Available online at www.sciencedirect.com

ScienceDirect

Journal of Bionic Engineering 14 (2017) 369–378

Energy Absorption in Functionally Graded Concrete Bioinspired by Sea Urchin Spines

Nicu Toader[1], Werner Sobek[1], Klaus G Nickel[2]

1. *Institute for Lightweight Structures and Conceptual Design* (*ILEK*), *Stuttgart Universität*, 70569 *Stuttgart*, *Germany*
2. *Institute for Geoscience* (*IFG*), *Applied Mineralogy*, *Eberhard-Karls-Universität Tübingen*, 72074 *Tübingen*, *Germany*

Abstract

Functionally Graded Concrete (FGC) is fabricated at the Institute for Lightweight Structures and Conceptual Design (ILEK) by using a layer-by-layer technique with two different technological procedures: casting and dry spraying. Functional gradations are developed from two reference mixtures with diametrically opposed characteristics in terms of density, porosity, compression strength and elasticity modulus. In this study the first mixture consists of Normal Density Concrete (NDC), with density about 2160 $kg \cdot m^{-3}$ while the second mixture helps to obtain a very lightweight concrete, with density about 830 $kg \cdot m^{-3}$. The FGC specimens have layers with different alternating porosities and provide superior deformability capacity under bulk compression compared to NDC specimens. In addition, the FGC specimens experienced a graceful failure behaviour, absorbing high amounts of energy during extended compression paths. The porosity variation inside the layout of tested specimens is inspired by the internal structure of sea urchin spines of *heterocentrotus mammillatus*, a promising role model for energy absorption in biomimetic engineering.

Keywords: biomimetic engineering, energy absorption, sea urchin spine, functionally graded concrete, graceful failure behaviour

doi: 10.1016/S1672-6529(16)60405-5

1 Introduction

In our study spines of *Heterocentrotus Mammillatus* (HM, Fig. 1), were the concept generator for designing functionally graded concrete specimens with high-energy absorption. Under bulk compression, sea urchin spines combine desirable properties such as cascading graceful failure behaviour and lightweight with up to 70% pore volume. This way, sea urchin spines can withstand high impact forces during the attack of a predator while the spine remains permeable to ensure its growth and regeneration[1]. Just as concrete, the construction materials forming the spine are brittle. The internal structure of HM spines is a highly porous Mg-calcite network (stereom) separated by more compact layers. All spine samples measured showed almost the same chemical composition of Calcite ($CaCO_3$) with up to 12 wt% $MgCO_3$[2]. The spines are characterised by concentric stereom layers separated by layers of higher density interpreted as former shell surface or growth layers[3]. The stereom inner structure is described as labyrinthic[4]. The porosity of the spine interior varies from 10% (almost fully dense) to 70%. Fig. 2 shows the density variation along an aboral spine of HM. Each layer has a roughly cylindrical shape and the dense ones tend to meet at the base. It is astonishing that sea urchin spines experience a graceful failure behaviour under compression forces, because the construction material is a brittle single-crystal like magnesium calcite ($[Ca_xMg_{1-x}]CO_3$)[5,6]. Their behaviour results from the hierarchic structure of the porous carbonate network (stereom)[7,8].

The idea of a Functionally Graded Concrete (FGC) was first put forward by Werner Sobek[9]. The motivation for developing graded building materials, with a continuous variation of the porosity in the inner structure of a construction component, is driven by the idea of adapting material characteristics precisely to the stresses that occur locally under load. The targeted positioning of lighter concrete mixtures in lower stress areas in com-

Corresponding author: Nicu Toader
E-mail: toader.nicu@gmail.com; nicu.toader@ilek.uni-stuttgart.de

ponents under bending stress such as floor elements, allows local mass savings of up to 60% by a density variation of the concrete from 2160 kg·m^{-3} down to 830 kg·m^{-3}[7]. Purely mineral, functionally graded wall components are capable of simultaneously fulfilling specifications concerning their load-bearing capacity, durability, architectural appearance and thermal insulation[10]. If we also add high deformability capacity and energy absorption for special requirements potentially imposed during the life span of a building, we have a new material, functionally graded concrete, which is able to fulfill a comprehensive design for civil engineering structures. In addition, FGC components minimise the resource utilization and permit full recyclability.

The implementation of deformation elements in structures that are prone to suffer an impact or be subjected to dynamic loads is one of the measures and strategies to improve the safety[12]. Deformation elements are components that transform the kinetic energy inflicted upon the structure during an impact load or a dynamic load into deformation energy[13]. A building experiencing impact loads or dynamic loads (car crash, derailed trains, earthquakes *etc*.) should dissipate energy through plastic deformations or through damping to avoid total collapse[14]. In impact events, building components are exposed to dynamic loading at a wide range of strain rates (Fig. 3). Therefore we have included the dynamic behaviour of concrete in the study of FGC, considering the dependence of the concrete strength and deformability on the strain rate. The strain rate can be defined as the change in strain of a material with respect to time.

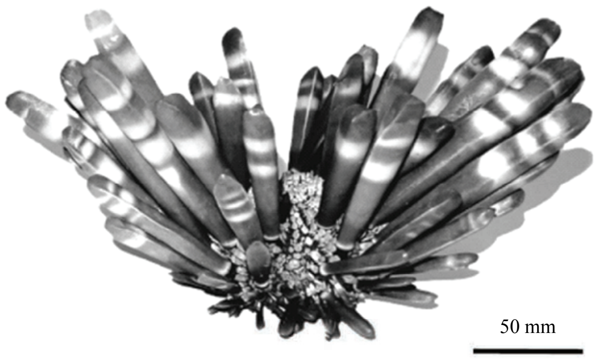

Fig. 1 Photograph of the biological role model sea urchin specie[1].

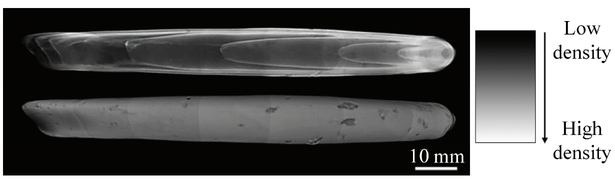

Fig. 2 X-ray CT scan showing the absorbance contrast (upper part) and surface scan (lower part) of the HM aboral spine (fully grown). The normalized intensity scales with the local density[11].

The objective is to develop graded concrete components which (as part of the load-bearing structure) will help the building to be damaged only locally without immediately collapsing after and extreme action such as a vehicle impact, derailed trains or earthquakes. Structures with graded concrete components will be able to absorb energy in their dissipative regions not only due to the reinforcement yielding, but instead or additionally by large quasi-plastic deformations of the concrete. This objective is part of the initiative of the Institute for Lightweight Structures and Conceptual Design (ILEK) to realize lightweight building components purely mineral and therefore fully recyclable for automatized production.

In this paper, we present the fascinating behaviour of gradient concrete cubes subjected to compression that show a deformability more than 10 times higher than normal density concrete. Consequently, we are facing a (plane) concrete that has a quasi-brittle behaviour when subjected to compression forces, unlike normal (plane) concrete that has a brittle behaviour.

2 Material and methods

2.1 Specimen preparation

For the production of concrete specimens two mixtures were used: one for normal density concrete and the other for lightweight concrete. The first mixture was prepared mixing cement (CEM I 52.5 R), sand (with aggregate size of 0 mm – 2 mm) and water. In the end, the Normal Density Concrete (NDC) had a mass of 2170 kg·m^{-3} and a mean value for compression resistance of 43.0 MPa. For the lightweight concrete mixture expanded glass was used to partially replace the sand. The expanded glass granules are spherical, have a closed surface, sizes of 1 mm – 2 mm (loose bulk density 220 kg·m^{-3}, particle density 350 kg·m^{-3}, crushing resistance 2.4 N·mm^{-2}) and 2 mm – 4 mm (loose bulk density 190 kg·m^{-3}, particle density 310 kg·m^{-3}, crushing resistance 2.2 N·mm^{-2}). The lightweight concrete had a mass of 830 kg·m^{-3} and a mean value for