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Fracture energy of ultra-high-performance fiber-reinforced concrete at high strain rates

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ABSTRACT

The fracture energy of ultra-high-performance fiber-reinforced concrete (UHPFRC) at high strain rates (5–92 s^{-1}) was investigated, and specimens with 1–1.5% fibers exhibited very high fracture energy (28–71 kJ/m^2). Evaluation of the rate effects on the UHPFRC fracture resistance, including fracture strength (f_t), specific work-of-fracture (W_S), and softening fracture energy (W_F), indicated that f_t and W_S were highly sensitive to strain rate, whereas W_F was not. The effects of fiber type, volume content, specimen shape and fiber blending on the fracture resistance at high and static strain rates differed significantly: 1) smooth fibers exhibited higher f_t and W_S at high rates than twisted fibers; 2) higher fiber volume content did not clearly generate higher W_S and W_F at high rates; 3) notched specimens generally exhibited higher fracture resistance than un-notched samples at both static and high rates; and 4) UHPFRC blending two fibers produced higher W_S and W_F than UHPFRC with mono fiber at high rates.

1. Introduction

Enhancing the resistance of civil infrastructure to earthquakes, impacts, and explosions is an urgent problem, owing to the increasing number of manmade and/or natural disasters, such as terrorist attacks, earthquakes, typhoons, and hurricanes [1]. In the event of such a disaster, civil infrastructure provides shelter to not only humans, but also communal property. The resistance of civil infrastructure to the effects of a disaster is strongly related to its energy absorption capacity at high-rate loads, which can potentially cause complete collapse or destruction [2]. Thus, enhancing the energy absorption capacity is one effective approach to preventing the collapse or destruction of civil infrastructure and further protecting human life under such extreme loads [3].

Various methods have been developed to improve the energy absorption capacity of civil infrastructure under impact or blast loads: (1) the provision of redundant load paths in the structural system to enhance the ductility of the entire structure [4]; (2) the wrapping or encasing of compressive regions in beams or columns to strengthen the ductility of the structural components [5,6]; (3) the addition of steel reinforcements to beam column joints or column slab joints to increase the connection ductility [7,8]; and (4) the addition of crumb rubbers or fibers to concrete, to improve the ductility of the material [9,10].

However, it is difficult to provide suitable redundant load paths considering all of the various terrorist attack scenarios [11]. Further, the wrapping and/or encasing of structural components is not appropriate for scenarios involving fire exposure [12], and the addition of steel reinforcements leads to over-reinforcement of connections [13]. Finally, although rubberized and fiber-reinforced concretes (FRCs) have exhibited higher energy absorption capacity than normal concrete (NC), their energy absorption capacity remains low, as the fracture energy is less than 10 kJ/m^2 [14]. Moreover, the addition of crumb rubber to concrete deteriorates the concrete's mechanical properties [15].

To overcome the limitations of the abovementioned methods, we propose to apply ultra-high-performance fiber-reinforced concretes (UHPFRCs) to civil infrastructure, because UHPFRCs have demonstrated considerably higher energy absorption capacity (as indicated by the fracture energy), than FRCs, rubberized concrete, and NC. UHPFRCs, which contain a small amount of deformed steel fiber (lower than 2% by volume), even exhibit a very high fracture energy of over 30 kJ/m^2 [16].

However, the reported high energy absorption capacity of UHPFRCs has primarily been measured at static rates and not at higher strain rates, because the UHPFRC fracture energy at high strain rates has been only minimally investigated to date. Nevertheless, it has been reported as being lower than 15 kJ/m^2, which is lower than that of high-performance fiber-reinforced cementitious composites (HPFRCCs), as shown in Fig. 1. In contrast, UHPFRCs have exhibited higher fracture energy than HPFRCCs at static rates. Clearly, further investigation is required in order to fully understand the energy absorption capacity

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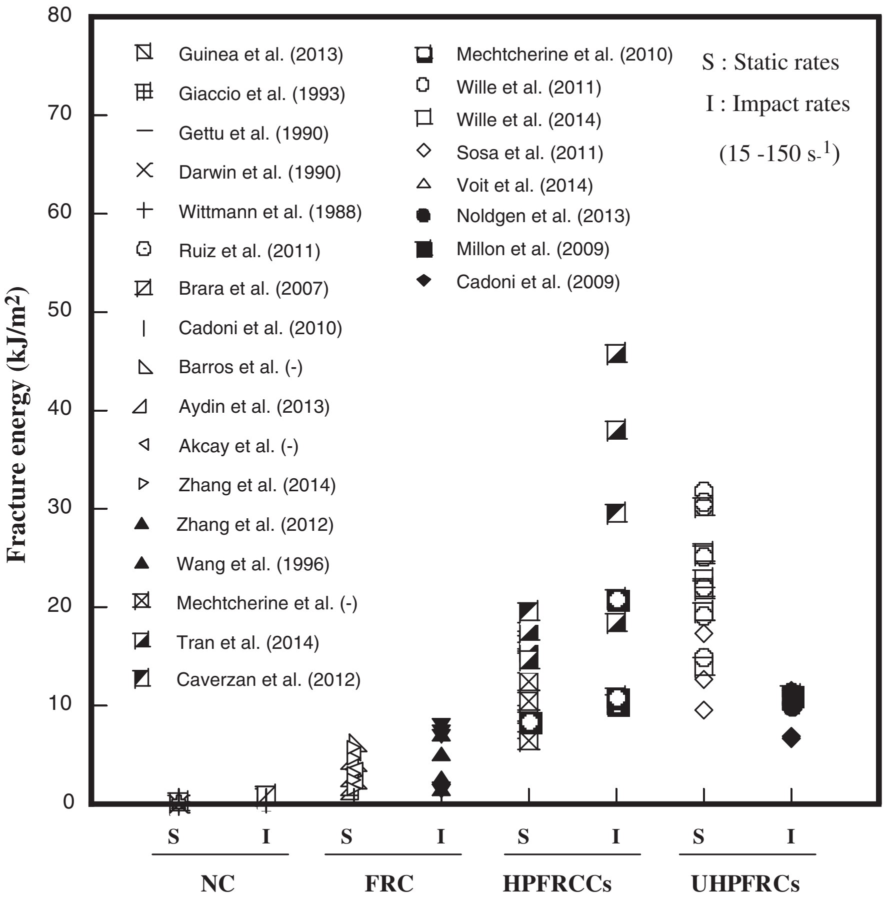

Fig. 1. Fracture energy of various cement based materials: NC, FRC, HPFRCCs, and UHPFRCs.

of UHFPRCs at high strain rates. In addition, the appropriate specimen shape for investigation of UHPFRC fracture energy at high strain rates is still undetermined, owing to the lack of standardized testing methods. Thus, the authors pose the following two questions regarding the fracture energy of UHPFRCs at high strain rates: 1) What is the reasonable specimen shape for measurement of the fracture energy? 2) How can the UHPFRC fracture energy at high strain rates be improved?

The aim of this study is to investigate the fracture energy of UHPFRCs at high strain rates. This will have implications for the practical application of these materials, by providing useful information concerning the abovementioned questions. The specific objectives are: (1) to discover and evaluate any rate effects on UHPFRC fracture energy; (2) to investigate the effects of fiber type and fiber volume content on the fracture energy at high strain rates; (3) to evaluate the effects of double edge notches on UHPFRC fracture energy at high strain rates; and (4) to evaluate the effects of blending fibers on UHPFRC fracture energy at high strain rates.

2. UHPFRC fracture energy at high strain rates

Ultra high performance concrete (UHPC) is a hydraulic cement based concrete with a compressive strength of 150 MPa or higher. To remedy the brittle behavior of UHPC, fibers have been added to improve its tensile strength, ductility and toughness, which has led to the development of Ultra high performance fiber reinforced concrete (UHPFRC) [17]. Recently, many researchers have been successful in developing the mechanical properties of UHPFRC and they have suggested different UHPFRC definitions [18–20]. UHPFRC considered in this study can be defined as a composite of UHPC and high strength steel fibers, exhibiting strain hardening behavior accompanied by multiple cracking with relatively high tensile strength over 9 MPa under direct tension.

The mechanical properties, including the fracture energy, of UHPFRCs have been intensively investigated at static rates [21–25]. Specifically, the fracture energies of various UHPFRCs at static rates

Table 1
Test series of tensile specimens.

Type of UHPFRCs	Specimen shape	Fibers				Notation
		Type 1	V_f (%)	Type 2	V_f (%)	
UHP-MFRC	Notched(N)	Smooth steel fiber (type b)	1.0	–	–	N-Sb10
			1.5	–	–	N-Sb15
		Twisted steel fibers (T)	1.0	–	–	N-T10
			1.5	–	–	N-T15
	Un-notched(U)	Smooth steel fiber (type b)	1.0	–	–	U-Sb10
			1.5	–	–	U-Sb15
		Twisted steel fibers (T)	1.0	–	–	U-T10
			1.5	–	–	U-T15
UHP-HFRC		Smooth steel fiber (type a)	1.0	Smooth steel fiber (type c)	0.5	U-Sa10Sc05
			1.0	Poly amide fibers (Pa)	0.5	U-Sa10Pa05