Magazine of Civil Engineering. 2021. 106(6). Article No. 10608

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.106.8

Performance investigation of demolition wastes-based concrete composites

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Keywords: cements, cement-based composites, binders, concretes, durability

Abstract. Due to man-made and natural anomalies occurring on planet Earth, there are a lot of destroyed cities, settlements and houses. The issue is how to rebuild these cities and how to use parts of the destroyed buildings and structures in making greener concrete. This paper aims to study the efficiency and effect of using concrete demolition wastes on the microstructure of greener concrete composites. We prepared demolition wastes-based concrete composite containing a greener supplemental cementing binder (GSCB) and fine aggregates of the previously produced concretes with high mechanical properties. The design of the compositions was determined by taking into account the law of affinity of microstructures of greener concretes. We studied the strengths, microstructural, morphological and thermal properties of raw materials and concretes at 28 days of curing. The dense microstructure was examined via the use of Portland cement and hydration products, which partially included previously unreacted clinker minerals presented in concrete waste and activated during its grinding. Results showed that replacing up to 20 % of Portland cement with the demolition waste of concrete structures as a GSCB improves compressive strength for different concrete applications. This is ensured by the affinity of the microstructure of concrete waste and newly synthesized concrete.

1. *Introduction*

A review of the scientific literature on the research topic revealed that technical progress in the production of concrete and reinforced concrete requires additional sources of raw materials, in particular, the use of high-quality aggregates [1–10]. According to Bassani et al. [4], the solution to this problem is hindered by an ever-growing shortage of mineral and energy resources, as well as environmental protection requirements [4–7]. Therefore, as reported by Sormunen and Kärki [8], the current task is the integrated

Lesovik, V.S., Ahmed, A.A., Fediuk, R.S., Kozlenko, B., Mugahed Amran, Y.H., Alaskhanov, A.Kh., Asaad, M.A., Murali, G., Uvarov, V.A. Performance investigation of demolition wastes-based concrete composites. Magazine of Civil Engineering. 2021. 106(6). Article No. 10608. DOI: 10.34910/MCE.106.8

use of deposits of low-quality raw materials and waste from related industries [8–10]. Planned demolition of obsolete buildings and structures, as well as natural and technological disasters, armed conflicts in various countries (including Iraq) produce large volumes of concrete waste [11–15]. According to Sakai [16] and Sharonova et al. [17], first of all, these wastes should be used for repair and restoration work and new construction at the places of their occurrence [16–18]. In this regard, it is relevant to use fragments of destroyed buildings and structures as raw materials for the production of building materials, including "green composites". Some papers [19–21] are devoted to the study of the possibility of using waste from destroyed buildings. However, the results of these studies are quite contradictory, which is explained by the different composition of waste from destroyed buildings in different countries. The rational use of technogenic products is possible only after their preliminary mechanical treatment, taking into account their chemical and material composition.

The theoretical basis for the design of composites using the specified raw materials is the transdisciplinary science of geomimetics developed by Lesovik et al. [22–23]. It uses the results of studies of natural processes to produce high-strength concrete and new generation building composites. In particular, one of the aspects of this science is the law of affinity of microstructures, which consists in the selection of raw materials with similar physicomechanical characteristics for a composite [24–27]. The law of affinity of microstructures for anisotropic materials involves the multilayered composites design and repair systems at three levels (nano-micro-macro). These systems are identical to the base matrix, which provides a route to a substantial growth in the materials durability [28]. The origin for the formulation of the law was the information obtained in the study of natural analogues of anisotropic and isotropic building composites [22–23]. The results were obtained on the waste of the destroyed buildings and structures of Iraq, which consist mainly of concrete, ceramic bricks and limestone wall blocks. United Nations reported that the demolition of buildings resulted from military and terrorist operations in Al Anbar, Kirkuk, Tikrit, Beiji, Diyal and Baghdad: 80,000 to 100,000 industrial and residential buildings were completely destroyed (Fig. 1). Meanwhile, the country's natural resources were severely depleted. Thus, the research gaps were related to the fact that concrete components, both binder and aggregate, have limited use and no solid conclusions were drawn. Meanwhile, concrete waste is closest in composition to newly synthesized concrete. The objective of the article is to conduct a performance investigation of demolition wastes-based concrete composite, including the physical and mechanical properties, produced by the use of fragments of destroyed buildings and structures.

Figure 1. Destroyed buildings.

1.1. Research significance

Driven by these facts, this paper scrutinizes the potential of fine-dispersed mineral additives (concrete waste) as a greener supplemental cementing binder (GSCB) and fine aggregate for lightweight and heavyweight concretes. This paper aims to study the effect of the structural patterns of concrete structures wastes on the microstructure of greener concrete composites. To achieve this goal, the following tasks were solved:

- study of the possibility of controlling the processes of microstructure formation in the synthesis of green concrete prepared based on concrete waste;
- develop rational compositions of green concrete using fine-dispersed mineral additives (concrete waste) as a greener supplemental cementing binder (GSCB) and fine aggregate;
- research the properties of modified cement systems for both heavyweight and lightweight concretes.

2. Materials and methods

2.1. Materials

Ordinary Portland cement (OPC) CEM I 42.5 N (Belgorod cement, Russia) was used as a binder. The chemical and mineralogical compositions, as well as the main technical characteristics are given in Tables 1 and 2. The specific surface area of Portland cement was 300–350 m^2/kg. The following raw materials were used as natural aggregates: sand of the Kursk deposit (Russia), granite crushed stone of the Erkilya deposit (Russia), and expanded clay fraction of 10–20 mm of the Aleksinsky plant (Russia). Characteristics of sand, gravel and expanded clay are presented in Tables 3-5.

Table 1. Chemical and mineralogical composition of the Portland cement CEM I 42.5 N.

Chemical composition (%)							Mineralogical composition (%)			
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Alkalis	C_3S	C_2S	C_3A	C_4AF
65.73	22.19	4.37	4.30	0.67	0.18	0.70	60.3	16.8	6.9	13.3

Table 2. Physicomechanical properties of the CEM I 42.5 N.

Setting time, h:min		Flexural strength, MPa		Compressive strength, MPa	
start	end	3 d	28 d	3 d	28 d
2:30	3:35	5.8	8.1	33.6	46.6

Table 3. Characteristics of the sand used.

Characteristics	Value
Bulk density, kg/m^3	1400
Fineness modulus	1.8
Content of dusty, clay and silt particles, % wt.	0.7
Specific gravity, kg/m^3	2500
Los Angeles abrasion value	3.64
Absorption capacity, %	9.91
Loss on ignition, % wt.	< 1
Sieve 0.9 mm residue, % wt.	< 1
Sieve 0.5 mm residue, % wt.	> 92

Table 4. Characteristics of gravel used.

Property	Characteristics	Value
Physicomechanical	Specific gravity, kg/m^3	2600
	Porosity, % vol.	4.1
	Compressive strength, MPa:	
	dry	168
	wet	156
	Los Angeles abrasion value	5.50
	Absorption capacity, %	16.5
Mineralogical	Microcline, % wt.	45–60
	Plagioclase, % wt.	15–20
	Quartz, % wt.	25–35
	Biotite, % wt.	2–5

Table 5. Characteristics of expanded clay.

Compressive strength, MPa	Freeze-thaw resistance, cycles	Water absorption, %	Density, kg/m^3
0.3–6	15	10–25	150–800

Table 6 lists the composition of the construction and demolition waste of Iraqi buildings and structures. As it can be seen from Table 6, 99.88% of the waste from construction and demolition because of hostilities in the cities of Iraq consists of rubble and cement concrete. The appearance of the crushed demolition waste is shown in Fig. 2.

Table 6. Composition of demolition waste.

Material	OPC	Crushed stone	Fiber	Wood	Metal	Plastic	Gypsum
Content, %	39.48	60.4	0.04	0.02	0.04	0.01	0.01

Figure 2. View of demolition waste.

Visual inspection of crushed stone from concrete waste shows that during crushing by a jaw crusher, intermittent interlayers of mortar component firmly adhered to the rock remain on its grains. Sections of crushed stone surface that do not have such a layer of cement-sand mortar contain thin films of hydrated phases. There is every reason to believe that this will provide increased adhesion of the cement matrix of concrete. The basis for this assumption is the fact that the adhesion of cement paste to various materials grows in a row: quartz < granite < limestone < clinker. These assumptions are based on our previous findings [22–27].

2.2. Methods

Demolition waste was crushed in a jaw crusher to obtain fractions of 2.5–5; 1.25–2.5; 0.63–1.25; 0.315–0.63; 0.16–0.315 and 0–0.16 mm. This raw material was used as a fine aggregate in further studies. To study the demolition waste as supplementary cementitious materials, they were further milled by a VM-20 ball mill (Russia) to sizes comparable to those of Portland cement.

The features of microstructure and compositions of the raw materials and products used as a result of the synthesis of Iraqi materials were studied using theoretical and empirical methods. The morphologies of the raw materials and the small concrete specimens of 15 mm×15 mm×4 mm were examined by scanning electron microscope (MIRA3 TESCAN, Brno, Czech) operated at the accelerating voltage of 8.0 kV. Differential-thermal analysis (DTA) and thermogravimetry (TG) were carried out using a Shimadzu DTG-60H thermogravimetric analyzer (Japan). The mix is poured into a cone 30 cm high, then after removing the cone, the amount of slump is measured. The average density of concrete was determined on specimens-cubes of 100×100×100 mm, dried to constant weight at 105 °C. The compressive strength of concrete specimens (six specimens for each composition) was measured for 10×10×10 cm specimens using a Shimadzu (Kyoto, Japan) tester with a capacity of 200 kN, according to the EN 12390-3. In the experimental work, the methodological foundations of the system-structural approach in building materials science “composition – technology – microstructure – properties” were used.

The chemical composition of the raw materials and the small concrete specimens was analyzed using an ARL 9900 WorkStation X-ray spectrometer (Thermo Fisher Scientific, Waltham, USA) with an integrated diffraction system. X-ray diffraction diagnostics of mineral crystalline phases (qualitative XRD) was carried out using the PDF-2 diffraction database. To determine the quantitative ratios of the crystalline phases, Rietveld full-profile quantitative XRD analysis was used. The calculations were carried out using the DDM v.1.95e program: its Derivative Difference Minimization algorithm makes it possible not to refine the approximation parameters of the complex structured background of the diffraction spectrum. Inorganic Crystal Structure Database (ICSD) data were used as structural models of mineral components for full-profile quantitative XRD analysis.

The error of all the results obtained does not exceed 5 %.

3. Results and Discussion

3.1. SEM images and XRD patterns of various fractions of demolition wastes

As a result of grinding the demolition waste, screenings of fractions of 2.5–5; 1.25–2.5; 0.63–1.25; 0.315–0.63; 0.16–0.315 and 0–0.16 mm were obtained. SEM images of the obtained screenings are shown in Fig. 3. The mineral composition of various fractions of demolition wastes is given in Table 7.

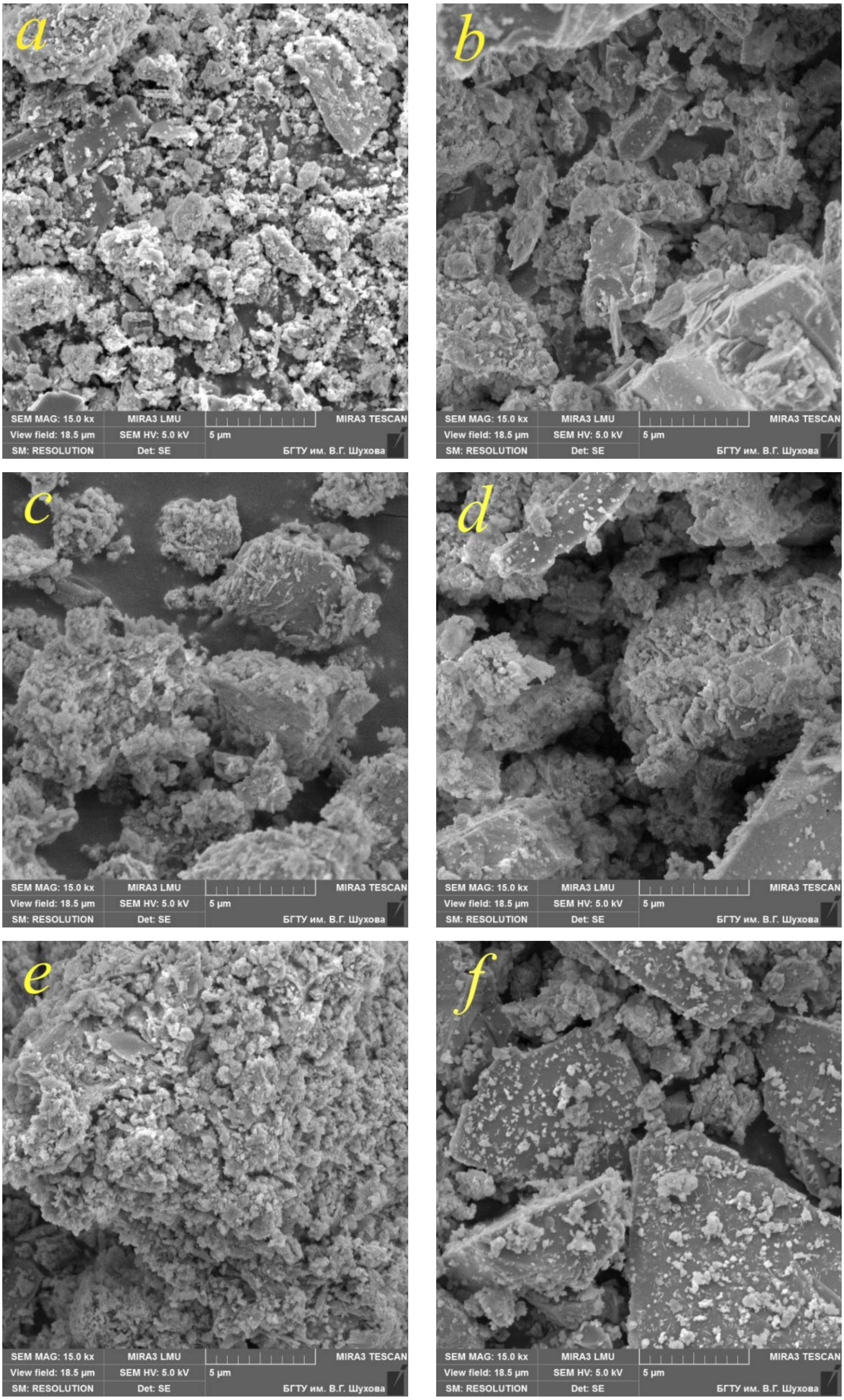

Figure 3. SEM images of demolition waste fractions: 0–0.16 (a); 0.16–0.315 (b); 0.315–0.63 (c); 0.63–1.25 (d); 1.25–2.5 (e) and 2.5–5 (f).

Table 7. The mineral composition of various fractions of demolition wastes (XRD patterns).

Particle sizes, mm	Mineral composition, %					
	SiO_2	$Ca(OH)_2$	$CaCO_3$	CSH	C_3S	C_2S
0.00–0.16	48.4	11.5	10.0	5.8	12.0	12.3
0.16–0.315	55.2	7.4	11.0	4.4	11.0	11.0
0.315–0.63	56.4	11.0	3.9	12.0	6.7	10.0
0.63–1.25	65.1	12.0	6.0	5.9	5.0	6.0
1.25–2.5	64.4	10.5	6.9	3.0	7.6	7.6
2.5–5	62.8	11.0	0	6.0	9.2	11.0

SEM images of various fractions of concrete waste show a significant amount of sharp particles, and this amount increases with decreasing size from 2.5–5 to 0–0.16 mm. This form of aggregate is the most rational, as it provides good adhesion between the aggregate and the cement matrix, thereby strengthening the interfacial transition zone.

The comminuted form of particles, as well as a high content of silica and clinker minerals in them, will contribute to their high activity, which is confirmed by the studies of other authors [2, 4, 6–10]. The crushed particle shape contributes to a large specific surface area, which reacts with the hydration products of the cement clinker. At the same time, the high content of silica and previously unhydrated clinker minerals contributes to the high reactivity of the particles of finely ground concrete waste.

3.2. Compressive strength

The tests were carried out to replace natural sand with artificial crushed sand in expanded clay concrete class C8/10 and heavyweight concrete class C16/20. The tests were carried out with partial and complete replacement of sand with demolition waste with a particle size of 1.8 mm. In this case, concrete mixtures were prepared on natural sand (control composition) and on artificial sand with partial replacement (30 % range) until the replacement was complete (Table 8–9). As the research results showed, the compressive strength of expanded clay concrete with the use of demolition waste increases, which is explained by an increase in adhesion with cement paste.

Table 8. Compositions and properties of expanded clay concretes.

Mix ID	Materials content, kg/m³					Slump, cm	Average density, kg/m³	Compress. strength, MPa
	Portland cement	Natural sand	Expanded clay	Demolition waste	Water			
LW-1	225	800	410	–	270	3–4	1670	16
LW-2	225	560	410	240	255	4–5	1600	17.2
LW-3	225	400	410	400	226	3–4	1625	19.8
LW-4	225	240	410	560	243	3–4	1562	17.9
LW-5	225	–	410	800	246	3–4	1564	17.7

Table 9. Compositions and properties of heavyweight concretes.

Mix ID	Materials content, kg/m³					Slump, cm	Average density, kg/m³	Compress. strength, MPa
	Portland cement	Natural sand	Crushed stone	Demolition waste	Water			
HW-1	475	600	1350	–	237	4	2360	27
HW-2	475	450	1350	150	237	4	2340	26.9
HW-3	475	300	1350	300	237	4	2365	26.5
HW-4	475	150	1350	450	237	4	2344	27.2
HW-5	475	–	1350	600	237	4	2350	26

Tests to replace natural sand with artificial crushed sand in heavyweight concrete also showed that the strength of concrete does not decrease, but even exceeds the control composition. This indicates that the artificial crushed sand obtained as a result of the classification of screening crushed fragments of destroyed buildings and structures can be used as fine aggregate in concrete. It was found that the obtained results of compressive strength for lightweight concrete exceed the results of other authors by 12–31 %, and for heavy concrete, by 15–36 % [4, 9–10, 19].

3.3. Microstructure of composite

Fig. 4 shows the contact zone between the cement paste and the aggregate from the waste of destroyed buildings. It is seen that there is a dense intergrowth and germination of concrete waste with the surface of the cement matrix and they look like a single whole. A dense contact zone is ensured by the fact that in the initial period, the aggregate absorbs water from the concrete mix. After the formation of a capillary-porous microstructure, the water from the pores of the aggregate is sucked out by clinker minerals and new growths, thereby increasing the degree of cement hydration without negatively affecting the workability of the concrete mix. If the concrete waste is not large and has not been hydrothermally treated, consequently, it may exhibit secondary (residual) cementitious properties due to the presence of incompletely hydrated particles of belite, as well as portlandite, the amount of which reaches 15–25 % in fresh concrete.

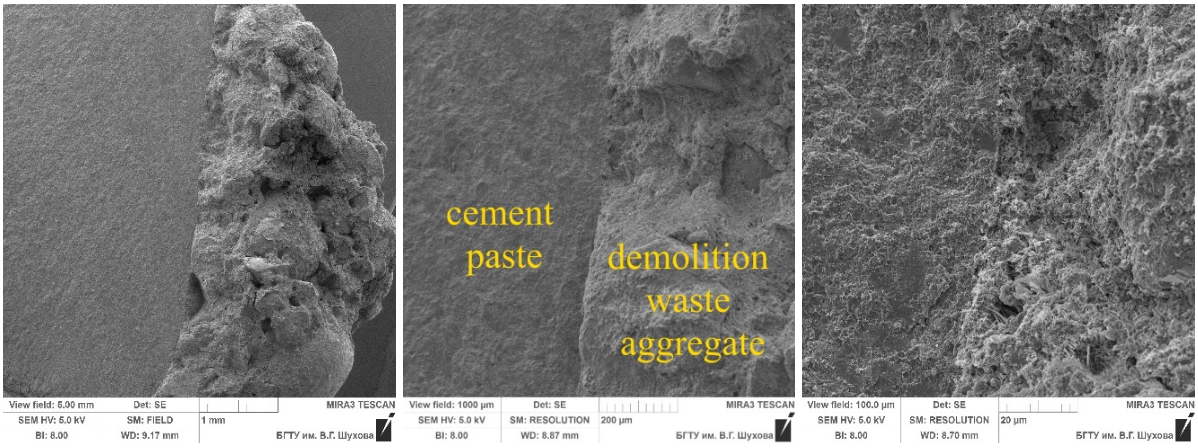

Figure 4. Contact zone between the cement paste and the aggregate from the waste of destroyed buildings.

Consequently, concretes with active fillers and aggregates from concrete wastes are characterized by its increased adhesion to the cement matrix, which provides final products with improved deformability, crack resistance, resistance to dynamic loads, and other properties. These findings, based on the law of affinity of microstructures, were proved by us earlier [22–23].

3.4. Compressive strength for concrete with milled demolition waste

Fig. 5 shows the dependences of the compressive strength on the amount of Portland cement replaced by milled demolition waste. At the same time, in accordance with the law of affinity of microstructures, concrete waste was milled until it reached a specific surface area of Portland cement (300-350 m^2/kg). This is confirmed by similar studies by Lesovik et al. [23] carried out for binder composites and aggregates of a different genesis.

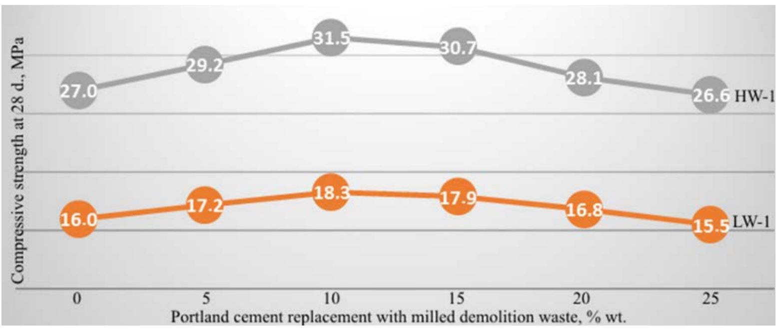

Figure 5. Dependences of the compressive strength on the amount of Portland cement replaced by milled demolition waste.

3.5. SEM images, XRD patterns and DTGA analysis

The addition of chemical and mineral additives to Portland cement leads to a change in the mechanism and rate of reactions of the interaction between clinker cement minerals and water. Mineral additives can interact with new growths of cement stone with the subsequent formation of new phases, which have a different effect on the properties of hardened cement stone. In this regard, the effect of concrete waste on the processes of cement paste hydration was tested using the methods of DTA and XRD.

The DTA pattern of hydrated Portland cement with the addition of milled concrete waste (Fig. 6) has an intense multi-stage endothermic effect with a maximum at a temperature of 101.8 °C, which is explained by the intensive removal of water. The endothermic effect with a maximum at a temperature of 447.6 °C is associated with the dehydroxylation of portlandite. The presence of such a pronounced endo effect of portlandite indicates that the active mineral additive – in this case, concrete waste – did not absorb and bind all calcium hydroxide, so the liquid phase of concrete is saturated with this hydroxide. In a medium of saturated lime solution, it is known that highly basic C-S-H (II) calcium hydrosilicates are stable, and not low-basic C-S-H (I) hydrosilicates. It follows from this that the most important binding component of Portland cement hardening products with the addition of concrete waste are the mentioned fibrous calcium hydrosilicates of the C-S-H (II) group.

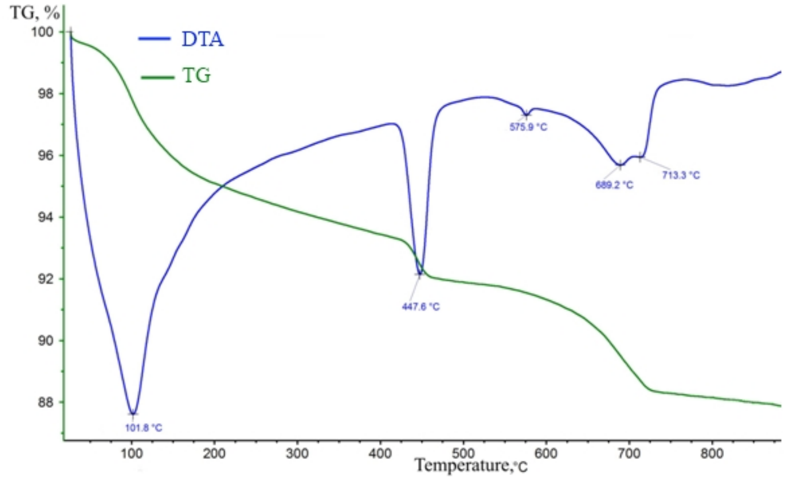

Figure 6. DTGA pattern of hydrated Portland cement with the addition of milled concrete waste.

Weak endo effects at 689.2 °C and 713.3 °C are mainly associated with decarbonization of weakly crystallized metastable forms of calcium carbonate $CaCO_3$, which were formed due to partial carbonization of calcium hydroxide. XRD pattern (Fig. 7) fully confirms the results of DTA data. The X-ray diffraction pattern of the same sample of hydrated cement with the addition of milled concrete waste has some peaks of the remains of unhydrated clinker minerals (d = 4.343; 4.270; 3.357 and 3.198 A). A small sharp peak with an interplanar distance of 2.637 A characterizes the presence of portlandite. The same is confirmed by the SEM image of developed concrete at the age of 28 days (Fig. 8). A dense microstructure is noted, provided by both Portland cement products and hydration, and, in part, by hydration products of previously unreacted clinker minerals present in the concrete waste and activated during its milling.

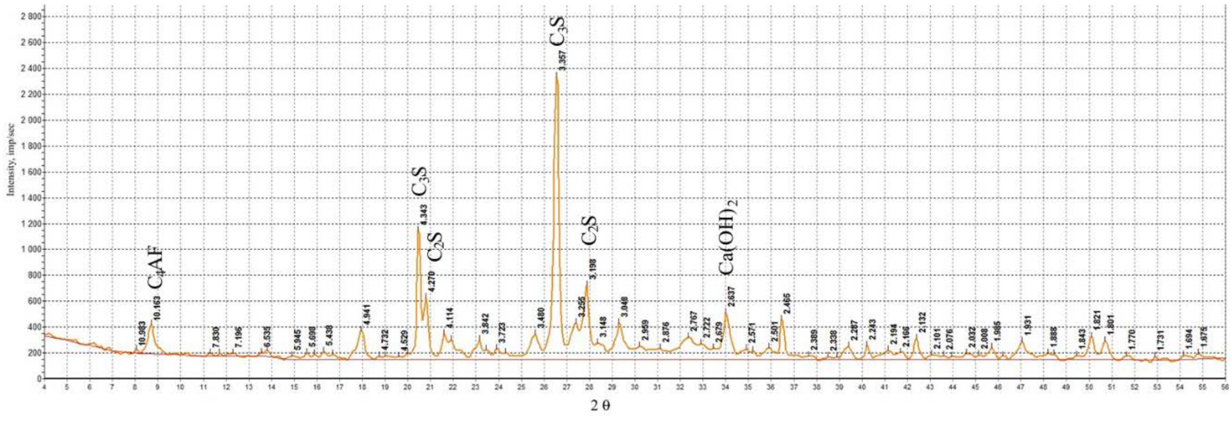

Figure 7. XRD pattern of hydrated Portland cement with the addition of milled concrete waste.

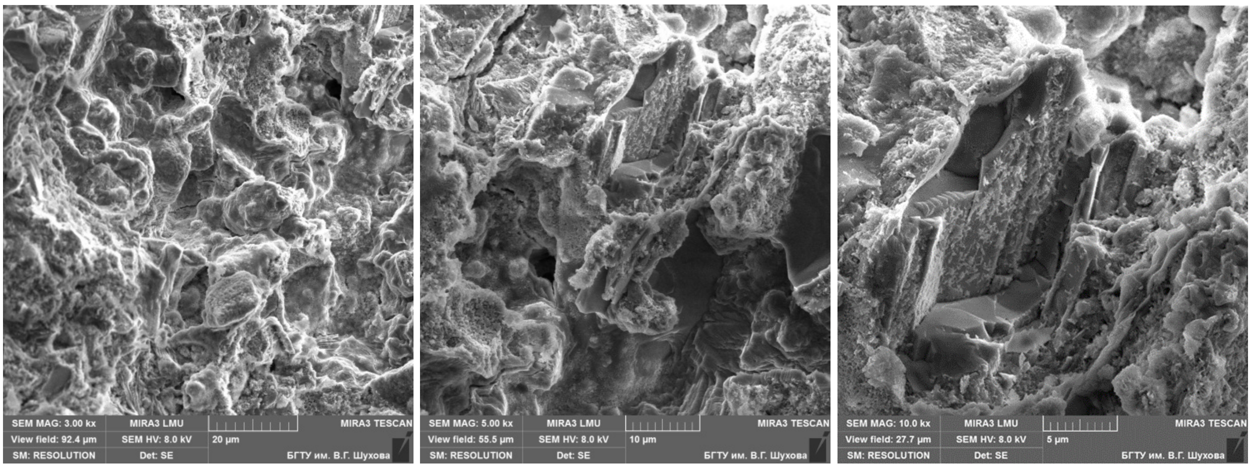

Figure 8. SEM image of developed concrete at the age of 28 days.

4. Conclusion

This article presents the possibility of recycling construction waste to solve two problems: waste disposal and improvement of the physicomechanical properties of concrete by adding recycled waste as a filler or aggregates. The sharp form of particles, as well as the high content of silica and clinker minerals in them, contribute to their high activity. Based on the results obtained, we can draw the following conclusions.

1. The use of demolition waste of buildings and structures as a fine aggregate gives similar results in the mechanical characteristics of heavyweight and lightweight concrete, as when using natural sand. This is due to the dense growth and sprouting of concrete waste to the surface of the cement matrix, as a result of which they look like its integral part.

2. In case of replacing up to 20 % of Portland cement, the demolition waste as a supplementary cementitious material allows obtaining better compressive strength of both heavy and light concrete. This is due to compaction of the microstructure by hydration products of previously unreacted clinker minerals present in concrete waste and activated by milling it. This allows the interfacial transition zone between the cement matrix and the aggregate to be compacted due to the formation of additional hydration products in a constant volume.

5. Prospects for further development of the topic

Further research can be aimed at creating completely cementless binders, using only finely ground concrete waste as a binder.

6. Acknowledgements

This work was financially supported by RFBR grant No. 18-29-24113 “Transdisciplinarity – as a theoretical basis for the rational use of technogenic raw materials for energy-efficient technologies for the production of new generation building composites”.

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