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Load-deflection Characteristic of Fibre Concrete Based on Waste Ceramic Aggregate

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1. Introduction

Concrete, mortars and other cement based composites are the most commonly applied construction materials in the world. Aggregate is the main component of any cement composite and covers from 60% to 80% of its volume. In total, worldwide annual production of all cement based composites consumes 20 billion tonne of different aggregate. Statistically global consumption of aggregate is equal to 3 tonne per person per year, which considerably influences natural environment, especially in fast developing countries in Asia and South America [24]. The production of commonly harnessed (in civil and structural engineering) ordinary concrete consumes large volumes of natural coarse and fine aggregate. The weight proportion of consumed coarse aggregate (e.g. gravel) and fine aggregate (e.g. sand) is approximately equal to 3:1 [26]. It is very rare that in a given location natural resources of fine and coarse aggregate are available in the needed proportion. In some areas there is excess of coarse aggregate and deficiency of fine aggregate (e.g. New Zealand), other are characterized by considerable excess of fine aggregate and deficiency of coarse aggregate [17]. Such natural conditions cause inefficient and unbalanced use of existing resources of mineral aggregate and associated with some high carbon dioxide emission practices such as long distance transport of aggregate of specific grading. Use of locally available ceramic waste as aggregate can solve two urgent ecological issues at the same time: utilising large volumes of construction/demolition waste and providing coarse aggregate in areas where it is in constant demand. Ceramic waste from construction industry is probably the most important part in the global volume of construction and demolition waste [7]. The most promising recycling process of ceramic waste is using it as a coarse aggregate for concrete. This topic generates growing research effort [11, 25] which resulted so far in successful applications in concrete elements characterized by less demanding mechanical characteristics, such as pavement slabs [4]. Harnessing WCA as a substitute of traditional aggregate creates a whole range of technological problems. The main issue is workability of fresh mix. WCA is characterized by very high water absorptivity which makes traditional concrete mix designing methods useless and preparation of a workable mix very tricky. Replacing traditional coarse aggregates by WCA also significantly influences the homogeneity of mechanical properties of cast concrete (populations of results are characterized by significantly higher standard deviation) and mechanical properties themselves. This phenomenon limits applications of concrete based on WCA only to elements characterized by less demanding mechanical characteristics. In order to evade these “performance” issues one can modify concrete mix based on WCA by an addition of engineered fibre. Steel fibre proved to be a very good solution for enhancing limited mechanical properties of concretes based on other than ceramic waste aggregates [9, 14] and thus promising achieving satisfactory results in case of WCA. On the other hand the size and shape of the aggregate particles directly affects the spacing and orientation of fibres [12, 23]. The WCA particles are of irregular shape and in many cases look like small blades rather than sphere-like grains. Such irregularities in aggregate geometry are known to cause local fibre anglomeration (fibre balls) and non-homogeneous fibre distribution. Achieving satisfactory mechanical properties of such a composite is now out of reach, which prevents from applying it in practice.

The objective of the planned research programme was to bypass all technological problems associated with WCA and fibre reinforcement used simultaneously. Achieved this way WCA composite would have versatile applications. Secondary structural elements, industrial floors and road pavements would be the most promising areas of implementation. The developed fresh mix should be characterized by good workability guarantying easy casting. The hardened composite should be characterized by mechanical properties enabling harnessing it as a structural material without limitations. Successful merging of cement matrix based on WCA and fibre reinforcement would create new opportunities for sustainable development of construction industry.

2. Waste ceramic aggregate

WCA was prepared on the basis of ceramic debris of construction origin. This raw ceramic waste consisted of broken and crushed wall blocks, hollow bricks and wire-cut bricks – all partially contaminated by cement mortar. This kind of ceramic debris is very common in Europe [4] and represents the waste emerging in building construction during: the very production of blocks and bricks, transportation to the building site, the execution of construction (e.g. facades, partition walls) and execution of subsequent works (e.g. opening grooves etc.) [7]. The WCA was prepared in two main stages: grinding and sieving. The ceramic waste was ground for 5 minutes in an electric industrial grinder with 21 steel spheres characterized by mass varied from 1343 g to 2650 g. As a result of grinding there was obtained a mixture of fine and coarse fractions of waste ceramic aggregate. Ground ceramic waste is presented in Fig. 1.

Fig. 1. Ground ceramic waste used as coarse aggregate
Rys. 1. Zmielony gruz ceramiczny zastosowany jako kruszywo grube

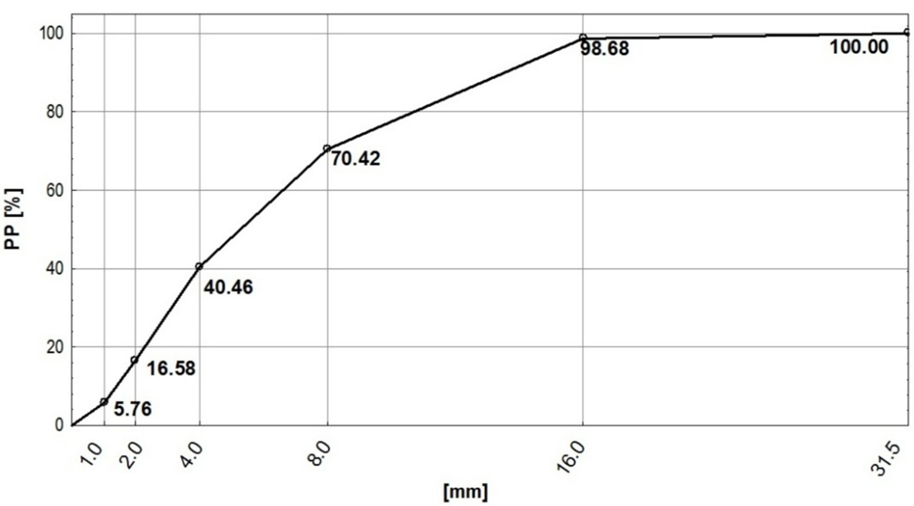


Fig. 2. Grading curve of harnessed WCA
Rys. 2. Krzywa uziarnienia zastosowanego WCA

Separating fractions characterized by diameter $\phi < 1$ mm and coarser fractions ($\phi \geq 1$ mm) of ground ceramic waste was the final stage of preparation of WCA. The grading curve of coarse WCA fractions prepared with the help of rectangular sieve set (according to EN 933-1:1997) is presented in Fig. 2. Other tested properties of WCA are summarized in Tab. 1.

Table 1. Properties of coarse fractions of WCA
Tabela 1. Właściwości grubych frakacji WCA

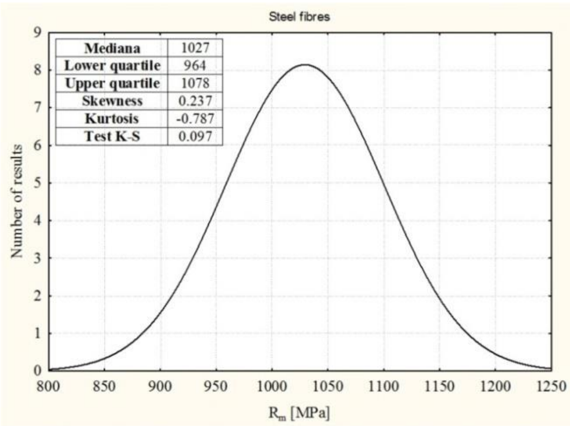
Loose bulk density	Compacted bulk density	Water absorptivity by weight
948 kg/m^3	1170 kg/m^3	22%

Large absorptivity of the WCA disabled traditional methods of concrete mix preparation. To achieve stable and homogeneous properties of the fresh concrete mix, WCA was pre-saturated for 7 days in tap water. Such a long term of pre-saturating was needed to guarantee full and uniform saturation of WCA. Pre-saturation, apart for enabling easy handling and mixing of fresh WCA concrete mix, was a key factor to benefit from internal wet curing [4, 16]. The contrivance of internal wet curing (also known as "autogenous curing") is based on the use of internal reservoirs providing a source of water to the cement paste to counteract the self-desiccation phenomenon. Pre-saturated WCA serves as a water reservoir which gradually releases water to replace the water consumed during hydration reactions. The concept that self-desiccation can be successfully resisted by partial replacement of ordinary aggregate by pre-saturated porous aggregate was conceived and demonstrated by various authors and thoroughly described in numerous previous publications [22, 32, 33]. It has been indisputably proven that employing porous aggregate for internal curing significantly mitigates or completely eliminates autogenous shrinkage of concrete [2, 6, 20, 34, 35]. The efficiency of the internal curing phenomenon is limited by both the content and the parameters of the applied porous aggregate (e.g.: water absorption, pore structure, grain size distribution, volume of open and closed voids etc.). The paste-aggregate proximity achieved in a given concrete mix is a decisive factor determining the radius which the internal curing water should readily penetrate.

3. Fibres

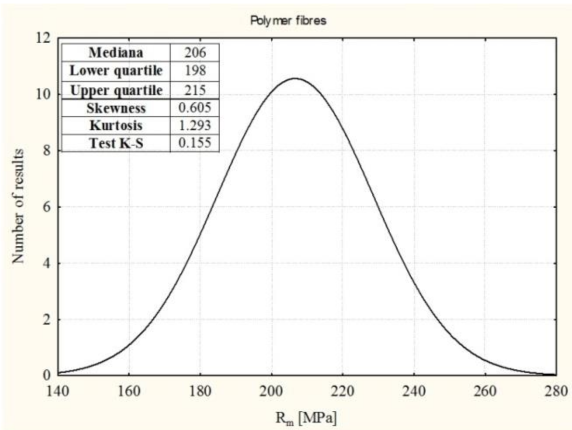
There were used two types of engineered fibre: hooked steel fibre and continuously embossed polymer fibre fabricated from modified polyolefins. Those fibres represent the most popular types of fibres widely used in civil and structural engineering industry [13]. Main geometrical and mechanical properties of both types of fibres, given by producers are summarized in the tables in Fig. 3 and Fig. 4.

The quality of both types of fibres was tested before harnessing them in the research programme. Apart from measurements of geometrical dimensions of fibres the tensile strength was checked. The test was performed with controlled (constant rate) increase of force (according to EN ISO 6892-1:2009) on the population of 30 randomly chosen fibres (sampling performed with the help of table of random numbers). Identification and rejection of outliers in all populations of results were performed with the help of Dixon's Q test. The normal (Gaussian) distribution of all populations of results were assessed using Kolmogorov-Smirnov Test (*K-S Test*). The results of fibre tensile strength are presented on the graphs in Fig. 3 and Fig. 4. It should be noted that tensile strength given by producer of polymer fibre and tensile strength evaluated during the research programme differ significantly (375 MPa and 206 MPa respectively). The quality and mechanical properties of used steel fibre were thoroughly described in the previous publication [15].



Characteristics given by producer	
Length [mm]	30
Diameter [mm]	0.55
Aspect Ratio [-]	55
Specific gravity [kg/m^3]	7860
Tensile Strength [MPa]	>1100
Modulus of Elasticity E [GPa]	210
Number of fibres per 1 kg	16750

Fig. 3. Tensile strength, geometry and characteristics of used steel fibres
Rys. 3. Wytrzymałość na rozciąganie, geometria i właściwości zastosowanych włókien stalowych



Characteristics given by producer	
Length [mm]	48
Diameter [mm]	n/a
Aspect Ratio [-]	~50
Specific gravity [kg/m^3]	910
Tensile Strength [MPa]	375
Modulus of Elasticity E [GPa]	6
Number of fibres per 1 kg	35000

Fig. 4. Tensile strength, geometry and characteristics of used polymer fibres
Rys. 4. Wytrzymałość na rozciąganie, geometria i właściwości zastosowanych włókien polimerowych

4. Other materials

Portland cement CEM I 42.5 (EN 197-1:2000) and tap water (EN 1008:2002) were used to prepare all mixtures. Sand of post-glacial origin (washed from all-in-aggregate during hydroclassification process) was employed as fine aggregate. This sand and its applications in different cement composites were described in numerous previous publications [14, 18, 19]. All mixes were modified by dosage of 1% of highly effective admixture (superplasticizer type FM) containing silica fume and characterized by density equal to 1.45 g/cm^3. This superplasticizer (and its influence on properties of the fresh mix) was described in previous work [14].

5. Mix proportions, curing and casting

The cement matrix mix was designed with the help of so-called "double enfolding method". This method is focused on creating sufficient amount of cement paste enfolding grains of fine aggregate and sufficient amount of mortar enfolding coarse aggregate. In this way a workable but at the same time tight mix is achieved. All mechanical properties of the hardened cement composite (e.g. compressive strength) are the outcome of this tightness. The theoretical mix design was scaled to accommodate water absorbed by WCA. 830 kg of WCA after being fully saturated carry 182.6 kg of water. Some of this water directly influences the consistency and some influences only the curing process. The amount of water was reduced to 92 kg/m^3. Fully saturated WCA and 92 kg/m^3 of water allowed maintaining stable consistency for all cast mixes. The mix design of one cubic meter is presented in Tab. 2.

Table 2. Mix proportions of one cubic meter
Tabela 2. Proporcje składników mieszanki na 1 m^3

WCA [kg]	Sand [kg]	Cement [kg]	Water [kg]	Admixture [kg]	TOTAL [kg]
830	652	307	92	3.1	1884.1

Specimens were in a form of cylinders (ϕ = 150 mm, h = 300 mm) and beams (b = 150 mm, h = 150 mm, l = 700 mm). Cylindrical specimens were used to test compressive strength according to EN

12390-3:2009 – Part 3 and modulus of elasticity according to ASTM C469 – Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. Prismatic specimens were used to test flexural tensile strength according to EN 14651:2005. A rotary drum mixer was used to prepare composite mixtures. Compaction of fresh concrete mix was performed externally using a vibrating table. Each specimen was vibrated in two layers, with each layer filling half of the thickness. Each layer was vibrated for 20 s (until a thin film of bleed water appeared on the surface). The first step of curing was to keep the specimens in their moulds covered with polyethylene sheets for 24 h. The specimens were then removed from their moulds and cured by storing them in a water tank (Temp: +21°C) for next 27 days.

6. Research programme

The research programme was organized in two main stages. The objective of the first stage was to determine the workability of fresh mix, density, compressive strength and modulus of elasticity of the composites in question. Measurement of workability was conducted according to Vebe procedure. This testing method was chosen because it is well suited for FRCC mixes [14]. Moreover, the treatment of concrete during the test is comparatively closely related to the method of placing *in situ* [26].
The second stage of the research involved measuring the flexural tensile strength according to the limit of proportionality (LOP) method (EN 14651:2005). The three-point flexural test was chosen as the most adequate for the research programme. In case of three-point test, beam is formed with a notch (5 mm wide, 25 mm deep) and the first crack always appears in the vicinity of the mid-span. In case of four-point test the test beam is formed without a notch and the first crack appears at the weakest cross section and the location of the crack cannot be predicted. 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. The loading rate was equal to 0.05 mm/min until achieving CMOD = 0.1 mm. Further on the loading rate was equal to 0.2 mm/min. Both load-CMOD and load-deflection curves were estimated.

The examination results were statistically processed, and values bearing the gross error were assessed on the basis of Grabbs criterion [3]. The objectivity of the experiments was assured by the choice of the sequence of the realization of specific experiments from a table of random numbers.

7. Results

The tested mixes were characterized by Vebe time ranging from t_{Vebe} = 11 s to t_{Vebe} = 12 s (workability class V2 according to EN 206-1). The compressive strength test and plotting stress-strain curves for tested FRCC constituted the core of the first stage of the research programme. Stress-strain curves for tested FRCC are presented in Fig. 5. The results of ultimate compressive strength density and modulus of elasticity of analysed FRCC are summarized in Tab. 3.

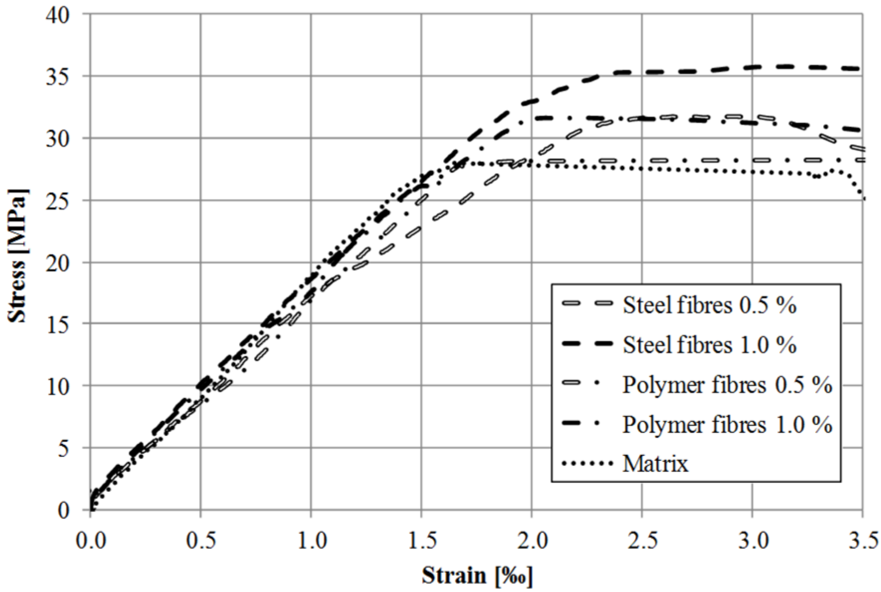


Fig. 5. Stress-strain curves for tested WCA composites
Rys. 5. Krzywe naprężenie-odkształcenie dla badanych kompozytów WCA

Bending load – mid-span deflection diagrams of tested FRCC are presented in Fig. 6. On the basis of load-deflection relations energy absorption of all tested composites was calculated. So-called "Pre-peak Energy" D_c and total amount of absorbed energy for maximal observed deflection of 4.0 mm were computed and are presented in Tab. 4.

Table 3. Density and compressive strength of tested WCA composites
Tabela 3. Gęstość i wytrzymałość na ściskanie badanych kompozytów WCA

	Matrix	Steel Fibre 0.5%	Steel Fibre 1.0%	Polymer Fibre 0.5%	Polymer Fibre 1.0%
ρ [kg/m^3]	1926.0	2001.8	1982.5	1934.2	1880.5
f_{cm} [MPa]	30.2	32.2	36.3	29.6	32.5
E_{cm} [GPa]	18.8	18.8	18.5	18.3	17.8

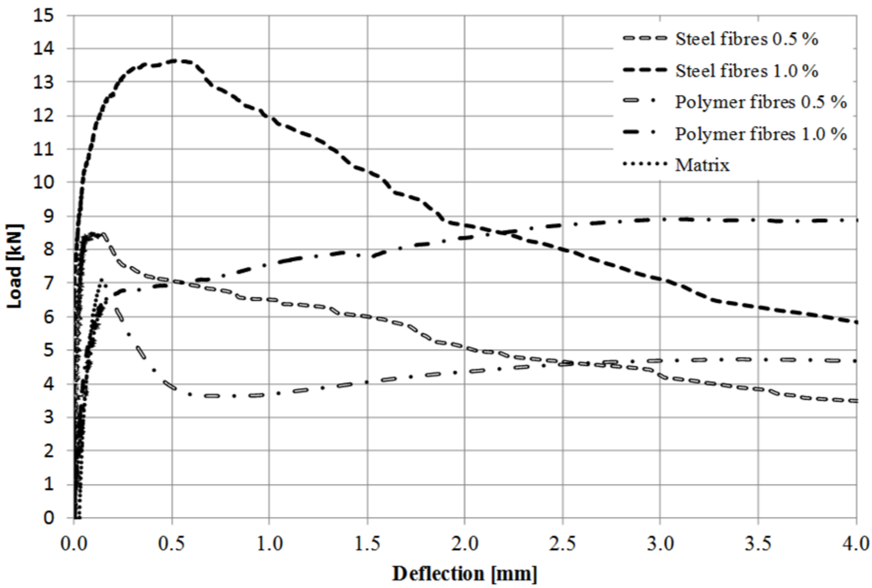


Fig. 6. Bending load-mid-span vertical deflection curves of tested WCA composites
Rys. 6. Krzywe obciążenie-ugięcie przy zginaniu elementów z WCA

Table 4. Energy absorption of tested WCA composites
Tabela 4. Gęstość i wytrzymałość na ściskanie badanych kompozytów WCA

	Matrix	Steel Fibre 0.5%	Steel Fibre 1.0%	Polymer Fibre 0.5%	Polymer Fibre 1.0%
Pre-peak Energy D_c [kN·mm]	0.73	0.64	6.44	0.76	24.46*
Deflection 4 mm [kN·mm]	n/a	21.54	37.50	17.71	32.13
**Due to shape of the curve with no peak in early stages of loading the value of calculated pre-peak energy D_c is very high.*					

On the basis of the achieved Load – CMOD diagram (according to European Standard EN 14651), four different values of the residual strengths (f_{R1}, f_{R2}, f_{R3}, f_{R4}) were calculated for all FRCC in question. These strengths corresponding to different values of the CMOD are difficult to incorporate to FRCC design procedures [30]. Therefore the residual strengths f_{R1} and f_{R3} which are significant for service and ultimate conditions are commonly assumed to characterize the global residual strength. This strength can be harnessed for serviceability limit states (SLS) analysis and ultimate limit states (USL) analysis. In "fib Bulletin 55, Model Code 2010" it was proposed that material behaviour at ULS will be related to the behaviour at SLS employing the f_{R3}/f_{R1} ratio. Basically, in order to classify the post-cracking strength of FRCC a linear elastic behaviour can be assumed by considering the characteristic residual strength significant for service (f_{R1}) and ultimate (f_{R3}) conditions. According to this procedure FRCC post-cracking residual strength is described by two parameters: namely f_{R1} (representing the strength interval) and a letter a, b, c or d (representing the ratio f_{R3}/f_{R1}). This classification properly represents the most common cases of FRCC softening and hardening. Traditional reinforcement substitution is enabled if relationships 1 and 2 are fulfilled. Full classification of tested FRCC according to "fib Bulletin 55, Model Code 2010" is summarized in Tab. 5

$$f_{R1}/f_{LOP} > 0.4 \tag{1}$$

$$f_{R3}/f_{R1} > 0.5 \tag{2}$$

Cross-sections of all tested beams were analysed. The uniformity of WCA spacing was assessed. In Fig. 7 an exemplary cross-section of FRCC beam is presented. The area of WCA was graphically separated and counted. On average the WCA was representing 58%±2% of total cross-section area.

Table 5. FRCC classification in compliance to "fib Model Code 2010"
Tabela 5. Klasyfikacja FRCC zgodnie z "fib Model Code 2010"

	Fibre [%]		
	Steel 0.5	Steel 1.0	Polymer 0.5
f_{R1} [MPa]	3.5	5.5	2.0
f_{R3}/f_{R1}	0.771	0.836	0.850
Class	3.0b	5.0b	2.0b
f_{R1}/f_{LOP}	1.167	1.667	1.000
Reinforcement substitution	enabled	enabled	enabled

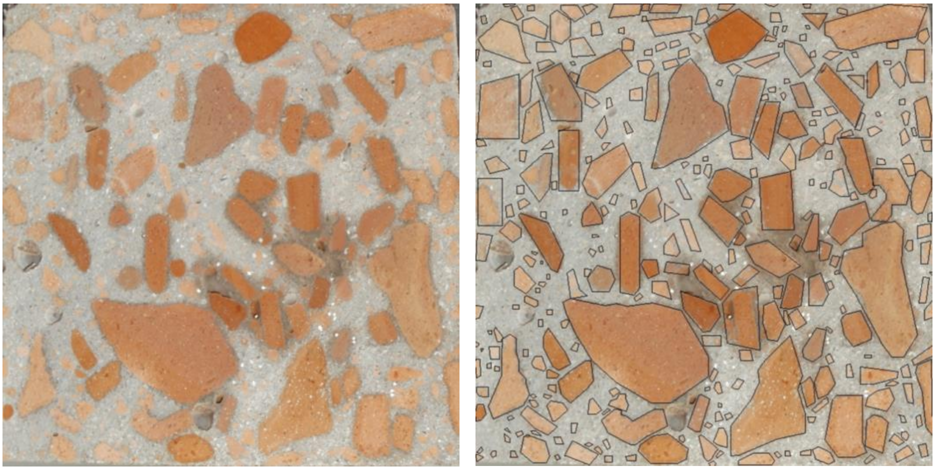


Fig. 7. Cross-section of a WCA cement matrix (left – plain, right – with graphically separated WCA)
Rys. 7. Przekrój cementowej matrycy WCA (z lewej – zwykły, z prawej – z graficznym zaznaczeniem WCA)

8. Discussion

This paper presents the results of a research programme conducted to study the possibilities of creating FRCC based on WCA and harnessing it as a regular structural material. The main obstacle associated with using ceramic coarse aggregates as a substitute of natural aggregates is its significantly higher water absorption. The rough texture and general greater water absorption characteristics of WCA result in a big water demand (comparing to natural aggregate) in order to maintain desired workability. This technological problem was bypassed by pre-saturating WCA. At the same time the mix benefits from internal wet curing phenomenon. The main benefit of internal water curing is a significant improvement of cement hydration reaction which results in achieving high compressive strength of the composite in comparison to compressive strength of waste ceramic (*circa* 15 MPa) used as an aggregate. Coarse aggregate interlock and bond between cement matrix and the fibre reinforcement are mechanisms that seem to work correctly in all analysed composites. Steel fibre reinforcement, in comparison to polymer fibre reinforcement, was more effective in achieving higher both compressive and flexural tensile strengths (although matrix modified by polymer fibres was characterized by higher relation f_{R3}/f_{R1}).

According to Ding [8] the relation of CMOD versus central displacement could be regarded as a material property for FRCC beam. Such relations could be very handy for choosing fibre type and designing the whole FRCC structure. The open crack width has been also shown to be a key parameter governing the serviceability and durability of SFRCC. In Fig. 8 there are presented CMOD – δ relationships of FRCC beams modified by different fibres and varied fibre content. As a main reference curve the relation evaluated on the basis of EN 14651 was chosen. The EN 14651 relation is closely followed by numerous research results obtained by: Chaia B. et al. [5], Ding Y. [8] and Oh B.H. et al. [27], on specimens of different sizes. The previous test results were achieved both using steel and polymer fibre but all composites were based on natural fine and coarse aggregate. In case of FRCC based on WCA analysed in this study all CMOD – δ relations are significantly less steep. This phenomenon is probably caused by the significantly lower modulus of elasticity of tested FRCC (ranging from 17.8 GPa to 18.8 GPa) comparing to

FRCC based on ordinary concrete matrix. WCA which constitutes 58%±2% of volume of cast FRCC significantly influenced its elastic characteristics.

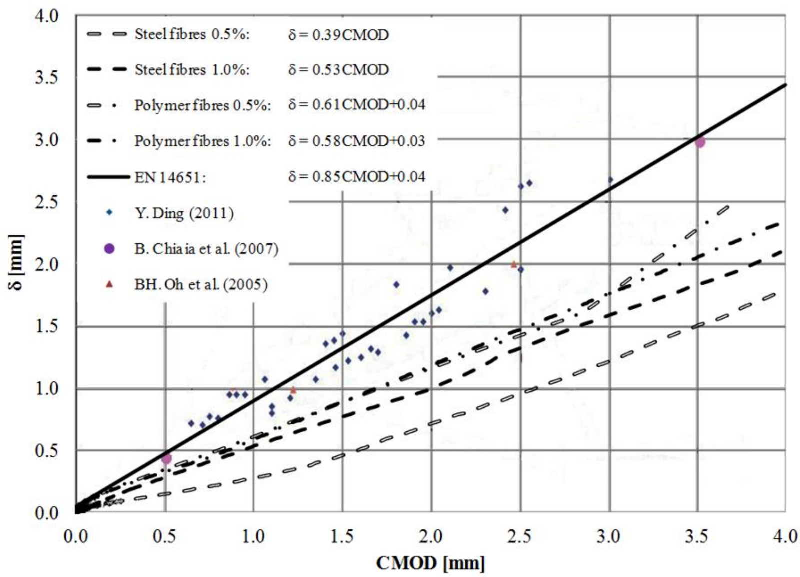


Fig. 8. Relationship between mid-span deflection and the CMOD
Rys. 8. Zależność pomiędzy ugięciem i CMOD

9. Conclusions

Density of analysed composites varied from 1880.5 to 2001.8 kg/m^3. Mixes modified by larger volume of fibre were characterized by smaller density. This phenomenon is associated with amount of air trapped in a mix [28, 29]. Basically, the larger the volume of fibre becomes the larger the volume of trapped air.

In case of mechanical properties of composites in question, one can compare stress-strain curves for tested FRCC (Fig. 5) with bilinear curves for ordinary concrete given by EN 1992-1-1:2004. For adequate compressive strengths the characteristic point of the curve (steep part of the curve transforms into a plateau relationship) given by EN 1992-1-1:2004 is located at strain equal to 1.75‰. In case of tested FRCC this point is located at strain ≥2‰ (only for pure matrix the point is located at strain close to 1.75‰).

The results of this experimental study indicate that the harnessing WCA for the production of non-structural and secondary structural FRCC elements is feasible. This research work forms the basis for further experiments on FRCC with the use of WCA. The research programme is a work in progress and some properties of mortars in question are still under investigation. The tests of properties requiring very long periods of time (e.g. freezing-thawing resistance, creep and shrinkage) are being carried out and will be described in a separate publication in the future. The achieved results of mechanical properties prove that FRCC with the use of WCA can be used to cast elements characterized by less demanding mechanical characteristics. Such production would be possible and promising to be feasible.

The conducted research programme was realized as a part of research project entitled "Impact resistant concrete elements with nonconvencional reinforcement" and founded by Polish "National Science Centre" (decision number: DEC-2011/01/B/ST8/06579).
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Charakterystyka obciążenie-ugięcie fibrobetonów na bazie ceramicznego kruszywa odpadowego

Streszczenie

W artykule opisano badania fibrobetonów na bazie ceramicznego kruszywa odpadowego. Jako zbrojenie rozproszone zastosowano dwa rodzaje włókien (stalowe i polimerowe) w ilość nieprzekraczającej 1,0% objętościowo. W badaniach określono podstawowe właściwości zaproponowanych fibrobetonów takie jak: konsystencję, gęstość, wytrzymałość na ściskanie czy też moduł sprężystości. Jednak główny nacisk badawczy położno na określenie zależności pomiędzy obciążeniem i ugięciem dla zginanych elementów belkowych zgodnie z EN 14651:2005. Na podstawie określonych zależności wg EN, możliwe było wyznaczenie rezydualnych wytrzymałości na rozciąganie przy zginaniu oraz przyporządkowanie badanym kompozytom klas określonych przez The International Federation for Structural Concrete (*fib*).