The use of waterjet cutting wastes in the production of building materials

Natalia Skanavi and Timofei Dovydenko

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: dovydenkotimofei@gmail.com

Abstract. Investigation and involvement in the production of new, earlier not used manufacturing waste and consumption is the current task directly associated with preservation of natural resources and protection of biosphere from pollution. To such waste, we refer dispersed waste of metalworking formed while cutting of metals, operation of crushing machines, etc. The purpose of this work is to study the composition and properties of waste from hydro-abrasion (waterjet) cutting of metals and estimation of their use in the production of building materials. They are related to V class of hazard the conditions of their formation are such that no new compounds arise complicating their possible application. The essence of the process of waterjet cutting, mechanism of waste formation, substance composition and volumes of waste accumulation at the enterprises, current situation in the sphere of their utilization is described. The composition and properties of the abrasive applied – garnet sand composed mainly of ferrous-aluminium garnet – almandite – one of the most hard and durable of known useful minerals. A complex investigation of waste from waterjet cutting was carried out: the average and bulk density, granulometric composition, chemical composition were determined, the electron microscopic study of various waste fractions was performed. It was found that in the process of cutting, the destruction of abrasive particles occurs, the size and shape of granules changes as well as the nature of their surface, a large amount of dust fraction appears, where particles of cut metal fall. At the same time, in the process of sand particles destruction, new abrasive faces arise, and their recycling is possible. It was established that waste of waterjet cutting of metals present very small, practically uniform heavy sands with high content of dust fraction, in the chemical composition of which prevail ferric oxides, silicon and aluminium oxides. Such characteristic of waste allowed mark possible ways of their application: 1) in the production of pottery work as inert additives and flux-additives, 2) in the production of Portland cement as corrective iron-containing additive and component of raw mix for high ferriferous cements; 3) as a filling agent in mortars, including special mortars, 4) as a pigment for voluminous painting of building materials, etc. Positive results have been obtained on the use of waste from waterjet cutting in the production of ceramics. A raw mix consisted by 50% (by mass) of montmorillonite clay and by 50% of waste from waterjet cutting of steel. After burning at 900° C, physical mechanical properties of samples have been determined. The results obtained permitted to make the conclusion about the possibility of using these waste as the poly-functional additive in the manufacture of ceramics.

1. Introduction

The utilization of the industrial and household waste is one of the most important areas of focus of the environmental protection and is directly related to the conservation of natural resources and the
protection of the biosphere against pollution. The total amount of waste accumulated and registered in Russia comprises approx. 40.7 billion tons [1]. The bulk of the accumulated and identified waste, namely 40.3 billion tons or almost 99% of the total amount of waste, pertains to the class V of hazard, i.e. virtually non-hazardous. The utilization rate of the class V waste comprises approx. 59%, which is extremely poor. This kind of waste should be utilized in the first place in view of the huge amount of its generation and accumulation; the storage of such waste requires hundreds of thousands hectares of land.

It is a currently important task to explore new earlier not utilized waste of this class and to involve it in the manufacture. This kind of waste includes dispersed waste of metalworking generated by metal cutting, shot blasting of parts, operation of sand blasting chambers, spattering, gas purification, etc. This waste is least explored or absolutely not explored in terms of its use in the manufacture of building materials.

The objective of our work is to explore the composition and the properties of the metal waterjet cutting waste and to assess the possibility of its use in the manufacture of building materials.

2. Waterjet cutting method
The waterjet cutting is a process of cutting material by a high-speed jet of water mixed with abrasive substance [2, 3]. This type of cutting involves a water jet passing through a 0.2÷0.8 mm hole, accelerating to the speed of approx. 300÷900 m/s, mixing with abrasive substance and directed to the surface to be cut under high pressure (200÷900 MPa). When the jet heats the material surface, its kinetic energy is converted into mechanical energy of destruction of the processed material and the cutting takes place. The physical sense of the waterjet cutting involves breaking off of material particles and carrying these away from the cut by a high-speed flow of hard-phase particles.

This method can be used for cutting almost any sheet materials, in the first place, ferrous and non-ferrous metals and alloys, as well as ceramics, concrete, natural rock, glass, plastic, etc. It is used in precision engineering, to obtain curvilinear cuts, as well as to create complex shapes in natural marble and granite; narrow cut (min. 0.2 mm) is used for inlay when manufacturing decorative articles.

The advantages of the waterjet cutting compared to other cutting methods (gas-oxygen, plasma-arc, laser cutting) are: low operating temperature in the place of cutting (60÷90°C), zero thermal influence on the material, low material expenditure rate (cut width 0.2÷3 mm), heavy thickness of pieces being cut (up to 300 mm and more), zero impact on the chemical composition of the alloyed steel, possibility to cut light-gauge materials in multi-layer packages, high process safety by virtue of absence of inflammable and explosive substances, environmental safety, etc.

3. Properties of the abrasive substance
The garnet sand is used as abrasive substance. Garnets are a vast group of minerals pertaining to the so-called orthosilicates (nesosilicates) according to their chemical composition [4]. The group of garnets includes different sorts of minerals, where the most wide-spread iron alumina garnet, the almandine Fe₃Al₂(SiO₄)₃, is used for waterjet cutting. This mineral is mainly of cherry-red colour with high Mohs hardness of 7÷8, high density of 4.1÷4.3 g/cm³, very high fracture resistance, zero toxicity for humans and environment. There are only a few commercial deposits of almandine. Main producers of the garnet sand are India, Australia, SAR, Czech Republic and China.

3.1. Grain size distribution
We explored the abrasive substance by R-Garnet JSC, one of the main Russian suppliers who have elaborated specifications for the garnet abrasive [5]. The sand moisture comprised 1.5%, the poured density – 2.31 g/cm³, the grain density – 3.805 g/cm³, the void ratio – 39.29%. The sand is clean, no organic impurities have been discovered. The grain size distribution (displayed in Table 1) was determined using standard sand sieves and no particles bigger than 0.63 mm were found. The fineness module made up 1.752. All researches have been performed using standard methods.
Table 1. Comparison of the grain size distribution of the abrasive substance and the waterjet cutting waste

| Sieve mesh size, mm | Garnet abrasive | Waterjet cutting waste |
|---------------------|-----------------|------------------------|
|                     | Partial residue, % | Total residue, % | Partial residue, % | Total residue, % |
| 0.315               | 75.6            | 75.6                   | 1.6               | 1.6                 |
| 0.16                | 24              | 99.6                   | 70.5              | 72.1                 |
| less than 0.16      | 0.3             | 99.9                   | 27.1              | 99.2                 |
| Total               | 99.9            | -                      | 99.2              | -                   |

3.2. Mineral and chemical composition

As result of crushing of the rock different-size sharp-edged grains are obtained. For waterjet cutting the abrasive sand with 180÷300 micrometre grain size is used. Approximate chemical composition of the sand (of Indian origin, Microblast 80 by Blastrite company), mass percent:

- SiO₂ - 31%
- Al₂O₃ – 21.6%
- Fe₂O₃ - 37%
- MgO – 7.4%
- CaO – 1.84%
- TiO₂ – 0.55%
- Na₂O, K₂O, MnO₂, P₂O₅ – less than 0.2%

As for the mineral composition, this sand comprises 96.9 % almandine, 2.4 % ilmenite and 0.4 % quartz. The ilmenite (or iron titanium oxide) is a rare mineral from the corundum-ilmenite family and pertains to complex oxides, its chemical formula is FeO·TiO₂. Its colour is ferrous black or steel grey.

The micrographs of the original abrasive made by an optical microscope (Figure 1, 2) clearly show non-transparent black ilmenite grains. The grains of almandine are of pink-red shades, transparent, clear, different-shaped but almost one size. Almost zero content of dust fraction and other inclusions is confirmed.

![Figure 1. Original garnet sand (abrasive), 60x. Transparent pink particles – almandine, dark particles – ilmenite](image1)

![Figure 2. Almandine particles in the original abrasive, 200x](image2)
4. Properties of the waterjet cutting waste

The waterjet cutting generates waste in form of sludge consisting of the garnet sand, particles of the cut metal and water. The sludge undergoes dehydration and the dry residue is stored on the territory of the company and transported to the solid domestic waste landfills if and when accumulated. One average performance waterjet cutting machine (e.g. Water Jet Sweden NC3015) generates min. 200 g dry waste per minute. The machine is operated round-the-clock and the productive time comprises 70÷80 % (the rest goes to resetting, cleaning, etc.) Thus, even one waterjet cutting machine operated by a company generates over 200 kg waste a day. As the waterjet cutting has clear advantages compared to other cutting methods, its share in the metal cutting shall grow, consequently the amount of waste generated shall grow too. Thus the company faces the task of storage and utilization of the waste.

4.1. Main properties and grain size distribution of the waste

The waste (homogenized average sample) of the waterjet cutting of ferrous metals by LLC SK Modul (Khimki) has been explored. The following results have been obtained: true density – 3.7 g/cm$^3$, poured density – 2.2 g/cm$^3$. The grain size distribution was determined using standard sand sieves (Table 1) and the grains smaller than 0.16 mm were sifted through a sieve no. 008.

Table 1 shows that large particles (bigger than 0.315 mm) of the original abrasive are broken in the course of metal cutting. A lot of small (0.16÷0.315 mm) and fine particles (less than 0.16 mm) is generated. However, such a change in the grain size disposition is also explained by the fact that the cut metal particles join the fine dust fraction. The dust fraction was sifted through a sieve no. 008 and the oversize comprised 31.3 %. That is 69 % of the dust fraction are smaller than 80 µm, which is comparable to the particle size of the Portland cement.

The assumption that the cut metal particles join the dust fraction was confirmed by the results of the electron microscope investigation of the waste and the elemental (spectral) analysis. The microscope investigation performed using a FEIQUANTA 200 scanning electron microscope showed that the particles sized 0.16 to 0.315 mm were gravel-like, irregular shaped, different-sized and represented the broken garnet sand. Breaking results in generation of new abrasive edges and sometimes the garnet abrasive is recycled and used repeatedly [6, 7].

Figure 3 displays a micrograph of the waste particles sized 0.08÷0.16 mm. Bigger particles of the broken abrasive sand grains can be seen covered by fine particles, debris of the abrasive and the cut metal. The fact that the fine particles mostly comprise metal can be confirmed by the shape and structure of particles (Figure 4, 5). The particles are sheet-like, laminated, sharp-edged. The particles are relatively similar in terms of shape and structure, the size is approx. 90 µm.

![Figure 3](image-url)

**Figure 3.** Micrograph of the waste particles of the metal waterjet cutting, grains sized 0.08÷0.16 mm, 800x
Figure 4. Micrograph of the waste particles of the metal waterjet cutting, grains sized 0.08÷0.16 mm, 1500x

Figure 5. Micrograph of the waste particles of the metal waterjet cutting, grains sized less than 0.08 mm, 1600x

4.2. Chemical and mineral composition of the waste
The chemical composition (determined by means of an ARLX'TRA X-ray diffractometer) of the waste proved to include a high content of iron oxide Fe₂O₃ – over 35 %. It may exceed the content in the original abrasive due to debris of the cut metal. This waste is not inferior to pyrite cinder and other iron-bearing industrial waste in the content of iron [8]. The content of the following substances was also significant:

- SiO₂ – 31.02%
- Al₂O₃ – 17.22%
- TiO₂ – 7.62%
- MgO – 6.74%

The titanium dioxide appears in the cut steel waste; the original abrasive contains only 0.55 % thereof. The content of the titanium dioxide in the waste requires an extra study.

4.3. General description of the waterjet cutting waste
Based on the comprehensive study of the composition and properties of the waterjet cutting metal waste, it can be described as follows: extra fine, almost uniform heavy sand with high content of dust fraction, with iron, silicon and aluminium oxides prevailing in its chemical composition.

5. Feasibility study of the use of the metal waterjet cutting waste for the manufacture of building ceramics
It appears the most practicable to use this waste for the manufacture of building ceramics, which share in the modern construction shall grow according to the forecasts [9]. Moreover, as there is a deficit of the quality raw material, the trend is to use artificial multi-component uniform batch mixtures often containing only an insignificant share of the natural raw material and mainly manmade raw material, i.e. industrial waste.

In order to study the waste behaviour (specifically, the metal component) under baking as part of ceramic mixture, sample blocks 5 cm on edge were produced. A polymineral clay raw material of the following composition was used [10]: quartz – 49 %, montmorillonite – 25 %, hydromica – 7 %, microcline – 5 %, kaolinite – 3 %, hematite – 2 %, anorthite – 1 %, amorphous phase – 8 %.
Chemical composition of the polymineral clay raw material: \( \text{Al}_2\text{O}_3 \) – 14.85\%, \( \text{SiO}_2 \) – 65.08\%, \( \text{Fe}_2\text{O}_3 \) – 11.65\%, \( \text{K}_2\text{O} \) – 3.45\%, \( \text{MgO} \) – 1.98\%, \( \text{TiO}_2 \) – 1.51\%, \( \text{CaO} \) – 1.24\%, \( \text{MnO}_2 \) – 0.24\%.

Trial composition of the ceramic mixture: 50% clay by 50% waste, water-solid ratio 18\% corresponding to the water content for the manufacture of articles by the method of plastic moulding. The mixture was poured into the mould uncompacted. The samples were dried under the temperature of 105°C and then baked under 900°C.

The baking resulted neither in distortion of samples, nor in cracks, nor in colour abnormalities. The average density of the samples after baking comprised 2.4 g/cm\(^3\), water absorption – 11.6\%, compression resistance – 13.47 MPa, which complies with the characteristics of the grade 125. The colour of samples is red.

The preliminary research confirms the possibility of use of the metal waterjet cutting waste in the manufacture of ceramic articles as a thinning agent for the coloration of the ceramic body (by virtue of high chromophore content, i.e. iron oxide and the cherry-red almandine contained in the waste). High content of iron compounds suggests the use of this waste as fluxing additive, however, the almandine resolves under the temperature exceeding 900°C to form ferromagnetic beads containing hercynite, ferrous cordierite and fayalite [11]. This probable process in the course of shaping of the ceramic body requires an extra study.

Considering the issue of coloration of the ceramic body it shall be born in mind that alongside the most wide-spread cherry-red almandine there are also purple, cherry-purple, crimson, red-brown and almost black varieties. The intensity of the red colour directly depends on the content of \( \text{Fe}^{2+} \). The almandine possesses a glassy, greasy, pitch lustre and its transparency varies from transparent to non-transparent.

6. Conclusions

According to the Federal Classificatory Catalogue of Wastes (FKKO 2017) the sand waste after waterjet cutting of ferrous and non-ferrous metals is referred to class V of hazard, i.e. is virtually non-hazardous. According to the generation mechanism and composition the metal waterjet cutting waste refers to mineral waste and by-products retaining natural properties, chemical and mineral composition of the original rock and natural minerals, and the recommendations for their treatment and use may be followed respectively [12]. This may be used after simple processing.

We research the possibility of use of this waste type in the following fields:

- manufacture of building ceramics (described above);
- cement manufacture – as corrective iron-bearing ingredient in the production of Portland cement clinker, as raw mixture component in the production of high ferriferous cements;
- as filling agent in general-purpose and special mortars;
- as colouring agent for the coloration of building materials [13];
- other methods of utilization.

The available literature on the waste utilization does not contain enough information regarding the use of the waterjet cutting waste, which can be particularly attributable to the absence of interest to the waste generated in small quantities. We find it essential to explore the possibilities to utilize not only the so called heavy tonnage industrial wastes, but also the wastes generated in moderate amounts, which is also a contribution to the solution of the problems of resource saving and environmental protection. Even wastes generated in small amounts may fill in the niche of the resource deficit in the production of this or that material.

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