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Mechanical and fracture properties of concrete reinforced with recycled and industrial steel fibers using Digital Image Correlation technique and X-ray micro computed tomography

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HIGHLIGHTS

- Steel fibers from end-of-life tyres (ELT) are promising application as a concrete dispersed reinforcement.
- We compare mechanical properties of plain concrete and concrete reinforced with recycled and industrial fibers.
- We show fracture process zone development using Digital Image Correlation during wedge splitting test (WST).
- We present 3D images from X-ray micro-CT of material micro-structure, distribution of air voids and fibers.
- We analyse shape, width and curvature of crack during deformation process using X-ray micro-CT in 3D.

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ABSTRACT

Paper presents investigation of fracture phenomenon in plain concrete and in concrete reinforced with both recycled steel fibers (RSF) and industrial steel fibers (ISF). The wedge splitting test (WST), which enables stable crack propagation for quasi-brittle materials, was carried out on 75 × 75 × 75 mm cube samples. Initially, fracture process zone development was investigated only on the surface of samples using Digital Image Correlation which is a non-destructive optical testing method. Furthermore, to analyse the 3D cracking phenomenon (formation, development, width, shape and curvature) X-ray micro computed tomography was used. Micro-CT images were taken during continuous deformation process - without unloading sample during scanning. X-ray micro-computed tomography was also used to visualise and characterise air voids and fibers (length, diameter and orientation) embedded in concrete. The mechanical properties of plain, RSF and ISF reinforced concrete in terms of compressive strength, tensile splitting strength, shrinkage, tensile and residual strength in 3-point bending were additionally described.

1. Introduction

Fracture process is a fundamental phenomenon in quasi-brittle materials like concrete [1–3]. It is very complex since it consists of main cracks with various branches, secondary cracks and micro-cracks [1]. During fracture, micro-cracks first arise in a hardening region on the stress-strain curve which change gradually during material softening into dominant distinct macroscopic cracks up to failure. The fracture process strongly depends upon a heterogeneous structure of materials over many different length scales, changing e.g. in concrete from the few nanometres (hydrated cement) to the millimetres (aggregate particles). Thus, understanding of a fracture process is of major importance to ensure the safety of the structure and to optimize the material behaviour.

Concrete is widely regarded as a brittle material due to its low tensile, and high compression strength. Nowadays, in order to increase ductility and material strength, most popularly industrial steel fibers (ISF) are added to concrete matrix. ISF can be of different types (hooked ended, corrugated etc.), lengths and diameters with the recommended content between 1.5% and 3% [4]. Studies of steel-fiber reinforced concrete are mainly focused on the effects of the geometric types, volume fraction and strength of steel fibers on the flexural or compressive behavior [4–7]. The use of steel fibers in concrete was expanded to the application of various fibers, such as synthetic, glass and carbon fibers or organic fibers. In particular steel and synthetic fibers were used to assess the properties and performance of concrete [8–10]. The influence of the combination

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of steel and synthetic fibers in the flexural strength and ductility of concrete was also analysed with respect to the shape, length and dosage of the fibers. In addition, several researchers examined the influence of the steel fibers in combination with steel bars reinforced concrete (hybrid reinforcement) [11].

Our interests concern ground floor slabs that are integral to the efficient operation of an industrial facility. Industrial floors are normally subjected to various types of loading and have common requirements of high strength, toughness, crack control and durability among others. The use of industrial steel fibers (ISF) in concrete flooring is advantageous over conventional grade slab wherein the residual load-carrying capacity is used and thus, increases the strength, toughness and results in economy of floor thickness apart from saving in construction time. Recently steel fibers recovered (RSF) from end-of-life tyres have been in the center of attention of researchers. Tyres are 100% recyclable and all components, i.e. rubber, metals and textiles, can be recycled and re-used in many commercial products, as concrete. Nowadays, there is a growing trend to use industrial wastes or by-products in the production of cementitious composite. A significant number of experimental studies have been conducted regarding the use of metal waste recycled fibers as a reinforcement and other industrial waste as admixtures or aggregate grains (recycled aggregate, PET or polyurethane foam light-weight aggregate) in the production of cementitious composite. The use of wastes in system of concrete elements has beneficial environmental and economic impacts. Strengthening concrete matrix with inhomogeneous recycled fibers (RSF), made of high quality steel, improves concrete mechanical properties such as: shrinkage, compressive strength, tensile strength, residual strength [12–16].

Except for mentioned mechanical properties, to preserve safety and durability of the fiber reinforced industrial floors a fracture phenomenon i.e. crack formation, evolution, shape and width should be carefully investigated. However, a direct observation of fracture is difficult because of a small scale at which microstructural events interact with a failure process. Different techniques like scanning electron microscopy (SEM) [17–19], high speed photography [20], laser speckle interferometry [21,22], acoustic emission [23–27], X-ray technique [28–31], Moiré method [32,33] and Digital Image Correlation (DIC) technique [34–39] have been used to experimentally investigate a fracture process in quasi-brittle materials (concrete, rock and masonry) at the laboratory scale.

The paper gives an insight into the possibilities of recycled steel fibres (RSF) to be used as an industrial floor reinforcement. The mechanical properties of plain, RSF and ISF reinforced concrete in terms of compressive strength, tensile splitting strength, shrinkage, tensile and residual strength in 3-point bending were described. However, the main objective and novelty of this study is to investigate fracture phenomenon in plain concrete and concrete reinforced both with ISF and RSF during wedge splitting test. Initially, fracture process zone development was investigated only on the surface of samples using Digital Image Correlation (DIC). Afterwards, to analyze 3D cracking phenomenon (formation, width, shape and curvature) X-ray micro computed tomography (micro-CT) images were taken during continuous deformation process (without unloading during scanning). This technique allows to obtain a continuous CMOD-force curve and preserve crack from closing during scanning. Moreover, X-ray micro-CT was used to visualize, measure and characterize fibers embedded in concrete.

2. DIC and micro-CT technique

The DIC technique has become one of the most popular method of fracture examination due to its availability, simplicity and low cost. In DIC method material displacements are obtained by tracking a random speckle pattern applied to the surface by means of digital images at different instances of deformation. Next strains, which are the best indicator for fracture process zones, based on displacements are calculated using standard finite-element shape functions. The method gives high resolution measurements of a displacement field. A correct local displacement vector for each interrogation cell is accomplished by means of a cross-correlation function between two consecutive brightness distributions in two digital images. The function calculates simply possible displacements by correlating all gray values from the first image with all gray values from the second image. The correlation plane is evaluated at single pixel intervals, what means that the resolution is equal to one pixel. By fitting an interpolation function to the region close to the peak, the displacement vector is established with a high accuracy (equal to the correlation offset). The peak in the correlation function indicates that two images are overlaying each other (thus, it indicates the 'degree of match' between two images). We used the Pearson's product-moment correlation function. The peak (best match) of the correlation function is usually not clearly distinguished as the correlation function produces results for each pixel of image. To precisely locate the peak, a sub-pixel interpolation was performed. As an interpolation function, the function sinc256 was used. It has been shown that the accuracy in strain measurements when compared with strain gauge data is within ±200μ. The performance of DIC is affected by many factors such as interpolation algorithm, shape function, subset size, sub pixel registration algorithm, sensor noise and lens distortion. DIC can be used both for 2D and 3D measurements. While 2D deformations can be measured with one camera, 3D deformations require use of two cameras both measuring the changes of the deformed surface at different angle. DIC technique allows to identify local strain mapping that can be used in determination of the fracture process zones and cracks that are certainly two key parameters needed to estimate the permeability, strength and durability of structural concrete components [34–39]. Moreover, full-field DIC experiments allow to determine Young modulus, Poisson ratio and measure off-plane properties [40]. DIC is widely used optical method for shape motion [41] and evaluation of creep degradation [42]. DIC technique can be applied to measurements of different materials like wood, concrete, polymers, steel etc. DIC is also widely used in experimental measurements of concrete reinforced with fibers [43–45]. However, this method has two drawbacks: (1) no information about microstructure and (2) no fracture process zone / crack (its shape and width) inside material can be achieved.

Recently, the application of high-resolution X-ray micro computed tomography significantly increased. The basic idea of this imaging technique goes back to Johan Radon, who proved in 1917 that an n-dimensional object can be reconstructed from its (n-1)-dimensional projections. However, the mathematical basis for the actual CT image reconstruction was presented by Cormack in 1964 and 1965. About 10 years later, Hounsfield submitted a patent, describing the first CT scanner, which was then built in 1975. The possibility of non-invasively imaging three-dimensional sections of a human body was of such importance that Cormack and Hounsfield were awarded with the Nobel Price for Medicine in 1979. Micro-CT is a non-destructive technique that provides three-dimensional images of the objects internal structure. The basic physical X-ray principal of computed tomography is the interaction of ionizing radiation with material, where the so-called photo-effect builds the main interaction mechanism. The photo-effect attenuates the photons proportionally to the third power of the order number of the elements and inverse proportional to the third power of the photon energy. Thus, the actual attenuation not only depends on the material but also on the