Bio-Inspired Method for Advanced Industrial Sludge Treatment with Closed Cycle Drying Process

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Abstract - The article describes a new bio-inspired process for the Advanced Treatment of Industrial Sludge with a Closed Cycle Drying Process (TAFIPACC).This process represents an innovation in the way of treating sludge and other shovellable residues deriving from machining and widespread industrial processes in the largest industrial installations, such as refineries, steel mills, chemical plants, glass processing installations, cosmetics manufacturing facilities, pharmaceutical manufacturing plants, paper mills. The process starts from the use of mixers in the production of concrete, and makes a thermal contribution to the material during mixing stage, thus separating part of these substances directing them to an integrated process of fractional distillation. The article introduces "clean-up" as a new process through an innovative stage of evaporation and distillation in a closed cycle which is able to separate and collect pollutants and volatile components that would be otherwise dispersed into the atmosphere as in the case of more traditional methods of open-cycle sludge drying.

Keywords - Industrial lime, treatment, pollution, energy recovery,environment, distillation

I. Introduction

Nowadays different industrial plant sludge treatment methods are in use. The main ones are:

- Centrifugation: it consists of separating water from sludge by means of application of a centrifugal force[1];
- Incineration: waste is eliminated by means of incineration, with the scope of obtaining energy. Only 70% of the volume of waste is eliminated with a subsequent ash disposal;
- Inerting - Stabilization: the process of making highly critical rejection for consistency and chemical-physical characteristics manipulatable and inhibiting the release of contaminants. The set of the two mechanisms involves the transformation of waste into an easily movable solid, with little surface area exposed to the surrounding environment, inside which the pollutants are trapped, stuck in insoluble compounds;
- Thermal Desorption: solid waste, such as soil and sludge, is heated causing the vapourization of all those contaminants characterized by a boiling point inferior to the heating temperatures. The TAFIPACC method assembles by integrating two types of processes closely related to each other: inerting - stabilization / thermal desorption and combining them into a single system. This means that the individual process deficiencies may be reset in a single cycle. In the TAFIPACC process, the treatment of a certain type of waste, such as industrial sludge, will allow reducing its volume and associated emissions, improving and minimizing the mobility of contaminated elements present in them. The high costs of numerous sludge treatment techniques currently in use have triggered the development of alternative techniques such as the one proposed. For the time being, it appears to be a more economical solution, which significantly reduces the mobility of pollutants resulting in less environmental impact.

II. The Process

TAFIPACC is a new automatic methodology for the treatment of polluted sludge that puts at the centre of the process 3 mc planetary mixers made of vibrated concrete [2] flanked by a series of devices that allow the extraction of the volatile portion of the worked refusal.

Such a machine will be equipped, on the underside, with a device for heating, which has never before been applied to a concrete mixer. It allows a desired increase of the temperature of the content within the mixing tank, causing the evaporation of volatile substances so that they separate from the sludge during treatment.

The functionality of this device implies the use of the heated air that will be made circulate in a cavity created around the mixing tank. The flow and temperatures will be regulated so as to control the thermal increments (critical factor under study).

Flanked to the mixer, an air recirculation circuit will be arranged. A high prevalence ventilator will suck up the air filled by vapour emitted from the mixing and heated sludge.

The air is then pushed through the radiators of two heat pumps. In its recirculation the air will pass from the first radiator, where the less volatile part of the vapour will condense to extract almost clean water.

The air will then pass from the second, cooler radiator enabling condensation of the most volatile elements, i.e. hydrocarbons at increased pollutant content to confer on the dedicated disposal. By doing this, it is avoided that these hazardous pollutants (e.g. harmful hydrocarbons, Benzene, Fluorene, Pyrene, etc.), may be dispersed into the atmosphere, as is the case in many traditional systems for industrial sludge drying which inflict great damage for the environment. In these first two radiators the initial hot air will cool; crossing the hot radiators of heat pumps it will regain temperature before returning into the mixer, obtaining indeed an energy recovery. Before entering the mixer, the fluid will pass through a rolling valve which will decrease the pressure inside the mixer (facilitating the evaporation) and increase pressure in the branches of the closed cycle where radiators are located (thus facilitating condensation in cold radiators).

A bag filter that saves impurities and dust entrance presides over the cleaning of this condensation line.

The mixer will also be equipped with a moisture detection probe that, by sending data to the supervising automation device, will allow constant monitoring of the drying progress and automatically maintain the determined values of residual moisture.

The machine will be sized to treat the quantity equal to 3 ton / h of polluted sludge and consequently produce 3 mc / h of high quality vibrated concrete, therefore it is suitable to be applied (using appropriate equipment available on the market) for the packaging of different kinds of high quality goods (e.g. tiles, building blocks, interlocking paving, heavy blocks for various uses, etc.). This places an added value to the sludge treatment process with a profitable use of the output material. To treat 3 tons of sludge, around 4.7 tons of clean inert and 0.6 tons of cement will be used.

These are the initial reference values that will be tested and optimized during the research. By treating 3 tons of sludge it is supposed that 30% of the liquid part from the sludge will be extracted by the circulation of air in the distillers. Of this liquid part, the desired goal is to obtain 50% clean and immediately usable water and the other 50% of water assigned to an integrated module in the prototype dedicated to the treatment of liquids with high content of pollution, whereas the residual water will be recovered by separating any contaminants present in it.

The TAFIPACC method, as the result of the combination of two types of sludge treatment (inerting - stabilization / thermal desorption) into a single system, permits a significant reduction of costs. Moreover, this proposed alternative technique is not only more economically advantageous but also minimizes the mobility of pollutants resulting in a lower environmental impact.

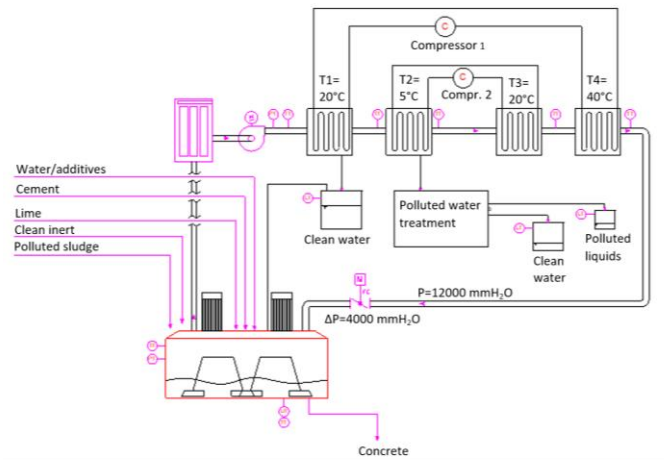

Fig. 1. Process diagram.

III. Planetary Mixer

The structure of the mixer consists of two parts:

- The power plant where the epicyclic reduction locates (Fig.2a);
- The mixing tank with a 4 m diameter (Fig. 2b).

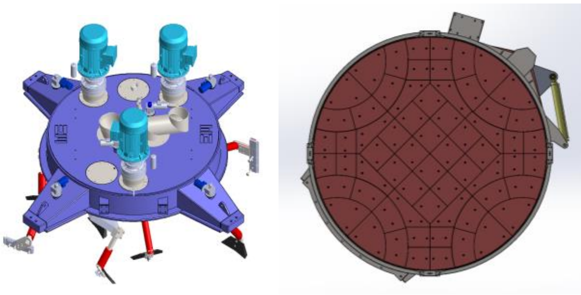

Fig. 2. (a) Power plant; (b) Mixing tank.

The electric motor, placed above the reducer cap, through an epicyclic water seal reducer and gears transmission, transfers the movement to the mixing equipment.

Every motor is connected to its own reducer which presents sprocket wheel which in turn gets started with the fifth wheel, namely a type of axial bearing for low rotational speed and high axle load applications. The fifth wheel is composed of an internal ring, fixed to the power loom, and the external slip ring supporting the whole disk.

To the plate carrier, bottomed scraping shovels, of side, and mixing stars are fixed.

The latter are joint to the fifth wheel so to be consequently dragged with the rotation of the second, which rotating around its own reference axis gears with the fixed crown.

The inferior part of the mixer consists of a mixing tank with an opening at the bottom closed by a rotating hatch whose automate opening occurs by means of a hydraulic cylinder once the mixing stage of concrete has finished.

This is hinged in its axis which rotates inside the sleeve. For this reason, the axis and its relative bearings must be suitably measured.

In order to get the tank sizing, some calculations based on "soft output volume" which indicates the finished product which derives from the conclusion of the manufacturing cycle and "vibrating output volume" which is the volume of the sleeve once it is implemented and thus vibrated, have been made.

Once the broad measures of the tank, and hence of the hatch, were stated, the measures of the hydraulic piston and supports, the fixed one (tank side) and the mobile one (hatch side), were determined assuring the correct alignment among these, thus avoiding transverse forces components which cause an early wear of the scroll bushing of the shank [3, 4].

By considering the exercise pressure as equal to 180 bar, the tangential force was calculated per unit lengh, which acts on the outer edge of the hatch through the balance of the moments with regard to the pole consisting of the axis of the hatch (Fig. 3).

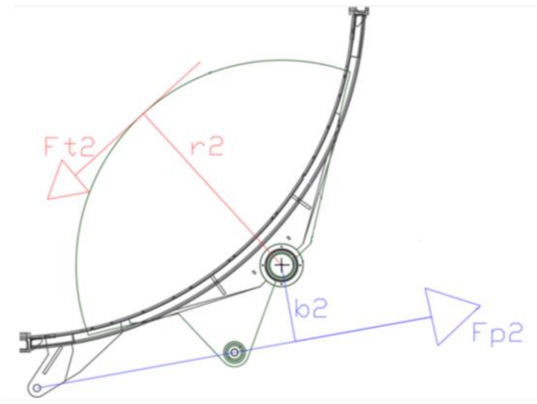

Fig. 3. Forces acting on the hatch.

For a watertightness of the tank, seals in polieuretano lodging on the contact surfaces of the tank and hatch are arranged. These, going through with a creeping contact, are subject to wear, hence the necessity of evaluating the tension degree (4) necessary to ensure tightness, avoiding excesses which cause an early wear of seals. In the solution of the matter, in addition to material, profile shape and the interference degree (5) between the fixed part (the tank) and the moving part (the hatch) of the seals couple play a leading role.

The door is supported by the shaft sized to withstand the stresses due to the weight of the concrete and the forces induced by the opening cylinder.

The shaft has a variable diameter along the axis due to the shoulders for the bearings, for which the correct coupling tolerance has been obtained [7].

IV. The Packaging of the Concrete

One of the techniques currently employed for inerting dangerous sludge is packaging in concrete containers for recycling as an aggregate [8].

In this way the pollutants present in the sludge are incorporated in the cement matrix at high strength avoiding the reaction with the atmospheric agents and enter the environmental life cycle.

Depending on sludge composition, hydrated lime which acts as a disinfectant and contrasts the odoriferous waste components can be used.

Since the proposed waste treatment process presupposes the use of concrete packaging, a reference to the guidelines for its production must be made. In order to obtain common medium strength and consistency, a cubic meter of concrete is composed of:

- Sand	720 kg
- Crushed	1280 kg
- Cement	300 kg
- Water	120l kg

The relationship between water and cement a / c = w is of a great importance.

For a perfect reaction of cement, a ratio w equal to 0.28 [9] which would be the reaction stoichiometric ratio would suffice. In reality, this ratio is slightly increased to allow a better hydration of cement and provide the mixture with certain workability.

An increase in the water-cement ratio over 0.4 leads to a degradation of the final characteristics of strength and permeability of concrete as shown in the charts below:

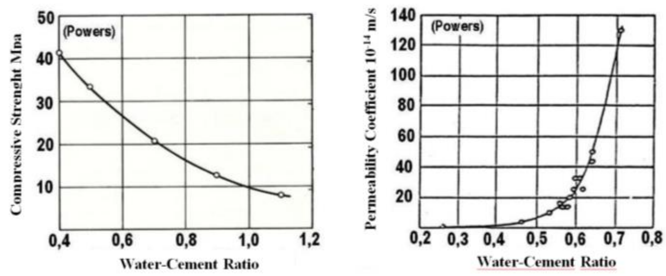

Fig. 4. Strength and permeability of concrete.

During the testing phase of TAFIPACC processes proposals to optimize the product output, both in terms of physical characteristics and costs, will be defined.

V. Details of the Process

To test the TAFIPACC treatment, the evaluation, by means of an appropriate analysis of the chemical - physical characteristics of any potential sludge to be treated, has been performed. The analysis allows both to choose the most suitable sludge in terms of the content of pollutants, with which to run tests, and to compare the chemical characteristics of the pre- and post-treatment sludge.

Tests have been carried out on the sludge falling within the category "CER 19:08:13, sludges containing dangerous substances coming from other treatments", i.e. sludge from industrial wastewater (hazardous).

The current methods for treating dangerous sludge are illustrated below; and a possible scenario of application of the method and its potential TAFIPACC benefit is simulated. The selected waste can actually be decomposed into its two main constituents:

Residue or dried substance at 105°C	% P	42.61
Water	%P	57.39

The sludge then presents traces of hydrocarbons and heavy metals. So 1000 kg of water results in about 570 kg of sludge. In the inerting process by means of concrete packaging, the water in the waste is used as the water to hydrate the cement. The following ratios, which are necessary to obtain good concrete, must have fixed values:

- The water/cement ratio is kept low in order to ensure the production of a concrete structure of high mechanical quality, as it is crucial that the pollutants are blocked in the cement matrix.

- the ratio of the inert part with the cement that by a ratio of the part of the hydraulic binder used and the solid inert part from the sludge and by the granulometric Joint employed, must be around 4 (+ Inert dry part of the sludge) = 3.85 (Cement)

- the ratio of lime and the solid matrix of the compound. Lime is used to disinfect and eliminate the odorous part of the waste. However, lime stabilization may allow odors to return; To eliminate this problem and reduce pathogen levels, addition of sufficient quantities of lime to raise and maintain the biosolids pH [10] Its effectiveness is proportionate to the quantity of lime used, relative to the entire solid matrix of the compound consisting of the solid part of the sludge, aggregates and concrete, resulting in a good value of about

0.17 (Lime) = 0.17 (+ Inert part dry sludge + cem.).

When the present amount of dry sludge and water is known, the amount of cement, lime and clean inert is obtained.

Therefore the components needed to prepare concrete with a ton of sludge are summarized below, stating the required weight and volume.

TABLE I. COMPONENTS REQUIRED FOR A SLUDGE TON.

Component Description	Weight [kg]	Specific Weight [t/mc]	Volume [lt]	Weight [kg/mc of concrete]
Sludge's Dried Part	426	1.6	266.25	112.546
Water (In the Sludge)	574	1	574	151.646
Cement	1435	3	478.33	379.116
Clean Inert	5113	2.6	1966.54	1350.82
Lime	1200	2.4	500	317.031
Concrete	**8748**		**3785.12**	**2311.15**

The numbers represent those which are necessary to pack concrete using the input of a ton of sludge according to the relations above. By converting the weight into volume, through the specific weight, it appears that in order to carry out the packaging of a ton of sludge a mixing tank of 3.78 mc is necessary (in red in the table). The relationship introduced above will be taken into account also in the preparation of a new formula to be used downstream of a preliminary dewatering of the sludge through the treatment using the new TAFIPACC plant. The only ratio that will be altered is the one between lime and the solid matrix of the compound. It will be reduced, without altering the quality of mps in output, since during the evaporation process inside the TAFIPACC treatment plant the particles containing the volatile odoriferous substances will also be removed.

Drastically decreasing the presence of such substances within the compound, it is also possible to reduce the amount of lime required to eliminate odours. It is prudently estimated that the intake of lime can be reduced by up to 20%, bringing the ratio of 0.17 down to 0.137.

If we aim to eliminate 15% by weight of the sludge in the analysis, it can be done by extracting 1000kg from the initial sludge and about 150lt of water incorporated therein prior to the production of concrete. Considering the same sludge without 150 kg of eliminated water, and keeping the relationships stable and unvaried, less than that from lime (0.17 to 0.137), the new formula will be as follows, highlighting the required values in green:

TABLE II. NEW FORMULA FOR A SLUDGE TON.

Component Description	Weight [kg]	Specific Weight [t/mc]	Volume [lt]	Weight [kg/mc of concrete]
Sludge's Dried Part	426	1.6	266.25	154.973
Water (In the dried Sludge)	424	1	424	154.245
Cement	1060	3	353.33	385.613
Clean Inert	3665.5	2.6	1409.82	1333.47
Lime	709.13	2.4	295.470	257.971
Concrete	**6284.7**		**2748.87**	**2286.27**

Below is a comparison between two treatment methods. The delta value between the weights suggested by the two formulas is highlighted.

TABLE III. COMPARISON BETWEEN TWO TREATMENT METHODS.

Component Description	Initial Formula [kg]	Formula After Treatment [kg]	DELTA [kg]
Sludge's Dried Part	426	426	0
Water (In the dried Sludge)	574	424	-150
Cement	1435	1060	-375
Clean Inert	5113	3666	-1447
Lime	1200	709	-491
Calcestruzzo	8748	6285	-2463

It can be stated that by using TAFIPACC treatment method, the following savings of valuable materials can be made, in terms of weight and price:

TABLE IV. SAVING OF MATERIAL.

Component	[kg]	[Euro/Ton]	[Euro]
Cement	375	70	26.25
Clean Inert	1447	5	7.2
Lime	491	107	52.6
Total			**86**

To treat then the same amount of sludge of 1000kg, a net saving of 86 euros in terms of savings of valuable material (aggregates, cement and lime) is obtained.

VI. PROCESS ENERGY BALANCE

Relative humidity RH (%)

The amount of water vapour that can be contained in one kg of dry air is not unlimited. Over a certain amount, the added steam condenses in the form of minute droplets (i.e. fog effect).

Relative humidity is the percentage of vapour contained in the air in relation to the maximum quantity holding in it at a certain temperature.

For example: 1kg of air at a dry bulb temperature of 20 ° C may at most contain 14.7g of water vapour (added steam should condense); therefore, the mixture consisting of 1kg of dry air and 14.7g of water vapour has, at a temperature of 20 ° C, the relative humidity equal to 100% (saturation conditions); however, at the same temperature, if 1kg of dry air contained 7.35g of steam (i.e. half of the maximum amount of steam miscible at 20°C), the mixture would be at a the relative humidity of 50%.

The relative air humidity is strictly related to the dry bulb temperature.

At parity of grams of water vapour present in a kg of dry air, the relative humidity increases as the temperature decreases; this can be explained as follows: the lower the air temperature, the lower the miscibility of the water vapour in the air [11].

The psychometric chart at a given pressure (the one reported herein at a pressure of 1,013 bar) represents curves of various UR percentages. In particular, the upper one is the curve of 100% RH that represents the dew point of water vapour mixed in function of temperature and also indicates the amount of water vapour miscible in 1 kg of air.

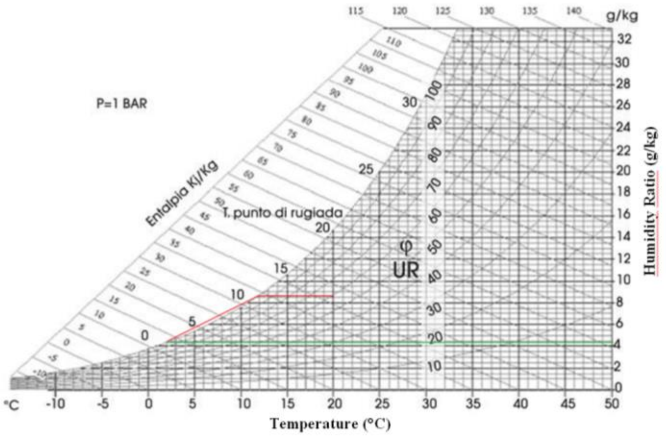

Fig. 5. Psychrometric chart

By varying the conditions of the fluid, the water vapour contained therein can then condense so that it is possible to pull it out in the liquid form. Observing a simplified diagram, it can be concluded that having a mass of air at 40 ° C at the relative humidity equal to 100%, the total amount of water contained in it results in almost 50 g / kg of air. Considering with a good approximation that 1 kg of air corresponds to 1mc of air under normal conditions, it can be stated that about 50 g / m3 of air are inside.

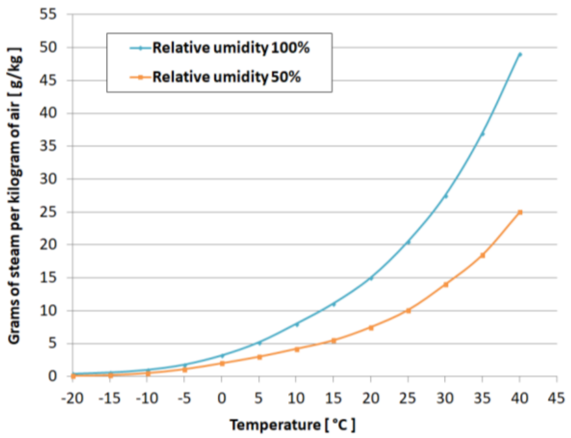

Fig. 6. Curves of the Various UR Percentages

If the air is cooled to 5 ° C, the water content miscible in it in the form of vapour passes from almost 50 g / kg to about 5 g / kg. As a result, 45 grams of water condense.

<u>Energy balance</u>

In order to estimate the energy contribution, the cycle envisaged by TAFIPACC method is briefly summarized. The method consists of a dehydration process of the sludge prior to the concrete packaging. Considering the same 1000kg of sludge and an elimination of water content equal to 15% by sludge weight, the system must expel 150lt of water. This process of water extraction from the sludge is completed in two distinct phases that require a certain energy intake.

In the first phase, it is necessary to evaporate water and the volatile polluting substances in the sludge to separate them from the sludgy mass and dissipate them in the air; whereas in the second phase the dissipated vapours are captured by the condensing coils.

Considering the process in more detail, its phases are indicated as follows:

1) Heating of the sludge and the interior of the mixer up to 40 °C.
2) Evaporation of the liquid part from the sludge in vapour state.
3) Air Circulation charge of steam inside the condensation circuit.
4) Decresing the ambient temperature (vapour charge) from 40 °C to 5 °C.
5) Condensation of water

For energy purposes, in steps 1) and 2) the energy to raise the temperature and to enable further evaporation must be produced. In point 3) energy is released to make the air circulate. In steps 4) and 5) the same energy must be subtracted from the current of air to decrease the temperature again and cause the vapours to condense.

To estimate the energy needed to carry out this cycle, the Specific Heat (CS) of the compounds involved must be taken into account:

CS $_{H2O(Liquid)}$ = 4.180 [J/(kg °C)]
CS $_{H2O(Steam)}$ = 1.940 [J/(kg °C)]
CS $_{Sludge\ (Dry\ part)}$ = 1.000 [J/(kg °C)]
CS $_{Humid}$ Air = 1.030 [J/(kg °C)]

Specific heat indicates the energy required for the temperature of a kg of compound to vary a degree. Latent heat of vaporization (lv) indicates the energy required to make the liquid evaporate.

$l_{v\ H2O}$ = 2.272 [J/g]

For purposes of energy calculation, it is assumed that for simplicity only water evaporates and then condenses, for the following reasons:

1) water is by far the largest part of the volatile components in sludge composition;

2) the latent heat of evaporation and condensation of water is among the highest. It is equivalent to 2272 (J / g), so, evaporation of 1 gram of water requires 2272 joules of energy (0.6311 watt-hours). Likewise, this energy must be subtracted from 1 gram of water vapour to condense it.

The energy needs are further examined point by point.

1) Increase in temperature from 15 ° C (average temperature between summer and winter is considered) at 40 ° of 1000 kg of sludge consisting of 426kg of dry part and 574 kg of water.

DT = 25 C

426 [kg] * 1.000 [J/(kg °C)] * 25 [°C] = 10.650 kJ → 2.95 kWh

574 [kg] * 4.180 [J/(kg °C)] * 25 [°C] = 59.982kJ → 16.6 kWh

To heat the sludge from 15 to 40 °, 19:55 kWh are then needed.

2) Evaporation of 150kg (150.000g) of water to subtract from the sludge, in order to get: 150,000 [g] * 2.272 [J / kg] = 340,800 kJ → 94.6 kWh

This energy will be administered to the sludge in two forms:

- 70 kWh heating resistors on the tank bottom
- 45 kWh Mixing (Friction)

The first cited energy will be delivered to the sludge in drying by the resistances that are mounted under the tank bottom. The second contribution will be provided by the mixing engine. The mixer will have installed engine power equal to 135kW.

This engine power will be fully exploited when the mixer works at full speed and full load. In the first phase of drying the mixer will contain only 1000kg of sludge which must be dehydrated. In this phase the mixing engines will exploit only a portion of the energy consumable by them which can be estimated at 30% of the nominal value corresponding to 45 kW.

This power is used to stir the sludge in drying, and then the friction of the material ultimately converts into thermal energy and therefore heat. Clearly, this power will be required for the longest duration of only one drying step.

After completing the dehydration, the mixer will be loaded with the other components to produce 2.8mc of concrete and employ 135kW for mixing a couple of minutes. This amount of energy is not considered because in any case there would be no matter TAFIPACC treatment.

3) To calculate the air inside the tank mixing with water from the sludge one can refer to the following psychometric chart (Fig. 3).

The content of water miscible with the air at a temperature of 40 ° C is almost 50 grams. Handing in the condensing coils will bring the temperature to 5 °. At this temperature, maintaining a relative humidity equal to 100%, the water vapour contained in the miscible kg of processed air passes from 50 to 5 grams. The water vapour-laden air after passing through the condenser coil will have then downloaded 45 grams of water.

A kg of air corresponds to approximately 1mc of air under normal conditions. We know that for every cubic meter of air, 45 grams of water can be extracted; so, in order to extract 150lt of water (150,000 grams) at least: 150,000 / 45 = 3333 cubic meters of air will have to be processed.

4) Taking the count on the basis of an hour and putting some mc flow to make up for any losses, it will be necessary to recirculate a fan at 4000mc / h flow rate. For a prevalence of approximately 400mm of water column, an aspirator of this kind will require a power of about 10kW.

Reduction of temperature from 40 °C to 5 °C 150 kg of water vapour in the air:

DT = 35 °C

150 [kg] * 1.940 [J/(kg °C)] * 35 [°C] = 10.185 kJ → 2.82 kWh

To cool the water vapor from 40 °C to 15 °C, 2.82 kWh are needed.

1) Condensation of 150kg (150.000g) of water to be subtracted from the sludge, so to get:

150.000 [g] * 2.272 [J/kg] = 340.800 kJ → 94.6 kWh

Once diffused water in the form of steam flows through the condenser batteries, 150lt of water are needed to condense again by using additional 92 kWh. The latent heat of condensation is in fact similar to that of evaporation.

The condensing coils will have an installed capacity of 95kW to condense the amount of 150 kg water vapour.

For simplicity of calculation the duration of the drying process equivalent to 1 hour is assumed, where the fan consumes 10kWh.

The following approximations are calculated by excess:

1) Heating Sludge	20kW
2) Evaporation	95KWh
3) Air-handling	10kWh
4) Steam cooling	5kWh
5) Condensation	95KWh
Total	225KWh

This allows calculating the required energy and power, so, in order to extract 150lt of water from the sludge, for the treatment of 1000kg of sludge, 225kWh are necessary.

It is emphasized that the above calculations have been carried out without considering the recovery of heat that could be implemented in the radiators, and are therefore certainly estimated above.

Economic analysis

Considering the price of electricity of 0.16 euros / kWh, the total costs will be 0.16 € / kWh x225 kWh = € 36 for the treatment of 1 ton of dangerous sludge.

Drawing up a balance between the precious raw material savings (as seen in the previous paragraph, and amounted to € 86) and the expenditure of additional energy, by using the proposed TAPIFACC treatment plant, the net cost savings for the dangerous sludge treatment of 1000kg will be:

COST SAVINGS = 86-36 = 50 Euro / Ton of Sludge

Below is shown the comparison of two different recipes usable with traditional system and system with TAFIPACC dehydration.

Furthermore, other important economic considerations can be discussed.

The table below compares two different treatment methods, i.e. the traditional system and TAFIPACC dehydration in terms of the composition of 1 cubic meter of concrete as a product of the two different methods:

TABLE V. COMPOSITIONS OF 1 CUBIC METER OF CONCRETE

	TRADITIONAL	**TAFIPACC**
Component Description	**Weight [kg/mc of Conc.]**	**Weight [kg/mc of Conc.]**
Sludge's Dried Part	112.55	154.973
Water (In the sludge)	151.65	154.245
Cement	379.12	385.613
Clean inert	1350.82	1333.47
Lime	317.03	257.971
Concrete	**2311.15**	**2286.27**

Using TAPIFACC method, a cubic meter of concrete is produced with a greater amount of dry sludge (154 kg vs. 112 kg) and fewer raw materials (lime, 257 kg vs. 317 kg).

From the economic viewpoint, the cost of waste contribution to the reception facilities would amount to 174 Euros per ton (see Annex to this report via email and the "anac" tender awarded € 1,081,700 to treat 5 800 tons of sludge).

Considered that the transport incidence is 12.5 € / t, the treatment costs per ton of sludge results in 1 081 700/5800 = 186.5 € / t; minus the shipping costs 1865.5-12.5 = 174 € / t, so the price for the treatment of 1 ton of sludge is 174 € / t). Considering the costs of valuable materials outlined in the table above, and learning that the selling price of 1 cubic meter concrete is 35 €, the treatment of 1 ton of sludge amounts to:

With TRADITIONAL method:

TABLE VI. TOTAL COST TO TREAT A TON OF SLUDGE WITH TRADITIONAL METHOD

Component Description	Weigt [kg]	Volume [lt]	Weight [kg/mc of conc.]	Cost [Euro/ton]	Total Cost [Euro]
Sludge's Dried Part	426	266.25	112.546	-174	-174
Water (In the sludge)	574	574	151.646	-174	
Cement	1435	478.33	379.116	70	100.45
Clean Inert	5113	1966.53	1350.82	5	25.565
Lime	1200	500	317.031	107	128.4
Concrete	**8748**	**3785**	**2311**		**80.415**

- Production: 3.78 cubic meters of concrete per ton of treated sludge

- Revenue from sale = 35 x 3.78 = 132.3 €

- Cost of raw material production (considering the negative supply of sludge) = 80.40 € per ton of treated sludge.

With the method TAFIPACC:

-Production: 2.75 cubic meters of concrete per ton of treated sludge

- Revenue from sale = 35 x 2.75 = 97.3 €

- Cost of raw material production (considering negative sludge supply) = 5.60 € per ton of treated sludge (i.e. spending less on raw materials than paying for the transfer of sludge)

- Energy costs (more than the traditional process) = 36 € per ton of treated sludge (see previous paragraphs).

TABLE VII. TOTAL COST TO TREAT A TON OF SLUDGE WITH TAFIPACC METHOD

Component Description	Weigt [kg]	Volume [lt]	Weight [kg/mc of conc.]	Cost [Euro/ton]	Total Cost [Euro]
Sludge's Dried Part	426	2665	154	-174	-174
Water (In the sludge)	424	424	154	-174	
Cement	1060	353	385	70	74.2
Clean Inert	3665	1409	1333	5	18.32
Lime	709.	295	257	107	75.87
Concrete	**6285**	**2748**	**2286**		**-5.59**

Therefore making an economic comparison between the two treatments for 1 ton of sludge, the following conclusions can be drawn:

TABLE VIII. MARGIN INCREASE WITH THE TAFIPACC PROCESS

	TRADITIONAL	TAFIPACC
Cost of raw material [Euro]	-80	5.6
Sale revenue [Euro]	132.3	97.3
Margin [Euro]	52.3	66.9
Margin increase for a tone of Sludge	**14.6 € (66.9-52.3)**	

Employing the TAFIPACC method, an additional gain of 14.6 € per ton of treated sludge equals about 30% margin more than the current (14.6 / 52.3) is derived.

Besides the economic advantage outlined above, there are other benefits which are difficult to quantify economically:

• 30% less production of blocks (2.7 compared to 3.7 cubic metres per 1 ton of sludge):

• Less handling within the plant;

• Less area for storage;

• More ease of sale (it must sell less);

• Minor volume needed to mix 1 ton of sludge (3.78 to 2.7 cubic meters);

• Smaller mixing bath (only 3mc,. mixers 2 mc, where 2 cycles are needed to treat 1 ton of sludge, and a mixer of 4 mc does not exist on the market)

• Fewer raw materials employed, less amount of storage needed;

• Greater ability to increase the amount sludge to be treated.

Considering the amount of sludge transferred in the last two years to the 4R, which is approximately 10 000 t, and supposing that it had been treated by using the TAFIPACC method, it would have resulted in a profit of 14.6 € / t x 10 000 t = 146 000 € over the last two years.

In recent years the 4R has limited the amount of sludge to be treated but in the coming years, thanks to the convenience of the TAFIPACC system, it will be able to treat about 30,000 tons of sludge.

With this amount of sludge the annual revenue would amount to around € 440 000.

Assuming the sale price at 4R (see paragraph 11 of this report) amounting to 80,000 €, the required amount of sludge to be treated in order to pay back the cost of the plant is about 5,600 t of sludge. Considering the current data on 4R sludge processing amounts one year will be enough.

VII. SCALED PROTOTYPE TESTING

Before launching the design, modeling and implementation of the TAFIPACC project prototype, a small prototype on a reduced scale was developed, in order to test the equipment and conduct tests on small amounts of sludge to find the right components to add in the mixing stage for waste recovery. Analyzing dozens of samples obtained during the tests with the scaled prototype of the TAFIPACC system, it was possible to identify a modus operandi that would permit optimization of the process in terms of energy and time.

Fig. 7. Scaled prototype.

After hundreds of tests with scale prototype the following conclusions can be drawn:

- The reducing process of the sludge weight improves if inert is also included in the process of mixing;

- The times of the sludge weight reduction decrease substantially with the addition of insulation in the tank mixing;

- The times of the sludge weight reduction diminish significantly with the increase of the temperature at which the mixing process and then the heating of the mixing tank take place.

CONCLUSIONS

In comparison to the currently available industrial sludge treatment methods, the proposed method intends to significantly reduce the mobility of contaminants contained in the sludge. The developed method allows extracting the volatile portion of the sludge by means of a heating device applied for the first time to a concrete mixer of great dimensions and thus resulting in lower environmental impact. This promotes a desired increase of temperature so as to trigger evaporation of volatile substances and enable their separation from sludge. The mixer, flanked by an air recirculation circuit, is also equipped with a moisture detection probe. An added value of a sludge treatment process is determined with the profitable reuse of the output material. To treat 3 tons of sludge, 4.7 tons of clean inert and 0.6 tons of cement were used. During the TAFIPACC process testing, the best solution to optimize the output was defined, both in terms of physical characteristics and costs incurred. In particular, tests and optimizations were performed using hazardous sludge "CER 19:08:13 sludges containing dangerous substances from other treatments", i.e. sludge from industrial wastewater (hazardous). By using the TAFIPACC method, in which the amount of dangerous substances inside the compound is dramatically decreased, it is also possible to reduce the amount of lime required to eliminate odors. It was estimated that it is possible to reduce the amount of lime by up to 20%, bringing the ratio of 0.17 down to 0.137. The research was concerned with the development of virtual models and relative analytic calculations, as well as the performance of experimental measurements in the field in order to optimize every single component to come up with innovative design. In particular, the research involved static and dynamic simulations, structural dimensioning and prototype creation of the main components of the plant using 3D printing technology on 1:10 scale.

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