https://doi.org/10.3311/PPci.14512

Periodica Polytechnica Civil Engineering, 63(4), pp. 1193–1203, 2019

Improving of Concrete Tightness by Using Surface Blast-cleaning Waste as a Partial Replacement of Fine Aggregate

Wojciech Kubissa[1*], Roman Jaskulski[1]

[1] Faculty of Civil Engineering, Mechanics and Petrochemistry, Warsaw University of Technology, Łukasiewicza 17, 09-400 Płock, Poland
[*] Corresponding author, e-mail: wojciech.kubissa@pw.edu.pl

Received: 05 June 2019, Accepted: 23 October 2019, Published online: 10 December 2019

Abstract

In the article the possibility of using surface blast-cleaning waste (copper slag based) as a replacement of fine aggregate in high performance concrete manufacturing was presented. Concrete with w/c ratio 0.45 and 360 kg/m^3 dosage of cements: CEM I 42.5R, CEM II/B-V 42.5N and CEM III/A 42.5N was tested. The consistency measured in table flow test was assumed as 420 ± 30 mm so superplasticizer was used. The replacement rate of the fine aggregate 0–2 mm with the copper slag (CS) waste was 66 %. Concrete mixtures with sand served as reference. The performed tests focused on: compressive and tensile strength (both after 28 days), sorptivity, free water absorption capacity, Torrent air permeability, and chloride ingress depth after salt fog treatment. A freeze resistance test was also carried out according to PN-B-06265. The obtained results showed that the strength and some other tested properties of concrete mixtures with copper slag waste were similar or better than those of the mixtures with sand. The results of the tests indicate that the concrete with copper slag waste is more tight than the concrete with sand and therefore is more durable.

Keywords

concrete, waste utilization, copper slag waste, durability, Torrent air permeability

1 Introduction

Sustainable development becomes one of the imperatives of modern developed societies and economies [1, 2]. One of its foundations is recycling of waste materials. Therefore the use of waste materials for the production of construction products including concrete is becoming more and more common. Unfortunately, the use of this type of materials, especially recycled concrete aggregates, usually causes a deterioration of the concrete properties. Therefore research in this area focuses in large part on how to prevent this deterioration. On the other hand, many waste materials added to the concrete improve its properties. The most known and tested additives with such a positive impact include silica dust, fly ash or blast furnace slag. However, the list of waste materials that may have a positive impact on concrete is not closed and recently a positive impact of using, among others, brick dust or CS is also noticed [3–6].

Copper slag is a by-product of process of copper extraction by smelting. It is almost inert material and its physical properties are similar to quartz sand [7]. After its usage as an abradant in the surface blast-cleaning process it is considered to be a waste which is in large amount disposed in landfills or stockpiles. Copper slag waste can be used as a sand replacement in building industry and its usage brings some environmental benefits: reduction of sand extraction from natural resources, saving the space which would be used as landfills and reduction of pollution resulting from leaching from stockpiled copper slag waste [8]. There are many potential applications and many of them have been described already [3, 9]. One of the most promising application is concrete production [10–12]. Copper slag used in production of concrete can improve its properties compared to concrete prepared with sand i. a. compressive strength [13, 14]. Using of copper slag can also improve the consistency of the mixture without changing the amount of mixing water [11, 15]. On the other hand it is possible to reduce the amount of water by 22 % retaining the same consistency and increasing the compressive strength of concrete up to 20 %. Using copper slag in concrete does not influence the contraction of the material [10]. Copper

Cite this article as: Kubissa, W., Jaskulski, R. "Improving of Concrete Tightness by Using Surface Blast-cleaning Waste as a Partial Replacement of Fine Aggregate", Periodica Polytechnica Civil Engineering, 63(4), pp. 1193–1203, 2019. https://doi.org/10.3311/PPci.14512

slag waste obtained in the process of surface blast-cleaning is more fine-grained. Its particle size is decreased and the content of 0–0.125 mm and 0.125–0.25 mm fractions is significantly increased. It also contains small amount of scraped particles of cleaned surfaces and their protective coatings [16, 17]. In paper [5] the use of blast-cleaning waste as a substitute for sand in concrete with dosage of cements 300 kg/m^3 and $w/c = 0.6$ was tested and described. When assessing the durability of concrete, it is particularly important to study the possibility of harmful substances penetrating into it, among others through mechanisms of diffusion, capillary rising, etc. To determine the susceptibility of material to these mechanisms, it is examined, among others, sorptivity, air permeability and the rate of chlorides penetration [18].

Air permeability can be determined using an Autoclam or Torrent device. Both of these methods are recommended when testing the shielding structures of nuclear power plants [19, 20]. They are also used to test the constructions of road infrastructure [21]. Numerous studies have shown that air permeability depends largely on the water content in concrete [19, 22–26]. It is the reason why in the presented research air permeability measurements were performed on the specimens twice in their natural moisture state after 56 and 90 days of maturing and after drying them in oven in temperature 65 °C

The measurement of concrete sorption is also used to determine its quality and may have practical application in assessing the durability of the structure [27]. The result of this test also depends to a large extent on the moisture of the concrete [28–31]. For this reason, the tests were carried out after drying the specimens to constant mass as described in [32].

An important feature of concrete that determines its durability is its resistance to chloride ions penetration, which is one of the reasons for the faster destruction of reinforced concrete structures. The penetration of the ions causes the corrosion of reinforcing steel. Rust arising on the surface of the reinforcing rods as a result of this process occupies many times more volume than steel. It leads to cracking and spalling of concrete and can also result in delamination of the concrete cover. [33, 34]

The rate of penetration depends to a large extent on the pore structure of the concrete and the ITZ zone, so it is important to properly shape the pore structure to make this transport more difficult. This can be done by enriching the cement with active mineral additives to seal the concrete structure [35]. The possibility of limiting the penetration of chlorides by using cements with additives and SCM is an important area of research in the search for more durable concrete.

The use of pozzolanic or hydraulically active additives allows to achieve a significant decrease in the chloride migration coefficient. For example, the use of cement containing calcareous fly ash and ground granulated blast furnace slag in mixtures with granodiorite aggregate allowed to reduce the D_{nssm} value by 38 % and 33 %, respectively, in relation to reference concrete after 28 days of curing, and after 90 days of curing the observed decrease was 41 % and 38 %, respectively. [35]

In the paper the use of blast-cleaning waste as a substitute for part of the sand in concrete with 360 kg/m^3 of 42.5 class cements and $w/c = 0.45$ was tested and described. Some researchers pay attention to the large impact of packing density on many concrete properties [36–39], therefore the concrete mixtures were prepared in two variants which differed from each other in consistency and workability. For each cement type two mixtures with CS were made. In one, the same dosage of superplasticizer as in the reference series was used. In the second, the amount of superplasticizer was experimentally determined in order to obtain consistency similar to the reference series. It was 420 ± 30 mm in table flow test (near the limit between F2 and F3 class).

The aim of the conducted research was to examine the possibility of sealing concrete and assessing the effectiveness of this action based on the measurement of sorptivity, air permeability and depth of chlorides penetration.

2 Materials and methods

Portland cement CEM I 42.5R, Portland-composite cement CEM II/B-V 42.5N and Blast-furnace cement CEM III/A 42.5N as per PN-EN 197 were used. Basic physical and chemical properties presented by the cement manufacturer are shown in Table 1.

All concrete mixes contained 360 kg/m^3 of cement by 0.45 w/c ratio. Fractions of river sand 0–2 mm and granite of 2–8 mm and 8–16 mm were used. Aggregates were at laboratory air-dry condition. Copper slag waste from blast cleaning was used as a partial replacement of sand. The ratio of substitution was 66 % of sand amount by volume. This amount of waste allowed for the aggregate grading curves both in the reference concrete mixture and in the concrete mixture containing waste, fit between the boundary curves. Superplasticizer conforming to the requirements of the standard PN-EN 934-2 was used. Regular tap water was used as mixing water.

Table 1 Basic physical and chemical properties of used cements

Cement type	Setting time start [min]	Setting time end [min]	Compressive strength [MPa]	Specific surface area (Blaine) [cm^2/g]	Specific gravity [g/cm^3]	SO_3 [%]	Cl [%]	Na_2O_{eq} [%]
CEM I 42.5R	176	231	57.9	3538	3.10	2.52	0.063	0.60
CEM II/B-V 42.5N	203	294	50.6	4888	2.82	2.66	0.063	1.12
CEM III/A 42.5N - LH/HSR/NA	201	306	58.3	4165	2.91	2.30	0.055	0.70

Grading curves of the used aggregates and the waste is shown in Fig. 1. Boundary grading curves were adopted according to PN-B-06250:1988. Median diameter according to the concept presented in [40] was also calculated for both fine aggregate components. Copper slag is characterized by $d_m = 0.347$ and sand by $d_m = 0.536$. Grading of the mixes of the aggregates differed mainly in the amount of finest fractions 0–0.125 mm. If only sand and granite were used, the portion of this fraction was about 0.3 % while after replacing 66 % of the sand with CS it increased to about 3.9 %. Nine concrete mixtures were prepared. Mix IDs and proportions are presented in Table 2. The consistency of fresh concrete was measured by slump test, in accordance with PN-EN 12350-2.

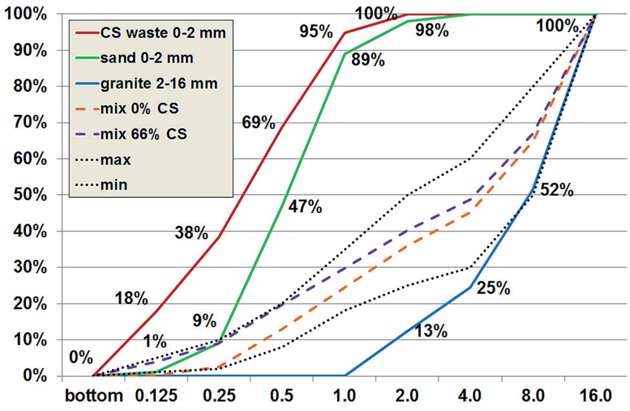

Fig. 1 Grading curves of aggregate fractions and their mixtures

Specimens were prepared and cured as per PN-EN 12390-2. They were cast in plastic moulds and compacted by double vibration (half and full) on a vibrating table. After 1 day they were demoulded and then water cured in the laboratory for 28 days.

2.1 Compressive and tensile strength test

The compressive strength test was conducted on 100 mm cube specimens on the 28 day of hardening. The test was carried out in accordance with PN-EN 12390-3. The splitting tensile strength test was conducted on the same type of specimens in accordance with PN-EN 12390-6. The strength tests were performed by using a press of 3000 kN compression force capacity. The rate of loading was maintained at 0.5 MPa/s for compressive strength test and 0.05 MPa/s for splitting tensile strength test.

2.2 Free water absorption and sorptivity test

The free water absorption test was conducted on the halves of cubic specimens of 100 mm edge by means of mass method. Specimens after splitting were stored 12 hours in water. Then the surface-dry mass of the specimens m_s were determined. Prior to the sorptivity test, the specimens had been oven-dried to the stable mass at a temperature of 105 °C. The measurements were conducted at the temperature of approximately 20 °C. The specimens were weighed (to determine mass m_d for calculation of

Table 2 Proportions of concrete mixtures [kg/m^3]

Material	Mixture ID CI0	CI66	CI66F	CII0	CII66	CII66F	CIII0	CIII66	CIII66F
CEM I 42.5R	360	360	360	0	0	0	0	0	0
CEM II/B-V 42.5N	0	0	0	360	360	360	0	0	0
CEM III/A 42.5N	0	0	0	0	0	0	360	360	360
natural sand (0–2 mm)	598	199	198	587	196	195	591	197	196
granite aggregate (2–8 mm)	621	621	618	610	610	608	614	614	612
granite aggregate (8–16 mm)	659	659	655	659	647	645	651	651	649
copper slag	0	449	447	0	441	440	0	444	443
water	162	162	162	162	162	162	162	162	162
Superplasticizer [% m.c.]	0.65	0.65	1.65	0.70	0.70	1.30	0.80	0.80	1.50
W / C	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
W + Sp/C	0.457	0.457	0.467	0.457	0.457	0.463	0.458	0.458	0.465

free water absorption) and then arranged in a water containing vessel. The specimens were immersed up to the height of 3 mm. In the specific time intervals from the beginning of the test the specimens were weighed again to define their weight gain resulting from water sorption. Subsequent weight measurements were conducted for 6 hours. Sorptivity S in g/(cm^2·h$^{0.5}$) was defined as a slope of the linear function expressing the dependence of the mass of the water absorbed Δm by the area F on the time root $t^{0.5}$ [32] as in Eq. (1):

$$\Delta m / F = S \cdot t^{0.5} \cdot \tag{1}$$

Free water absorption has been calculated using Eq. (2):

$$n = (m_s - m_d) / m_s , \tag{2}$$

where:

n - free water absorption [%],

m_s - mass of the fully soaked specimen [g],

m_d - mass of the specimen dried to stable mass [g].

Mass of a specimen dried to stable mass has been the same value as the starting mass in sorptivity test.

2.3 Torrent air permeability test

The air permeability test was carried out by the Torrent method. Test was conducted on two 150 mm cube specimens, which were water cured by 28 days and then stored in air-dry conditions (T = 20 ± 2 °C; RH = 55 ± 10 %) until the age of 90 days. Air permeability was tested on four sides of each specimen perpendicular to the direction of concreting. Before the test, the moisture content of the specimens was determined using a moisture meter determining the moisture content of concrete from 0 to 7 % on the basis of impedance measurement and recommended by the Swiss Standard SIA 262/1 Annex E and [21]. The moisture content after curing in air-dry conditions was in the range 4.2–4.5 %. Tested surfaces of the specimens were sufficiently smooth did not have any major damage or defects what enabled proper fixing of the equipment and conducting of the test. The interval between testing the same side of each specimen was at least 1 hour to allow the equalize the pressure in the pores of concrete with the atmospheric pressure. After conducting the air permeability test of air-dried concrete the specimens were oven dried in temperature 65 °C for 30 days. Then the test was performed again on dry specimens after cooling them to temperature 20 ± 2 °C. In the case of concrete series prepared with CEM III/A cement, the moisture content of specimens after 30 days of drying was significantly higher than in other concrete series. Therefore those specimens were dried for an additional three weeks in temperature 65 °C so that the moisture content measured by moisture meter was lower than 1.0 % at the time of air permeability test.

2.4 Depth of chloride penetration

The chloride penetration depth test was performed in a dedicated chamber. Before placing the specimens in the chamber, they were sealed on four sides with the agent creating an impermeable layer. The penetration of chlorides followed the two opposite surfaces of the specimen, vertical at the time of concreting. The chamber test included 60 cycles, which consisted of exposing specimens for two hours to a 10 % NaCl solution - a salt spray at 30 °C, and then, for four hours drying the specimens at 35 °C. After removing the specimens from the chamber they have been cut in half and depth of penetration of chlorides was determined on the cut surface. The surfaces of the specimens were sprayed with silver nitrate which reacts with chlorides to form a white coating on the surface. This allows for a proximal measurement of the depth at which chlorides penetrated into the concrete. The depth of penetration was determined in three places at the top and in three places at the bottom of the cut specimen. For each specimen, the measurement was made on two halves, which gave a total of 12 individual depth penetration values. The depth of chloride penetration was determined as the average of twelve measurements of chloride penetration depth for one specimen.

2.5 Frost resistance test

The PN-EN 206 standard does not define the methodology of frost resistance tests and criteria for its evaluation. In order to determine the resistance of concrete to cyclic freezing/thawing, it is necessary to use the provisions of national standards and technical specifications such as PN-B-06265 [41], which is the national supplement to the PN-EN-206 standard. It is given there, among others frost resistance testing methodology and assessment criteria on the basis of which it defines classes and categories of frost resistance.

The freezing resistance test of concrete was carried out on cubic specimens with an edge of 100 mm after 28 days of curing in water. The test named "The ordinary method" from PN-B-06265 was used. It consists in the verification of the assumed degree of frost resistance F of the concrete corresponding to the index N, which is equal to the number of predicted years of use of the structure. The method used allows taking into account both the degree of internal destruction of concrete, characterized by the decrease of the compressive strength of the concrete, as well as external damage, determined visually and by the loss of mass of the specimen. The degree of frost resistance of concrete is achieved if the following conditions are met after the required number of freezing/thawing cycles specified in its symbol:

- the specimens do not show any cracking,
- the total weight of concrete loss in the form of, damaged corners and edges, spatter, etc. does not exceed 5 % by weight of specimens before the start of freezing/thawing cycles,
- reduction of compressive strength in comparison to reference specimens is not higher than 20 %.

According to the adopted procedure, the test consists in subjecting concrete specimens to freezing/thawing cycles, and the duration of the full cycle is at least 6 hours. The procedure involves testing at least 12 specimens from one batch of concrete, with at least half of this number being reference specimens. These specimens shall not undergo freezing/thawing cycles and shall be stored in water at 18 ± 2 °C throughout the test. Specimens subjected to freezing/thawing cycles should be weighed with accuracy to 0.2 % after being removed from water before the test. Freezing takes place in air at –18 ± 2 °C and lasts at least 4 hours. Thawing of specimens in water at +18 ± 2 °C takes from 2 to 4 hours. After the last freezing/thawing cycle, specimens are weighed and subjected to compressive strength test. The average weight loss of specimens after the test ΔG is calculated according to the Eq. (3).

$$\Delta G = (G_1 - G_2) / G_1 \cdot \Delta 100\% , \tag{3}$$

where:

G_1 – average mass of the fully saturated specimens before the first freezing/thawing cycle [kg],

G_2 – average mass of the fully saturated specimens after the last freezing/thawing cycle [kg].

And the average drop in compressive strength of specimens ΔR after the test is given by Eq. (4).

$$\Delta R = (R_1 - R_2) / R_1 \Delta 100\% , \tag{4}$$

where:

R_1 – average compressive strength of fully saturated reference specimens [MPa],

R_2 – average compressive strength of fully saturated tested specimens after the last cycle of freezing/thawing [MPa].

3 Research results

Research results are presented in the Table 3. Each value in the table is an average of six measurements expect abrasion test result which is an average of four measurements and fresh concrete slump which is an average of three measurements. Due to paper content limitations we can only represent some of the obtained data in figures.

3.1 Consistency of concrete

Particle size, finer than in the copper slag which is not used for sandblasting, and high dust content results in increased water demand of aggregate and lowers the consistency of the mixture. There was a change in the consistency class from F2/F3 to F1 for all cements used when replacing 66 % of sand with the waste. There were no problems with compaction and specimen preparation, but there were significant differences in the workability. The mixture with CEM II cement and waste of consistency F3, CII66F had a significantly worse workability compared to the reference mix CII0. In the case of other cements, no such difference was observed. Obtaining the same consistency like of reference concrete, the ones mixed with

Table 3 Test results

Parameter	ID of mixture								
	CI0	CI66	CI66F	CII0	CII66	CII66F	CIII0	CIII66	CIII66F
Flow [mm]	395	315/C	410	410	310/C	415	410	330/C	440
Compressive strength 28d [MPa]	55.0	53.3	60.2	54.6	57.4	60.4	66.4	61.3	62.5
Compressive strength 90d [MPa]	60.8	62.0	68.2	63.0	67.3	70.5	73.7	68.6	72.0
Tensile strength 28d [MPa]	3.20	3.79	3.20	3.27	2.98	3.52	3.79	3.85	4.12
Water absorption [%]	4.79	4.51	4.58	5.25	5.00	4.96	5.26	5.08	4.86
Sorptivity [$cm^3/(cm^2*h^{0.5})$]	0.091	0.076	0.067	0.088	0.085	0.089	0.061	0.063	0.047
F-T ΔG [%]	-0.08	0.06	0.13	-0.12	0.05	0.03	-0.04	0.00	-0.01
F-T ΔR [%]	6.26	2.01	3.37	9.21	5.77	4.17	4.09	7.89	4.05
Cl- ingress - 60 cycles [mm]	6.69	8.83	5.64	8.69	7.69	7.28	6.97	6.33	5.92

Flow: C - collapse of the concrete sample after lifting the cone the waste required the usage about two times the dose of superplasticizer. At different cements, the amount of additional superplasticizer was different. For concrete with CEM I cement it was necessary to add up to 1.65 % of superplasticizer on cement base to achieve a consistency such as of the reference concrete with 0.65 % of superplasticizer. In the case of CEM II cement, the difference was the smallest, and the amount of superplasticizer was 1.3 % and 0.7 % respectively in the mixture with waste and reference. A significant amount of the superplasticizer in the CI66F and CIII66F series caused a hardening slowdown and the specimens could not be demoulded after 24 hours. In the remaining series, the concrete after 24 hours was completely hardened.

3.2 Compressive and tensile strength

Results of compressive strength test performed after 28 days are presented in Fig. 2.

In the case of reference series the lowest compressive strength after 28 days was achieved in the case of CII0 concrete. CI0 concrete had compressive strength, higher by 0.9 % and CIII0 concrete with blast furnace cement had a strength of 21.8 % higher than CI0 concrete. After adding copper slag waste to the mixtures but without using the superplasticizer the values of compressive strength form a different pattern. This time the CI66 concrete achieved the lowest strength, the CII66 concrete strength was 6.1 % higher and the highest was the strength of the CIII66 concrete which was 15.1 % higher than the strength of CI66 concrete. After addition of superplasticizer the compressing strength values had even out. The difference between the highest CIII66F, and the lowest CI66F compressive strength value was only 3.8 %, and the compressive strength of CII66F concrete was only 0.4 % higher than lowest value.

If the concrete series made with the same type of cement are compared, three different trends can be seen, although partially similar. For concrete with CEM I and CEM III/A cement replacing most of the sand with copper slag waste had caused the reduction in compressive strength of 3.2 % and 7.7 % respectively. Adding superplasticizer caused the increase in compressive strength value, but only in case of CI66F concrete the achieved value was higher than the reference one (of 9.3 %). CIII66F concrete achieved the compressive strength value lower of 6.0 % than the concrete with the same cement but without the copper slag waste and superplasticizer. Compressive strength values of concrete with CEM II/B-V cement increased after both replacing the sand with copper slag waste (increase of 3.6 %) and addition of superplasticizer (total increase of 10.7 %)

The increase in compressive strength between 28th and 90th day is illustrated in Fig. 3. It was in the reference series from 10.4 % for the series with CEM I to 15.5 % for the series with CEM II/B-V. In almost all cases, the greatest increase in strength occurred when CEM II/B-V cement was used, and the smallest in series with CEM I cement. The exception is the CIII66 series, which showed a lower strength increase than series CI66 and CII66. In the case of concrete with blast-furnace cement, the increase in strength after 90 days in relation to the 28-day strength is lower than usually shown in the literature [42], but this is a specific feature of strength class 42.5 blast-furnace cement [42]. This is probably due to the larger s Blaine specific surface area equal 4165 cm^2/g and thus increased reactivity of the cement. The addition of copper slag waste, regardless of the type of cement and the consistency of the concrete mix, caused higher compression strength increase between 28 and 90 days. This indicates that copper slag waste is an additive with some pozzolanic activity, which in the long run increases the strength

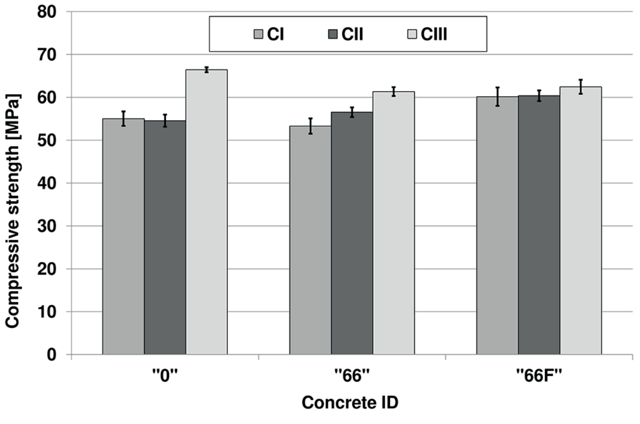

Fig. 2 Compressive strength of tested series after 28 days

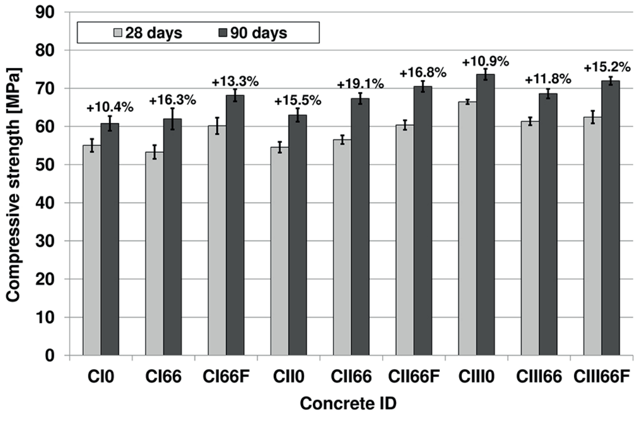

Fig. 3 Comparison of compressive strength after 28 and 90 days

and sealing of the concrete structure. A similar effect of sand exchange with copper slag waste was observed by Jaskulski in the case of CLSM blends [43].

The effect of decreasing the strength of concrete with blast-furnace cement after the addition of copper slag waste may be a surprise. This effect is visible both in the compressive strength test results after 28 days and after 90 days. Perhaps it is the result of a kind of competition between two materials undergoing pozzolanic reaction (blast furnace slag and copper slag waste) with the free lime necessary for this reaction to occur. This effect requires further research including confirmation in more extensive research.

The ratio of tensile strength to compressive strength was from 5.27 % for the CII66 series to 7.10 % for the CI66 series. These are typical values for the concrete strength achieved. There was no dependence of this ratio on the addition of copper slag waste and the type of cement.

Similar values of compressive strength increments and tensile strength/compressive strength ratio were found in [44], which describes the tests of concrete with 53 grade ordinary Portland cement conforming to IS 12269:2013 [45] in which part of sand was replaced with a copper slag with a coarser grain size.

3.3 Free water absorption and sorptivity

The addition of copper slag waste reduced the sorptivity of concrete. In concrete with CEM I cement, the sorptivity was reduced after the exchange of sand with CS waste. The decrease in sorptivity was 16.6 % and 26.3 % for CI66 and CI66F series, respectively, compared to CI0 series. In the case of concrete with CEM II B-V cement, the sorptivity of all series was very similar and the differences reached maximally 3.2 %. In CEM III/A concrete, the sorptivity of CIII66 series increased slightly (3.2 %) compared to the result of the reference series, while in the case of CIII66F series, the sorptivity decreased by 23.1 %. The obtained results are consistent with the observations presented in paper [5].

The water absorption of concrete with a given type of cement was about 5 % lower after substitution of sand with the waste. The average water absorption of reference concrete with cement CEM II/B-V and CEM III/A was about 10 % higher than that of CEM I series. Concrete with CEM I cement and CII66F and CIII66F series fulfilled the water absorption requirements of technical specifications relating to concrete for bridge structures, whereas CII0, CIII0, CII66 and CIII66 concrete series had water absorption > 5 % and slightly exceeded these requirements.

3.4 Torrent air permeability and RH changes in time

The results of RH measurements after 56 and 90 days and drying of the specimens are shown in Fig. 4. The measurements were made with moisture meter. Each of the results is an average of 4 measurements on 4 walls of two cubic specimens (total average is calculated from 32 measurements).

The RH values measured after 56 days were similar. They ranged from 4.21 in the series CIII66 to 4.53 in the series CIII0. Between the 56th and 90th day a decrease in RH ranging from 5.27 % in the CI66 series to 12.0 % in the CIII66F series was observed. The lowest decrease in RH was observed for the CEM I series (from 5.27 % to 6.47 %). In the case of concrete with CEM II B-V and CEM III/A the decrease in RH was from 7.80 % to 9.80 % with the use of less superplasticizer and about 12 % in the case of other series. After 30 days of drying in oven at 65 °C, the series with CEM I and CEM II/B-V, regardless of CS waste addition, reached RH < 1, which indicates almost complete drying of the specimens. Concrete with CEM III/A dried slower and RH after 30 days ranged from 1.33 for CIII66F to 1.42 for CIII0. In order to allow direct comparison of kT results in dry samples, it was decided to continue drying the CEM III/A series until RH < 1 was reached.

Fig. 5 shows the results of air permeability measurements carried out by Torrent apparatus. Due to large differences between the obtained values, a logarithmic scale was used on the vertical axis of the graph.

In the case of all series with CS waste, the differences between the k_T values between 56 and 90 days were small. It can be a result of compensation of the effects of humidity drop inside the specimens by changes in the pore system and the resulting sealing of the material. The change in the case of series with sole sand regardless of the type of cement was greater and ranged from 128.2 % to 69.4 % in the case of series CII0 and CI0, respectively. The values of

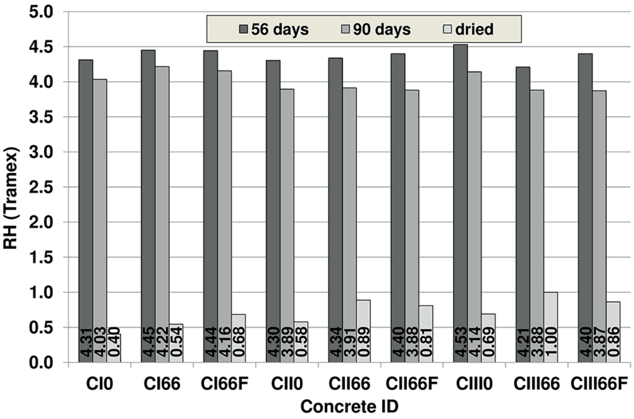

Fig. 4 Values of RH test results

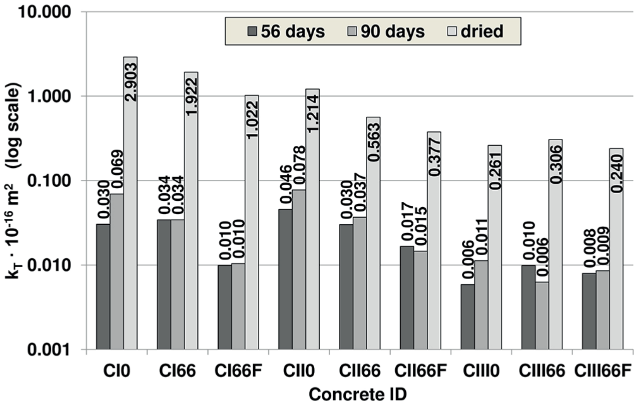

Fig. 5 Torrent k_T air permeability test results

the k_T coefficient of concrete after 56 and 90 days, whose moisture content ranged from 3.87 to 4.53 (according to the used instrument indications) were small and allowed to qualify it in terms of quality as "good" on the basis of the criteria presented in [46]. The CEM III cement series even reached (or slightly exceeded, as in the case of the CIII0 series after 90 days and the CIII66 series after 56 days) the value of the permeability coefficient allowing to qualify these series as "very good".

The results obtained after drying the specimens in the case of reference series confirm partially (within the range of the difference between CEM I and CEM III cements) the dependence of the k_T coefficient value on the cement type described by Tracz [47, 48]. However, the permeability of concrete with Portland-composite cement with fly ash (CEM II/A-V in Tracz and CEM II/B-V in this paper), much higher than in the case of other cements, was not confirmed.

It is worth mentioning that in the studies conducted by Tracz no covercrete moisture was measured. It was assumed, however, that the specimens are in a conventional air-dry state. Reference was made to Torrent's instruction manual, according to which such a state reaches covercrete after two weeks of no contact with water. This approach does not take into account the fact that covercrete moisture may vary from series to series due to different drying rates of the specimens.

For the dried specimens the highest k_T air permeability value of $2.903 \cdot 10^{-16}$ m² was obtained in the test of reference concrete with CEM I. The permeability of CII0 concrete with CEM II/B-V cement was 58.2 % lower, and the permeability of CIII0 concrete with CEM III/A cement was 91.0 % lower than the permeability of CEM I reference concrete. The influence of CS waste addition in concrete with CEM I and CEM II/B-V on the obtained k_T values is similar. CS waste addition with the same amount of superplasticizer reduced k_T by 33.8 % and 53.7 % in CI66 and CII66 series respectively. While maintaining the same consistency of the mixture, the effect of CS waste addition on the reduction of k_T was greater and the differences amounted to 64.8 % and 69.0 %, respectively, in the case of CI66F and CII66F series (in comparison with CI0 and CII0).

In concrete with CEM III/A cement the air permeability in all series was similar and much lower than in concrete with other types of cement. In comparison to the CIII0 series, the CIII66 series had a higher permeability by 17.4 %, while the CIII66F series had a lower permeability by 8.3 %. The influence of CS waste on the sealing of the concrete structure is clear. In the "F" series, the influence of a larger amount of superplasticizer can be seen, which by modifying the consistency of the concrete mixture enabled better packing of its constituents, which could be reflected in a higher tightness of the concrete. By classifying the concrete on the basis of the results obtained after drying the specimens, the series with CEM I cement and the reference series with CEM II/B-V cement were rated as "poor" while the remaining series as "moderate". The CI66F series was close to meeting the requirements for "moderate" concrete quality. The CEM III series met the requirements to be classified as "moderate".

3.5 Depth of chloride penetration

The concrete series with CS waste prepared with more superplasticizer were more resistant to chloride penetration than the reference series. The difference was similar for all cement types and ranged from 15.1 % for CIII66F series to 16.3 % for CII66F series. Concrete with CS waste and the same amount of superplasticizer as in the reference series for CEM I cement proved to be less resistant to chloride ingress than concrete with sand only. The difference in penetration depth of chlorides was 32.0 %. In the case of other types of cement, the concrete with CS waste with a denser consistency was characterized by a lower penetration depth of chlorides compared to the series with only sand. The difference was 11.5 % and 9.2 % for CII66 and CIII66 series respectively. Comparing the results of the reference series with different types of cement, the lowest penetration depth of chlorides of 6.69 mm was observed for the CI0 series. CII0 and CIII0 series had chloride penetration depth higher by 29.9 % and 4.1 %, respectively. Lower penetration of chloride ions in the series where copper slag is used may result from finer grain size of this material in relation to sand. As it was stated earlier, the value of median diameter in the case of copper slag was $d_m = 0.347$, and in the case of sand d_m = 0.536 The correlation of this parameter with the susceptibility of concrete to penetration of chloride ions was described in the paper [49], where the gradual conversion of sand into imperial smelting process (IPS) slag caused an increase in chloride ions diffusion coefficient in stationary conditions. In this case, the median diameter of ISP slag was almost 50 % higher than the same parameter in the case of sand.

3.6 Frost resistance

The weight loss of specimens of all series was minimal and reached maximum 0.13 % in case of CI66F series. In the case of a part of the series, there was a slight increase in the mass of specimens up to 0.12 % in the case of the CII0 series. No failure of the samples was found after 150 freeze-thaw cycles. All series met the requirements of frost resistance class F150. The strength decrease in the reference series CI0 and CII0 was 6.26 % and 9.21 %, respectively. In the case of series with added CS waste, the decrease in strength was lower than in the reference series. The difference was from 37.3 % to 67.9 % for CII66 and CI66 series respectively. In the series with CEM III/A cement the reduction of strength was about 4.0 % in the case of series CIII0 and CIII66F. The decrease of strength in the case of CIII66 series was about twice as big.

4 Conclusions

Replacing a part of the sand with blast-cleaning waste does not aggravate any of the tested properties of concrete.

Greater content of fine particles in the CS waste compared to sand affected the consistency of concrete mixtures. In the case of 66 % sand replacement it changed from 420 ± 20 mm to 320 ± 10 mm in table flow test.

To obtain the same consistency of CS waste mixes (the F series) as for mixes with sand only, a superplasticizer in the amount of 1.3 to 1.65 % of cement weight was added. High content of superplasticizer delays hardening, however, does not have a negative effect on the strength of concrete in the longer term.

The decrease of concrete sorptivity by 26.3 % and 23.1 % was recorded in the case of CI66F and CIII66F series, respectively, in comparison to the corresponding reference series.

In all series containing CS waste, a slight decrease in water absorption was noted.

All series met the requirements of the degree of frost resistance F150.

The concrete series with CS waste, especially those prepared with more superplasticizer, were more resistant to chloride penetration than the reference series. The difference was similar for all cement types and was most likely a result of finer gradation of the waste material. It is confirmed by the median diameter d_m calculations.

The influence of CS waste on the sealing of the concrete structure, resulting in lower air permeability, is clear. In the "F" series, the influence of a larger amount of superplasticizer can be seen, which by modifying the consistency of the concrete mixture enabled better packing of its constituents, which could be reflected in a higher tightness of the concrete.

Acknowledgements

The work has been supported by the Town of Płock through the Mayor's Research Grants Programme "Collaboration with Universities".

References

[1] Holden, E., Linnerud, K., Banister, D. "The Imperatives of Sustainable Development", Sustainable Development, 25(3), pp. 213–226, 2017. https://doi.org/10.1002/sd.1647

[2] Broman, G. I., Robert, K.-H. "A framework for strategic sustainable development", Journal of Cleaner Production, 140(1), pp. 17–31, 2017. https://doi.org/10.1016/j.jclepro.2015.10.121

[3] Gorai, B., Jana, R. K., Premchand "Characteristics and utilisation of copper slag - a review", Resources, Conservation and Recycling, 39(4), pp. 299–313, 2003. https://doi.org/10.1016/S0921-3449(02)00171-4

[4] Shi, C., Meyer, C., Behnood, A. "Utilization of copper slag in cement and concrete", Resources, Conservation and Recycling, 52(10), pp. 1115–1120, 2008. https://doi.org/10.1016/j.resconrec.2008.06.008

[5] Kubissa, W., Jaskulski, R., Simon, T. "Surface blast-cleaning waste as a replacement of fine aggregate in concrete", Architecture, Civil Engineering, Environment, 10(3), pp. 89–94. 2017. https://doi.org/10.21307/acee-2017-038

[6] Kočí, V., Maděra, J., Jerman, M., Žumár, J., Koňáková, D., Čáchová, M., Vejmelková, E., Reiterman, P., Černý, R. "Application of waste ceramic dust as a ready-to-use replacement of cement in lime-cement plasters: an environmental-friendly and energy-efficient solution", Clean Technologies and Environmental Policy, 18(6), pp. 1725–1733, 2016. https://doi.org/10.1007/s10098-016-1183-2

[7] Meenakshi Sudarvizhi, S., Ilangovan, R. "Performance of Copper slag and ferrous slag as partial replacement of sand in Concrete", International Journal for Computational Civil and Structural Engineering, 1(4), pp. 918–927, 2011.

[8] Gursel, A. P., Ostertag, C. "Life-Cycle Assessment of High-Strength Concrete Mixtures with Copper Slag as Sand Replacement", Advances in Civil Engineering, 2019, Article ID 6815348 2019. https://doi.org/10.1155/2019/6815348

[9] Dhir, R. K., de Brito, J., Mangabhai, R., Lye, C. Q. "Sustainable Construction Materials-Copper Slag", Woodhead Publishing, Cambridge, UK, 2017. https://doi.org/10.1016/C2015-0-00465-8

[10] Ayano, T., Sakata, K. "Durability of Concrete with Copper Slag Fine Aggregate", International Concrete Abstracts Portal, 192, pp. 141–158, 2000.

[11] Al-Jabri, K. S., Al-Saidy, A. H., Taha, R. "Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete", Construction and Building Materials, 25(2), pp. 933–938, 2011. https://doi.org/10.1016/j.conbuildmat.2010.06.090

[12] Alp, I., Deveci, H., Süngün, H. "Utilization of flotation wastes of copper slag as raw material in cement production", Journal of Hazardous Materials, 159(2–3), pp. 390–395, 2008. https://doi.org/10.1016/j.jhazmat.2008.02.056

[13] Al-Jabri, K. S., Hisada, M., Al-Saidy, A. H., Al-Oraimi, S. K. "Performance of high strength concrete made with copper slag as a fine aggregate", Construction and Building Materials, 23(6), pp. 2132–2140, 2009. https://doi.org/10.1016/j.conbuildmat.2008.12.013

[14] Ambily, P. S., Umarani, C., Ravisankar, K.,Prem, P. R., Bharatkumar, B. H., Iyer, N. R. "Studies on ultra high performance concrete incorporating copper slag as fine aggregate", Construction and Building Materials, 77, pp. 233–240, 2015. https://doi.org/10.1016/j.conbuildmat.2014.12.092

[15] Wu, W., Zhang, W., Ma, G. "Optimum content of copper slag as a fine aggregate in high strength concrete", Materials & Design, 31(6), pp. 2878–2883, 2010. https://doi.org/10.1016/j.matdes.2009.12.037

[16] Lim, T.-T., Chu, J. "Assessment of the use of spent copper slag for land reclamation", Waste Management & Research, 24(1), pp. 67–73. 2006. https://doi.org/10.1177/0734242X06061769

[17] dos Anjos, M. A. G., Sales, A. T. C., Andrade, N. "Blasted copper slag as fine aggregate in Portland cement concrete", Journal of Environmental Management, 196, pp. 607–613, 2017. https://doi.org/10.1016/j.jenvman.2017.03.032

[18] Yang, K., Nanukuttan, S., McCarter, W. J., Long, A., Basheer, M. "Challenges and opportunities for assessing transport properties of high-performance concrete", Revista ALCONPAT, 8(3), pp. 246–263, 2018. https://doi.org/10.21041/ra.v8i3.301

[19] Kubissa, W., Glinicki, M. A. "Influence of internal relative humidity and mix design of radiation shielding concrete on air permeability index", Construction and Building Materials, 147, pp. 352–361, 2017. https://doi.org/10.1016/j.conbuildmat.2017.04.177

[20] IAEA "Ageing Management of Concrete Structures in Nuclear Power Plants", Vienna, Austria, Rep. NP-T-3.5, 2016.

[21] Torrent, R., Denarie, E., Jacobs, F., Leemann, A., Teruzzi, T. "Specification and site control of the permeability of the cover concrete: The Swiss approach", Materials and Corrosion, 63(12), pp. 1127–1133, 2012. https://doi.org/10.1002/maco.201206710

[22] Parrott, L. J. "Moisture conditioning and transport properties of concrete test specimens", Materials and Structures, 27(8), pp. 460–468, 1994. https://doi.org/10.1007/BF02473450

[23] Abbas, A., Carcasses, M., Ollivier, J.-P. "Gas permeability of concrete in relation to its degree of saturation", Materials and Structures, 32(1), pp. 3–8, 1999. https://doi.org/10.1007/BF02480405

[24] Romer, M. "Effect of moisture and concrete composition on the Torrent permeability measurement", Materials and Structures, 38(279), pp. 541–547, 2005. [online] Available at: https://www.rilem.net/publication/publication/385?id_papier=7230 [Accessed: 20 May 2019]

[25] Liu, J., Agostini, F., Skoczylas, F. "From relative gas permeability to in situ saturation measurements", Construction and Building Materials, (40), pp. 882–890, 2013. https://doi.org/10.1016/j.conbuildmat.2012.11.092

[26] Nakarai, K., Shitama, K., Nishio, S., Sakai, Y., Ueda, H., Kishi, T. "Long-term permeability measurements on site-cast concrete box culverts", Construction and Building Materials, 198, pp. 777–785, 2019. https://doi.org/10.1016/j.conbuildmat.2018.11.263

[27] Basheer, L., Kropp, J., Cleland, D. J. "Assessment of the durability of concrete from its permeation properties: a review", Construction and Building Materials, 15(2–3), pp. 93–103, 2001. https://doi.org/10.1016/S0950-0618(00)00058-1

[28] Basheer, P. A. M., Nolan, É. "Near-surface moisture gradients and in situ permeation tests", Construction and Building Materials, 15(2–3), pp. 105–114, 2001. https://doi.org/10.1016/S0950-0618(00)00059-3

[29] Basheer, P. A. M., Nolan, É. A., McCarter, W. J., Long, A. E. "Effectiveness of In Situ Moisture Preconditioning Methods for Concrete", Journal of Materials in Civil Engineering, 12(2), pp. 131–138, 2000. https://doi.org/10.1061/(ASCE)0899-1561(2000)12:2(131)

[30] Yang, K., Basheer, P. A. M., Magee, B., Bai, Y. "Investigation of moisture condition and Autoclam sensitivity on air permeability measurements for both normal concrete and high performance concrete", Construction and Building Materials, 48, pp. 306–314, 2013. https://doi.org/10.1016/j.conbuildmat.2013.06.087

[31] Nokken, M., Hooton, R. "Dependence of Rate of Absorption on Degree of Saturation of Concrete", Cement, Concrete and Aggregates, 24(1), pp. 20–24, 2002. https://doi.org/10.1520/CCA10487J

[32] Kubissa, W., Jaskulski, R. "Measuring and Time Variability of The Sorptivity of Concrete", Procedia Engineering, 57, pp. 634–641, 2013. https://doi.org/10.1016/j.proeng.2013.04.080

[33] Vázquez, E., Barra, M., Aponte, D., Jiménez, C., Valls, S. "Improvement of the durability of concrete with recycled aggregates in chloride exposed environment", Construction and Building Materials, 67(A), pp. 61–67, 2014. https://doi.org/10.1016/j.conbuildmat.2013.11.028

[34] Wang, L., Ueda, T. "Mesoscale Modeling of Chloride Penetration in Unsaturated Concrete Damaged by Freeze-Thaw Cycling", Journal of Materials in Civil Engineering, 26(5), pp. 955–965, 2014. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000901

[35] Glinicki, M. A., Jóźwiak-Niedźwiedzka, D., Gibas, K., Dabrowski, M. "Influence of Blended Cements with Calcareous Fly Ash on Chloride Ion Migration and Carbonation Resistance of Concrete for Durable Structures", Materials, 9(1), pp. 1–15, 2016. https://doi.org/10.3390/ma9010018

[36] Wong, H. H. C., Kwan, A. K. H. "Packing density of cementitious materials: part 1 - measurement using a wet packing method", Materials and Structures, 41(4), pp. 689–701, 2008. https://doi.org/10.1617/s11527-007-9274-5

[37] Kwan, A. K. H., Wong, H. H. C. "Packing density of cementitious materials: part 2 - packing and flow of OPC + PFA + CSF", Materials and Structures, 41(4), pp. 773–784, 2008. https://doi.org/10.1617/s11527-007-9281-6

[38] Li, L. G., Kwan, A. K. H. "Packing density of concrete mix under dry and wet conditions", Powder Technology, 253, pp. 514–521, 2014. https://doi.org/10.1016/j.powtec.2013.12.020

[39] Li, L. G., Lin, C. J., Chen, G. M., Kwan, A. K. H., Jiang, T. "Effects of packing on compressive behaviour of recycled aggregate concrete", Construction and Building Materials, 157, pp. 757–777, 2017. https://doi.org/10.1016/j.conbuildmat.2017.09.097

[40] Katzer, J. "Median diameter as a grading characteristic for fine aggregate cement composite designing", Construction and Building Materials, 35, pp. 884–887, 2012. https://doi.org/10.1016/j.conbuildmat.2012.04.050

[41] PKN "PN-B-06265:2018-10 Concrete - Specification, performance, production and conformity - National supplement of PN-EN 206+A1:2016-12", Polish Committee for Standardization, Warsaw, Poland, 2018.

[42] Dziuk, D., Giergiczny, Z., Garbacik, A. "Calcareous fly ash as a main constituent of common cements", Roads and Bridges – Drogi i Mosty, 12(1), pp. 57–69, 2013. https://doi.org/10.7409/rabdim.013.005

[43] Jaskulski, R., Kubissa, W. "Mechanical properties of copper slag waste based CLSM mixtures", In: 13th International Conference "Modern Building Materials, Structures and Techniques", Vilnius, Lithuania, 2019, pp. 16–17.

[44] Farooq, M. U., Kumar, P. N. "Estimating the Strength of Concrete Cube using Copper Slag in the Replacement of Fine Aggregate", International Journal of Research in Engineering, Science and Management, 1(12), pp. 292–296, 2018. [online] https://www.ijresm.com/Vol_1_2018/Vol1_Iss12_December18/IJRESM_V1_I12_66.pdf [Available: 15 May 2019]

[45] Bureau of Indian Standards "Ordinary Portland Cement, 53 Grade - Specification (First Revison)", Bureau of Indian Standards, New Delhi, India, 2013.

[46] Torrent, R., Frenzer, G. "A method for rapid determination of the coefficient of permeability of the "covercrete"", In: Proceeding of International Symposium Non-Destructive Testing in Civil Engineering, Berlin, Germany, 1995, pp. 985–992.

[47] Tracz, T., Śliwiński, J. "The effect of concrete surface polishing on permeability evaluated with Torrent's method", In: Awarie Budowlane 2013, Szczecin, Poland, 2013, pp. 873–880. (in Polish)

[48] Tracz, T., Śliwiński, J. "Przepuszczalność betonu określana przy przepływie gazu metodą laboratoryjną i polową - porównanie wyników i ich korelacja (Concrete permeability determined at gas flow using laboratory and field methods - comparison of results and their correlation)", In: Proceedings of Concrete Days 2012, Wisła, Poland, 2012, pp. 949–958. (in Polish)

[49] Szweda, Z., Ponikiewski, T., Katzer, J. "A study on replacement of sand by granulated ISP slag in SCC as a factor formatting its durability against chloride ions", Journal of Cleaner Production, 156, pp. 569–576, 2017. https://doi.org/10.1016/j.jclepro.2017.04.072