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Wastewater and Abrasive Sludge Recycling Solutions from Abrasive Water Jet Cutting Machines (AWJCM)

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Abstract: *Due to the pressure that landfills have on the environment, the article deals with the possibility of recycling waste from abrasive water jet cutting machines (AWJCM) because this waste either takes the path of storage (abrasive sludge) or is discharged into public sewer systems (wastewater). Thus, for the abrasive sludge, two new mortar recipes were proposed, made by replacing fractions of sand with abrasive sludge. The series of cast samples R1 and R2 were subjected to mechanical tests and an increase in bulk density was found with the replacement of parts of the sand component with abrasive sludge, a decrease in mechanical tensile strength in bending and compression, which can be explained by the fact that wet abrasive sludge was used. Another line of research addressed the study of the possibility of reusing discharged wastewater. From this point of view, chemical analyzes were performed for two water samples on the basis of which it could be concluded that the recovered wastewater can be reused in the water supply installation of the abrasive water jet cutting machines. Based on the results obtained, it can be said that the resulting waste can be a raw material for the construction of building materials and can contribute to a considerable reduction in drinking water consumption.*

Keywords: *Waste recycling, abrasive sludge, wastewater, new mortars, AWJCM*

1. Introduction

Compared to conventional cutting processing techniques, abrasive water jet cutting with all the advantages it offers (precision, speed, obtaining complex geometries / shapes, non-modification of the structure of processed materials or diversity of materials) has the disadvantage of large quantities of water and abrasives used, but also the large volume of waste generated in the form of wastewater and sludge (mixture of water, organic/inorganic materials resulting from the discharged materials and abrasive), waste that currently has its way of storage.

In abrasive water jet cutting technology the main parameters are water pressure and its stability, but also the amount of water, the parameters that actually determine the energy of the water jet in the cutting head, energy that is transformed into kinetic energy [1], [2]. The principle of abrasive water jet cutting technology is presented in Fig.1 [1]. As abrasive water jet processing is the result of the interaction between the jet and the material being processed, the speed of the jet and the abrasive material used play an essential role in the quality of the product and the cost-effectiveness of the process. The efficiency of the cutting technology is also ensured by the use of dedicated software used for 2D contour drawing, 3D engraving, multi-axis processing, etc.

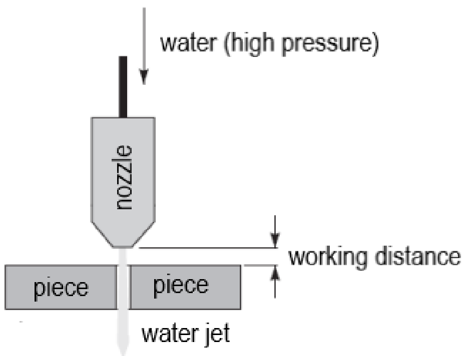

Fig. 1. The principle of abrasive water jet cutting technology [1]

However, with all its advantages, from the point of view of the disadvantage of the large quantities of waste generated, it can be said that the abrasive water cutting industry contributes to the pressure that the industrial sector puts on the environment.
From the analysis of the specialized literature, but also of the previous researches of the authors, it was concluded that, at present, no recycling practices are used, but they are evacuated, collected and temporarily stored in the company in barrels or bags, after which they take the storage final [3], [4], [5], [6]. On the other hand, it has been found that the route of abrasive sludge (disposal-collection-storage) has the greatest negative influence on the environment and for this reason these amounts should be reduced as much as possible.
From the point of view of the recycling of waste generated by abrasive water jet cutting machines / installations, two directions of analysis can be deduced:
- wastewater recycling;
- recycling of abrasive sludge.

With regard to recycling options, the following directions can be addressed:
- on-site recycling:
  - reuse of wastewater after settling and filtration;
  - reuse of the abrasive after drying the sludge and separating the abrasive;
  - reuse of processing waste;
  - the use of dry sludge to stabilize the soil.
- off-site recycling:
  - the use of abrasive sludge in construction materials.

In this context, of the options presented above, it is necessary to consider for the on-site recycling option, whether the abrasive sludge producer has the necessary space for sludge storage and drying and whether the benefit of reducing abrasive costs is substantial, and for off-site recycling, an analysis of the cost of transporting the abrasive sludge to the recycling site is important.
However, we should look at the environmental benefits of recycling and reusing this waste. For this reason, the article addresses on-site recycling options for wastewater and off-site recycling for abrasive sludge. Thus, chemical analyzes were taken and performed for the wastewater samples, and for the integration of the sludge in building materials, recipes were proposed that integrate the sludge in its state of collection, after the separation of the manufacturing waste, for which they were made tests on which mechanical strength tests were performed (tensile strength by bending and compressive strength).
Previous studies by some of the authors of this article have proposed a plant for the separation of the components of the mixture of wastewater, sludge and solid metals [3], so that the resulting waste is a raw material for new or classic building materials and contributes to the considerable reduction of drinking water consumption. Basically, the purpose of this article is to study whether the separate components can be used to make new mortars and whether the recovered wastewater can be reused in the water supply installation of abrasive water jet cutting machines.

2. Methods of analysis for the determination of solutions for the recycling of components of the mixture of wastewater and abrasive sludge

2.1. Analysis methods for wastewater recycling and reuse

The method of analyzing the composition of the wastewater resulting from the abrasive water jet cutting process is atomic absorption spectrophotometry AAS. The AAS atomic absorption spectrophotometry method, compared to classical methods, is much more accurate and uses a smaller amount of reagents, being used to control water quality. The method is part of the optical methods that are based on measuring the radiant power adsorbed by a population of free atoms; practically in absorption the main role is to atomize the sample.
In the first stage, the calibration curves were drawn based on which the concentrations of the metals present in the wastewater were determined. The possible metals present in the wastewater were sought, taking into account the materials that were cut.

For an assessment of the quality of the decanted wastewater and the evaluation of the presence of metals in the wastewater, two samples P1 and P2 were collected, in two different periods, periods in which the quantity and type of material discharged were followed. Samples P1 and P2 were collected in plastic containers which were filled to the brim.
Sample P1 was taken after settling the abrasive sludge resulting from the cutting of 50% stainless steel and 50% carbon steel. The P2 sample was taken after settling the abrasive sludge resulting from the cutting of 65% aluminum, 30% stainless steel and 5% carbon steel.
Thus, for the P1 sample, the concentration of Fe, Ni and Cr was monitored, and for the P2 sample, the concentration of Ca, Mg, Fe, Mn, Cr and Ni was monitored.
Given the possible reuse of the decanted water in the water supply installation of the abrasive water jet cutting machine, for the P1 test the water TDS was performed for the purpose of a general evaluation of the total inorganic salts, but also of the organic matter dissolved in water (Ca, Mg, etc.).
The possible presence of natural dissolved solids that may occur from the dissolution of components resulting from the cutting of materials or from abrasive material used for water jet cutting may cause some problems in cutting water supply installations with increasing TDS. In addition, for these reasons, the pH and conductivity of the water samples P1 and P2 were determined within 4 hours from the time of sampling.
Electrical conductivity is useful as an overall assessment of the quality of wastewater analyzed and has only been determined for the P1 sample because it remains relatively constant. Once established, it can be used as a basis for comparison with common conductivity measurements. Significant changes in conductivity could be an indicator if the range of materials cut is diversified.

2.2. Methods of analysis for recycling and reuse of abrasive sludge

In the literature, regarding the recycling and reuse of abrasive sludge there is an overview of the indicators and methods of analysis used in assessing the sustainability of sludge management in wastewater [7], while indicators that directly address the sustainability of abrasive sludge were less approached. However, four methods are generally used to assess the sustainability of the sludge part of wastewater treatment, namely: Life Cycle Assessment (LCA), Exergy Analysis (ExA), Economic Analysis or Cost-Benefit Analysis (CBA) and Analysis of Wastewater emergency (EmA), and a fifth method was later added, namely Environmental Risk Assessment (ERA), as it was used to assess the wastewater treatment process, including sludge treatment.
Life cycle assessment (LCA) is a common assessment method for wastewater treatment with the main application of assessing different categories of environmental impacts, such as the impact on global warming potential, depletion of resources or the ozone layer, ecotoxicity or degradation of the landscape. The main advantages of LCA are that the assessment process is described and standardized (ISO 14040, 2006 / AMD1,2020), that it can be applied to a wide range of areas, in terms of wastewater use and sewage sludge.
The main advantage but also the limiting factor of the Exergy Analysis (ExA) is that the whole assessment is based on a single quantifiable indicator: exergy but it only measures the efficiency of the processes, without giving an assessment of the various impacts on the environment. Emergency analysis (EMA) has recently become a more popular method of analysis, but its conclusion is that an outside investment is needed to repair the damage and replace the natural and human capital lost due to pollution.
Economic analysis (CBA), in the context of the environment, has only one indicator, all aspects of sustainability being expressed in monetary terms (called internalization in economic evaluation). The main environmental economic tools are cost-benefit analysis, life cycle cost and total cost assessment and the fifth method, Environmental Risk Assessment (ERA) examines the risk that threatens ecosystems and society related to technology, processes, or risk substances qualitatively or quantitatively.
Regarding the field of research done by us on this abrasive waste resulting from the use of abrasive water jet cutting machines and taking into account the resulting abrasive sludge, it is observed that it is composed of abrasive sand type Garnet. For the research presented in this article, the abrasive sludge was collected manually and stored for 7 days for settling (Fig.2).

Fig. 2. Abrasive sludge storage for settling

The decanted abrasive sludge was chemically analyzed to determine the concentration of metal components, and the results are presented in Table 1.

Table 1: Concentration of metals present in the abrasive sludge

Metal components	Zn	Cu	Ni	Fe	Mn	Cr	Ti
Concentration	175±10ppm	84±10ppm	207±15ppm	41.4±1%	0.7±0.02%	0.1±0.01%	1.3±0.04%

The analyzed abrasive sludge test is the result of the technological process of cutting 65% aluminum, 30% stainless steel and 5% carbon steel.
Three new mortar recipes were made, of which this article presents the first two recipes, R1 and R2. The structure of the recipes is a combination between the mortar recipe for determining the cement class (according to SR EN 196-1) and the sludge composition resulting from the chemical analysis (Table 1) correlated with the experience of the research team in the field.
The stages of the mortar tests are:
- establishing the recipes for the R1 and R2 test series (Table 2);

Table 2: Proposed recipes

New mortars Recipes	Cement CEM II A-LL 42.5R [g]	Sand 0.5/1-Sort 3 [g]	Abrasive sludge with a moisture content of 12.7% [g]	Superplasticizer Additive Master Glenium 27 [g]	Mixing water [ml]
R1	450	900	450	4.5	175
R2	450	675	675	4.5	175

- weighing of the materials used (Fig. 3) which was made with the Kern EW electronic balance with the precision of 0.1 g;

a) b) c) d) e)

Fig. 3. Weighing materials used
cement, b) sand, c) abrasive sludge, d) additive, e) water

- mixing the mixture (Fig. 4) which was made with the Auto-Mortar Mixer;

Fig. 4. Mixing materials used

- casting the samples (Fig. 5) in molds previously greased with BASF Master Finish RL 450 stripping agent

Fig. 5. Pour mixture

- compacting of the mixture by mechanical shocks (60 + 60 shocks) (Fig. 6);

Fig. 6. Compaction by mechanical shocks

- the samples were removed at the age of 1 day; it is observed that they do not show edge degradation (Fig. 7);

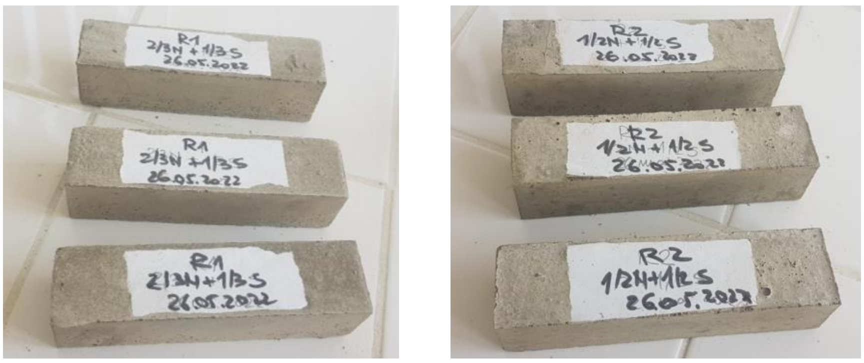

Fig. 7. The appearance of the samples after stripping

- immersing the samples in the pool with drinking water at a temperature of + - 20°C, until the moment of their testing (Fig. 8);

Fig. 8. Immersion of samples

- performing mechanical tests (Fig. 9) with a hydraulic press, using a loading speed of (50 + -10) N/sec for the bending test and (2400 + -200) N/sec for the compression test. The results obtained represent the arithmetic mean of the individual results in N/mm^2. The humidity of the abrasive sludge used for the samples is 12.7%.

a) b) c)

Fig. 9. Mechanical tests
a) bending tensile test, b) compression test, c) hydraulic press

3. Results and discussions

3.1. Results and the establishment of solutions for recycling and reuse of wastewater

The concentrations of metals present in the wastewater resulting from the cutting process, corresponding to the two samples taken are presented in Table 3 and Table 4, respectively.

Table 3: Concentration of metals present in decanted water - Sample P1

Sample	Content of Sample P1 [mg/l]			TDS (totally dissolved solids) [mg/l]
	Fe	Ni	Cr	
OLC wash water	0.045	sld(*)	sld(*)	333
	Detection limit [mg/l]			
	0.001	0.001	0.001	

sld$^{(*)}$ = below the detection limit

Table 4: Concentration of metals present in the decanted water - Sample P2

Sample	Content of Sample P2 [mg/l]					
	Ca	Mg	Fe	Mn	Cr	Ni
OLC wash water	14.8	3.9	sld(*)	sld(*)	sld(*)	0.01
	Detection limit [mg/l]					
	0.003	-	0.001	0.001	0.001	0.001

sld$^{(*)}$ = below the detection limit

The detection limits specified in Table 3 and Table 4 are below the maximum allowable concentrations for the detected metals. The concentrations below the detection limit, indicated in the two tables can be considered zero.

The pH and conductivity of the two wastewater samples, P1 and P2, were performed in order to compare the values obtained for the wastewater that is proposed to be reused with their values required for abrasive water jet cutting machines.
As indicators of general appreciation and not of water potability, pH and conductivity were determined only for sample P1, determined at 23 °C. For pH, a value of 8.5 was determined, which indicates a moderate alkaline character, and the determined value of electrical conductivity is 6 μS/cm. The Romanian drinking water law [8] specifies for water quality values lower than 2500 μS/cm, which means that the TDS is approximately 1250 mg/l, and the EPA (United States Environmental Protection Agency) [9] recommends performing laboratory tests for TDS greater than 500 mg/l or a conductivity greater than 1000 μS/cm.
As mentioned above in Chapter 2.1, the value of 333 mg/l determined for the P1 water sample, being below the limits established by both the Romanian drinking water law and the EPA, which means that in a general assessment, wastewater decanted meets drinking conditions.
From the point of view of the presence of metals (Fe, Ni, Cr) and the main ions (Ca, Mg), in the two water samples, it is observed in Table 5 that the allowed values for industrial waters [10] from technological processes of mechanical processing, but not the permissible ones for surface waters [11].

Table 5: Comparison of values for metals detected in wastewater

Contaminate	U.M.	Measured values		Permissible limit values	
		P1	P2	Surface water	Industrial water from mechanical processing
Metals					
Fe	**[mg/l]**	0.045	sld(*)	0.1	5
Ni	**[mg/l]**	sld(*)	0.01	0.01	0.5
Cr	**[mg/l]**	sld(*)	sld(*)	0.005	1
Main ions for the sample P2					
Ca	**[mg/l]**	14.8		180	300
Mg	**[mg/l]**	3.9		40	100
Mn	**[mg/l]**	sld(*)		-	1

The comparative analysis between the permissible limits for industrial and surface water was carried out in view of the direction of sludge recycling on the one hand to stabilize the land and on the other hand to analyze its reuse for feeding the abrasive water jet cutting machine in safety conditions.
Following the results obtained on the basis of chemical analyzes, it can be seen that the waste water resulting from the technological process of cutting with abrasive water jet can be reused to supply the cutting machine or for other technological processes. These measures will contribute to a considerable reduction in the consumption of drinking water and thus of the energy consumed for its production.

3.2. Results and the establishment of solutions for recycling and use of abrasive sludge

The attempt to recycle and use abrasive sludge on new construction materials materialized in these researches by making three series of new mortar recipes, three samples each, of which in this article are presented the series of samples R1 and R2. The structure of their recipes is a combination between the mortar recipe for determining the cement class (according to SR EN 196-1) and the composition of the abrasive sludge resulting from the chemical analysis, correlated with the experience of the research team in the field. Thus, in the sample series R1 (2/3N + 1/3S) 1/3 of the total amount of sand (N) with abrasive sludge (S) was replaced and in the sample series R2 (1/2N+1/2S) 1/2 of the total amount sand (N) was replaced with abrasive sludge(S).
The average values by series of the physical-mechanical characteristics of the samples were determined at the age of 7 days (Table 6).

Table 6: Physical-mechanical characteristics at 7 days on the R1 and R2 mortar sample series

Sample series	Apparent density ρ_a [Kg/m^3]	$\Delta\rho_a$ [%]	Bending tensile strength f_{ti} [N/mm^2]	Δf_{ti} [%]	Compression strength f_c [N/mm^2]	Δf_c [%]
R1	2331.25	4.13	4.48	-19.19	32.88	-31.99
R2	2427.73		3.62		22.36	

From the comparative analysis of the values of the physical-mechanical characteristics determined at the age of 7 days (Table 6), respectively of the apparent density, of the tensile strengths in the bending and of the compressive strengths, for the series of new mortar samples made R1 and R2 can be seen that by switching from the R1 mortar recipe to the R2 mortar recipe, with the increase in the amount of abrasive sludge in the recipe and the decrease in the amount of sand at the same time, the apparent density increased by 4.13% while the tensile strength from bending decreased by 19.19% and compressive strength by 31.99%.
It is observed that the apparent density of the samples from the two studied series exceeds 2000 kg/m^3 and the compressive strengths exceed the value of 20 N/mm^2, as such the abrasive sludge resulting from the technological process of cutting with abrasive water jet can be reused to make new materials such as new mortars that could be included in the field of construction repair mortars.
The physical-mechanical characteristics are to be determined at the age of 28 days and the experimental program that is in progress will continue with other new mortar recipes.

4. Conclusions

Currently, the wastewater and abrasive sludge, analyzed in this paper is a problem, but the results obtained and presented above show that they are a resource in terms of both wastewater and abrasive sludge.
Unfortunately, in Romania there are no major concerns regarding the prevention, reduction and recycling of industrial waste. Redesigning the entire chain of current production systems could lead to the concept: waste from one process can be a raw material for another or even for itself. In this regard, the results presented above show that wastewater resulting from the process of cutting abrasive water jet can be a resource for the cutting machine or other technological processes dependent on drinking water, after a simple decantation.
From the point of view of the current abrasive sludge route, it can be said that its integration into the construction materials proposed in the article could significantly contribute to reducing the amount of landfilled waste, which puts pressure on the environment.
Therefore, the waste that is the subject of this article may be a shortcoming or a resource only depending on how we manage it.
As future research directions, the authors aim to create new recipes for obtaining construction materials that use this waste and the results to form a basis for other researchers and research in the field.

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