Advances in Concrete Construction, *Vol. 13, No. 6 (2022) 423-431*
https://doi.org/10.12989/acc.2022.13.6.423

Stress-related energy dissipation and damping model of concrete considering moisture content

Baodong Liu*[1], Pengyuan Zhang[2a] and Wenjuan Lyu[3b]

[1]*School of Civil Engineering, Beijing Jiaotong University, No.3 Shangyuancun, Haidian District, Beijing, China*
[2]*China Construction Third Bureau Technology Innovation Development Co., Ltd., Wuhan 430000, Hubei, China*
[3]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628CN Delft, The Netherlands*

(*Received May 6, 2021, Revised May 17, 2022, Accepted May 24, 2022*)

Abstract. Although the influence of moisture content on the mechanical properties of concrete has been studied for a long time, research related to its influence on the damping and energy dissipation property of concrete structure is still very limited. In this paper, the relationship between damping property and moisture content of concrete using cyclic uniaxial compression is firstly presented, and the mechanism of the influence of moisture content on concrete damping and energy dissipation capacity is analyzed. Based on the experimental research, moisture-related damping and energy dissipation model is proposed. Results show that the dissipated energy of concrete and loss factor increase as the moisture content increasing. The energy dissipation coefficient reflecting the influence of stress level of concrete under cyclic load, decreases first and then increases as the moisture content increasing. The mechanism of moisture-related energy dissipation behavior can be divided into the reactive force of water, the development of the internal micro cracks and the pore water pressure. Finally, the proposed moisture-related damping and energy dissipation model are verified.

Keywords: concrete; energy dissipation; experimental; material damping; moisture content

1. Introduction

Many hydraulic concrete structures were served in under-water environment for years, the moisture content of which is different from the common used concrete structures in inland area. The change of moisture content of hydraulic structures has a great influence on static mechanical characteristics, such as concrete strength (Bartlett and MacGregor 1994, Ross *et al.* 1996, Shen and Xu 2019), modulus of elasticity (Liu *et al.* 2014) and cracking process (Rossi and Boulay 1990, Rossi 1991). Considering the fact that dynamic properties of concrete structures are related to static mechanical characteristics (Rossi *et al*. 1992, Chopra 2012), the change of moisture content has a great influence on energy dissipation behavior under dynamic load.

Damping is an important dynamic property indicating the energy dissipation capacity of a structure during vibration (Chopra 2012). The dissipated energy of concrete structure is greatly influenced by damping and increases with the increase of the damping. Considering the dissipated energy of concrete structure is influenced by many factors, material damping of concrete is an indicator which takes no account of structural factors. Research on the influence of moisture content on material damping behavior is of great importance from the optimization perspective of concrete mix design or working conditions. Firstly, some researchers found that the damping and energy dissipation capacity of concrete is increased by incorporating silica powder or viscoelastic additives, such as styrene-butadiene latex, rubber power, recycled tires and calcium carbonate particles (Bowland 2011). Also, the damping and energy dissipation property is influenced by the aggregates used in concrete mix, such as recycled aggregate (Liang *et al.* 2015, Liang *et al.* 2016, Li *et al.* 2018, Li and Xiao 2021).

Except for material conditions, the energy dissipation property of concrete is apparently influenced by load conditions, such as load frequency, load level. Wang and Li (2013) studied the influence of cyclic stress range, concrete strength and steel ratio on the energy dissipation properties of FRP columns. Mei *et al.* (2018) studied the relationship between concrete damping and stress amplitude of concrete with a viscoelastic model. Wang *et al.* (2019) proposed a nonlinear damping and responses for recycled aggregate concrete frame under earthquake loading with shaking table tests. Zhang *et al.* (2020) established a nonlinear damping model with different load indexes with cyclic uniaxial compression test, such as stress range, strain range and stress level. Researchers also studied the loading rate-dependent damping properties from viscoelastic perspective (Mei and Wang 2020, Zhang *et al.* 2020).

Many studies have shown that moisture content has a significant impact on the microstructure and mechanical properties of concrete (Davis and Troxell 1929, Johnston

*Corresponding author, Professor
E-mail: baodongliu@vip.sina.com
[a]Ph.D.
E-mail: impyzhang@gmail.com
[a]Ph.D.
E-mail: wenjuanlv1990@outlook.com

ISSN: 2287-5301 (Print), 2287-531X (Online)

1967, Shoukry 2011, Liu *et al.* 2014), which will change the dynamic characteristics and the seismic performance of concrete structures during the vibration. However, it can be seen that most of the researches on damping of concrete are mainly focus on the structural or material damping, which did not take into account the effect of working moisture content. Limit research related to the influence of moisture content on dynamic mechanical properties of concrete is available. Swamy and Rigby (1971) studied the effect of drying on damping property of cementitious materials and established the damping equations in both the saturated and dry state. But the research conducted by Swamy and Rigby failed to consider the damping behavior under different moisture contents and corresponding analytical model was not considered. Rashetnia *et al.* (2020) conducted half-power bandwidth test with different moisture conditioning for asphalt concrete. But the research was focus on natural frequency and dynamic elastic modulus, which failed to analyze the damping property. It can be seen that research related to the influence of moisture content on concrete damping and energy dissipation properties is still need further investigation.

In this research, the effect of moisture content on damping and energy dissipation behavior of concrete is analyzed. Firstly, different moisture contents were considered and cyclic uniaxial compression test was conducted to study energy dissipation behavior considering different moisture contents. Then based on hysteretic loop analysis under cyclic compression, moisture-related loss factor and dissipated energy model were established. Furthermore, to consider the influence of cyclic stress level, moisture-related energy dissipation coefficient was investigated. Mechanism of moisture-related damping was also analyzed. Finally, the proposed moisture-related loss factor and energy dissipation model were verified by experimental data in published literature.

2. Materials and experimental program

2.1 Materials and specimen details

The cement used in this experiment was grade 42.5 ordinary Portland Cement which was produced in the Lima cement plant of China. Natural coarse aggregate was limestone with the apparent density of 2660 kg/m^3 and maximum size of 26.5 mm. The fine aggregate was river sand with the fineness modulus of 2.68. Fly ash and JK-05 pumping admixture were also used.

The strength grade of the concrete used in in this experiment reached C30, and the concrete mix was 1:0.57:2.61:3.46:0.03:0.29 (cement: water: fine aggregate: coarse aggregate: JK-05 pumping admixture: fly ash). The specimens were cured under the standard conditions with a temperature of 20±2°C and RH>95%.

2.2 Moisture content and mechanical property

Five moisture contents were considered in cyclic uniaxial compression test, namely C1, C2, C3, C4 and C5, as shown in Table 1. All the specimens were placed into the electric thermostat blast drying box with the temperature of 45°C until the mass no longer changed, which could be considered as oven dry condition and the moisture was 0%. The mass of oven dry specimens was recorded as m_0. The specimens of C2, C3, C4 and C5 were put into a plastic tank for different immersion times. The mass after immersion was recorded as m_1. The moisture content ρ was calculated by $\rho=(m_1-m_0)/m_0$.

Table 1 Moisture content and mechanical property

No.	Mass after oven dry m_0/g	Mass after immersion m_1/g	Moisture content ρ/%	Compressive strength MPa	Modulus of elasticity MPa
C1	7.290	-	0	52.81	25802
C2	7.286	7.337	0.70	40.40	27190
C3	7.323	7.440	1.60	47.30	28974
C4	7.358	7.564	2.80	43.16	31352
C5	7.344	7.603	3.53	40.64	32800

Considering that the material and concrete mix used in this experiment were the same batch as Liu *et al.* (2014), the compressive strength and modulus of elasticity against different moisture contents could be obtained based on the relationships among moisture content, compressive strength and modulus of elasticity given by Liu *et al.* (2014). The results of compressive strength and modulus of elasticity were shown in Table 1.

2.3 Test setup

The electric-hydraulic servo multi-function testing machine was used for cyclic uniaxial compression test with the load capacity of ±500 kN, which is shown in Fig. 1(a)-(b).

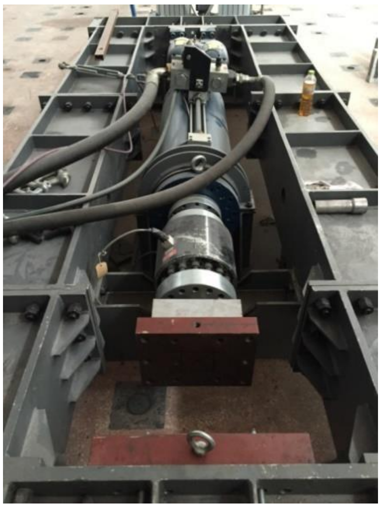
The prism specimens were 100×100×300 mm (Mei *et al.* 2018, Zhang *et al.* 2020). The axial displacement was obtained by laser displacement sensor and strain gages, and the axial force was obtained by the force transducer. The uniaxial compressive force-displacement hysteretic loop could be measured by the axial force and displacement, which could be used for the calculation of material energy dissipation of concrete.

2.4 Loading scheme

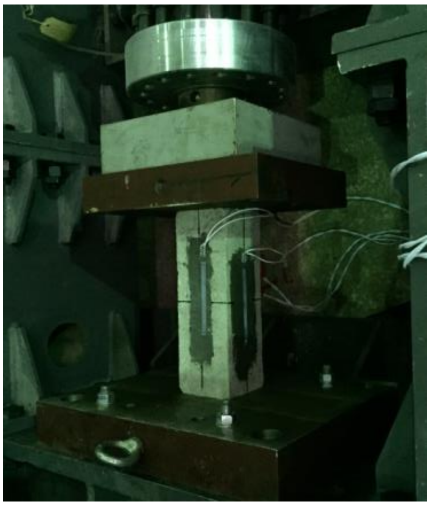
The loading program in this experiment were sinusoidal load with 30 cycles and load circular frequency ω of 1 Hz. As shown in Fig. 2, the sine wave was $F_{output}=F+0.5\Delta F\cdot\sin(\omega t)$ where ω was load circular frequency, F was the mean loading force, and ΔF was the cyclic loading force amplitude.

In order to ensure that the specimens were loaded in the elastic range, the mean loading force F was 100 kN, and the cyclic loading force amplitude ΔF was 150 kN according to the compressive strength with different moisture contents.

3. Experimental results and discussion



(a) Electric-hydraulic servo multi-function testing machine



(b) The prism specimen

Fig. 1 Test setup

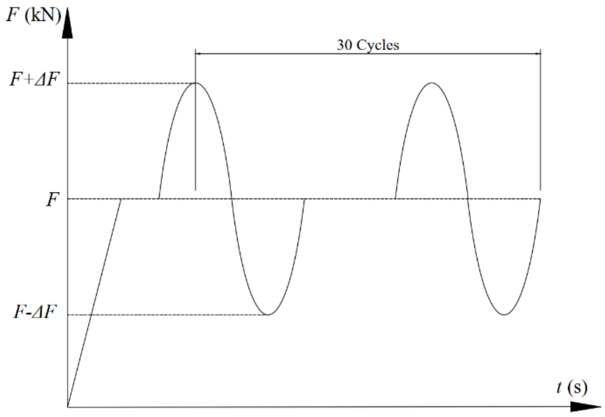
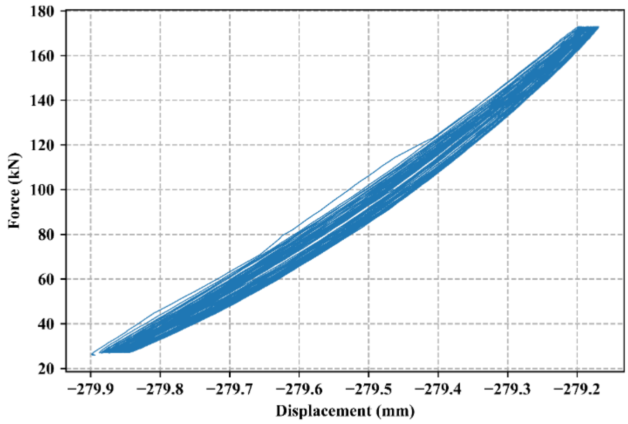
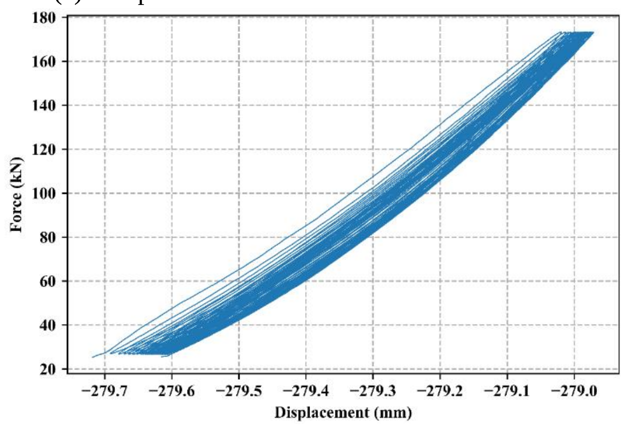


Fig. 2 Loading scheme



(a) C1 specimen with the moisture content of 0%



(b) C3 specimen with the moisture content of 1.60%

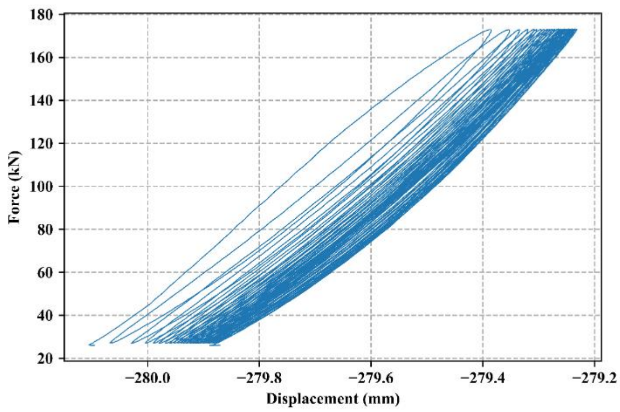
Fig. 3 Experimental hysteretic loops with different moisture contents

3.1 Effect of moisture content on the energy dissipation property

The experimental hysteresis loop of concrete specimens is shown in Fig. 3(a)-(c). With the increase of moisture content, the hysteretic loop of concrete materials tended to be fatter, indicating that the energy dissipation capacity of concrete increased with the increase of moisture content. The residual deformation of the first hysteresis loop of each group of concrete is the largest, and tends to increase with the increasing of moisture content. Obvious fatter effect and residual deformation can be observed in C5 specimen, which has the highest moisture content.

Fig. 4 shows the calculating results of the area of each hysteresis loop by numerical integral method. It can be seen that with the increase of moisture content, the area of first hysteretic loop in each group increased. For the C5 specimen which has the highest moisture content, the area of first loop is twice as much as that of the dry condition. The area of the first ten cycles of C5 specimen is significantly higher than the corresponding hysteresis loop of other moisture contents, which is not distinct in other moisture conditions. The discrepancy of area for each specimen is tend be smaller as the cycle number increases.

Nonlinear regression analysis is used to analyze the mean value and standard deviation of the area of hysteresis loop of each concrete group, as shown in Fig. 5. With the increase of moisture content, the average value and standard deviation of the area of hysteretic loop each group are increased, along with the greater data variation, fatter hysteretic loops and better energy dissipation capacity.



(c) C5 specimen with the moisture content of 3.53%

Fig. 3 Continued

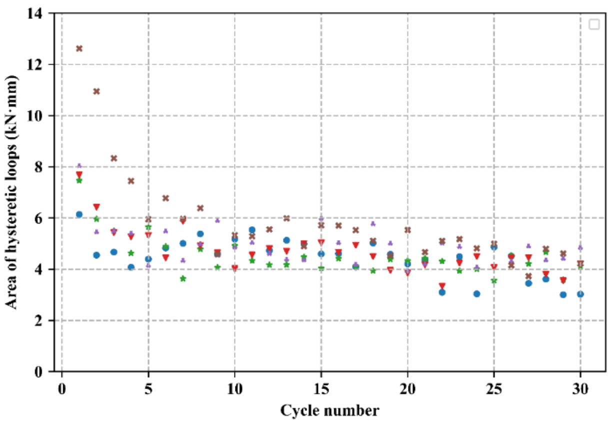


Fig. 4 Area of the hysteretic loops

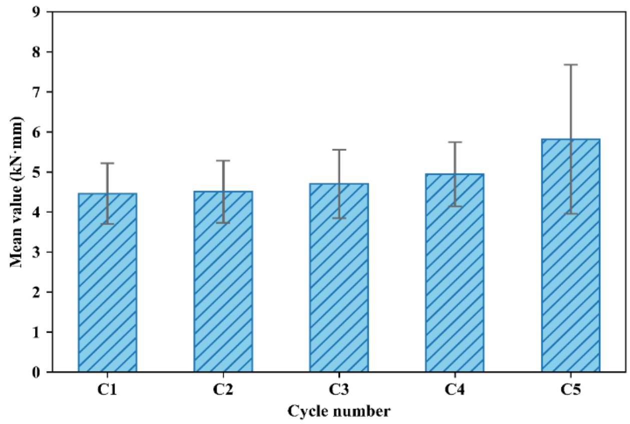


Fig. 5 Mean value and standard deviation of the areas of the hysteretic loops

3.2 Moisture-related loss factor

Fig. 6 shows the stress-strain relationship of concrete under cyclic uniaxial compression. The specific damping capacity, ψ, is defined as the ratio of cyclic dissipated energy ΔU and cyclic strain energy U, which is calculated by

$$\psi = \frac{\Delta U}{U} = \frac{S_{ABCD}}{S_{ACE}/4} \tag{1}$$

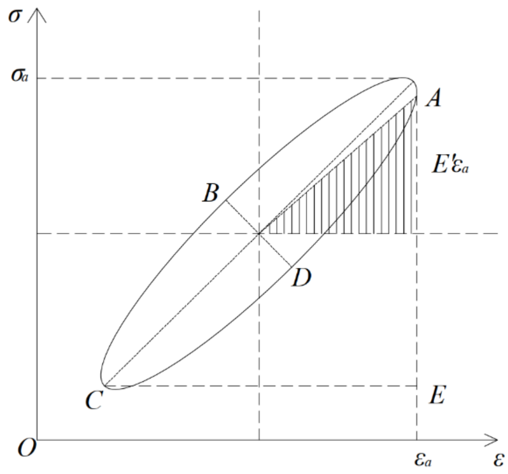


Fig. 6 Diagram of hysteresis loop

Table 2 Loss factor of concrete with different moisture contents

No.	U/mJ	ΔU/mJ	η
C1	133.80	1720.53	0.0495
C2	135.24	1624.95	0.0530
C3	140.85	1624.88	0.0552
C4	148.22	1624.88	0.0581
C5	174.45	1686.94	0.0658

The loss factor η which indicates the damping capacity of concrete is calculated by

$$\eta = \frac{\psi}{2\pi} = \frac{2S_{ABCD}}{\pi S_{ACE}} \tag{2}$$

In this experiment, applied force-displacement hysteretic loop is used instead of stress-strain relationship. The calculation of loss factor takes the following form

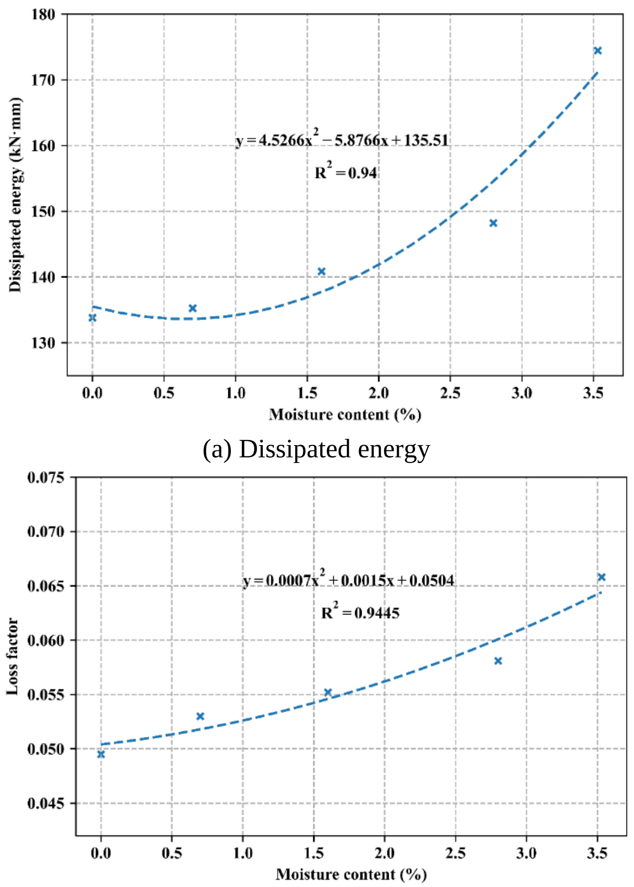
$$\eta = \frac{\psi}{2\pi} = \frac{4S_{ABCD}}{\pi \cdot \Delta F \cdot \Delta v} \tag{3}$$

where ΔF is the cyclic loading force amplitude given in kN and Δv is the cyclic displacement amplitude given in mm.

For the reason that the higher moisture content comes with greater data variation, the cyclic dissipated energy ΔU and cyclic strain energy U are calculated by the areas of hysteresis loops with 30 cycles. The loss factors of concrete with different moisture contents are shown in Table 2.

Fig. 7(a)-(b) indicates the relations between the moisture content and dissipated energy, loss factor, respectively. With the increase of moisture content, the dissipated energy and loss factor of concrete are increased. For dissipated energy, it is slowly increased in the early stage of immersion and relatively fast in the late stage of immersion, and the loss factor is increased with linear relationship. In the range of 0%~3.5% moisture content, the dissipation capacity of concrete materials was increased by 30%, and the loss factor is increased by 33%.

The relations between the moisture content ρ given by % and dissipated energy ΔU given by J, loss factor, respectively, are fitted and take the following regression equation.



(a) Dissipated energy

(b) Loss factor

Fig. 7 Relationship between dissipated energy dissipation property and moisture content

$$\Delta U = 4.5266\rho^2 - 5.8756\rho + 135.51$$
$$R^2 = 0.9400 \tag{4}$$

$$\eta = 0.0007\rho^2 + 0.0015\rho + 0.0504$$
$$R^2 = 0.9445 \tag{5}$$

The dissipated energy in this paper is calculated based on the size of 100×100×300 mm specimen. The energy dissipation per unit volume of the concrete could be obtained by dividing the dissipated energy ΔU by the volume of specimen (0.003m^3). The formula between energy dissipation factor per unit volume $\Delta U'$ given by J and moisture content ρ given by % takes the following form.

$$\Delta U' = 1508.9\rho^2 - 1958.5\rho + 45171$$
$$R^2 = 0.9400 \tag{6}$$

It can be seen that the quadratic polynomial fitting result is of high precision, which can be used for practical calculation. According to the relation curve between moisture content and immersion time given by Liu (2014), the common used saturated moisture content of the concrete specimen used in this experiment is about 4%.

3.3 Moisture-related energy dissipation behavior with different stress levels

The dissipated energy is not only affected by moisture content, but also influenced by applied cyclic load. Lazan (1968) found that there was a nonlinear relationship between the maximum stress amplitude and the energy dissipation per unit volume for different materials, which could be expressed as

$$\Delta W = J\sigma_a^{\ n} \tag{7}$$

where ΔW is the energy dissipated by damping per unit volume of material in one vibration period given by mJ, J is the energy dissipation coefficient which indicated the natural damping characteristic of materials, σ_a is the maximum stress amplitude given by MPa and n is the energy dissipation index. To evaluate the moisture-related energy dissipation behavior under different cyclic load levels, energy dissipation coefficient is analyzed.

Considering a harmonic load condition $\sigma = \sigma_a(\cos\omega t + i\sin\omega t) = \sigma_a e^{i\omega t}$ is subjected to the system. Because of the viscoelastic properties of concrete, the expression of strain can be expressed by $\varepsilon = \varepsilon_a e^{i(\omega t-\varphi)}$, where σ_a is the stress amplitude given in MPa, ε_a is the strain amplitude given in $\mu\varepsilon$, ω is the load frequency, φ is the phase lag.

The dynamic modulus E^* of concrete, which indicates the phase lag between stain and stress, could be expressed as

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_a e^{i\omega t}}{\varepsilon_a e^{i(\omega t-\varphi)}} = \frac{\sigma_a}{\varepsilon_a}\cos\varphi + i\frac{\sigma_a}{\varepsilon_a}\sin\varphi \tag{8}$$

With the definition of the storage modulus E' as $\frac{\sigma_a}{\varepsilon_a}\cos\varphi$ and the loss modulus E'' as $\frac{\sigma_a}{\varepsilon_a}\sin\varphi$, the loss factor of concrete η also can be expressed as

$$\eta = \frac{E''}{E'} \tag{9}$$

Substituting Eq. (9) into Eq. (8), the equation is expressed as

$$E^* = E'(1+i\eta) \tag{10}$$

The relation between σ_a, ε_a and η can be established with the combination of Eqs. (8)-(10), which can be expressed as

$$E = \frac{\sigma_a}{\varepsilon_a} = E'\sqrt{1+\eta^2} \tag{11}$$

where $E = \frac{\sigma_0}{\varepsilon_0}$ is the modulus of elasticity.

The strain energy ΔW with the maximum strain range is

$$W = \frac{1}{2}\times\varepsilon_a\times E'\varepsilon_a = \frac{E'\varepsilon_a^{\ 2}}{2} \tag{12}$$

Substituting Eq. (8) and Eq. (11) into $\eta = \frac{\Delta U}{2\pi U} = \frac{\Delta W}{2\pi W}$, the loss factor with maximum strain range can be expressed as

$$\eta = \frac{J\sigma_a^{\ n}}{\pi E'\varepsilon_a^{\ 2}} \tag{13}$$

Substituting Eq. (11), which indicates the relation between stress range and strain range, into Eq. (13), and considering the modulus of elasticity E instead of storage modulus E', the energy dissipation coefficient J of concrete versus stress range σ_a and strain range ε_a can be calculated as

$$J(\sigma_a)=\frac{\eta}{(1+\eta^2)^{1/2}}\frac{\pi}{E}\sigma_a{}^{2-n} \tag{14}$$

$$J(\varepsilon_a)=\frac{\eta}{(1+\eta^2)^{1/2}}\frac{\pi}{E^{n-1}}\varepsilon_a{}^{2-n} \tag{15}$$

If both strain range ε_a and stress range σ_a are used to express the strain energy ΔW, the strain energy can be expressed as

$$\eta=\frac{JE'(1+\eta^2)}{\pi}\sigma_a{}^{n-2}=\frac{JE'_\sigma}{\pi}\sigma_a{}^{n-2} \tag{16}$$

where E'_a is the storage modulus versus stress range σ_a. Then, the storage modulus versus stress range E'_a and the storage modulus versus strain range E' can be expressed as

$$E'_\sigma = E'(1+\eta^2) \tag{17}$$

The plastic deformation can be ignored in the range of 40% ultimate strength, and considered as elastic material. Considered that the stress range of the test in this paper is in the range of 2.5 MPa and 17.5 MPa, it could be considered that the concrete material is in the elastic stage. The stress range σ_a has little influence on the energy dissipation coefficient J and loss factor η of concrete materials, indicating that the energy dissipation index n can be set as 2.

Substituting the formula given by Liu (2014) which indicates the relationship between elasticity modulus E of concrete and moisture contents and Eq. (6) into Eq. (14), the moisture-related energy dissipation coefficient can be described by the equation as

$$J=\frac{0.0007\rho^2+0.0015\rho+0.0504}{(1+(0.0007\rho^2+0.0015\rho+0.0504)^2)^{1/2}}\frac{\pi}{1982.3\rho+25802} \tag{18}$$

Fig. 8 shows the energy dissipation coefficient with the moisture content range of 0%-4%. Moisture-related energy dissipation coefficient shows a different tendency from moisture-related dissipated energy. With the increase of moisture content, the energy dissipation coefficient of concrete decreases first and then increases. In the moisture content range of 1%-1.5%, the energy dissipation coefficient of concrete material is firstly decreased, with the minimum value of 5.90 MPa^{-1} at 1.5% moisture content, and then increases to the maximum value of 6.27 MPa^{-1} in the range of 1.5%-4% moisture content. From Eqs. (14)-(15), the energy dissipation coefficient and the modulus of elasticity has a different relationship.

At the beginning of immersion, the water has not penetrated completely into the concrete, the modulus of elasticity of concrete is increased, leading to the decreasing of energy dissipation coefficient. When water has fully penetrated into the concrete, although it is still in the elastic stage, the interior micro-cracks of concrete gradually expanded. The friction between interfacial micro-cracks is the main factor, leading to the increase of the energy dissipation coefficient under the cyclic load.

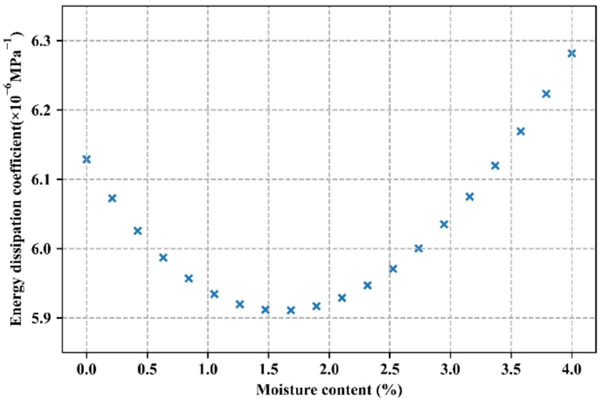


Fig. 8 Relationship between energy dissipation coefficient and moisture content

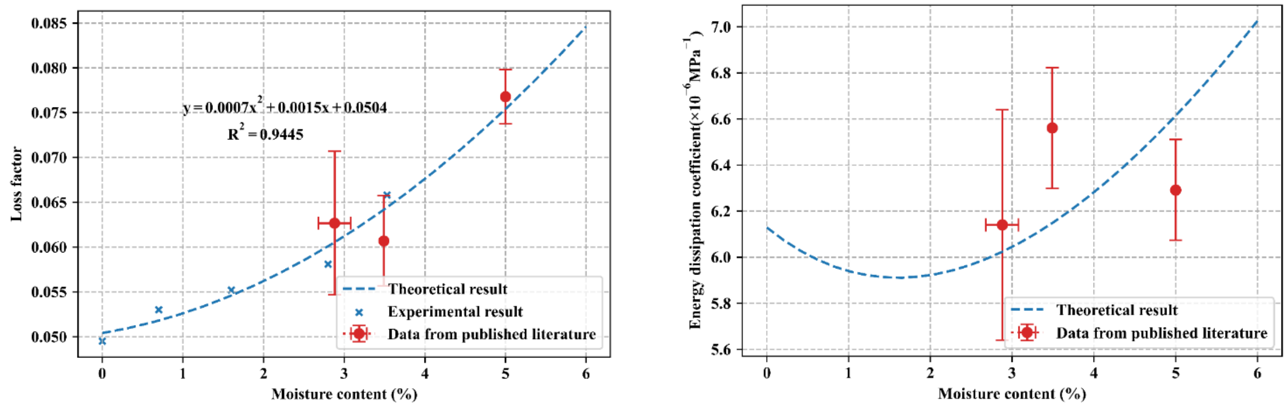
3.4 Mechanism of moisture-related damping property of concrete

Moisture content has a significant effect on damping energy dissipation of concrete materials. Concrete is a kind of multiphase nonhomogeneous mixture, consisting with solid particles, hardened cement pastes and initial defects, the mechanical properties of which are highly influenced by environmental conditions. The solid particles include coarse aggregates, the non-hydrated cement paste and contaminant. The hardened cement pastes include fine aggregates, cement, water and interfacial transition zones (ITZ) after hydration reaction.

Therefore, as a composite material, concrete has a high variation of mechanical properties, complex mechanism of vibration damping energy dissipation. The damping and energy dissipation behavior is affected by different influencing factors, including mix composition, load condition and working condition. The change of which can be contributed to the change of internal microstructures of concrete (Chung 2003, Gu *et al.* 2007).

When vibration load is applied on coarse aggregate and mortar, the transmission of vibration energy in cement matrix encounters coarse aggregate and pore structures, which leads to plastic slip or dislocation motion at interfacial transition zones. As for the saturated concrete, water is penetrated into the pore structure, giving a reactive force to coarse aggregate and cement paste when encounters the dislocation or slippage. This phenomenon will produce an internal material damping effect to dissipate part of the vibration energy.

Micro-cracks and pore structures are existed in concrete before the load is applied. The ITZ structures consisting with micro-cracks, pore structures and calcium hydroxide crystals, are located between coarse aggregate and cement stone, which play an important role in the stress-strain relationship of concrete. Moisture gradient is developed in the internal of concrete by the change of environmental



(a) Moisture-related loss factor (b) Moisture-related energy dissipation coefficient

Fig. 9 Validation of moisture-related damping and energy dissipation behavior

moisture content. The moisture gradient will affect the speed of the cement hydration and moisture evaporation, producing a corresponding stress field and deformation field, accelerating the development of the internal micro-cracks and leading to the formation of macroscopic crack on the concrete surface. The closure, expansion, slip and friction between the matrix and ITZ structures will cause energy dissipation. One the other hand, many studies have shown that the strength of concrete decreases with the increase of moisture content, for the reason that the pore water pressure in the concrete reduces the friction resistance of concrete cracking and accelerates the expansion of the micro cracks and concrete damage (Wang and Li 2007). Sliding among the interface during vibration causes greater the energy dissipation.

In addition, the free water in concrete moves after being vibrated and causes friction with the solid phase of matrix to dissipate part of vibration energy. At the same time, as a viscoelastic material, gel water is also conducive to improve the damping capacity of concrete, and the adsorbed water in C-S-H gel in saturated cement paste can also increase the energy dissipation of the material.

3.5 Validation of moisture-related damping and energy dissipation behavior

Although the published literature related to both moisture content and cyclic uniaxial compression behavior is limited, several cyclic uniaxial test results have been considered to compare with proposed moisture-related damping and energy dissipation model for validation purpose (Suaris *et al.* 1990, Bahn and Hsu 1998, Sima *et al.* 2008, Sadowski and Pietras 2014, Breccolotti *et al.* 2015, Neuenschwander *et al.* 2016, Hu *et al.* 2018). The loss factor and energy dissipation coefficient can be obtained with the aforementioned method. Except for the studies conducted by Sadowski and Pietras (2014), and Neuenschwander *et al.* (2016), the experiments used for validation purpose were conducted in laboratory environment and the test specimens were in air dry condition. Considering the relative humidity of air dry specimens is ranging from 0.64-0.76 (Zhang *et al.* 2016) and the maximum moisture content of concrete specimen is usually 4.13% (Tan *et al.* 2019), the moisture content of air dry specimens is set as 2.88%±0.25%. it’s worth noting that higher maximum moisture content is also observed by Sadowski and Pietras (2014). Considering the limited number of related studies, higher moisture content is also considered in the validation process. The validation result of moisture-related damping and energy dissipation behavior is shown in Fig. 9.

It can be seen that the present moisture-related damping model shows satisfactory agreement with the published experimental results. When it comes to energy dissipation coefficient, higher variation is observed with different moisture contents. The reason is that energy dissipation capacity of concrete is not only depended on moisture content, but also modulus of elasticity, which will increase the uncertainty of the results.

4. Conclusions

In this research, the moisture-related loss factor and energy dissipation factor coefficient model has been established based on experimental research and Lazan’s stress-related damping theory. The following conclusions from the executed research work can be summarized as follows:

- The fatter the hysteretic loop of cyclic uniaxial compression is with the increase of moisture content, indicating the increase of energy dissipation capacity of concrete.
- Quadratic polynomial function relation is found between the loss factor of concrete and the moisture content, which can be potentially used in the energy dissipation calculation of actual structure.
- The damping property is not only related to the moisture content, but also related to the cyclic stress level.
- The moisture-related material dissipation coefficient formula is obtained based on the Lazan’s theory and the complex damping theory, which decreases first and then increases with the increase of moisture content.
- The mechanism of the influence of moisture content on the damping energy dissipation can be divided into

the reactive force of water to coarse aggregate and cement paste when encounters the dislocation or slippage, the development of the internal micro cracks caused by the moisture gradient and the pore water pressure, and the friction between free water and solid matrix, and the viscoelasticity of gel water.

Acknowledgments

The research described in this paper was financially supported by the National Science Foundation of China (Grant No. 51278031).

References

Bahn, B.Y. and Hsu, C.T.T. (1998), "Stress-strain behavior of concrete under cyclic loading", *ACI Mater. J.*, **95**, 178-193.

Bartlett, F.M. and MacGregor, J.G. (1994), "Effect of moisture condition on concrete core strengths", *ACI Mater. J.*, **91**(3), 227-236.

Bowland, A.G. (2011), "Comparison and analysis of the strength, stiffness, and damping characteristics of concrete with rubber, latex, and carbonate additives", Ph.D. Dissertation, Virginia Tech., Blacksburg, USA.

Breccolotti, M., Bonfigli, M.F., D'Alessandro, A. and Materazzi, A.L. (2015), "Constitutive modeling of plain concrete subjected to cyclic uniaxial compressive loading", *Constr. Build. Mater.*, **94**, 172-180. https://doi.org/10.1016/j.conbuildmat.2015.06.067.

Chopra, A.K. (2012), *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, Prentice Hall, Upper Saddle River, USA.

Chung, D.D.L. (2003), "Structural composite materials tailored for damping", *J. Alloy. Compd.*, **355**(1-2), 216-223. https://doi.org/10.1016/s0925-8388(03)00233-0.

Davis, R. and Troxell, G. (1929), "Modulus of elasticity and Poisson's ratio for concrete and the influence of age and other factors upon these values", *Proc. ASTM*, 678-710.

Gu, J., Wu, G. and Zhang, Q. (2007), "Effect of porosity on the damping properties of modified epoxy composites filled with fly ash", *Scr. Mater.*, **57**(6), 529-532. https://doi.org/10.1016/j.scriptamat.2007.05.019.

Hu, X., Lu, Q., Xu, Z., Zhang, W. and Cheng, S. (2018), "Compressive stress-strain relation of recycled aggregate concrete under cyclic loading", *Constr. Build. Mater.*, **193**, 72-83. https://doi.org/10.1016/j.conbuildmat.2018.10.137.

Johnston, C.D. (1967), "Concrete and its constituent materials in uniaxial tension and compression", Ph.D. Dissertation, Queen's Univ. of Belfast, Belfast, UK.

Lazan, B.J. (1968), *Damping of Materials and Members in Structure Mechanics*, Pergamon Press, London, UK.

Li, T. and Xiao, J. (2021), "The damping property of damaged recycled aggregate concrete after loading", *J. Build. Mater. Eng.*, **35**, 102096. https://doi.org/10.1016/j.jobe.2020.102096.

Li, T., Xiao, J., Sui, T., Liang, C. and Li, L. (2018), "Effect of recycled coarse aggregate to damping variation of concrete", *Constr. Build. Mater.*, **178**, 445-452. https://doi.org/10.1016/j.conbuildmat.2018.05.161.

Liang, C., Liu, T., Xiao, J., Zou, D. and Yang, Q. (2015), "Effect of stress amplitude on the damping of recycled aggregate concrete", *Mater.*, **8**(8), 5298. https://doi.org/10.3390/ma8085242.

Liang, C., Liu, T., Xiao, J., Zou, D. and Yang, Q. (2016), "The damping property of recycled aggregate concrete", *Constr. Build. Mater.*, **102**, 834-842. https://doi.org/10.1016/j.conbuildmat.2015.11.026.

Liu, B.D., Lv, W.J., Li, L. and Li, P.F. (2014), "Effect of moisture content on static compressive elasticity modulus of concrete", *Constr. Build. Mater.*, **69**, 133-142. https://doi.org/10.1016/j.conbuildmat.2014.06.094.

Mei, S. and Wang, Y. (2020), "Viscoelasticity: A new perspective on correlation between concrete creep and damping", *Constr. Build. Mater.*, **265**, 120557. https://doi.org/10.1016/j.conbuildmat.2020.120557.

Mei, S., Su, L., Li, P. and Wang, Y. (2018), "Material damping of concrete under cyclic axial compression", *J. Mater. Civil Eng.*, **30**(3), 04017295. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002146.

Neuenschwander, M., Knobloch, M. and Fontana, M. (2016), "Suitability of the damage-plasticity modelling concept for concrete at elevated temperatures: Experimental validation with uniaxial cyclic compression tests", *Cement Concrete Res.*, **79**, 57-75. https://doi.org/10.1016/j.cemconres.2015.07.013.

Rashetnia, R., Kusam, A., Yadav, S., Pour-Ghaz, M. and Tayebali, A. (2020), "Quantifying moisture damage in asphalt concrete using axisymmetric flexural vibration technique", *Int. J. Pavement Eng.*, **23**(3), 523-535. https://doi.org/10.1080/10298436.2020.1757671.

Ross, C.A., Jerome, D.M., Tedesco, J.W. and Hughes, M.L. (1996), "Moisture and strain rate effects on concrete strength", *ACI Mater. J.*, **93**(3), 293-300.

Rossi, P. (1991), "Influence of cracking in the presence of free water on the mechanical behaviour of concrete", *Mag. Concrete Res.*, **43**(154), 53-57. https://doi.org/10.1680/macr.1991.43.154.53.

Rossi, P. and Boulay, C. (1990), "Influence of free water in concrete on the cracking process", *Mag. Concrete Res.*, **42**(152), 143-146. https://doi.org/10.1680/macr.1990.42.152.143.

Rossi, P., van Mier, J.G.M., Boulay, C. and Le Maou, F. (1992), "The dynamic behaviour of concrete: influence of free water", *Mater. Struct.*, **25**(9), 509-514. https://doi.org/10.1007/bf02472446.

Sadowski, T. and Pietras, D. (2014), "Description of degradation process of rubberized lean concrete", *Solid State Phenomena*, **216**, 67-72. https://doi.org/10.4028/www.scientific.net/SSP.216.67.

Shen, J. and Xu, Q. (2019), "Effect of moisture content and porosity on compressive strength of concrete during drying at 105°C", *Constr. Build. Mater.*, **195**, 19-27. https://doi.org/10.1016/j.conbuildmat.2018.11.046.

Shoukry, S.N., William, G.W., Downie, B. and Riad, M.Y. (2011), "Effect of moisture and temperature on the mechanical properties of concrete", *Constr. Build. Mater.*, **25**(2), 688-696. https://doi.org/10.1016/j.conbuildmat.2010.07.020.

Sima, J.F., Roca, P. and Molins, C. (2008), "Cyclic constitutive model for concrete", *Eng. Struct.*, **30**(3), 695-706. https://doi.org/10.1016/j.engstruct.2007.05.005.

Suaris, W., Ouyang, C. and Fernando, V.M. (1990), "Damage model for cyclic loading of concrete", *J. Eng. Mech.*, **116**(5), 1020-1035. https://doi.org/10.1061/(asce)0733-9399(1990)116:5(1020).

Swamy, N. and Rigby, G. (1971), "Dynamic properties of hardened paste, mortar and concrete", *Matériaux et Constr.*, **4**(1), 13-40. https://doi.org/10.1007/bf02473927.

Tan, C., Li, Z., Gao, Y., Han, J., Han, J. and Du, X. (2019), "Study on free absorption of concrete with different strength grades and sizes", *Concrete*, **11**, 34-38.

Wang, C., Xiao, J., Wang, C. and Zhang, C. (2019), "Nonlinear damping and nonlinear responses of recycled aggregate concrete frames under earthquake loading", *Eng. Struct.*, **201**, 109575. https://doi.org/10.1016/j.engstruct.2019.109575.

Wang, H.L. and Li, Q.B. (2007), "Meso-mechanism of effects of free water on mechanical properties of concrete under confined compression", *J. Tsinghua Univ. (Sci. and Technol.)*, **47**(9), 1443-1446.

Wang, Y. and Li, X. (2013), "Non-linear damping of FRP-confined damaged reinforced concrete columns", *Eng. Struct.*, **57**, 289-295. https://doi.org/10.1016/j.engstruct.2013.09.027.
Zhang, J., Wang, J. and Gao, Y. (2016), "Moisture movement in early-age concrete under cement hydration and environmental drying", *Mag. Concrete Res.*, **68**(8), 391-408. https://doi.org/10.1680/jmacr.15.00293.
Zhang, P., Wang, Y., Liu, B., Guo, K. and Xiao, J. (2020), "Rate-dependent damping properties of recycled aggregate concrete from creep perspective", *Constr. Build. Mater.*, **273**, 121691. https://doi.org/10.1016/j.conbuildmat.2020.121691.
Zhang, P., Wang, Y., Mei, S., Liu, B. and Xiao, J. (2020), "Nonlinear damping properties of recycled aggregate concrete short columns under cyclic uniaxial compression", *Constr. Build. Mater.*, **246**, 118445. https://doi.org/10.1016/j.conbuildmat.2020.118445.

CC