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Quantification of initial defects in concrete caused by low temperature curing before 28d

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ABSTRACT: The service life of concrete buildings in North China are much shorter than the designed life. One important reason often neglected by scientists is that concrete in those cold regions has initial defects caused by insufficient curing before 28d. In this study the mechanical strength and frost resistance of concrete specimens (LD-3 and LD-7, cured under -20 ºC to 28 d right after standardly cured for 3d and 7d respectively) containing different initial damage were considered.The initial defects in the two series of concrete specimens are firstly quantified by resonance frequency and elastic wave velocity and the results show that the initial damage extent of LD-3 concrete is about twice of LD-7 concrete. Results of the SEM images and mercury intrusion porosimetry (MIP) tests show that LD-3 concrete has a higher content of harmful pores. It can be concluded that initial defects in concrete caused by low temperature curing before 28d can be described as lower elastic wave velocity and higher content of harmful pores.

1 INTEODUCTION

With the lowest temperature of -40ºC in winter and a long winter duration of at least 5 months, concrete structures built in North China are suffering serious durability issues. One important fact related with their poor durability and often neglected by scientists is that the concrete in the existing structures in North China contains initial defects caused by insufficient curing. Most scientists focus on the performance of concrete under low temperature well cured in the standard curing room with no initial defects (Berner, et al. 1985; Cai, et al. 2011; Montejo, et al. 2008; Qiao, et al. 2016; Xie, et al. 2014) while some others (Husem and Gozutok 2005;Ba HJ, et al.2002; Duan Y, et al. 2014; Zhang RX, et al.2012) focus on the effects of low temperature curing on the development of strength and durability of concrete. However, it is still unclear that what are exactly intial defects caused by low temperature curing and how we can quantify them.

Accordingly, two series of concrete specimens contains different extent of initial defects caused by early-age curing under -20 ºC were investigated. The initial defects were characterized quantitatively by initial damage extent calculated by natural frequency and elastic wave velocity, respectively. Furthermore, microstructural analysis of concrete was also carried out by

SEM and mercury intrusion porosimetry (MIP)tests to reveal the generating mechanism of the defects.

2 EXPERIMENTAL PROGRAM

2.1 Materials and mixing proportion

Medium-heat Portland cement PMH42.5 in China and type I fly ash were used. Natural river sand was used as fine aggregates with a fineness modulus of 2.45. Two grades of stones were used as coarse aggregates. The sizes of the medium grade of stones which were made of mixing two kinds of natural stones together were in the range of 20mm-40mm. The sizes of the small grade of stones which were made of mixing one kind of natural aggregates and one kind of man-made limestone stones together were in the range of 5mm-20mm.

JM-II superplasticizer was used as water-reducing agent with a water reduction rate of 18.5%. ZB-1G air-entraining agent was used and the actual air void content entrained in the fresh concrete was about 4.0%.

The mixing proportion of concrete specimens was seen in Table 1.

Table 1. Mixing proportion of concrete specimens

W/C	Sand radio (%)	FA (%)	Admixture dosage (%)		Amount of raw materials (kg/m^3)				
			Water-reducing agent	Air-entraining	Water	Cement	FA	Sand	Stone
0.4	35	25	0.7	0.008	128	240	80	674	1244

2.2 Generation of initial defects in concrete

Low temperature initial defects in this study means defects generated in concrete specimens which were standardly cured for only a few days and then exposed to low temperature environment before 28d age. Two series of concrete specimens with different extent of initial defects were produced. They are cured in the standard curing room for 3d and 7d respectively and then stored in a freezer with a constant temperature of -20 ºC inside till 28d. The two series of specimens are marked as LD-3 and LD-7 respectively and the controlled specimens cured in the standard curing room for 28d are marked as LB.

2.3 Testing procedure

All the concrete specimens for mechanical tests and freeze-thaw (FT) tests were produced according to the Test code for hydraulic concrete (SL352-2006) of China. Mechanical tests were performed to get the compressive strength and splitting tensile strength. The dimensions of specimens for the mechanical tests were 10cm× 10cm × 10cm. Specimens for FT tests were 10cm× 10cm × 40cm in dimension and were put in rubber containers filled with water and kept in the chamber of the FT testing machine. Rapid freezing and thawing method was used and resonant frequency tests of the specimens at different FT cycles were tested to get the dynamic modulus of elasticity.

Furthermore, microstructural analysis of concrete specimens were carried out by S-4800/EX-350 scanning electron microscope (SEM) and PoreMasterGT60 mercury porosimeter.

2.4 Quantitative characterization of low temperature initial defects

2.4.1 Elastic wave velocity test

Ultrasonic wave testing and impact-echo testing are two frequently used non-destructive detecting tools in concrete structures. Unlike ultrasonic method which is sensitive to the saturation status, aggregate size, steel bars or temperature(Ji JL, et al.2008) in concrete, impact-echo method is little affected by water content in concrete and is easy to perform onsite(Lv XB, and Wu JY.2016). Previous studies has revealed that there is a quadratic correlation between the dynamic modulus of elasticity of concrete and the P-wave velocity (Lv XB, and Wu JY.2016). It suggests that P-wave velocity can be used to quantify damage extent in concrete like the resonant frequency method.

The elastic wave velocity testing system is composed of four components, the sensor, the hammer, the data collecting device and the controlling computer, as shown in Figure 1.

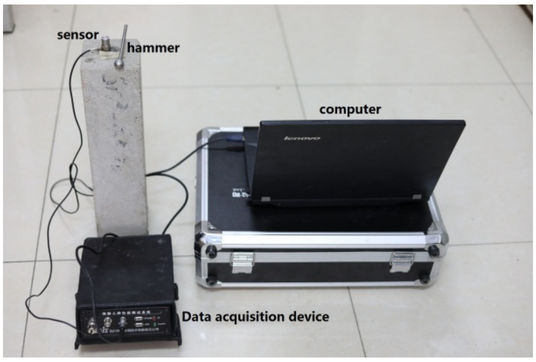


Figure 1. Elastic wave velocity testing system

2.4.2 Quantitative characterization of low temperature initial defects

Initial damage extent is proposed to quantify the initial defects in concrete specimens, which is defined as the reduction value of the relative dynamic modulus of elasticity (RDME) compared to specimens cured for 28d in the standard curing room (they were taken as specimens without initial defects). Initial damage extent can be calculated based on either resonant frequency or elastic wave velocity as follows,

$$D_{IN} = 1 - \frac{f_m^2}{f_0'^2} \quad (1)$$

$$\mathrm{D}_{IN} = 1 - \frac{V_m^2}{V_0'^2} \quad (2)$$

Where D_{IN} in formula (1) and formula (2) is the initial damage extent. It can be seen that for concrete standardly cured for 28d the D_{in} is 0 and for concrete containing initial defects the value is in the range of 0 to 1.

f_m, v_m (m=3 or 7) is the resonant frequency and elastic wave velocity of the concrete specimen containing initial defects. f_0', V_0' is the resonant frequency and elastic wave velocity of concrete specimens cured for 28d in the standard curing room.

3 RESULTS AND ANALYSIS

3.1 Mechanical testing results

The compressive strength and splitting-tensile strength of the concrete specimens are shown in Figure2 . It can be seen from Figure 2 that the mechanical properties of LD-3 and LD-7 series were significantly smaller compared with the LB series. The compressive strength of the LD-7 and LD-3 series is 57% and 31% of LB series, respectively, and the splitting tensile strength is 62% and 41%, respectively. The shorter the standard-curing period, the greater the reduction in mechanical strength.

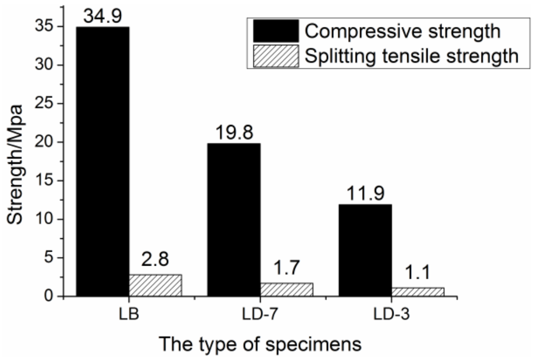


Figure 2. Compression strength and splitting tensile strength of three series of concrete specimens

3.2 Frost resistance of the concrete specimens with initial defects

Variations of the RDMEs of the series of concrete specimens with freeze-thaw cycles are shown in Figure 3.

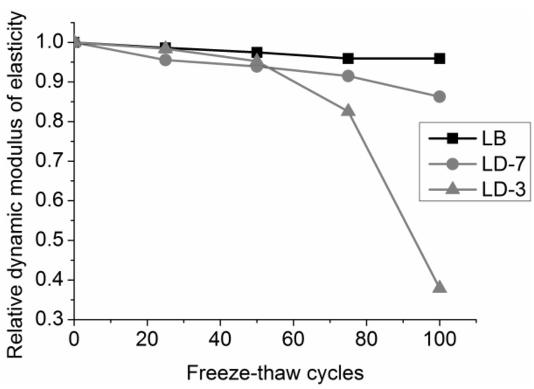


Figure 3. Variations of relative dynamic elastic modulus of concrete with freeze - thaw cycles

It can be seen from Figure 3 that the RDMEs of the three series concrete specimens decreases gradually with the increase of freeze-thaw cycles. When the number of freeze-thaw cycles is lower than 50 times, the RDMEs decrease gradually at the same speed. However, when the FT cycles are greater than 50, The RDMEs of LD-3, LD-7 series decrease more rapidly than LB. In addition, when the FT cycles are greater than 100, the RDME of LD-3 series is smaller than 40%, indicating they have already been destroyed according to the Testing code (SL352-2006).

It can be seen that LD-3 and LD-7 series have lower frost resistance than LB and LD-3 has the weakest frost resistance.

4 INITIAL DAMAGE EXTENT

Compared with concrete specimens of LB series, the initial damage extents of LD-3 and LD-7 series are calculated by the resonant frequency and elastic wave velocity, respectively. The results are shown in Figure 4.

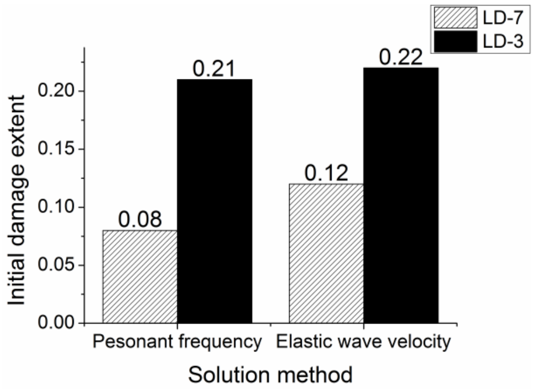


Figure 4. Initial damage extents of LD-3 / LD-7 series based on natural frequency and elastic wave velocity

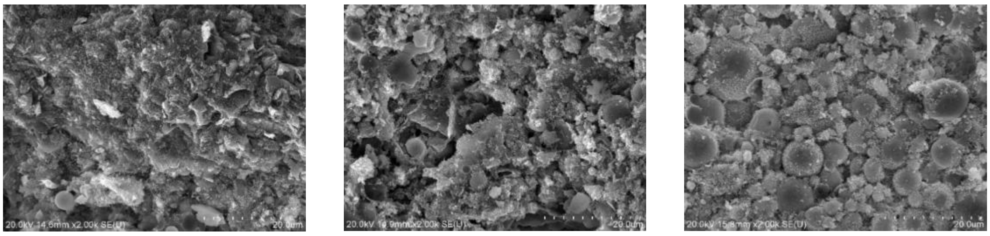
It can be seen from Figure 4 that initial damage extents in LD-3/ LD-7 series calculated by resonant frequency and elastic wave velocity are 0.21/0.08, 0.22/0.12, respectively. The initial damage extent of LD-3 series is about twice of LD-7 series.

It can also be seen that both the elastic wave velocity and the resonant frequency can be used to quantify the initial defects in concrete, and the initial damage extent values calculated by different ways are close.

5 MICROSTRUCTURAL ANALYSISI

5.1 SEM image analysis

SEM images of the local microstructure of mortar samples in the three series of concrete specimens are shown in Figure 5.



(a) LB series (b) LD-7 series (c) LD-3 series

Figure 5. SEM images of local microstructure of the three series concrete specimens

The magnification of all the SEM images shown in Figure5 is 2000 times. It can be seen from Figure5 (a) that the hydration degree of LB series is complete, the structure is dense and no obvious pore can be seen. It can be seen from Figure5 (b) that the internal structure of the LD-7 series of concrete matrix is loose, and some spherical pits caused by fly ash particles felling off could be seen. As can be seen from Figure5 (c), the LD-3 matrix is very loose, and a large number of exposed fly ash particles can be seen packing together without many hydration products. The SEM images indicate that for concrete specimens exposed to low temperature at early age (LD-3 and LD-7) the hydration is not sufficient.

5.2 MIP results

Pores in concrete can be divided into four groups according to their diameter, harmless pores (pore diameter <0.02um), less harmful pores (pore diameter ranging from 0.02um to 0.05um), harmful pores (pore diameter ranging from 0.05um to 0.2um), and more harmful pores (pore diameter >0.2um) (Wu ZW, and Lian HZ. 2000).

The percentage of different types of pores in the three series of concrete can be obtained based on the MIP results, as shown in Figure 6.

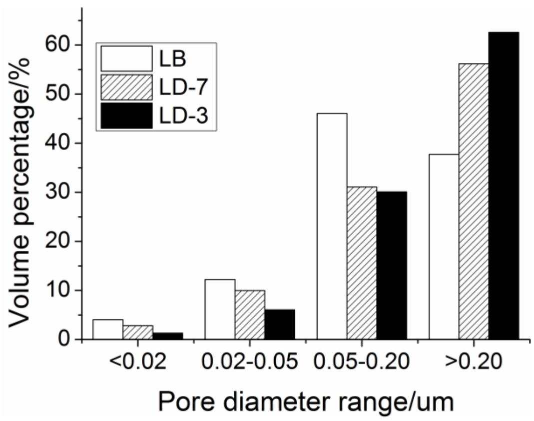


Figure 6. Comparison of pore structure of the three series of concrete

As seen from Figure 6, for LD-3 and LD-7 series pores in the more harmful pores group account for 56.2% and 62.6% of total pore volume, respectively, while that of the LB series is 37.7%. Also for LB series pores in the groups of harmless pores and less harmful pores account for 16.3% of the total pore volume while that of LD-7 and LD-3 is 12.8% and 7.4%, respectively.

Zhao Tiejun (Zhao TJ, et al.2004) proposed critical pore size as a characterizing parameter of the pore structure obtained by MIP. It is defined as the maximum pore size measured where the cumulative volume changes suddenly in the MIP results. Studies have shown that(Zhao TJ, et al.2004) the critical pore size decreases with the increase of the hydration extent of concrete. The cumulative volume and porosity of the three series of concrete pores are shown in Figure7.

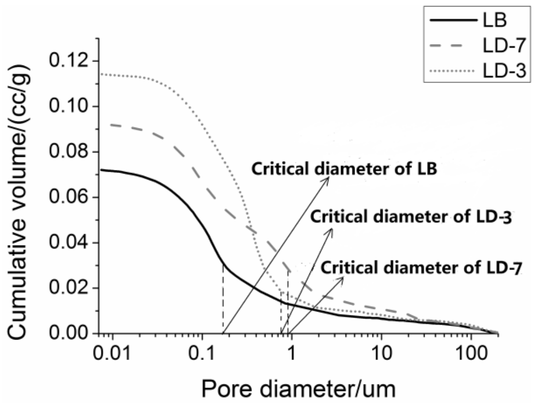


Figure 7. Cumulative volume of pores in three types of concrete samples

It can be seen from Figure 7 that the critical pore sizes of LD-3 and LD-7 are about 0.8u m, while that of LB series is about 0.18 um, far smaller than LD-3/LD-7.

The microstructural analysis shows that for concrete exposed to low temperature environment too early before 28d the cement hydration is not complete and the critical pore size get much greater than concrete cured for 28d. Also the volume of more harmful pores is much larger than standardly cured concrete.

6 CONCLUSION

(1)The compressive strength, tensile strength and frost resistance of the LD-3 and LD-7 series of concrete specimens were much lower than the LB series which were standardly cured for 28 d. LD-3 series of concrete have the lowest mechanical strength and frost resistance.

(2)The initial defects of the concrete can be quantified by initial damage degree calculated from the elastic wave velocity and the natural frequency. The initial damage degrees of LD-3 is about twice of LD-7.

(3)Microstructural analysis shows that due to exposure to low temperature environment at early age, the hydration of cementitious materials in LD-3 and LD-7 is not complete and the micro structure is loose. The more harmful pores in LD-3 and LD-7 are much larger than LB in volume and the critical pore size of the pore structure is much greater than LB. The earlier the exposure age, the more initial defects in the concrete

(4)Low temperature initial defects reduces the mechanical properties and frost resistance of concrete. The shorter the standardly curing time, the earlier the exposure time, the greater the initial defects and the more significant in the reduction of the mechanical properties and the frost resistance. Therefore, we must pay attention to early age curing of concrete in the construction process in North China to ensure there are no or fewer initial defects in concrete structures.

(5)Results show that elastic wave velocity is a promising parameter to quantify initial damage caused by low temperature curing in concrete specimens. And echo-wave method is a feasible way of quantifying low temperature initial damage in in-situ concrete structures because elastic wave can be easily obtained with the corresponding testing system. So in the future more in-situ experiments will be performed on concrete structures to quantify the initial damage by echo-wave method.

7 AKNOWLEDGEMENTS

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REFERENCES

Berner, D., Jr Bc Gerwick, and M. Polivka.1985,Static and Cyclic Behavior of Structural Lightweight Concrete at Cryogenic Temperatures.

Cai, Xiao Ping, et al..2011,Effect of Low Temperature on Mechanical Properties of Concrete with Different Strength Grade. *Key Engineering Materials* ,477:308-312.

Montejo, Luis A, et al.2008,Cyclic Response of Reinforced Concrete Members at Low Temperatures. *Journal of Cold Regions Engineering* ,22(3):79-102.

Qiao, Yi, et al.2016,Influence of low temperature on dynamic behavior of concrete. *Construction & Building Materials* ,115:214-220.

Xie, Jian, Xiaomei Li, and Honghai Wu.2014,Experimental study on the axial-compression performance of concrete at cryogenic temperatures. *Construction & Building Materials* ,72(72):380–388.

Ba HJ, et al. 2002,Influence of constant minus-temperature an varied minus-temperature curing on properties of concrete. *Journal of Harbin University of C.E. and Architecture* ,35(1):81-85. (in Chinese)

Duan Y, et al.2016, Compressive strength growth of minus temperature (-3℃)curing concrete. *Bulletion of The Chinese Ceramic Society*,35(1):244-249. (in Chinese)

Ji JL, Li HJ, and Yan GL.2008,Effect of temperature on ultrasonic wave velocity in concrete. *Journal of Building Materials* ,11(3):349-352. (in Chinese)

Lv XB, and Wu JY.2016,*Impact elastic wave theory and application*: China Water & Power Press. (in Chinese)

Zhang RX, et al.2012 ,Experimental study on strength growth of low temperature curing concrete. *Concrete,*(5):19-21. (in Chinese)

Wu ZW, et al.2000 , *High performance concrete:* Atomic Press. (in Chinese)

Zhao TJ, Zhu JS, and Feng NQ.2004, Characterization parameters in concrete pore analysis. *Academician Wu Z W's Proceedings of the 60 - year Academic Symposium on Science and Education.* (in Chinese)