Characterization of functionally graded concrete produced with fibres and recycled aggregates

Tong Hu1,*, Ricardo Chan1, Isaac Galobardes1, Xingzi Liu1, Charles K.S. Moy1, Jian Li Hao1 and Kristian Krabbenhoft2

1 Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China
2 School of Engineering, University of Liverpool, Liverpool L69 3GH, United Kingdom

*Corresponding author. E-mail address: tong.hu14@alumni.xjtlu.edu.cn

Abstract. Conventional reinforced concrete is widely used in the pavement construction despite its technical drawbacks, economic and environmental issues. To address these matters, the concept of functionally graded material (FGM) with materials that present changeable properties over its volume is adopted on concrete, generating functionally graded concrete (FGC). However, more studies are needed to understand how this material performs. In this study, six mixes of FGC concretes were produced to assess the effect of the recycled aggregate and different depths of the fiber reinforced layer on the flexural performance. Besides, the inductive method was performed to estimate the fiber content and distribution in the mixes. The outcomes of the study highlight the inductive method as a good tool to perform the quality control of the mixes and that FGC produced with recycled aggregates and fibers present great potential in terms of Serviceability Limit States (small deflection).

1. Introduction

Conventional reinforced concrete (RC) is widely used in construction. However, this traditional material presents drawbacks regarding technical issues and high carbon footprint [1]. In that sense, fiber reinforced concrete (FRC) may improve RC drawback in terms of controlling crack propagation [2]. Moreover, fibers might partially, or totally, substitute traditional reinforcement leading to economic advantages [3]. Current studies present FRC as an optimization of RC to produce certain types of applications such as pavements or tunnel linings [4]. However, the homogenous distribution of fibers in the whole volume of concrete makes it a non-efficient economic material for applications under bending [4]. On the other hand, to reduce the RC environmental drawbacks, recycled aggregate is used to substitute natural aggregate in concrete [5]. Recycled aggregate concrete (RAC), despite the low mechanical properties it presents, leads to a reduction of demolition waste land occupation and quarry exploitation [1].

The concept of functionally graded material (FGM) to create composite materials that present changeable properties over its volume, can be adopted to combine the benefits of FRC and RAC generating a functionally graded concrete (FGC) [6]. In that sense, this paper aims to present an investigation on the flexural performance of FGC produced with fibers, natural and recycled aggregates. Besides, since the performance of concrete reinforced with fibers is directly correlated
with their distribution [4], an assessment of the fiber content and its spatial orientation by means of the inductive method is presented [7].

2. Methodology

2.1. Materials
Portland cement CEM 42.5N, complying with the requirements of EN 197-1:2000 [8], was used. Mixes were produced with tap water controlled at room temperature (20°C). Two types of aggregate, natural and recycled, were used. Limestone was used as natural aggregate, whereas the recycled aggregate was composed by local demolition waste (Suzhou, China). The particle size distributions are the ones presented in Liu, X. et al. (2018) [1].

Table 1 presents the main properties of the aggregates: saturated surface dry density ($\rho_{SSD}$), water absorption ($W_{A24}$), uniformity coefficient ($C_u$) and coefficient of curvature ($C_z$). These properties were assessed based on the requirements of the standards EN 933-1:2012 [9] and EN 1097-6: 2013 [10]. Notice that the recycled aggregates possess lower $\rho_{SSD}$ but higher $W_{A24}$ than the natural one, which is in accordance with other studies [5]. This could be explained due to the existence of mortar bonded on the coarse recycled aggregate surface. Additionally, the recycled aggregates presented higher values of $C_u$ and $C_z$ indicating that it possessed a wider range of particle size distribution.

| Aggregate type | $\rho_{SSD}$ (Mg/m$^3$) | $W_{A24}$ | $C_u$ | $C_z$ |
|----------------|-------------------------|-----------|-------|-------|
| Natural        | Fine                    | 2.77      | 2.62% | 2.78  | 0.88  |
|                | Coarse                  | 2.67      | 1.10% | 2.46  | 1.29  |
| Recycled       | Fine                    | 2.18      | 15.07%| 8.64  | 0.83  |
|                | Coarse                  | 2.42      | 7.54% | 19.29 | 8.26  |

Finally, hooked-end steel fibers were used in the study complying the requirements of the standard EN 14889-1:2006 [11]. The fibers presented 60 mm length and aspect ratio of 80, being recommended to produced fiber reinforced concrete [1]. Only one content of fiber was adopted: 40kg/m$^3$.

2.2. Concrete mixes
Six concrete mixes were considered (Figure 1). These include three types of concrete: Portland cement concrete with natural aggregate (PCC), fiber reinforced concrete (FRC) and fiber reinforced recycled aggregate concrete (FRRAC). All FGC mixes are designed to absorb tension in the bottom layer since the study aims studying the flexural behavior of the mixes [12]. In order to study the effects of the layer reinforced with fibers different depths are considered: 100% (mixes A and D, respectively), 50% (mixes B and E, respectively) and 25% (mixes C and F, respectively). All FGC are produced with PCC in the upper layer.

Figure 1 Concrete mixes considered in the study

2.3. Reference mix design and mix production
Mixes were produced with 475 kg/m$^3$ and a water – cement ration (w/c) of 0.45. Notice that the actual amount of water used was adjusted with consideration of the water absorption results presented in Table 1. The amount of both coarse and fine aggregates were 790 and 890 kg/m$^3$ and 805 and 715 kg/m$^3$ for natural and recycled aggregate mixes, respectively.
To simulate the flexural behavior of the FGC pavement, slabs with dimensions 500×150×1000 mm were adopted. The slabs were produced following the process described in Liu, X. et al. [1]. Notice that the time interval between pouring two layers of concrete was less than 20 min according to other studies to assure bonding between layers [6]. Pouring of concrete adopted was the same for all mixes, ensuring similar fiber orientation [4]. A total of 18 slabs (3 samples per mixes) were casted. After curing for 24 hours, these specimens were demolded and submerged until testing age (28 days).

2.4. Test methods

2.4.1 Inductive method

The Inductive method is a semi-non-destructive test that uses an electrical coil and its electromagnetic properties in order to estimate the quantity of the fibers in concrete (Figure 2.a). The methodology was developed by researchers of the Universitat Politècnica de Catalunya [7]. Its basic concept is that placing a sample reinforced with fibers in the middle of an electromagnetic field a variation of its inductance (ΔL) is observed. Then placing the sample into the coil in different positions, different ΔL are obtained. Analysing the sum of them (ΔLT) the fiber content and its orientation is estimated. Notice that the inductive method needs to be calibrated since the results depend on the type of fiber used.

![Inductive equipment](image1.png)

![Extraction location](image2.png)

![Reference fiber orientation](image3.png)

Figure 2 The inductive method

Two cylindrical cores were extracted from two slabs per each mix after the bending test, entailing a total of 24 samples (100φ×100 mm) (Figure 2.b). These sample were evaluated producing 96 ΔL readings.

2.4.2 Bending test

The FGC flexural performance was assessed by means of the four-point bending test (Figure 3) based on an adaptation of the American Standard ASTM C 1609/C 1609M – 06 [13]. Notice that the geometry of the slabs, and therefore the setting up of the test, is not in accordance with international guidelines. However, this is not relevant since the purpose of this study is just comparing the flexural performance of the FGC mixes. The results obtained from this test are load – vertical deflection curves.

![Testing machine](image4.png)

![Dimension of the setup](image5.png)

Figure 3 The bending test
3. Results and analysis

3.1. Inductive method

3.1.1 Calibration of the inductive method

To calibrate the method, three Styrofoam cylinders (100φ×100 mm) were used followed the methodology described in [14]. The relationship between the content of fibers (\(C_{f,i}\)) and \(\Delta L_T/V\) (\(V\) is the volume of the samples) is presented in Figure 4. This relationship is used to estimate the \(C_{f,i}\).

![Figure 4 The calibration equation](image)

\[ C_{f,i} = 0.0096 \cdot \Delta L_T/V \]
\[ R^2 = 0.98 \]

3.1.2 Content and orientation of fibres

Table 2 presents the results obtained by means of the inductive method: content of fibers (\(C_{f,i}\)) and orientation (\(C_x\), \(C_y\), \(C_z\), respectively). Besides, the variation of the results is shown in brackets.

| Parameter \(C_{f,i}\) (kg/m\(^3\)) | A      | 49.31  | (3.79%) |
|------------------------------------|--------|--------|---------|
|                                    | B      | 51.81  | (26.20%)|
|                                    | C      | 51.42  | (16.44%)|
|                                    | D      | 42.55  | (11.94%)|
|                                    | E      | 63.00  | (32.78%)|
|                                    | F      | 51.27  | (40.27%)|

| Parameter \(C_x\) (%)          | A      | 35.75  | (24.01%)|
|--------------------------------|--------|--------|---------|
|                                 | B      | 40.23  | (5.42%) |
|                                 | C      | 33.18  | (10.13%)|
|                                 | D      | 39.74  | (8.78%) |
|                                 | E      | 31.24  | (15.07%)|
|                                 | F      | 38.63  | (11.99%)|

| Parameter \(C_y\) (%)          | A      | 43.35  | (6.19%) |
|--------------------------------|--------|--------|---------|
|                                 | B      | 36.26  | (1.91%) |
|                                 | C      | 41.77  | (4.70%) |
|                                 | D      | 40.49  | (5.00%) |
|                                 | E      | 41.15  | (7.93%) |
|                                 | F      | 31.22  | (12.05%)|

| Parameter \(C_z\) (%)          | A      | 20.90  | (28.27%)|
|--------------------------------|--------|--------|---------|
|                                 | B      | 23.51  | (9.23%) |
|                                 | C      | 25.05  | (6.88%) |
|                                 | D      | 19.77  | (11.27%)|
|                                 | E      | 27.61  | (8.54%) |
|                                 | F      | 30.14  | (9.63%) |

Table 2 Inductive method results

The content of fibers (\(C_{f,i}\)) results obtained are higher than the reference design value (40 kg/m\(^3\)). The increase is equal to 12% on average. This increment may be related to a non-homogeneous distribution of the fibers in the matrix as observed in other studies [15]. Regarding the orientation, fibers are orientated on average 36, 40 and 24% in X, Y and Z, direction (Figure 2.c). Therefore, 76% of fibers are orientated in the XY plane having an effect on the flexural performance. This tendency is in accordance to other studies, said that fibers tend to be oriented parallel to the walls or surfaces of the formwork and perpendicular to the flow direction for a free surface flow [15]. Notice that the orientation is a qualitative assessment where all fibers contribute to all three directions. Hence, the results obtained for \(C_z\) do not imply the fibers are in vertical position [7].

3.2. Flexural performance

The results obtained are presented in Table 3. It shows the values of load (F) related to flexural tensile strength (\(F_t\)) and load related to residual flexural tensile strength regarding short and long vertical displacements (\(F_{L/1200}\) and \(F_{L/300}\), respectively). Furthermore, the table presents the coefficient of variation of the results in brackets. Notice that \(F_{L/1200}\) and \(F_{L/300}\) are related to Serviceability and
Ultimate Limit States, respectively[16]. Besides, Figure 5 presents the corresponding F-Displacements curves obtained.

Regarding the results obtained for $F_1$, mixes produced with conventional aggregate (A, B and C) present similar values (around $25 \, kN$), whereas mixes produced with recycled aggregates (D, E and F) present values from $17$ to $30 \, kN$. This difference is due to the content of recycled aggregates in the mix. The higher it is, lower is the value of $F_1$. These results were expected since recycled aggregates lead to lower mechanical properties. On the other hand, results related to the Ultimate Limit States ($F_{L/300}$) depend on the thickness of the fiber reinforced layer independently of the type of aggregate use in the mixes. This result, also expected, was already observed in previous studies [1, 5]. Finally, results related to Serviceability Limit States ($F_{L/1200}$) follow different tendencies considering both type of aggregate and thickness of fiber reinforced layer in the mix. As expected, mixes produced with conventional aggregates present higher $F_{L/1200}$ values for higher thickness of fiber reinforced layer. However, mixes produced with recycled aggregates present the opposite tendency, being mix F the one that presents higher results. This result shows the potential of FGC produced with recycled aggregates and fibers, since combination of two layers of PCC and FRRAC (mixes E and F) present better results (for small displacements) than full FRRAC (mix D).

### Table 3 Bending test results

| Parameter          | Concrete mix | A      | B      | C      | D      | E       | F       |
|--------------------|--------------|--------|--------|--------|--------|---------|---------|
| $F_1$ (kN)         |              | 26.32  | 24.60  | 24.78  | 17.19  | 22.45   | 29.11   |
|                    |              | (6.81%) | (8.91%) | (9.72%) | (6.91%) | (9.97%) | (6.18%) |
| $F_{L/1200}$ (kN)  |              | 25.64  | 19.98  | 13.24  | 12.63  | 15.79   | 24.30   |
|                    |              | (3.06%) | (29.27%) | (21.03%) | (28.55%) | (12.23%) | (12.26%) |
| $F_{L/300}$ (kN)   |              | 27.92  | 17.41  | 8.34   | 14.60  | 11.11   | 4.87    |
|                    |              | (12.98%) | (23.68%) | (9.09%) | (25.51%) | (9.61%) | (16.19%) |

![Figure 5 Load – Displacement curves of the bending test](image)

4. **Conclusions**

An investigation on the flexural performance of FGC produced with fibers, natural and recycled aggregates and an evaluation of the fiber content and its spatial orientation by means of the inductive method was presented in this paper. The results presented showed that the inductive method is a great tool to perform the quality control of the FGC. In that sense, results obtained for $C_{f,i}$ are 12% on average higher than the reference design value (40 kg/m$^3$). On the other hand, the orientation of fibers results show that 76% of them are orientated in the XY plane following the same tendency regular FRC presents in other studies. Finally, regarding the FGC flexural performance, mixes produced with conventional aggregates presented expected results, whereas FGC mixes produced with recycled aggregates showed better performance and great potential compared with FRRAC mix considering Serviceability Limit States (small displacements).
References

[1] Liu X, Yan M, Galobardes I, Sikora K. Assessing the potential of functionally graded concrete using fibre reinforced and recycled aggregate concrete. *Construction and Building Materials*. 2018;171:793-801.

[2] Gong C, Ding W, Mosalam KM, Günay S, Soga K. Comparison of the structural behavior of reinforced concrete and steel fiber reinforced concrete tunnel segmental joints. *Tunnelling and Underground Space Technology*. 2017;68:38-57.

[3] Meng G, Gao B, Zhou J, Cao G, Zhang Q. Experimental investigation of the mechanical behavior of the steel fiber reinforced concrete tunnel segment. *Construction and Building Materials*. 2016;126:98-107.

[4] Blanco A. Characterization and modelling of SFRC elements [Doctoral thesis]. Spanish Universitat Politècnica de Catalunya.; 2013.

[5] Chan R, Santana MA, Oda AM, Paniguel RC, Vieira LDBP, De Figueiredo AD, et al. Analysis of potential use of fibre reinforced recycled aggregate concrete for sustainable pavements. *Journal of Cleaner Production*. 2019;218:183-91.

[6] Rio O, Nguyen VD, Nguyen K. Exploring the Potential of the Functionally Graded SCCC for Developing Sustainable Concrete Solutions. *Journal of Advanced Concrete Technology*. 2015;13(3):193-204.

[7] Cavalaro SHP, Lopez R, Torrents JM, Aguado A. Improved assessment of fibre content and orientation with inductive method in SFRC. *Materials and Structures*. 2015;48(6):1859-73.

[8] BSI. *BS EN 197-1:2000 Cement*. Composition, specifications and conformity criteria for common cements London: BRITISH STANDARDS INSTITUTION (BSI); 2000.

[9] BSI. *BS EN 933-1:2012 Tests for geometrical properties of aggregates*. Determination of particle size distribution. Sieving method. Determination of particle size distribution Sieving method. London: BRITISH STANDARDS INSTITUTION (BSI); 2012.

[10] BSI. *BS EN 1097-6:2013 Tests for mechanical and physical properties of aggregates*. Determination of particle density and water absorption. London: BRITISH STANDARDS INSTITUTION (BSI); 2013.

[11] BSI. *BS EN 14889-1:2006 Fibres for concrete*. Steel fibres Definitions, specifications and conformity. London BRITISH STANDARDS INSTITUTION (BSI); 2006.

[12] Liao L, de la Fuente A, Cavalaro S, Aguado A. Design of FRC tunnel segments considering the ductility requirements of the Model Code 2010. *Tunnelling and Underground Space Technology*. 2015;47:200-10.

[13] ASTM. *ASTM C1609 / C1609M - 06 Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)*. American Society for Testing and Materials; 2007.

[14] Silva C, Galobardes I, Pujadas P, Monte R, Figueiredo A, Cavalaro S, et al. Assessment of Fibre Content and Orientation in SFRC with the Inductive Method. Part 2: Application for the Quality Control of Sprayed Concrete 2015.

[15] Pujadas P, Blanco A, Cavalaro S, de la Fuente A, Aguado A. Fibre distribution in macro-plastic fibre reinforced concrete slab-panels. *Construction and Building Materials*. 2014;64:496-503.

[16] ACI. *544.4R-18: Guide to Design with Fiber-Reinforced Concrete*. USA: American Concrete Institute; 2018.