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# Dynamic strengths and toughness of an ultra high performance fibre reinforced concrete

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ABSTRACT

The results of dynamic compression, splitting and notched three-point bend tests of the ultra high performance fibre reinforced concrete, known under the trade name CARDIFRC, are presented. The tests have been performed using the Kolsky method and its modifications for dynamic splitting and notched three-point bend testing. The mechanical data (strength, time and energy characteristics) of this material at high strain rates have been obtained. It is shown that these characteristics are sensitive both to the strain rate and to the stress rate. A unified interpretation of these rate effects based on the structural–temporal approach is presented. It is shown that the time dependence of the dynamic compressive and split tensile strengths and of the dynamic toughness of CARDIFRC can be predicted by the incubation time criterion.



## 1. Introduction

An increase in the strength and reliability of construction materials and structures at a reduced cost is one of the main tasks of construction industry. It can be achieved by using new and improved construction materials, such as fibre reinforced concrete. In contrast to ordinary concrete, the fibre reinforced concrete is much stronger in compression, tension and shear, has much higher impact and fatigue resistance, higher toughness, frost resistance, and thermal and fire resistance.

That is why fibre reinforced concrete is a highly suitable material for building structures in the energy sector, for instance solar energy storage water tanks, nuclear containment vessels, etc. Concrete civil and military infrastructure (e.g. buildings, barracks, bridges, tunnels, containment structures for hazardous, toxic materials, inflammable materials, etc.) is susceptible to catastrophic failure under intense sudden overloading (e.g. due to blasts, explosions) for which it is not designed. In the uncertain times facing us these days such infrastructure needs to be made less susceptible by using a material with high energy absorption capacity, such as the fibre reinforced concrete.

CARDIFRC [1–4] is an ultra high performance fibre reinforced cement based composite characterised by high compressive and flexural strengths and high toughness. This has been achieved by the use of a large amount (6% by volume) of 6 and 13 mm long (0.15 mm diameter) brass-coated steel fibres in a dense matrix of cement and silica fume. The matrix contains

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**Nomenclature**

| | |
|---|---|
| $F(t)$ | intensity of the local force field |
| $F_C$ | static limit of the local force field |
| $\tau$ | incubation time |
| $\alpha$ | a parameter sensitive to the level (or amplitude) of the intensity of the local force field |
| $H(t)$ | Heaviside function |
| $\sigma(t)$ | stress |
| $P$ | magnitude of stress |
| $f(t)$ | a function that varies between 0 and 1 over a certain time interval $T$ |
| $\sigma_{\max}$ | maximum stress |
| $\varepsilon_{\max}$ | maximum strain |
| $\tau_{\max}$ | time to the initiation of fracture |
| $\sigma_c^{compr}$ (or $\sigma_{compr}$) | static compressive strength |
| $\sigma_c^{tensile}$ | static split tensile strength |
| $\dot{\sigma}$ | rate of stress rise |
| $\dot{\varepsilon}$ | rate of strain growth |
| $E$ | modulus of elasticity |
| $t^*$ | time to failure |
| $\sigma_*$ | limit stress |

only very fine quartz sands optimally graded to reduce water demand without affecting workability. This is achieved by novel mixing procedures. Computerized Tomography imaging and image analysis of cut sections have confirmed that these procedures ensure remarkably homogeneous mixes with a uniform distribution of fibres [2].

A correct and rational analysis of dynamically loaded structures requires an understanding of the behaviour of the mechanical properties of materials at high strain rates. Therefore a study of the behaviour of modern construction materials at high rates of deformation and fracture is necessary. The study of the behaviour of concrete and other building materials under dynamic loading has engaged the attention of many researchers [5–21]. Many dynamic tests of concrete were conducted by Malvern et al. [5,6], Ross et al. [7–10] and Malvar and Ross [11]. Bischoff and Perry [12] provided a review of the behaviour of concrete under compression at high strain-rates. Malvar and Crawford [13] described the effect of strain rate on the tensile strength of concrete. Bragov et al. [14] carried out dynamic compressive testing of cement-based materials on an experimental set-up that realized the traditional Kolsky technique (or split Hopkinson pressure bar (SHPB) technique), as well as on a stand for testing specimens under explosive loads. Klepaczko [15] described an experimental/theoretical study of mortar and concrete at high strain rates in tension, compression and shear. Schuler et al. [16] obtained the tensile strength and the specific fracture energy of concrete in spall tests. Forquin et al. [17] performed tests on concrete under confinement at high rates of strain. Jiao et al. [18] conducted compression tests on steel fiber-reinforced high-strength concrete at medium strain rates in the range $10^1$–$10^2$ $s^{-1}$ using the SHPB testing method. Li et al. [19–21] conducted a critical analysis of the SHPB technique as applied to brittle materials. However, the results of these studies are inconclusive and often contradictory. Thus, the problem of studying the mechanical properties of cement-based materials under dynamic loading remains is far from being completely solved, especially as newer cement-based materials with superior performance characteristics are constantly being developed.

In this paper an experimental study of the new and promising construction material, the high performance fibre reinforced concrete, CARDIFRC is presented. The study of dynamic mechanical properties of this material was performed using the Kolsky method and its modifications for dynamic splitting (the Brazil test) and notched three-point bend testing.

One of the major problems faced in the prediction of the dynamic strength of any material is discussed below based on the test results of CARDIFRC. This problem relates to the dependence of the mechanical characteristics on the history and method of loading. A critical value can be considered as a material constant under quasi-static loading conditions. Under dynamic loading, the critical properties are characterized by very strong instabilities and can vary by several orders of magnitude. As a result, the dynamic system behaviour often appears unpredictable.

The main reason for above-mentioned difficulty in modelling the dynamic strength lies in the absence of an adequate limiting condition which determines the moment of fracture. This problem can be resolved based on the structural micromechanics of fracture and the concept of the incubation time of fracture that takes into account the kinetic processes that lead to micro-rupture [22,23]. The effects of "instability" become important in the transition from slow loading to loading with periods comparable with the scale determined by the incubation time of fracture. The incubation time is a result of relaxation processes that precede the development of micro-structural defects in the material.

The results of the tested high performance fibre reinforced concrete will be interpreted on the basis of the concept of the incubation time of fracture [22–27].