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THE INFLUENCE OF THE STRAIN RATE ON THE STRENGTH OF CONCRETE TAKING INTO ACCOUNT THE EXPERIMENTAL TECHNIQUES

Małgorzata PAJĄK*

*Dr.; Faculty of Civil Engineering, The Silesian University of Technology, Akademicka, 44-100 Gliwice, Poland
E-mail address: *malgorzata.pajak@polsl.pl*

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Abstract

Based on extensive literature review the behaviour of concrete under wide range of compressive and tensile strain rates is presented. The dynamic compressive strength of concrete can achieve the value of DIF (dynamic increase factor) equal about 3.5, and the dynamic tensile strength even 13. However, the strain rate response of concrete in tension and compression in all range of strain rate differs much. In compression strain rate sensitivity should be investigated in two domains, because of the shift of test results. The reason of division is probably connected with influence of the method of testing and especially with the specimen shape and size. The article presents also the strain rate sensitivity of new types of cement-based materials, like RPC, which appears not to differ much from the sensitivity of normal concrete.

Streszczenie

W artykule, w oparciu o szeroki przegląd literaturowy, przeanalizowano zachowanie betonu poddanego szerokiemu zakresowi ściskających i rozciągających szybkości przemieszczeń. Wytrzymałość betonu poddanego dynamicznym szybkościom przemieszczeń ściskających może osiągnąć 3.5-krotną wartość wytrzymałości statycznej. Dynamiczne szybkości przemieszczeń rozciągających mogą spowodować, że beton osiągnie aż 13-krotną wartość wytrzymałości statycznej. Jednakże odpowiedź betonu na szybkości przemieszczeń rozciągających znacznie się rożni od odpowiedzi betonu na szybkości przemieszczeń ściskających. Wrażliwość betonu na szybkość przemieszczeń ściskających powinna być rozważana w dwóch zakresach, ze względu na skok wyników badań. Przyczyna tego podziału jest prawdopodobnie związana z metodą badania, a w szczególności z wymiarami i kształtem próbek. W artykule zostały również przeanalizowane nowego typu materiały, takie jak RPC, których zachowanie okazało się nie odbiegać od zachowania betonu zwykłego.

Keywords: **Concrete; Strain rate; Compressive strength; Tensile strength; Method of testing.**

1. INTRODUCTION

The behaviour of concrete structures under different strain rates has been extensively studied. Many concrete structures can be affected by high strain rates coming from different sources, like natural hazards (tornadoes, earthquakes or ocean waves) or industrial accidents (Figure 1) [1]. The example of concrete structure can be a nuclear power station, which must be prepared to withstand dynamic loads due to explosions and impact loadings. To properly design the concrete structure for all types of loadings the understanding of concrete behaviour under wide range of strain rate is required.

Abrams was the first researcher who noted, in the 1917, that the response of concrete under wide range of strain rates differs from what is observed under quasi-static condition [2]. Further, many investigators confirmed the rate effect on strength, strain and modulus of elasticity of concrete in compression, tension and bending. Researchers proved the influence or lack of influence of the parameters like moisture content, temperature or type of gravel on rate dependence of concrete. The discussion in this article is focused on the experimentally observed strain rate effect on mechanical properties of concrete in compression and tension with taking into account the experimental techniques and related to them specimen shape and size.

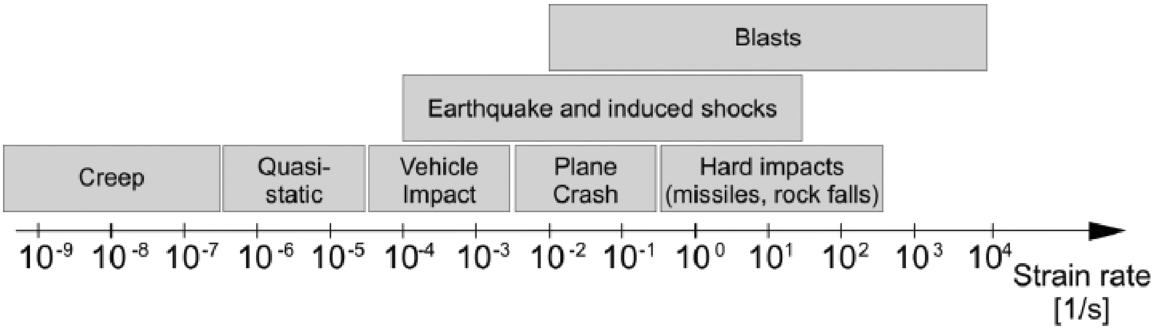

Figure 1.
Strain rate according to real loads [1]

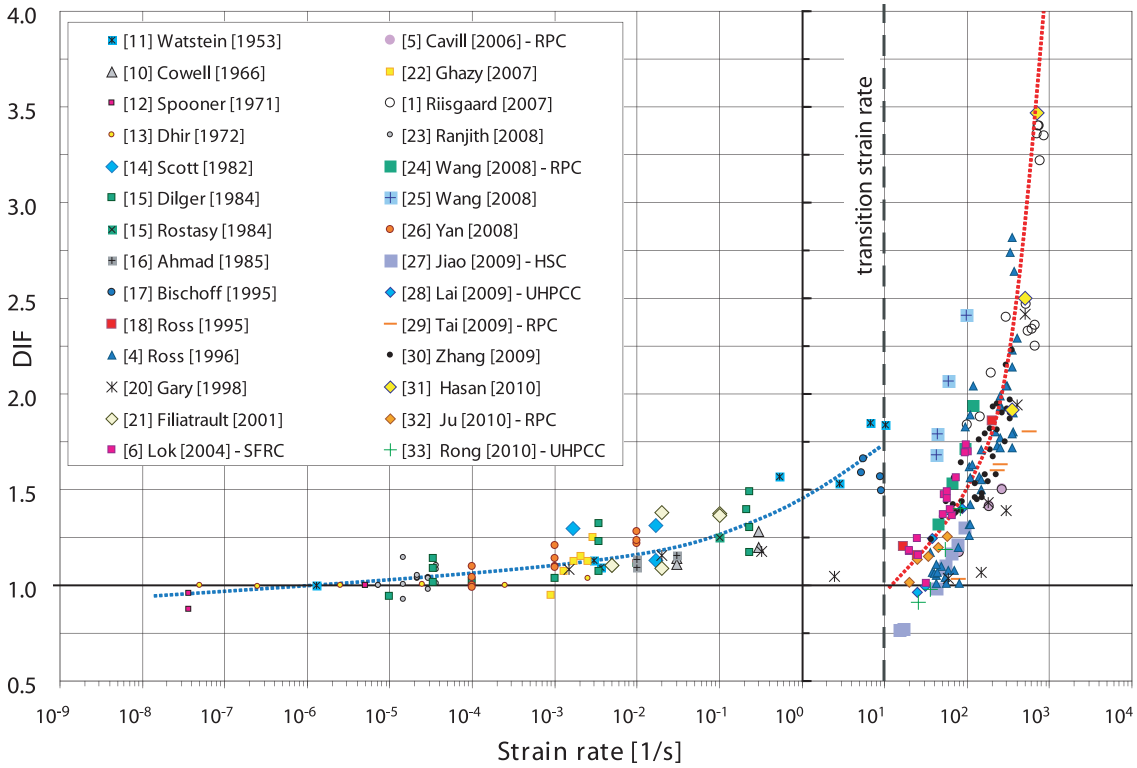

Figure 2.
Strain rate effect on compressive strength of concrete

2. THE INFLUENCE OF THE STRAIN RATE ON THE STRENGTH OF CONCRETE

A summary of available test data of concrete and other cement-based materials subjected to different compressive and tensile strain rates are presented respectively in Figure 2 and Figure 3. The results are presented as DIF versus log of strain rate. Dynamic increase factor (DIF) is defined as the ratio of the dynamic strength to quasi-static strength. Such definition of DIF is optimal because it normalizes different quasi-static initial strengths due to different specimen scale and different maturity [3,4].

In this paper not only normal concrete is considered. Nowadays, many new types of cement-based materials are used. The development of technology let to improve many properties of normal concrete, like strength and durability. An example of new type of ultra-high-performance concrete can be the reactive powder concrete (RPC), which is widely investigated because of its common use [5]. In Figure 2 all new

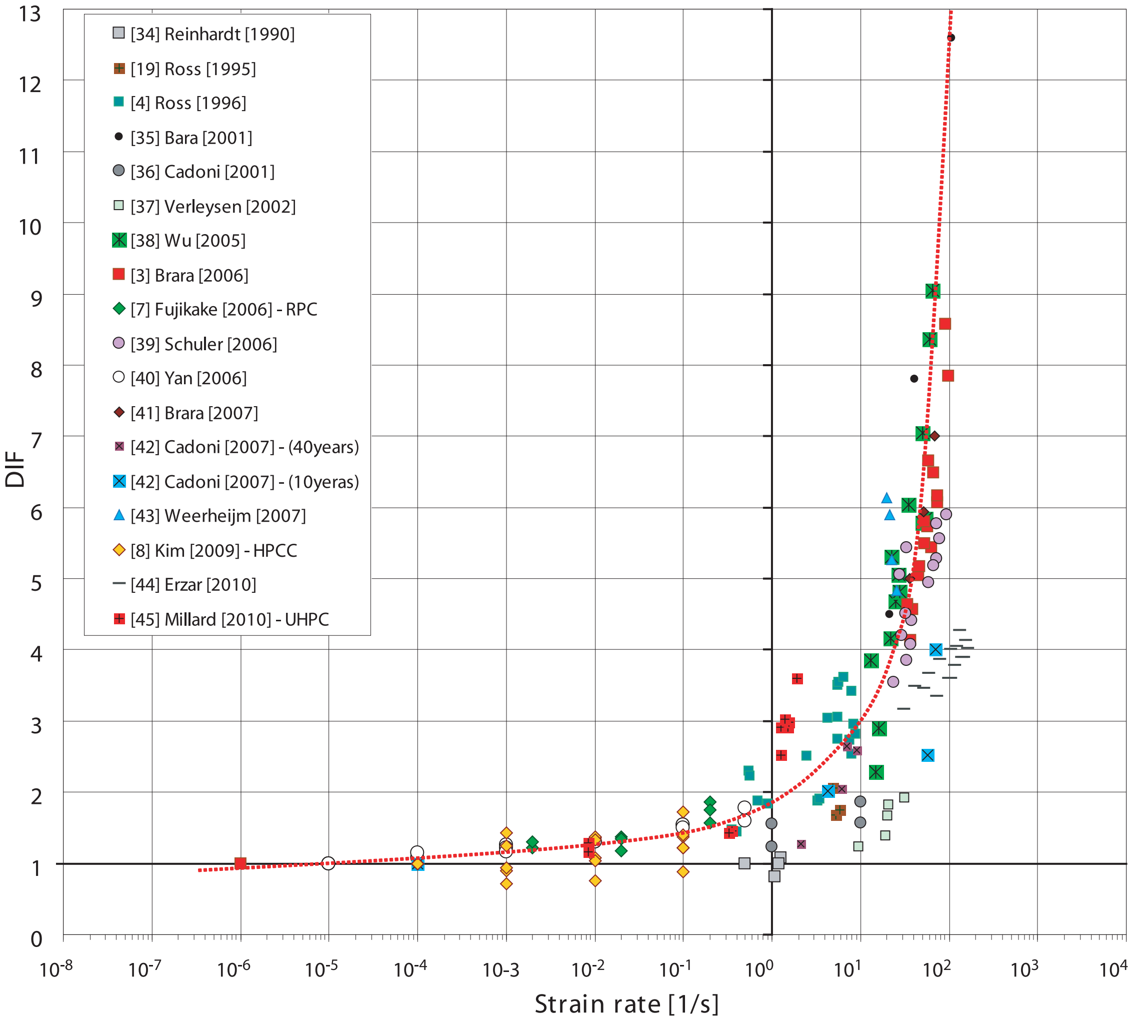

Figure 3.
Strain rate effect on tensile strength of concrete

types of materials are pointed: UHPCC – ultra high performance cementitious composites, HSC – high strength concrete. One of the most important ingredients of new types of cement-based materials are steel fibers. Figure 2 and Figure 3 present also the results obtained from tests on cement-based materials with the addition of steel fibers (Figure 2: Cavill [5], Lok [6] 0.6%; Figure 3: Fujikake [7] 2%, Kim [8] 1%). According to Pająk [9] the addition of steel fibers usually used in structures, less than 2% of volume fraction, does not affect the strain rate sensitivity of concrete.

All collected results are direct form the authors' work, apart from Cowell's results, which were redrawn after Cotsovos [10].

2.1. Strain rate sensitivity of concrete in compression

Analyzing Figure 2 an increase in concrete strength with increasing strain rate can be observed. However, the results cannot be approximate with one line. All range of strain rates should be investigated in two domains according to the behaviour of concrete. In the first region the slow increase in concrete strength with the increasing strain rate can be observed. The maximum dynamic compressive strength in this range is equal to about 1.8 times the quasi-static strength (blue line). In the second range of strain rates the response of concrete is changing. The shift of the results can be seen with the pronounced strength increase. The DIF factor achieves the values from 1.0 or even less than 1.0 to about 3.5 (red line). The value of strain rate in which the answer is changing is called the transition strain rate. Many authors assign the transition strain rate as the strain rate: 60-80 [1/s] – Ross [19,4]; ~10 [1/s] – Bischoff [18]; Brara [3]. In the author's opinion the transition strain rate for compression is close to 10 [1/s] as is shown in Figure 2. Maybe, the question should be not the position of transition strain rate, but the real cause of the shift of the presented results shown in Figure 2? Probably there are some factors that strongly influence the results and causes their shift? This issue will be discussed later on it this paper.

2.2. Strain rate sensitivity of concrete in tension

The strain rate sensitivity of concrete in tension is graphically presented in Figure 3. The significant increase of tensile strength, about 13 times the quasi-static strength, with the increasing strain rate can be observed. The available results indicate that behaviour of concrete under different tensile strain rates is more uniform in comparison to compression. In the author's opinion the transition strain rate cannot be assigned so, there is only one line to describe the response of concrete in wide range of strain rates. However, some researchers assigned the transition strain rate: ~1 [1/s] – Brara [3]; 5 [1/s] – Ross [19]; 1-10 [1/s] – Ross [4].

2.3. Comparison of the strain rate compression and tension response of concrete

The comparison of results of concrete in wide range of compressive and tensile strain rates is shown in Figure 4. The rate effect is pronouncedly higher in tension than in compression. In the author's opinion there are no significant differences in behaviour of concrete in compression and tension for strain rates lower than 10^{-1} [1/s]. The real differences in the behaviour of concrete appear for higher strain rates. The large increase in strength of concrete starts for lower strain rates in tensile than in compression. In tensile the DIF factor seem to increase asymptotically to strain rate about $2 \cdot 10^{2}$ [1/s] to reach the value about 13.0. Whereas, in compression the asymptote is about 10^{3} [1/s] with the maximum value of DIF = 3.5.

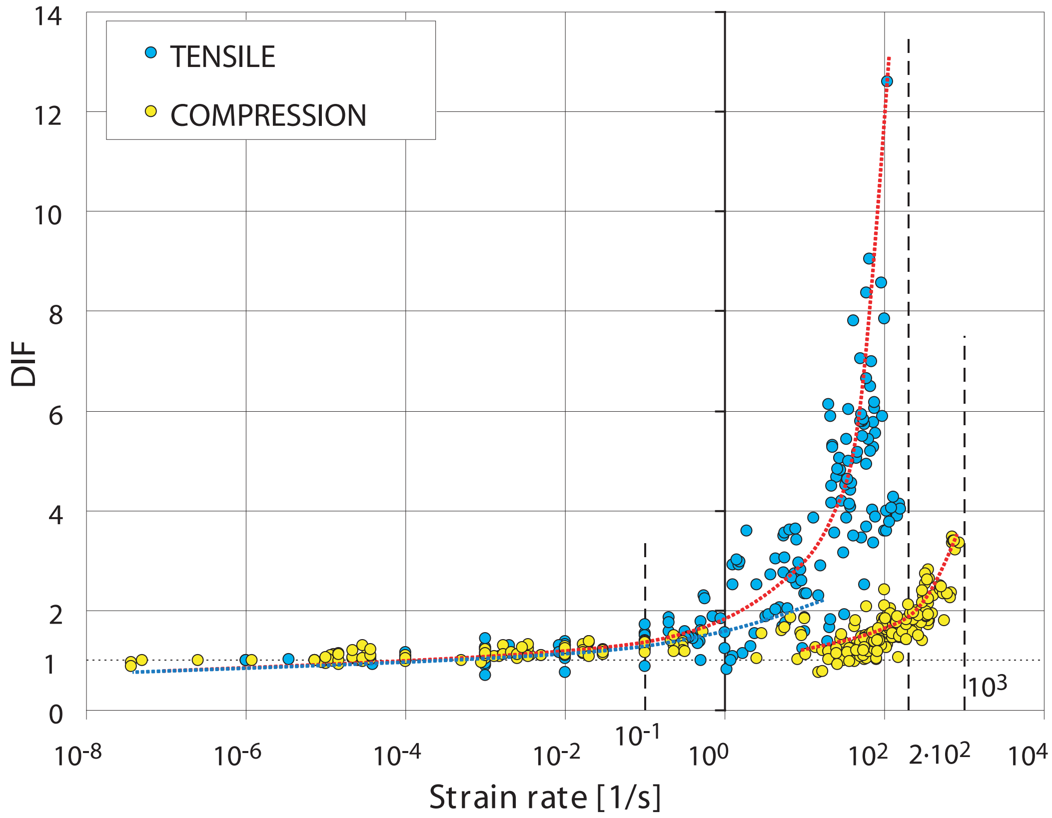

Figure 4.
Comparison of strain rate effect on tensile and compressive strength

2.4. Strain rate sensitivity of new cement-based materials

No apparent differences in the strain rate sensitivity of new types cement-based materials in comparison to normal concrete were observed. The values of DIF factor achieved for new types of cement-based materials in compression and tensile did not differ much from the values of DIF obtained for normal concrete. This materials are characterized by very high strength of concrete, which may be even 800 MPa! [32]. However, the ultimate strength of the materials presented in this paper is not much over 300 MPa. Thus, probably the ultimate strength of concrete is the factor that does not affect the strain rate sensitivity of concrete.

3. THE INFLUENCE OF THE EXPERIMENTAL TECHNIQUE ON THE STRAIN RATE SENSITIVITY OF CONCRETE

All presented results are characterized by scatter, what is associated with, among others, different testing techniques, size and shape of specimens.

To study the behaviour of concrete under wide range

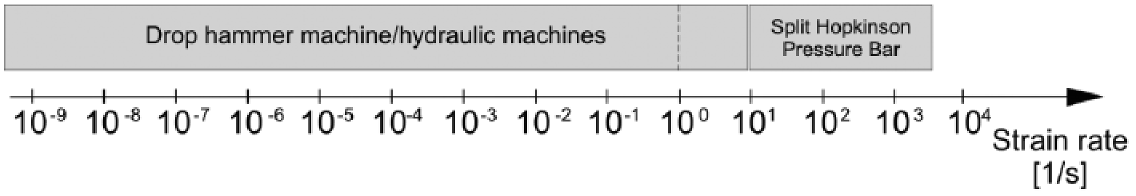

Figure 5.
Strain rates according to typical testing machines

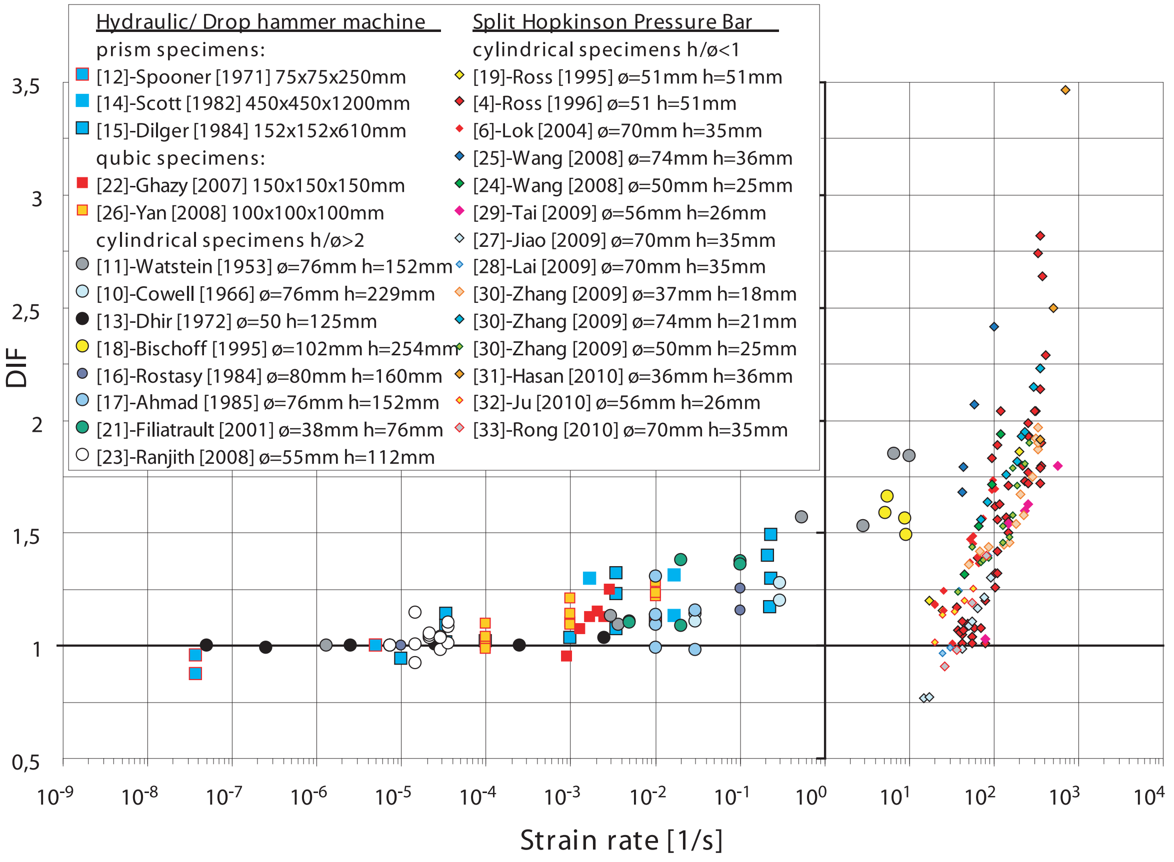

Figure 6.
Strain rate sensitivity of concrete in compression according to specimen shape and size and testing machine

of strain rates three main groups of machines are used: hydraulic machines, drop hammer machines and Split Hopkinson Pressure Bar (SHPB). The range of strain rates that can be investigated in the use of each machine is presented in the Figure 5. There are also two more testing machines: Taylor Anvil and Flyer Plate. Unfortunately, there is a lack of available tests conducted with the use of this machines, so it is not considered in this paper.

To examine the influence of these factors on the behaviour of concrete in compression (Figure 6) and tensile (Figure 8) the results were distinguished according to the method of testing and specimen size and shape.

3.1. Compression

Comparing Figure 2 and Figure 6, the superposition of the transition strain rate and the method of testing can be observed. The hydraulic and drop hammer machines are not able to achieve the values of strain rates higher than transition strain rates (10 [1/s]). Meanwhile, in the use of the SHPB only strain rates above than transition strain rate can be obtained.

Analyzing research conducted with the use of hydraulic machines and drop-hammer machines, for strain rates less than 10 [1/s], some scatter of results can be observed. These machines let use all shapes (cubic, cylindrical, prismatic) and sizes of the specimens. Based on Figure 6 no apparent differences in strain rate sensitivity of concrete specimens connected with the variety of tested specimens shapes and sizes was observed. However, the ratio of the height of the specimen to its diameter (cylindrical) or width (prism) for all presented results is equal or even bigger than 2, apart from cubic specimens.

In the author's opinion the results obtained from SHPB test are characterized by the biggest scatter. Essential information about the SHPB are necessary for further investigation.

The Split Hopkinson Pressure Bar (SHPB) is used to determine dynamic material behaviour at strain rates between $10^0 \div 10^4$ [1/s]. It was originally developed by Kolsky and modified by Hopkinson [29]. In Figure 7 the main parts of the SHPB are presented: projectile, incident bar, transmitter bar and the specimen [46]. The incident wave is produced by the projectile to propagate into the bar. One part of the wave is transmitted into the specimen and the other part is reflected at the interface between bar and the specimen. In the compression test the transmitted wave causes failure of the specimen. In the tensile test the compressive wave propagates through the specimen to be reflected in the opposite direction at the free end of the specimen. The transmitted bar is usually removed in the tensile test [43]. The reflected tensile wave causes the spall of the specimen. Schuler [39] claims that those experiments are restricted to brittle materials which are characterized by much higher compressive strength than tensile strength. According to Weerheijm [43] the compressive stress wave should be about 30% of quasi-static compressive strength. Erzac claims [44], based on post-mortem studies, that the compressive wave which first propagates through the specimen does not cause any damage in the specimen and has no consequence on the tensile results.

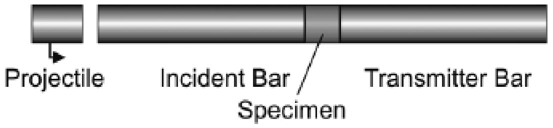

Figure 7.
Split Hopkinson Pressure Bar [46]

The work of this device is based upon one-dimensional wave propagation theory. Two more main assumptions which are the base of SHPB technique are that in the axial direction the stress and strain are uniform while specimen inertia and friction effects are negligible. To ensure the main assumptions it is necessary to reduce as much as possible the diameter of the specimen, what has the biggest influence on the length of the equipment, cause too stocky bars can distort the results. For example the specimen with a diameter of 75 mm should have the equipment 10-12 m long. On the other hand the concrete specimen contains usually large size aggregate, so it should be about several times the size of the aggregate, to be representative for the material. Furthermore, to ensure that inertial effects in the specimen are minimized, the length of the specimen is taken as small as possible [46].

Thus, the variety of dimensions of the specimens used in SHPB is very small. All used specimens have cylindrical shape with the maximum diameter of 75 mm and length up to about 50 mm. The length-diameter ratio (λ) for all presented in this paper specimens is in the ranges of $0.3 \div 1.0$. It is well known, that uniaxial stress state in a specimen is when the is equal to 2, like in the test conducted with the use of hydraulic and drop hammer machines. The stress state in the specimens usually used in SHPB tests is in fact a triaxial strain state, because the reduction of the length of the specimen inevitably contribute to the radial confinement in the specimen. Some researchers call the studies conducted in SHPB tests as "pseudo strain rate effect". Zhang [30] proposes even to conduct corresponding numerical simulations to SHPB laboratory tests, to correct the pseudo strain-rate effects.

It is worth mentioning that, some researchers modified the SHPB to get the machine able to investigate large size specimens. Cadoni presented the machine called Hopkinson Bar Buddle (HBB) which lets analyze the cube specimen with the dimension of 200 × 200 × 200 mm [36]. As it was mentioned earlier, the specimen should be large enough to be representative for the heterogeneous materials like concrete. This purpose was surely achieved. However, Cadoni conducted tests using this machine only in tension and not in compression.

3.2. Tension

Analyzes of the influence of the specimen shape and size and the method of testing on the tensile strain rate sensitivity of concrete were conducted. In Figure 8 the results were distinguished according to specimen size and shape. The letter put after the size of the specimen describes the type of the test: "D" – direct tensile; "S" – split tensile and "F" – flexural tensile. Generally, as it was mentioned before, the tensile results show no shift of the results as it was noted in compression. It can be attributed to the fact that the stress state in direct tensile test is uniaxial. The triaxial stress state is obtained in the specimen in the tensile splitting and flexural tensile tests. However, the scatter of the results obtained from SHPB tests are also very pronounced as it was in compression. However, the results obtained in splitting and flexural tensile test correspond well with the results from direct tensile test. Also the shape and size of the specimens seem not to influence the strain rate sensitivity of concrete.

One more issue should be taken into consideration when talking about scatters of results. The assumption of presenting different results in one figure was to use dynamic increase factor. DIF should be the value from comparison of the specimens with the same shape and size. Unfortunately, in the SHPB test the DIF factor is defined by some researchers as the

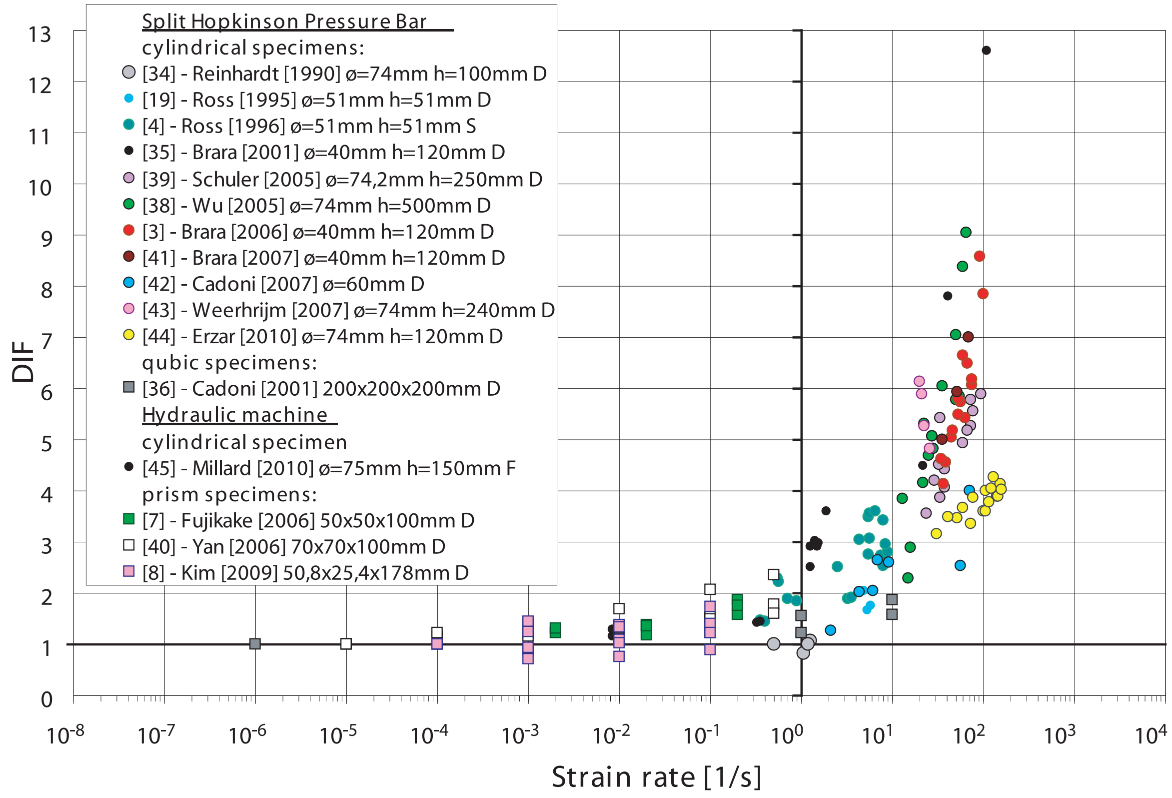

Figure 8.
Strain rate sensitivity of concrete in tension according to specimen shape and size

ratio of dynamic strength established on the small specimens with $\lambda = 0.3 \div 1.0$ to quasi-static strength obtained from the tests on the large specimens with $\lambda = 2.0$ (usually in hydraulic machine). Maybe the values of DIF would be different when dynamic to quasi-static strength is established on the specimens with the same shape and size. For example, Schuler [12] determined the quasi-static tensile strength in the Brazilian tests, while the dynamic strength was conducted in SHPB direct tensile test. However, tests conducted by Ross [19], who used the specimens with the same size for the dynamic and quasi-static tests indicate apparent shift of strain rate sensitivity of concrete in compression (Figure 2).

4. SUMMARY AND CONCLUSIONS

The results of concrete in compression in all range of strain rates indicate that it should be investigated in two domains of strain rates. The strain rate where the answer is changing is called the transition strain rate. In the first region the slow strength increase with the increasing strain rate can be observed. In this range the DIF factor achieves the value about 1.8. The second domain is characterized by pronounced strength increase with DIF equal 3.5. However, there is a shift of the results in the point of the transition strain rate. It was shown that the transition strain rate determine the boundary of the technical scopes of testing machines. For strain rates lower than 10 [1/s] the tests are conducted with the use of hydraulic or drop hammer machines, while for higher strain rates only the SHPB is used. The specimens usually used in this device have the ratio of height to diameter with the range of $\lambda = 0.3 \div 1.0$. Thus, the obtained stress state in the specimen in SHPB test is probably triaxial no uniaxial as it usually is in hydraulic and drop hammer machines. Than, the values of DIF factor are probably affected by the possible triaxial stress state in the specimen. Maybe, this fact is an explanation of the shift of results in compression.

The strain rate sensitivity of concrete in tensile is significant in comparison to compression. The dynamic strength of concrete can achieve the value of 13 times the quasi-static strength. Analyzing presented tensile results under wide range of strain rates no transition strain rate can be pointed out. Generally, the behaviour of concrete under different tensile strain rates is more uniform than in compression, with no shift of the results. The explanation of the lack of the shift (Figure 3) can be the fact that direct tensile test gives the uniaxial stress state.

The comparison of the tensile and compressive strain rate sensitivity was performed in the paper. In the author's opinion the strain rate behaviour of concrete under strain rates about 10^{-1} [1/s] is similar in compression and tensile. The presented comparison indicates that the real differences start from higher strain rates, where the increases of DIF factor are pronouncedly higher in tension than in compression. The results seems to tend to the asymptote, which is about $2 \cdot 10^2$ [1/s] in tension and 10^3 [1/s] in compression.

The specimen shape and size probably do not affect the strain rate response of concrete, providing that the proportions of the specimen dimensions ensure the uniaxial stress state in the specimen, what was discussed earlier.

The tests conducted using hydraulic and drop hammer machine are characterized by less scatter than the research made using SHPB. It is connected with the investigated range of strain rates. The results obtained from SHPB tests are close to each other, but when analyzing one value of strain rate the differences in the values of DIF are very pronounced. The explanation can be the fact that the results from SHPB test are very close to possible asymptote. Further, the time of the test is very short, what can additionally distort the results because of the technical scopes of the measure.

The values of dynamic increase factor obtained from tests of new cement-based materials correspond well to the presented results from the normal concrete tests. This fact leads to conclusion that ultimate strength, much higher for new types of cement-based materials than normal concrete, has no influence on the strain rate sensitivity of concrete.

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