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Dynamic behaviour of concrete containing aggregate resonant frequency

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ABSTRACT

The need to design blast resistant civilian structures has arisen due to aggressor attacks on many civilian structures around the world. Achieving vibration and wave attenuation with locally resonant metamaterials has attracted a great deal of consideration due to their frequency dependent negative effective mass density. In this paper, metaconcrete, a new material with exceptional properties is formed. The aggregates in concrete are substituted with spherical inclusions consisting of a heavy metal core coated with a soft outer layer. The physics of the metamaterial was first established, and mass in mass spring and effective mass system were shown to be equivalent. Then the engineered aggregate was tuned so that band gap was activated due to resonant oscillations of the replaced aggregate. In the numerical experiment conducted, the resonant behaviour causes the wave to be forbidden in the targeted frequencies. The proposed metaconcrete could be very useful in various civil engineering applications where vibration suspension and wave attenuation ability are in high demand.

1. Introduction

Recently, the design and construction of metamaterials with unconventional properties have become an area of active research. Metamaterials are artificial structures, typically periodic (but not necessarily so), composed of small meta-atoms that, in the bulk, behave like a continuous material with unconventional effective properties [1–3]. Further descriptions of metamaterials have been given by other researchers [4, 5]. The first acoustic metamaterials appearing in the literature were so-called locally resonant sonic crystals [6] with acoustic resonators built into individual unit cells. The development of these acoustic metamaterials has led to groundbreaking demonstrations of the mass density law, often used in sonic shielding. The question of realization of negative mass density and modulus has been established by Huang et. al. [1], hence negative mass and/or modulus can be detected when dynamic loading of a definite frequency is applied to properly designed material systems, forming acoustic metamaterials. Metamaterial with manufactured microstructures can display uncommon property, such as negative electric permittivity, negative magnetic permeability, negative refractive index, and negative effective mass which does not exist in nature. These unique properties can then be used to design attractive features. Depending on the design of the material systems, the metamaterials can be single-negative (mass or modulus), or double negative (mass and modulus) [7]. For example, a negative modulus has been observed at ultrasonic frequencies in a duct lined with an array of Helmholtz resonators [8–10]. Negative density has been reported in a discrete structure consisting of a network of discrete masses and springs [11, 12]. Our modern appreciation of the use of engineered structures to guide wave properties began with photonic and phononic crystals [13, 14]. Over the past few years metamaterials have been the subject of a very extensive interest, as attested by numerous periodicals in highly focus and wider public publications [5, 6]. Currently, research on metamaterials is developing and expanding fast due to relatively simple building blocks that can be assembled into structures that are similar to continuous materials. Yet these structures have unusual wave properties that differ substantially from those of conventional media. New tools to control and manipulate these classical waves; elastic waves and electromagnetic waves are extremely desirable.

Extensive studies on the mechanical behaviour of concrete for protection against short duration dynamic loading effects have been made in the last few decades [15]. The new designs of building structures by architects have made generators, and other vibrating machines to be installed on the top floors due to lack of space. So, we now have reinforced concrete being subjected to varying dynamic loadings. In addition, high strain-rate concrete induced from intense dynamic loadings have been found also in concrete material

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frequently used in civil and defense engineering[16]. In this work, Kong et. al. [16] defined three zones of stress strain enhancement approaches; overstress, consistency and simplified approach. In all these approaches, the stress strain effect is considered in the models. Hence, the subject of concrete under dynamic loading as gain momentum in the civil engineering world. Concrete is a composite material composed of fine and coarse aggregate bonded together with a fluid cement (cement paste) that hardens over time [17–19]. Metaconcrete is a new type of concrete where the standard stone and gravel aggregates are replaced by engineered inclusions [20]. Metaconcrete aggregates present a layered structure consisting of aggregate in form of a heavy core and a soft outer coating. This metaconcrete uses the principles of metamaterials to instigate resonance at or near the eigenfrequencies of the inclusions in the concrete mix. The aggregate is designed in such a way to be tuned that resonance is activated at particular frequencies of the applied load [20–22]. The activation of resonance within the aggregates in turn results in weakening of the motion of the elastic waves. This metaconcrete is similar to the model by the composites that Liu et. al. [6] used in which microstructural unit consisting of a solid core material with a relatively high density and a coating of elastically soft material.

The protection of buildings and structures from terrorist or accidental explosions is becoming an increasingly important consideration for many government, military, and even civilian facilities [23, 24]. Metaconcrete, recently introduced in Mitchell et al. [20] represents an example of such a system that can reduce the effect of dynamic loading on concrete. Metaconcrete is an altered concrete developed for the purpose of reducing the propagation of waves caused by dynamic loading, such as the blast loading profile generated by an explosion [22].

The study of electromagnetic and acoustic waves in irregular dispersion has been extensively carried out by researchers in recent years, but its application in civil engineering structures and composites receives much less attention. In the present study we further show the proposed model of metaconcrete to prevent wave propagation in arrays of the cells. The specific objectives are: (1) to explain the physics behind negative effective density theoretically, (2) establish the forbidden wave propagation in a periodic metaconcrete numerically through the dispersion curve and (3) to reveal the actual working mechanism of this metaconcrete for absorption of low frequency elastic waves.

2. Basic principles of effective mass densities: hidden forces

2.1 Single mass-spring unit

Let us introduce the basic principles of mass-in-mass lattice model that has been discussed in literatures [1, 25]. As demonstrated in Fig. 1(a), the outer hollow body of mass m_1 is assumed to be rigid and a solid mass m_2 is connected to the outer mass by a spring having linear spring constant k_2. In this model, we allow mass m_2 to be in the hidden region. Consequently, it turns out that the body has an effective moment of inertia which is frequency dependent. An external harmonic force $F(t)$ is applied to the mass-in-mass unit.

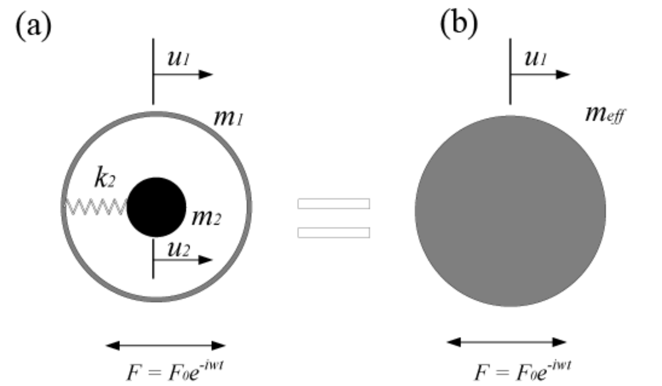

Fig 1. (a) The mass-spring structure with negative effective mass; (b) its equivalent effective model

Newton's second law gives us

$$\begin{aligned} m_2\ddot{u}_2 &= k_2\left(u_1 - u_2\right) \\ m_1\ddot{u}_1 &= k_2\left(u_2 - u_1\right) + F \end{aligned} \tag{1}$$

The force is presented as

$$F = F_0 e^{-i\omega t} \tag{2}$$

where F_0 is the amplitude. Assuming the steady-state harmonic motion, the solution can be obtained by substituting the displacements

$$u^j = u_0^j e^{-i\omega t}, \qquad j = 1, 2 \tag{3}$$

into Eq. (1) which gives

$$\left\{\left[m_1 + \frac{k_2}{\left(\omega_0^2 - \omega^2\right)}\right]u_0^1\omega^2 + F_0\right\}e^{-i\omega t} = 0 \tag{4}$$

where $\omega_0^2 = k_2/m_2$. The above equation indicates that, in the view of external force, the two-object system m_1 and m_2 can be considered as a homogenous one-object system m_1 with the resonant frequency ω_0 and an effective mass is obtained as

$$M_{eff} = M_1 + \frac{k_2}{\left(\omega_0^2 - \omega^2\right)} \tag{5}$$

One can infer from this equation that, when an external force is applied to mass m_1 , a hidden force that is dependent on the frequency makes the effective mass to be negative as the forcing frequency approaches the local resonant frequency. In fact, the magnitude of the effective mass would become unbounded at the frequency ω_0 as shown in Fig. 2.

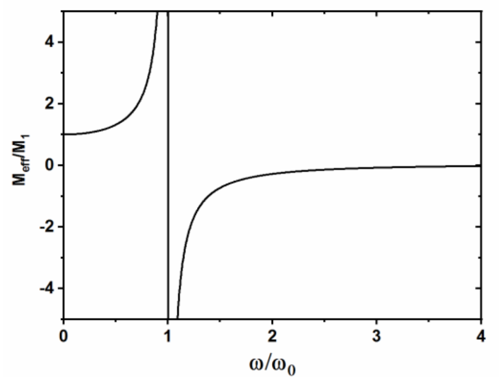

Fig 2. Dimensional effective mass M_{eff}/M_1 as a function of ω/ω_0

When the inner mass is fixed, effective dynamic mass in Eq. (5) becomes [26];

$$M_{eff} = M_1\left(1 - \frac{\omega_1^2}{\omega^2}\right) \tag{6}$$

where $\omega_1^2 = k_2/m_1$. In this situation, below the cut off frequency, the effective mass is negative. When the mass-spring structures are connected by springs of elastic constant K, the dispersion relation for lattice system with distance a is derived to be [26];

$$M_{eff}\omega^2 = 4K\sin^2\frac{\boldsymbol{q}a}{2} \tag{7}$$

where $\boldsymbol{q}$ is the Bloch wave vector. From Eq. (7), it is seen that the wave vector $\boldsymbol{q}$ takes imaginary values at frequencies of negative effective mass. It means that the lattice waves will be forbidden in this frequency band.

2.2 One-dimensional periodic lattice model

To verify the blocking effect due to negative effective mass, a finite lattice system is considered as done by Huang et. al [1] in Fig. 3 (a).

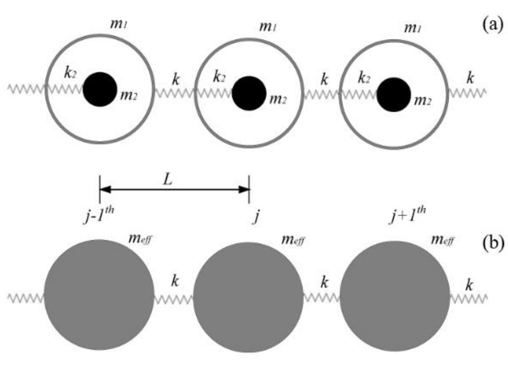

Fig 3. Infinite mass-in-mass lattice structure [1]

The equations of motion for the $(j)^{th}$ unit cell are

$$m_1^j\ddot{u}_1^j + k\left(2u_1^j - u_1^{j+1} - u_1^{j-1}\right) + k_2\left(u_1^j - u_2^j\right) = 0 \tag{8}$$

$$m_2^j\ddot{u}_2^j + k_2\left(u_2^j - u_1^j\right) = 0 \tag{9}$$

The history of the displacement for the $(j + n)$th unit cell is expressed as:

$$u_\gamma^{(j+n)} = \beta_\gamma e^{i(\boldsymbol{q}x + n\boldsymbol{q}L - \omega t)} \tag{10}$$

where β_γ is complex wave amplitude, ω is angular frequency, and γ= 1 and 2. Substituting Eq. (10) in Eqs. (8) and (9), then the determinant of the coefficient matrix gives the dispersion equation which can be obtained as

$$e^{2i(qx-\omega t)}\begin{bmatrix} 2kk_2 - \left(2km_2^j + k_2\left(m_1^j + m_2^j\right)\right)\omega^2 + m_1^j m_2^j\omega^4 \\ -2k\left(k_2 - m_2^j\omega^2\right)\cosh\left(iqL\right) \end{bmatrix} \tag{11}$$

From the equation above, Fig. 4 shows the dispersion curve for $m_2/m_1 = 25$, $k_2/k = 0.1$, and $\omega_0^2 = k_2/m_2 = 20\,rad/s$. The lower branch of the dispersion curve as shown in Fig 4 is frequently called the acoustical branch. This name comes from the fact that the frequency in it are of the same order of magnitude as acoustical or supersonic vibrations. The upper branch is frequently called the optical branch, because of the fact that its frequencies are of the order of magnitude of infrared frequency. The implication of the dispersion curve is that no frequency can pass within the band gap around 1Hz and 5 Hz. The practical implication of this will be shown in session 4.

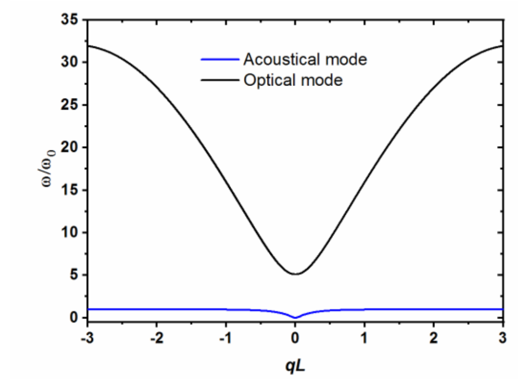

Fig 4. Nondimensionalized dispersion curve for the mass-in-mass lattice model

Then, let us consider an effective monatomic lattice system in Fig 3(b) with only effective masses M_{eff} connected by springs with spring constant k. We write the equation of motion for the effective mass at lattice point j as [27]

$$m_{eff}\ddot{u}^j + k\left(2u^j - u^{j+1} - u^{j-1}\right) = 0 \tag{12}$$

For a harmonic wave, the displacement history of the lattice point $j+n$ have the form

$$u^{(j+n)} = \beta e^{i(\boldsymbol{q}x + n\boldsymbol{q}L - \omega t)} \tag{13}$$

Substituting (13) into (12), and looking for a nontrivial solution we obtain the dispersion equation:

$$\omega^2 = \frac{2k_1\left(1 - \cosh\left(i\boldsymbol{q}L\right)\right)}{m_{eff}} \tag{14}$$

If the effective monatomic lattice system is equivalent to the original mass-in-mass lattice system, then the dispersion curves of the two systems must be identical. In other words, in equation (14) the effective mass M_{eff} must be selected so that the relation between ω and $\boldsymbol{q}$L is same as that for the original mass-in-mass system. Substituting equation (14) in (11), the effective mass parameter is obtained as

$$m_{eff} = M_1 + \frac{m_2\omega_0^2}{\omega_0^2 - \omega^2} \tag{15}$$

which is equivalent to Eq. (5)

3. Concrete structure with negative effective mass

In this section, wave propagation of the proposed metaconcrete structure is numerically studied. The material properties of the structure are detailed in Table 1. The geometry of the unit cell; the matrix is a square shape of length L is 100mm, the radius of the coating is 33mm, and the radius of the core is 20mm. For this numerical investigation, the outer radius of the core remains at 20 mm (maximum size of coarse aggregate used in construction industry) for the two aggregate inclusion cases studied. The unit cell is modelled in COMSOL and the material is selected for different layers. Solid model is used and periodic condition is set to all the sides using Floquent periodicity. Eigenfrequency study is performed to get the dispersion curve.

Table 1. Material constants used in the simulations

Material	ρ(kg/m³)	*E* (GPa)	v
Mortar	2,500	30	0.20
Lead	11,400	16	0.44
Rubber	900	0.01	0.49
Nylon	1150	1.0	0.40

3.1 The use of aggregate as the core in resonant frequency

We can use the one–dimensional spring–mass model in Section 2 to form a simplified model of a metaconcrete for an infinite periodic system. The unit cell used for the periodic condition in COMSOL Multiphysics is shown in Figure 5 (a) .This will allow us to investigate the formation of band gap type behaviour and to check the internal behaviour of the aggregate in term of the mode shapes. First, to explore the band gap behaviour, band diagram of the structure with inclusion of aggregate as the core is built where the wave frequency is plotted against the normalized wave number k. Three models are compared in this section; unit cell with steel core with rubber as coating, unit cell with steel core with nylon as coating and a control experiment is carried out with a control sample that has the same configuration, but without aggregate inclusion and coating. From the comparison of Fig.5, it can be immediately revealed that the metamaterial inclusion has significant effects on the wave behaviour of the structure, especially at the low-frequency range. The most remarkable observation is that of the band gap for the resonant in Fig 5 (b) and (c). The coating with softer material produced a band gap within frequency range of 0.95-1.2 kHz whereas for nylon coating we have 4.6-6.3 kHz. It is known that increasing the mass density of the core will tend to shift the band gap zone toward lower frequency [4, 25]. These results reveal that for rubber coating, elastic waves will not pass in the frequency range 0.9-12kHz whereas for harder coating of nylon no wave can pass in the range 4.6-6.3 kHz. This is contrast to the concrete without any inclusion as shown in Fig. 5 (d). In Fig.5 (d), no band gap is observed in the frequency up to 1000 kHz.

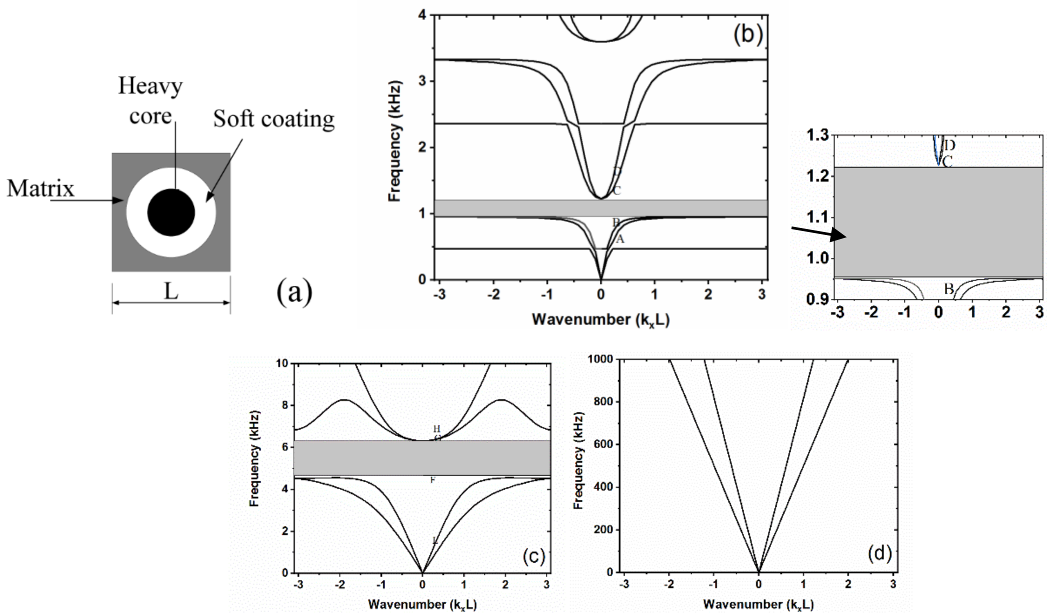

Fig 5 (a) Cross section of a coated lead that forms the basic structure unit (b) dispersion curve for metaconcrete with steel inclusion with rubber soft coating; (c) dispersion curve for metaconcrete with steel inclusion with nylon soft coating; (d) dispersion curve for metaconcrete without inclusion. Where A, B, C, D, and E, F, G and H correspond to normalized wavenumber $k_x L = 0.314$ for (b) and (c) respectively

3.2 Vibration Mode Shapes

To further illustrate this phenomenon, vibration modes of the metaconcrete with aggregate resonant with rubber and nylon cases from the FE simulation are demonstrated in Fig. 6. The internal working of the resonant aggregate is seen to contrast in acoustic and in optic region for the rubber coating material. The modal displacements of the second and third bands represented by A and B show the activation of the aggregate inclusion movement within the matrix. This is prior to the stop band where there will be complete wave attenuation. After the stop band the soft coating tends to dominate the maximum displacement in the matrix. In addition at the point, the displacement of the core shift towards zero displacement.

When we have soft material as coating it makes the core to oscillate rapidly around the resonant. For a more stiff coating as we have in nylon, this represents a stiffer spring connecting the core and the matrix, hence slow movement of the core with respect to the matrix even around the resonance frequency of the system. This resulted in having the band gap at a higher frequency than the rubber coating. Therefore, in order to achieve lower band gap for the same core material, soft spring/material is preferable to be used.

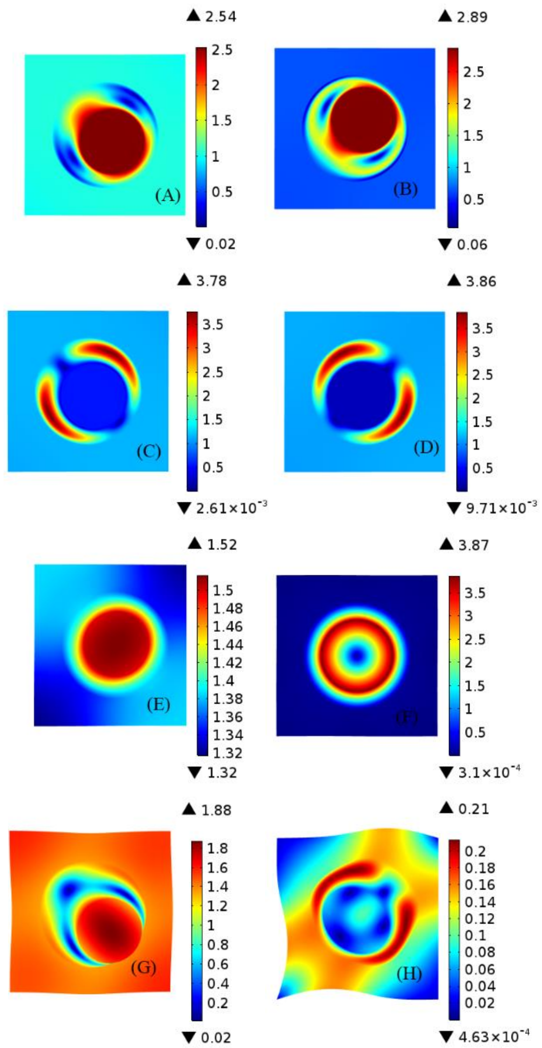

Fig 6. Modes of the four branches correspondent to normalized wavenumber $k_x L = 0.314$ for Fig 5 (b) and (c).

4. Computation of wave transmission from metaconcrete slab models

To further characterize the unique propagation properties of elastic waves in this metaconcrete made of aggregate resonators, we conducted displacement transmission on one-dimensional chained sample as shown in Fig 7. Theoretical analyses as indicated in session 3 revealed that metaconcrete containing resonant aggregates can trap and prevent the transmission of propagating waves, particularly at or near the natural frequency of the inclusion. Therefore, we investigate the same periodic arrangement of the unit cell under prescribed displacement. The 21 unit cell is arranged in a wave guide and prescribed displacement of 1m is assigned in x direction. The resulting waves in the wave guide are then observed at different frequencies.

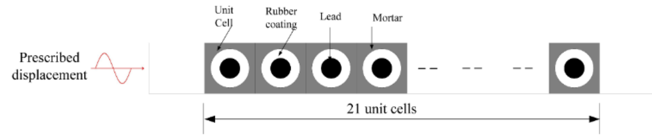

Fig. 7. Solid model of metaconcrete with locally resonant aggregates

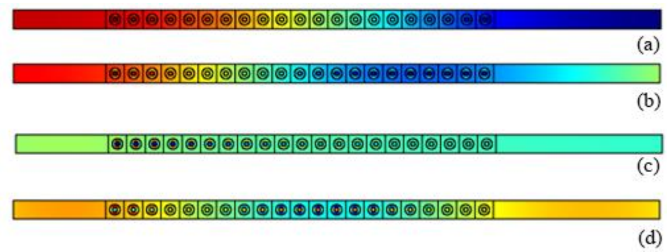

Fig. 8. Wave propagation in metaconcrete. (a) 740 Hz (b) 860 Hz (c) 1100 Hz, and (d) 2000 Hz.

As illustrated in Fig. 8, for frequencies below and above the stop band, there is wave propagation whereas, within the band gap, no wave can pass. For example, in Fig 8 (a) and (b) the metaconcrete for frequency of 740 Hz and 860 Hz allows the passage of waves as can be observed in the displacement plots. Energy is seen propagating within the duct. This is because the frequency is not within the band gap as shown in Fig. 5 (b). For frequency within the band gap such as illustrated in Fig 8 (c), the prescribed displacement in the incident side is negated at the transmitting side after the metaconcrete. This is because the resonating mass within the matrix eliminated the propagating waves. However, for practical use, the number of unit cell needed to attenuate the transmitting wave energy should be adequately determined. With this new metaconcrete structures, dynamic failure of materials which have been the burning issue of concern in civil engineering structures, and defense projects can be reduced [28–30]. Hence metaconcrete using aggregate resonant can be used to target the frequency of wave propagation of stress wave in concrete structures.

5. Conclusion

In the present study, we have highlighted the theory of a mass in a mass spring unit system as suitable for the explanation of the basic concept of concrete with negative effective (dynamic) mass in metaconcrete. The metaconcrete inclusion, which is responsible for the local resonance, composes of a heavy core and a soft coating layer. The inclusion is achieved by replacing the aggregate in the concrete matrix with the heavy core. The resonant frequency of the aggregate provides a means to achieve band gap which prevents elastic waves to propagate within frequency range 0.95-1.2 kHz and 4.6-6.3 kHz for rubber and nylon coating, respectively. Furthermore, the same aggregate configuration is then modelled in periodic arrangement a waveguide using COMSOL, which allowed blocking of described displacement at reflecting boundary for frequency within the band gap. The proposed metaconcrete could have many promising applications in the construction industry where dynamic loadings are paramount.

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