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Research paper

Strength and durability characteristics of concretes with crushed side window glass as partial aggregate substitution

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Abstract: Taking into account the numerous previous attempts to use waste glass for concrete production, an approach was proposed based solely on car side window glass waste. Only side window waste emerging during the production of car side windows was used during the research program. In this way, all key properties of the waste glass were under control (purity, granulometric properties, etc.). Two types of concretes with crushed side window glass, playing the role of coarse aggregate, were created. Concretes were differentiated by the amount of added crushed side window glass, which replaced 10–50% of the natural aggregate. Created concretes were thoroughly tested in the state of both a fresh mix and hardened composite. Consistency and air content of fresh mixes were tested. Slump was ranging from 15 mm to 20 mm and air content was ranging from 2.5% to 3.1%. Hardened composites were used to test apparent density, compressive strength, water absorption, water-tightness and resistance to freeze–thaw cycles. It was proven that concrete with side window glass as partial aggregate substitution is characterized by satisfactory mechanical properties (compressive strength after 28 days of curing was ranging from 51.9 MPa to 54.7 MPa), enabling its application as ordinary structural concrete. Properties of both fresh concrete mixes and hardened concretes based on crushed side window glass are similar to a reference concrete. It was proved that it is possible to replace up to 50% of natural coarse aggregate by crushed side window glass. Possible applications of the concretes in question were proposed. Experience gained during the research program is likely to be useful for tests of using crushed side window glass sourced from decommissioned cars and trucks. Areas where future research is needed are indicated.

Keywords: glass, recycling, substitution, waste aggregate

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1. Introduction

Modern concrete was born in 1820s when industrial scale production of Portland cement was started. Over last 200 years, the production of both cement and concrete was growing steadily imposing larger and larger pressure on natural environment. Currently, global production of concrete surpassed one cubic meter per person per year [1, 2]. This situation causes numerous environmental problems associated both with cement production and aggregate acquisition. Deposits of natural aggregates shrink and at the same time increasing amounts of industrial waste are being stored in landfills. Over last 40 years, vast number of research programs was conducted aiming to utilize numerous waste materials for concrete production. Traditional, three ingredients (natural aggregate, cement, water) ordinary concrete, gradually become a multi-material composite. Such waste materials as fly ash [3], post metallurgical slag and sludge [4], silica fume [5], waste sand of different origin [6], crushed red and white ceramics [7], recycled old concrete [8], waste steel fiber [9] and pet flakes [10] were used to modify concrete mixes. Different researchers have also successfully experimented with using locally available waste materials, such as marble sludge [11], marble dust [12], ceramic [13], rice husk [14], volcanic ash [15], waste glass powder [16], pumice powder [15], wastes from the production of mineral wool [17] and sea shells from mussels [18] for cement production. One of such locally available waste material which could be utilized as an aggregate for concrete is glass of different types and origins. In the USA alone, over 9.2 million tonnes of different types of glass is being discharged as municipal waste every year [19]. On the other hand, glass production uses significant volumes of natural resources. Around 1.73 kg of raw material and 0.15 m^3 of water is needed for the production of 1 kg of sheet glass. The majority of the waste glass is mixed and contains impurities. Therefore, its efficient recycling is disabled. One should also remember that based on composition, waste glass can be classified as: vitreous silica, alkali silicates, soda-lime glass, borosilicate glass, lead glass, barium glass, aluminosilicate glass, etc., which additionally complicates the possible process of recycling. Since the 1960s [19], many research programs were focused on using crushed glass as aggregate for concrete production. The outcomes of these research programs were unsatisfactory. The influence of quality of used waste glass on properties of cast concretes proved to be high. Moreover, the achieved concretes were characterized by high brittleness and they were prone to cracking. These obstacles prevented the introduction of such concretes to the construction industry. Many research teams directed their efforts to modify cement by glass powder [20, 21]. Using waste glass powder, instead of crushed glass, enables much higher homogeneity of utilized waste material [22, 23]. However, extra energy is needed to make powder from crushed glass. In the authors' opinion, many technological problems associated with using crushed glass as aggregate are caused by the quality of waste material. Using only one type of locally available glass would enable production of concretes with predictable and uniform mechanical characteristics. In Authors' opinion car side window glass represents such opportunity. Windscreen glass as internally glued adheres together after breaking and was rejected from the research program.

Old decommissioned cars are transported to local disassembly stations. Significant part of demounted parts is being sold. Car bodies go to ironworks. Old tires are transported to recycling centers where they are transformed into rubber granulate and steel fiber. Side window glass is usually crushed during the demounting process and litters the grounds of a disassembly station. Moreover, there are no collection points for such type of glass. In authors' opinion side window glass should be demounted in a more controlled way and used for production of an aggregate. Car disassembly stations are scattered all over the world and can serve as a source of a locally available waste aggregate. Side window removed from an old car is easily transformed into waste aggregate using basic ball mill. By changing the length of grinding coarse or fine aggregate is achieved. Keeping above facts in mind the authors decided to focus their research effort on using waste glass created during the production of side windows. Such waste is inevitable but creates very interesting opportunities. The waste is pure, of the same chemical characteristics, and one have full control of its granulometric properties. The research program presented in this paper focused on using large volumes of such waste glass to replace natural aggregate. The novelty of the proposed approach is based on using locally available crushed side window glass. In the authors' opinion, the concrete industry should be decentralized to achieve full sustainability. During the current research program the idea of waste aggregate sourced from crushed side window glass was developed. The properties of hardened concretes were thoroughly examined. It was proven that waste side window glass is a viable solution as a replacement of natural aggregate and the achieved concretes can be utilized as structural building material.

2. Design of experiment

The research program was divided into four main stages. During the first stage, the properties of aggregates and aggregate mix compositions were of interest. Three natural aggregates were used to achieve the optimum aggregate mix. Subsequently, the aggregate mix was modified by partially replacing coarse aggregate with crushed side window glass and by adjusting the amount of sand. Altogether, seven aggregate mixes were chosen for further research. During the second stage, concrete mixes characterized by a w/c ratio of 0.5 were created. Concrete mixes were based on the aggregate mixes and modified by superplasticizer. Consistency and air volume in the fresh mixes were tested. Both tests served as quality control of the created concretes. The third stage was solely dedicated to hardened concrete. Two types of cube specimens (150 × 150 × 150 mm and 100 × 100 × 100 mm) were cast and cured. Curing took place in a water tank with a temperature of 20°C ±0.5°C. For each mix, 13 specimens with a size of 150×150×150 mm and 12 specimens with a size of 100 × 100 × 100 mm were cast. The apparent density of hardened concrete, compressive strength, water absorption and watertightness were tested using 150 × 150 × 150 mm cube specimens. Apparent density (as a non-destructive test) was tested using all 12 cube 150×150×150 mm specimens of each type of cast concrete. Subsequently, the specimens were utilized for other (destructive) tests. Five were used for compressive strength test.

Three were used for water absorption tests and depth of water penetration. The remaining two specimens were used during the fourth stage of the research program for analysis of internal structure of a hardened concrete. The watertightness was tested for 72 hours while keeping the specimens under water pressure of 0.5 MPa. The surface exposed to water pressure was hammered (in order to remove cement slurry). After the test, specimens were split and the depth of water penetration was assessed. Resistance to freeze–thaw cycles was tested using 100 × 100 × 100 mm cube specimens. The cycles were realized according to PN-88/B-06250 [24]. The specimens were frozen in air conditions at a temperature of −20° C for 4 hours. Subsequently the thawing process was initiated using warm water (temperature of +20°C) for 4 hours. Altogether, 100 cycles were executed (3 cycles per day) lasting 33 days and 8 hours. The last stage of the research program was focused on studying the internal structure of the hardened concretes using digital image analysis.

3. Used aggregates

During the research program, four types of aggregates were used: sand (S), coarse aggregate 1 (CA$_1$), coarse aggregate 2 (CA$_2$) and recycled aggregate from crushed side window glass (CWG). Sand, coarse aggregate 1 and coarse aggregate 2 were of natural postglacial origin [25, 26]. The recycled aggregate from crushed side window glass was obtained from the local producer of car side windows and windscreens. The side windows used for creation of the CWG were discarded during the last phase of the quality control process. For the purpose of the research program, the side windows were manually crushed into smaller pieces using traditional hammers. Smaller pieces were placed in a basic laboratory ball mill. The mill was characterized by volume and rotation speed of 44 dm^3 and 52 rev./min. respectively. By controlling the length of grinding coarse or more fine particles were achieved. Finally the grinded CWG was sieved to divide it into fractions. Images of raw CWG inside ball mill (just after opening the mill) and CWG divided into fractions are presented in Fig. 1.

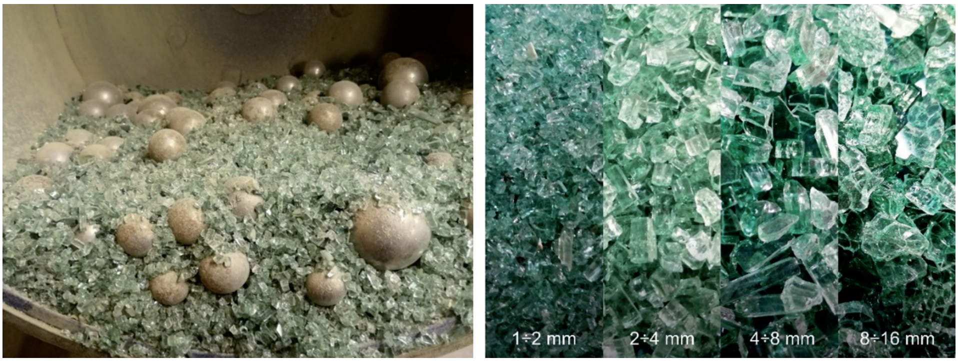

Fig. 1. CWG inside ball mill (left) and CWG divided into fractions (right)

The chemical composition of CWG was tested using ordinary SEM/EDS methodology. The average composition was as follows: O = 46.91%, Si = 27.54%, Na = 10.76%, Ca = 8.50%, Mg = 2.50%, Al = 2.01%, Fe = 0.87%, K = 0.39%, C = 0.34%, S = 0.18%. The density of CWG was established using traditional Le Chatelier's flask procedure.

Granulometric properties of all aggregates were tested using rectangular sieves with openings from 0 to 16 mm. The sieve analysis was conducted according to PN-EN 933–1:2012 [27]. The median diameter (d_m) was calculated for all aggregates in question according to the methodology described in [28]. The fineness moduli (by Kuczyński U_K, by Abrams U_A and by Hummel U_H) used in different countries were also calculated for the aggregates in question. The density (ρ), loose bulk density (ρ_{lb}) and compacted bulk density (ρ_{cb}) of the aggregates were tested according to EN 206-1 [29]. Finally, the Los Angeles abrasion test was conducted for natural coarse aggregates according to PN-EN 1097-2:2020-09 [30]. Aggregate resistance category LA30 according to PN-EN 12620+A1:2010 [31] can be assigned to both natural coarse aggregates. The results of the aggregates' tests are summarized in Table 1.

Table 1. Sieve analysis and densities of used aggregates

Fraction[mm]	Type of aggregate			
	S	CA_1	CA_2	CWG
	[%]			
0.000–0.063	0.5	0.1	0.5	0
0.063–0.125	2.7	0.1	0.4	0
0.125–0.250	18.5	0.1	0.5	0
0.250–0.500	45.4	1.7	0.5	0
0.500–1.000	25.4	6.0	0.5	0
1.000–2.000	6.2	13.0	1.6	0.7
2.000–4.000	1.3	39.0	6.9	55.7
4.000–8.000	0	32.7	22.6	42.2
8.000–16.000	0	7.3	66.5	1.4
	[mm]			
d_m	0.406	3.487	8.000	3.770
U_K	3.163	6.157	7.445	6.443
U_A	2.091	5.076	6.360	5.361
U_H	62.890	152.710	191.350	161.290
	[kg/m^3]			
ρ	2650	2650	2650	2560
ρ_{lb}	1505	1657	1415	1345
ρ_{cb}	1653	1781	1582	1464
	[%]			
Los Angeles	n/a	29.7		n/a

4. Process of composing aggregate blends

The process of achieving the best aggregate blend was conducted experimentally using only natural aggregates. Initially, CA_2 was blended with CA_1. The CA_1 was dosed to CA_2 as long as the compacted bulk density of the aggregate blend was getting higher. After reaching the certain (optimal) proportion of CA_1 and CA_2, the compacted bulk density of the aggregate blend was getting smaller. The peak of the compacted bulk density was recognised as the most dense aggregate blend. Subsequently the optimal blend of CA_1 and CA_2 was blended with sand using the same methodology. The peak of the compacted bulk density of the three aggregates was recognized as the most dense aggregate blend. This aggregate blend was used to create the reference concrete (R). The granulometric properties of CWG were similar to CA_1; thus, during the process of composing the aggregate blend, CWG was used to replace CA_1. The amount of replaced CA_1 was equal to 10, 30 and 50% (by weight) and the modified aggregate blends were named G1, G3 and G5, respectively. The apparent density of both aggregates was similar; thus, volume differences during replacing by weight were negligible. This approach was thoroughly described and discussed in a previous publication [32]. Achieved aggregate blend compositions are presented in Table 2.

Table 2. Sieve analysis (cumulative percentage) of used aggregate blends

Fraction[mm]	Type of aggregate						
	R	G1	G3	G5	S1	S3	S5
	[%]						
0.000–0.063	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0.063–0.125	1.2	1.2	1.2	1.2	1.2	1.3	1.3
0.125–0.250	6.5	6.5	6.5	6.4	6.7	7.1	7.4
0.250–0.500	19.9	19.8	19.6	19.5	20.4	21.4	22.4
0.500–1.000	29.6	29.3	28.6	27.9	30.1	30.9	31.8
1.000–2.000	37.5	36.6	34.8	33.1	37.3	37.0	36.6
2.000–4.000	56.8	56.6	56.3	56.0	57.0	57.4	57.8
4.000–8.000	77.5	77.8	78.3	78.8	77.9	78.5	79.2
8.000–16.000	100.0	100.0	100.0	100.0	100.0	100.0	100.0

In order to attain aggregate blends characterized by the same fineness modulus, a correction of the amount of sand was done. The sand modified aggregate blends are named S1, S3 and S5 for the amount of CWG equal to 10, 30 and 50%, respectively.

5. Concrete mixes

Using all seven aggregate blends (R, G1, G3, G5, S1, S3, S5), the concrete mixtures were designed. CEM I 42.5R and ordinary tap water were used to create the concrete mixes. All mixes were modified by a commercially available superplasticizer characterized by density of 1.085 kg/dm^3 and pH equal to 5 (±1). The superplasticizer fulfilled the requirements of PN-EN 934-2 [33]. The composition of the mixes is presented in Table 3.

Table 3. Composition of tested concrete mixes (kg/m^3)

Component	R	G1	G3	G5	S1	S3	S5
Cement	300						
Water	150						
Superplasticizer	1.35						
Aggregate	1982						
S	546	546	546	546	564	600	637
CA$_1$	862	776	603	431	758	549	340
CA$_2$	574						
CWG	–	86	259	431	86	259	431

The mixing procedure using the planetary mixer lasted 90 seconds. The consistency of the fresh concrete mixes was assessed using an ordinary slump test according to PN-EN 12350-2:2019 [34]. The achieved results (presented in Fig. 2) allowed us to classify the consistency of all mixes as S1 according to EN 206-1 [29].

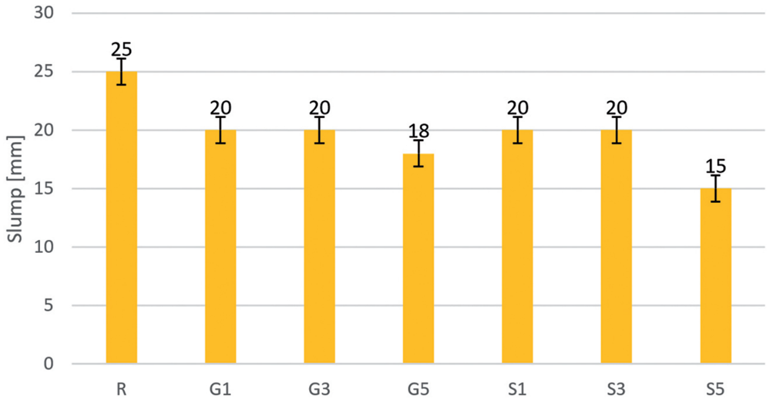

Fig. 2. Slump test results of tested fresh mixes

After the slump test the volume of air in the fresh mixes was tested using a pressure method according to PN-EN 12350-7:2019-08 [35]. The results of these tests are presented in Fig. 3.

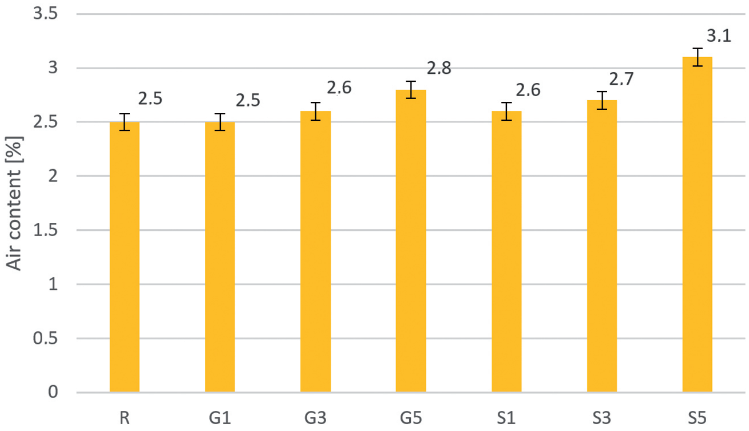

Fig. 3. Air content in the tested fresh concrete mixes

The air content ranged from 2.5% (for fresh concrete mix R and G1) to 3.1% (for fresh concrete mix S5). Specimens were cast in two layers and compacted using a vibrating table.

6. Properties of hardened concretes

The first test conducted on hardened concrete specimens checked their dimensions and mass. As it is a non-destructive procedure, all available specimens were checked. Subsequently the apparent density was calculated for all specimens. The whole procedure fulfilled the requirements of PN-EN 12390-7:2019-08 [36]. Values of apparent density ranged from 2274 to 2305 kg/m^3 for concretes S5 and R, respectively. Specific populations of results for a given concrete were characterized by high homogeneity. No outliners were noted. This is an indicator of a very good quality of cast specimens. The densities are presented in Fig. 4.

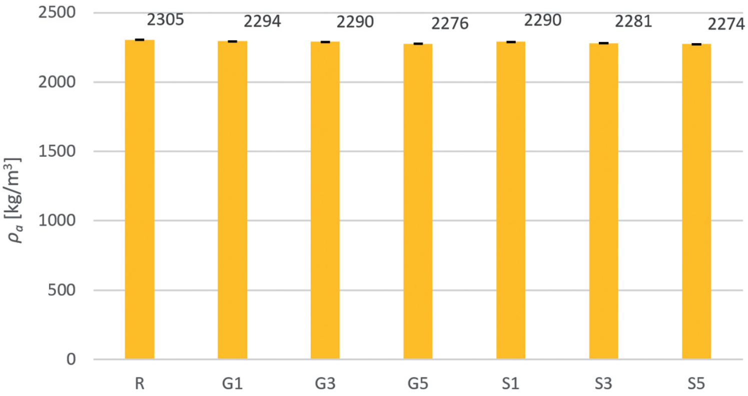

Fig. 4. Apparent density of hardened concretes

In both G and S mixes, the density was slightly influenced by the addition of CWG. Replacing natural aggregate characterized by density of 2650 kg/m^3 with CWG characterized by 2490 kg/m^3 is well mirrored by the achieved results.

The compressive strength (f_c) test conducted after 28 days of curing was the first destructive test. For each test, five cube specimens of size 150 × 150 × 150 mm were used. The test was conducted according to PN-EN 12390-3:2019-07 [37]. The results of the compressive strength test are presented in Fig. 5.

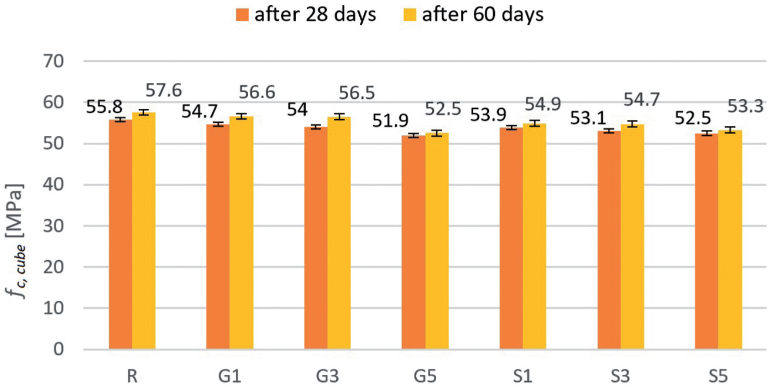

Fig. 5. Compressive strength of tested hardened concretes

The reference concrete was characterized by the highest compressive strength of 55.8 MPa. The lowest compressive strength was achieved by concrete mix G5. The differences between specific mixes were small (3.9 MPa between the highest and the lowest result). Taking into account the number of tested specimens, hardened concretes R, G1 and G3 (after 28 days of curing) could be described as strength class C40/50, and concretes G5, S1, S3 and S5 could be described as strength class C35/45. The gains in strength after 60 days of curing in comparison to 28 days of curing are relatively small and do not influence the assigned strength classes.

Water absorption was tested using three cube specimens of size 150 × 150 × 150 mm. The test was executed according to PN-88/B-06250:1988 [24]. The achieved results are presented in Fig. 6. The water absorption for all concretes was almost the same and equal to 4.6%–4.7% (by weight). The partial replacement of natural aggregate by CWG did not influence this property in any noticeable way. The water-tightness test was executed according to PN-EN 12390-8:2019-08 [38]. The used apparatus was equipped with six standings for specimens. Water under pressure was fed from the bottom of the cube specimens through a circular area with the diameter of 100 mm. After maintaining the water pressure (0.5 MPa) for 72 hours, the depth of water penetration h_w was measured on split specimens (see Fig. 7).

The depth of water penetration for particular concretes is presented in Fig. 8. The value of h_w ranged from 85 mm to 98 mm for concretes G1 and S5, respectively. The freeze–thaw test was conducted using cube specimens of size 100 × 100 × 100 mm. The test was

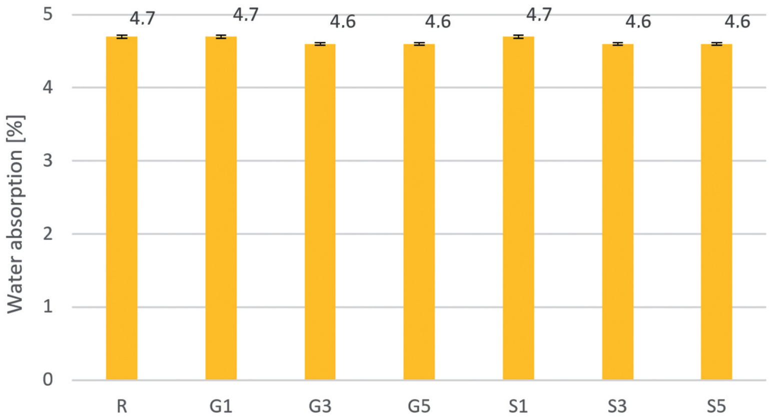

Fig. 6. Water absorption (by weight)

Fig. 7. Exemplary cross-section of a specimen after water-tightness test

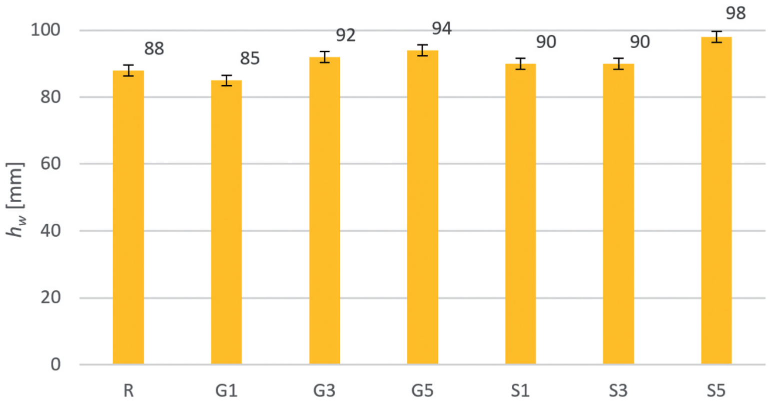

Fig. 8. Depth of water penetration

executed utilizing the methodology described in PN-88/B-06250:1988 [24]. A population of 12 specimens was used for the test for each type of concrete in question. Six specimens formed a reference population. They were left for further curing in water. The remaining six specimens were exposed to freeze–thaw cycles. After 100 cycles, both mass and compressive strength were tested. No loss of mass was registered in any of concretes in question. Freeze–thaw cycles only influenced the compressive strength in a noticeable way. The difference Δ_{fc} between the strength of reference specimens and specimens exposed to freeze–thaw cycles was calculated. The results are presented in Fig. 9. Strengths achieved by reference specimens were presented in Fig. 5 as 60 days results (after scaling them to 150 mm cubes).

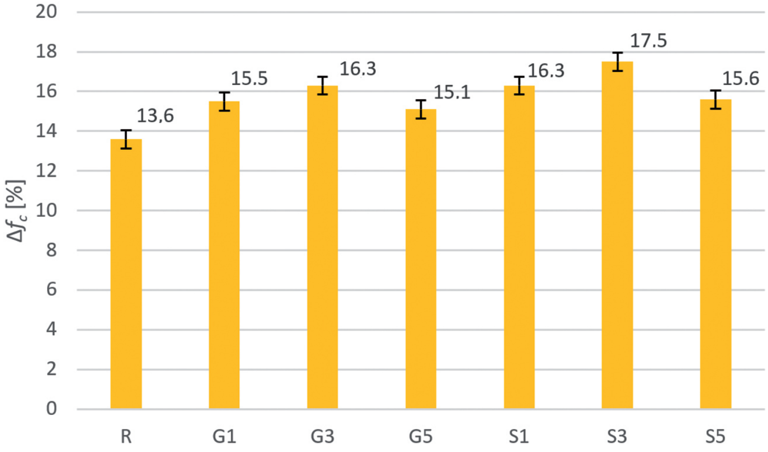

Fig. 9. Loss of compressive strength after 100 freeze–thaw cycles

The value of Δ_{fc} ranged from 13.6% to 17.5% for the reference concrete and S3 concrete, respectively.

The internal structure of the hardened concretes was studied using digital image analysis of specimen cross-sections. The volume and character of air pores were of special interest. The test was conducted according to PN-EN 480-11:2008 [39] with the help of Lucia Concrete software. The testing procedure was thoroughly described in the previous publication [32]. The testing stand is presented in Fig. 10. The apparatus SEM-EDX (LEO Electron Microscopy Ltd, England) enabled evaluation of the air pore distribution and CWG spacing in the volume of the hardened concrete. The porosity characteristics of concretes sourced from digital image analysis are presented in Table 4.

Total air content ranged from 1.77% to 3.00% for mixes G1 and S5, respectively, while the reference concrete was characterized by $A = 2.80\%$. Only mixes with 50% of CWG (G5 and S5) were characterized by total air content higher than in the case of the reference concrete. The rest of the mixes were characterized by significantly lower values of total air content. The achieved results support the thesis that replacing natural aggregate by CWG does not negatively influence the properties of hardened concrete.

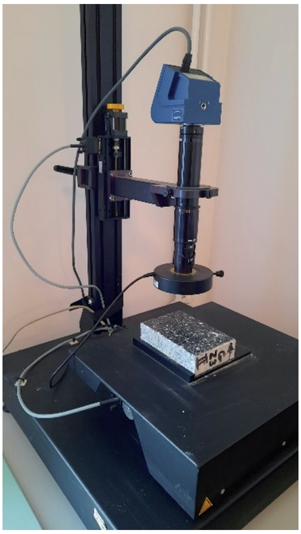

Fig. 10. Lab stand for digital image analysis of specimens cross-sections

Table 4. Porosity characteristics of tested concretes

Concrete mix	Total air content A [%]	Surface of the air α [mm^{-1}]	Spacing factor L [mm]	Micro-air content A_{300} [%]
R	2.80	18.8	0.3	0.6
G1	1.77	21.5	0.3	0.6
G3	2.47	13.9	0.5	0.4
G5	2.86	18.9	0.3	0.6
S1	2.58	12.8	0.5	0.3
S3	2.53	13.6	0.5	0.3
S5	3.00	13.9	0.4	0.4

7. Discussion

Cross-sections of the concrete specimens are presented in Fig. 11. In the images, both CWG and natural aggregate particles are clearly visible. The concrete matrix is densely packed with no voids or cracks. While analyzing the images presented in Fig. 11 one should remember that surfaces of CWG particles are smoother than that of the natural aggregate. Therefore, the bonding properties of CWG with cement paste are lower than in case of a natural aggregate. At the same time the shape of the CWG particles (with sharp edges – see Fig. 11) are more likely to interlock and create very effective (in terms of compressive strength) aggregate spacing. In authors' opinion influence of smooth surfaces of CWG particles is significantly limited by sharp edges influencing particle spacing and

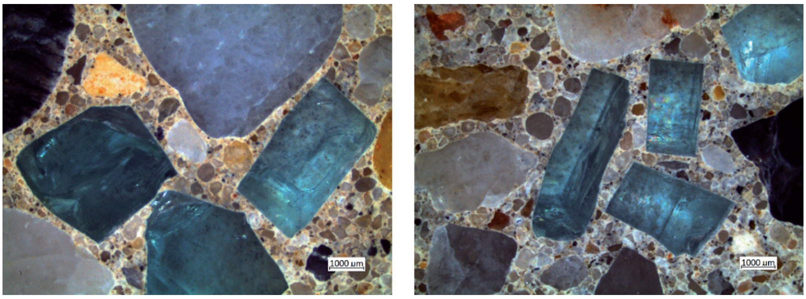

Fig. 11. Cross-sections of the concrete specimens with CWG particles

interlocking. Values of achieved compressive strengths (Fig. 5) which differ in range of 3% between reference concrete and concretes with CWG seem to confirm this assumption.

The observed character of the concrete matrix goes along with the achieved results of relatively high water-tightness and resistance to freeze–thaw cycles.

In general, all of the achieved characteristics of fresh concrete mixes and hardened composites with CWG are similar to those of ordinary reference concrete. Using concretes with up to 50% of CWG replacing natural coarse aggregate has many benefits: it limits waste disposal costs, conserves the environment by saving significant volumes of natural aggregates, and extends the life span of existing landfill sites. No extra energy is needed to harness CWG as a natural aggregate replacement. Future research efforts associated with CWG for concrete production should be focused on designing procedures for such concrete mixes and utilizing CWG fine fractions for concrete production. Study of whether CWG as partial aggregate substitution causes alkali aggregate reaction should also be conducted. Thorough tests and analysis concerning flexural and tensile strengths of CWG concretes should be performed. Finally, durability performance of CWG concretes should be established by testing abrasion resistance (e.g., by Boehme method) and comparing it to already tested resistance to freezing–thawing and watertightness. One should also consider adding fiber to CWG concretes and assessing their ability to efficiently interact with such reinforcement. Separate research effort should be dedicated to development of sustainable methods of sourcing windscreen glass. Current ways of scrapping cars are not friendly for production of CWG based aggregates.

Taking into account that in 2016 the number of scrapped cars in Europe surpassed 5 million a year, the amount of CWG available for concrete production is huge. Combining a smart approach to source CWG from scrapped cars with the proposed approach to create concrete (with up to 50% of CWG replacing natural aggregate) forms a feasible technological solution. The current state of the art enables production of CWG concretes using ordinary equipment and techniques. Properties of CWG concretes, both in fresh mix and hardened concrete states, enable one to treat them in the same way as ordinary concrete. Elements of secondary importance and basic structural applications seem to be the best use of CWG concretes during the initial stage of introducing them to the construction industry. After gaining new knowledge about their other properties (which were proposed to be tested – see above comments), more elaborate structural applications would be enabled. It would be interesting to merge CWG concretes with some other recycled approaches to concrete (e.g., waste steel fiber, blended locally produced cement, granite dust [40], diabase dusts [41] or lime powder [42]). In this way, CWG concrete would become even more green and sustainable.

8. Conclusions

The conducted research program allows us to draw the following conclusions:

- It is feasible to replace up to 50% of natural coarse aggregate by CWG;
- The properties of both fresh concrete mix and hardened concrete based on CWG are similar to those of a reference concrete;
- The air content in the fresh CWG mixes is the same (differences smaller than the precision of the testing method) as that in the ordinary (reference) concrete;
- The apparent density of CWG concretes is the same (differences smaller than ±1.5%) as that of the ordinary (reference) concrete;
- The matrix of concrete with CWG is densely packed with no voids or cracks;
- The water absorption of all concretes in question was the same and equal to 4.65% ± 0.05%;
- The reference concrete was characterized by the highest compressive strength of 55.8 MPa. All CWG concretes were characterized by slightly lower compressive strength (by 1.1 MPa to 3.9 MPa for concretes G1 and G5, respectively);
- CWG concrete is characterized by reasonably high durability properties, enabling its application for structural components exposed to elements;
- Future key research programs should cover utilizing CWG fine fractions for concrete production. Studies of whether CWG as partial aggregate substitution causes alkali aggregate reaction should be also conducted.

References

[1] P.K. Mehta, “Global concrete industry sustainability”, *ACI Concrete International*, vol. 31, no. 2, pp. 45–48, 2009.

[2] V. Penttala, “Concrete and sustainable development”, *ACI Materials Journal*, vol. 94, no. 5, pp. 409–416, 1997, DOI: 10.14359/325.

[3] J. Gołaszewski, T. Ponikiewski, A. Kostrzanowska-Siedlarz, and P. Miera, “The influence of calcareous fly ash on the effectiveness of plasticizers and superplasticizers”, *Materials*, vol. 13, no. 10, art. no. 2245, 2020, DOI: 10.3390/ma13102245.

[4] J. Pizoń, J. Gołaszewski, M. Alwaeli, and P. Szwan, “Properties of concrete with recycled concrete aggregate containing metallurgical sludge waste”, *Materials*, vol. 13, no. 6, art. no. 1448, 2020, DOI: 10.3390/ma13061448.

[5] M. Ghalehnovi, N. Roshan, A. Taghizadeh, E.A. Shamsabadi, S.A. Hadigheh, and J. de Brito, “Production of environmentally friendly concrete incorporating bauxite residue and silica fume”, *Journal of Materials in Civil Engineering*, vol. 34, no. 2, art. no. 04021423, 2022, DOI: 10.1061/(ASCE)MT.1943-5533.0004060.

[6] L. Evangelista and J. de Brito, “Durability performance of concrete made with fine recycled concrete aggregates”, *Cement & Concrete Composites*, vol. 32, no. 1, pp. 9–14, 2010, DOI: 10.1016/j.cemconcomp.2009.09.005.

[7] S. Seitl, P. Miarka, H. Šimonová, P. Frantík, Z. Keršner, J. Domski, and J. Katzer, "Change of fatigue and mechanical fracture properties of a cement composite due to partial replacement of aggregate by red ceramic waste", *Periodica Polytechnica Civil Engineering*, vol. 63, no. 1, pp. 152–159, 2019, DOI: 10.3311/PPci.12450.

[8] K. McNeil and T.H.K. Kang, "Recycled concrete aggregates: A review", *International Journal of Concrete Structures and Materials*, vol. 7, pp. 61–69, 2013, DOI: 10.1007/s40069-013-0032-5.

[9] M. Pająk, M. Krystek, M. Zakrzewski, and J. Domski, "Laboratory investigation and numerical modelling of concrete reinforced with recycled steel fibers", *Materials*, vol. 14, no. 8, art. no. 1828, 2021, DOI: 10.3390/ma14081828.

[10] J. Thorneycroft, J. Orr, P. Savoikar, and R.J. Ball, "Performance of structural concrete with recycled plastic waste as a partial replacement for sand", *Construction and Building Materials*, vol. 161, pp. 63–69, 2018, DOI: 10.1016/j.conbuildmat.2017.11.127.

[11] E.I. Arslan, S. Aslan, U. Ipek, S. Altun, and S. Yazıcıoglu, "Physico-chemical treatment of marble processing wastewater and the recycling of its sludge", *Waste Management & Research*, vol. 23, no. 6, pp. 550–559, 2005, DOI: 10.1177/0734242X05059668.

[12] H.Y. Aruntas, M. Guru, M. Dayi, and I. Tekin, "Utilization of waste marble dust as an additive in cement production", *Materials and Design*, vol. 31, no. 8, pp. 4039–4042, 2010, DOI: 10.1016/j.matdes.2010.03.036.

[13] J. Halbiniak, J. Katzer, M. Major, and I. Major, "A Proposition of an in situ production of a blended cement", *Materials*, vol. 13, no. 10, art. no. 2289, 2020, DOI: 10.3390/ma13102289.

[14] M. Nehdi, J. Duquette, and A.E. Damaty, "Performance of rice husk ash produced using a new technology as a mineral admixture in concrete", *Cement and Concrete Research*, vol. 33, pp. 1203–1210, 2003, DOI: 10.1016/S0008-8846(03)00038-3.

[15] K.M.A. Hossain, "Blended cement using volcanic ash and pumice", *Cement and Concrete Research*, 2003, vol. 33, no. 10, pp. 1601–1605, 2003, DOI: 10.1016/S0008-8846(03)00127-3.

[16] J. Halbiniak and M. Major, "The use of waste glass for cement production", *IOP Conf. Series: Materials Science and Engineering*, vol. 585, art. no. 012008, 2019, DOI: 10.1088/1757-899X/585/1/012008.

[17] R. Kubiliute, R. Kaminskas, and A. Kazlauskaite, "Mineral wool production waste as an additive for Portland cement", *Cement and Concrete Composites*, vol. 88, pp. 130–138, 2018, DOI: 10.1016/j.cemconcomp.2018.02.003.

[18] F. Soltanzadeh, M. Emam-Jomeh, A. Edalat-Behbahani, and Z. Soltan-Zadeh, "Development and characterization of blended cements containing seashell powder", *Construction and Building Materials*, vol. 161, pp. 292–304, 2018, DOI: 10.1016/j.conbuildmat.2017.11.111.

[19] C. Shi and K. Zheng, "A review on the use of waste glasses in the production of cement concrete", *Resources Conversation and Recycling*, vol. 52, no. 2, pp. 234–247, 2007, DOI: 10.1016/j.resconrec.2007.01.013.

[20] N.N. Anisah, M. Awang, and K. Kartini, "Effect of using windscreen glass waste powder (WGWP) as cement replacement on the mechanical properties of mortar", *Journal of Physics: Conference Series*, vol. 1532, art. no. 012011, DOI: 10.1088/1742-6596/1532/1/012011.

[21] G.M. Sadiqul Islam, M.H. Rahman, and N. Kazi, "Waste glass powder as partial replacement of cement for sustainable concrete practice", *International Journal of Sustainable Built Environment*, vol. 6, no. 1, pp. 37-44, 2017, DOI: 10.1016/j.ijsbe.2016.10.005.

[22] H. Elaqra, M. A. A. Haloub, and R. Rustom, "Effect of new mixing method of glass powder as cement replacement on mechanical behavior of concrete", *Construction and Building Materials*, vol. 203, no. 35, pp. 75–82, 2019, DOI: 10.1016/j.conbuildmat.2019.01.077.

[23] Z. Kalakada, J.H. Doh, and S. Chowdhury, "Glass powder as replacement of cement for concrete – an investigative study", *European Journal of Environmental and Civil Engineering*, vol. 26, no. 3, pp. 1046–1063, 2022, DOI: 10.1080/19648189.2019.1695149.

[24] PN-88/B-06250:1988 Beton zwykły (Ordinary concrete).

[25] J. Katzer and J. Kobaka, "The assessment of fine aggregate pit deposits for concrete production", *Kuwait Journal of Science and Engineering*, vol. 33, no. 2, pp. 165–174, 2006.

[26] J. Katzer and J. Kobaka, "Influence of fine aggregate grading on properties of cement composite", *Silicates Industriels*, vol. 74, no. 01–02, 2009.

[27] PN-EN 933-1:2012 Tests for geometrical properties of aggregates – Part 1: Determination of particle size distribution – Sieving method.

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

[29] PN-EN 206 + A1: 2016-12 with national supplement PN-B-06265:2018-10 Concrete. Requirements, properties, production and compliance.

[30] PN-EN 1097-2:2020-09 Tests for mechanical and physical properties of aggregates – Part 2: Methods for the determination of resistance to fragmentation.

[31] PN-EN 12620+A1:2010 Aggregates for concrete.

[32] J. Katzer, J. Halbiniak, B. Langier, M. Major, and I. Major, "Influence of varied waste ceramic fillers on the resistance of concrete to freeze–thaw cycles", *Materials*, vol. 14, no. 3, 2021, DOI: 10.3390/ma14030624.

[33] PN-EN 934-2+A1:2012 Admixtures for concrete, mortar and grout – Part 2: Concrete admixtures – Definitions, requirements, conformity, marking and labelling.

[34] PN-EN 12350-2:2019-07 Testing fresh concrete – Part 2: Slump test.

[35] PN-EN 12350-7:2019-08 Testing fresh concrete – Part 7: Air content – Pressure methods.

[36] PN-EN 12390-7:2019-08 Testing hardened concrete – Part 7: Density of hardened concrete.

[37] PN-EN 12390-3:2019-07 Testing hardened concrete – Part 3: Compressive strength of test specimens.

[38] PN-EN 12390-8:2019-08 Testing hardened concrete – Part 8: Depth of penetration of water under pressure.

[39] PN-EN 480-11:2008 Admixtures for concrete, mortar and grout – Test methods – Part 11: Determination of air void characteristics in hardened concrete.

[40] G. Prokopski, A. Huts, and V. Marchuk, "The use of granite dust as an effective filler of concrete mixtures", *Archives of Civil Engineering*, vol. 67, no. 4, pp. 159–174, 2021, DOI: 10.24425/ace.2021.138492.

[41] T. Rudnicki and R. Jurczak, "The impact of the addition of diabase dusts on the properties of cement pavement concrete", *Archives of Civil Engineering*, vol. 68, no. 1, pp. 395–411, 2022, DOI: 10.24425/ace.2022.140175.

[42] M. Kępniak and P. Woyciechowski, "Influence of sand substitution with waste lime powder on the concrete carbonation", *Archives of Civil Engineering*, vol. 67, no. 4, pp. 383–392, 2021, DOI: 10.24425/ace.2021.138506.

Charakterystyki wytrzymałościowe betonów z tłuczoną samochodową szybą boczną zastosowaną jako częściowy zamiennik kruszywa

Słowa kluczowe: kruszywo odpadowe, recykling, szkło, zamiennik

Streszczenie:

Biorąc pod uwagę liczne dotychczasowe próby wykorzystania szkła odpadowego do produkcji betonu, zaproponowano podejście oparte wyłącznie na odpadach otrzymywanych z szyb samochodowych. W programie badawczym wykorzystano wyłącznie odpady pochodzące z szyb bocznych powstające podczas utylizacji samochodów. W ten sposób wszystkie kluczowe właściwości szkła odpadowego były pod kontrolą (czystość, właściwości granulometryczne, itp.). Powstały dwa rodzaje betonów z tłuczoną szybą samochodową, pełniącą rolę grubego kruszywa. Betony różnicowano ilością dodanego kruszonego szkła, które zastępowało 10–50% kruszywa naturalnego. Powstałe betony zostały przebadane zarówno na etapie świeżej mieszanki betonowej, jak też związanego już betonu. Zbadano konsystencję i zawartość powietrza w świeżych mieszankach. Opad wahałsię od 15 mm do 20 mm, a zawartość powietrza wahała się od 2,5% do 3,1%. Betony związane zastosowano do badania gęstości pozornej, wytrzymałości na ściskanie, nasiąkliwości, wodoszczelności i odporności na cykle zamrażania-rozmrażania. Wykazano, że beton z częściowym zastąpieniem kruszywa potłuczonymi bocznymi szybami samochodowymi charakteryzuje się zadawalającymi właściwościami mechanicznymi (wytrzymałość na ściskanie po 28 dniach wiązania wahała się od 51,9 MPa do 54,7 MPa), umożliwiającymi zastosowanie go jako zwykłego betonu konstrukcyjnego. Zarówno mieszanki betonowe, jak również betony, powstające na bazie bocznych szyb samochodowych mają właściwości zbliżone do betonu referencyjnego. Wykazano, że możliwe jest zastąpienie do 50% naturalnego kruszywa gruboziarnistego kruszonym szkłem pochodzącym z bocznych szyb samochodowych. Zaproponowano możliwe zastosowania omawianych betonów. Doświadczenia zdobyte podczas realizacji programu badawczego mogą być przydatne do testów dotyczących wykorzystania tłuczonych szyb bocznych pochodzących z wycofanych z eksploatacji samochodów osobowych i ciężarowych. Wskazano również obszary, w których potrzebne są dalsze badania.

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