STATIC AND DYNAMIC CHARACTERISTICS OF FIBRE REINFORCED WCA CONCRETE

KATZER Jacek [1], DOMSKI Jacek [2]

Abstract

There are multiple obstacles associated both with technology and properties of waste ceramic aggregate (WCA) concrete, preventing its wide production and application in construction industry. In the research programme these limitations were addressed through utilizing engineered steel fibre and the process of internal curing. Majority of mechanical properties of the composites were tested according to European standards dedicated for ordinary and fibre concretes. Dynamic properties were tested utilizing tailored lab stand for impact tests. Created fibre reinforced concretes are characterized by compressive strength reaching 52 MPa. Values of their residual flexural strengths enable substitution of conventional reinforcement. Dynamic properties of the composites were tested on large scale specimens mounted on a specially tailored laboratory stand. After laboratory tests numerical analyses were conducted.

Keywords: ceramic, waste, aggregate, recycling, steel fibre

1. Introduction

Construction and building materials are often manufactured hundreds of kilometres away from a building site **[5]**. The production affects local environment but this influence on ecosystem is unseen from the building site. Likewise, extraction of raw materials for the production can occur far from the point of manufacture, affecting another local ecosystem. Disposal of manufacturing waste and used construction materials will affect yet another ecosystem. To break down this chain of bad influences on local ecosystems, waste aggregates are becoming increasingly popular raw material for concrete production. Concrete is the most commonly applied construction material in the world **[2]**. Global annual production of concrete consumes 20 billion tonne of different aggregates **[1]**. Statistically, about 3 tonne of aggregate is used per person per year. Waste ceramic aggregate (WCA) can be an answer to this problem solving two urgent ecological issues at the same time: utilising large volumes of construction/demolition waste and providing locally available coarse aggregate. So far waste ceramic aggregate has been usually used to cast elements characterized by lesser mechanical characteristics (e.g. pavement slabs) **[6]**. One of the main issues associated with replacing traditional coarse aggregates by WCA is the homogeneity of mechanical properties of cast concrete and mechanical properties

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themselves. To bypass those technological problems authors decided to embrace a new approach to the problem and modify concrete mix based on WCA by an addition of engineered steel fibre **[9, 10]**.

2. Used materials

Tested fibre composites were created on the basis of coarse WCA. This aggregate was prepared using red ceramic debris (Fig. 1) of broken and crushed wall blocks, hollow bricks and wire-cut bricks. Such red ceramic waste (very common in Europe **[6]**) is mainly associated with production of wall elements, their quality control, transportation to the building site, execution of construction and subsequent works **[11]**. The process of preparation of WCA was divided into grinding and sieving. Firstly, red ceramic waste was ground for 5 minutes in an electric industrial grinder **[4]**. Secondly, fractions characterized by diameter ϕ < 1mm and coarser fractions (1mm $\leq \phi \leq$ 31.5 mm) of ground all-in-WCA were separated. During the research programme only coarser fractions (1mm $\leq \phi \leq$ 31.5 mm) of WCA were used. The grading curve of utilized WCA, prepared with the help of rectangular sieve set (according to EN 933-1:1997) as well as both bulk densities (bulk and compacted) and water absorptivity by weight were tested. Results of these tests are presented in Fig. 2 **[4, 12]**. Natural sand of post-glacial origin (washed from all-in-aggregate during hydro-classification process) was employed as fine aggregate. This sand was thoroughly described in multiple previous publications **[3, 7]**.

Fig. 1: Red ceramic debris and WCA created from it

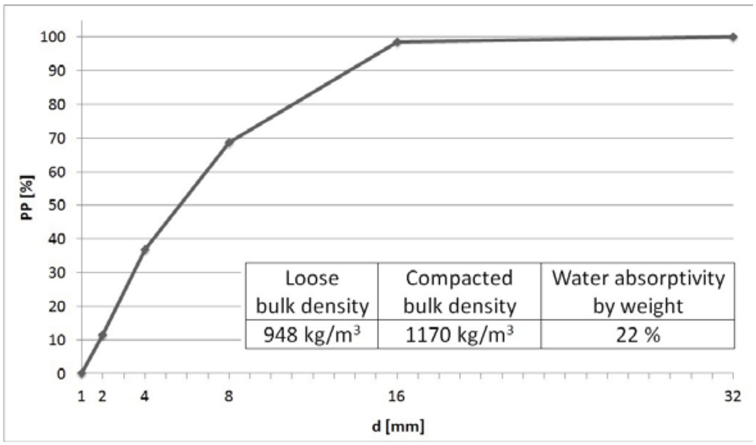

Fig. 2: Sieve analysis and other properties of used WCA

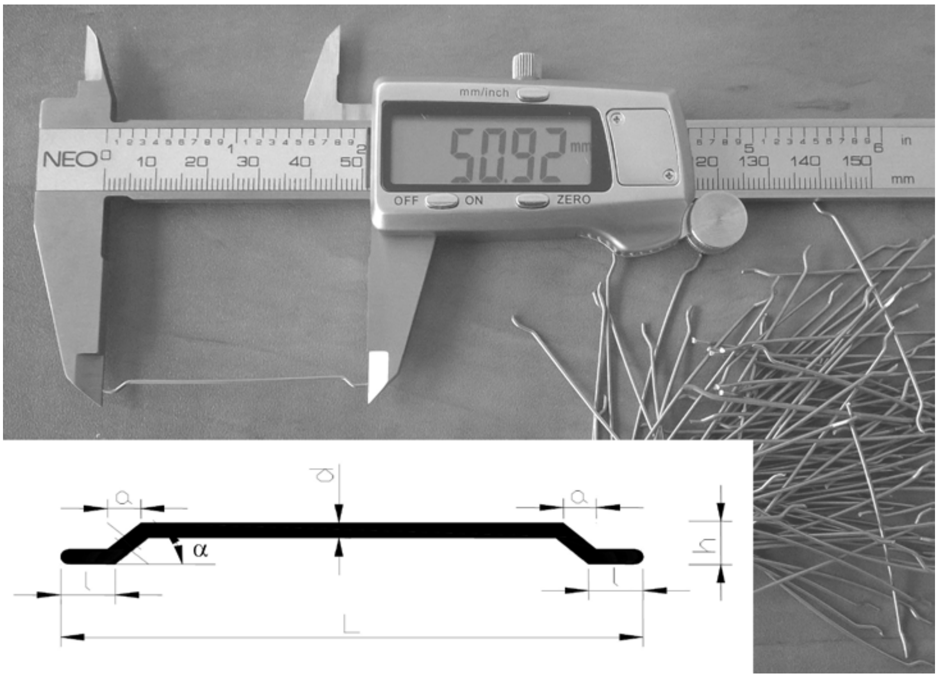

Fig. 3: Engineered hooked steel fibre

As fibre reinforcement only most common and commercially available engineered steel fibres were considered. Taking into account the worldwide scale of production of different fibre shapes and amount of available scientific data **[23]**, hooked steel fibres made from cold drawn wire were chosen as reinforcement. A photo and a schematic diagram of used steel fibres are presented in Fig. 3. Geometrical and mechanical characteristics of these fibres are summarized in Tab. 1. Fibre intrinsic efficiency ratio (*FIER*) defined by Naaman **[13]** as the ratio of bonded lateral surface area of fibre (Ψ), to its cross sectional area (A) was chosen to describe the main geometrical characteristics of used fibres (1).

$$FIER = (\Psi \cdot L)/A \tag{1}$$

Tab. 1: Mechanical properties and geometrical characteristics of used fibres

L [mm]	*d* [mm]	*L/d* [-]	*FIER* [mm]	Hook [mm]	R_m [MPa]	Ductility [no. of bends]	Steel [-]
EN 14889-1: 2006		-	$(\Psi \cdot L)/A$ **[13]**	$l + (a^2 + h^2)^{0.5}$ **[23]**	EN ISO 6892-1: 2009	EN 10218-1: 1994	EN 14889-1: 2006
50	1.00	50	12.279	6.228	935	9	Group I

Portland cement CEM I 42.5 (EN 197-1:2000) was used as a binder and tap water (EN 1008:2002) were used to compose the mixes. To maintain desired consistency all mixes were modified by admixture of 1% of highly effective superplasticizer. The superplasticizer (type FM) contains silica fume and is characterized by density of 1.45 g/cm^3. This superplasticizer and its influence on properties of fresh fibre reinforced mixes was described in previous work **[8]**.

3. Research programme

There were tested four composites reinforced by fibres in following volumes: 0.0%, 0.5%, 1.0% and 1.5%. To enable utilization of traditional rotary drum mixer and ordinary casting/compacting methods all fresh mixes had to be characterized by consistency class C2 tested according to EN 206-1:2000. Due to significant absorptivity of the WCA traditional techniques of concrete mix preparation were ruled out. WCA was kept for 7 days in tap water to achieve full and uniform saturation. Pre-saturation guaranteed stable properties of the fresh concrete mixes during handling, mixing and casting. It also allowed to benefit from internal wet curing process (“autogenous curing”) **[14-18]**. The theoretically calculated mix proportions had to be scaled to take into account large amount of water absorbed by WCA. Some of this water directly influences the consistency and some influences only the curing process. The amount of tap water added to the mix was significantly reduced. Fully saturated WCA and 92 kg/m^3 of water allowed to keep stable consistency by all cast mixes. Mix proportions are presented in Tab. 1.

Tab. 2: Mix proportions per one cubic meter

Ingredient	WCA (water)	Sand	Cement	Water	Superplasticizer	Total
[kg]	830 (182.6)	652	307	92	3.1	1884.1

Compaction of fresh mixes was conducted in two layers on a vibrating table. For initial 24 hours all the specimens were kept in their moulds covered with polyethylene sheets. After demoulding, the specimens were cured by storing them in a water tank (temp: +21^{o}C ± 1^{o}C) for the following 27 days.

There were cast four types of specimens: cubes (150 mm · 150 mm · 150 mm) and cylinders (φ=150 mm, h=300 mm) – for compressive strength tests, splitting tensile strength tests (EN 12390-6:2009) and static modulus of elasticity; beams (b=150 mm, h=150 mm, l=700 mm) – for flexural tensile strength tests according to EN 14651:2005 and shear strength according to JCI-SF6; circular plates (φ=1000 mm, h=100 mm) – for impact tests on tailored lab stand. Plates were mounted on three massive supports of a steel lab stand **[22]**. A schematic localization of a plate, plate supports and impact area is presented in Fig. 4. During the test, a plate was loaded by the free fall of 40 kg mass from the height of 1.0 m. After each impact the deflection of a plate was measured in 17 points.

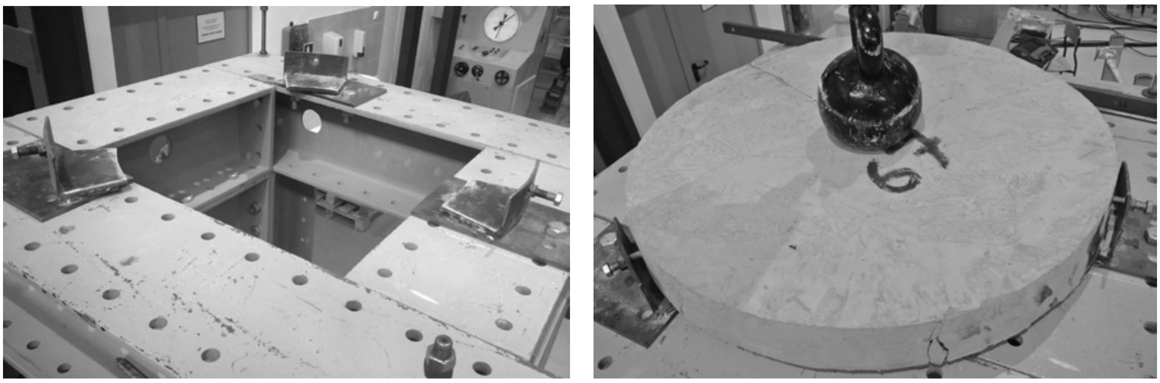

Fig. 4: Lab stand for impact tests and a slab during the impact test

Density check and ultrasound tests were conducted on all available specimens. During the flexural test the deflection and the crack mouth opening displacement (CMOD) were measured for all beams. For evaluating the residual tensile strength (f_R), the responses of the FRCC beams at CMOD 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm were of special interest.

4. Achieved results

The density of all hardened composites is presented in Fig. 5. Unreinforced matrix is characterized by density of 2001 kg/m^3. With the increasing addition of fibre the density of the composites is getting larger and larger. The density of the composite reinforced by maximum volume of fibre (1.5%) is equal to 2075 kg/m^3.

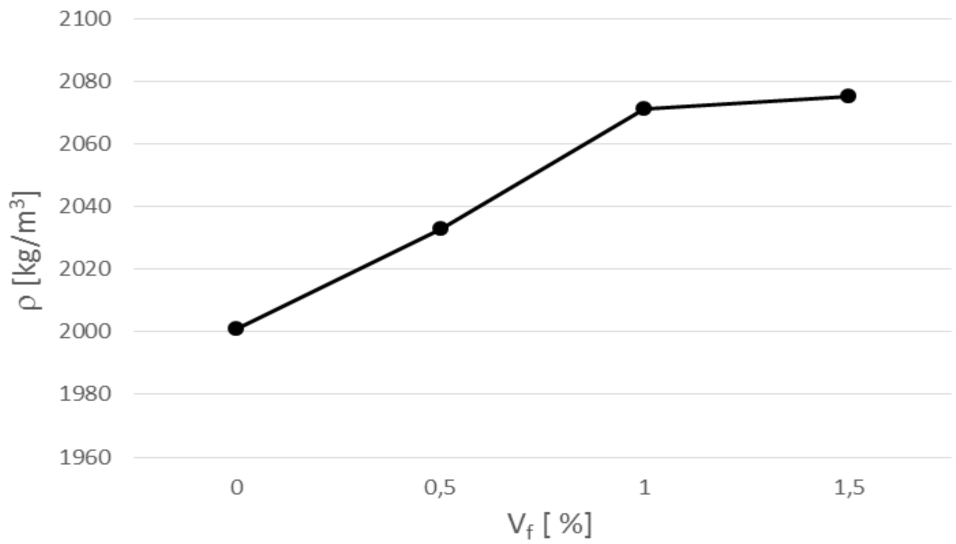

Fig. 5: Density of hardened composites

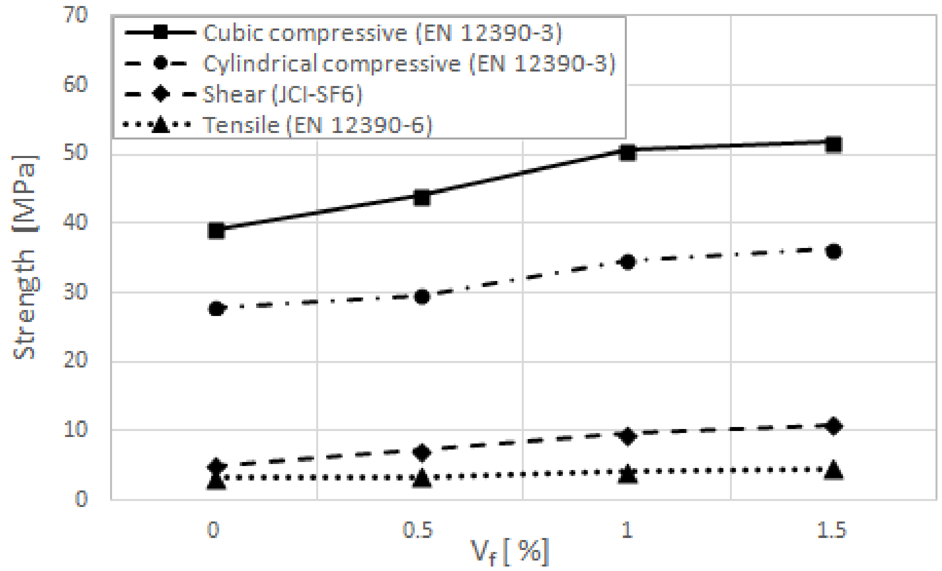

Fig. 6: Strength characteristics of tested composites

Strength characteristics of tested composites are presented in Fig. 6. All four strengths are growing higher and higher along the increasing volume of added fibres. Compressive strength of unreinforced matrix was equal to 27.9 MPa and 39.1 MPa for cylinder and cube specimens respectively. In both cases for V_f = 1.5% strength is over 30% higher than the strength of the matrix. The difference between cylinder and cube compressive strengths exceeds 15 MPa. According to EN 206-1 (ordinary concrete) this difference should be close to 10 MPa. It proves that the strength class dedicated for ordinary concrete is subjected to large inaccuracy and provides misleading information in case of fibre reinforced WCA composites.

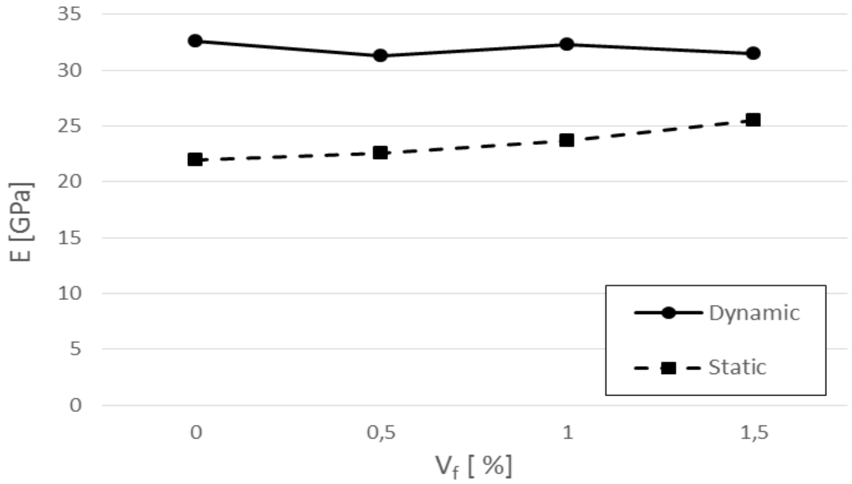

Fig. 7: Dynamic and static modulus of elsticity

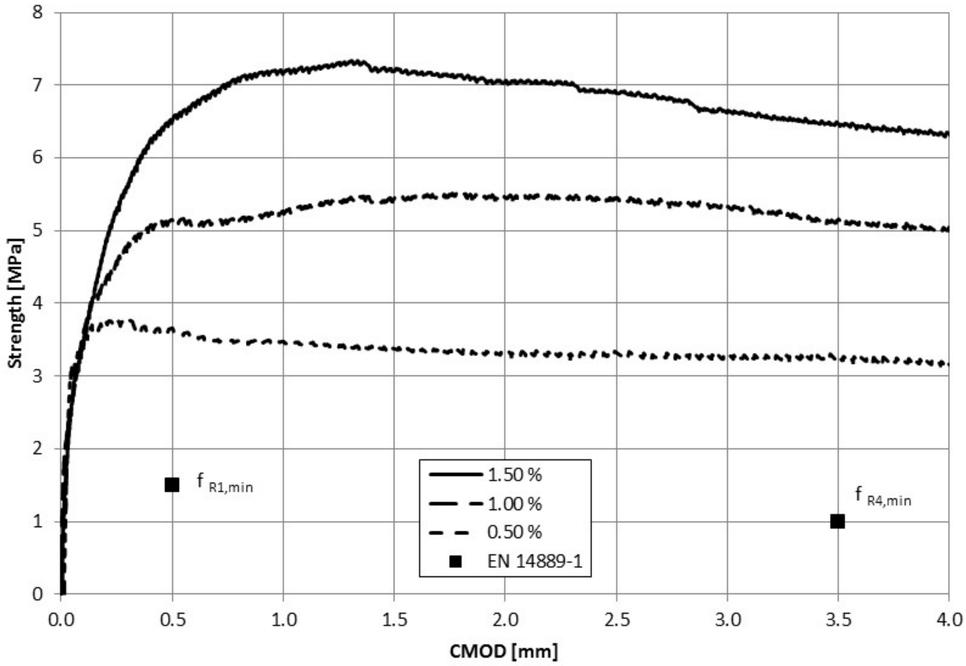

Fig. 8: Flexural characteristics of tested composites

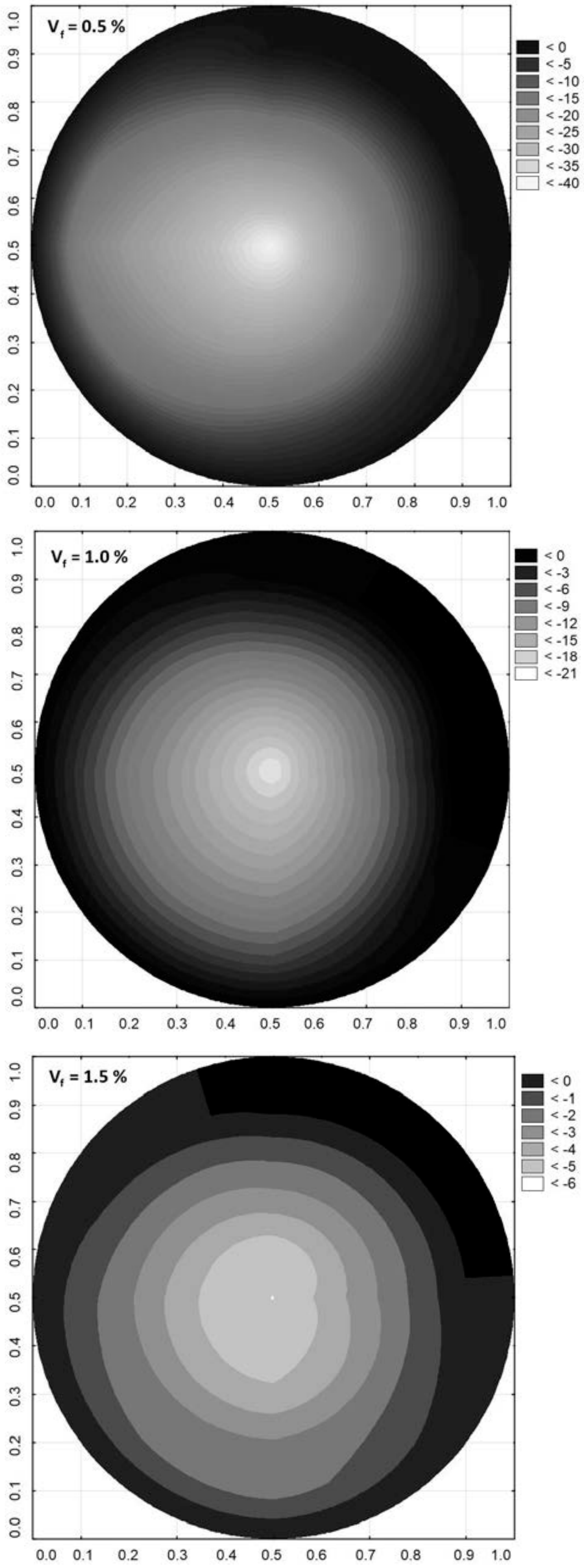

Fig. 9: Deflection of the slabs [mm] after 8th impact

Tensile strength ranges from 3.1 MPa for unreinforced matrix to 4.6 MPa for composite reinforced by maximum fibre volume (improvement of 46%). Nevertheless the largest changes in strength were observed during the shear test. Fibre reinforcement influenced the shear strength by 117.7% for V_f = 1.5%.

Results of the tests of dynamic and static modulus of elasticity are presented in Fig. 7. Unreinforced matrix is characterized by the lowest value of static modulus of elasticity. The changes in values of modulus of elasticity are small. Its values range from 22 GPa to 25 GPa. Changes in values of dynamic modulus of elasticity are even smaller as they range from 31.5 to 32.6 GPa.

Results of the tests of flexural tensile characteristics (strength-CMOD) of fibre reinforced WCA composites are presented in Fig. 8. Minimum strength conditions for $f_{R,1}$ and $f_{R,4}$ defined by EN-14889-1:2006 were also marked in the figure. Achieved values of residual strengths $f_{R,1}$ and $f_{R,4}$ of all tested WCA fibre reinforced composites are significantly larger than minimum strength conditions. All the residual flexural strengths: f_{LOP}, $f_{R,1}$, $f_{R,2}$, $f_{R,3}$ and $f_{R,4}$ can be easily read from Fig. 8. Residual strengths $f_{R,1}$ and $f_{R,3}$ are commonly assumed to characterize service (SLS) and ultimate (ULS) conditions respectively. According to requirements of Model Code 2010 [24] there were computed values of two factors: $f_{R,3}$ / $f_{R,1}$ > 0.5, $f_{R,1}$ / f_{LOP} > 0.4. These factors are crucial for assessing if conventional reinforcement substitution is enabled. All tested fibre concretes meet the conditions defined by both factors, thus conventional reinforcement substitution is enabled. Strength class of all fibre concretes was defined. Concretes with addition of V_f = 0.5%, 1.0% and 1.5% are characterized by strength classes 3c, 5c and 6c respectively.

The results of the impact tests are presented in Fig. 9, where deflection (δ) of all slabs after 8 impacts is presented. Slabs were considered as destroyed when deflection was reaching 40 mm (ASTM C 1550-12a). The unreinforced slab was ultimately destroyed after the first impact. The slab reinforced by 0.5 % of fibre reached the deflection of 39.7 mm after 8 impacts. For the slab reinforced by 1.0 % of fibre the critical deflection of 36.6 mm was reached after 11 impacts and for the slab reinforced by 1.5 % of fibre it was equal to 41.5mm after 19 impacts. Therefore in Fig. 9 deflection of the slabs after 8 impacts was presented. It was the highest number of impacts when all tested slabs were characterized by $\delta \leq 40$ mm. The deflection was in this case equal to 39.7 mm, 20.0 mm and 6.0 mm for V_f equal to 0.5 %, 1.0 % and 1.5 % respectively.

5. Discussion and conclusions

On the basis of the conducted research programme the following conclusions were drawn:

- Using strength class of ordinary concrete to describe fibre reinforced WCA composites is subjected to large inaccuracy and may provide misleading information.
- Mechanical properties of WCA composites let us classify them as 3c, 5c and 6c. It means that these composites belong to neither post-crack softening composites nor to post-crack hardening composites.
- Tested fibre reinforced WCA concretes are characterized by mechanical properties enabling substitution of conventional reinforcement.

- Unreinforced slabs were ultimately destroyed after the first impact. The exact amount of energy required for destruction of this slab is unknown due to “accuracy” of the test (one impact).
- Tests performed on the entire set of plates show that the presence of fibres in concrete matrix significantly influences a dynamic response to impact loads.
- Deflections of slabs (after equal energy input of 8 impacts) are in proportion of 1:3.3:6.6 for composites reinforced by 0.5, 1.0 and 1.5 % of fibre respectively.

Acknowledgements

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