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Assessing the potential of functionally graded concrete using fibre reinforced and recycled aggregate concrete

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HIGHLIGHTS

- The FGC possess high potential to minimize drawbacks of the traditional concrete.
- The Barcelona test can be applied to FGC facilitating the material quality control.
- Costs and embodied CO_2 were analysed showing the advantages of FGC.
- The FGC may be used to design more sustainable structures.

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ABSTRACT

Despite ordinary Portland cement concrete presenting low performance in tension and a negative impact on the natural environment, it is the most used construction material. Researchers have noted that the usage of fibres as reinforcement and recycled aggregates, instead of natural ones, may minimize these issues. The concept of functionally graded material for new composite materials is proposed to address these problems. In this paper, five different concrete mixes were produced to analyse the potential of using functionally graded concretes (FGC) for sustainable structures. Their mechanical performance, a sustainable quality control method for these materials and their costs and embodied CO_2 were analyzed. The results show that FGC, even though showing a post-cracking flexural performance lower than conventional FRC, possesses high potential in terms of structural design based on Model Code 2010 specifications. The equations provided to use the Barcelona test to control the material, which is more environmentally friendly than the standardized beam test, may facilitate the introduction of FGC in the construction market. Finally, considering costs and embodied CO_2, FGC presents a good prospect to be used as structural material for future sustainable concrete elements.

1. Introduction

Concrete is a construction material that is widely applied around the world. The popularity of conventional concrete, or ordinary Portland cement concrete, is due to its many advantages, such as high compressive strength or low cost. However, this concrete also has some drawbacks regarding technical and environmental aspects. It is a brittle material and it presents a low performance in tension, which is about 10% of its compressive strength [1]. To address this matter, fibres can be used as reinforcement. They possess an ability in controlling crack propagation, in terms of both number and width [2], compared to traditional reinforced concrete. Moreover, as presented in different studies fibres might partially or totally substitute traditional reinforcement leading to economic advantages [3]. Due to these benefits, fibre reinforced concrete (FRC) is widely applied in pavement and tunnel constructions [4]. However, researchers have stated that the fibre distribution within the whole volume of the concrete element makes it a non-efficient economic material for some applications (e.g. structures under bending) [5].

On the other hand, concrete presents a negative impact on the natural environment. Regardless of the CO_2 emission from cement production, the exploitation of quarries brings potential impacts regarding the mining of natural aggregates [6]. Using waste materials from demolition may contribute to sustainable development. The usage of recycled aggregates significantly reduces the depletion of natural aggregates, which minimizes the environmental impact due to the aggregate extraction and reduces the occupation of land. Although there is no evidence that the use of recycled aggregates generates less CO_2 than the use of natural aggregates, the recycled aggregates still have the potential to be used to design

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more environmental concrete structures since their embodied carbon varies for different case studies [7]. Besides, the use of demolition waste to produce recycled aggregate concrete (RAC) increases the life cycle of the structures [8]. Furthermore, fuel consumption and CO_2 emission related to aggregate transportation may be reduced [9]. In contrast, RAC presents a decrease of its mechanical properties increasing the content of recycle aggregates [10].

The use of FRC and RAC could minimize the challenges that concrete is facing. In order to combine the benefits of these two special concretes, functionally graded material (FGM) concept was introduced. This aims to create more efficient composite materials that allow changeable properties over their volume [11]. The concept applied to concrete generates functionally graded concretes (FGC), which are produced in multiple layers of concretes with different properties to optimise the features of the whole component. Cyclic loading or energy absorption studies showed that the FGC present better performance than conventional concrete [12,13]. Other studies focused on economic aspects related to the content of fibres in FRC fibre content showing how the material performance is not affected when reducing the content of fibres [11]. However, there is a lack of research on the effect of the combination of fibres and recycled aggregates.

In that context, this study aims to explore the potential of a new FGC produced using fibres and recycled aggregates to develop more sustainable structures. With that aim four main aspects were studied: (1) mechanical performance; (2) proposal of a sustainable quality control method; (3) costs, and (4) embodied CO_2. In that sense, five different concrete mixes are considered. The experimental program carried out to achieve the mechanical properties of the mixes will be explained though two test methods: the bending test defined by the European standard EN 14651/210+ A1 [14] and the Barcelona test [15]. The results obtained from the two methods were correlated to make possible the use of the Barcelona test, which can be more sustainable, to control the FGC mechanical behaviour. Finally, the embodied carbon and the cost of the materials used to produce the concrete mixes will be presented and used to estimate the values taken by each FGC. The results of these three analysis are then discussed and conclusions are presented.

2. Experimental program

2.1. Materials

2.1.1. Cement, water and aggregates

A Portland cement CEM 42.5N, which fulfilled the requirements of the EN 197-1/2000 [16], was used in this study. Tap water at room temperature (20 °C) was utilized. Two types of aggregates were used: natural and recycled. The type of natural gravel is limestone and recycled aggregates were collected from a demolished concrete construction site. Fig. 1 shows the grading of the fine aggregates (FA) and coarse aggregates (CA) and compares them to the limitations for the fine aggregates (LFA) and the limitations for the coarse aggregates (LCA) specified by the EN 933-1/2012 [17].

Notice that the particle grading were slightly out of the limits specified by the standard EN 933-1/2012, especially in case of the recycled coarse aggregates. However, this is not relevant to this study since the aim is to compare the mechanical performance of fibre reinforced and FGC rather than trying to obtain expectable strengths. Therefore, the objective was guaranteeing that all natural and recycled aggregates used for production of the mixes were from the same source and presented consistent properties.

Table 1 presents the main properties of the aggregates. These are the saturated surface dry density (*SSDD*), the water absorption (*WA*), the uniformity coefficient (C_U) and the coefficient of curvature (C_Z). These properties were assessed to optimize the concrete mix designs. Notice that *SSDD*, *WA*, C_U and C_Z were assessed regarding the standards EN 933-1/2012 [17] and EN 1097-6/2013 [18].

It is observed that the recycled aggregates have lower *SSDD* but higher *WA* than the natural aggregates which is in accordance with other studies [19]. This is due to some mortar being attached on the surface of *RA*, resulting in lower *SSDD*. In addition, high porosity of the mortar contributes to the high *WA* values of *RA*. On the other hand, the recycled aggregates presented higher values of C_U and C_Z indicating that the natural aggregates had a wider range of particle size distribution.

2.1.2. Superplasticizer and fibres

A superplasticizer (SP) was applied in all mixes to improve their workability [20]. The SP Viscocrete 530P supplied by Sika Group, with an approximate density of 0.6 g/cm^3 at 23 °C and 7.0 pH was used. A structural steel fibre GSF07560 supplied by Ganzhou Daye Metallic Fibres was used (Fig. 2). This is a fibre widely used for FRC, which have a length (*L*) of 60 mm and an aspect ratio (*L/D*) of 80. The fibre content was 40 kg/m^3 (0.5% in volume), which is a typical value for FRC [12,21].

2.2. Concrete mixes

Fig. 2 presents the models of five concrete mixes considered in this study. These are divided in two main groups: concrete mixes reinforced with fibres (A, B) and FGC mixes (C, D, E). Notice that the FGM concept is applied to produce FGC with two layers with equal thickness.

The first group embraces a conventional FRC (A) and a fibre reinforced recycled aggregate concrete (FRRAC) (B). The second group considers three different FGC mixes: Portland cement concrete (PCC) + FRC (C); recycled aggregate concrete (RAC) + FRRAC (D), and a PCC + FRRAC (E).

All FGC consider the bottom layer reinforced with fibres, since concrete pavements or concrete precast tunnel lining are usually subjected to bending, and therefore, the upper and bottom layers are under compression and tension, respectively [21]. Since concrete can carry relatively low loads in tension, the reinforcement is required within the bottom layer. The last mix (PCC + FRRAC) is considered because PCC, containing natural aggregates, would provide high compressive stress in superior layers. Besides, FRRAC is used to resist tensile stress because the residual tensile strength of a concrete reinforced with fibres only depends on their content, and thus, the mechanical properties of the recycled aggregates do not influence it [22].

2.3. Reference mix designs

A total of four mix designs are needed to produce the concrete mixes described above. Table 2 presents the two reference mix designs defined in this study. The first embraced PCC and FRC, whereas the second considered RAC and FRRAC, respectively. For the two reference mix designs cement equals to 475 kg/m^3 and a w/c ratio equals to 0.45. Notice that the amount of water used in the project

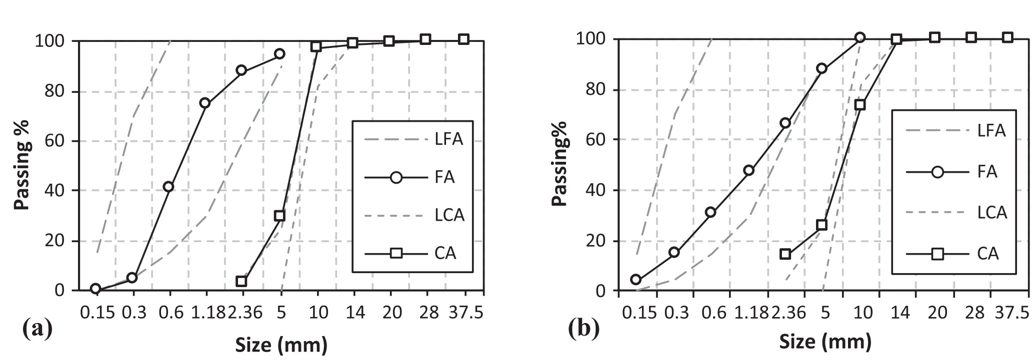

Fig. 1. Particle size distribution of natural a) and recycled aggregates b).