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Influence of the pore morphology of high strength concrete on its fatigue life

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ABSTRACT

The use of porous concrete in structural elements subjected to compression cyclic loads is inevitable in those situations in which it is necessary to withstand, simultaneously, important amount of freeze-thaw cycles and cyclic loads. However, the presence of pores, which is essential to withstand freeze-thaw cycles, can drastically reduce the fatigue life of concrete in some cases.

This paper analyses a total of 60 40-mm edge cubic specimens, belonging to 5 series, each of them with a different content of air entraining agent. The specimens were first scanned using computerized tomography scan in order to visualize the internal porosity of the specimens. Through the use of specific software, the morphological parameters of the porosity of each test was defined. Nine specimens of each series were tested at cyclic compression load until fatigue failure. The fatigue life of each specimen was obtained. Using these data, the characteristic fatigue life of each series were obtained.

The comparison between the morphology of the porosity and its fatigue life provides interesting relationships, which allow to understand better how the porosity influences the response to compression fatigue of the concrete. Finally, empirical relationships between porosity morphological parameters and fatigue life were obtained. The correlations show that a greater porosity leads to a lower fatigue life. And also, concretes with a higher percentage of small pores show a better behaviour against fatigue.

1. Introduction

Fatigue is a process of mechanical deterioration of a material leading to its collapse, caused by the repeated action of cyclic loading, in such a way that its maximum strength is always below the maximum loading that a undamaged specimen of the material could resist under static loading until failure.

Behaviour of concrete structures under fatigue is an issue of great scientific and technological concern. The progressive improvement on the concrete strength allows the building of increasingly slender structures. In these new structures, live loads, usually cyclic in nature, represent an increasing percentage of the total loads affecting the structure. In some singular structures, like concrete wind turbine towers or bridges belonging to high-speed rail lines, fatigue failure due to cyclic loads is the most important design criterion, above “conventional” static failure due to extreme loads.

Cyclic loads in concrete provoke, in the macroscopic level, a variation of the mechanical properties of cement paste, highlighting a reduction of the strength and stiffness and an increase of the total strain, that is, a structural damage [1–6]. The progressive growth of these damage leads to fatigue collapse.

In the microscopic level, damage results in birth and growth of micro-defects (mainly cracks) which leads to a progressive degeneration of internal structure [7,8]. Microcracks initiate at the border of the pores and progress parallel to compression direction. A detailed analysis of the fracture surfaces suggest that crack surfaces connect pores of the specimen, following the path of minimal energy [9]. Since pores are sensitively randomly distributed throughout the specimen, damage is randomly distributed throughout concrete, instead of concentrated, as occurs for example in metals.

Much research has shown how porosity substantially affects on the macroscopic behaviour of concrete, in aspects such as strength, stiffness and fatigue among others [10–13]. This is not a specific feature of concrete, but it happens in all porous materials, like rocks [14,15].

In most of the concrete structures subjected to cyclic loads, porosity of concrete is a secondary issue, that is, it is an implicit/inherent feature

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of the material, which is not taken into account when the design of the concrete mixture is performed. However, there is a relevant amount of situations where concrete structures are simultaneously subjected to freeze-thaw cycles and cyclic loads. Some of the most representative cases are those like concrete towers and bridges placed in areas where freeze-thaw cycles are intense (north of USA and Canada or the north of China and Europe, among others). In these regions, local standards related to concrete require the use of concrete with a relatively high minimum amount of air entraining agent (AEA), in order to satisfactory withstand the freeze-thaw cycles. However, the porosity negatively affects its behaviour under fatigue [14–17].

The pores can be classified into micropores (size less than 1 µm), mesopores (size between 1 µm and 10 mm) and macropores (size greater than 10 mm) [16]. There are several methods to analyse the pore structure. The traditional ones are nitrogen absorption and mercury-intrusion porosimetry (MIP) [18,11]. These traditional methods show two main limitations. First, they can only provide the pore-size distribution but not the pore distribution, shape, etc. Second, these techniques can only provide information about the open porosity and not about the closed porosity.

During the last decades a novel technology is being successfully applied to concrete, that is, computed tomography (CT) scan technology. Beyond the use of CT scan in medicine, much research has been conducted to analyse the internal microstructure of concrete [19–26]. Only a small amount of this research is focused on porosity.

This paper is focussed on the analysis of influence between porous morphology and fatigue behaviour. To this, concrete specimens belonging to different series were performed. Each series is made with a different amount of AEA. That affects the porosity; not only the total amount of air entrained is different, but also the number of pores, pore-size distribution, spacing, etc. The specimens were first scanned using a computer tomography (CT) scan and next they were tested under compression cyclic load up to fatigue failure. The results obtained from CT-Scan and fatigue testings allow to define correlations between fatigue behaviour of concrete and pores morphology.

This paper is structured as follows. The experimental procedure is presented in Section 2; the results of the CT-Scan and the fatigue tests are described and discussed in Section 3; and finally the conclusions are found in Section 4.

2. Experimental program

2.1. Materials

A total of 5 series of high strength concrete have been casted. They have been identified from A0 to A4. Table 1 shows the mixture used. A total of 60 cubic specimens were used in this work, in set of 12 specimens by series

The AEA used was MasterAir 100 (BASF, Ludwigshafen am Rhein, Germany). The nanosilica used was MasterRoc MS 685 (BASF, Ludwigshafen am Rhein, Germany). Siliceous aggregate was used, with a nominal maximum aggregate size of 6 mm. Portland cement with high initial strength CEM I 52.5 R was used. The specimens tested were cubes 40-mm edge, cut from a prismatic specimen of 160-mm length, 40-mm width, 40-mm height using a 2.8-mm thickness diamond radial cutting disc. A total of 3 cubic specimens were obtained from a prism. The ends of the prism were discarded (Fig. 1).

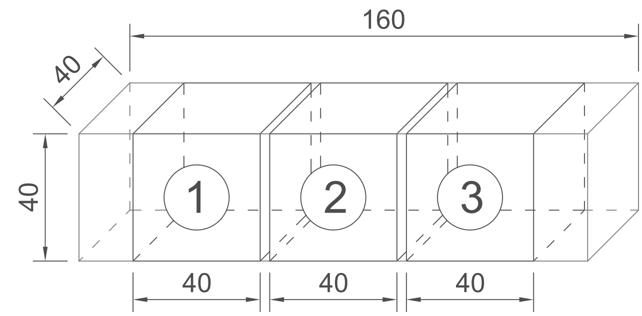

Fig. 1. Scheme of the cubic specimen performance.

At each series, 3 specimens were tested under static compression until failure, in order to obtain the compression strength of the concrete. The rest of the specimens were first scanned using a CT-scan and next, they were tested under cyclic compression until fatigue failure.

2.2. Test

Three cubic specimen of each series were used to obtain the average compression strength of the material. Table 2 shows the values obtained. The data in brackets is the standard deviation. The rest of the specimens, 9 per series, were subjected to a cyclic test until fatigue failure, in order to obtain the fatigue life of the different series. The testings were carried out with a frequency of 2 Hz and with a compression range varying from $\sigma_{max} = 0.80{\cdot}f_{cm}$ to $\sigma_{min} = 0.05{\cdot}f_{cm}$, where f_{cm} is the average compression strength of their series. The stress level was chosen to assure a theoretical low number of cycles up to failure and, in consequence, to reduce the aging effect on the test campaign.

The number of specimens tested under fatigue loading adopted is considered as enoas an average value

2.3. Scanning of the specimens

Before the fatigue testings, the cubic specimens were scanned using a CT-Scan, which has become a non-destructive powerful tool to analyse the internal microstructure of material. A total of 45 specimens were scanned. A GE Phoenix v|tome|x scanner was used (General Electric, Boston, MA, USA). It is equipped with an X-ray tube of 300 kV/500 W. This facility includes a post-process software, which provides sectional images of the specimen with a size of 2048 × 2048 pixels. The pixel size is 30 µm. The spacing between slices is 30 µm. A total of 1334 images are obtained from each cubic specimen. The software assigns a grey level to each voxel (volumetric pixel), varying from 0 to 255 (0 means black and 255 means white), depending on the real density of the matter at this point. Light grey voxels corresponds to more dense points and dark grey, to less dense, i.e., pores. The final result of the CT-Scan is a matrix including X, Y and Z coordinates of the voxel centre of gravity and a number, from 0 to 255, regarding the density. The total amount of voxels per specimen is approximately 2.4×10^9.

Table 1
Concrete mixture.

Dosage	A0	A1	A2	A3	A4
Cement (kg/m^3)	720.0				
Water (kg/m^3)	225.0				
Superplasticizer (kg/m^3)	25.0				
Nanosilica (kg/m^3)	11.0				
Aggregate (kg/m^3)	1445.0				
Air Entraining Agent (kg/m^3)	0.00	0.72	1.44	2.16	2.88
Ratio air entrainment/Cement	0.0%	0.1%	0.2%	0.3%	0.4%

Table 2
Average compression strength and standard deviation.

Series	f_{cm} (MPa)
A0	100.0 (1.4)
A1	100.6 (0.5)
A2	88.8 (7.2)
A3	72.7 (3.8)
A4	90.8 (7.7)