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COMMENTARY - 75 YEARS OF RILEM: MATERIALS AND STRUCTURES

M&S Highlight: Bischoff and Perry (1991), Compressive behaviour of concrete at high strain rates

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The 1991 article by Bischoff and Perry, "Compressive behaviour of concrete at high strain rates" [1], is currently the most-cited article ever published in *Materials and Structures*, with over 1000 citations according to the Scopus database. This article is a very substantial piece at 26 pages in length, and presents a highly detailed literature review and data compilation that summarises the then-current state of the art related to concrete subjected to compressive load as a function of strain rate. The discussion is derived from the 1988 PhD thesis of the first author [2], with the additional inclusion of information from 1988 CEB recommendations. The behaviour of concrete under variable strain rates has been a topic of importance and interest since the groundbreaking publication of Abrams in 1917 [3], and this review has offered an invaluable resource to the community by providing both detailed discussion and graphical summaries of the relevant historical data sets spanning from 1917 until the mid-1980s, which had originally been published in languages including English, German, Japanese, and Swedish. The review covers strain rates from 10^{-8} to 10^3 s^{-1}—i.e., from creep to blast loading (Fig. 1).

The main focus of the review and discussion of Bischoff and Perry [1] is on the higher strain rate range, considering the types of strain rates induced by impacts and blasts. This is an important and challenging range in which to conduct experimental testing, and the review provides key insights and recommendations regarding how such high strain rates can be applied and controlled accurately, and how factors such as inertial effects within the specimen and apparatus can be appropriately incorporated into analysis of the results obtained. There have been obvious advances since the date of publication because of the digitalisation of experimental setups, which has offered a step-change in the ability to control, measure and interpret processes which take place as rapidly as the experiments discussed here, but the wisdom embodied in the recommendations provided by Bischoff and Perry is highlighted by the fact that their paper continues to be used and highly cited 30 years after publication.

The latter sections of the paper of Bischoff and Perry [1] provided discussion of the relationships embodied in the compiled data sets for compressive strength and for deformation behaviour, and analysed

This commentary is part of our celebration of 75 years of RILEM, highlighting Materials and Structures' most highly influential and cited publications.

Highlighted paper: P.H. Bischoff & S.H. Perry (1991). Compressive behaviour of concrete at high strain rates. Materials and Structures 24(6), pp. 425–450.

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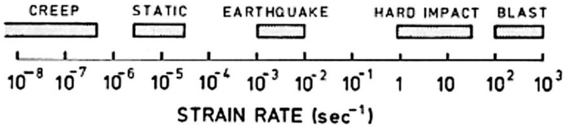

Fig. 1 Magnitudes of strain rates that can be imposed on concretes in compression, classified by Bischoff and Perry [1] according to loading cases which can induce each strain rate. Copyright 1991 RILEM Publications

the physical meanings underpinning some of these. A logarithmic relationship between strain rate and measured uniaxial compressive strength was proposed, with the material returning a higher measured strength (or higher *Dynamic Increase Factor*, DIF, which is defined as the ratio of measured strength at a given strain rate to the static strength) as the strain rate is increased above levels corresponding to static testing ($\sim 10^{-5}$ s^{-1}). There is a very wide scatter in the collected data, Fig. 2, and the 1988 CEB recommendations show a prediction of bilinear behaviour with a change in gradient at a strain rate of 30 s^{-1}. These recommendations contain a concrete grade (compressive strength) dependence which has been updated in later formulations such as the fib Model Code 2010. There is significant difference between various equations that have been proposed, and encoded in standards, to describe the strain rate dependence of compressive strength [4], and the uncertainty and causes of experimental scatter identified by Bischoff and Perry have evidently propagated into the different expressions utilised by different standardisation bodies. This includes discussion at a fundamental level regarding whether the observed high-strain-rate increase in DIF is actually a material property at all, or whether this behaviour is in large part (or even solely) due to lateral confinement from inertial and frictional effects during testing [5, 6]. Bischoff and Perry [1] discussed this as a possible interpretation of the available data, but as a possibility rather than as a confirmed conclusion, and subsequent investigations have further explored this possible interpretation from both experimental and numerical modelling viewpoints as the range of available techniques has advanced over the past 30 years.

The Bischoff and Perry data set is still used as a reference point to provide graphical comparisons of different strain rate dependency relationships and reproduced in other published papers, e.g. [5, 8],

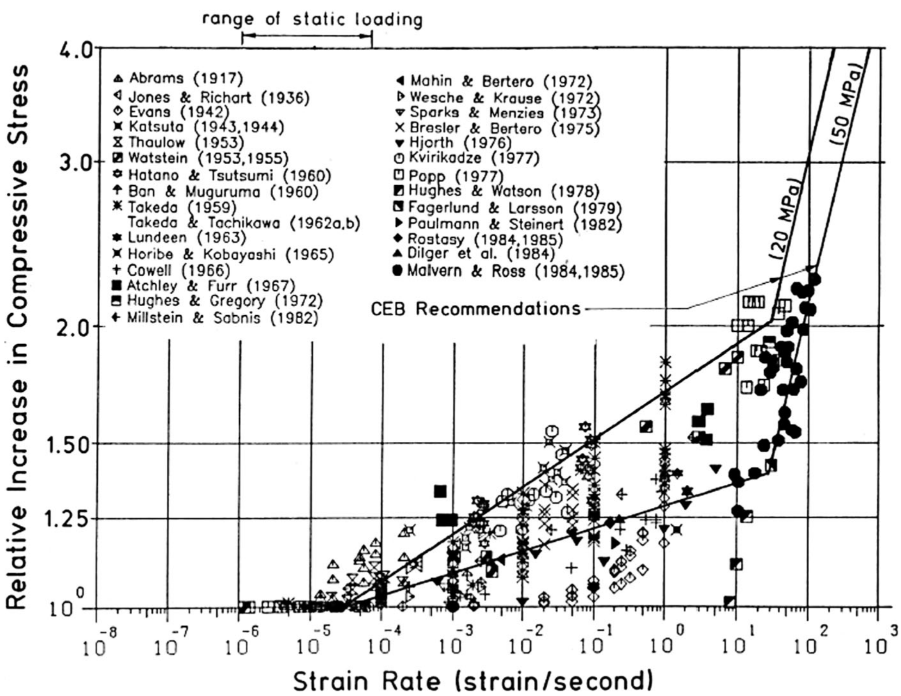

Fig. 2 Influence of strain rate on compressive strength of concretes, along with the 1988 CEB recommendations [7]. Reproduced from [1], Copyright 1991 RILEM Publications

showing the enduring value of this work as a collection and critical assessment of a very large body of data. Their analysis has also been used as a key reference point in studies of materials other than concrete, particularly in the field of rock mechanics [9], and also for analogous studies of concrete under applied tensile force at high strain rates [10]. The influence of moisture on the strain rate dependence of mechanical properties was mentioned only briefly by Bischoff & Perry [1], but subsequent work—including the text of the 1996 RILEM Robert L'Hermite Medal lecture of P. Rossi [11]—has added significant depth to the available technical insight in this area.

Current RILEM work related to this topic includes TC 288-IEC "Impact and Explosion" (https://www.rilem.net/groupe/288-iec-impact-and-explosion-377) which has produced outputs including a database of high strain-rate test facilities [12] and is closely connected to an Action Group of *fib* (TG10.1 AG12, Impact and Explosion). The intention of this group is to ensure that documents such as the *fib* Model Code can enable structural designers to more fully reflect the state of the art in materials testing and development. Such initiatives clearly depend on the availability of high-quality, critically-assessed databases, and this is one of the key contributions which has led the 1991 paper of Bischoff and Perry [1] to be such a prominent and highly-cited contribution to the technical literature, and the most-cited *Materials and Structures* article published to date.

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