Assessment of selected parameters of concrete composite containing recyclate obtained from fire-resistant cullet

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Abstract. The purpose of the work is to determine the possibility of using waste from waste heat-resistant cullet as a filler in concrete composites. The article discusses the results of testing selected performance properties of the designed concrete composite. The samples were tested for mechanical properties: compressive strength, impact resistance. Research also included identifying structural changes in the designed composite.

1. Introduction

For many years a growing interest has been recorded globally in waste management with respect to technology, neutralisation or its re-use. Numerous legal acts have been developed in European and national legislation, and several organisational solutions and educational programmes pertaining to correct handling of waste have been implemented. In its support of sustainable development in the construction sector, in 2015 the European Commission adopted a plan relating to a closed loop economy. Such an approach to the economy contributes to its enhanced innovativeness, reduces the amount of generated waste and limits the usage of natural resources [1].

Glass waste used as aggregate for concrete does not require any special processing. The technological process entailing the production of concrete mixture does not require any changes as compared to concrete comprising traditional aggregate. The adoption of recycling will help us make a contribution towards management of waste, limiting the usage of natural resources, reducing transport costs, as well as of building waste disposal and storage [2-5].

The main two factors that determines the selection of appropriate raw material are its technical parameters and its price [6]. Studies have been already executed for years which concern the impact of the volume of used overcrushed recycled aggregate on actual concrete strength. Selected results of compressive strength of concrete have been compiled and presented in studies [1, 7-11]. Results of conducted tests do not allow an unequivocal determination of the impact that the volume of cullet exerts on concrete strength.

Researchers have found that a bigger volume of recycled material tends to reduce the compressive strength of concrete. The rate at which strength in concrete produced based on recycling aggregate develops is higher than in the case of natural aggregate especially after 28 days. This results from the presence of remnants of old unhydrated cement that adhere to the surface of particles reacting with water. Consequently it increases the rate of strength development, as has been presented in studies [9-12]. The strength of concrete is affected by the initial humidity of recyclate [13], which may become
reduced by even 30% or may grow to 20%. It has been proven that the quality of concrete made of recycled aggregate depends on the implementation method, the amount of contamination and the raw material of which the recyclate had been made. Some scientists recommend limiting coarse fractions of recyclate to 30% to assure better workability.

Cullet stored in piles does not decompose, and poses a serious problem for the surroundings [14,15-18]. Given its structure and chemical composition it poses no direct risk for the natural environment. The current technological progress allows full management of cullet waste. Used glass is a perfect secondary material, which offers the possibility of repeated recycling. Furthermore, glass is also resistant to mould and humidity, which makes it an attractive raw material. Crushed heat resistant cullet may serve as an alternative solution to natural aggregate. Glass added to a concrete composite material affects properties, both physical and mechanical ones.

The goal of the conducted review of literature [19-25] was to find ways of using materials for needs of producing ceramics, binders, mortar, concrete, insulating materials, for the production of glass fibres, foam glass, mats, insulation plates, laminates and bituminous materials. Studies [26, 27] have been performed with the aim of finding possibilities of using cullet, among others as substitute of natural aggregate for concrete, substitute of natural soils or for needs of building roads and subgrades. For needs of tests use was made of cullet coming from diverse sources, such as from float type window glazing, car windows and windscreens, safety glass, crystal glass, mirrors, colourless, green and brown packaging glass and CRT glass.

Cullet may be used as a substitute of cement, sand and aggregate. Strength tests have proven that after a 28-day period of curing concrete had a lowered strength as compared to the control trial (application of cullet as cement substitute). On the other hand, after 90 and 180 days of curing a much smaller impact was recorded of the presence of cullet on the reduction of strength of composites. Tests were carried out on samples having diverse shapes and dimensions. This proves the pozzolanic reactivity of cullet with the passage of time [20]. Strength test results are correlated with pozzolanic reactivity. A strength decrease of ca. 10% may be observed in case of applying a 10% cullet admixture, where in the event of 30% of recyclate the decrease comes up to ca. 25% for the majority of tested samples. The usage of cullet as substitute of fine aggregate with 0/2mm grading requires taking into consideration the type of glass to be used, because it affects the strength properties. With time the decreasing in the strength of composite as compared to the executed control trial becomes reduced [28].

In addition observations of the topography of the tested material under scanning electron microscopy (SEM) allows the presumption that waste obtained from recycling with high strength glass is characterised by a more dense microstructure as compared to a common sample [29].

Researchers [30-35] studied the dynamic behaviour of diverse types of composites. Testing was conducted of the cement matrix damping, and an analysis was implemented of dynamic properties of concrete with a high damping degree. Recently appeared scarce but promising reports pertaining to the use of the vibration damping factor in concrete composites modified by polymers and recycled aggregate (CRT glass) [31]. However, dynamic properties of concrete produced with the use of recyclate were rarely assessed.

2. Research materials and methods

The composition of concrete was designed with the use of the computational and experimental method. The water and cement relation, which had been adopted for the production of concrete mixtures, equalled to 0.6. The concrete mixture that was required to produce the samples was made using CEM I 42.5 R Portland cement, fine and coarse aggregate, glass, volatile ash and superplastifier.

The control mixture was modified by filler consisting of bromosilicate heat resistant cullet, and then introduced to the trial batch by reducing the contents of aggregate and allowing for the volume of replaced materials. This aggregate is basically classified as recycled. It is generally obtained from broken heat resistant utensils kept in a storage area on the premises of the glass mill in Wolomin.

Three different concrete mixtures were used for testing. In the basic mixture the aggregate volume was adjusted with respect to the amount of recyclate (5% and 10%). The produced samples were
subjected to such tests, as: compressive strength test, test of resistance and strength to elevated temperature, impact strength test and structure tests with the use of scanning electron microscopy. The tests were conducted on a few research stands. The choice of sample for testing was random.

Compressive strength testing was carried out with the use of hydraulic press of the Controls Advantest 9 system. The determination was carried out pursuant to standard [37] after 28 and 180 days of sample curing. The samples were tested at the laboratory temperature of 20°C. Strength was determined as the mean value from three measurements calculated with the use of the following equation:

\[ f_c = \frac{F}{A_c} \text{ [MPa]} \]  

where: \( F \) – destructive load, [N]; \( A_c \) – cross-section area of the sample, [mm\(^2\)].

The selected sample groups were heated at the temperature of 400°C and 800°C, which had been previously dried to constant mass at the temperature of 105°C±5°C, after 28 days of their curing. The testing was executed in PK 1100/5 special furnace. The temperature increase in the furnace chamber takes place according to the standardised curve "temperature-time" [38] described by the following dependence (2):

\[ T = 20 + 345 \cdot \log(8t + 1) \text{ [°C]} \]

where: \( T \) - temperature, [°C]; \( t \) - time, [min].

Monitoring the distribution of temperature in the studied element is done with the use of thermocouples that meet requirements of the standard [39]. Attempts were made to assure that the temperature increase in the furnace was similar to a standard fire. The distribution of temperature was monitored in a specially drilled witness sample. Three openings were made in the sample to allow inserting measurement thermoelements. This enabled the determination of temperature distribution and the maximum value on various sample parts. Samples were heated at temperature of 400°C and 800°C. Once the assumed temperature has been achieved, it was then maintained for 60 minutes. Afterwards the heating process was discontinued and the samples were left to cool down to room temperature for about 24 hours.

The dynamic test was conducted using type DP FEST 1000 drop hammer. During the test the sample provided on a metal bench was broken by a single blow of the hammer and then measurement was executed of labour conforming to the energy used for its breaking. The test was performed at laboratory temperature maintained close to 20°C. The samples were hit from the height of 595.4 mm with the identical potential energy of 150 J. For needs of testing use was made of samples that had undergone thermal processing.

Afterwards the structure of hardened concrete was tested with the use of the FEI Quanta 650 FEG scanning electron microscope. Observations were conducted after spraying with coal or an alloy of gold and palladium in a vacuum sputter Q 150 E. The thickness of the sputtered layer was ca. 50 nm. The testing was conducted on formulations (deposits) specially prepared for this purpose. Preparation of the surface comprise its grinding with sand paper.

Scanning microscopy was then used to assess the microstructure and phase structure of hardened concrete mortars with the addition of crushed heat resistant cullet and as comparison of concrete containing only natural aggregate.

3. **Review of results**

A part of the samples has been heated up at temperatures of 400°C and 800°C. The temperature distribution in the chamber furnace was closely monitored. In witness samples thermocouples have been provided to allow controlling of temperature. Tests of temperature distribution in the element have proven that the biggest temperature increase takes place in time. In the initial stage the sample tends to absorb heat from the surroundings much quicker over its entire surface on the border of the point of
contact of the air-concrete phase. However, the deeper the sample penetrated by heat, the slower the temperature growth. Temperatures have become equalised after ca. 2.5 hours of heating. This suggests that the sample has become heated evenly over its entire volume. In the third stage (cooling down) a bigger increase was recorded for temperature of internal than external layers.

Next destructive tests were conducted on samples heated up at a temperature of 400°C and 800°C, to verify the strength of materials on the impact of fire temperatures.

The conducted studies have shown that high temperatures lead to weakening and a decrease in compressive strength of the tested material. Cracking is formed in the sample structure, which weakens the contact area aggregate-slurry. It was found that the higher the exposition temperature of samples to the elevated temperature, the bigger the decrease of compressive strength. A considerable decrease in material strength has taken place at the temperature of 800°C.

After heating and cooling several samples were subjected to further tests in line with the adopted experimental plan. The samples were hit with equal energy of 150 J. The impact energy has been selected in such a way as to assure splitting of the test sample at any given temperature. An example diagram of impact loading of a concrete sample has been presented on figure 3.
Vibration damping was observed. As time lapses a decrease takes place in the amplitude of free vibrations. As the distance from the source grows, the damping causes a reduction in the amplitude of a moving wave. This results from energy dissipation.

Observations performed on sample fractures with the use of a scanning microscope enabled a qualitative impact of the of heat resistant cullet, microstructure and phase composition of hardened slurry. Thermal and shock loads have causes the formation of macroscopic deformations in concrete. Samples of deformed concrete were used to show the defect that consisted of a mesocrack occurring in contact joints of aggregate with matrix.

![Figure 3. Diagrams obtained from a drop hammer: a) force-trajectory, b) force-time](image)

4. Summary and conclusions
A review of conducted studies has clearly shown that waste consisting in bromosilicate cullet may serve as supplement of aggregate obtained from natural resources. On the basis of conducted studies, the following conclusions may be drawn:

- replacement of natural aggregate in the concrete mix by a cullet fraction causes changes to physical and strength parameters of the planned concrete,
- replacement of natural aggregate by recycled material allows limiting the possibility of water absorption by concrete,
- testing has shown that replacement of natural aggregate by heat resistant cullet causes a reduction in concrete strength by ca. 19-20% after a 28-day curing period as compared to composite with an addition of 5% and 10%),
- after 180 days the compressive strength of concrete containing a 10% glass admixture was lower by 14% than in the case of concrete without such additive, which may limit the use of the composite in selected structural solutions,
- an admixture of 5% and 10% of cullet causes a decrease in impact strength of concrete as compared to control concrete,
- an increase in load rate causes a decrease in thermal deformations, and the higher the temperature, the bigger the loading rate of composite and the lower impact strength,
- an increase in temperature weakens the structure of the composite, and the samples become cracked on the surface. Weakened concrete containing an admixture of heat resistant cullet is less resistant to impact load.
- scrutiny of the surface of samples after destruction enables the determination of the type of deformations that occur in it.

The results obtained from conducted testing confirm the possibility of producing special concrete modified by waste materials originating from heat resistant cullet. These types of concrete are characterised by satisfactory performance parameters. It should be emphasised that given the lack of normative regulations in the scope of tests of impact strength of concrete, serious difficulties exist in attempts at comparing the obtained results of laboratory tests with data available in the literature, and consequently their interpretation requires the implementation of further research.

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