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EVALUATION OF TECHNICAL AND ECONOMICAL VIABILITY OF THE INDUSTRIAL CO-OPERATION OF ALUMINUM PROCESSING AND CEMENT INDUSTRY ENVIRONMENTAL DIMENSION OF THE SOLUTION

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ABSTRACT

Secondary aluminum processing produces considerable amounts of dross, which cannot be directly exploited for aluminum recovery. The objective of this study is to examine the possibility of industrial co-operation between the aluminum and cement industries. It is shown that it is possible to use dross stemming from secondary aluminum processing to substitute raw materials in the raw meal with aluminum oxides, such as bauxite and kaolin. Experimental measurements were carried out in order to characterize aluminum dross, the raw meal and clinker produced with the use of aluminum waste. Cement was industrially produced and issues relating to the industrial production are considered. The work examines the situation in Greece regarding environmental, legislative and economical issues. The solution appears to be economically viable and could solve a large problem for the Greek aluminum industry.

1 INTRODUCTION

During aluminum processing a significant amount of dross is produced. The amount and quality of the dross depends on the raw material (pure aluminum, scraps) as well as on the smelting technology applied, and it is commonly between 2-8 % of the metal quantity. When dross is skimmed the aluminum content is between 80 and 90 %. When a proper fluxing technique is used aluminum content is reduced to 40-50%.

Fluxing techniques and production practices strongly change throughout different industries giving several types of dross, normally called white and black. White dross is produced from primary aluminum production. In this case, fluxing inside the furnace is practically absent and the color of dross skimmed is gray or metallic white. Secondary aluminum smelters melt old casting and a low-grade aluminum scrap and produce black dross with the addition of fluxes. The latter are composed of mixtures of sodium and potassium chlorides, and contain small amounts of fluorides. At high molten-metal temperatures, the flux melts and becomes dark. Only one third of the dross is suitable for aluminum recovery (non-salt slag), while the rest gives aluminum oxide, which is classified as toxic and hazardous waste in the European Catalogue for Hazardous Waste following the Technical Working Group of Basel Convention (Basel Convention, 1997).

The use of rotary furnaces and high amounts of salts (mixture of sodium and potassium chloride) for aluminum recovery produces salt slugs, which are classified as hazardous. This quality is not examined in the present paper.

Greece produces up to 2500 tn of non-salt slag per year and about 10000 tn of salt slag. Salt slag is temporarily stored in order to be sent abroad for further processing. The exploitation of non-salt slag is currently examined.

The objective of the presentation is to study the suitability of the aluminum dross produced by the Greek industry as a raw material for the Greek cement industry. Chemical analyses of the aluminum dross and the cement produced with dross were performed. Cement with aluminum dross is also industrially produced, in order to identify the real-scale problems encountered during the use of aluminum dross as a raw material for the cement industry. Furthermore, a cost-benefit analysis regarding the benefits of such cooperation between the cement and aluminum industries is carried out.

2 TECHNICAL ANALYSIS

The scope of the technical analysis is to examine whether the aluminum dross can be used as a substitute for bauxite or kaolin in the cement production and to which percentage. The steps followed are shown in Figure 1 and explained in tables 1 through 3.

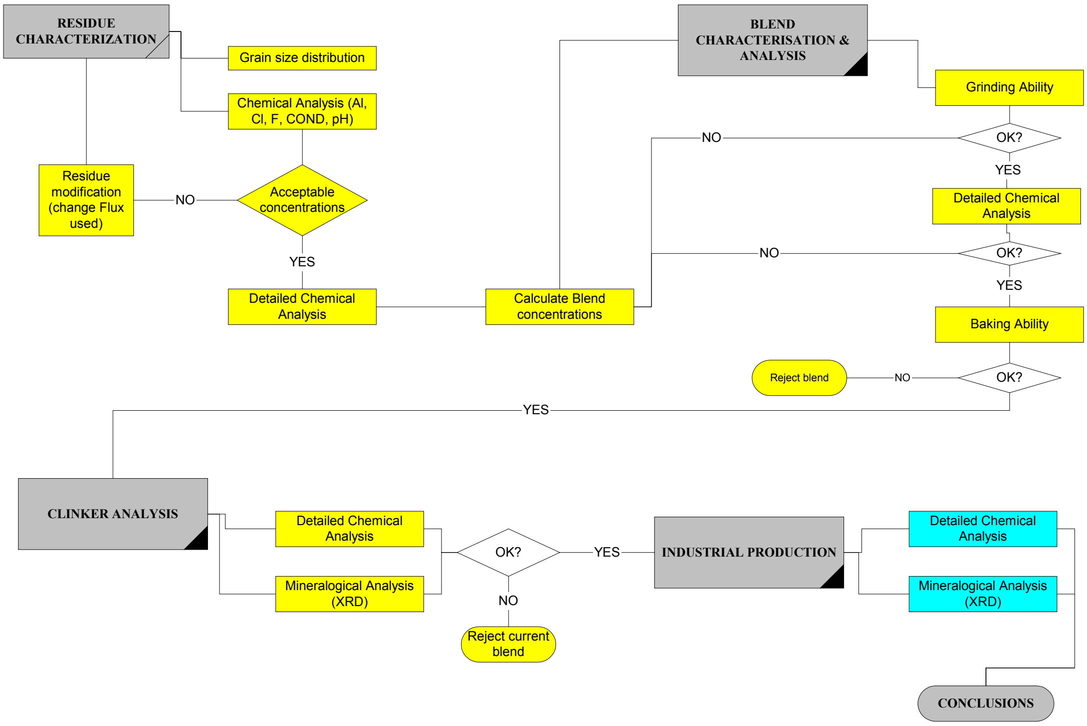

Figure 1 Flow diagram of technical analysis

STEP 1. Aluminum dross is collected and analysed

Table 1 Aluminum dross analysis

Aluminum dross analysis		
Analysis	**Reason**	**Industrial importance**
Grain size distribution	Determine the way of handling of the material (transport, storage, feeding, comminution)	Feeding in the industrial process
Chemical analysis (Cl)	Determine the suitability of the residue as clinker raw material	Coating problems in precalciner and kiln
Detailed chemical analysis – main constituents' content (mainly Al)	Determine the suitability as clinker raw material	Calculate the raw material synthesis

STEP 2. The test raw meal containing the residue is examined in comparison to a reference one, similar to an industrial one. The analyses performed are shown in Table 2.

Table 2 Raw meal analysis

Raw meal analysis		
Analysis	**Reason**	**Industrial importance**
Grindability		Raw meal comminution process
Detailed chemical analysis	Conformity with preset tests	
Burnability tests (MUSIKAS, FLS)	Comparison to a raw meal with known industrial burnability	Behavior of the raw meal in the sintering process

STEP 3. The quality of the test clinker is examined in comparison to the reference one, produced the same way (Table 3).

Table 3 Clinker Analysis

Clinker analysis		
Analysis	**Reason**	**Industrial importance**
Detailed chemical analysis		Quality of the clinker
Microstructure characteristics		Quality of the clinker

STEP 4. The cements produced by grinding properly the above clinkers arte comparatively examined regarding their conformity to the quality specifications.

Table 4 Cement Analysis

Cement analysis		
Analysis	**Reason**	**Industrial importance**
Detailed chemical analysis	Comparison with specification	Quality of cement
Physical and mechanical testing	Comparison with specification	Quality of cement

STEP 5. If the study in semi-industrial scale in the laboratory shows that the cement produced conforms the specification, an industrial test is carried out and the industrial clinker is examined as described in step 3 and 4.

2.1 Characterization of the residue

Experimental Tests

Non-salt slag from three Greek industries of secondary aluminum processing was used in this work (Aluminum of Viotia, ATEM, ADG). The suitability of the residue as a raw material was studied by examining the grindability and by measuring the grain size distribution (Figure 2), aluminum, Cl^-, water concentrations, conductivity in a water solution and pH (Table 5) in a water solution.

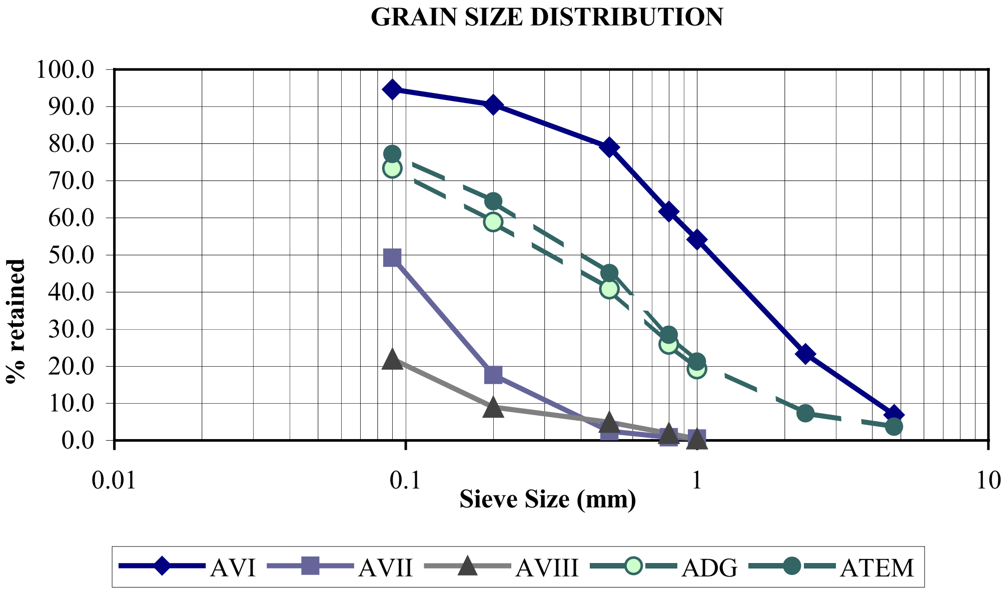

Figure 2 Initial size distribution of different origin aluminum dross samples

The grain size distribution analysis is performed in order to determine the way of handling of the material (transport, storage, feeding, comminution) and is important for the feeding in the industrial process. Figure 2 shows that all samples have acceptable grain sizes and samples AVII and AVIII have smaller and more homogeneous grain sizes than other samples.
The chemical analysis (Table 5) examines whether the residue is suitable to be used as raw material in the cement production. Of great importance is their water and chlorine content. All samples have acceptable water contents and their chlorine content is not greater that the acceptable 4%.

Table 5 Chemical analysis of the aluminum dross samples

SAMPLE	AVI	AVII	AVIII	ADG	ATEM
%Al	13.0	5.0	8.0	18.44	19.75
%Cl	1.4	2.4	5.4	0.62	0.72
%H	12.0	8.0	-	-	-
Conductivity(mS)	3.1	5.3	9.0	-	-
PH	12.1	12.7	8.8	-	-

The grindability of the pure dross from different producers (as well as of different dross-raw meal mixtures) has been examined. Due to the composition of the dross, the grinding and pulverization experiments have been preformed in a prototype ring-mill developed at NTUA (Spitas *et al.,* 1999).
Table 6 shows the size percentage of material below 90 μm, obtained after comminution. Table 6 also shows the time required achieving the final size range. Samples AVIII, ADG and ATEM seem to better fulfill the industrial requirement of P(d<90μm)=90%.

Table 6 Size distribution of aluminum dross samples after comminution

Sample	time(sec)	P(d<90μm) (%)
AVI	480	44.7
AVII	300	75
AVIII	480	86.4
ADG	600	80
ATEM	600	83

Energy requirements for grinding the samples to the acceptable size range [P(d<90μm)=90%] have been established and are shown in Figure 3. The power consumed for the comminution of each sample has been recorded and the specific energy requirements have been calculated in kWh/kg. Figure 3 shows that energy requirements for the comminution of the aluminum dross samples are nearly independent of the raw material origin and the initial size distribution of the raw material.

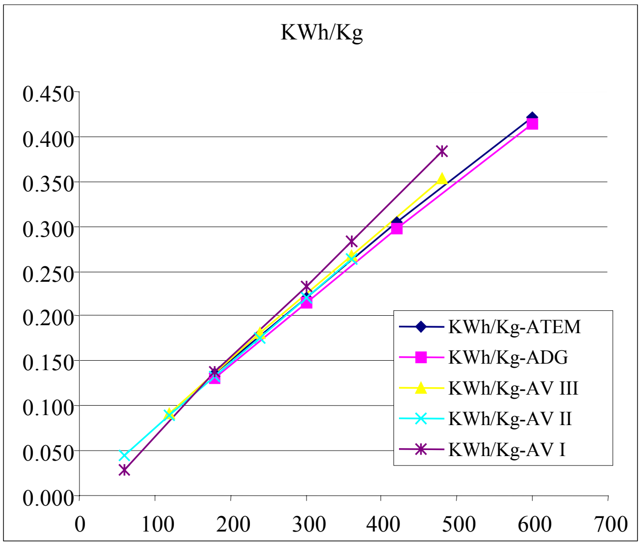

Figure 3 Grain size distribution of the residues

Further tests were performed regarding humidity, density, grain size distribution and detailed chemical and mineralogical analysis in order to calculate the percentage of the residue for the raw meal. Detailed chemical analysis is shown in Table 7.

Table 7 Detailed chemical analysis of the aluminum residue (%)

Sample	AVI	AVII	AVIII	ADG	ATEM
SiO_2	0.43	0.62	0.54	0.80	0.90
Total Al as Al_2O_3	67.19	73.46	63.00	73.27	74.37
Fe_2O_3	0.57	1.38	0.99	0.49	0.47
CaO	1.96	4.20	4.48	2.52	1.96
MgO	2.02	4.85	6.16	4.24	5.66
K_2O	0.46	0.82	1.08	0.66	0.54
Na_2O	2.22	2.16	3.30	9.23	6.47
Total Cl^-	3.09	6.38	8.16	1.99	2.34
Water soluble Cl^-	0.54	1.77	1.77	0.40	0.36

Discussion of results

The analysis shows that samples could be used in the production of clinker raw meal. Water content is also within acceptable levels, so as not to produce unpleasant odors. The only critical issue was the high concentrations of Cl^-, which in the determination of total chlorides appeared to be far beyond 4%. This result was obtained because the detailed analysis determines the total chlorides, while the analysis performed by the aluminum industry calculated only the water-soluble Cl^-. ADG and ATEM samples have high concentrations of Na_2O, which is not desirable wanted in high percentages.

2.2 Preparation and testing of the raw meal and clinker

Its high concentration in Al and its low concentration in Fe_2O_3 make the residue suitable to be used as raw material for white cement production. A typical raw meal for white cement clinker contains usually limestone, kaolin and siliceous sand. The aluminum waste is used as a:

- partial substitute of kaolin, increasing the need for SiO_2, which means that more siliceous sand should be used
- total substitute of kaolin, increasing the need for SiO_2, which means that more siliceous sand should be used

The selected raw meal compositions are shown in Table 8.

Table 8 Compositions of tested raw meal

Raw Materials	Raw meal 1 (Reference)	Raw meal 2 (1%)	Raw meal 3 (3 %)
% Limestone	80.70	80.85	81.42
% Kaolin	12.43	8.75	0.00
% Siliseous sand	6.87	9.40	15.35
% Residue	**0**	**1.00**	**3.23**

The examined raw meals contained 1% and 3% of the residue and were compared against a reference raw meal (0% residue). The tests performed regard the grindability of the raw meal (Figure 4), chemical analysis (Figure 5), MUSIKAS burnability (Figure 6), FLS burnability.

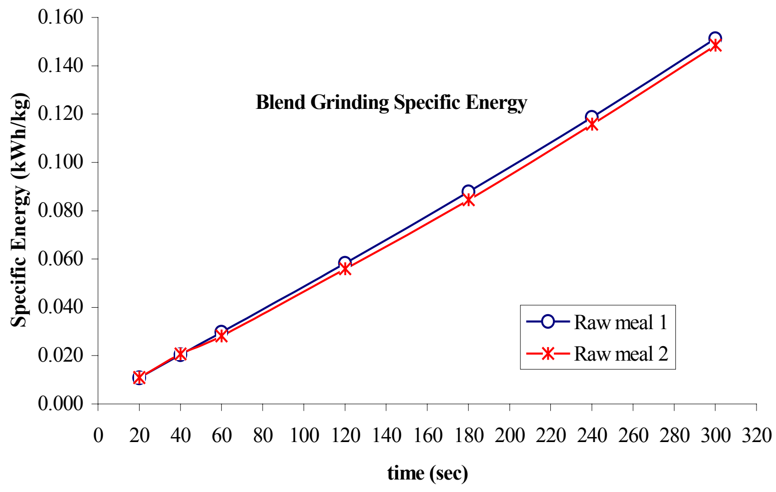

Figure 4 Grinding specific energy of raw meal 1 and 2 (Reference and 1% of aluminum dross)

The grinding tests showed that the raw meal containing the aluminum residue has the same grinding behavior with the reference raw meal (Figure 4), and therefore it does not demand any higher energy consumption for the raw meal production.

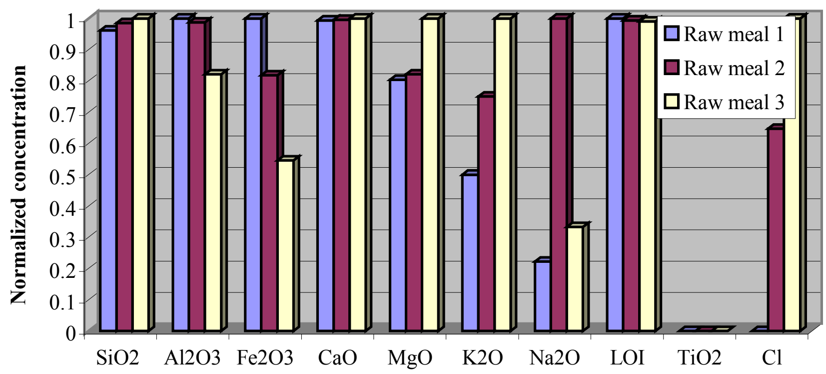

Figure 5 Chemical analysis of the three raw meal compositions

The chemical analysis of the raw meal compositions showed that the only significant difference from reference raw meal concentrations was the chlorine concentrations that are within the acceptable levels. The analyses of the three raw meals were in agreement with the preset targets.

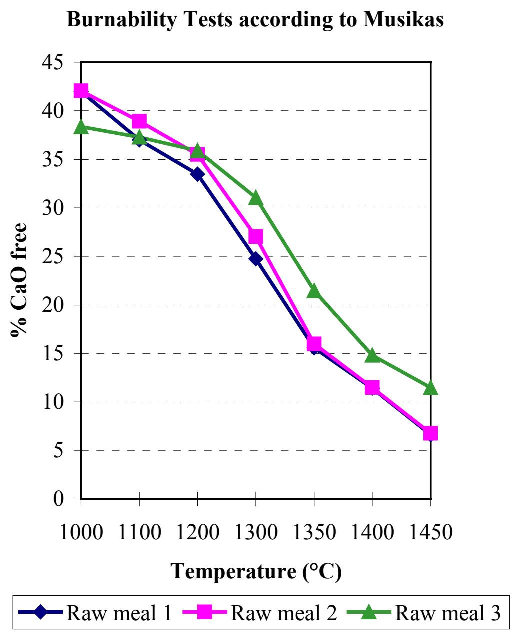

Figure 6 Burnability tests according to Musikas.

Musikas burnability tests (Figure 6) showed that raw meal 3 showed bad burnability and it was excluded from clinker production. Aluminum dross is not responsible for the bad burning behavior of raw meal 3. This difference in burnability is due to the absence of kaolin from the synthesis of raw meal 3.
The clinker produced by the raw meals 1 and 2 is chemically analysed (Figure 7) and subjected in mineralogical XRD analysis.

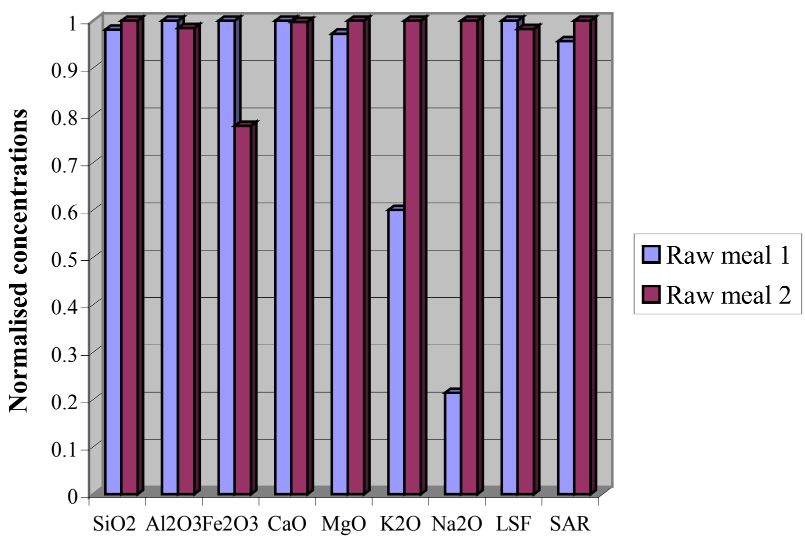

Figure 7 Chemical analysis of the produced clinker

Chemical analysis (Figure 7) showed that raw meal 2 produced acceptable clinker concentrations and is therefore suitable for cement production. Mineralogical analysis (XRD) showed that the microstructure of clinker 2 (produced by raw meal 2) was almost the same with the microstructure of reference clinker.
As a result raw meal 2 was characterised suitable for cement production.

2.3 Industrial Cement Production - Problems encountered

The use of aluminum dross as raw material by the cement industry presents a number of problems:

- *Transportation, handling and storage*. The small particle size of the aluminum dross results to great losses during its transportation and handling. Furthermore, the small particles make the mixing of the waste with other raw materials extremely difficult without the necessary and suitable storage, transport and weighing infrastructure for an additional raw material, with those characteristics. Its high concentration in aluminum nitrates causes unpleasant odors when in contact with water. The particular aluminum dross was delivered in big bags in order to avoid losses during transportation, but that made its handling during cement production difficult.
- *Clinker production*. High Cl^- content increase the coating formation in the precalciner, which is a big hindrance in the clinker production process. Control of the chlorine is an important factor in this process.
- *Production planning*. Aluminum dross is provided in very small amounts and therefore the proper amount has to be first stored, in order to plan a clinker production containing aluminum dross. This demands extra storage and suitable weighing-feeding facilities.

3 ENVIRONMENTAL ISSUES AND ECONOMICAL VIABILITY

3.1 Legislative situation

The basic environmental problem posed by the secondary aluminum processing is the production of salt and non-salt slag, which are classified as toxic and dangerous wastes (Basel Convention, TWG, 1997). According to the Greek Law no aluminum processing industry can acquire permission to operate, if it cannot provide a certificate for the safe disposal of the waste (GR-Law 2516/1997).

3.2 Economical Analysis

Greek aluminum industries are obliged to pay significant sums of money in order to obtain temporary certificates of operation. This implies that the operation of aluminum industry without a permanent certificate of operation is not profitable. On the other hand, if an aluminum industry makes investments to modify the process in order to supply its waste to the cement industry the operation would be extremely profitable.

For the cement industry the use of aluminum dross as raw material can be of no cost at all if the rotary kiln has a by-pass installed. The cement industry can profit by substituting kaolin and bauxite with aluminum dross. On the other hand, the installation of a kiln with a by-pass is an expensive investment, which should not be 100% attributed to the use of aluminum dross. By taking into consideration only a small amount of the investment for the use of aluminum dross, the result obtained is that the current proposed solution is economically viable for the cement industry whether it possesses a kiln with by-pass or not.

3.3 Aluminum Industry

The handling of aluminum dross makes necessary the installation of some equipment (sieves, silos), in order to handle and store aluminum dross that would be used in the cement industry. The cost of the equipment is estimated to be 147.000 € and it includes:

- Sieve equipment for dross screening
- Dross mixer
- Vehicle to transport big bags
- Buildings

The operating cost is:

- Energy – 20hWh/t incoming
- Labor costs – 1 man-hour / t incoming (8,8 €/man-hour)
- Packing – 2.94 €/t incoming
- Transportation costs – 14.67 €/t incoming (for a distance of 200km)
- Maintenance costs – 1.47 €/t incoming

Furthermore, management costs are estimated as 20% of the operating cost. The depreciation of the equipment is 7 years.

The income of the unit is expected to be:

- From the waste suppliers (the unit is paid 0,12 €/kg)
- From the receivers of the products (the products are sold 0,24 €/kg)

The disposal of the rest of the dross to the cement industry gives no income to the unit, because it is common practice to pay the industries that absorb waste, instead of expecting to be paid for providing the waste.

Two cases are examined:

- **Case 1** – The aluminum industry does not give the aluminum dross to the cement industry. The aluminum industry is obliged to pay a certain amount of money every year, in order to acquire a temporary certificate of operation.
- **Case 2** – The aluminum industry gives the dross to the cement industry. Some extra equipment costs need to be made (storage SILO), but the company does not have to pay every year for a temporary certificate of operation. The packaging costs are zero, because the transportation of aluminum dross to the cement industry would be done with silo trucks (bulk).

Table 9 summarises the economical analysis of an investment for dross handling for both cases It should be noted that the Net Present Value (NPV) of the investment is calculated according to the following equation:

$$NPV = \sum_{1}^{n} \frac{(money\ flux)_i}{(1 + \text{interest})^i}$$

Table 9 Economical analysis of the investment for the aluminum industry

Incoming Raw Material	1500 t/year	
Expenses (€)	**Case 1**	**Case 2**
Energy	1,584.74	1,584.74
Labor costs	13,206.16	13,206.16
Packaging	4,402.05	0.00
Transportation costs	22,010.27	22,010.27
Maintenance	2,201.02	2,201.02
Management	8,680.85	7,800.44
Equipment depreciation	20,962.16	23,058.78
Sum of Annual Expenses	102,394.30	69,861.02
Income (€)	271,460.00	271,460.00
NPV (€)	**141,408.00**	**171,813.02**

Comparing the two cases and effectiveness index can be calculated:

$$\text{Effectiveness} = \frac{\text{potential investment}}{\text{present situation}} = \frac{\text{case 2}}{\text{case 1}} = 1.22$$

If the index is greater that one, the investment is profitable.

3.4 Cement Industry

If the cement industry chooses to use aluminum dross as raw material it has to take into consideration the reduction of kaolin and bauxite, which means the reduction of the cost of the raw materials, as well as the potential installation of a kiln with a by-pass. Three cases are examined:

- **Case 1** – It is the present situation. The costs of the raw materials are only taken into consideration, because they will change in the cases 2 and 3.
- **Case 2** – The use of aluminum dross is assumed. The cement industry is assumed to already posses a kiln with by-pass and only the reduction of the raw materials used is taken into consideration. It is assumed that only one third of kaolin is substituted (1% residue concentration in the raw meal).
- **Case 3** – The use aluminum dross is assumed, as well as the installation of a kiln with by-pass. Only 1% of the cost of the equipment is calculated for the use of aluminum dross. The reduction of the raw materials used is also taken into consideration.

Table 10 Economical analysis for the cement industry (1000 tn Kaolin)

EXPENSES (€/year)	Case 1	Case 2	Case 3
Kaolin	41000 €	27333 €	27333 €
Equipment cost/year	-	-	628026*0.01 €
TOTAL COST	41000 €	27333 €	33613 €

Table 10 shows that the substitution of kaolin with the residue is profitable for the cement industry. Even when the installation of a by-pass kiln is necessary (case 3) the investment continues to be profitable.

4 CONCLUSIONS

The experimental production of cement with the use of aluminum dross as raw material showed that such a solution is technically viable. This was also verified by a test industrial production of cement, which also made possible the identification of some practical difficulties that cannot be shown in the laboratory. Those difficulties could be overcome by some modifications on the overall procedure:

- In order to avoid destruction of the grinding mill, it is suggested that the aluminum industry sieves the dross, so that only the small grains are delivered for use by the cement industry.
- For solving problems of unpleasant odors and losses, the construction of a storage silo for the dross in the aluminum industry is obligatory. The transportation of the material can then be made with silo trucks. This solution solves also the problems of dross handling and feeding to the cement production line.
- In order to solve chlorine problems the cement industry should install a rotary kiln with a by-pass for exhaust gases, which is a very expensive investment. Most cement industries nowadays however, already posses such a kiln.

The economical analysis showed that such a solution could be viable for both industries. Aluminum industry solves its main problem of obtaining a permanent certificate of operation by assuring the disposal of its waste. Cement industry gains a raw material that can substitute expensive raw materials such as bauxite and kaolin at no cost at all (if a kiln with by-pass is present).

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