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Shrinkage and flexural behaviour of free and restrained hybrid steel fibre reinforced concrete

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HIGHLIGHTS

- Free shrinkage strains are not affected significantly by addition of steel fibres.
- GGBS reduces shrinkage strains.
- Recycled tyre steel fibres can replace manufactured steel fibres partially.

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ABSTRACT

The effect of restrained shrinkage on the mechanical performance of concrete and steel fibre reinforced concrete (SFRC) requires more investigation, especially when using recycled tyre steel fibre (RTSF). This paper examines the free and restrained shrinkage strains and the mechanical performance of seven SFRC mixes. Results show that both free and restrained average shrinkage strains are very similar in all blends of fibres and they exhibited non-uniform shrinkage through the height of the section. All examined blends meet strength requirements by MC-2010 for fibres to replace part of the conventional reinforcement in RC structures.

1. Introduction

In water retaining structures or bridge elements, serviceability limit state (SLS) design aims to control crack widths to achieve a target life span by providing relatively large amounts of surface steel reinforcement. In such structures, the additional reinforcement is required to control cracks induced by restrained shrinkage, which creates further constructability challenges. To reduce the amount of additional surface reinforcement, shrinkage can be mitigated by reducing paste/aggregate ratio, minimising C_3S content in cement, using expansive or shrinkage reducing additives, and internal curing materials [1].

Shrinkage cracking can also be controlled by adding randomly distributed steel fibres as successfully utilised by the construction industry in pavements and tunnels [2–4]. Steel fibres can enhance the performance of concrete in flexure, shear and punching whilst at the same time help control shrinkage cracking and reduce spalling [5–7], depending on the amount and characteristics of the steel fibres, such as type, shape and aspect ratio [8–11]. Recycled tyre steel fibres (RTSF) are also available and were found to be good in controlling micro-cracks [12,8]. RTSF can improve flexural toughness and post cracking performance and can successfully substitute manufactured fibres partially or fully in some applications [9,13].

In most published research on RTSF [4,14,15], a single type of fibre is used as reinforcement. Recently, some studies investigated blends of manufactured and recycled steel fibres with different shapes and aspect ratios [9,16], but the recycled fibres used were not classified raising reliability and repeatability concerns. The cleaning process of RTSF has been improved significantly recently and improved classified fibres have become available [17–19]. Hence, there is a need to investigate the effect of hybrid steel fibres (both manufactured and classified RTSF) on concrete exposed to free and restrained shrinkage.

The impact of steel fibres on free shrinkage of concrete is not clearly understood, with some researchers reporting an increase due to the increase in air voids, whilst others reporting either a decrease due to the internal restraint provided by the fibres or

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insignificant changes due to the cancelling effect of the two actions [4,14,15,20]. Nonetheless, the effect of steel fibres on free shrinkage is known to vary depending on water-to-binder ratio, volume and type of admixtures, method of concrete laying (conventional, self-compacted concrete (SCC) or roller compacted concrete (RCC)), time of vibration, etc. [21].

In concrete structures, shrinkage of concrete is restrained by different actions internally and externally. External restraint can arise due to friction or reaction against the ground, concrete supporting elements or adjacent rigid structures, whilst internal restraint is provided by aggregates and reinforcement [22,23]. It is also known that aggregates tend to settle and concentrate at the bottom of the mould whilst water and air rise due to vibration and surface tamping. These phenomena can cause differences in compressive strength and elastic modulus at the top and bottom of the element [24,25]. As more paste and water are found near the top surface, this can cause much higher shrinkage strains in that region. Non-uniform distribution of aggregates and water can create non-uniform shrinkage through a section and lead to additional curvature in concrete elements [4]. RILEM TC 107-CSP [26] determines shrinkage from the change in the distance between the centres of the two ends of a cylinder, which means that its approach is unable to capture the effect of aggregate sedimentation. To the knowledge of the authors, none of the design codes or standards deal with curvature due to the non-uniform shrinkage and this can lead to underestimate of long-term deflections and crack widths.

Free shrinkage tests on small elements are not normally able to develop enough internal tensile stresses to crack the concrete, hence, restrained shrinkage tests are needed to understand the cracking behaviour of restrained concrete [12]. Restraint causes tensile stresses in the concrete, which theoretically could increase with time due to concrete maturity, but creep is expected to relieve some of these stresses and reduce the probability of cracking [23,27,28]. Normally, it is difficult to quantify the degree of restraint imposed on an element, as it depends on the type of application, the location of the member in the structure and environmental conditions [3,29]. However, there are several tests to assess the restrained shrinkage of concrete [1], with the most used being the ring test [30,31]. Though simple and popular, this test can only be used for comparison purposes, as it only detects the stress and time of the first crack. Another disadvantage of this approach is that the sectional size needs to be kept relatively small (to enable cracking at a reasonable time frame) and this enhances boundary effects and makes the concrete section less representative of sections in practice.

Active systems with larger specimens [32–34] can be used to restrain concrete shrinkage by fixing one end of a linear element whilst the other end is attached to an actuator which keeps the total length constant. In active systems, cracks tend to occur when the strain is being adjusted and this can affect the time at which cracking takes place [35]. Furthermore, full and active restrain is rarely found in practice, where restrain depends on the relative stiffness of the restraining structure and is mitigated by creep. For these reasons, and for simplicity, passive systems [36,37] can be used by restraining concrete specimens through fixing bolts onto rigid structural elements. Younis (2014) [4] proposed the use of a passive restraining frame able to hold three prisms at the same time. The use of linear elements also enables shrinkage measurements to be taken at different levels through the section and examine shrinkage curvature.

The aim of this work is to examine the effect of restrain on shrinkage and mechanical performance of hybrid SFRC mixes. The performance of SFRC prisms comprising different fibre blends and subjected to a combination of restraining, curing and drying conditions are studied and compared. Ground granulated blast-furnace slag (GGBS) and RTSF are used, along with manufactured fibres, to control the amount of shrinkage strains and limit the propagation of concrete cracking under restrained conditions.

This paper comprises three main sections along with an introduction and conclusions. The first section presents the experimental programme including the examined parameters, the physical and mechanical characteristics of the examined materials and testing methodology. This is followed by a discussion on the results obtained from free and restrained shrinkage tests of hybrid SFRC prisms *(blends of manufactured undulated steel fibres (MUSF) and RTSF)*. The level of restrain imposed by restraining frames is assessed through a finite element numerical analysis and used to gain additional insight into the effect of restraint level on overall behaviour. Finally, in the third section the paper discusses the effect of restrained shrinkage and different drying conditions on the flexural performance of the examined concrete mixes.

2. Experimental programme

2.1. Parameters

The experimental programme examined seven SFRC mixes in addition to a control mix made of plain concrete, as shown in Table 1. Each mix was used to manufacture twelve control cubes (100 mm), six prisms (100 × 100 × 500 mm) for free shrinkage measurement and three prisms, which were cast in a restraining steel frame as shown in Fig. 1a [4]. Three prisms (out of the six) were stored in a mist room (MR) to monitor autogenous shrinkage. The other three specimens were stored under controlled environmental (CR) conditions (temp: 23 ± 2 °C and RH: 40 ± 5%) to quantify drying shrinkage. The restrained specimens (RS) were stored under the same conditions as the CR specimens.

2.2. Measurements

Shrinkage measurements were taken using a 200 mm demountable mechanical ‘‘DEMEC” strain gauge at the top and bottom of both sides of all prisms for 300 days. Fig. 1(b and c) shows the measurement layout for free and restrained shrinkage, respectively. It should be noted that a 100 mm ‘‘DEMEC” strain gauge was used to measure the deformation at the boundaries between concrete and restraining frame.

Table 1
Steel fibre types and contents.

Mix	MUSF L (mm)	MUSF Ø (mm)	MUSF Dose (kg/m^3)	RTSF Dose (kg/m^3)	RTPF Dose (kg/m^3)	Batch number
P	–	–	–	–	–	1, 2, 3
M30	55	0.8	30	–	–	1
M20R10	55	0.8	20	10	–	2
M20R10P1	55	0.8	20	10	1	3
R30	–	–	–	30	–	3
M35	60	1.0	35	–	–	1
M45	60	1.0	45	–	–	1
M35R10	60	1.0	35	10	–	2