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Specific Properties of Waste Ceramic Aggregate Concrete Reinforced by Steel Fibre

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1. Introduction

Ordinary concrete is probably the most common construction material in the world. Aggregates constitute around 80% of its volume. Yearly global consumption of aggregates for concrete production is equal to 3,000 kg/person (Malhorta & Mehta 2005). Pre-cast concrete elements are often manufactured dozens of kilometres away from the construction site (de Brito J et al. 2005, Malhorta & Mehta 2005). Their production significantly affects numerous local environments. To limit this bad influence of concrete production on local ecosystems one can utilize waste aggregates for its production. Waste ceramic aggregate (WCA) obtained from red ceramic debris is one of possible solutions. Harnessing WCA in concrete production would address two important sustainable development issues at the same time: firstly – utilising significant quantities of construction and demolition waste; secondly – providing locally available aggregate (de Brito J et al. 2005). So far WCA has been utilized to create secondary elements characterized by lesser mechanical characteristics (Hendriks & Janssen 2003, Łapko & Grygo 2014). Replacing natural aggregates by WCA creates multiple technological problems resulting in poor homogeneity of mechanical properties of created concrete. To overcome these technological hindrances authors decided to enhance WCA concrete mix by steel fibre reinforcement (Katzer & Domski 2012). Engineered hooked steel fibre proved to be very efficient in improving mechanical characteristics of concretes based on fine waste aggregates (Cichocki et al. 2014). Taking into account results achieved by other researchers testing concretes based on different waste aggregates and steel fibre reinforced concretes (SFRC) it seems feasible to achieve satisfactory mechanical characteristics in case of WCA-SFRC.

2. Used Materials

Fibre concrete for the research programme was composed on the basis of coarse WCA (prepared using red ceramic debris). The process of preparation of WCA comprised grinding for 5 minutes in an electric industrial grinder (Cichocki et al. 2014) and sieving (fractions characterized by diameter ϕ < 1mm and ϕ > 31.5 mm were separated). The sieve analysis of WCA in question was conducted with the help of rectangular sieve set (EN 933-1:2012). Loose bulk densities, compacted bulk density and water absorptivity by weight were also tested. Results of these tests are presented in Tab. 1 (Cichocki et al. 2014).

Table 1. Properties of used WCA
Tabela 1. Właściwości zastosowanego WCA

Median diameter	Hummel fineness modulus	Loose bulk density	Compacted bulk density	Water absorptivity by weight
[mm]	[–]	[kg/m^3]	[kg/m^3]	[%]
2.65	168.57	948	1170	22

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 previous publication (Cichocki et al. 2014). Hooked steel fibres made from cold drawn wire were chosen as reinforcement. This type of fibre is most commonly used in civil and structural engineering. Geometrical and mechanical characteristics of this fibre is summarized in Tab. 2. Fibre intrinsic efficiency ratio (*FIER*) defined by (Naaman 2003) 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 fibre. As a binder Portland cement CEM I 42.5 (EN 197-1:2000) was used. Tap water (EN 1008:2002) and admixture of 1% of highly effective superplasticizer were utilized to prepare the mixes and maintain desired consistency. The used 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 SFRC mixes was described in previous work (Cichocki et al. 2014).

Table 2. Mechanical and geometrical characteristics of used steel fibre
Tabela 2. Cechy mechaniczne i geometryczne użytych włókien stalowych

L	d	L/d	FIER	Hook	R_m*	Ductility**	Steel***
[mm]	[mm]	[–]	[–]	[mm]	[MPa]	[№ bends]	[–]
50	0.80	62.5	252.96	6.27	1147	7.0	Group I
*- EN ISO 6892-1:2009, **- EN 10218-1:2012, ***- EN 14889-1:2006.							

3. Research programme

The tested composites were reinforced by fibre in following volumes: 0.0%, 0.5%, 1.0% and 1.5%. All fresh mixes were characterized by consistency class C2 tested according to EN 206-1:2000. Such consistency enables utilization of a traditional rotary drum mixer and ordinary casting/compacting methods. The used WCA was characterized by significant absorptivity therefore traditional techniques of concrete mix preparation were ruled out. Before the use, WCA was fully pre-saturated to guarantee stable and uniform properties of the fresh concrete mixes during handling, mixing and casting. Thanks to pre-saturation there was also utilized "autogenous curing" process (sometimes known as "internal wet curing") throughout the curing time (Suzuki et al. 2009). Computed mix proportions based on dry aggregates had to be adjusted to take into account significant volume of water absorbed by WCA. Some of this absorbed water directly influences the consistency and some influences only the curing process but the proportions are unknown. That is why the reduction of added tap water had to be conducted using a traditional "trial and error method". Fully saturated WCA and added tap water had to keep stable consistency by all cast mixes. Mix proportions were as follows: saturated WCA – 830 kg, sand – 652 kg, cement – 307 kg, tap water – 92 kg, superplasticizer – 3.1 kg. The amount of water trapped in saturated WCA was equal to 182.6 kg. The mass of all ingredients for casting one cubic meter of WCA concrete was totalling 1884.1 kg.

A vibrating table was utilized for two layers compaction of fresh mixes. Curing lasted 28 days. During the first day specimens were kept in moulds covered with polyethylene sheets. After demoulding, for the following 27 days the specimens were kept in a water tank (temp: +21°C ± 1°C). The prepared specimens and conducted tests are summarized in Tab. 3.

Table 3. Prepared specimens and conducted tests
Tabela 3. Wykonane próbki i przeprowadzone badania

Specimens		Tests	
Shape	Size [m]	Property	Code
Cube	$b = 0.15$, $h = 0.15$, $l = 0.15$	compressive strength splitting tensile strength	EN 12390-3:2009 EN 12390-6:2009
Cylin-der	$\varphi = 0.15$, $h = 0.30$	compressive strength static modulus of elasticity	EN 12390-3:2009 EN 12390-13:2013
Beam	$b = 0.15$, $h = 0.15$, $l = 0.70$	flexural tensile strength shear strength	EN 14651:2005 JCI-SF6
Circular plate	$\varphi = 1.00$, $h = 0.10$	impact tests	tailored lab stand

Circular plates used for impact tests on tailored lab stand were mounted on three massive supports of a steel lab stand (see Fig. 1) (Cichocki et al. 2014).

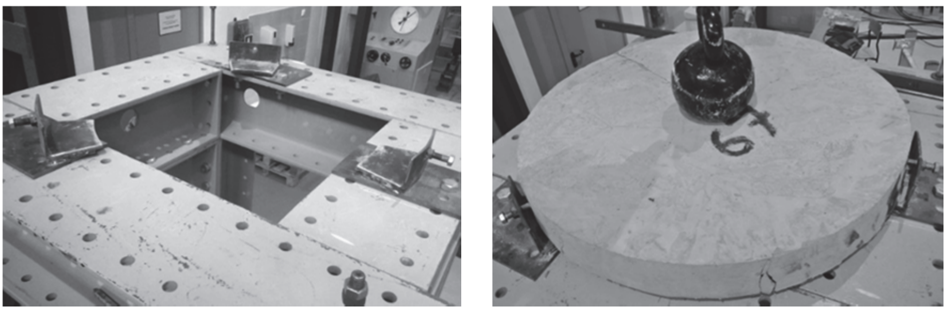

Fig. 1. Tailored lab stand for impact tests and a slab during the test
Rys. 1. Stanowisko do badań uderzeniowych płyt i płyta podczas badań

During the test each plate was loaded by the free fall of 40 kg mass from the height of 1.0 m. After each impact the deflection of the plate was measured in 17 points. The test was thoroughly described in previous publication. Density check and ultrasound tests were conducted on all available specimens.

4. Achieved results

Unreinforced concrete is characterized by density of 2001 kg/m^3. With the increasing fibre volume the density of the composites is getting larger and larger to finally achieve the value of 2080 kg/m^3 for WCA-SFRC reinforced by maximum volume of fibre (1.5%).

Strength properties of tested WCA-SFRC are presented in Fig. 2. All four strengths are growing along the increasing volume of reinforcement. Unreinforced matrix is characterized by compressive strength equal to 27.9 MPa and 39.1 MPa for cylinder and cube specimens respectively. In both cases strength of WCA-SFRC reinforced by 1.5% of fibre is over 30% higher than the strength of the matrix. The difference between cylinder and cube compressive strengths of such WCA-SFRC exceeds 16 MPa. This difference in strengths of ordinary concrete (EN 206-1) is close to 10MPa, therefore the strength classes dedicated for ordinary concrete are subjected to large inaccuracy in case of WCA-SFRC.

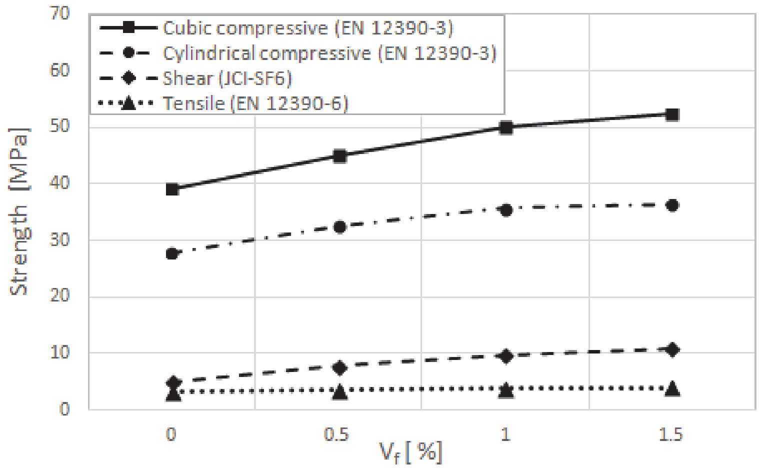

Fig. 2. Compressive, shear and tensile strength of tested WCA-SFRC
Rys. 2. Wytrzymałość na ściskanie, ścinanie i rozciąganie próbek WCA-SFRC

Tensile strength ranges from 3.1 MPa for unreinforced matrix to 4.0 MPa for the composite reinforced by maximum fibre volume (improvement of 29%). Nevertheless the largest changes in strength were observed during the shear test. Fibre reinforcement influenced the shear strength by 116% for $V_f = 1.5\%$.

Results of the tests of dynamic and static modulus of elasticity are presented in Fig. 3. The changes in values of static and dynamic modulus of elasticity are small. The matrix is characterized by the lowest value of static modulus of elasticity (22 GPa) and the highest value of dynamic modulus of elasticity (32.6 GPa). The values of static modulus of elasticity of WCA-SFRC are from 23 GPa to 24 GPa. Dynamic modulus of elasticity of WCA-SFRC ranges from 28.6 to 29.4 GPa.

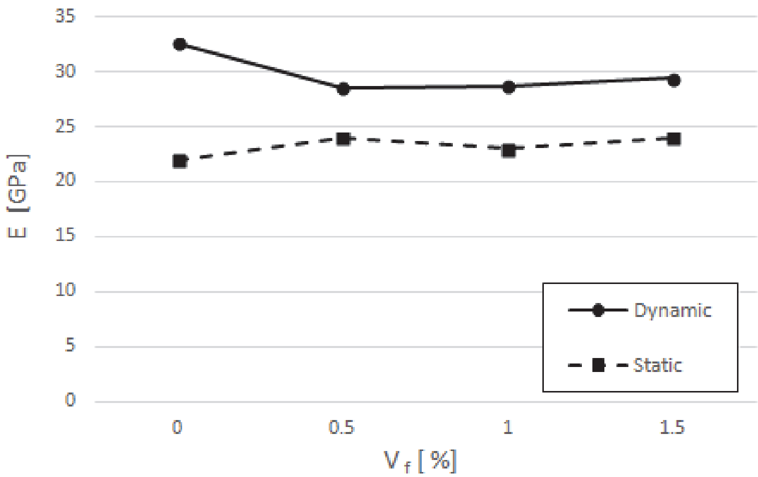

Fig. 3. Dynamic and static modulus of elsticity of tested WCA-SFRC
Rys. 3. Dynamiczny i statyczny moduł sprężystości próbek WCA-SFRC

Flexural tensile characteristics (in a form of strength-CMOD relation) of tested WCA-SFRCs is presented in Fig. 4 with minimum strength conditions for $f_{R,1}$ and $f_{R,4}$ (defined by EN-14889-1:2006). Achieved values of residual strengths $f_{R,1}$ and $f_{R,4}$ of all tested WCA-SFRCs are significantly larger than the required minimum. There were computed values of two factors: $f_{R,3} / f_{R,1} > 0.5$ and $f_{R,1} / f_{LOP} > 0.4$ for all WCA-SFRCs. According to the requirements of Model Code 2010 these factors are crucial for assessing if conventional reinforcement substitution is enabled. All tested WCA-SFRCs met the conditions defined by both factors, thus conventional reinforcement substitution is enabled. Strength class of all WCA-SFRCs was defined as follows: WCA-SFRC with 0.5% – class 3c; 1.0% – class 4c; 1.5% – class 7d.

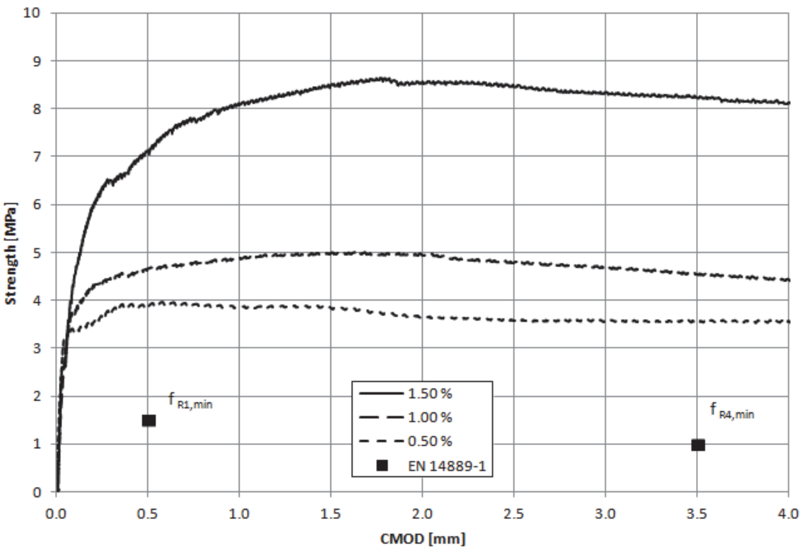

Fig. 4. Flexural properties of tested WCA-SFRC
Rys. 4. Wytrzymałości podczas próby zginania dla próbek WCA-SFRC

The results of the slab impact test are presented in Tab. 4. Slabs were considered as destroyed when deflection (δ) was reaching 20 mm. The unreinforced slab was ultimately destroyed after the first impact. In Tab. 4 deflection of the slabs after 6 impacts was presented. It was the highest number of impacts when all tested slabs were characterized by $\delta \leq 20$ mm.

Table 4. Results of the slab impact tests
Tabela 4. Wyniki badań uderzeniowych płyt

V_f [%]	0.5	1.0	1.5
δ – after 6 impacts [mm]	18.7	4.4	3.0
Failure after № of impacts [–]	8	15	22
δ_{MAX} [mm]	22.9	23.2	18.9

5. Conclusions

- Using strength class of ordinary concrete to describe WCA-SFRC is subjected to significant inaccuracy and may provide misleading information.
- Mechanical properties of WCA-SFRC let us classify them as 3c, 4c and 7d.
- Tested WCA-SFRCs are characterized by mechanical properties enabling substitution of conventional reinforcement.
- Deflections of slabs (after equal energy input of 6 impacts) are in proportion of 1:1.5:6.0 for composites reinforced by 0.5%, 1.0% and 1.5% of fibre respectively.

Acknowledgments

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Specyficzne właściwości betonu na bazie ceramicznego kruszywa odpadowego zbrojonego włóknami stalowymi

Streszczenie

Artykuł składa się z pięciu zasadniczych rozdziałów i cytowanej literatury. W rozdziale pierwszym omówiono specyficzne właściwości odpadowych kruszyw ceramicznych na podstawie przeprowadzonych studiów literaturowych. W kolejnym rozdziale przedstawiono właściwości i cechy zastosowanych w badaniach materiałów składowych analizowanego kompozytu. Określono m.in. gęstość w stanie luźnym i utrzęsionym oraz nasiąkliwość ceramicznego kruszywa odpadowego. Oznaczono również kilka podstawowych cech zastosowanych włókien stalowych, tj. ich właściwości geometryczne i mechaniczne, smukłość, FIER. Jako spoiwo przyjęto cement CEM I 42,5, zaś jako domieszkę zastosowano superplastyfikator typu FM. Ostateczny skład mieszanki betonowej (na 1 m^3), zaprezentowany w rozdziale trzecim, stanowią: namoczone kruszywo ceramiczne (WCA) – 830 kg, piasek – 632 kg, cement – 307 kg, dodana woda – 92 kg i superlpastyfiaktor – 3,1 kg. W rozdziale trzecim omówiono również sposób wykonywania i pielęgnacji elementów próbnych. Przedstawiono program badań, w którego skład weszły badania: modułu sprężystości, wytrzymałości na ściskanie na próbkach sześciennych o boku 150 mm oraz walcowych o średnicy 150 mm i wysokości 300 mm, wytrzymałości na rozciąganie przy rozłupywaniu na próbkach kostkowych o boku 150 mm, wytrzymałości resztkowych i granicy proporcjonalności belek o przekroju 150 × 150 mm i długości 700 mm oraz wytrzymałości przy ścinaniu połówek belek. Jako niekonwencjonalne badanie przeprowadzono próbę dynamiczną w postaci masy (40 kg) spadającej z wysokości 1m na płytę (o średnicy 100 cm i grubości 10 cm) podpartą w trzech punktach rozmieszczonych na jej krawędzi co 120 stopni. Wyniki z przeprowadzonych badań wraz z ich analizą zamieszczono w rozdziale czwartym. Określono m.in. gęstość kompozytów, która zawierała się w przedziale od 2001 do 2080 kg/m^3, wytrzymałość na ściskanie, która wyniosła C27,9/39,1 dla matrycy bez włókien, do C36,3/52,3 dla kompozytu z największą ilością zbrojenia rozproszonego. Podobny przyrost wytrzymałości zaobserwowano w przypadku wytrzymałości na ścinanie, gdzie uzyskano 4,97 MPa dla matrycy i 10,75 MPa dla WCA z włóknami w ilości 1,5 %. Wytrzymałość na rozciąganie przy rozłupywaniu zmieniała się od 3,12 do 3,97 MPa. Moduł sprężystości statyczny i dynamiczny dla kompozytów z włóknami wyniósł odpowiednio 23-24 GPa i 28,6-29,4 GPa. Na podstawie wytrzymałości resztkowych i granicy proporcjonalności określono klasy wg Model Code 2010 dla kompozytów o różnej procentowej zawartości włókien: 0,5% – klasa 3c, 1.0% – klasa 4c 1.5% – klasa 7d. Ostatnimi z analizowa-

nych wyników było ugięcie i zniszczenie płyt. Po sześciu uderzeniach masy ugięcie wyniosło 3,0-18,7 mm dla WCA z 1,5 i 0,5% włókien, zaś ich zniszczenie miało miejsce odpowiednio po 8, 15 i 22 uderzeniach masy. Ostateczne podsumowanie z przeprowadzonych badań i analiz zamieszczono w rozdziale piątym.

Abstract

The paper consists of five main chapters and a list of references. The first chapter is focused on presenting specific properties of ceramic waste aggregates based on extensive literature studies. The properties and characteristics of the materials used to prepare the fibre composites in question are presented in the following section. Such properties as density in the loose state and compacted state and absorption of waste ceramic aggregate was of special interest. Some basic properties of used steel fibres such as: their geometric and mechanical properties, aspect ratio, FIER were established. Cement CEM I 42.5 was adopted as a binder. There was also used superplasticizer type FM. The final composition of the concrete mix (per 1 m^3) is presented in the third chapter. The adopted mix composition is as follows: saturated waste ceramic aggregate (WCA) – 830 kg, sand – 632 kg, cement – 307 kg, water – 92 kg, superplasticizer – 3.1 kg. Casting and curing of concrete elements is described in the third chapter. The research programme comprised such standard tests as: test of modulus of elasticity, compressive strength test conducted on cubes (150 mm · 150 mm · 150 mm) and cylinders (diameter of 150 mm and a height of 300 mm), a tensile strength test at splitting conducted on cubes (150 mm · 150 mm · 150 mm), the residual strength test at limit of proportionality limit conducted on beams (150 mm · 150 mm · 700 mm) and the shear strength test conducted on beam halves. There was also conducted an unconventional dynamic test. Namely, the weight of 40 kg was free falling from the height of 1 m on a slab creating an impact load. The slab was 100 cm in diameter and 10 cm thick. It was supported in three points located on its circumference (apart by 120 degrees). The results of the study together with the analysis are presented in chapter four. The density of the composites ranged from 2001 to 2080 kg/m^3. The compressive strength was from C27.9/39.1 for the matrix without fibre to C36.3/52.3 for the composite with the maximum amount of added fibre. A similar increase in strength was observed for shear strength which ranged from 4.97 MPa to 10.75 MPa for WCA matrix and composite with 1.5% of fibre respectively. Tensile splitting strength varied from 3.12 to 3.97 MPa. Static and dynamic modulus of elasticity of fibre composites ranged from 23 to 24 GPa and from 28.6 to 29.4 GPa respectively. On the basis of achieved residual strengths and limits of proportionality, strength class was assigned to composites following Model Code 2010. The assigned strength classes were as follows: 0.5% of fibre – class 3c, 1.0% of fibre – class 4c, 1.5% of fibre – class 7d. The last of the analysed results was deflection and the process of destruction of tested slabs. After six impacts, the slab deflection ranged from 3.0 to 18.7 mm for WCA concrete reinforced by 1.5 and 0.5% of the fibres respectively. The ultimate destruction of slabs was recorded after 8, 15 and 22 impacts. The final summary of the conducted research and performed analyses is presented in chapter five.

Słowa kluczowe:
ceramiczne kruszywo odpadowe, piasek odpadowy, włókna, beton

Keywords:
waste ceramic aggregate (WCA), waste sand, fibres, concrete