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ADHESION OF STRUCTURAL STEEL TO CONCRETE WITH RECYCLED CRUSHED SANITARY CERAMICS AGGREGATE

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ABSTRACT

Today, the use of recyclable materials has been the focus of researchers around the world. The use of recycled concrete aggregates, although beneficial for environmental reasons, brings many problems. One of the basic factors is the presence of old mortar and impurities in these aggregates. Therefore, it is necessary to conduct comprehensive studies in this field. Hence, the paper presents the results of testing the adhesion of B500SP structural steel to concrete subjected to thermal loads in the range of 300–700°C. The concretes were designed exclusively based on waste aggregate made of precious waste ceramics and two types of cement: CEM I 42.5 R portland cement and Górkal 70 alumina cement. The method of direct pulling of a steel rod from the concrete cover (pull-out test) was used in the tests. The test results confirmed that the adhesion of the selected steel grade to concrete based on recycled aggregate does not differ from the results obtained for concrete with natural aggregate.

Key words: adhesion, steel, concrete, fire temperatures, residual strength

INTRODUCTION

The interaction between steel and concrete, often referred to as adhesion, is influenced by several mechanical and chemical factors. The most important of these include the friction acting at the interface between the two materials (Morley & Royles, 1997). Many technological factors also affect grip. In the case of ribbed bars, a very important factor influencing the friction is the mechanical mesh, and the greater the roughness of the bar surface. In the case of reinforcing bars, the shape of the sprinkler is also important (Ogrodnik & Szulej, 2017). The research conducted so far by Tariq and Bhargava (2020) shows that the adhesion phenomenon is also influenced by the type, shape, and form of the aggregate grains used in concrete production. This problem is particularly complicated when recycled aggregates (RA) are used in concrete production. Although research on RA has been going on for almost 70 years, its use is still limited. The report prepared in 2017 by the European Aggregates Association (UEPG) shows that in developed countries, the share of recycling aggregate in the production of aggregates reaches up to 34% (the Netherlands). However, in Poland, this share is only about 3%. Recycled concrete aggregates (RCA) are quite commonly used worldwide (de Brito, Pereira & Correia, 2005). However, this type of aggregate has some disadvantages. One of the problems with the use of concrete recyclate is the fact that apart from natural aggregate, the components of this aggregate are also old cement mortar and impurities. According

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to extensive research, it should be assumed that the adhered mortar constitutes 20–35% of the RCA volume (Afroughsabet, Biolzi & Ozbakkaloglu, 2017), and in extreme cases, this value may exceed 45% (Liu, Xiao & Sun, 2011). Importantly, the specific gravity of RCA is also lower than for natural aggregate. Also, the concrete mixes made based on RCA are often characterised by inferior workability. This is attributed to the higher RCA absorption capacity, rough surface, and more irregular shapes, as well as increased water demand. For many years, research has also been conducted on the impact of the amount of RCA used on the strength of concrete. In general, it is difficult to clearly interpret the impact of the amount of RCA on the strength of concrete; however, most researchers indicate that with an increase in the RCA content, the compressive strength of concrete tends to decrease, which was confirmed in the works by Beltrán, Barbudo, Agrela, Galvín and Jiménez (2014), and Kurda, Brito and Silvestre (2017). A new and unrecognised direction of research is the use of crushed sanitary ceramics as aggregate for concrete. The research conducted so far by Guerra, Vivar, Llamas, Juan and Moran (2009) has shown that with the increase in the share of this type of aggregate, the strength of concrete increases by up to 10%. The researchers emphasised that precious ceramics, apart from crushing, do not require any additional treatments in the form of washing, which is necessary in the case of RCA aggregates. The use of sanitary ceramics as aggregate for concrete has also turned out to be beneficial concerning special concretes resistant to fire conditions, which was confirmed in work by Szulej, Ogrodnik and Klimek (2019). The article describes the results of research on the adhesion of reinforcing steel grade B500SP to concrete based on two types of cement (CEM I 42.5 R portland cement and Górkal 70 alumina cement), made exclusively on the basis of crushed sanitary ceramics aggregate. The test itself was performed using the pull-out method. It is one of the basic methods of testing steel adhesion to concrete (Dohojda, Filipchuk & Makarenko, 2021). Some of the test samples were pre-heated at high temperatures.

MATERIAL AND METHODS

Characteristics of materials for making samples

The specimens were reinforced with ribbed steel, grade B500SP, class A-IIIN in accordance with the PN-H-93220:2018-02 standard (Polski Komitet Normalizacyjny [PKN], 2018) with a diameter of Ø10 mm and a length of 720 mm. The strength parameters of steel are presented in Table 1. The chemical composition of the steel used in the tests is presented in Table 2. The mean values of the results of determinations were calculated on the basis of five research trials.

Table 1. Strength properties of B500SP structural steel

Parameter	Designation	Value
Yield point [MPa]	f_{yk}	500–625 (542)[a]
The ratio of the characteristic tensile strength to the yield point [-]	f_{tk}/f_{yk}	1.15–1.35 (1.17)[a]
Minimum elongation [%]	A5	16.0 (18.9)[a]
Elongation under the highest stress [%]	ε_{uk}	8.0 (12.5)[a]

[a]Self-determination results.

Source: own work.

Table 2. Chemical composition of B500SP structural steel

Analysis	Maximum content [%]						
	C	Mn	Si	P	S	Cu	N
Smelting	0.22	1.60	0.55	0.050	0.050	0.80	0.012
of the product	0.24	1.65	0.60	0.055	0.055	0.85	0.013

Source: own work.

The compositions of the mixtures were determined by the method of three equations, and two types of cement were used for their production – CEM I 42.5 R portland cement and Górkal 70 alumina cement. When designing the mixture, a constant value of the water-binder coefficient w/s = 0.4 was assumed. This proportion was adopted due to the limitation of the maximum content of capillary pores in the structure of the cement matrix. Only recycled sanitary ceramics were used as aggregate. The phase composition of sanitary ceramics was assessed based on the results of the diffraction analysis. The test was performed at room temperature using a PANalytical X'Pert PRO MPD X-ray diffractometer from PANanalytical with a PW 3020 goniometer. As the source of X-ray emission, a copper lamp (CuKa = 1.54178 Å) was used. The PANalytical X'Pert HighScore software was used to process the diffraction data. Identification of mineral phases was based on the PDF-2 Release 2010 database formalised by the JCPDS-ICDD. Figure 1 shows a diffractogram of the phase composition of aggregates.

Based on the X-ray analysis, it can be concluded that the main mineral components of the ceramic aggregate are mullite, recognised by the characteristic interplanar distances d_{hkl} = 5.376; 3.425; 3.390; 2.882; 2.427; 2.294; 2.208 Å. There is also minor quartz recognized by d_{hkl} = 4.255; 3.344; 2.456; 2.283; 2.237; 2.128; 1.981 Å and cristobalite d_{hkl} = 4.055; 3.140; 2.847; 2.486 Å and calcite d_{hkl} = 3.861; 3.040; 2.283; 2.096 Å. Apart from the crystalline phases, the aggregate used for the tests contains an amorphous substance (aluminosilicate glaze), the presence of which is visible in the diffraction patterns by raising their background in the angular range from 15° to 35°. Weight compositions of concrete mixes for the preparation of samples are summarised in Table 3.

Table 3. Weight compositions of basic concrete mixtures [kg·m^{-3}]

Concrete series	Cement		Ceramic aggregate		Water
	portland CEM I 42.5 R	alumina Górkal 70	fraction 0–4 mm	fraction 4–8 mm	
PA-00	476.0	–	997.14	398.86	202.0
CA-00	–	476.0	997.14	398.86	202.0

Source: own work.

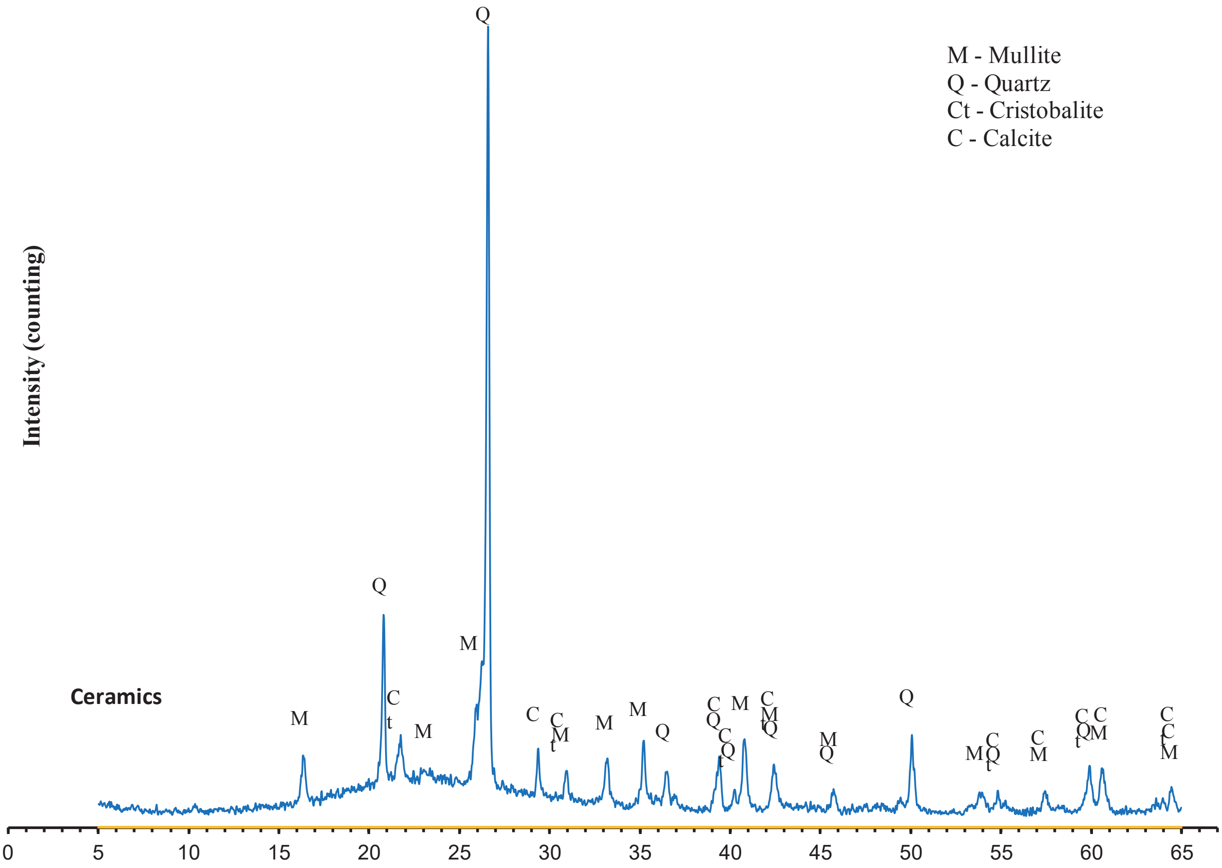

Fig. 1. Diffraction pattern of the mineral composition of the ceramic aggregate

Source: own work.

To test the adhesion of steel to concrete, cylindrical samples with a steel bar were prepared. The size (diameter) of the samples was determined on the basis of previous tests (Bednarek, Ogrodnik & Pieniak, 2010). The dimensions of the samples also correspond to the requirements developed by the RILEM regarding the dimensions of samples for testing steel adhesion to concrete using the pull-out method (RILEM, 1983). The samples were designed as cylinders with a diameter of 100 mm, and a height of 150 mm (Fig. 2). The sizes of the samples were selected in such a way that during the heating at high temperatures, the temperature at the interface between concrete and steel would be equalised as quickly as possible. In the selected samples, in order to be able to measure the temperature distribution at the contact between the rod and concrete during the annealing and the forming of the samples, a special channel with a diameter of 3 mm (marked with the Number 3 in Figure 2) was made, enabling the placement of the measuring thermocouple. Points 1 and 2 in Figure 2 show the places for mounting measuring thermocouples.

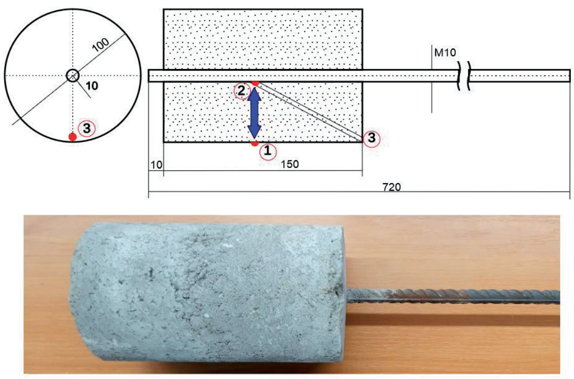

Fig. 2. Samples for testing along with marking the location of measuring thermocouples (all dimensions in mm)

Source: own work.

Before the samples were formed, reinforcing bars were prepared and subjected to the oxidation process. Next, the bar was placed in the moulds, and the samples were formed, while also checking, after vibration, whether the reinforcing bar was positioned vertically. All prepared samples were demoulded 2 days after concreting, and then matured for the first 14 days in a water bath. For the next 28 days, the samples were matured in laboratory conditions at a temperature of 20 ±2°C, in air-dry conditions with an average relative humidity of 50%.

Thermal conditions for carrying out tests on the adhesion of steel to concrete

The thermal load of the adhesion test specimens was carried out in the PK 1100/5 electric chamber furnace. For concrete of higher classes and ribbed steel, the initial limit temperature at which the adhesion drop begins is approximately 300°C. Therefore, the tests assumed that the samples would be annealed at three temperatures of 300°C, 700°C, and an intermediate value of 500°C. The standard temperature-time curve according to the PN-EN 1363-1:2012 standard (PKN, 2012) and a new version – the PN-EN 1363-1:2020-07 standard (PKN, 2020) was adopted as the basis for annealing. The scheme of annealing of individual samples is shown in Figure 3.

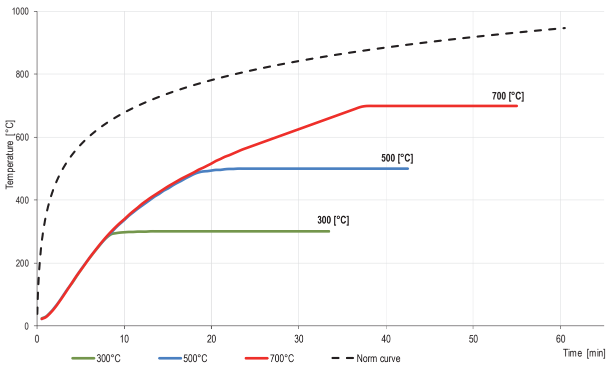

Fig. 3. The temperature distribution assumed in the tests with the heating time marked

Source: own work.

After reaching the assumed temperature, it was kept in the oven for 60 min in order to equalise it in the whole volume of the sample. The furnace was then turned off and the samples were freely cooled for another 24 h until the temperature was around 20°C. In all cases, the temperature was measured for 240 min. An example of the temperature distribution during the test is presented in Figure 4.

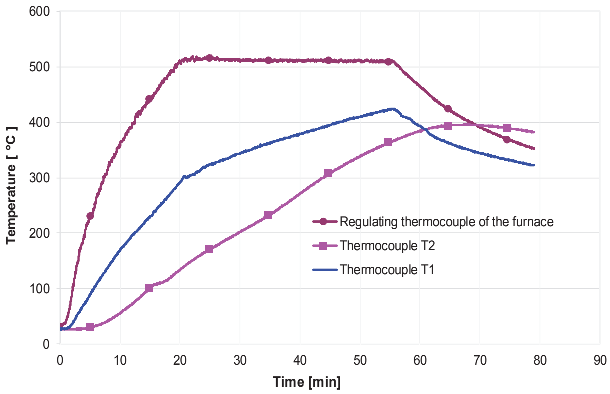

Fig. 4. The temperature distribution assumed in the tests with the heating time marked

Source: own work.

Testing the adhesion of steel to concrete in post-fire conditions

The research was carried out with the use of a universal VEB Thüringer Industriewerk Rauenstein FPZ 100/1 ripper (Fig. 5), which makes it possible to introduce a tensile or compression force statically and maintain it in a vertical system at an assumed constant level. The individual samples were placed on the stand and loaded with the force applied to the rod pulling the rod out of the concrete.

Fig. 5. Stands for testing the adhesion of steel to concrete

Source: own work.

The device has four ranges of traverse travel speed, and four ranges of set tensile forces. The machine power supply is 230/400 V, and the maximum generated force is 100 kN. During the adhesion test using the direct pull-out method, the range of I–III was used, which realises the traverse travel of 0.021–0.84 mm·min^{-1}. The test determined the maximum force (f_{cr}) necessary to pull the bar out of the concrete sample, causing the bar to shift. The results of the adhesion force were recorded using the APL measuring application.

RESULTS AND DISCUSSION

The research was carried out on seven samples in each group. As part of the research, the adhesion force after initial thermal load was determined, as well as, for comparison purposes, of samples not subjected to annealing. During the tests, the concrete cover was ruptured most often; the typical behaviour of the samples is shown in Figure 6.

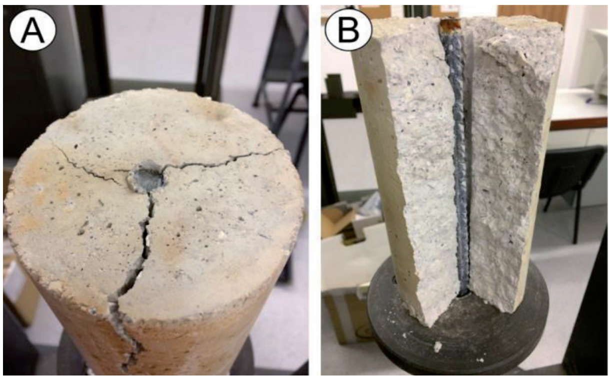

Fig. 6. An example of failure while testing the adhesion strength of a CA-00 concrete sample: A – top surface; B – side surface

Source: own work.

In the first stage of the study, small scratches were formed in the centre of the samples that propagated to the outer surface. Their size increased with increasing load until the moment when the bar was displaced (Fig. 6A). At this point, there was a sudden drop in force which is visible in the courses of breaking the adhesion force. In some cases, the sample was completely ruptured, as a result of which some of the covers came loose from the samples (Fig. 6B). The selected course of breaking the adhesion strength of B500SP steel for the selected temperature is shown in Figure 7.

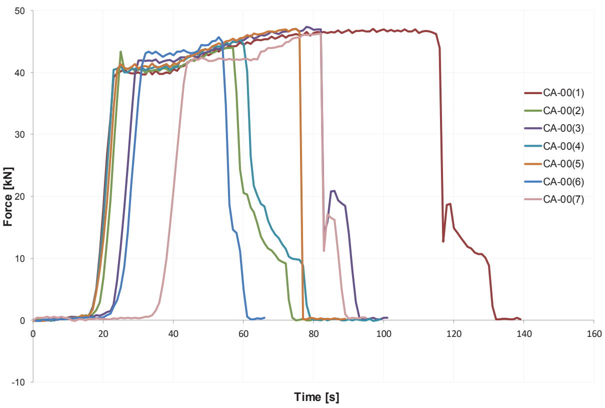

Fig. 7. Time histories of breaking the adhesion strength of CA-00 concrete samples pre-heated at the temperature of 500°C

Source: own work.

Comparison of the average strength of adhesion of B500SP steel to samples made of CEM I 42.5 R portland cement and Górkal 70 alumina cement with recycled aggregate made of sanitary ceramics at a temperature of 20°C and after preliminary annealing is shown in Figure 8.

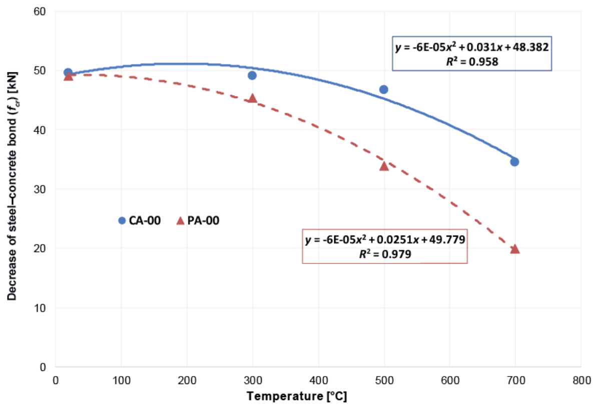

Fig. 8. Average value of the strength of adhesion of steel B500SP to concrete based on Górkal 70 alumina cement (CA-00) and CEM I 32.5 R portland cement (PA-00)

Source: own work.

Comparing the obtained average results of the adhesion strength of B500SP steel to concretes composed on the basis of CEM I 42.5 R portland cement and Górkal 70 alumina cement, it can be noticed that with the increase of the temperature at which the thermal pre-treatment was performed, the value of the average adhesion strength decreases both for PA-00 and CA-00. At a normal temperature of 20°C, the adhesion of steel to concrete with recycled aggregate was almost identical for both designed concretes. These differences grew with increasing annealing temperature. The results are from the alumina cement used, which can be used in thermally loaded structures. Compared to the research by Bednarek, Ogrodnik, Kamocka-Bronisz and Bronisz (2012) in which gravel aggregate of 2–8 mm fraction and Vistula sand were used, the average values of the adhesion forces of B500SP steel to concrete prepared based on a recycled aggregate made of sanitary ceramics and CEM I 42.5 R portland cement are significantly higher in the entire range of temperatures considered. In the mentioned work at temperatures of 600°C, the decrease in adhesion of B500SP steel to the designed concrete was about 44%, while for 800°C it was about 83%. For CA-00 concrete at the temperature of 300°C, no significant difference in the adhesion force was observed compared to the test results obtained at the normal temperature of 20°C. At higher annealing temperatures, it is 6.0% (500°C) and about 30% (700°C), respectively. In the case of PA-00 concrete, the adhesion loss was 5.9% at 300°C, 29.7% at 500°C, and 58.7% at the highest temperature, respectively.

CONCLUSIONS

The use of RCA aggregates, although beneficial for environmental reasons, brings with it many problems. One of the basic factors is the presence of old mortar and impurities in these aggregates. Such a problem does not exist concerning aggregate resulting from the crushing of precious ceramics. The research confirmed the possibility of their application in reinforced concrete structures exposed to high temperatures, which occur during fires. The results of the B500SP steel adhesion test to selected concretes after the initial temperature loading of the samples proved that for the samples with CEM I 42.5 R portland cement and Górkal 70 alumina cement to 300°C, there was no decrease in steel adhesion to concrete. Only preliminary heating to 500°C causes a slight reduction of the adhesive strength. It is especially visible for PA-00. As the temperature rises to 700°C, the adhesion loss continues to increase.

Authors' contributions

Conceptualisation: P.O., A.P. and A.G.; methodology: P.O.; validation: P.O. and A.G.; formal analysis: P.O. and A.P.; investigation: P.O.; resources: P.O. and A.P.; data curation: P.O.; writing – original draft preparation: P.O. and A.P.; writing – review and editing: P.O., A.P. and A.G.; visualisation: A.G.; supervision: P.O.; project administration: P.O.; funding acquisition: P.O.

All authors have read and agreed to the published version of the manuscript.

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PRZYCZEPNOŚĆ STALI KONSTRUKCYJNEJ DO BETONU Z KRUSZYWEM RECYKLINGOWYM Z CERAMIKI SZLACHETNEJ

STRESZCZENIE

W artykule przedstawiono wyniki badań przyczepności stali konstrukcyjnej B500SP do betonów poddanych obciążeniom termicznym w zakresie 300–700°C. Betony zostały zaprojektowane wyłącznie na bazie kruszywa odpadowego wykonanego z odpadowej ceramiki szlachetnej oraz dwóch rodzajów cementów: portlandzkiego CEM I 42,5 R i cementu glinowego Górkal 70. W badaniach wykorzystano metodę bezpośredniego wyciągania pręta stalowego z otuliny betonowej (ang. *pull-out test*). Wyniki badań potwierdziły, że przyczepność wybranego gatunku stali do betonu na bazie kruszywa recyklingowego nie różni się od wyników uzyskanych dla betonu z kruszywem naturalnym.

Słowa kluczowe: przyczepność, stal, beton, temperatura pożarowa, wytrzymałość resztkowa