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Effect of different types of fibers on the microstructure and the mechanical behavior of Ultra-High Performance Fiber-Reinforced Concretes

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ABSTRACT

This study investigates the effect of adding different types of fibers on the microstructure and the mechanical behavior of cementitious composites, in particular on UHPC. These fibers were distinguished mainly by their differing nature (steel, mineral and synthetic), their dimensions (macroscopic or microscopic), and their mechanical properties. The microstructure of the specimens was examined by using SEM observation and by measuring the porosity, the intrinsic permeability and the P-wave velocity. The mechanical behavior under loading has been studied using a uni-axial compression test which combines the gas permeability and the acoustic emission (AE) measurement. This work focuses on the cracking process under mechanical loading. The experimental results show that the fiber has a relatively slight influence on the compressive strength and elastic modulus of concrete, except for the steel fiber which improves the strength because of its intrinsic rigidity. However, The addition of fiber significantly reduces the lateral strain at peak loading and increases the threshold of initial cracking ($\sigma_{k\text{-}ci}$) and that of unstable cracking ($\sigma_{k\text{-}pi}$). Therefore, the fibers clearly restrain the cracking process in concrete under the mechanic loading.

1. Introduction

The engineering characteristics of ultra high performance concretes UHPC are different from those of conventional concrete, thereby rendering UHPC extremely popular in a large variety of applications in the construction industry, in particular for high-rise buildings and longspan bridges [1,2]. In addition, UHPC possesses a uniform high density and very low impermeability, which gives it excellent resistance to aggressive environments and disintegrating agents, thus improving the durability of concrete buildings and structures [3,4]. While the relatively high compressive strength of UHPC is an attractive advantage; this strength works against the ductility of the concrete by causing a pronounced increase in brittleness [5]. The UHPC always possesses a steeper descending stress–strain curve in compression compared to normal strength concrete. This rapid decrease in compressive strength in the post-peak load region brings about a predominantly brittle mode of failure [6]. To improve the concrete's ductility without sacrificing its compressive strength, one popular strategy is the addition of discrete fibers as reinforcement in UHPC [7].

Over the last decade, Ultra-High Performance Fiber-Reinforced Concretes UHPFRC have become a subject of great interest for engineers, due to the fact that the fiber addition is observed to yield an improvement in various characteristics of normal ultra high performance concretes UHPC. The incorporation of fibers reduces shrinkage and cracking and also provides ductility both under tension as well as compression.

The effects of fibers on the properties of concrete are always difficult to identify due to the extreme heterogeneity of concrete. The actual fiber that must be used depends mainly on the application needed for the concrete. These fibers may be distinguished by their different physical or chemical properties, such as the fiber's nature (steel, mineral or synthetic), its geometry (macro fiber vs. micro fiber), as their aspect ration L/ϕ and their mechanical properties, etc.

Generally these different properties of fiber yield different effects when added to their respective concretes. For the microstructure of concrete, Ivan [8] indicated that the micro fiber (shorter than 0.1 mm) has a more homogenous distribution in

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concrete, leading to a higher packing density of cement matrix. Keer [9] reported that synthetic fiber increases the permeability of concrete due to their porous interfacial transition zone (ITZ). As far as the mechanical performances of concrete are concerned, various researchers [10–13] have studied the fibers' effect on concrete under compression or tension. They have reported that the fibers increase the tensile strength of concrete, but not necessarily its compressive strength. They have also found that the macro fiber has an efficacious capacity against the macro cracking of concrete in the post-peak phase. [14] reported that fibers with a greater ratio of L/ϕ yield a higher compressive strength in the concrete. Zheng [15] showed that fibers with higher tensile strength and higher elastic modulus could significantly improve the mechanical performance of concrete.

In this paper we present the effect of different types of fibers on the microstructure and the mechanical behavior of Ultra High Performance Concrete -UHPC, the microstructure of the specimens was examined by using SEM observation and by measuring the porosity, the intrinsic permeability and the P-wave velocity. The mechanical behavior under loading has been studied using a uniaxial compression test which combines the gas permeability and the acoustic emission (AE) measurement. This work concentrates specifically on the cracking process under mechanical loading.

2. Material and experimental techniques

2.1. Materials and mixtures

The materials used in this work are: Portland cement (CEM I 52.5) with limestone filler and siliceous filler; with the mineralogical composition given in Table 1. The aggregate used is normalized silica sand having 1730 kg/m^3 bulk density and 2.65 specific gravity, and a water/cement ratio of 0.27. Six different types of fibers have been used in this study, distinguished mainly by their different nature (steel, mineral and synthetic), their different dimensions (macroscopic or microscopic) and by their mechanical properties, as given in Table 2.

We have used Ultra High Performance Fiber Reinforced Concrete specimens in this work. Seven composite mixtures were prepared, a reference mixture without fiber UHPC and six mixtures with different types of fibers added with a fiber volume fraction of 1% UHPFRC.

The experimental investigations were performed on cylindrical specimens (40 × 60) mm. The top surface and the lower surface of the specimens were properly polished before the test to ensure two surfaces sufficiently smooth and parallel. 3 specimens were prepared for each composite and each test in order to calculate their average.

2.2. Experimental techniques

The microstructures of the UHPC and UHPFRC specimens were examined by using SEM observation and by measuring the porosity, the intrinsic permeability and the P-wave velocity. The mechanical behavior under uniaxial compressive stress was investigated by measuring the ultimate strength, Young modulus, deformations, permeability change, and acoustic emission (AE).

Table 1
Mineralogical composition of the used cement.

Phase	% In mass
CaO	61.7
SiO_2	17.2
Al_2O_3	5.7
Fe_2O_3	3.9
MgO	0.8
Na_2O	0.41
K_2O	0.77
SO_3	3.1
Cl^-	0.04

2.2.1. Apparent porosity test

The apparent porosity (Pa) is identified according to RILEM recommendations 49TER [16]. The sample is dried during several days in order to remove any moisture from the voids. The apparent porosity is then calculated using formula (1).

$$\Phi = \frac{(M_{sat.air} - M_d) \times \rho_{water}}{M_{sat.air} - M_{sat.water}} \quad (1)$$

where, $M_{sat.air}$: saturated mass in air (g); $M_{sat.water}$: immersed saturated mass in water (g); ρ_{Water}: water density; M_d: dry mass.

2.2.2. Gas permeability measurement

The gas permeability measurement depends on the porosity, the pore geometry, the pore tortuosity, and most importantly the pore connectivity of the material measured [17], and is an important method for characterizing the microstructure of a material. The gas used for the measurement must be inert and dry in order to avoid the interaction between the gas and the material measured, so we have chosen helium. The gas permeability calculated was based on the gas flux, which was measured when the specimen was under a constant percolating gas pressure, once steady-state gas flow was established. In this work, we assumed that a steady-state gas flow was established when the variation of outflow gas flux measured was less than 2% during a period of 10 min.

The gas permeability was then calculated by the Darcy relationship [18] for the laminar flow of a compressible fluid through a porous body under steady state conditions according to formula (2):

$$K_a = \frac{2\mu QLP_2}{S\left(P_1^2 - P_2^2\right)} \quad (2)$$

where K_a (m^2) is the apparent gas permeability of the specimen; Q (ml/min) is the outflow gas flux measured; P_1 is the constant percolate gas pressure (we have chosen 0.6 Mpa); P_2 is the atmospheric pressure (P_2 = 0.1 MPa); μ is the dynamic viscosity of helium gas = 2×10^{-5} Pa s at 20° C; S is the cross sectional area of the specimen, and L is the length of the specimen.

It must be noted that the apparent gas permeability depends on the specimen's geometry and the gas pressure used, which might influence the measurement precision. In order to eliminate these influences out of our specimen, we measured the intrinsic gas permeability K_v (m^2) of specimens using the relationship proposed by Klinkenberg (3):

$$K_a = K_V\left(1 + \frac{\beta_k}{P_m}\right) \quad (3)$$

where P_m is the average value of the gas pressure P_1 and P_2; β_k (Pa) is the Klinkenberg coefficient. This K_v is the limiting value of gas permeability when the Pm tends toward infinity, so like this measurement of permeability is effected by the liquid. The determination of K_v consists of measuring K_a at different percolate gas pressure (P_1 = 0.4, 0.5, 0.6, 0.7 and 0.8 MPa), and plotting against the inverse of the gas pressure ($1/P_m$).

2.2.3. P-wave velocity measurement

P-wave velocity measurement is a very convenient method for the non-destructive testing of a given material [19–21]. P-wave