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Cracking behavior of steel fiber reinforced waste sand concrete beams in flexure – Experimental investigation and theoretical analysis

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ABSTRACT

Waste sands resulting from coarse aggregate extraction are becoming an increasingly pressing ecological issue in northern Poland, the Middle East or North Africa. In order to manage the waste sand, a fine-grained composite with the addition of steel fibers has been developed. As steel fibers constitute 1.2% of the composite, it has been called Steel Fiber Reinforced Waste Sand Concrete (SFRWSC). The physico-mechanical and rheological properties of the composite meet the requirements of construction materials and make it more effective than ordinary concrete. In order to prove SFRWSC's usefulness in the production of construction elements, experimental investigations on flexural behavior of full-scale conventionally reinforced concrete beams have been carried out. The test specimens were divided into three series differing as to the conventional reinforcement ratio. It has been demonstrated that SFRWSC can be readily used in the production of bending structural elements as regards cracking limit state. Steel fibers decrease considerably crack spacing and crack width. The analysis also includes cracking moment, maximum crack width – average crack width relation as well as variability of the obtained results. Next, the experimental research results have been compared with the calculation results according to RILEM and Model Code 2010 provisions. It has been proved that crack widths calculated in accordance with the aforementioned international regulations are underestimated in relation to experimental values. The obtained results highlight the necessity to correct these methods before using them for designing elements made from SFRWSC and Steel Fiber Reinforced Concrete (SFRC).

1. Introduction

One type of fiber-reinforced concrete is Steel Fiber Reinforced Waste Sand Concrete (SFRWSC), which has been developed in the Department of Concrete Structures and Concrete Technology at Koszalin University of Technology. This composite has been created primarily to manage waste fine aggregate remaining after hydroclassification process in local mines [1,2]. The possibility of reusing waste sand is both economically and ecologically beneficial solution for reclaiming excavation sites. To date, comprehensive research on physico-mechanical properties of this composite has been conducted [3]. The obtained results show that the addition of steel fibers significantly increases, among others, concrete compressive/tensile/shear strength, frost/abrasion resistance and static modulus of elasticity [3,4]. High parameters of strength in SFRWSC, particularly tensile strength and residual strengths, show that this composite can be used in the production of construction elements. Therefore, it can be expected that the addition of steel fibers to conventionally reinforced bending elements will not only increase their load bearing capacity, stiffness and ductility but will also contribute to the reduction of crack spacing and crack width [5–14].

Calculating crack width in fiber-reinforced concrete structural elements with conventional reinforcement has been the subject of many publications [14–20]. However, the most practical propositions are to be found in RILEM TC-162-TDF [17] recommendation as well as FIB Model Code 2010 [18] pre-standard. These regulations are relatively new and it is not easy to evaluate them. The research in this field is still insufficient and its results show disagreement. As far as RILEM method is concerned, Domski [19] has rightly observed that the fiber content is not considered to influence crack spacing. Kelpsa et al. [5] have proved that crack widths calculated in accordance with RILEM are clearly overestimated in relation to experimental values. While assessing the method of calculating crack widths according to Model Code 2010, Tiberti et al. [20] have observed that the matrix's compressive strength has a major influence on crack spacing in axially tensile specimens with conventional reinforcement. This observation is not taken into account in the standard. The necessity to correct this method has also been signaled by Biolzi and Cattaneo [10]. Crack spacing and crack width values measured in the author's own research have turned out to be

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Fig. 1. View of steel fibers used in the research.

considerably bigger than calculated ones. For this reason, further research is recommended to improve the above-mentioned methods.

The aim of the research was to assess the influence of steel fibers on crack spacing and crack width in bending SFRWSC beams. RILEM and Model Code 2010 methods of calculating cracks as well as selected propositions to correct these methods were also assessed. The obtained research results constitute some progress toward improving the existing calculation methods. Simultaneously, researchers tried to demonstrate that SFRWSC can be used in the production of bending structural elements as regards cracking limit state.

2. Test specimens

In order to produce SFRWSC, waste sand (fractions ranging from 0.125 to 4 mm) from a local mine of natural aggregates was used in the quantity of 1570 kg/m$^{3.}$ As a binder, Portland cement CEM II/AV 42.5R (420 kg/m^3) was applied. Other ingredients were: silica fume (21 kg/m^3), superplasticizer BETOCRETE 406 FM (16.8 kg/m^3) and steel hooked-end fibers (Fig. 1) with the aspect ratio $\lambda = l/d = 62.5$ ($l = 50$ mm, $d = 0.8$ mm). The volume content of steel fibers was optimized to achieve possibly the most beneficial physico-mechanical and rheological properties of the material and was equal to 1.2% (94.5 kg/m^3). Applying superplasticizer as well as adding silica fume enabled a w/c = 0.38 ratio to be obtained. In order to prepare the SFRWSC mix, dry ingredients were mixed first (2 min). Next, water and superplasticizer were added (mixing time: 5 min). Steel fibers were added into the drum of the mixer at a rate of 20 kg/min, as the last ingredient of the mix. The drum rotated at high speed for 5 min afterwards. The characteristics of steel fibers and waste sand used in the research are presented in the papers [1,3,4].

An experimental study was conducted on nine reinforced concrete beams which were divided into three series depending on the conventional reinforcement ratio (Table 1). In addition, all beams with steel fibers were produced in two variants - with and without stirrups - with a view to examining the influence of stirrups on cracking. Mechanical properties of the bars used as the longitudinal reinforcement are presented in Table 2.

Table 1
Characteristics of tested beams.

Series number	Beams	Dimensions [mm]	Tensile reinforcement [mm]	Stirrups [mm]	Volume fraction [%]
1	B1	150 × 200 × 3300	2#8	#6 @	–
	BF1			125	1.20
	BF1a			–	
2	B2		2#12	#6 @	–
	BF2			125	1.20%
	BF2a			–	
3	B3		2#16	#6 @	–
	BF3			125	1.20%
	BF3a			–	

Table 2
Mechanical properties of steel bars.

Diameter [mm]	Yielding stress [MPa]	Tensile strength [MPa]	Modulus of Elasticity [GPa]
8	559	596	197
12	597	690	208
16	535	625	207

Fig. 2 presents geometry, static scheme of tested beams, details of conventional reinforcement as well as placement of electrical-resistance gauges for measuring tensile reinforcement strains.

For each beam, small-size elements were produced to determine the compressive strengths (in total, 30 cylinders made from a composite without steel fibers and 30 cylinders with fibers – diameter and height of specimens were equal to 150 and 300 mm respectively) as well as the residual strengths (30 prisms whose dimensions were 150 × 150 × 700 mm).

Having been cast in moulds, all specimens were tightly wrapped in foil and stored at a temperature of 20 ± 2 °C. After 2 days, the specimens were demoulded, covered amply with water and rewrapped in foil. For the next 28 days, the specimens were cured under the same conditions. The specimens were tested 30 days after moulding since 2 more days were needed to prepare them for testing.

3. Research methodology

The beams were tested on a specially-prepared stand for inverted simply-supported beam (Fig. 2). Static load was applied by traverse with constant speed of ~0.25 kN/s underneath the beam by means of a hydraulic jack. When yield stress was achieved in tensile reinforcement (compare Table 2), the load was controlled by the beam's deflection speed, which was 0.1 ± 0.025 mm/s.

The beams were tested using SAD256 data acquisition system and ARAMIS 4M optical-measurement system. SAD256 was used to measure the load force "P", deflection (5 linear variable displacement transducers LVDT), strain of the beam's one lateral surface (17 LVDTs) as well as tensile reinforcement strain (6 electrical-resistance strain gauges). ARAMIS 4M optical-measurement system (Fig. 3) made it possible to track precisely the process of crack formation and crack propagation. The system also enabled the strain of the beam's second surface to be measured. During the test, ARAMIS 4M system takes photos of the examined surface at a given frequency. The system's software divides the examined area into tiny elements called facets and then designates their spatial coordinates. As a result, the location of the facets is known at each testing stage. By analysing the changing distances between the facets, the areas of crack formation can be detected and the crack pattern in the tested elements can be obtained for each testing stage (compare Fig. 6). As a result, the width of cracks as well as distances between them can be measured. The area of the tested surface was 1 m long and it covered the length of the beam between points where load was applied. All sensors of both SAD256 and ARAMIS 4M systems recorded measured displacements and load at a frequency of 1 per 2 s. The measurement accuracy for the ARAMIS 4M system was 0.01 mm.

Residual strengths were tested in accordance with EN 14651 [21] (Fig. 4). The compressive strength of SFRWSC was tested according to EN 12390-3 [22].