Advanced Materials Research *Online: 2012-09-28*
ISSN: 1662-8985, Vol. 568, pp 147-153
doi:10.4028/www.scientific.net/AMR.568.147

Effect of dynamic loading on mechanical properties of concrete

Jiwei Deng [1, 2, a], Changwu Liu [1, 2, b] and Jianfeng Liu [1, 2, c]

[1]State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China;

[2]College of Water Resource and Hydropower, Sichuan University, Chengdu 610065, China

[a]minddeng@163.com, [b]xxssd@263.net, [c]Ljf7908@yahoo.com.cn

Key words: Concrete; uniaxial compression test; loading rate; mechanical characteristics

Abstract. Concrete structures have to bear dynamic loads in daily work, strength and deformation characteristics of concrete under dynamic loads differ from the characteristics under static loads, and this difference may become a key factor to restrict the structural safety under certain conditions. Using the MTS815 test system, the dynamic uniaxial compression tests of concrete specimens were conducted. The mechanical characteristic parameters of strength, elastic modulus, peak strain and the stress-strain curves at different loading rates of concrete specimens have been studied. The results reveal that concrete is a rate-sensitive material, as a small loading rate may lead to the rapid growth of strength; the variation rule of peak strain is not obvious with the increase of loading rate, thus the peak strain can be regarded as a fixed value in actual projects; the higher the loading rate is, the greater the concrete strength and the elastic modulus are; the elastic modulus increases essentially due to the improvement of structural stiffness; concrete specimens with the same mix proportion have similar stress-strain curves and the loading rate has little effect on the shape of the curve.

Introduction

Concrete structures have to bear a variety of dynamic loads in daily work, such as earthquakes, explosions and wind loads. The strength and deformation characteristics of concrete under dynamic loads differ from the characteristics under static loads, and this difference may become a key factor to restrict the structural safety under certain conditions [1].

Since people found that the compressive strength of concrete has the rate sensitivity in uniaxial compression tests in 1917, many domestic and foreign scholars have done a series of dynamic load tests to study the concrete material [2]. In the past, researches were mainly concentrated on the mechanical properties of concrete under high strain rates when concrete structures beard impact loads, such as shells, bombs and explosions, but the study of structures in the course of normal use had not been paid enough attention to [3].

Owing to the effect of experiment equipments and technical constraints as well as the shortage of concrete specimens in experiments, the test results were not accurate and different researchers got different results. Thus the awareness of the mechanical properties of concrete under dynamic loading, such as the effect of the increase of loading rate on the improvement of strength, is still in controversy.

In response to the issues above, the dynamic uniaxial compression tests of concrete specimens with the strength grades from C30 to C60 were conducted at the loading rates from 0.002mm/s to 7mm/s, to study the mechanical characteristic parameters of strength, elastic modulus, peak strain and the stress-strain curves at different loading rates of concrete specimens. This is of great significance to realizing the dynamic mechanical properties of concrete and the improvement of the dynamic design of concrete structures as well as the ensuring of structural safety.

Introduction of the Experiment

Experimental Equipment. The test was carried out on the MTS815 program-controlled servo concrete and rock mechanics test system in the College of Water Resource and Hydropower of Sichuan University. The MTS815 system is a all-digital computer control system noting load, stress, displacement and strain values, and synchronously drawing the load–displacement and the stress-strain curve when a experiment is conducted.

Specimen Preparation. The concrete specimens used in the test were standard cylindrical specimens with the size of 100mm in diameter and 200mm in height. The Mount Emei brand ordinary Portland cement, coarse aggregate consisted of gravel with a maximum particle size of 15mm, fine aggregate comprised of medium sand and the local drinking water were used as materials to make concrete specimens. The mix proportions of concrete are shown in Table 1.

Table 1 Mix proportions of concrete [kg/m^3]

strength grade	cement grade	cement	water	sand	gravel
C30	P·O 32.5	478	210	616	1 096
C40	P·O 42.5	524	220	630	1 026
C50	P·O 52.5	481	173	645	1 098
C60	P·O 52.5	518	176	594	1 105

Experimental Program. The dynamic uniaxial compression tests of concrete specimens with the strength grades of C30, C40, C50 and C60 were conducted at the loading rates of 0.002, 0.02, 0.2, 1 and 7mm/s. In order to reduce the impact of discrete data on the results, each case contains nine test specimens and 180 specimens in total. The loading rate of 0.002mm/s, the corresponding strain rate is about $10^{-5}s^{-1}$, is regarded as the static loading rate, and the compressive strength is seen as the static compressive strength. All tests were loaded to the residual strength stage to analyze the stress-strain curves.

Experimental Results and Analysis

Loading Rate on the Compressive Strength. The compressive strength of concrete specimens under different loading rates are shown in Fig. 1 (to distinguish the compressive strength images, images of C50 and C40 are shifted left and right in the figure, and so are the Fig. 2 and Fig. 3). From Fig. 1, in the same strength grade, the compressive strength of concrete specimens under dynamic loading are generally greater than the strength under static loading, and with the raising of loading rate, the dynamic compressive strength tend to increase. Under the same loading rate, the compressive strength of the C30 specimens are the lowest, and the strength of C40 and C50 are close to each other while the strength of C60 are slightly higher than the C40 and C50 specimens. What's more, the static compressive strength of C50 and C60 specimens are lower than their corresponding design strength of 50MPa and 60MPa. The probably reason of this phenomenon is that the P·O 52.5 cement used in this test is partly damped after the analysis of the whole experiment process.

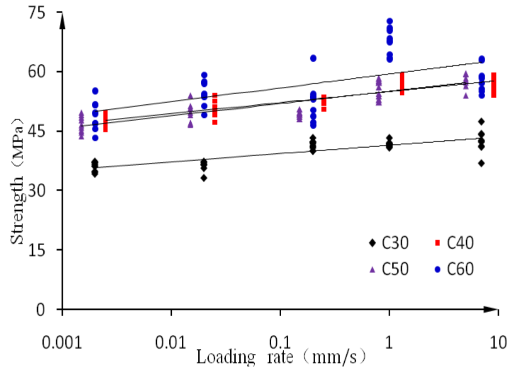


Fig. 1 Compressive strength under different loading rates

The images of the formulas fitting the compressive strength are shown in Fig. 1, and the compressive strength and loading rate meet the form of Eq. (1) in these formulas.

$$f_c = a \cdot \ln \varepsilon_v' + \beta \tag{1}$$

Where ε_v' is the loading rate and f_c is the compressive strength, while α and β are the fitting coefficients. The fitting results of α and β are listed in Table 2.

Table 2 Fitting values of formula parameters

strength grade	C30	C40	C50	C60
α	0.90	1.22	1.34	1.52
β	41.46	55.34	54.07	59.42

Table 2 shows that, the concrete compressive strength of the same strength grade raises while the loading rate increases; the higher the concrete strength grade is, the bigger the coefficient α is, indicating that the increase in loading rate has greater impact on the compressive strength of concrete with the higher strength grade.

Eq. (2) is the derivative of Eq. (1), and the conclusion can be draw from Eq. (1) that the growth speed of strength slows down with the increase of loading rate.

$$f_c' = \frac{a}{\varepsilon_v'} \tag{2}$$

Where f_c' is the growth rate of the compressive strength.

According to the average compressive strength of concrete specimens at different loading rates (Table 3), strength of C30 and C40 specimens increases by 2.2% and 5.9% related to the static load when the loading rate is 0.02mm/s; the strength of C30 and C40 specimens increases only 1.9% and 0.6% related to the loading rate of 1mm/s when the loading rate is 7mm/s. That indicates the concrete is a rate-sensitive material, and the increase of loading rate can lead to the rapid growth of strength when the loading rate is small, but when it is big enough, the effect of a further increase of loading rate declines.

Table 3 Mean values of the strength under different loading rates [MPa]

strength grade	loading rate [mm/s]				
	0.002	0.02	0.2	1	7
C30	36.08	36.86	41.62	41.72	42.51
C40	47.77	50.60	52.60	56.75	57.09
C50	46.82	49.65	47.41	55.61	57.84
C60	48.98	54.89	52.39	67.68	58.27

Loading Rate on the Peak Strain. The peak strain corresponding to the maximum stress of specimens under different loading rates are shown in Fig 2. The peak strain values are very small and discrete, and the variation rule of the peak strain of concrete specimens with the same strength grade is not obvious with the increase of loading rate from Fig 2. The peak strains of C30 specimens are smaller than other specimens, and the peak strains of C40, C50 and C60 are close to each other. Combined with Fig 1, the conclusion that the peak strain of concrete has certain relationship with its compressive strength may be drawn. Therefore, in actual projects the peak strain can be seen as a fixed value related to the concrete strength grade rather than the loading rate.

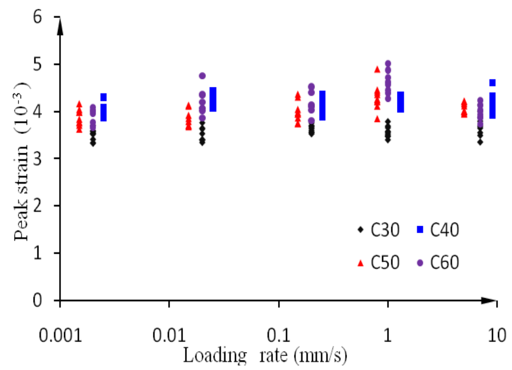


Fig. 2 Concrete peak strain under different loading rates

Loading Rate on Secant Modulus. The stress-strain curve is approximately a straight line when the stress is between 20% and 70% of the compressive strength analyzed from of the stress-strain curves of different specimens, and the secant modulus is taken from 0.5 times the compressive strength at the stress-strain curve in this test.

Combined with the secant modulus at different loading rates in Fig 3, the secant modulus of concrete specimens with the same strength grade improve along with the increase of loading rate; and under the same loading rate, the secant modulus is relatively greater if the strength grade is higher, as the data shown in Table 4.

Compared the data in Table 4 with Table 3, the secant modulus growth rates of concrete specimens with different strength grades are different under the same loading rate related to their static load, indicating that the increase of loading rate does not directly affect the growth of the concrete secant modulus. While under each loading rate, $\sigma_{C40}/\sigma_{C30}$ shows a good correspondence with E_{C40}/E_{C30}, and the former ratio is about 1.2 times the latter one, demonstrating that the growth of elastic modulus relates to the growth of the compressive strength of the test specimens.

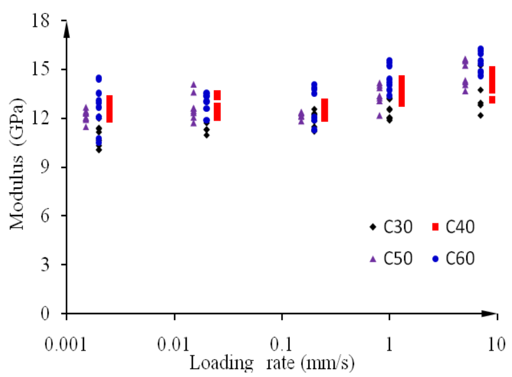


Fig 3 Concrete secant modulus under different loading rates

The reason is that, the increase in loading rate leads to the reduction of internal cracks in test specimens, and the viscous effect of internal free water in material results to the improvement of structure resistance, preventing the deformation and failure of specimens and improving the stiffness of concrete material, thus causing the increase in secant modulus. Therefore the essence of the increases of concrete elastic modulus along with the loading rate is due to the increase in specimen stiffness rather than the increase of loading rate itself.

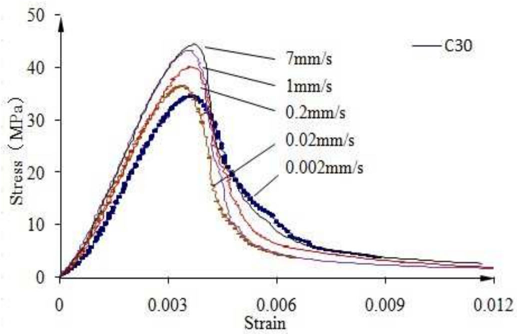
Table 4 Mean secant modulus under different loading rates [GPa]

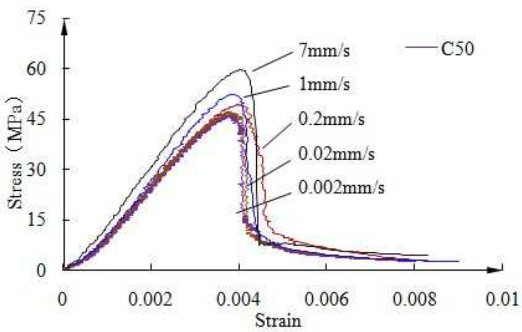
strength grade	loading rate [mm/s] 0.002	0.02	0.2	1	7
C30	11.00	11.04	11.76	12.26	12.97
C40	12.27	12.35	12.40	13.65	13.90
C50	12.15	12.66	11.44	13.19	14.41
C60	12.69	12.73	12.79	14.46	15.36

Loading Rate on the Stress-Strain Curve. The stress-strain curves of C40, C50 and C60 are similar to each other from the image statistics, so only the curves of typical specimens of C30 and C50 under different loading rates are shown in Fig 4.

From Fig 4, the stress-strain curves of concrete specimens with the same mix proportion are similar to each other and the loading rate has little effect on the shape of the curves. The greater the loading rate is, the higher the stress is to produce the same strain, the longer the linear elastic stage is in the stress-strain curve, and the higher the stress yield point is. With the increase of the loading rate, the ascend stage of the stress-strain curve approximately turns to a straight line, and the area that the curve surrounded is bigger, indicating that more energy is absorbed. When the strength grade is greater, stress decreases more rapidly to the residual strength with the growth of the strain, and the destruction of concrete material is more likely to be brittle failure.

Though the mathematical description of the concrete stress-strain curve is quite a lot, such as polynomial, rational fraction, power function and exponential form, a universal concrete constitutive model has not yet been established, and the commonly used models are the Guo-Zhenhai model and the CEB-FIP model.





(a) (b)

Fig. 4 Typical specimen stress-strain curves under different loading rates

The Guo-Zhenhai model adopts a sectional function to simulate the ascending and descending stages of the stress-strain curve, the model is shown as Eq. (3) [4].

$$\begin{cases} y = bx + (3-2b)x^2 + (b-2)x^3 & 0 \le x \le 1 \\ y = \dfrac{x}{a(x-1)^2 + x} & x \ge 1 \end{cases} \tag{3}$$

Where σ/f is the vertical coordinate Y, $\varepsilon/\varepsilon_c$ is the abscissa X, and ε_c is the peak strain. X and Y in Eq. (4) and Eq. (5) have the same meanings with Eq. (2) and will not be repeated again.

CEB-FIP model adopts Eq. (4) to simulate the unified stress-strain curves.

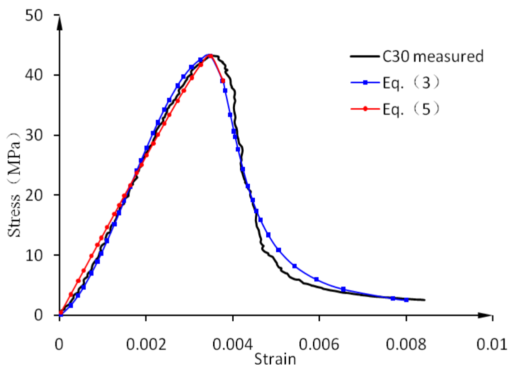
$$\mathrm{y} = \frac{ax - x^2}{1 + (a-2)x} \tag{4}$$

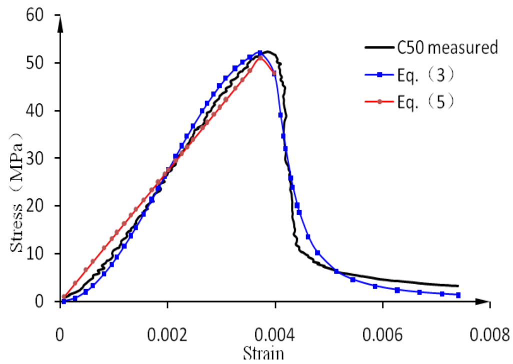
Where $a=E_p/E_{pr} \geq 1$, and E_0 is the initial elastic modulus while E_c is the secant elastic modulus at the maximum stress.

The error of this model is large, so some scholars improved it as the Eq. (5) shows.

$$\begin{cases} y = \dfrac{ax - x^2}{1 + (a-2)x} & 0 \le x \le 1 \\ y = \dfrac{x}{a(x-1)^2 + x} & x \ge 1 \end{cases} \tag{5}$$

In this paper, Eq. (3) and Eq. (5) are used to simulate the concrete stress-strain curves, using the method of minimum squares to fit the measured data in experiment, and the fitting results are shown in Fig. 5.





(a) (b)

Fig. 5 Fitting results of stress-strain curves of typical specimens

From Fig. 5, the CEB-FIP model and the Guo-Zhenhai model can simulate the stress-strain curve at the ascent stage well enough, but the ascent stage of the CEB-FIP model is approximately a straight line, which has a lager error in compaction stage and yield stage than the Guo-Zhenhai model. Both models use the same formula to simulate the descending stage of the curve, so their images overlap with each other. The destruction of C30 concrete specimens show ductile failure and both models simulate the stress-strain curve well from the damage stage to the residual stage. The C40, C50 and C60 specimens with the higher strength grades tend to brittle failure, but the simulation results of the curves are ductile failures, and the simulated results of the residual stress are lower than the measured data, thus the two models have large errors to simulate the stress-strain curve of brittle failure.

Conclusions

(1)Concrete is a rate-sensitive material, so the dynamic compressive strength is higher than the static compressive strength; The increase of loading rate can lead to the rapid growth of the compressive strength when the loading rate is small, but if the loading rate is big enough, the effect of a further increase of loading rate declines.

(2)The peak strain values are very small and discrete, and the variation rule of peak strain of the same strength grade concrete is not obvious with the increase of loading rate. The peak strain can be seen as a fixed value related to the concrete strength grade rather than the loading rate in actual projects.

(3)The secant modulus of concrete with the same strength grade improves along with the increase of loading rate; and under the same loading rate, the secant modulus is relatively greater if the strength grade is higher. The essence of the increases of concrete elastic modulus along with the loading rate is due to the increase in specimen stiffness rather than the increase of loading rate itself.

(4)The stress-strain curves of concrete specimens with the same mix proportion are similar to each other and the loading rate has little effect on the shape of the curves. The CEB-FIP model and the Guo-Zhenhai model can simulate the stress-strain curve at the ascent stage well enough. Both models simulate the descending stage of the stress-strain curve well when the failure of the specimen is ductile failure, but the fitting error is large if it is brittle failure.

Acknowledgement

Supporting Funds: National Key Basic Research Development Program (973 Program) (NO. 2010CB226802);

National Natural Science Foundation-Funded Projects (NO. 50879049);

National Natural Science Foundation &Coal Fund United Key Projects (NO. 51134018)

Reference

[1] Jishu Sun: Concrete. Vol. 6 (2011), p. 49-52

[2] Dongming Yan: Experimental and Theoretical Study on the Dynamic Properties of Concrete (Dalian University of Technology Publication, China 2006).

[3] Jiarui Qi: Concrete. Vol. 2 (2010), p. 48-52

[4] Yidong Xu: Building Technician. Vol. 1 (2009), p. 17-19

Advanced Research on Civil Engineering and Material Engineering
10.4028/www.scientific.net/AMR.568

Effect of Dynamic Loading on Mechanical Properties of Concrete
10.4028/www.scientific.net/AMR.568.147

DOI References

[2] Dongming Yan: Experimental and Theoretical Study on the Dynamic Properties of Concrete (Dalian University of Technology Publication, China 2006).
10.1007/BF02841230