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Research Article

Influence of Early Age on the Wave Velocity and Dynamic Compressive Strength of Concrete Based on Split Hopkinson Pressure Bar Tests

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The effect of early age on the mechanical properties of concrete was investigated in this study. A uniaxial compression test was performed on split Hopkinson pressure bar (SHPB) equipment with a large diameter of 75 mm. The experimental results indicated that before 7 days, concrete showed viscoelasticity and had good deformation ability and low sensitivity to incident energy. In addition, the concrete exhibited the characteristics of quasi-brittle materials, and the sensitivity of the incident energy improved with age. The threshold value of the incident energy at early ages had an insignificant effect on the stable age concrete. The threshold value was 50% of the corresponding age's critical incident energy, while it was 75% after 7 days.

1. Introduction

As one of the most commonly used building materials, the mechanical properties of concrete must meet design requirements after 28 days of curing, which is in contradiction with modern construction methods that are dedicated to shortening the construction period. To accelerate the construction progress, multi-subsection blasting methods [1] have always been used, while the effectiveness of the supporting structure at an early age is inevitably affected by the blasting impact loading. The main problem in this task is that the supporting structure at an early age responds to the blasting impact loading which may cause cracks and microseismic events at the same time [2–4]. The compressive strength is one of the fundamental parameters in structural design to determine the engineering service life. Hence, understanding the influence of early-age impact on the dynamic compressive strength of the stable age concrete is very important.

Lew and Richard first studied the compressive strength, splitting tensile strength, and bond strength of early-age concrete in 1978 [5].Since then, the scope of early-age concrete studies has been broadened. Kim and Han [6, 7] as well as Kanstad and Hammer studied the correlation of compressive strength and the elastic modulus with the change of curing temperatures, ages, and cement types and proposed a model that could predict the splitting tensile strength and elastic modulus on the basis of experiments without knowing the compressive strength [8]. Yia and Kim investigated the effect of concrete strength and age on the stress-strain curves of concrete, proposing a more reasonable mold that accurately predicted the ascending branch of the stress-strain curve and the descending branch within a minimum deviation range [9]. Based on experimental research, the formulas for calculating the required strength to the loading moment of monolith foundations, walls, columns, and coverings were suggested by Baiburin [10]. The designing of the early loading technology was given, and the results of the in-place early-age covering loading tests were presented. A new experimental procedure that uses digital image correlation (DIC) to measure deformation has been developed to measure tensile strain capacity, tensile strength, and the tensile E-modulus of concrete during the first 24 h of age [11]. The authors [12] provided an application to the maturity method to estimate the strength development of concrete in place during construction, which could transform, in real time,

the temperature history of on-site concrete into strength. Bertagnoli and Gino [13] proved a simplified approach for determining the time evolution of stresses developing at the early age of curing concrete slabs of composite beams and the different types of cement. This approached featured a variable time evolution of the hydration process, and different external temperatures were taken into account. Their approach can be regarded as a simple generalization of the method adopted in the current practice and is based on assuming full interaction between the slab and the profile. Zreiki and Bouchelaghem [14] proposed a practical approach to characterize the early-age behavior of massive concrete structures on-site and to identify a macroscopic 3D chemo-thermo-viscoelastic model from simple tests performed in the laboratory. They also employed a restrained shrinkage ring test to identify a basic creep model at early concrete age. Zhang and Yang [15] developed a new prediction model of the early-age strength and elastic modulus and the coefficient of variation for each variable, based on large numbers of experimental results, which can provide good prediction of the development of mechanical properties of concrete structures during aging. The mechanical properties including compressive strength, splitting strength, and modulus of elasticity of early-age concrete cured under both temperature-matching curing and isothermal 20°C curing were investigated by Wang and Yan[16]; they created a model that can predict the compressive strength, splitting strength, and elasticity modulus by finite element method measurements or calculations. The concrete temperature at early ages was proposed, which is valid in real structures. In addition, Jin and Li [17] obtained the complete strain-stress cure for young concrete and studied the effect of static load level, curing conditions, and loading age at early ages on the mechanical properties of stable concrete. The adverse effects caused by differential axial shortening become significant with the increasing height of high-rise buildings. Du and Liu [18] presented an experiment under a step-by-step load, which was employed to approximately simulate the load history of the axial components during the construction process; the researchers found that the strain development of early-age concrete under a step-by-step load is substantially affected by the loading age and stress amplitude.

Previous studies have focused on the mechanical properties, strain-stress curves, and mechanical properties prediction models of early-age concrete subjected to static loading. However, there is little information in the literature on the mechanical properties under dynamic loading conditions.

Although the authors have studied the mechanical properties of early age concrete under static, dynamic, and repeated impact loading, a damage constitutive model that can reflect the variation in dynamic mechanical properties with age has been proposed [19–21]. However, the effects of early age on the dynamic compressive strength of stable age concrete have not been examined.

In this work, the effect of early-age impact on the dynamic compressive strength of concrete was investigated under different factors including loading age and impact level. In this paper, the uniaxial compression tests were carried out at the ages of 1, 3, 7, 14, and 28 days by using a 75 mm diameter SHPB bar. The results were compared and analyzed systematically to illustrate the effect of the different impact levels and ages of 1, 3, 7, and 14 days on the mechanical properties of concrete (28 days).

Table 1: Concrete mixture proportions.

w/c	Unit weight (kg/m^3)				AC (%)
	Cement	Aggregate	Sand	Water	
0.46	397	853	786	182	4

2. Experimental Program

2.1. Concrete Mixture and Specimen Preparation. A Φ75 ×37.5 mm cylindrical specimen was used in this test. The cement used in the experiments was ordinary Portland cement (ASTM Type I); river sand was used as the fine aggregate, while crushed limestone gravel passing the 16 mm sieve was used as the coarse aggregate [22]. The mixture proportion of the concrete is given in Table 1.

After casting, all specimens were subjected to moist curing at 20±1°C. It is not easy to grind the end of specimens at early ages, so after casting for 12 h, the capping method, which uses ultra-rapid-hardening cement, was used. The cylinders were demolded at an age of 24 h. After mold removal, the samples were stored in a standard moist room at 20±1°C until testing.

2.2. SHPB Test Apparatus. Figure 1 shows the SHPB testing system, which consists of an incident bar and a transmitted bar, with a specimen sandwiched between them, and a striker that impacts the incident bar to produce a compressive stress wave. The incident stress wave propagates along the incident bar towards the specimen. When the stress wave reaches the interface of the incident bar and the specimen, part of the wave reflects back to the incident bar, while the rest transfers into the transmitted bar. Both pressure bars have the same dimension of Ø75–2000 mm, and the absorption bar is Ø75–1000 mm. Strain gauges are attached at the center of the pressure bars. The bars are made of stainless steel with Young's modulus of 225 GPa, density of 7697 kg/m^3, elastic wave velocity of 5410 m/s, and Poisson's ratio of 0.28. The test system adapts to load heterogeneous brittle material under a high strain rate; a constant strain rate of half-sine stress wave loading can be obtained using a spindle-shaped striker [23].

ε is used to denote the measured strain signal on the bars, where the subscripts I, R, and T represent the incident, reflected, and transmitted pulses, respectively, according to the one-dimensional stress wave theory. Then, the engineering stress, strain, strain rate, and incident energy of the sample can be expressed:

$$\sigma = \frac{A_e}{2A_s} E_e \left[\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)\right] \quad (1)$$

$$\varepsilon = \frac{C_e}{L_s} \int_0^t \left[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)\right] dt \quad (2)$$

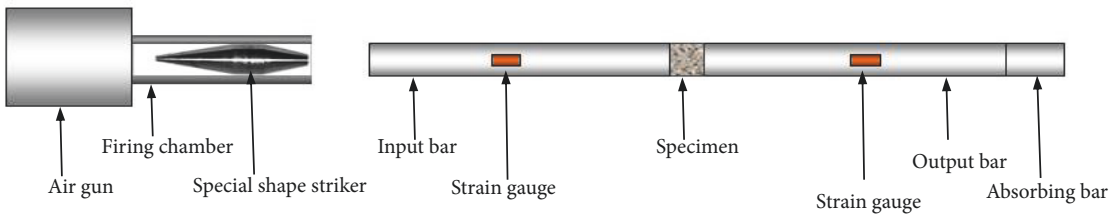


Figure 1: Sketch of the SHPB experimental system.

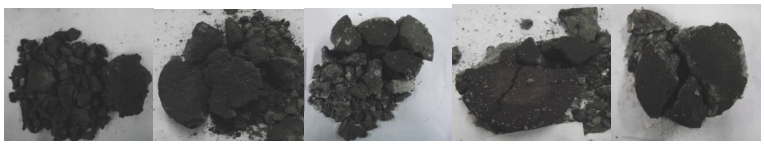


Figure 2: Critical failure modes of concrete with different ages.

Table 2: Critical failure strength of different age concrete under signal impact.

Age/day	Incident energy/J	Strain rate/s^{-1}	Strength/MPa
1	50	29	5.88
3	58	30	12.39
7	74	42	17.95
14	80	33	26.07
28	85	35	31.65

$$\dot{\varepsilon} = \frac{C_e}{L_s}\left[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)\right] \quad (3)$$

$$E_I = \frac{A_e}{\rho_e C_e}\int_0^t \sigma_I^2(t)\,dt \quad (4)$$

where A_e, C_e, E_e, and ρ_e are the cross-sectional areas, wave velocity, Young's modulus, and density of the bars, respectively. A_s and L_e are the cross-sectional area and the length of the specimen, respectively. E_I is the incident energy.

For the SHPB test, several assumptions were specified to ensure the validity of (1)-(2) as follows: (1) the propagation of the stress wave in elastic bars agrees with the one-dimensional stress wave theory; (2) the specimen reaches the stress equilibrium state before failure; (3) the friction and inertial effects of the specimen can be ignored.

2.3. Testing Method. To investigate the effect of the early-age impact on the dynamic compressive strength of concrete after a stable age, the impact test was designed as follows:

(1) The critical incident energy (E_{IC}) and the failure dynamic strength of the concrete are obtained for when the sample breaks into several large pieces (critical failure, shown in Figure 2) at each age under a single impact (shown in Table 2). The specimen will not break when the impact incident energy is less than E_{IC}, which means that it will continue curing after impact. In this test, the specimen will be impacted at the age of 1, 3, 7, 14, and 28 days. Before the age of 14 days, the specimen that does not break during the impact will be put back in the standard room until 28 total days are reached; the specimen will be impacted again, and the mechanical properties will be compared with those of a specimen that cures in a standard moist room for 28 days. For example, if the specimen impact at an age of 1 day is not broken, it will be put back in the standard room for another 27 days (28 in total) and then impacted again. The mechanical properties will be compared with the specimen that cures in the standard moist room for 28 days.

(2) Ensure the impact incident energy of each loading age. In this paper, 50% and 75% of the E_{IC} mentioned above were utilized, which can be achieved by adjusting the air pressure and position of the striker.

(3) Place the specimen. The specimen was placed between two long elastic pressure bars, and the end-friction effect was minimized with smearing butter. According to the first step, the specimen would be put back in the standard moist room for 28 days if it was not broken, and a protective case with a sponge at the bottom (as shown in Figure 3) was arranged to avoid negative effects on the experimental results due to the dropping impact.

(4) SHPB test based on the experimental design. Typical signals obtained from the SHPB tests are illustrated in Figure 4, and the dynamic mechanical properties were calculated by (1)-(4).

In addition, the wave velocity was obtained with a geotechnical quality detector as a parameter to characterize the strength of concrete of all the concrete specimens at 1, 3, 7, 14, and 28 days of age (CE-9201, shown in Figure 5). The detector can generate a high-voltage short rectangular wave. A wide-band ultrasonic (mechanical) wave is generated and picked up by the receiver, whose signal is amplified after traveling through the material. The time that it takes for the wave to travel from the transmitter to the receiver can be read from the detector, and the velocity can be calculated by

$$V = \frac{L}{t} \quad (5)$$

where L is the length of specimen.

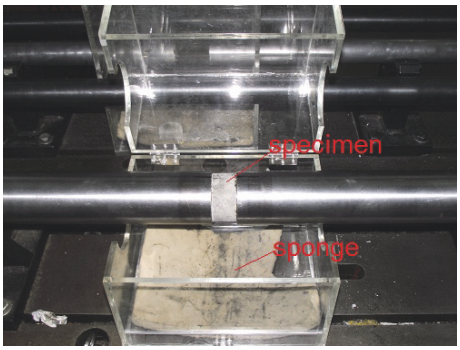


Figure 3: Protective case.

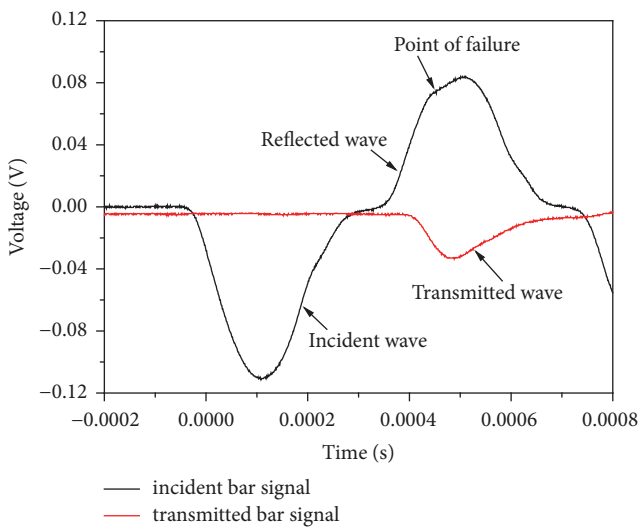


Figure 4: Typical waveform of the compression test.

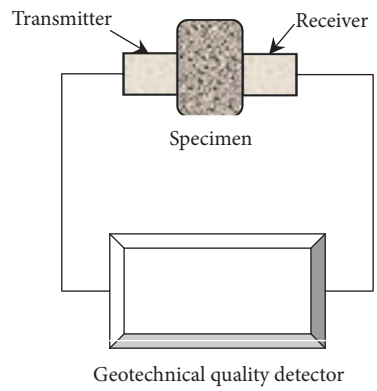


Figure 5: Schematic diagram of the geotechnical quality detector.

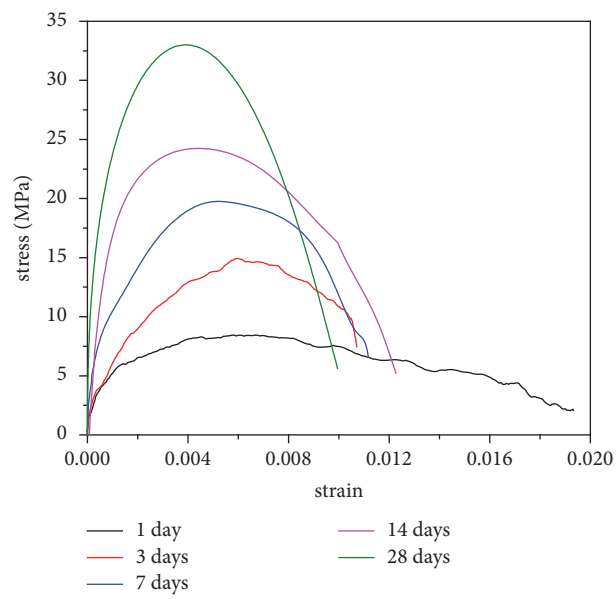


Figure 6: Stress-strain curves of different age concrete under single impact load.

3. Experimental Results and Discussion

3.1. Comparison of Stress-Strain Curves. A comparison of the characteristics of concrete for different ages was created and is shown in Figure 6. Figure 6 shows the stress-strain curves of concrete for different ages with uniaxial compressive impact loading at a strain rate of approximately 45 s^{-1}.

From Figure 6, it can be seen that the strain corresponding to the maximum stress and failure strain is relatively large for early-age concrete and decreases rapidly with age, while there is no obvious change for the concrete after 7 days of age.

The result reflects the nature of the hydration process and viscous characteristics of early-age concrete. At these ages, the hydration products are still growing. Calcium silicate hydrate and calcium hydroxide have not strongly interlaced together, and there are more voids and moisture in the early-age concrete. As a result, the boundary sliding between groups of hydration products can easily occur, and more deformation can be achieved [22]. Then, with the increase in age, Young's modulus of concrete increases, while the critical strain and failure strain decrease. This result indicates that the viscoelasticity of concrete gradually transfers towards the quasi-brittle with age.

3.2. Effect of Impact with Different Curing Age on Wave Velocity. Figure 7 shows the variation in concrete wave velocities with age under standard curing conditions. It can be seen from Figure 7 that the wave velocity has a positive logarithmic relationship with age under the no impact cases. The wave velocity increases rapidly before 7 days of age and relatively slowly after 7 days of age [24].

The effect of early-age impact (1, 3, 7, and 14 days) on the concrete wave velocities with age is shown in Figure 8. From the figure, it can be seen that the wave velocity of concrete continues growing with age after impact at the age of 1, 3, and 7 days. The decreased magnitude of wave velocity due to impact at the age of 1 day is the greatest, but the wave velocity increases fastest after curing and exceeds the original level at the age of 28 days. A similar trend is observed for the wave velocity at the age of 3 and 7 days, but to a different degree. Both of the levels cannot be restored to the original level at the age of 28 days. Additionally, the wave

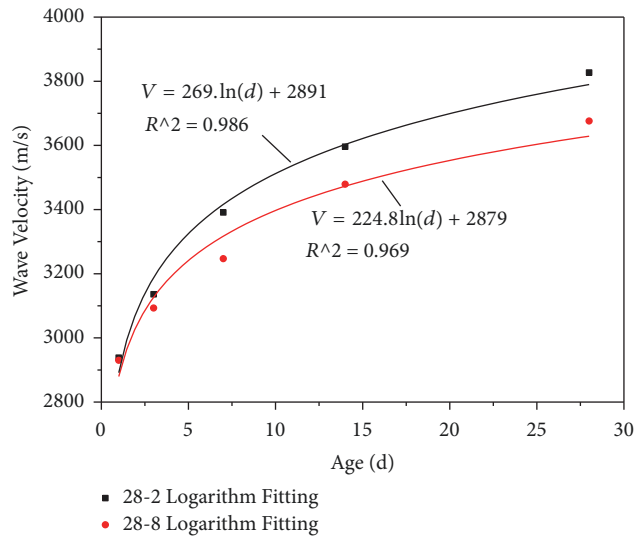


Figure 7: Variation in wave velocity of concrete with ages.

velocity of concrete subjected to impact at the age of 14 days grows slowly after curing, and the wave velocity is obviously much less than that of the original level at the age of 28 days.

The wave velocity growth model of concrete due to impacting at different ages is mainly affected by the mechanical properties of concrete transfer with age [25]. Before the age of 7 days, the concrete is viscous and easy deformed; therefore, the wave velocity is susceptible to external impact. Additionally, the concrete can recover quickly after curing because it still has good viscoelasticity. As the nature of concrete gradually converts from viscoelastic to quasi-brittle with age, although the impact effect on concrete decreases under the same impact level, the internal structure of concrete is destroyed and cannot be restored. This result corresponds to the fact that the wave velocity does not increase with age after impact at the age of 7 days.

3.3. Effect of Impact Incident Energy on Wave Velocity. The early-age impact had a significant influence on decreasing wave velocity of concrete, for which the decreasing degree and the growth rate after curing were reduced with the impact age.

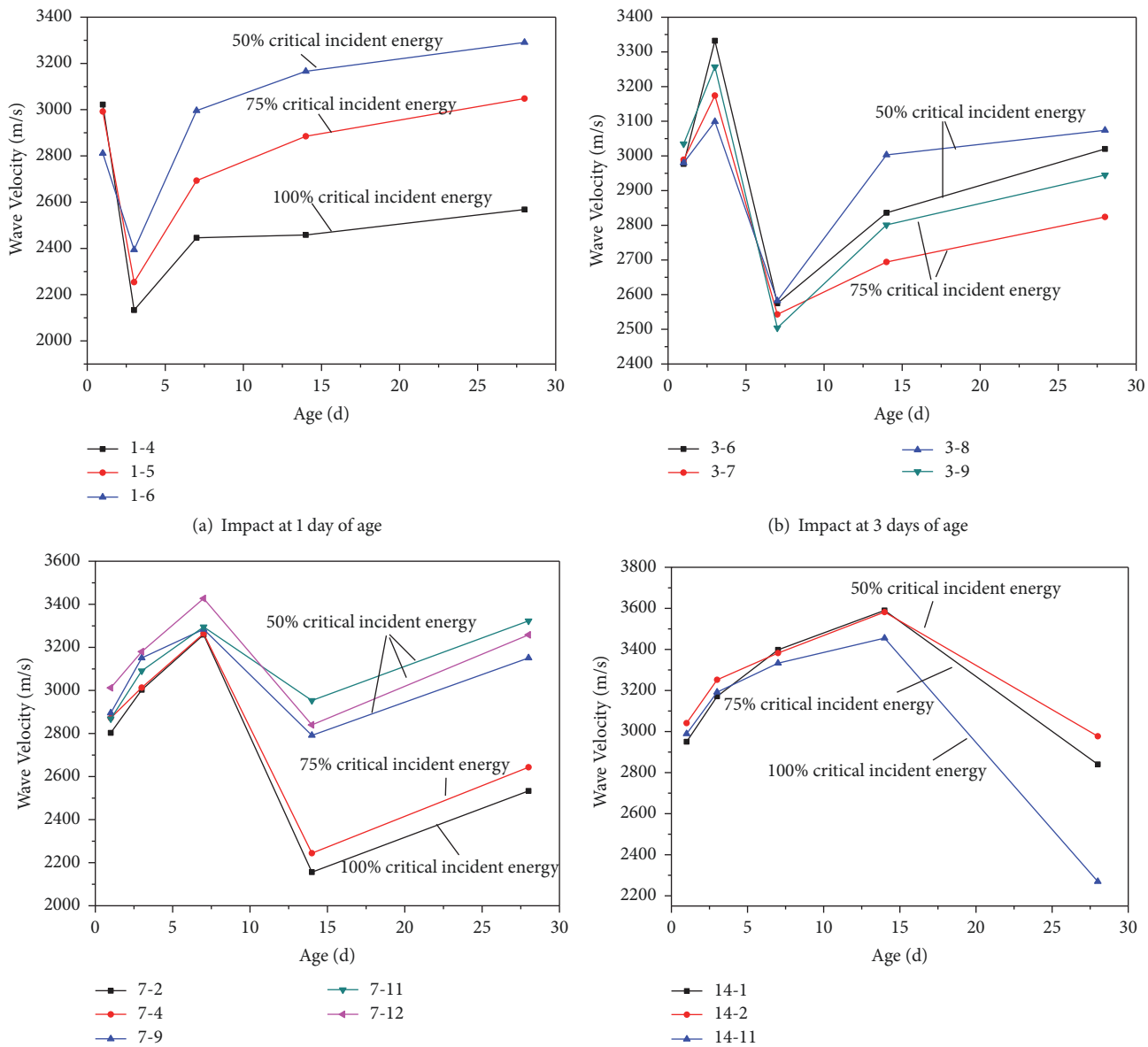
It can be seen from Figure 8(a) that the growth trend of the wave velocity of the concrete subjected to impact at 1 day of age under the impact level of 50% and 75% E_{IC} is similar to that of the concrete in the standard curing condition. While the impact level is close to E_{IC}, there is no obvious growth during the curing time. As shown in Figures 8(b) and 8(c), the wave velocity variation patterns of concrete under the impact level of 50% E_{IC} perform in a similar trend at an age of 3 and 7 days. While the impact level reaches 75% of the critical incident energy, the concrete impact at the age of 7 days is damaged severely, and the wave velocity declines rapidly. Compared with the wave velocity of the concrete subjected to the impact before 14 days, the velocity wave of the concrete that was impacted at 14 days of age grows relatively slowly. The growth rate decreases with the increase in the incident energy (see Figure 8(d)).

The above results reveal that when the external impact incident energy is less than 50% of the corresponding age's E_{IC}, the wave velocity of the concrete subjected to impact before 7 days will grow normally with age. However, it would be very difficult for the wave velocity to recover from the impact after being impacted at an age of 7 days.

3.4. Effect of Impact with Different Age on Dynamic Strength. The variation in dynamic strength of concrete with ages under the impact level of E_{IC} is shown in Figure 9. From the figure, it can be seen that the dynamic strength has a positive logarithmic relationship with age under E_{IC} impacting. The dynamic strength increases rapidly before 7 days and relatively slowly after 7 days.

Table 3 shows the effect of different loading ages on the damage energy of concrete at 28 days of age. From Table 3, it is clear that after impact at the age of 1 and 3 days under the impact level of 50% of the corresponding age's E_{IC}, the specimens after curing for 28 days (for the totally 28 days) were probably broken under the impact level of no less than 100% E_{28IC} (critical incident energy of 28 days). In comparison, specimens previously subjected to impact at an age of 3 days under the impact level of 75% E_{3IC} would be fully fragmented under the impact of 50% E_{28IC} after curing for 28 days. Specimens previously subjected to impact at an age of 7 days under the impact level of 50% E_{7IC} would be critically damaged under the impact of 75-100% E_{28IC} after curing for 28 days. Specimens previously subjected to impact after 7 days under the impact level of 75% E_{7IC} were fractured into large pieces under the impact of 75% E_{28IC} after curing for 28 days. Those specimens previously subjected to impact at an age of 14 days under the impact level of less than E_{14IC} were broken only when the impact level reached or exceeded E_{28IC} after curing for 28 days.

The above analysis shows that early-age impact at different ages has a distinct influence on dynamic strength of concrete at the stable age. The effect of early age on the dynamic strength of specimens at the stable age was small when the specimens were previously subjected to an impact at an age of 1, 3, and 7 days under the impact level of 50% of the corresponding E_{IC}. However, there is an evidential effect on the dynamic strength of specimens at the stable age under the impact level of 75% of the corresponding E_{IC}. Moreover, there is minimal change in the dynamic strength for the specimens previously subjected to impact at an age of 14 days under the impact level equal to or less than 75% E_{14IC}. The difference of influence of early-age impact at different ages on the dynamic strength of concrete at the stable age may be attributed to the mechanical properties of concrete change from viscoelastic to quasi-brittle behavior with age. Before an age of 7 days, the viscoelastic behavior of the concrete allows it to be more deformed, and the deformation can recover to the original level after impact if the impact level is less than 50% of the corresponding E_{IC}. However, under the impact level at or above 75% of the corresponding E_{IC}, the deformation is too large and beyond the deformation capacity of concrete so that it is unable to recover to the original level. This result



(a) Impact at 1 day of age

(b) Impact at 3 days of age

(c) Impact at 7 days of age

(d) Impact at 14 days of age

Figure 8: Effect of impact with different on the wave velocity of concrete.

corresponds to an evidential effect on the dynamic strength of specimens at a stable age. Considering that the stiffness of the concrete increases with age and the concrete reveals more characteristics of a quasi-brittle material, the impact after an age of 14 days has minimal effect on the dynamic strength of concrete at a stable age.

3.5. Effect of Incident Energy on Dynamic Strength. As seen from Figure 10, the dynamic strength of concrete for each age has a positive logarithmic increase relationship with incident energy, and the corresponding growth rate becomes larger with age. The dynamic strength grows rapidly when the impacting incident energy is less than E_{IC}, while the growth rate of the dynamic strength begins to decrease when the impacting incident energy exceeds critical incident energy. The decreased magnitude decreases with age. This observation indicates that the sensitivity of the dynamic strength to the incident energy increases with age but will begin to decrease when the incident energy exceeds E_{IC}. This reversal is mainly because the early-age concrete shows a viscoelastic behavior and is more easily deformed with the increase in incident energy. However, with age, the concrete begins to reveal more quasi-brittle material characteristics, and the deformation capacity decreases. Therefore, the changes in the equivalent incident energy create a more significant effect on the changes of the dynamic strength of the concrete.

4. Conclusions

In this study, impact compression tests of concrete at five different early ages were conducted with SHPB. The mechanical

Table 3: Effect of impact with different age on the dynamic strength of concrete at age of 28 days.

Serial number	Impact level	Dynamic strength/MPa		Failure shape (impact at 28 days)
1-1	50% 120%	4.08	24.91	fragmentation with large degrees
1-2	50% 50%	3.85	17.4	intact
1-3	50% 75%	4.50	20.35	local crack crush
3-1	50% 50%	7.91	17.98	intact
3-2	50% 75%	8.39	23.4	intact
3-3	50% 130%	10.9	30.51	crush
3-4	75% 50%	10.19	16.14	fragmentation, exit large degrees
3-5	100% 75%	11.91	20.48	crush
7-1	50% 75%	7.73	20.2	critical failure
7-2	50% 100%	8.44	21.74	fragmentation with large degrees
7-3	75% 75%	13.69	18.19	fragmentation with large degrees
7-4	75% 100%	12.89	19.26	crush
7-5	100% 50%	16.71	23.94	crush
14-1	50% 130%	7.83	21.71	critical failure
14-2	75% 75%	15.3	15.56	intact
14-3	75% 130%	12.93	23.22	fragmentation with large degrees
14-4	75% 150%	12.34	24.1	crush
14-5	50% 130%	7.83	21.71	critical failure

Note: the first number of the serial number indicates the specimen age, and the second number indicates the specific number; the first value of impact level indicates the impact level of first impact, and the second value of impact level indicates the impact level at 28 days.

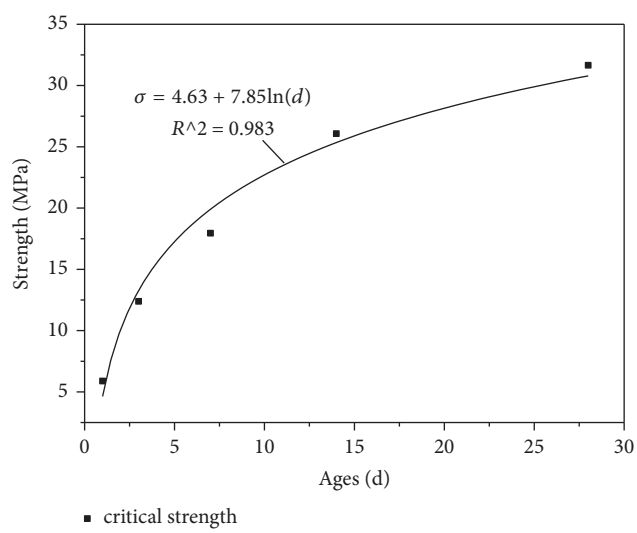


Figure 9: Variation in dynamic strength with age in critical incident energy.

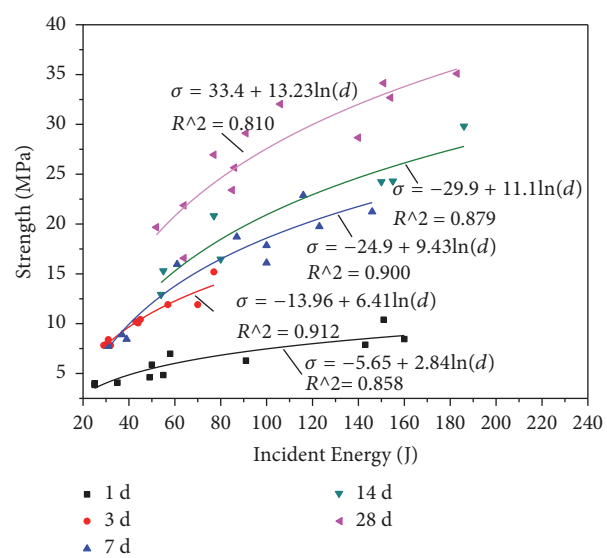


Figure 10: Variation in the dynamic strength with incident energy at different ages.

properties of specimens (28 days) previously subjected to impact at the ages of 1, 3, 7, and 14 days were comparatively analyzed with those of specimens under standard curing conditions for 28 days. The following conclusions can be drawn:

(1) The mechanical properties of concrete convert from the viscoelastic to the quasi-brittle, and the sensitivity of the dynamic strength to the incident energy increases with age. The impacting effect on the wave velocity of concrete decreases with an increase in age.

(2) Concrete that experienced impacts at different ages has a distinguishing influence on the dynamic strength of the concrete at a stable age. The sensitivity of the incident energy is improved with age. The threshold value of the incident energy at early ages has no significant effect on the stable age concrete, and the value was 50% of the critical incident energy at a corresponding age and 75% after 7 days.

Therefore, in practical engineering, when using a concrete blasting process before 7 days of curing, the external disturbance load should be strictly controlled to 50% of

corresponding age's E_{IC} to ensure the concrete supporting structure performs well and effectively.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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References

[1] M. Wang, X. Shi, J. Zhou, and X. Qiu, "Multi-planar detection optimization algorithm for the interval charging structure of large-diameter longhole blasting design based on rock fragmentation aspects," *Engineering Optimization*, pp. 1–15, 2018.

[2] L. Dong, W. Shu, G. Han, X. Li, and J. Wang, "A Multi-Step Source Localization Method with Narrowing Velocity Interval of Cyber-Physical Systems in Buildings," *IEEE Access*, vol. 5, pp. 20207–20219, 2017.

[3] L. Dong, W. Zou, X. Li, W. Shu, and Z. Wang, "Collaborative localization method using analytical and iterative solutions for microseismic/acoustic emission sources in the rockmass structure for underground mining," *Engineering Fracture Mechanics*, 2018.

[4] X. Li and L. Dong, "An efficient closed-form solution for acoustic emission source location in three-dimensional structures," *AIP Advances*, vol. 4, no. 2, Article ID 027110, pp. 1–8, 2014.

[5] H. S. Lew and T. W. Reichard, "Mechanical Properties of Concrete at Early Ages," *ACI Journal*, vol. 75, no. 10, pp. 533–542.

[6] J.-K. Kim, S. H. Han, and Y. C. Song, "Effect of temperature and aging on the mechanical properties of concrete: Part I. Experimental results," *Cement and Concrete Research*, vol. 32, no. 7, pp. 1087–1094, 2002.

[7] J. K. Kim, S. H. Hun Han, and S. K. Kyun Park, "Effect of temperature and aging on the mechanical properties of concrete: part II. Prediction model," *Cement and Concrete Research*, vol. 32, no. 7, pp. 1095–1100, 2002.

[8] T. Kanstad, T. A. Hammer, Ø. Bjøntegaard, and E. J. Sellevold, "Mechanical properties of young concrete: Part II: Determination of model parameters and test program proposals," *Materials and Structures/Materiaux et Constructions*, vol. 36, no. 258, pp. 226–230, 2003.

[9] S.-T. Yi, J.-K. Kim, and T.-K. Oh, "Effect of strength and age on the stress-strain curves of concrete specimens," *Cement and Concrete Research*, vol. 33, no. 8, pp. 1235–1244, 2003.

[10] A. K. Baiburin, "Technology of the Early Age Concrete Loading," in *Proceedings of the 2nd International Conference on Industrial Engineering, ICIE 2016*, pp. 2157–2162, rus, May 2016.

[11] E. Roziere, R. Cortas, and A. Loukili, "Tensile behaviour of early age concrete: New methods of investigation," *Cement and Concrete Composites*, vol. 55, pp. 153–161, 2015.

[12] M. Benaicha, Y. Burtschell, and A. H. Alaoui, "Prediction of compressive strength at early age of concrete - Application of maturity," *Journal of Building Engineering*, vol. 6, pp. 119–125, 2016.

[13] G. Bertagnoli, D. Gino, and E. Martinelli, "A simplified method for predicting early-age stresses in slabs of steel-concrete composite beams in partial interaction," *Engineering Structures*, vol. 140, pp. 286–297, 2017.

[14] J. Zreiki, F. Bouchelaghem, and M. Chaouche, "Early-age behaviour of concrete in massive structures, experimentation and modelling," *Nuclear Engineering and Design*, vol. 240, no. 10, pp. 2643–2654, 2010.

[15] D. Zhang and W. Yang, "The experimental study of early-age strength and elastic modulus of concrete," *Advanced Materials Research*, vol. 163-167, pp. 1192–1197, 2011.

[16] J. Wang and P. Yan, "Evaluation of early age mechanical properties of concrete in real structure," *Computers and Concrete*, vol. 12, no. 1, pp. 53–64, 2013.

[17] X. Jin and Z. Li, "Investigation on mechanical properties of young concrete," *Materials and Structures*, vol. 33, no. 10, pp. 627–633, 2000.

[18] C. Du, T. Liu, D. Zou, and J. Teng, "Time dependent strain development of early age concrete under step-by-step load history," *Construction and Building Materials*, vol. 86, pp. 133–139, 2015.

[19] X.-B. Li, S.-M. Wang, L. Weng, L.-Q. Huang, T. Zhou, and J. Zhou, "Damage constitutive model of different age concretes under impact load," *Journal of Central South University*, vol. 22, no. 2, pp. 693–700, 2015.

[20] X. B. Li, S. M. Wang, F. Q. Gong, H. P. Ma, and F. P. Zhong, "Experimental study of damage properties of different ages concrete under multiple impact loads," *Chinese Journal of Rock Mechanics and Engineering*, vol. 31, no. 7, pp. 2465–2472, 2012.

[21] S. M. Wang, X. B. Li, F. Q. Gong, and J. Zhu, "Experimental study of mechanical properties of different ages concrete under static and dynamic load," *Engineering Mechanics*, vol. 30, no. 2, pp. 143–149, 2013.

[22] P. H. Bischoff and S. H. Perry, "Compressive behaviour of concrete at high strain rates," *Materials and Structures*, vol. 24, no. 6, pp. 425–450, 1991.

[23] X. B. Li, T. S. Lok, J. Zhao, and P. J. Zhao, "Oscillation elimination in the Hopkinson bar apparatus and resultant complete dynamic stress-strain curves for rocks," *International Journal of Rock Mechanics and Mining Sciences*, vol. 37, no. 7, pp. 1055–1060, 2000.

[24] Y. Zhou, J. Gao, Z. Sun, and W. Qu, "A fundamental study on compressive strength, static and dynamic elastic moduli of young concrete," *Construction and Building Materials*, vol. 98, pp. 137–145, 2015.

[25] D. K. Panesar and B. Shindman, "Elastic properties of self consolidating concrete," *Construction and Building Materials*, vol. 25, no. 8, pp. 3334–3344, 2011.