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Economic Optimization of Carbosulcis Underground Waste Disposal Plant

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In recent years, increasing environmental pressure against surface methods of mine waste disposal and concern about safety of mining operations have resulted in an increase in the popularity of filling of underground voids. In different countries, underground filling operations have been carried out using coal combustion by-products (CCBs).
The Carbosulcis CCBs disposal plant processes two different kinds of wastes: Pulverized Coal Combustion (PCC) fly ash and Atmospheric Fluidized Bed Combustion (AFBC) fly ash.
Our aim in this paper is to assess economic optimization of the Carbosulcis S.p.A. CCBs disposal plant. Actually, the present work is a trial to participate in the efforts to throw more light on feasibility of this kind of plant through an optimization study for the prediction of the minimum CCBs disposal cost as function of the ash feed flow rate for different values of fly ash concentration in the slurry and by evaluating the influence of a rheological modifier.

1. Introduction

European coal mines have used sand waste rock from mining operations and coal combustion by-products (ashes and slag) since the end of the 19th century to provide roof support and to fill underground voids. Fills used in coal mining have evolved from early loosely dumped rock (pillars constructed from rock) and hydraulically placed sand backfills (since 1893) through pneumatic (since1920) and through (since 1947) stowing up to today's hydraulically transported cemented fills with fly ash and flue-gas desulphurization by-products. The use of fly ash, tailing, cement and water mixture as compaction grout of roof fall material in gob area has had a very great impact on mining practice in Polish and German coal mines. With its introduction in 1967 immediate benefits appeared, realized through improvements in the productivity of caving long walls. Grouting the caving area results in a 90-95% reduction of spontaneous ignitions, in improved ventilation and utilization, in the reduction of heat load and in improved face conditions in particular stability of gates.
The most effective filling of mining voids, when it comes to environmental benefits, are obtained when a given technology allows to fill a void almost immediately after the extraction of a certain deposit.
Difficulties of a fill quality control increase proportionally to the increased depth of mining operations.
Filling long walls, both in the case of full backfilling and grouting of roof fall rocks in a gob area, should be carried out simultaneously with mining out of a deposit by means of short-step filling/injection. The full backfill has to be kept close to its side, no more than 8 m away. Practice shows that with an appropriate choice of grain-size of waste material and fill methods, a considerable improvement in water management can be obtained as well as in the fill quality.
At present, "Monte Sinni" Coal Mine in Sardinia is the only operating underground coal mine in Italy. The "Carbosulcis S.p.A." company possesses the mining concession on this coal basin. The whole reserve is supposed to amount up to 600 millions tons of sub-bituminous coal, while current concession permits for mining of 50 millions tons of coal. The coal bed is situated at the reasonable depth for the mining area. The mine operates at an average depth of 400 m (seams are located from 250 m down to 700 m), with use of long wall system.

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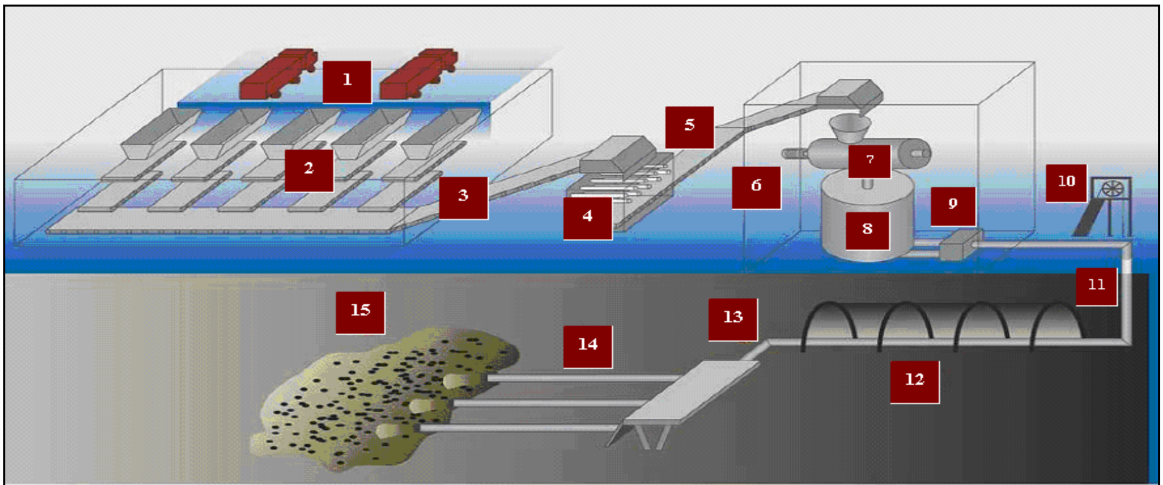
Since 2004 this Company has started building a new plant not directly connected with mining performances, in order to carry out environmental as well as economic impacts of coal mining activities. Actually, in recent years, increasing environmental pressure against surface methods of waste disposal and concern about safety of mining operation have resulted in an increase in the popularity of filling of underground voids. In different countries, underground filling operations have been carried out using coal combustion by-products (CCBs).
Moreover, Carbosulcis has signed a contract with Enel (Ente Nazionale dell'Energia Elettrica) Production in order to supply washed coal, but also to dispose ashes, gypsum and waste coming from the near fluidized circulating bed power unit.

2. Plant description

The Carbosulcis CCBs disposal plant processes 2 Mt/y of fly ashes. The plant mainly consists of two sections as follows: surface unit, for slurry processing and pumping, as well as an underground section made by the pipeline system for backfilling in the disposal areas. A representative scheme is shown in Figure 1.
The trucks arriving from CPP unload wastes to the plant supply, in order to feed the plant hoppers. There are five different hoppers. The plant management system allows collecting from each hopper a pre-set quantity of materials to grant correct proportions of the components, according to the mixture recipes. Material quantities extracted from each hopper are continuously monitored by a weighing belt down streaming the feeder belt. If the weight gauge detects a different quantity from the settled one, the Programmable Logic Controller (PLC) forwards the information to the feeder belt engine which accordingly modifies the speed. The material discharged by the hoppers is collected by a belt and taken to the disc separator that cuts out the > + 30 mm fraction. Then the material is sent from the disc separator to the process tower through another belt. At the discharge to process tower, mass and moisture are measured. These data are sent to PLC that drives the water pump in order to add the needed quantity. The water and the solid wastes are finally sent to the plough mixer for components mixture. At the end of mixing operations the slurry is sent to the 100 m^3 tank where is kept in motion by an agitator. From the tank the slurry is extracted and checked online for viscosity and density. If these parameters are correct, the pumping process can start. The agitator is a multiple marine propeller.
The injection of the slurry will be made by two pumps with maximum flow of 160 m^3/h . Through a regulation device the pressure in the working activities must be 80 bars (regime conditions) or 120 bars (maximum operating conditions). The pipes will be DN 150 PN 250 type except for the face systems, where, due to limited space, the pipes will be DN100 PN64 type.



1 dumping stations
2 weighing belts
3 collecting belt
4 disc separator
5 conveyor belt
6 process building
7 mixer
8 mixer vessel
9 double – piston pumps
10 headgear
11 shaft pipeline
12 mine
13 underground pressure pipeline
14 trailing pipes
15 fracture zone

Figure 1: General scheme of underground waste disposal plant

The slurry is pumped from the surface to the face and then injected into the goaf. A flexible pipe DN100 PN64 type lays on the face. Every 10.5 m from a three-way valve, an injection pipe departs perpendicularly to the face direction, into the backfill zone. The injection pipes are 15 m long each; they are fixed to the armored face conveyor and are dragged following the face advance. The monitoring system consists of pressure gauges every 500 m along the piping, while the safety system consists in emergency valves located in the same positions of gauges that allow to release pressure and then to operate with mobile high pressure pump, in case of clogging. In case of pipeline clog, it is possible to prevent slurry hardening in the pipes by injecting high pressure clear water into them. In case the pumping process must be interrupted for long time, it is necessary to clean the pipeline before, in order to prevent clogging of the pipes. In that case, clean water will be pumped from surface and a cleaning sponge will be inserted and pumped down from the sponge insert unit located in the process tower, and then recovered in another device located along the pipeline at the junction of the head gate. The cleaning water can be pumped to special tanks placed in the line.

3. Properties of fly ash used and rheology of fly ash slurries

The Carbosulcis CCBs disposal plant processes different kinds of wastes: Pulverized Coal Combustion (PCC) and Atmospheric Fluidized Bed Combustion (AFBC) fly ash. Actually, the Carbosulcis-managed underground disposal is deployed for not hazardous wastes made by the Enel Coal Power Plant (CPP) of Portoscuso, about 5 km far from the mine site. Waste materials, consisting of coal combustion by-products, such as ashes and gypsum, are pumped from the treatment and pumping station on the surface, to fill the gob areas of the underground long wall production panels.

The Coal Power Plant, owned by ENEL, located in Portoscuso includes two sections:

1. Section 3 is a 240 MW Pulverized Coal Combustion (PCC) group equipped with two desulphurization towers, that produces three waste categories mainly. According with the European Waste Catalogue (EWC) the wastes are: coal fly ashes (EWC 10 01 02); calcium-based reaction wastes from flue-gas desulphurization in solid form (EWC 10 01 05): FGD waste calcium-based reaction wastes from flue-gas desulphurization in sludge form (EWC 10 01 07);
2. Section 2 is a 350 MW AFBC group that carries out desulphurization directly in the furnace bed producing a FBC fly ash (EWC 10 01 02).

At present, Sardinia is experiencing a decrease in overall electrical consumption; within it, the Sulcis province in particular, lacking favorable structural conditions for energy costs, before the closing of some high energy consumption industries, absorbed about 2/3 of the installed regional capacity. The situation above described implies that ENEL produces electrical energy just by means of the most efficient Section 2 (AFBC coal power plant).

Anthony et al. (2001) reported that Atmospheric Fluidized Bed Combustion (AFBC) processes enable in situ SO_2 removal, but generate large amounts of wastes difficult to reuse and landfill. Actually, fluidized bed combustion fly ash, whose disposal and utilization is made difficult by their high quantity and low quality, can be conveniently disposed by this plant in underground backfills after a suitable preparation treatment.

Nonetheless, a drawback of this process is the partial conversion of free CaO to the sulphation product ($CaSO_4$): this poses problems in land filling of the spent sorbent, due to exothermal and expansive phenomena upon hydration. Moreover, FBC residues also contain fuel-derived ash characterized by a poor pozzolanic activity (Bernardo et al., 2003): hence, these wastes are generally unsuitable for recycling in traditional fields such as cement and concrete industries.

The AFBC fly ash as received has a specific gravity of 1990 kg/m^3 (determined by using Standard Pyknometer Method) and a minimum size of particles approximately of 5 mm. Specific gravity is an important design parameter as it determines the settling characteristics of the slurry.

The chemical/physical characterization of the reactivated wastes was carried out by means of X ray diffraction (XRD) analysis and scanning electron microscopy (SEM). Figure 2 reports the SEM image of Gypsum in fly ash produced by combustion of Sulcis coal in Enel power plant and XRD pattern for AFBC fly ash before hydration.

In order to achieve a good performance in both pumping and hydraulic transportation of fly ash slurries is needed to use a specific additive. Actually, the addition of additives in a small amount improves the performance of slurry pumps. Pump head and efficiency improve with the use of polymer and surfactant additives (Chand et al., 2009). In this case, Rheotec G.A.4, at a concentration of 0.1 % by weight of fly ash has been used as a rheological modifier.

Both a Rotovisco RV 20 and a Fungilab Rotational Viscometer were used for obtaining the rheological characteristic of fly ash slurries at various concentrations.

The RheoWin Data Manager software for interactive evaluation of the measured data, showed that the variation of the shear stress as function of the shear rate for all concentrations exhibits a non-Newtonian behavior. In fact, all data measured are well described by the following equation:

$$\tau_y = \tau_0 + \eta_p \cdot \dot{\gamma} \quad (1)$$

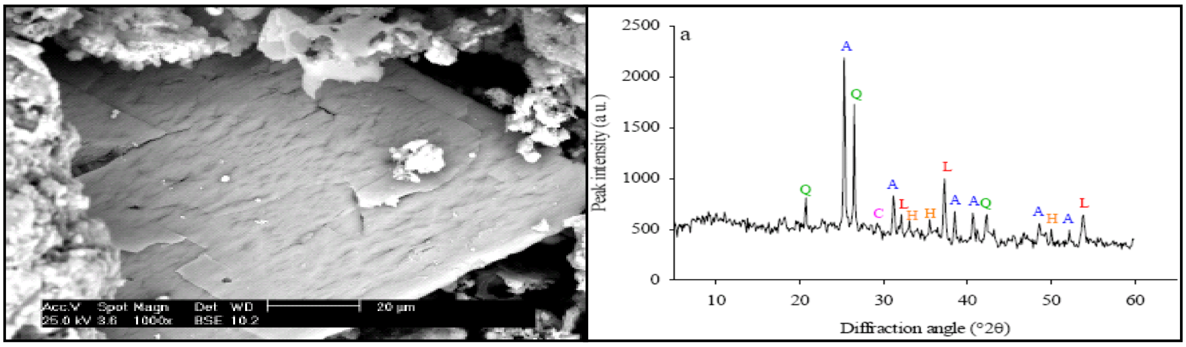


Figure 2: SEM image of Gypsum in fly ash produced by combustion of Sulcis coal in Enel Gr. 2 AFBC and XRD spectrum of AFBC fly ash (A = anhydrite, C = calcite, H = hematite, L = lime, Q = quartz)

Where, τ_y is the yield stress and η_p the Bingham plastic viscosity. So, more specifically, the fly ash slurries show a Bingham plastic behavior.
The rheological parameters of fly ash slurries with and without additive at different concentrations are reported in Table 1 and Table 2, respectively.

Fly Ash Conc.	Yield stress	Slurry Viscosity	R^2
[wt%]	[Pa]	[mPa-s]	-
50	0.016	1.28	0.952
55	0.037	3.24	0.983
60	0.130	5.18	0.989
65	0.460	24.00	0.998
70	0.502	62.84	0.979

Table 1: Rheological properties of fly ash slurries with additive (0.1 % by weight of fly ash)

Fly Ash Conc.	Yield stress	Slurry Viscosity	R^2
[wt%]	[Pa]	[mPa-s]	-
50	0.025	2.10	0.983
55	0.087	5.13	0.975
60	0.200	8.15	0.969
65	0.760	30.00	0.998
70	1.080	137.64	0.991

Table 2: Rheological properties of fly ash slurries without additive

4. Results and discussion

In the present paper specific cost of wastes disposal in the underground is calculated without considering that there will be a loss of mine productivity due to backfilling.
Specifically, we choose to optimize the ash feed flow rate by considering both the influence of the additive agent and different values of ash concentration in the slurry.
The specific cost of wastes disposal is calculated as the ratio between total costs and waste flow rate disposed in the underground backfills. The total cost is calculated by considering the contribution of the fixed and variable costs. The fixed costs are calculated as a function of the capital costs while only the most significant components of the variable cost are considered in this calculation.
Then, the total cost includes the following parameters: depreciation of the three parts constituting the whole plant, cost of the energy source used and costs of manpower, materials and chemicals used in the process. A depreciation of 6% over 25 years is assumed, so the amortization factor is 0.078. All the costs are brought up to date when required, by using the Marshall & Swift indices.

The objective function is calculated as the sum of the specific costs of the wastes disposal plant, so we take into account the depreciation of the investment (fixed cost), the cost of manpower, chemical (additive), handling and electric energy used during the operation:

$$C_{tot}(Q_{ash}) = \sum_i C_{fixdir,i} + C_l + C_{chem} + \sum_i C_{electr,i} + C_{handl} \quad (2)$$

We fixed 6,240 hours per year of operation for the whole plant. Moreover, the cost of additive is 2 €/litre. handling and labour costs are 75 €/hours and 52 €/hours, respectively.
For the electricity cost we evaluated the sum of the specific cost of pumping, mixing and transportation by means of belt conveyors:

$$\sum_i C_{electr,i} = C_{pump} + C_{mix} + C_{transp} \quad (3)$$

As reported in the annual report of the Italian Authority of the Energy and Electricity a cost of 0.155 €/kWh has been assumed in this calculation for the electric energy; whereas C_{pump} and C_{mix} have been calculated by using the correlations reported in the above paragraph. In ungassed systems with spacing between impellers of at least one impeller diameter, the power dissipated by multiple impellers is approximated by the following relationship:

$$P_{mix} = n \cdot P_s \quad (4)$$

Where n is the number of impellers and P_s is the power dissipated by a single impeller. According to Metzner et al. (1957), we have calculated the power consumption as a function of geometric, kinematics and fluid property parameters for non-Newtonian fluids.
In the CCBs plant reciprocating pumps move the fluid using one or more oscillating pistons, while valves restrict fluid motion to the desired direction. This type of pump was used extensively in the 19th century as boiler feed water pumps. Now reciprocating pumps typically pump highly viscous fluids like concrete and heavy oils, and serve in special applications that demand low flow rates against high resistance. As reported by Grzina et al. (2002), we have solved the problem of calculating the power consumption for pumping by using the Bingham slurry method.
The total energy consumption in a conveyor system is the sum of the components of three parts: a) the energy needed to run the empty conveyor, b) the energy needed to move the material horizontally over a certain distance, c) the energy needed to lift the material a certain height. So, this energy consumption can be represented as follow (J. N. De la Vergne, 2003):

$$\sum_i E_{transp,i} = E_{ec} + E_h + E_l \quad (5)$$

In order to find the optimum cost of the disposal plant as a function of the ash feed flow rate for this process, a computer program has been written in Fortran 90 language. So the cost function was evaluated by means of a subroutine (Buzzi - Ferraris et al., 2013), which is able to find the minimum of a continuous function. The program assumes the values of all the physical and design parameters. Using these data, the program is able to calculate the minimum disposal cost of fly ash for this plant. The result of these calculations is shown in Figure 3, in case of pumping fly ash slurries without an additive, whereas Figure 4 shows the result in pumping fly ash slurries with an additive.
The specific cost of wastes disposal as function of the fly ash feed flow rate, allows the optimum value (4.687 €/ton) with a 70% by wt. of solids and by using the rheology modifier, for a feed flow rate relatively high (205 ton/h). This is due to the better physical properties obtained by using the additive, which reduce the energy consumption for both pumping and mixing.

5. Conclusions

In the present work, we evaluated the economic aspect of disposing wastes in underground voids of the only active Italian coal mine. In particular, by using a computer program we obtained the results reported in the Figures 3 and 4, which show that fly ash slurries with a maximum concentration of 70% weight can be transported cost-effectively with slurry pumps. There is a significant difference in the rheological parameters of the slurries of fly ash. Actually, by using a rheology modifier a minimum specific cost of 4.687 €/ton, with a 70% by wt. of solids has been found. This has been compared to the minimum disposal cost of 4.957 €/ton, with 50% by wt. of solids (5.7508 €/ton, with 70% by wt. of solids), without using this kind of additive. Moreover, by using a rheology modifier, an homogeneity trend of the plots has been found.

Finally, this sustainable technology converts mineral by-products into a highly concentrated mixture of water and solid matter, and under the pressure of the rocks around, this mixture dries and bonds with the mining debris, adding structural properties to the geological system. So it can be concluded that this project seems both to be profitable economically and to provide guarantees from a technical point of view.

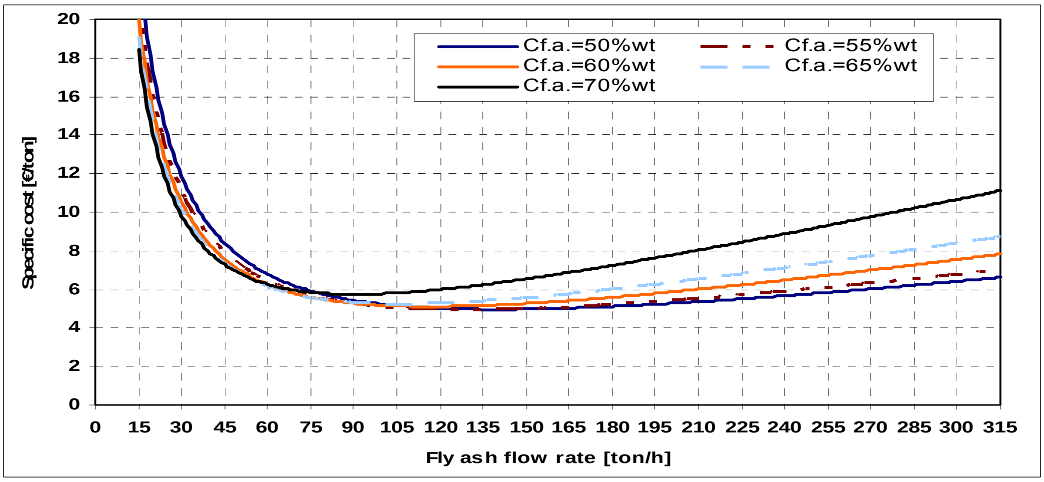


Figure 3: Specific cost of wastes disposal as function of fly ash feed flow rate without additive

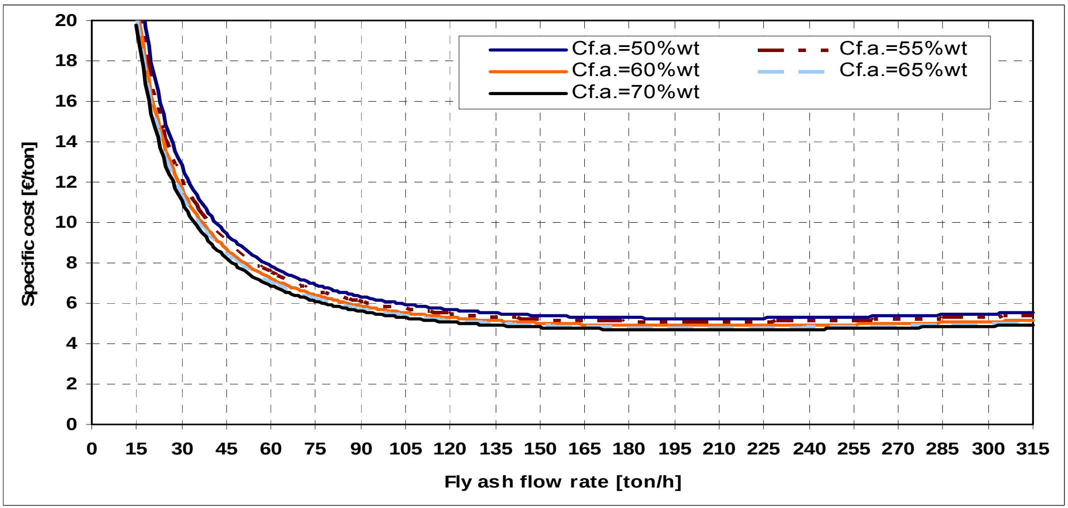


Figure 4: Specific cost of wastes disposal as function of fly ash feed flow rate with additive

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