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Dynamic properties of concrete in direct tension

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Abstract

An experimental study on the strain-rate dependent behavior of concrete in tension was carried out by means of a servo-hydraulic testing machine. The specimens were made in dumbbell shape and the tested strain rate ranged from 10^{-5}/s to $10^{-0.3}$/s. Strain-rate effects on the tensile strength, the modulus of elasticity, the critical strain, the Poisson's ratio and the energy absorption capacity of concrete were studied. More emphasis was placed on the influence of temperature and moisture content on the strain-rate sensitivity. All test data were analyzed, discussed and compared with available reference materials. In addition, strain-rate effects on the damage pattern of specimens were studied. It was observed that the fractured surfaces of the specimens became more and more flattened and a number of coarse aggregates were broken along the failure surfaces. Based on this phenomenon an explanation to the physical mechanisms of strain-rate enhancement during rapid loading was proposed.
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Keywords: Concrete; Strain-rate effect; Tensile strength; Moisture content; Temperature effect; Failure behavior

1. Introduction

Concrete is a material that is sensitive to the rate of loading. For various dynamic loadings which concrete structures are subjected to, such as earthquake shock, impact or explosion, the strain rates can be of different orders of magnitudes. Moreover, such rate-dependent behavior is affected by environment factors to a great extent. These factors, such as temperature, moisture content, etc., have to be taken into consideration, because concrete may be dry, partially wet or completely wet. In some areas of China, in winter concrete may be exposed to a temperature as low as −30 °C. Understanding the dynamic behavior of concrete under various circumstances is an issue of great significance for application in civil engineering.

A lot of efforts have been dedicated to the research in this field [1–5]. More emphasis has been placed on the compressive behavior, for which more data is available, and less on the tensile response, because the behavior in compression is more easily measured. The effect of strain rate on the strength of concrete is typically represented as a dynamic increase factor (DIF), i.e., the ratio of dynamic to static strength versus strain rate on a semi-log or log–log scale. Various test devices and procedures have been used in the study [2], such as splitting Hopkinson pressure bar (SHPB), impact of dropping weight and close-in explosions. In these researches, the sizes of the specimens were usually relatively small: for impact tests, the specimens' diameters were 2 in. (51 mm) [4]; while for SHPB, specimens with diameters varying from 0.5 to 2 in. (12.7 to 51 mm) were used [5,6]. Most research studied the dynamic tensile strength and modulus of elasticity. Some tests studied the effect of moisture content on the dynamic properties but the strain rates were limited to a quite narrow range. Malvar and Ross [2] reviewed the strain-rate effect in tension. They concluded that DIF might be expressed as a bilinear function of strain rate in a log–log plot with a slope change at a strain rate $\dot{\varepsilon}_c$ of 1.0/s. Beyond this critical point, even more significant increases in strength were observed. It differs somewhat from the CEB (Comite Euro-international du Beton) model code [7], which gives $\dot{\varepsilon}_c = 30$/s. In reality, slope change takes place not at a definite point, but in a transition region, which depends on a great many factors. Zielinski et al. [8] experimented on wet and dry concrete and found that there was no definite change of dynamic tensile strength when the moisture condition changed.

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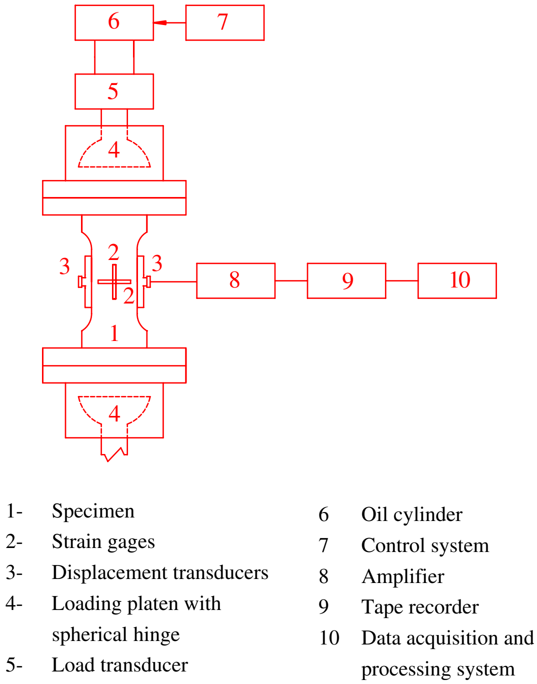

Fig. 1. Schematic diagram of testing system.

Several investigators have reported strength increases in wet concrete greater than those exhibited by dry concrete. Rossi and Van Mier [3] considered that it was the free water contained in micropores of concrete which caused the increase of strength at high strain rate. Many hypotheses concerning the physical mechanisms of strain-rate enhancement have been proposed. Founded upon experimental and analytical works on micro-concrete, Rossi and Toutlemonde [9] came to the following conclusions: (1) at strain rate smaller than approximately 1.0/s, the main physical mechanism was a viscous mechanism similar to the Stéfan effect [10] that countered the development and propagation of macrocracks. (2) At strain rates greater than or equal to approximately 10/s, the forces of inertia became predominant. (3) The viscous effects together with the forces of inertia also had the consequence of increasing the Young's modulus of the concrete but to a much smaller extent than the tensile strength. Cadoni et al. [11] used Hopkinson Bar Bundle (HBB) to carry out experiments on large sized concrete specimens of 20 cm cubes with aggregates from powder to 25 mm maximum size. The specimens were subjected to different curing conditions to study the effect of internal humidity conditions on the strain-rate enhancement. They confirmed that the level of free water inside the concrete had an important influence on the sensitivity of the concrete response. In addition, they proposed a wave propagation concept for the physical explanation of the phenomenon. They found that stress waves running across the voids and microcracks in concrete led to a considerable increase in stress in that region, while voids filled up with free water would reduce the damage. A survey of literature shows that there is still a lack of test data concerning the effect of temperature on the strain-rate sensitivity of concrete. Furthermore, due to the difference in loading instrument, data acquisition system and the diversity of the specimens, the available information on dynamic response of concrete subjected to uniaxial tension is conflicting. Further work, in particular more test data, is needed.

This paper aims to obtain more realistic characterization of concrete in tension for the application in earthquake engineering. Dynamic experiments were performed with larger sized specimens and different experimental technique. More emphasis was placed on the effect of temperature and moisture content on the strain-rate sensitivity. The strain rates covered a range from 10^{-5}/s to nearly 10^{0}/s. The strain-rate effects on the tensile strength, elastic modulus, critical strain, Poisson's ratio and energy absorption capacity were systematically studied. Based on the experimental results a concept for physical explanation of strain-rate enhancement during rapid loading was proposed.

2. Experimental analysis

2.1. Experimental setup

Dynamic tests were performed using an MTS 810 testing machine. The machine is a programmable displacement-controlled loading system and can produce tensile and compressive loads at a maximum nominal rate up to 150 mm/s. Its force capacity is 100 kN and stiffness is 2.6×10^{8} N/s. The measurement system consists of DPM-8H strain amplifier, INV306D intelligent signal processor and DASP software. The highest frequency can reach up to 10^{4} Hz. Foil strain gauges, 50 mm in length and 5 mm in width, were used to measure strain histories during dynamic fracture process. Two crossed gauges were glued onto the middle of each side of specimen to measure the longitudinal and transverse strains respectively. In addition, two pairs of Linear Variable Differential Transformer (LVDT) were fixed on the specimens to measure the displacement after the appearance of cracks. A tape recorder was also used for recording data at higher strain rates. Two computers were used in the experiments: one served as control system and the other as data acquisition system (see Fig. 1).

2.2. Specimens

The specimens for tension test were dumbbell-shaped, as shown in Fig. 2 and the accompanying specimens were cubic,

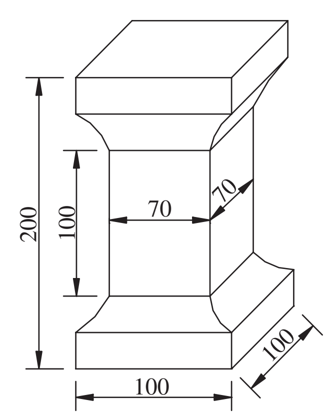

Fig. 2. Dimensions of dumbbell-shaped specimen (unit: mm).

Table 1
Concrete mixes used for specimens

Designed 28-day strengths	Cement	Water	Gravel	Sand
10 MPa	1.00	1.02	5.35	4.38
20 MPa	1.00	0.69	3.93	2.63

100 mm in length, which were used to measure the compressive strength and splitting strength. Two types of concrete mixtures were used and they were designed to have characteristic 28-day compressive strength of 10 MPa and 20 MPa respectively. The mix proportions are listed in Table 1. The materials used were type 32.5 R Portland cement, general river sand, tap water, and crushed gravel. The maximum grain size was 10 mm. This choice was a compromise between the need to employ a concrete representative of those used in industrial applications and the desire to have a reasonable scale of heterogeneity with respect to the dimensions of the specimens. Both dumbbell-shaped specimens and cubic specimens were cast in steel molds and compacted by vibrator. Having been demolded in the next day, they were put in a water tank for 2 days, and then cured in a fogroom for 28 days; afterwards they were naturally cured in the laboratory. The average values of measured compressive strengths and the splitting strengths at 28 days are listed in Table 2.

All the dumbbell-shaped specimens were tested within 10 days. So it was regarded that the properties of concrete specimens did not change during the period of testing. No one group of the specimens with its datum exceeding the average of the whole group by 15% was observed among the 37 groups obtained during curing. This ensured the reliability of the test results.

2.3. Experimental procedure

2.3.1. Treatment of specimens

Specimens were tested with different water contents and different temperature environments, and they were divided into five groups: A, B, C, D and E. Table 3 presents characteristics of the specimens of each group including water–cement ratio, water content and temperature.

After taking the specimens out of the laboratory, polishing four side surfaces with sand paper, scrubbed out sundries on the surfaces by acetone, the pair of strain gauges were attached onto each side surface by epoxy. Once the strength of epoxy reached a certain value, the strain gauges were covered with paraffin to prevent the change in their resistance caused by the change of temperature and water content. The frames used to fix the LVDT were also stuck onto the two opposite side surfaces. Both

Table 2
Strengths of concretes at 28 days

Designed 28-day strengths	Compressive strength (MPa)	Splitting strength (MPa)
10 MPa	10.7	0.83
20 MPa	21.2	2.33

Table 3
Characteristics of the specimens

Group	w/c	Water content (%)	Temperature at testing (°C)
A	0.69	0.3	20
B	1.02	0.3	20
C	0.69	4.8	20
D	0.69	0.3 [a]	−30
E	0.69	4.8 [a]	−30

[a] Water content measured before congealment.

ends of the specimens were attached to steel plates by JGN-II structural adhesive made in China, which has a tensile strength of 35 MPa and is widely used in building construction.

For Groups A and B, the specimens were tested soon after the above-mentioned preparations have been made, they were kept in the room temperature with normal water content, 0.3% (by weight). For Group C, when the above-mentioned preparations had been finished, the specimens were submerged in tap water for 60 h (too long time would influence the hydration of the concrete specimens). According to the experiments performed beforehand, the specimens could be fully saturated (the water content was 4.8% by weight) if they were kept in water no less than 60 h. For Group D, prior to testing, the specimens were put in a low-temperature chamber for 70 h, which was maintained at nearly −30 °C (actually −32 to −28 °C). For Group E, after curing under water for 60 h, they were covered with a layer of plastic sheet, and then put into the low-temperature chamber for 70 h. Thus, only a small amount of water contained in the specimens could be lost during the freezing process.

2.3.2. Setting of specimens and testing device

The tensile tests were carried out soon after all the preparations were completed. The specimen was placed on the MTS experimental apparatus, then the two steel end plates of the specimen were fixed to the upper and lower heads of the testing machine with the help of 8 bolts (18 mm in diameter). Preliminarily adjustments were made to align the central line of the specimen with the centerline of applied load. Then an initial pressure of 0.5 MPa was applied to check whether the deformations of the four longitudinal strains were close to each other. If not, the bolts were unloaded and readjusted. When the final state appeared satisfactory, the displacement transducers were fixed, the initial voltage of the load amplifier adjusted, then the initial values were collected and the computer's acquisition system was zeroed. Finally, a load up to the failure of specimen was applied. The total time for a tensile test was less than 10 min.

3. Test results and discussion

The range of strain rate typically for earthquake loading is commonly from 10^{-4}/s to 10^{-1}/s. In this study, we investigated the strain rates of 10^{-5}/s, 10^{-4}/s, 10^{-3}/s, 10^{-2}/s, 10^{-1}/s, 10^{0}/s respectively for specimens belonging to Groups A, B and C and strain rates of 10^{-5}/s, 10^{-3}/s, 10^{-1}/s for specimens belonging to Group D. Limited by the capacity of loading system, the highest strain rate actually reached was $10^{-0.3}$ /s. Considering the fact that the tensile strength of fully saturated concrete under low temperature of −30 °C is sufficiently high, i.e. several times that of the concrete under room temperature, the strength enhancement with loading rate is of minor interest, and thus the tests of Group E were conducted only at a quasi-static strain rate (10^{-5}/s).

3.1. Strength characteristics

The test results are presented in Table 4. The values of tensile strength were recorded to be the maximum axial stress during each test. Control cubes were tested simultaneously with the direct tension tests to obtain the splitting tensile strength and compressive strength. The values of f_c and f_s are also listed in this table.

By least square curve fitting of the experimental data, the DIF may be expressed as a linear function of strain rate on the semi-log scale.

In this study, the quasi-static strength, i.e. the starting point of the curve where DIF = 1, is chosen as 10^{-5}/s. In the literature, this value is around 10^{-5}/s to 10^{-8}/s. Malvar and Ross [2] assumed 10^{-6}/s. CEB curves [7] start at 30×10^{-6}/s which is closer to the recommendation of ASTM C496 for a standard tensile splitting test. In the region 10^{-6}/s to 10^{-5}/s, the DIF is relatively insensitive to the strain rate.

Formulas for Groups A, B, C and D are given below.

For Group A:

$$\mathrm{DIF} = 1.0 + 0.134\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{1}$$

where DIF $= f_t/f_{ts}$; f_t = dynamic tensile strength at $\dot{\varepsilon}_t$; f_{ts} = quasi-static tensile strength at $\dot{\varepsilon}_{ts}$; $\dot{\varepsilon}_t$ = strain rate in the range from 10^{-5} to $10^{-0.3}$/s; $\dot{\varepsilon}_{ts}$ = quasi-static strain rate, 10^{-5}/s.

Table 4
Strengths of specimens

Group	Strain rate (1/s)	Number of specimens	f_t (MPa)	f_c (MPa)	f_s (MPa)
A	10^{-5}	5	2.21	32.8	3.21
	10^{-4}	3	2.39		
	10^{-3}	3	2.79		
	10^{-2}	6	2.87		
	10^{-1}	4	3.40		
	$10^{-0.3}$	3	3.93		
B	10^{-5}	4	1.18	17.9	1.94
	10^{-4}	3	1.36		
	10^{-3}	3	1.44		
	10^{-2}	3	1.54		
	10^{-1}	5	1.82		
	$10^{-0.3}$	4	1.88		
C	10^{-5}	3	1.30	24.46	2.45
	10^{-4}	3	1.59		
	10^{-3}	3	1.82		
	10^{-2}	3	2.20		
	10^{-1}	3	2.70		
	$10^{-0.3}$	3	3.07		
D	10^{-5}	3	2.53	33.3	3.76
	10^{-3}	4	2.93		
	10^{-1}	4	3.79		
E	10^{-5}	4	6.32	40.2	6.47

For Group B:

$$\mathrm{DIF} = 1.0 + 0.135\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{2}$$

For Group C:

$$\mathrm{DIF} = 1.0 + 0.265\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{3}$$

For Group D:

$$\mathrm{DIF} = 1.0 + 0.115\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{4}$$

It is seen that the general trend of strength enhancement with strain rates is very similar to that given in the literature for relatively small specimens [2]. Viscous resistance due to the presence of free water in concrete appears to have an important effect on strain-rate sensitivity. Comparison between Eq. (1) and Eq. (3) shows that the strength increases in fully saturated concrete are much greater than those experienced by concrete with normal moisture content. As regards to the effect of moisture content on the static strength, quite different phenomena are observed. The static strength decreases in fully saturated concrete at 1.30 MPa as compared to the concrete with normal moisture content at 2.21 MPa (see Table 4). This is due to the fact that the presence of moisture forces the gel particles apart and reduces the van der Waals forces [12].

Unlike the results from other studies [13], where concrete with the lower compressive strength exhibited the higher DIF in tension; in our study, no appreciable strength increase for specimens of Group A with f_c = 32.8 MPa as compared to that for Group B with f_c = 17.9 MPa (see Eqs. (1) and (2)) was observed.

It is generally considered that lower strength concrete is less dense than the higher strength one, i.e., it possesses more micropores, the viscous resistance becomes more pronounced, this results in the higher DIF in tension. However, this is not always the case, for example, in our situation, the mix proportion has been optimized; the lower strength concrete is nearly as dense as that of the higher strength one. This might be the reason why in our case the lower strength concrete has nearly the same DIF as that of higher strength one.

In our experiment it was observed that the free water in micropores of the specimens had frozen under very low temperature. The frozen water also contributes to the resistance of concrete. In quasi-static tests, the tensile strength of concrete with normal water content at −30 °C (2.53 MPa) is higher than that at room temperature (20 °C; 2.21 MPa) by 14.5%. However, in a comparison made between Group D and Group A (see Eqs. (1) and (4)) we noticed that when subjected to rapid loading, the strength enhancement for specimens at low temperature (−30 °C) is not so sensitive to the loading rate as that for specimens at room temperature (20 °C). This may be attributed to the fact that the resistance of frozen water is less sensitive to the loading rate than the viscous resistance of free water.

Fully saturated specimens under low temperature (−30 °C) display significant increases in quasi-static strength than that under room temperature (20 °C). From comparison between the results of Group E and that of Group A, this ratio reaches

a. Strain rate: 10^{-5}/s **b. Strain rate: 10^{-3}/s** **c. Strain rate: $10^{-0.3}$/s**

Fig. 3. Figure of typical rupture of specimen.

6.32 MPa/2.21 MPa = 2.96 (see Table 4). And it was observed that in this case when specimens were loaded up to failure very loud sound could be created, which might indicate higher brittleness of the frozen concrete.

From these results it can be inferred that frozen concrete possess very high strength and it is less sensitive to the loading rate.

It was found that the fractured surfaces of the specimens became more and more flattened with the increasing strain rate; and an increasing number of coarse aggregates were broken along the fractured surfaces, typical modes of which are depicted in Figs. 3 and 4.

These phenomena remind us that the experimentally observed strain-rate enhancements can be physically explained based on the microstructure and properties of concrete. Concrete is a composite material mainly consisting of different sized aggregate particles which are embedded in a cement paste matrix. Many researches show that a large number of bond microcracks exist at the interfaces between coarse aggregate and mortar [14,15]. Under loading action some of the microcracks can be developed due to the difference in stiffness between aggregates and mortar. Thus, the aggregate–mortar interface constitutes the weakest link in the composite system. In case of quasi-static loading, the failure is closely associated with the mechanism of internal progressive microcracking. At first, the bond cracks at the aggregate–mortar interface start to extend owing to stress concentration at crack tips. Then, some cracks at nearby aggregate surfaces start to bridge in the form of mortar cracks, meanwhile, other bond cracks continue to grow slowly. Finally, the microcracks through the mortar coalesce together all the bond cracks and complete disruption occurs. The fracture surface of the specimen mainly passes through the mortar and the aggregate–mortar interfaces. This leads to a rough surface (see Figs. 3a and 4a). However, crack velocity in concrete has been shown experimentally to increase with strain rate [16]. Therefore, at low strain rates crack has time to seek the path of least resistance. However, when subjected to rapid loading, the creation of new cracks is forced to propagate through regions of greater resistance, and a greater amount of microcrack may be required before a continuous fracture surface can be formed. Thus, a certain part of coarse aggregates are broken during loading and the fractured surfaces of the specimens become more flattened (see Fig. 3b and c, also Fig. 4b and c). The higher the loading rate, the more fractured coarse aggregates.

As a consequence, at rapid loading, failure will take place at a higher stress level than that in static loading. Comparing Eq. (1) (condition of room temperature and normal water content) with the formula proposed by Malvar and Ross [2], it is revealed that in our cases strength enhancement with strain rates is greater than that given by Malvar and Ross [2]. Table 5 shows the comparison of our results with that recommended by Malvar and Ross [2] and the CEB model code [7]. This is due to the fact that the presence of coarse aggregates leads to the larger force needed to break them into pieces. This gives an explanation to

a. Strain rate: 10^{-5}/s **b. Strain rate: 10^{-3}/s** **c. Strain rate: $10^{-0.3}$/s**

Fig. 4. Typical fracture surfaces at different strain rates.

Table 5
Comparison of different formula on the strength enhancement with increasing strain rate

	Strain rate (/s)					
	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}
CEB model code	1.000	1.082	1.171	1.267	1.371	1.483
Malvar's formulation	1.000	1.088	1.184	1.289	1.402	1.526
Eq. (1)	1.000	1.134	1.268	1.402	1.536	1.670

the physical mechanism of strain-rate enhancement. It is the higher resistance of concrete material attributed to the strength of coarse aggregates that result in a higher stress level to bring them to failure.

3.2. Deformation behavior and energy absorption capacity

The creation of cracks on the surface of the specimen gradually changes the uniformity of the deformation of the specimen. The value of strain recorded by a strain gauge is, actually, an average within the measurement coverage of the gauge or LVDT. Typical stress–strain curves of saturated concrete specimens in Group C are shown in Fig. 5.

3.2.1. Modulus of elasticity

The modulus of elasticity is typically calculated as either a secant or a chord modulus. A secant modulus is calculated from the origin to a defined point on the stress–strain curve, usually within 30% to 60% of the sample's ultimate strength. The chord modulus is usually evaluated according to ASTM C 469 between the stress and strain pairs at 50 millionths strain and at 40% of the ultimate strength. In this study, the dynamic and static elastic modulus were measured as the chord modulus according to ASTM C 469-02.

Many researchers have reported that at rapid loading a higher modulus is obtained [12,17,9]. It is the viscous resistance of free water and the resistance of coarse aggregates in concrete which delay both the creation of microcracks and the propagation of initial microcracks. These actions delay the development of cracks and increase the Young's modulus. As pointed out by Rossi and Toutlemonde [9], the viscous resistance, or the Stéfan effect has a greater influence on the strength than on the Young's modulus. As a consequence, the strain rate affects the Young's modulus to a much smaller extent than the tensile strength. In this study, the average values of the modulus observed in the quasi-static test for Groups A, B and C are 2.86×10^4 MPa, 2.03×10^4 MPa and 1.89×10^4 MPa respectively. The relative rate that elastic modulus increases with the strain rate is summarized in Table 6.

By least squares linear regression, formulas are obtained to express the ratio of dynamic to static elastic modulus as a function of strain rate shown below.

For Group A:

$$E_t/E_{ts} = 1.0 + 0.023\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{5}$$

For Group B:

$$E_t/E_{ts} = 1.0 + 0.037\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{6}$$

For Group C:

$$E_t/E_{ts} = 1.0 + 0.188\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{7}$$

In these equations, E_t is the modulus of elasticity; and E_{ts} is the quasi-static modulus of elasticity (at a strain rate of 10^{-5}/s).

As described previously in the case of tensile strength, the static elastic modulus of saturated concrete (Group C) is lower than that of concrete with normal water content (Group A). The phenomenon is completely parallel to that of tensile strength (see Section 3.1). The presence of moisture forces the gel particles apart, so that static elastic modulus of saturated concrete (Group C) is lower than that of concrete with normal water content (Group A). And due to the viscous resistance of free water in micropores the strain-rate enhancement of elastic modulus of saturated concrete (Group C) is more significant than that of concrete with normal water content (Group A) (see Eqs. (5) and (7)).

In general, the strain-rate enhancement for modulus of elasticity is less pronounced than that for tensile strength. Though some difference exists between the strength DIF of Group D (under low temperature condition) and that of Group A (under room temperature condition) (see Eqs. (4) and (1)), the slighter difference between the strain-rate dependence of E_t/E_{ts} of Group A and Group D observed in this study may be considered possible. As the effect of temperature on the strain-rate sensitivity of modulus of elasticity is a problem less reported in the literature, more studies are needed to improve our knowledge in this field.

3.2.2. Critical strain

Data fit of the stress–strain curves obtained for different strain rates shows that at higher strain rate the peak of the stress becomes sharper (see Fig. 5). Many investigators have studied the effect of strain rate on the critical strain (strain at peak stress); most studies pay regard to the compressive behaviors.

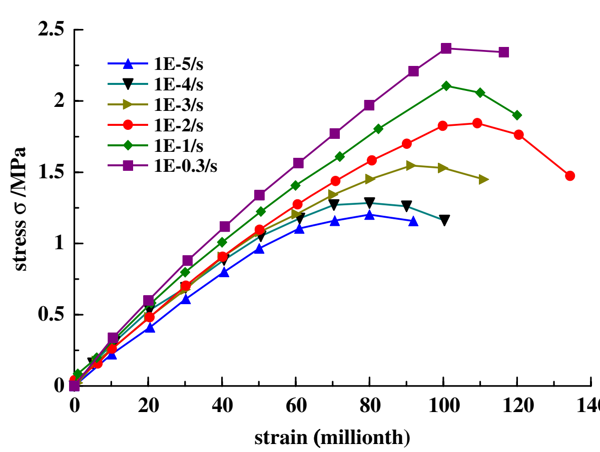

Fig. 5. Typical stress–strain curves of saturated concrete (Group C).

Table 6
Relative increase of elastic modulus

Group	Strain rate (/s)				
	10^{-4}	10^{-3}	10^{-2}	10^{-1}	$10^{-0.3}$
A	4.0%	9.0%	10.1%	11.4%	12.1%
B	1.3%	4.9%	9.3%	12.0%	18.0%
C	28.3%	30.8%	45.8%	70.7%	100.1%

The experimental results obtained by different authors are contradictory. Some indicate an increase of the critical strain at peak stress and some a decrease as strain rate increases. Bazant and Oh [18] suggested a slight increase of critical strain with increasing strain rate. Bischoff and Perry [1] summarized the results of previous research; they found the change in critical compressive strain ranged from a decrease of 30% to an increase of 40% for strain rates up to 10/s when compared to the static loading case of 10^{-5}/s. According to their opinion, most results showed that the average increase could vary from 10% to 30% (where negative results had largely been discounted) for strain rates as high as 10/s, it was less than the average increase of 60% to 80% in the compressive strength and also significantly less than the 250% increase expected for the critical tensile strain at comparable strain rates. They supposed the discrepancy of the results could be due to variation in test methods, leading to different failure pattern, or simply because of deficiencies in the measurement technique. The SHPB test conducted by Grote et al. [19] at very high strain rates ranging from 290/s to 1500/s showed that the critical compressive strain increased slightly with increasing strain rate. However, the amount of increase was very small and might well be within the range of experimental error.

In this study, an increasing tendency of critical tensile strain with the increasing strain rate is observed for each group of the tests.

At quasi-static strain rate, the strains corresponding to the peak stress for Groups A, B, C are 73.8×10^{-6}, 70.1×10^{-6} and 75.0×10^{-6} respectively. The critical strain gradually increases as strain rate increases. By least squares regression, the curves that fit well with the experimental data can be expressed as follows.

For Group A:

$$\varepsilon_p/\varepsilon_{ps} = 1.0 + 0.203\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{8}$$

For Group B:

$$\varepsilon_p/\varepsilon_{ps} = 1.0 + 0.109\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{9}$$

For Group C:

$$\varepsilon_p/\varepsilon_{ps} = 1.0 + 0.067\log(\dot{\varepsilon}_t/\dot{\varepsilon}_{ts}) \tag{10}$$

wherein ε_p denotes the strain corresponding to the peak stress at strain rate $\dot{\varepsilon}_t$; ε_{ps} denotes the strain corresponding to the peak stress at quasi-static strain rate $\dot{\varepsilon}_{ts}$, 10^{-5}/s.

A comparison made between Eqs. (8), (10) and Eqs. (5), (7) shows opposite tendencies for the strain-rate effect of moisture content on the critical strain from that on the modulus of elasticity. This may partly be due to the fact that the critical strain is mainly affected by the static strength [1], and the presence of moisture reduces the static strength [12]. This is a matter that very few works have actually been discussed.

Comparing Eq. (8) with Eq. (9) indicates that stronger concretes normally possess a greater critical strain than weaker concretes, this agrees with the point of view of Bischoff and Perry [1] on the compressive behavior of concrete, a stronger material should exhibit greater deformation.

For the same reason as that for the modulus of elasticity, temperature exerts insignificant influence on the strain-rate sensitivity of critical strain. No much change of the tendencies of critical strain along with strain rate between Group D and Group A exists. This may have some relation with the fact that the critical strain is mainly controlled by the static strength. It is interesting to note that the static strength of Group D (33.3 MPa) approaches that of the Group A (32.8 MPa) (see Table 4). In addition, the factors that affect strain-rate dependence of critical strain are not well known; it is still a problem of contentiousness, and more research is required.

Table 7
Suggested Poisson's ratio for each group

	Group			
	A	B	C	D
Poisson's ratio	0.16	0.15	0.17	0.15

3.2.3. Poisson's ratio

The specimens of Groups A, B, C and D were equipped with both longitudinal and transverse strain gauges in order to assess all the deformation behaviors. From the test results obtained, it seems that there is no definite increasing or decreasing tendency for Poisson's ratio with the increasing strain rate for all the groups tested. For example, the Poisson's ratios obtained in Group A vary from 0.12 to 0.18 and it seems to keep constant with the variation of strain rate. Thus the Poisson's ratio is suggested as 0.16 for Group A. Accordingly the Poisson's ratios for Groups B, C and D are suggested as listed in Table 7.

Very little information concerning the strain-rate effect on Poisson's ratio is available. CEB recommendations [7] assume that Poisson' ratio is independent of loading rate, because of the scarcity of results. Takeda and Tachikawa [20] noticed an increase in Poisson's ratio for concrete loaded in tension during rapid loading. Paulmann and Steinert [21] did not observed any changes in Poisson's ratio for strain rate as high as 0.2/s.

Table 8
Relative increase in energy absorption capacity

Group	Strain rate (/s)				
	10^{-4}	10^{-3}	10^{-2}	10^{-1}	$10^{-0.3}$
A	1%	55%	63%	70%	91%
B	30%	31%	47%	68%	74%
C	28%	54%	78%	70%	134%

3.2.4. Energy absorption capacity

Energy absorption capacity can be defined as the area under the stress–strain curve up to the peak stress level. In comparison with the results of quasi-static tests, there is a considerable increasing trend in energy absorption capacity at higher stain rates. The relative increase at higher strain rates is summarized in Table 8. This tendency is attributed primarily to the fact that due to strain-rate enhancement behavior of concrete, at higher strain rate fracture is forced to propagate through region of greater resistance, e.g., along with the increases of strain rate, some aggregate–mortar cracking may be changed through aggregate cracking, thus a higher stress level is needed to bring the specimens to failure, and the energy absorption capacity increases.

4. Conclusions

Based on the researches cited above the main conclusions are summarized as follows:

(a) The general trend of strength enhancement with strain rates is similar to that given in the literature for relatively small specimens, but a more intensive strength increase in our cases is exhibited. The presence of free water in concrete has an important effect on the strain-rate dependence; saturated concrete has displayed more significant increases in strength with strain rate. At low temperature of −30 °C, the strength increase is less sensitive to strain rate than the concrete under room temperature condition.

(b) Strain-rate enhancement for modulus of elasticity is less pronounced than that for tensile strength. Temperature condition exerts little influence on the strain-rate sensitivity of the elastic modulus and also on the critical strain. Critical strain increases slightly with increasing strain rate. The strain-rate effect of moisture content shows opposite tendencies on the critical strain than on the elastic modulus. Stronger concrete possesses a greater critical strain than weaker concretes. No definite increase of Poisson's ratio was observed. Energy absorption capacity significantly increases with the increasing strain rate for both saturated concrete and concretes with normal water content.

(c) Founded upon experimental observation an explanation on the physical mechanisms of strain-rate enhancement is proposed. At rapid loading cracks are forced to propagate through regions of greater resistance and thus a higher stress level is needed to bring the specimens to failure. And the fractured surfaces become more and more flattened with the increasing strain rate. Due to the presence of coarse aggregates, large forces are required to break them into pieces along the failure surface.

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