Water Content Diagnostics of Concrete Using Nonlinear Acoustics Means

Dao ZHOU [1], Xiaozhou LIU [1*], Xiufen GONG [1], Li MA [2]
[1]Key Laboratory of Modern Acoustics, Ministry of Education, Institute of Acoustics, Nanjing University, Nanjing, 210093, China

Phone: +86-25-83594503, Fax: +86-25-83315557；E-mail: dugozhou@gmail.com, xzliu@nju.edu.cn, zligong@nju.edu.cn
[2]Institute of Acoustics, Chinese of Academy of China, 100080, China
E-mail: mary1968@tom.com

Abstract

It is known that water or moisture affects the concrete strength seriously. In this paper, the concrete strength is evaluated from the relationship between water content and the acoustic nonlinearity parameter. To measure the influence of water content, a test piece was put in an oven to change the amount of water. Acoustical parameters were measured while one kilogram of water was vaporized until the weight of the concrete was no longer changed. All results were measured at the first natural frequencies of the concrete rod with one acoustically rigid boundary and one acoustically compliant boundary. The results of measurements were made on nonlinear parameters γ_1 and γ_2 as a function of the water content in concrete. The result of $\gamma_1 \neq \gamma_2$ reflects the asymmetry of the compressive and expansion processes, and the phenomena of γ_1 and γ_2 changing reversely with water content also proved the difference of these two processes. Moreover, nonlinear parameter and frequency shift are more sensitive to the damage of the concrete than the linear parameters obtained by the traditional acoustics methods. So, this method based on nonlinear acoustics maybe provides a better means of the Non Destructive Testing (NDT) of concrete.

Keywords: Concrete; NDT; nonlinear parameters

1. Introduction

[*] Project supported by the by the National Natural Science Foundation of China (No.10674066) and State Key Laboratory of Acoustics.
[*] Corresponding author, Email address: xzliu@nju.edu.cn

Concrete, especially Ultra High Performance Concrete (UHPC), is well known to be a complex, multi-scale material[1]. The hardening of concrete caused by the reaction of hydration of the cement is a well study process[2] and there are many papers considering the linear elastic properties of concrete during curing[3, 4]. However, hardened concrete shows strong nonlinear properties[5]. Non-destructive method by nonlinear means is possible to help us detect the strength of concrete.

The strength of concrete is one of the most important characteristics for accessing the quality of concrete. It is known that the concrete strength is governed by its water content[6]. In the current investigation, a test piece with different water content was used to estimate acoustic nonlinearity of concrete. Using this test piece, the changes of the sound propagation velocity, quality factor (Q value), second and third harmonics, and other nonlinear characteristics in accordance with the change of water content were measured. Based on these results, an estimation of concrete water content was discussed.

2. Experimental Procedure

A test piece was constructed to investigate the nonlinear performances dependence on the change of water content in concrete at the first natural frequency of the rod. The natural resonance frequency of a rod with one acoustically rigid boundary and one acoustically compliant boundary can be determined from the condition:

$$F_n = F_1(2n-1), F_1 = c/4L, n = 1, 2, \ldots \quad (1)$$

where L is the length of the rod, c is the longitudinal wave velocity in the rod, the number n refers to the longitudinal mode number of the rod.

The test sample was $8\times5\times5cm^3$ in size. And the weight ratio of cement, sand, and carpolite was 1:2.46:4.19 and 1.8 tons of water was injected in one cubic meter of concrete. We put the concrete sample in water for two weeks until the weight of the sample did not increase at all. The water content α (%) can be obtained from Eq. (2) using their weight at the completion of drying:

$$\alpha = \frac{W_m - W_h}{W_h} \quad (2)$$

where W_m (grams) is the weight at the time of measurement and W_h (grams) is the weight at the time of drying.

After the test concrete sample was entirely saturated, its weight increased from 422 to 454 grams, the sound velocity decreased from 2927 to $2562m/s$ and the density increased from 2400 to $2630Kg/m^2$. So, we can infer that the saturation of the test piece was 7.6%. An oven was used to dry the sample at 70^0C gradually for each measurement. This procedure was repeated until the weight change of the concrete was no longer observed.

Transmitting transducer and the end of concrete sample close to emitting transducer were fixed tightly to experimental bracket. An accelerometer was set above the other end of the sample. Its weight was so small that the corresponding rod boundary was considered acoustically soft. High-temperature coupling agent was used between the transmitter and the sample. During the whole experiment, the relative positions and interface pressure among the transducer, sample and accelerometer should be kept unchangeable.

The accelerometer's receiving sensitivity was $10mv/g$ $(1.02mv/(m/s^2))$ and its -3dB frequency range was from 5 to 100 KHz (352A60, PCB PIEZOTRONICS, ICP, USA). The transmitting transducer was Lead Zirconate Titanate (PZT) transducer (25K-P28F, Shantou Ultrasonic Co., Ltd., China). This ultrasonic transducer emitted a tone-burst signal (duration time was 8 cycles, pulse repetition frequency was 100 Hz) at the first natural frequency (7- 8 KHz). As the experimental results shown, the second harmonics of the transmitter was 35 dB lower than that of the first harmonics when the acoustic power was 1W.

To measure the change of Q value with driving voltage, the emitting voltage of arbitrary waveform generator (Agilent, 33250, Loveland, CO, USA) was increased from 30mv to 300mv at 30mv intervals. In order to compare the change of the first three harmonics of the test sample, power spectrum of the received signal was obtained.

3. Results and Analysis

With the increase in water content, the amplitude of the second harmonics decreases and the third harmonics reflected by those stresses increases gradually (Fig.1.). The decrease of the second harmonics demonstrates the classical nonlinearity becomes weaker with the increase of water content. On the other hand, the increase of the third harmonics reflects that the non-classical nonlinearity becomes stronger. In concrete, the non-classical nonlinearity is so remarkable that the amplitude of the third harmonics increases obviously despite the classical nonlinearity decreases at the same time. Moreover, the third harmonics is even higher than the second harmonic if the water content is larger than 1.3 % (Fig.2.).

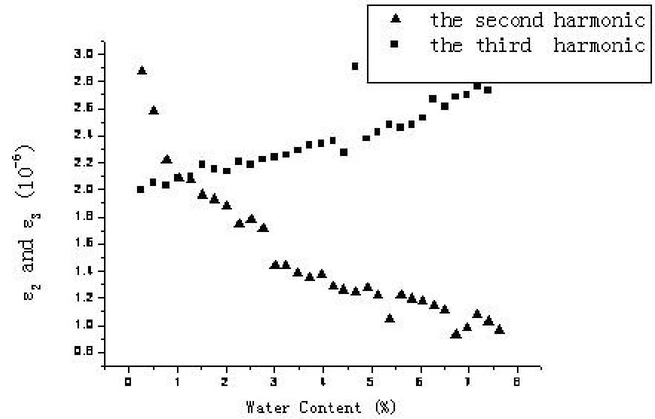
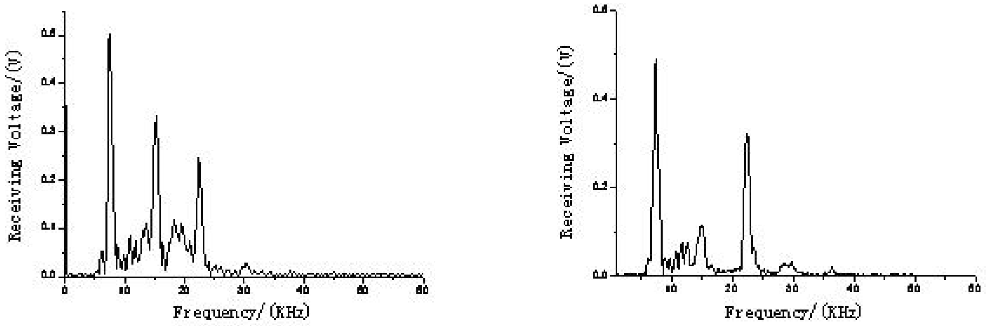


Figure 1. The second and third harmonic frequency strain amplitude in relation to water content



(a) (b)

Figure 2. The amplitude spectrum of the receiving signal at the water content of 0.26% (a) and 7.6% (b)

Resonance frequency shift is also measured at different water content when the driving voltage is 300mv (Fig.3.). The resonance frequency shift increases about five times with the increase of water content. Apparently, the resonance frequency shift is more sensitive than linear parameters such as sound velocity and density. So, we can conclude that the resonance frequency shift could provide a means to value the water content of concrete.

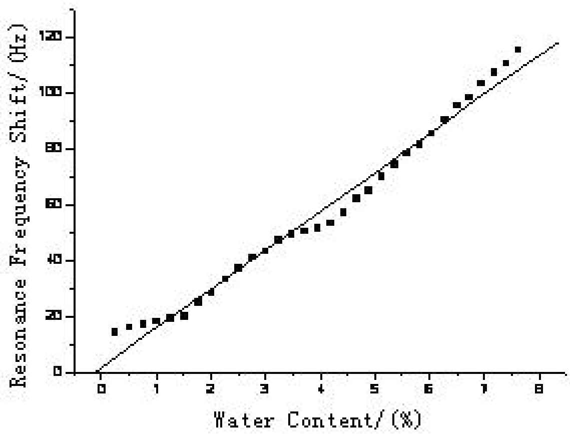


Figure 3. Resonance frequency shift versus water content

From Nazarov's theory[7,8], the nonlinear parameters γ_1 and γ_2 can be calculated from Eq. (3-4):

$$|\gamma_1-\gamma_2| = \frac{16*V_2}{V_0^2 k_n^2 L\sqrt{(\frac{8+3\pi}{24\pi})^2+(\frac{1}{6\pi})^2}} \qquad (3)$$

$$\gamma_1 + \gamma_2 = \frac{45LV_3\sqrt{9u_3^2\omega_n^4 + 4(1+\frac{81(4+\pi)}{70(8+3\pi)})^2\delta_N^2}}{(2n-1)\omega_n V_0^2\sqrt{(\frac{2}{15\pi})^2 + (\frac{1}{30\pi})^2}} \tag{4}$$

where V_0, V_2, V_3 are the displacement amplitude at the free end of the rod at the first, second and third harmonics, respectively. δ_N is the nonlinear frequency shift.

If we suppose $\gamma_1 > \gamma_2$, the value of γ_1 *and* γ_2 can be obtained (Table 1). From the results, the trend of the changes of compressive and expansion processes are reverse with the increase in water content. Therefore, the asymmetry of these two processes becomes weaker. The nonlinear parameter γ_2 increases as much as two times with the increase of water content, which maybe provides a better index to evaluate the water content in concrete.

Table 1
Nonlinear parameters for the test sample

Water Content (%)	0.26	3.00	5.37	7.62
γ_1	$1.54*10^7$	$1.43*10^7$	$1.38*10^7$	$1.34*10^7$
γ_2	$5.66*10^6$	$9.54*10^6$	$1.04*10^7$	$1.14*10^7$

Q value also changes with the diving force (Fig. 4). For the fully saturated concrete sample, Q value increases from 6.1 to 8.5 if the diving voltage increases ten times.

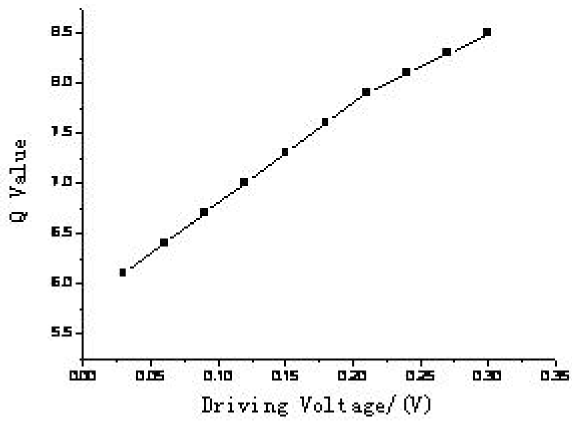


Figure 4. Q value versus driving force

4. Conclusions

The nonlinear characteristics including resonance frequency shift and nonlinear parameters change distinctively with the water content, which may provide a means to estimate the water content in the concrete. And this method can be extended to the assessment of the concrete strength.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (No: 10674066) and State Key Laboratory of Acoustics.

References

[1] C. Vernet, J. Lukasik, and E.Prat, "Nanostructure, porosity, permeability and diffusivity of ultra-high performance concrete," in proceedings of intern. Symp. on HPC and RPC, edited by P.C. Aitein et al. (RILEM Publisher, Sherbrooke, 1998), Volume 3, pp17-35.

[2] G. De Schutter and L, Taerwe, "Specific heat and thermal diffusivity of hardening concrete," Cem. Concr. Res , Volume 25, 1995, pp593-604.

[3] A. Boumiz, C. Vernet, and F. Cohen Tenoudji, "Mechanical properties of cement pastes and mortars at early ages: Evolution with time and degree of hydration," Adv. Cem. Based Mateo, Volume 3, 1996, pp94-106.

[4] V. Morin, F, Cohen Tenoudji, P. Richard, A. Feylessoufi, and C.Verent, "Ultrasonic spectroscopy investigation of the structural and mechanical evolutions of reactive powder concretes," Proceedings of Intern. Symp. on HPC and RPC, edited by P.C. Aitein et al. (RILEM Publisher, Sherbrooke, 1998), Volume 3, pp119-126.

[5] P.A. Johnson, "The new wave in acoustic testing" Mater. World 7, 1999, pp544-546.

[6] M. Terill, M. Richardson and A.R. Selby, "Non-linear moisture profiles and shrinkage in concrete members", Magazine of Concrete Resesrch, Volume 137 Number 38, 1986, pp220-225

[7] V.E. Nazarov, L.A. Ostrovskii, I.A. Soustova, and A.M. Sutin "Anomalous acoustic nonlinearity in metals" , Sov. Phys. Acoust , Volume 34 Number 3 1988, pp284-288.

[8] V.E. Nazarov and A.B. Kolpakov "Experimental investigations of nonlinear acoustic phenomena in polycrystalline zinc",J.Acoust.Soc.Am, Volumn 107 Number 4, 2000,pp1915-1921.