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Abstract

The problem related to the reuse of sludge deriving from the cutting of ornamental stone is a relevant topic for many countries. Even if many studies are carried out on the recovery of sludge resulting from carbonatic cutting rocks the reuse of silicatic sawing sludge remains a challenge due to higher amount of metals than carbonatic stone sludge.

Two kind of silicatic sawing sludge reuse in the building sector have been analysed on the basis of their physical-chemical characteristics. The recoveries were planned based on the sludge metals content. The first use, as CLSM (Control Low Strength Material), provided the use of sludge as filler with the goal to increase the capacity to dissipate thermal energy, due to the passage in the sub-road network of sub-services. The second reuse is for thermo-eco-mortar for plaster, as filler which allow a thermal insulation and at the same time a good mechanical resistance. The properties of mortar for plaster and of CLSM have been evaluated by means technological test on specimens made with different composition (mix design).

The choice of the type of recovery was carried out on the basis of chemical and magnetic separations carried out during the sludge characterization steps. Moreover, chemical analysis and leaching tests were performed on the finished product to verify the amount of metals present in the product obtained.

Economic evaluation has been carried out on the cost sludge disposal in comparison with its recovery as raw material for building construction, demonstrating an interesting approach not only on the environmental but also on the economic point of view.

Keywords: ornamental stone, sawing sludge, eco-mortar, CLSM

Introduction

The directive 2008/98/EC defines the concept of “end-of-waste” and the priority order of hierarchy actions for waste management. “Prevention” action is a measure aimed at reducing the amount of waste and the content of hazardous materials; “re-use, recycling and recovery” of waste are all actions aimed at increasing resource efficiency, and reducing environmental impact. The rock processing waste managing option, according to European Strategies on Best Available Technique (BAT), is for land use, e.g., as aggregates or for restoration.

Sawing sludges are produced through the cutting operations during the processing of ornamental stones, made by means of different techniques (gangsaw, diamond blade, diamond wire) depending upon the mineralogical composition of the original stone. The residual sludge obtained is classified as inert waste (EWC code 010413) and normally it is intended to landfill disposal. Due to huge quantities yearly produced (5 million tons in UE according to Graziani et al., 2015 and Zichella et al., 2018), the management of residual sawing sludge represents an environmental and economic issue to solve. Currently, the reuse of secondary raw material and reduction of waste is one of the main tasks of European Commission's Strategy on the Prevention and Recycling Waste (EC raw material strategies) for circular economy criteria. Unfortunately, their recycling as a valuable secondary raw material is a challenging task as a consequence of their very fine particle size distribution, high water content and the presence of heavy metals, deriving from wear and tear of cutting tools (Careddu et al., 2016; Choorackal et al., 2019a; Singh Chouhan et al., 2019; Zichella et al., 2020 a) which prevents their direct reuse without any treatment or processing because of its potential contaminating.

Several studies tried to identify potential industrial applications in which sludge may be employed, mainly in the field of construction and building materials. Al-Hamaiedeh et al. (2013), analyzing the effect of adding different amount of granite sludge powder in cement mortar and concrete, observed an increase in the setting time and in the compressive strength of concrete. Amin et al. (2017) and Mashaly et al. (2018) investigated the feasibility of using granite sludge as a supplementary cementitious material in mortar and concrete. They highlighted that the addition of granite sludge resulted in a negligible reduction in the mechanical properties if the substitution percentage does not exceed 20%. The positive effects of granite by-product in the production of mortar and concrete were also pointed out by Singh et al. (2016, 2017), while Da Silva et al. (2020) highlighted that the replacement of the fine aggregate by granite powder in the mortar resulted in a lower depth of carbonation, considering the variable exposure time, increase the durability of the mortar.. Ghannam S. et al. (2016) study the sand replacement with powder composed of iron and granite sludge; this experiment showed an increase of strength resistance on concrete.

The feasibility of using silicate sawing sludge in CLSM and in plaster production was assessed in the present study. The aim is to investigate the potential reuse of sawing sludge exploiting the chemical and mineralogical properties of the same. Chemical analysis and leaching test were also considered to demonstrate that the use of the cement may reduce the release in the environment of heavy metals, which were highly present in the original employed sludge, due to the encapsulation phenomena provided by the hydraulic binder.

Materials and Methods

Two type of sludge, named hereinafter A and B and both deriving from cutting plants located in the north-west of Italy, were considered in the experimental investigation. Details of sludges are listed in Table 1.

Table 1. Details of employed sludge

Sludge type	Stone type	Composition	Cutting technology	Possible reuse
A	Serizzo	quartz 30%, plagioclase 25%, orthoclase 26%, biotite 10%, muscovite 5%, epidote 3%, accessory 1%.	Gangsaw	CLSM
B	Luserna	quartz 50%, plagioclase 15%, alkaline feldspar 20%, white mica 5%, chlorite 5%, epidote 5%.	Diamond wire	plaster

A preliminary investigation was carried out for the particle size distribution analysis, performed according to UNI EN 933 Part 1 [18]. The particle size distribution (Fig. 1) the curve is very similar for both samples analysed.

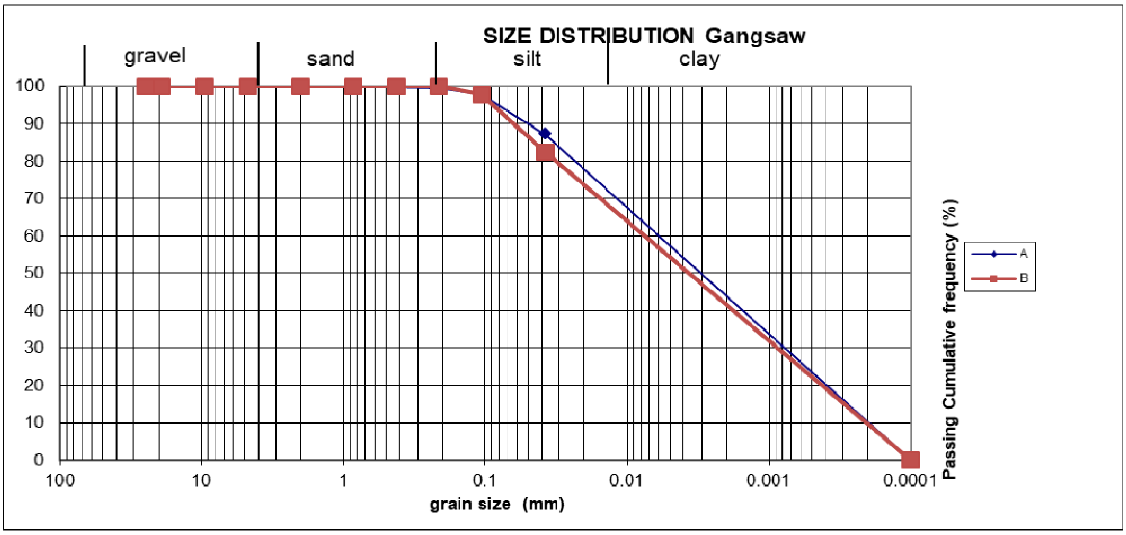

Figure 1. Particle size distribution results of sludge A (deriving from Serizzo gangasaw cutting) and B (deriving from Luserna diamond wire cutting).

Sawing sludge, from diamond wire and gangsaw cutting, contains a fraction from the mineral part and a metal fraction derived from the tool's wear. For this reason, magnetic separation (table 2), chemical analysis (table 3) and leaching tests (table 4) were performed on the sawing sludge sample A and B. The quantification of the metal content in the sludge is necessary to define what is now a waste, a secondary raw material that can be used in other production processes (in accordance with European Directive 2008/98/EC). Magnetic separation, by means of Eriez Magnetic Separator (Kolm-type high gradient), was performed to identify the quantity of metal content in the sludge sample. One of the main requirements for plaster application is thermal insulation. A low metal content can produce a lower thermal conductivity since metals are good thermal conductors. For CLSM application, instead, the high value of metal content is essential to highlight the effect on CLSM thermal properties. The results obtained, with the law threshold concentration limits, are reported in Table 3 and 4 respectively for chemical analysis and leaching test.

Table 2. Results of magnetic separation performed on sawing sludge.

Sludge code	Magnetic fraction [%]	Amagnetic fraction [%]
A	2.96	97.04
B	1.95	98.05

Table 3. Chemical composition (heavy metals, iron) of employed sludge (threshold limits in accordance with the Italian D.Lgs. 152/2006 Annex 5, title V, part IV and Art. 8 of the D.M. 05/02/1998).

Sludge type	**Ba**	**Cu**	**Zn**	**Co**	**Ni**	**V**	**Cd**	**Cr_{tot}**	**CrVI**	**Pb**	**Fe**
	[mg/kg]										
A	68	186	54.5	10.4	86.5	25.6	<1	130	<5	4.7	34.28
B	<5	41.89	24.82	26.15	<0.01	<1	<0.1	18.21	<5	23	43.40
Threshold limits for reuse											
Industrial/Commercial	-	600	1000	250	500	-	15	800	15	1000	-

Table 4. Leaching test results of employed sludge (threshold limits in accordance to MD-186, 2006).

Sludge type	**Ba**	**Cu**	**Zn**	**Co**	**Ni**	**V**	**Cd**	**Cr_{tot}**	**CrVI**	**Pb**	**Fe**
	[mg/l]	[mg/l]	[mg/l]	[μg/l]	[μg/l]	[μg/l]	[μg/l]	[μg/l]	[μg/l]	[μg/l]	[mg/l]
A	<0.01	<0.001	<0.001	4.49	<1	5.48	<1	<1	<0.01	<1	0.03
B	<0.1	<0.031	<0.01	<10	<1	<1	<0.1	<1	<0.01	<1	1.3
Threshold limits for reuse											
	1	0.05	3	250	10	250	5	50	-	50	-

Results and Discussion

The results obtained from CLSM final product tests and Plaster final products tests are reported respectively in table 5 and 6.

Table 5. Technical data sheet of CLSM samples. A50: sample A with 50g of cement in the mix design; A100: sample A with 100g of cement in mix design. (Source data: Zichella L. et al. 2020 b).

CLSM TESTS CARRIED OUT	**A50 (A)**	**A100 (A)**
Sludge quartz content [%]	39.94	
Sludge Specific gravity [g/cm^3]	2.67	
Sludge Metal content [%]	2.96	
Mix design W/P ratio	0.85	0.75
Mix design Thermal conductivity [W/m*K]	0.51	0.84
Flowability diameter [cm]	24.5	22.8

Table 6. Technical data sheet of plaster sample. (Source data: Zichella L. et al. 2020 c)

TESTS CARRIED OUT	Plaster (B)	TEST CARRIED OUT	Plaster (B)
Fresh condition – density [kg/m3]	1380	Compressive strenght after freeze and thaw [MPa]	10.76
Dry condition – volumic mass [kg/m^3]	1264	Compressive strength category (UNI EN 998-1)	CS IV
Fresh condition – slump test -Hargerman cone diameter: 100mm	No evident slump	Flexural strenght[MPa]	1.03
Thermal Conductivity - 15 days [W/m*K]	0.302	Flexural strength after freeze and thaw [MPa]	0.93
Thermal Conductivity - 68 days [W/m*K]	0.204	Water absorption [%]	19÷20
Thermal Conductivity – dry condition [W/m*K]	0.201	Resistance salt crystallization cycle	No evident decay.
Pull off [MPa]	1.55	Flexural strength after salt crystallization cycle [MPa]	1.67
Compressive strenght [MPa]	11.97	Water absorption after salt crystallization cycle	Breakdown of sample during saturation step.

Concerning CLSM products, it can be assert that the mix design A50 and A100, meets the requirements for this application. Some observation can be supported, in particular:

- change of w/p ratio, achieve a significantly change on workability, fluidity and thermal conductivity properties, on the other side, affect not much the resilient response of the materials;
- an increase of cement content produce a worsening of fluidity properties, while in dry condition an improving of resistance and thermal conductivity;
- thermal conductivity values are better than CLSM with standard aggregates, due to the sawing sludge quartz and metals content.
- leaching test on CLSM samples shows that there is no release of metals, as the cement mortar well incorporates the sawing sludge metals.

Concerning Thermal-Eco-Mortar for plaster application, sawing sludge with low content of metals as B (Luserna stone cutting with diamond blade), improved the rheological, thermal and physical performance, conferring a light macroporous cellular structure by means adding organic foam. This characteristic facilitate plaster installation even for high thickness. The mechanical strength and thermal conductivity obtained exceed the values of standard plaster, making this ecofriendly plaster an excellent product, ideal for energy saving of buildings and in environments with high presence of humidity. Resistance to salt crystallization reported a breakdown of samples after water absorption test. This feature should be investigated by comparing the results of a normal production plaster.

Conclusion

Nowadays there is no market or regulation to enhance the recovery of silicate sawing sludge as CLSM or Plaster. The studied recoveries were carried out on sludge without any treatment for economic advantages and to avoid disposal in landfill. For those sludge with high metals concentration limits, a pre-treatment could be provided through a magnetic separation. Magnetic separation could be a good method to be applied at industrial level, which could be considered a treatment of normal industrial practice, as it does not change the state of the material. This method not added any substances, simply divided the sludge in two by-products (magnetic and amagnetic), with an high degree of purity. Magnetic product, rich in metals, can be reused in other productive sectors, or disposed in landfills (economic advantage due to a reduction of quantities dispose to landfill). Amagnetic product, mostly lithoids material, could be reused in building sector. The recovery of sludge as it is and/or after magnetic separation could turn a unidirectional system into a circular system. An economic evaluation demonstrates that a reuse of sawing sludge as byproduct it brings an economic saving of 10% for material considered as inert and 35% for material considered as special non-hazardous waste.

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