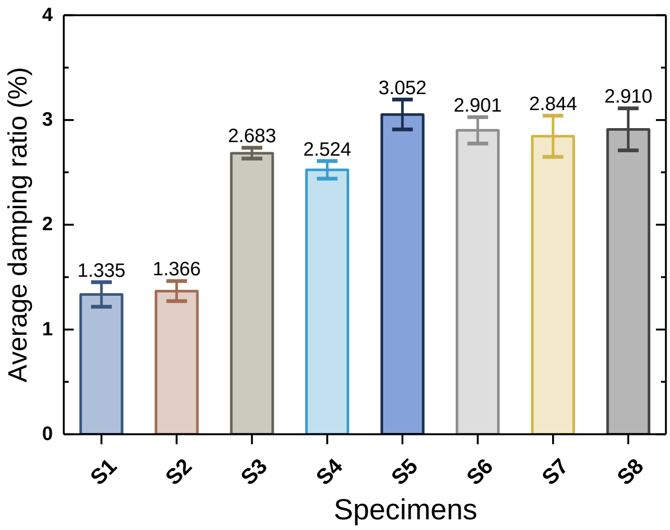


Figure. 4. Average equivalent damping ratio for eight specimens (Xu et al., 2021).

4 Conclusions

This study investigated the damping properties of cementitious metaconcrete specimens with resonant RCSBs. The metaconcrete specimens with different aggregate configurations, namely three volume fractions of RCSBs (i.e., 9.2%, 18.4% and 22.9%), and three sizes of RCSBs (i.e., 22 mm, 18 mm and 15 mm) were prepared and tested. The following conclusions can be drawn.

1. Metaconcrete specimen with resonant aggregates (i.e., RCSBs) had a higher equivalent damping ratio than plain mortar and normal concrete with natural aggregates.

The average equivalent damping ratio of metaconcrete specimen can substantially increase, about double, as compared with the normal concrete specimen.

2. Increasing volume fraction of RCSBs led to higher equivalent damping ratio. The average equivalent damping ratio increased by 20.9% when the RCSBs volume fraction increased from 9.2% to 22.9%.
3. Distribution of RCSBS in mortar matrix has no obvious influence on vibration and damping properties of tested specimens.

These results indicate that metaconcrete can be an effective construction material for seismic resistance through its high damping property besides its ability for mitigating wave propagations, therefore can be used for structure constructions to resist multi-dynamic hazards.

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