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Fracture Mechanical Properties of Cement Based Composites with Various Amount of Waste Aggregates

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Abstract

The importance of sustainability and recycling has become increasingly recognized and understood in academia and industry over the last several decades. Recycling of construction and debris waste is one of many avenues that provide a great opportunity to prevent waste material from entering landfills and reduce the construction industry reliance on decreasing natural resource supplies. The research program focused on fracture parameters of cement based composites with various amount of waste aggregate was conducted. There were prepared composites based on specifically composed aggregates (mixture of natural sand and red waste ceramic aggregate). There was utilized simplex experiment design. Altogether, 6 mixtures of aggregates were prepared. The aim of this contribution is to present and compared basic fracture parameter values. Flexural and compressive strength and fracture toughness were of special interest. All of these tests are important for a practical application of concrete with ceramic aggregates for structures.
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Keywords: Cement based composites; fracture mechanics; waste aggregate; stress intensity factor, fracture properties;

1. Introduction

Ceramic materials have been used for a long time for a multitude of uses and continue to be a common material used for making goods such as earthenware and sanitary ware [1] [7]. Ceramics are also commonly used as a building material, for example ceramic floor and wall tiles, and various clay building bricks. Ceramic waste from construction industry is probably the most important part in the global volume of construction and demolition waste [5] [6] [14]. The most promising recycling process of ceramic waste is using it as a coarse aggregate for concrete [2]. Worldwide, there is a growing research effort to successfully harness ceramic waste in construction industry [10]. Replacing traditional coarse aggregates by waste ceramic aggregates (WCA) also significantly influences the homogeneity of

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mechanical properties of cast concrete (populations of results are characterized by significantly higher standard deviation) and mechanical properties themselves [5] [19]. This phenomenon limits applications of concrete based on WCA only to construction elements characterized by less demanding mechanical characteristics.

The aim of the contribution is to introduced the pilot fracture mechanical properties of the set of various concrete with waste aggregates. The research program is based on red ceramic waste that is ground and replace different amount of natural aggregates in concrete. The variables being monitored for all concrete in the contribution are flexural strength, compression strength and fracture toughness. The influence of possible replacement of natural aggregates by waste ceramic aggregates on mentioned fracture properties is discussed.

Nomenclature

3PBT	three-point-bend test
a	crack length [mm]
E	Young's modulus [MPa]
K	stress intensity factor [MPam$^{1/2}$]
K_{IC}	fracture toughness [MPam$^{1/2}$]
L	length of the specimen [mm]
LEFM	linear elastic fracture mechanics
P	load/force [N]
P_{max}	maximal value of the load [N]
S	span of the specimen [mm]
SIF	stress intensity factor
t	thickness of the specimen [mm]
W	width of the specimen [mm]
α	relative crack length [-]
σ	stress [MPa]

2. Materials and specimens

To evaluate the mechanical properties of concrete made with ceramic material, concrete test specimens were made in various moulds appropriate for the test plan. The composition of 1 m^3 of fresh studied concrete mixtures is introduced in Tab. 1. There are mixtures marked from 1 to 6, 1 – only natural aggregates and 2-6 with various amount of ceramic waste. All studied mixtures were prepared in laboratory mixer in 30 liter volume. Immediately after the mixing, the fresh concrete was placed into steel moulds. For compressive strength tests 150 mm × 150 mm × 150 mm cubes were prepared. For flexural strength and fracture toughness tests beams of 40 mm × 40 mm × 160 mm were made. The specimens were unmoulded at the age of 24 hours and given to laboratory cellar with constant temperature of +20°C±1°C. They were stored in these conditions until the test started.

After the preparation the bulk density of each mixture was measured and the results are shown in Tab. 2, where the average values, median and average deviation are shown. One of the advantage of using the ceramic waste is that the value of density decrease with increase value of replacement of sand by ceramic waste and therefore for the same volume of concrete has less weight.

Table 1. Composition of fresh concrete mixtures without and with ceramic waste.

Series	w/c	Cement CEM I 42.5 R	Water [8]	Sand	Waste ceramic aggregate	Viscocrete 5
	[-]	[g]	[g]	[g]	[g]	[g]
1	0.5	450	225	1350	0	5
2	0.5	450	225	1215	101	5
3	0.5	450	225	1080	202	5
4	0.5	450	225	945	304	5
5	0.5	450	225	788	394	5
6	0.5	450	225	657	493	5

Table 2. Bulk density of studied mixtures without and with ceramic waste.

Series	Average	Median	Average deviation
	[g/cm^3]	[g/cm^3]	[%]
1	2271.48	2269.24	0.63
2	2234.58	2235.84	0.39
3	2185.28	2188.28	0.78
4	2133.97	2126.95	0.81
5	2144.81	2144.73	0.54
6	2109.22	2107.71	0.72

3. Experimental results

Basic fracture mechanical properties of six studied composites, tested in a traditional static way are reported in the following sections. The flexural strength, compressive strength and fracture toughness are the subjects of the interest.

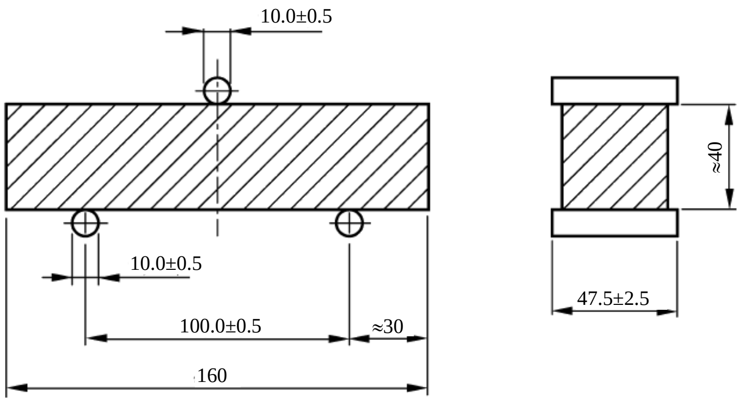

Fig. 1. Set up for measurement of flexural strength [9].

3.1. Flexural strength of test specimens

The flexural strength test was conducted in compliance with European Standard [9], values of flexural strength were determined via three point bending tests on prismatic specimens. In Fig. 1, the set up for measurement of flexural strength is shown.

The obtained results from flexural test are presented in Tab. 3, where average value, median and average deviation are listed.

Table 3. Flexural strength of test specimens.

Series	Average [MPa]	Median [MPa]	Average deviation [%]
1	5.7	5.7	2.12
2	6.3	6.2	4.21
3	6.9	6.8	3.49
4	7.6	7.9	10.23
5	7.3	7.6	5.24
6	7.8	7.8	0.51

3.2. Compressive strength of test specimens

Compressive strength test results are important in studying concrete, especially when considering the use for structural applications. The test was conducted in compliance with European Standard [9], on halves of beams 40 mm × 40 mm × 160 mm. The obtain results from compressive test are mentioned in Tab. 4, where average value, median and average deviation are presented.

Table 4. Compressive strength of test specimens.

Series	Average [MPa]	Median [MPa]	Average deviation [%]
1	46.1	46.4	1.89
2	51.1	51.1	1.61
3	58.4	58.8	1.27
4	57.2	57.7	5.14
5	61.9	61.7	2.77
6	63.6	65.4	2.69

3.3. Fracture toughness

For calculation of fracture toughness values, the data from three-point-bended test (3PBT, which is traditionally used [21][22][15][17]) were evaluated. The specimens were beams 40 mm ×40 mm ×160 mm (120 mm) with notch (*a/W*=0.1). From test, the maximal values of force was recorded and following equation was used [20],[12]:

$$K = \sigma\sqrt{\pi a}\, f\left(a/W\right) \tag{1}$$

where a is a crack length,

$$f(a/W) = 0.9926 + 0.4862(a/W) - 12.479(a/W)^2 + 73.153(a/W)^3 - 124.29(a/W)^4 , \quad (2)$$

seen in e.g. [18],[23] and

$$\sigma = \frac{3SP}{2tW^2} \quad (3)$$

where S is a span, P is a force, t is a thickness and W is a width of a specimen. In case that force reaches maximal value P_{max} the maximal value of stress intensity factor for given material is called fracture toughness K_{IC} [MPa m$^{1/2}$]. Obtain results for fracture toughness are presented in Tab. 5.

Table 5. Fracture toughness of test specimens.

Series	Average [MPa m$^{1/2}$]	Median [MPa m$^{1/2}$]	Average deviation [%]
1	0.543	0.541	2.51
2	0.539	0.573	9.04
3	0.580	0.564	4.63
4	0.649	0.637	2.83
5	0.666	0.675	2.99
6	0.676	0.680	10.70

4. Discussion

The overall objective of this experiment program was to use a material that would otherwise be considered waste as an ingredient to replace a natural material ingredient in concrete with no or minimal change on the concrete properties. Therefore, for this choice of an optimum level of ceramic waste, the experimental campaign was prepared. For presentation/interpretation of the results, the normalized values of flexural strength, compressive strength and fracture toughness, based on results shown in Tab. 3-5, are shown in Fig. 2. Generally, the replacement of natural sand by ceramic waste up to 36%, improves the measured fracture mechanical properties. It is clearly evident that flexural and compressive strength increase with increasing content of ceramic waste. One can note that the compressive strength results show improvements over many other ceramic studies, in particular when compared to coarse aggregate replacement schemes [3][16]. In paper [1], the following information is published: the waste ceramic returned flexural strength decrease as much as 25% with 100% replacement. Nevertheless, in the studied case there was registered up to 36% increase of the flexural strength. The values of fracture toughness for set-2 decrease, but very little. Furthermore, the variability of all the properties tested increased markedly as well, see fracture toughness: set-2 and set-6, and flexural strength set-4. The difference between the weakest and strongest composites is equal 24% and it is reached for fracture toughness set-6.

5. Conclusions

The results of this study indicate that the use of recycled ceramic aggregate as a replacement for aggregate in concrete is certainly feasible and the following conclusions can be drawn from the research program described in the paper:

- A mixture of waste ceramic aggregates allows to achieve the flexural strength, compressive strength and fracture toughness of a cement composite higher than in case of ordinary natural sand. One of the advantage of using the ceramic waste is that the value of density decrease and the same amount of concrete has less weight. The best fracture mechanical properties, the set-6 shows, where the ceramic waste approximately replaced 36% of natural sand. Additionally, following a systematic, strict testing regime that limits the number of variables provides more linear results when compared to tests performed in other studies, indicating that strict control of the source material properties lends to improved prediction capabilities of concrete products produced.

- The research program should be continued using fatigue load. It should be focused on more sophisticated mechanical characteristics of composites in question to allow full scale modelling [4][11][13].

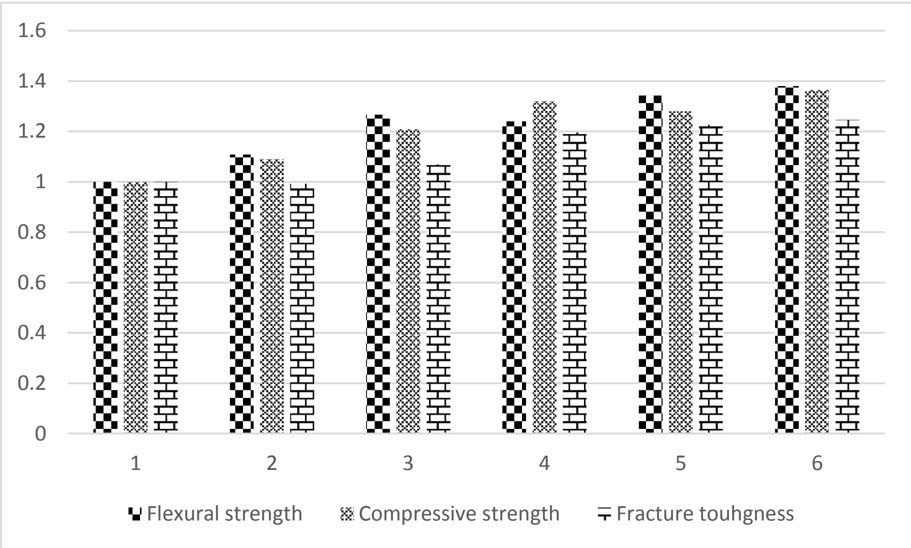

Fig. 2. The normalized values of flexural strength, compressive strength and fracture toughness, based on results shown in Tab. 3-5

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