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Recycling of Industrial and Urban Wastes in Brick Production – A Review

M. Dondi, M. Marsigli, B. Fabbri

Abstract

The following paper provides an overview of the current status of knowledge about the recycling of industrial and urban wastes in brick production based on studies of literature from the last 20 years. The experiments were made by authors from Italy, Russia, Great Britain, Spain, Germany and the USA. Waste materials fuel waste (53 publications), fly-ash (16 publications), fluxing wastes (10 publications) and plasticity reducing and plastifying wastes (12 publications) are dealt with.

Tile & Brick International 13 (1997) [3]

1 Introduction

Industrial activities produce a certain amount of substances which are not consistent with the purposes of such a production process. These by-products, which in most cases cannot be directly reused, represent production wastes and raise the issue of how to dispose of them in the best possible manner. The bodies used in the brick industry are, generally, very heterogeneous, since they consist of clay raw materials with a very wide-ranging overall composition [1, 2]. For this reason, such bodies can tolerate the presence of different types of waste materials, even in high percentages. Incorporating such wastes into brick bodies always involves at least two environmental advantages: Recycling and inertisation of wastes, which are often pollutant and difficult to dispose of, and savings in clay raw materials.

Furthermore, the addition of industrial and urban wastes to brick raw materials often has positive effects on the properties of the semi-finished articles and the products even if it reduces performances in a number of cases. The effects involve the whole course of manufacture (shaping, drying and firing) and have repercussions on the properties of the finished products, such as shrinkage, porosity and mechanical strength. Finally, in many cases, there are also variations in energy consumption, which may be reduced due to the calorific contribution provided by many types of wastes.

This work is basically aimed at providing an overview, through bibliographic research, on the current state of knowledge on the recycling of industrial and urban wastes in the brick industry, and to complete the experimental activities that have been carried out for some time at the IRTEC of Faenza (Italy). Therefore, the scientific literature of the last 20 years was reviewed, i.e. of the period in which the energy-environmental emergencies provided strong incentive for studies concerning the use of waste materials that would otherwise be unusable. About 80 specific articles were found, plus some general reviews about the disposal problem regarding production wastes [3 – 9]. Most of the articles were written by researchers operating in Italy, Russia, Great Britain, Spain, Germany and the USA.

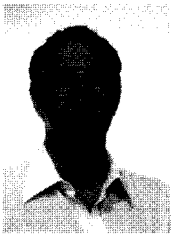
In this review, wastes were divided into four main categories based on their principal effect:

- Fuel wastes
- Fly-ash
- Fluxing wastes
- Plasticity reducing and plastifying wastes.

The subject of fuel wastes has been discussed in a great number of articles (53). This type of waste involves residues coming from a wide range of industrial production processes, for which the common factor is, in particular, the high content of organic and/or carbonaceous substances which give them a high calorific value. Fly-ash from thermal power plants was discussed in 16 articles, a large number of which were published in the 1980s. The wastes with a mainly fluxing effect are represented by sludge, rich in heavy metals, from the ceramic, metallurgical and mechanical industries. They were studied in about 10 papers. The last category includes wastes with a silicate composition which have mainly plasticity reducing or plastifying effects in brick bodies. About a dozen articles examined this type of waste.

2 Fuel Wastes

About half of the works examined discussed industrial wastes as potential energy carriers in the brick-firing phase, as a result of the combustion of the high percentages of organic and/or carbonaceous substances contained in such wastes. This category includes residues from the plants which treat urban wastes, coal processing wastes, textile and tanning industry wastes, as well as the wastes from petroleum, paper and wood processes. Fly-ash from thermal power plants often has high calorific



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values and might be included within the area of fuel wastes. However, the issue regarding the use of fly-ash is quite complex and was discussed in a large number of articles, and therefore it was decided to dedicate a specific chapter to this type of waste. The calorific values reported in the literature refer to wastes from different sources and range from 1200 to 33,000 kJ/kg (Table 1).

In general, the additions, in terms of the quantity of waste that can be used in ceramic bodies, are rather modest (almost never more than 10 mass-%) and the main effects (in addition to the energy savings during firing) include an increase in the porosity of the articles (making them more lightweight) and a reduction of the shrinkage and the mechanical strength of the same.

2.1 Wastes from Sewage Sludge Treatment Plants

The composition of this type of waste is obviously quite variable as a result of the different origin of such wastes and the different treatment processes applied to them. A common characteristic is the high content of organic substances: From 10 – 20 mass-% in the incinerator ash of solid urban wastes [10] to values ranging from 30 – 60 mass-% and higher for sewage sludge [11]. These wastes are often first dried and in some cases fired at 450 °C [10,12]. An abundance of data on the chemical composition of the inorganic part which is basically silicate, does not exist (Table 2); while the contents of heavy metals such as Pb, Zn, Cr, Cu, etc., can not be ignored [11-13].

Although it is generally acknowledged that these waste materials do have a significant calorific contribution, such a contribution is difficult to quantify because of the extreme variability of the characteristics of the products tested. With an estimated calorific value of approximately 10,000 kJ/kg of dry fraction (Table 1) the fuel savings are estimated to be from 10 % [11] to 40 % and higher [13].

Type of Waste	Calorific Value [kJ/kg]	Reference
Sewage sludge	10,038	[12]
	23,079	[16]
Paper industry sludge	7753	[23]
	7812	[20-22]
	7014 ÷ 19,068	[26]
Sawdust	15,960	[24-25]
	16,905	[27]
Wool wash water treatment sludge	1747	[30]
Waste down (textile industry)	18,900 ÷ 29,400	[29]
Exhausted mineral oils	7140	[23]
Tanning industry wastes	~ 84,000	[31]
Coconut pith	12,852	[49]
Olive residues	18,677	[53]
	1260 ÷ 4200	[38]
Coal mining wastes	3528 5796	[36]
	5565	[37]
Petroleum coke	31,500-32,340	[24]
	33,180	[46]
	1680 ÷ 4200	[5-6]
	1470 ÷ 5473	[56]
Fly-ash	2100 ÷ 5460	[24]
	9030	27
	11,638	59

Table 1
Calorific value of fuel wastes

With regard to the quantity of waste added to the clay, it ranges from values of < 2 mass-% [10] up to 25 – 30 mass-% [14 – 15]. Higher quantities irremediably invalidate the technological properties of bricks [11 – 12]. Finally, it is important to mention the environmental benefits related to the savings of raw materials and the disposal of what are potentially polluting substances [16, 17].

It was found that the effects on the raw bodies are represented mainly by an increase in plasticity, with an improvement in the rheological properties which makes shaping easier [11,14]. The reasons for such a reaction involve the fibrous structure of a large part of the added organic fraction. The results do not agree with the dry shrinkage (Table 3), which does not seem to develop in one particular manner. In fact, cases are reported involving a significant increase in shrinkage with the

Table 2
Chemical composition of the inorganic fraction of fuel wastes

[Mass-%]	Sewage Sludge		Paper Industry Sludge		Coal Mining Wastes				Exhausted Mineral Oils	Rice Hulls	
Reference	[10]	[64]	[20-22]	[23]	[36]	[37]	[38]	[42]	[23]	[51]	
SiO_2	53.2	41.9	35.2	58.6	49	54.1	56.0	66.6	60.7	97.9	98.3
Al_2O_3	10.5	34.7	28.0	32.3	33	29.1	27.7	19.4	16.4	1.1	1.0
TiO_2		1.3	-	0.9		1.4	1.4		0.7		
Fe_2O_3	3.1	4.3	1.4	2.0	6	5.8	6.7	7.6	7.2	0.5	0.4
MnO								2.6	0.1		
MgO	2.8	1.5	7.1	3.5	1	1.5	1.6	1.1	2.8	-	-
CaO	15.5	3.3	26.1	1.1	1	2.5	1.8	2.6	6.7	0.5	0.3
Na_2O	10.5	0.3	0.2	0.2	8	0.4	0.5	1.0	1.0		
K_2O	1.9	2.6	1.0	1.3		3.6	3.6	0.9	2.6		
P_2O_5	2.5	5.5									
SO_3		-	0.8	0.1		1.3	1.0		1.6		
ZnO			0.2						0.1		
Total	100.0	95.4	100.0	100.0	98	99.7	100.3	101.8	99.9	100.0	100.0
C						11.4	6.8				
L.o.I.	17.0	-	50.1	64.7				22.7	31.3	81.5	2.3

Provenance of Waste	Sewage Sludge Treatment Plants				Paper Industry	Sawdust			Wool Wash	Tanning Plants			Coal Mining	Petrol. Coke	Petrol. Waxes	Coconut Pith	Rice Hulls(fired)		Harbour Sludge	Ground Tyres
Reference	[10]	[11]	[12]	[15]	[20-22]	[25]	[27]	[28]	[30]	[33]	[34]	[35]	[37]	[46]	[47]	[49]	[50]	[51]	[54]	[34]
Waste addition to the body [mass-%]	0.5-12	20-40	33	1-50	2-10	3-4	3-5	10	10	10-40	1-2.5	2	6-20	1-2.5	1-20	10-30	13-26	10-40	10	1-5
Shaping technique	P	E	E	E	E	E	E	E	E	M	E	E	E	E	E	M	E	M	E	E
Dry bending strength [MPa]	-	-	-	-	-	-	-	4.5	4.9	-	-	7.5	0.5**	7-8	3-6**	-	1.5	-	-	-
Drying shrinkage [%]	-	5-6	5	-	-	5-6	-	4.3	4.5	-	-	5.4	4-5	-	6-8	-	4-5	-	-	-
Firing temperature [°C]	980-1020	950-1050	1000	1015	985	–	–	920	950	950-1050	900-1000	850-1000	850	1000	920	700-900	1150	1000	1050	900-1000
Water absorption [%]	-	38-40	-	10-26	15-22	-	15-18	28	22	13-19	25-29	8-13	2-14	-	13-38	-	11-16	14-19	28	23-29
Linear firing shrinkage [%]	-	5-8	4	14-22*	0	0.5	-	1	0	5-8	6-8*	0-2	-	-	< 1	22-34*	-	< 1	-	6-8*
Bending strength (fired) [MPa]	5-11	2-4	-	-	11-14	9-12	17-19	13	8	2-4	9-14	11-13	-	17-20	-	-	3-5	-	3.7	8-22
Compressive strength (fired) [MPa]	-	-	14	18-36	-	-	-	30	-	20-54	-	-	3-4	-	14-16	-	26-66	22-27	21.5	-

* Total shrinkage (drying + firing) P = pressing E = extrusion M = moulding
** Dry compressive strength

Table 3 Technological properties of bricks containing fuel wastes

formation of cracks during the drying process [11,15] or cases involving a reduction in dry shrinkage and the drying sensitivity [12].

In fired articles, there is a general increase in water absorption and a subsequent reduction in the density of the brick, for example 15 % less for additions of 30 mass-% of sewage sludge [18]. The firing shrinkage tends to increase and often quite significantly. These structural variations effect the mechanical strength, which decreases mainly from 4 to 30 %, and even 50 % for additions of sludge of more than 40 vol-% [18]. A negative aspect is the development, during firing, of unpleasant odours, for which the firing cycle conditions must be carefully considered [12,15]. In addition, efflorescence [12] and "black core" phenomena may also occur.

2.2 Paper Industry Sludge

The sludge from paper industry waste-water treatment processes has an organic substance content of about 20 mass-% of dry weight [19 – 22] and calorific value of around 8400 kJ/kg (Table 1). Because of the large quantity of organic substances with a low boiling point, in particular water, simple drying at 100 °C decreases the weight by more than 50 mass-% [20 – 22]. The inorganic component consists mainly of SiO_2, Al_2O_3 and, in some cases, of MgO and CaO (Table 2).

Experiments were conducted whereby less than 10 mass-% of this dried sludge was added to the bodies (Table 3); the optimum quantity ranges from 3 - 8 mass-% [19 – 22]. These additions lead to a slight increase in the working-moisture content of the body and dry shrinkage. No particular problems were noted in the extrusion and drying processes [20 – 22], even though in some cases there are some difficulties during the dosage and extrusion phase due to the fibrous parts contained in the sludge [23].

The properties of the fired products are not particularly influenced by the modest additions of paper industry sludge. Only slight increases in water absorption were found along with a tendency to generate efflorescence, with a slight reduction in mechanical strength and sometimes a deterioration in the appearance of the finished product [23]. With regard to fuel savings, they range from negligible values [19 – 23] up to savings of about 18 % [20 – 22].

However, there are conflicting conclusions about the use of paper industry waste sludge. It would seem to be economically advantageous especially because of its energy contribution, without compromising the quality of the finished product [20 – 22]. In effect, the recycling of these wastes has now become a reality in a number of Italian brick-manufacturers [1].

2.3 Sawdust

Sawdust from the wood-manufacturing industry, in addition to the clay raw material, can be used to produce lightweight bricks. The use of sawdust also saves energy, and as such, savings may reach up to 15 % of the global need [24]. The calorific value generated ranges from 7000 – 19,000 kJ/kg, with a maximum frequency of around 17,000 kJ/kg (Table 1).

The quantities of sawdust added to the clay are always limited; in fact, the optimum values are around 4 – 5 mass-% (Table 3). The particle size of the sawdust must be balanced among the various fractions and in any case the maximum size of the particles must be < 2 mm, to avoid preliminary grinding [25]. The use of this type of waste improves clay workability and reduces drying time [24 – 25], even if in some cases there are problems during the extrusion and drying phase, a reduction of green strength and dry strength values and an increase in the working-moisture content [26].

The fired product is lightweight, with a subsequent improvement in the thermal and acoustic properties. Water absorption tends to increase even considerably, while shrinkage remains the same, or is at the most slightly reduced. The mechanical strength decreases from 10 to 30 %, but this is not a problem if the objective is to obtain a lightweight product. Overall, from an economic and technological point of view, it is possible to introduce small quantities of sawdust into the brick bodies [24 – 26]. The negative aspects involve the formation of efflorescence [27] or the emission, in the form of gas, of noxious elements [27 – 28]. Sawdust is currently used by a small number of Italian brickworks as an addition to the clay body and as a furnace fuel [1].

2.4 Wastes from the Textile Industry

The use of textile industry wastes (fibrous wool-waste and wool-wash water treatment sludge) in the brick production process has positive effects in regards to fuel savings – up to 20 % [24] – even if there are great differences in calorific value depending on the origin of the wastes. With regard to fibrous wool, the waste additions to the body do not exceed 1.5 mass-% [24, 29], while for wool wash sludge, the quantities indicated are 10 mass-% [30]. This is due to the different quantity of organic substances, which for the wool sludge is only about 20 mass-% out of the dry amount [30]. For waste down there are so many problems related to the dimensions of the filaments that preliminary grinding is required.

The presence of "textile wastes" in the aforementioned quantities basically does not change the properties in green and dry brick, while it increases water absorption, reduces bending strength (about 20 % out of the total) and decreases the volume weight (Table 3) of the fired product. Even though the use of such wastes is possible from the technological, energy and environmental points of view, there are insufficient data about their effective recycling in the brick industry. Most of the obstacles regarding their use refer to transport and treatment costs.

2.5 Tanning Industry Wastes

Recycling the wastes produced by tanning plants, whether they are disposal sludge [31 – 34] or tanned hide residues [35], is problematic because they contain polluting elements, and most importantly chromium. In fact, this sludge, which can potentially be used as a fuel, considering its significant calorific value (Table 1), must undergo continuous toxicological and environmental controls. Therefore, the sludge dosage in brick bodies depends mainly on the chromium content. Additions do not exceed 10 % of waste and in general make the fired products lightweight, improving the heat insulating characteristics (Table 3). In particular, the chrome tanned hide residues (addition of 2 mass-%) have plasticity reducing effects on the body, i.e. they make drying easier, reduce shrinkage and bending strength, and increase porosity [31 – 32, 35]. Finally, from a technological point of view, tanning wastes can be recycled, but the emission of unpleasant odours during firing and the release of chromium from the products must be kept under strict control.

2.6 Coal Mining Wastes

Numerous surveys have been carried out to verify the possibility of reusing these wastes [36 – 45]. The waste products derived from coal mining and refining processes (whether solid mining wastes or washing wastes), generally have a significant but variable calorific value (Table 1) which ensures major energy savings, estimated to range from 20 to 40 %, with peaks of even 60 % [36, 41]. The inorganic component of such wastes consists mainly of clay minerals and quartz; therefore, the chemical composition is rich in silica, alumina and iron oxide, with generally reduced contents of alkaline and alkaline-earth elements (Table 2).

These materials are very heterogeneous and to such an extent that for some of them preliminary refining and/or grinding is recommended, while others can be used as they are. As a consequence, the quantity of waste added to the clay varies greatly: The most frequent content is around 5 – 15 mass-% [36, 37, 39], but some authors believe they can be almost completely used as an alternative raw material to clay for producing bricks [38, 42].

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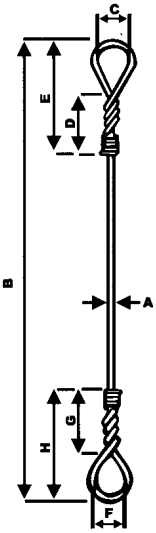
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Reference	[28]		[34]	[56]			[57]	[58]	[59]			[60]	[62]	[63]	[64]		[65]
SiO_2	47.9	30.9	58.5	48.1	47.0	41.4	37.6	51.0	44.0	48.4	50.4	59.9	53.5	31.5	49.9	49.0	67.8
TiO_2	6.6		0.9					0.7	1.3	1.1	1.1		2.6	1.5	0.9	1.2	
Al_2O_3	30.0	17.0	23.0	23.8	24.0	37.9	39.3	22.7	33.1	29.8	27.8	25.2	32.1	16.0	25.6	27.7	7.1
Fe_2O_3	7.8	7.0	7.9	9.1	10.3	6.0	9.8	8.0	8.6	10.5	11.1	11.3	5.8	31.0	14.1	8.8	
Mn_3O_4							0.1		0.1	0.1	0.1						
MgO	1.3	1.7		4.3	4.3	2.4	4.6	3.6	2.4	3.0	2.6	<0.1	1.5		1.2	4.0	3.6
CaO	3.5	2.5	2.3	7.2	7.5	10.0	9.7	7.9	2.1	3.1	3.6	<0.1	2.3	15.0	1.4	1.3	6.0
SrO	0.1								0.1	<0.1	<0.1						
BaO									0.2	0.2	0.1						
Na_2O	1.2	0.9		1.1	1.0	0.2	0.3	0.6	1.5	1.4	1.0	0.2	0.1		0.7	1.0	
K_2O	1.1	2.3	2.1	2.5	2.5	0.4	0.3	2.2	2.0	1.9	1.9	0.5	0.8		3.5	0.7	
P_2O_5	0.4						0.2		0.5	0.3	0.2				-	-	
V_2O_5									0.2	0.2	0.1						
SO_3	0.4			1.8	1.5	0.9						0.1			0.5	0.6	2.2
C	0.6	35.0															
L.o.I.			2.3					3.2	4.3	3.5	3.7	2.8	1.6	0.6	9.3	3.3	11.1

Table 4 Chemical composition [mass-%] of fly-ash experimented in brick manufacture

The technological characteristics of the products obtained with these materials vary in relation to their present plasticity reducing and plastifying action. In any case, they tend to improve the drying behaviour and, in general, the mechanical strength of the semi-finished products. There is also an increase in the porosity of the fired products, while shrinkage is influenced differently according to the nature of the waste added (Table 3). These structural variations may lead to an even considerable reduction of the mechanical strength of the finished products [45].

The use of coal wastes, whether mixed with clay or as a complete raw material, provides rather positive results from a technological and especially economic point of view. In some cases it was possible to obtain high-quality and low-cost products [36]. However, grinding and refining treatments as well special attention in the firing process, especially during the preheating phase, are often needed.

2.7 Petroleum Refinery Wastes

The petroleum refinery wastes have a high calorific value, of around 31,000 kJ/kg (petroleum coke) and therefore introducing them into the bodies guarantees significant fuel savings. Petroleum coke, obtained from the heaviest fractions of petroleum distillation (tars), is also used as a ground dust (particle diameter < 100 μm) by a small number of Italian brickworks [1]. It is added to brick bodies in percentages that are always less than 2.5 mass-% [46]. In these experiments, there were no significant changes in the quality of the final product, except for a reduction of the bending strength (max. 15 %) which does not, however, compromise acceptance.

With 1 – 2 mass-% petroleum wax additions to the body, it is possible to produce bricks with good heat insulating properties. These properties are obtained due to a considerable increase in the porosity of the fired product, which however does imply a large decrease in mechanical strength (Table 3). The presence of petroleum wax has a positive effect on both dry and firing shrinkage [47].

2.8 Other Fuel Wastes

These wastes come from various sources, but all have significant contents of fuel substances, which basically lead to a reduction in firing consumption. Research

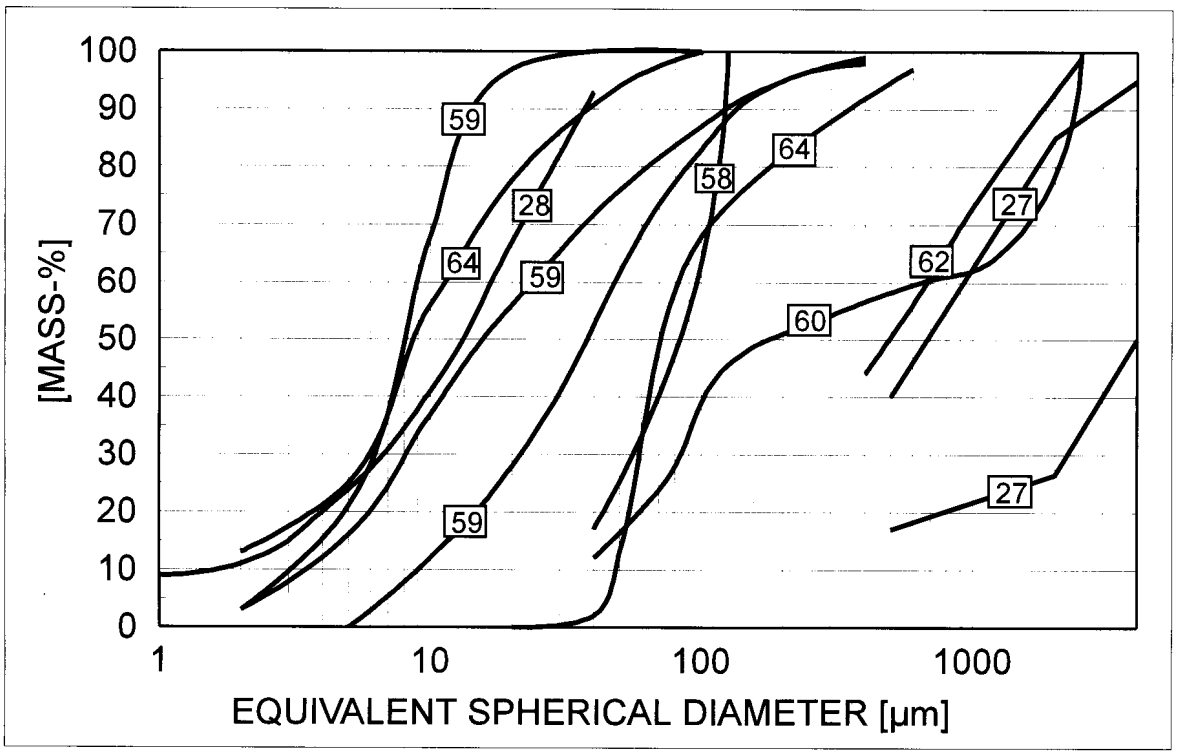


Fig. 1
Particle size distribution of fly-ash experimented in brickmaking. Reference numbers are indicated

activities were carried out on exhausted mineral oils, and the relative calorific value is estimated to be around 7000 kJ/kg (Table 1). The inorganic component of these wastes consists mainly of SiO_2, with significant contents of Al_2O_3, Fe_2O_3 and CaO (Table 2). When they are added to the body in percentages that are not greater than 5 mass-%, extrusion is easier and fired products can be obtained with the same or even slightly better technological characteristics, and with good thermo-acoustic properties as a result of the significant increase in porosity. Additions of more than 5 mass-% cause structural defects with a major development of "black core" phenomena [23, 48].

Coconut pith mixed with clay can be used to produce lightweight blocks and have considerable energy benefits. For additions of 20 mass-% of waste the fuel savings are estimated to be 17 % due to the equitable calorific value (about 12,000 kJ/kg). The products obtained (Table 3) have less shrinkage, but also much less mechanical strength than the bricks without coconut pith residues [49].

Rice hulls consist almost exclusively of silica and volatile components (Table 2). The hulls are added to brick bodies to obtain a certain amount of savings in fuel and raw materials, and to obtain lightweight bricks with an equitable quality level. The percentage of hulls tested range from values of less than 10 mass-% (hulls fired at 150 °C) up to values of 40 mass-% of the body (hulls fired at 700 °C). Optimum values are considered to be around 20 mass-% [50 – 51]. Such wastes seem to decrease the mechanical properties of fired products considerably [50 – 51], even if in some cases there is a slight improvement [52]. However, there is also an increase in water absorption (Table 3) and efflorescence [50]. The use of olive residues and ground foliage in brick bodies is frequent in some areas of intense olive tree cultivation in Italy and in Spain. Drying behaviour is improved, while fired products present higher porosity and a slightly lower bending strength [53]. There are rather negative results regarding the use of harbour sludge from dredging operations in brick production. Additions of harbour sludge < 10 mass-% of the body worsen the characteristics of the fired products and provide limited energy benefits (Table 3). The main restriction in using this type of waste is still the emissions of fluorine, sulphur and especially chlorine during firing, and the major increase of efflorescence on the products [54]. Finally, some further examples concerned polystyrene recycled from packings [55] and ground tyres [34].

3 Fly-ash

The use of coal as a fuel in thermal power plants generates solid inert residues called "ash" which also contain small quantities of unburned carbonaceous particles. On average, it can be assumed that 150 g of ash are obtained from 1 kg of coal and that ash contains about 6 to 24 g of unburned coal particles [56]. About 20 % of the residue precipitates on the bottom of the combustion chamber (bottom-ash), while the remaining 80 % consists of very fine particles (fly-ash) which are trapped by special filters installed along the outlet piping of the gaseous combustion products. A medium-sized thermal power plant generates several hundred tonnes of ash every day [56 – 57]. The physical and chemical characteristics of the ash vary greatly especially in relation to the type of coal and furnace used.

From a general overview of the works considered, the particle size distribution of the fly-ash varies generally from 5 – 200 µm, with a mean grain size of around 30 – 50 µm (Fig. 1). As a consequence, the use of fly-ash does not generally require grinding. In addition, the particles tend to have a spherical shape and thus provide good plasticity in the bodies [57]. These are mainly amorphous materials (glass silica), with a very low crystalline component consisting of mullite needles [56]. The chemical composition is also quite varied (Table 4): Silica (30 – 55 mass-%), alumina (15 – 40 mass-%), iron (5 – 14 mass-%) calcium (1 – 15 mass-%), magnesium (1 – 5 mass-%), sodium (0.1 – 1.5 mass-%) and potassium (0.2 – 3.6 mass-%) in addition to other trace elements.

- to be continued -

Recycling of Industrial and Urban Wastes in Brick Production – A Review (Part 2)*

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*Part 1 was published in TBI 3/97

The extreme variability of the physical-chemical characteristics of the fly-ash makes it very complicated to describe a single framework for its possible use. It is enough to consider that bodies were tested with a clay/fly-ash ratio that ranges from 10:1 up to values of less than 1:1. The fly-ash was used as a material to partially replace clay and as a material which provides an energy contribution during firing as its calorific value ranges from 1470 to 11,760 kJ/kg (Table 1). The fuel savings during the firing phase, indicated in 12 out of the 16 works examined, is still quite variable since it depends on many factors [56 – 58].

The addition of fly-ash to clay raw materials leads to a generalised improvement in the behaviour of the bodies in the shaping and drying phases. Fly-ash in the bodies generally has a plasticity reducing effect and improves drying, reducing the formation of fissures and cracks [24, 56 – 57, 59 – 62]. However, its use in a finely divided state may also give the bodies added plasticity [5]. Instead, there might be a slight decrease in dry strength, which however does not invalidate the characteristics of the product [24]. When there are greater quantities of fly-ash than clay in the body [59 – 60], there are drastic reductions in dry shrinkage (from 5 – 1 %) along with a considerable worsening of the mechanical properties of the articles (Table 5).

With regard to the characteristics of the materials produced with clay/fly-ash mixes, there is a frequent tendency to improve the mechanical properties of the products, which can be attributed to the formation of mullite [63] during firing. Firing shrinkage tends to increase with the content of fly-ash, while there is no specific development for porosity. This situation is caused by the use of different compositions and varying quantities of fly-ash in the body [34, 58 – 59, 63]. The influence of the particle size distribution must also be emphasised. Fine fly-ash seems to reduce water absorption to a great extent and to improve the mechanical properties, firing shrinkage and the bulk density compared to samples which contain the same quantity of fly-ash, but with a coarse particle size distribution [59]. Furthermore, the use of fly-ash seems to reduce efflorescence [24, 28, 56].

In conclusion, tests were performed on additions of these materials to the clay in very different quantities according to the main function of the fly-ash in the brick body. The values range from a few percentage points (< 10 mass-%), if the fuel effect is favoured, to the almost total replacement of the clay raw material. With regard to the economic nature of the use of fly-ash, it ranges from very positive [58, 61], or in any case recommendable [28, 57, 59, 62 – 65], to negative results [24, 66]. These economic assessments are influenced moreover by aspects which are not part of the technological process, such as those involving the high transport costs [56].

4 Fluxing Wastes

Another group of wastes is represented by sludge coming from the glazing lines of ceramic tile manufacturers, plating plants and metallurgical and mechanical processes. These wastes basically have a silica-alumina composition (silica + alumina > 50 mass-%) for which there is an extremely variable content of heavy metals and alkaline and alkaline-earth elements [67]. In particular, the PbO content could have reached very high levels, while today the use of lead in glazing has been reduced and, as a consequence, its quantity in the sludge

Table 5 Technological properties of bricks containing fly-ash

Reference		[27]	[28]	[34]	[56]	[58]	[59]	[60]	[61]	[62]	[63]	[64]	[65]
Fly-ash addition to the body	[mass-%]	3–5	10–20	10–20	6–30	20–60	10–100	70–80	–	10–50	90	70–100	50–75
Shaping technique		E	E	E	–	M	P	P	E	P	P	P	M
Dry bending strength	[MPa]	–	4–7	–	2–3	–	0.1–3	–	–	–	–	–	–
Drying shrinkage	[%]	–	4–5	–	3–5	–	0–6	2–3	1–2	1–2.5	–	–	–
Firing temperature	[°C]	–	920	900–1000	–	1000	1100	1100	1050–1120	980–1080	1000–1200	1100	1000
Water absorption	[%]	10–11	25–28	22–27	–	8–40	5–25	20–22	14–25	24–37	–	–	<1
Linear firing Shrinkage	[%]	–	~1	5–8*	–	2–8	5–32	2–3	–	1.5–4	2–6	–	–
Bending strength (fired)	[MPa]	18–20	13–17	8–17	–	–	–	–	2–8	1–20	–	–	–
Compressive strength (fired)	[MPa]	–	26–33	–	–	28–48	1–28	5–9	10–21	20–25	4–75	3–21	14–25

* total shrinkage (drying + firing) P = pressing, E = extrusion, M = moulding

Reference	[23]	[67]	[67]	[67]	[67]	[67]	[67]	[68]	[69]	[70]	[71]
SiO_2	8.9	49.0	39.8	52.9	41.5	41.0	34.1	31.7	46.6	39.0	33.4
TiO_2		0.2	0.6	0.1	1.6	2.8	0.6	1.4	0.3	1.3	1.3
ZrO_2		3.8	2.7	2.9	6.4	2.0	2.0	7.3	9.1	6.0	4.9
B_2O_3		8.0	6.4	8.6	5.4	3.9	6.4	7.8	7.8	9.1	7.9
Al_2O_3	16.7	9.2	12.1	9.9	11.8	13.1	10.8	5.0	10.9	9.0	8.6
Fe_2O_3	10.2	1.4	3.9	1.0	5.7	3.7	3.8	3.0	1.7	4.7	4.2
Cr_2O_3	7.9	0.1	0.2	0.1	0.1	0.1	0.2				
MnO	0.2	<0.1	0.2	<0.1	0.3	1.8	0.3	0.3		1.4	1.4
MgO	1.2	0.3	0.4	0.3	1.1	0.6	0.3	0.2	0.6	0.2	0.2
CaO	3.2	3.3	6.3	1.5	7.0	4.5	7.6	2.2	5.1	2.2	2.1
CoO		0.2	<0.1	<0.1	<0.1	<0.1	<0.1				
NiO	0.2	0.1	0.1	<0.1	<0.1	<0.1	0.1				
CuO	4.0	<0.1	<0.1	<0.1	0.4	1.8	0.1				
ZnO	9.6	0.3 5.4	0.3 2.0	2.0	4.0	4.4	1.7	1.8	1.9	1.3	1.4
CdO	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1				
BaO								0.2		0.5	0.3
PbO	0.3	9.0	11.4	11.0	5.8	0.5	16.8	34.0	6.5	18.5	16.4
Li_2O		0.1	0.1	<0.1	0.1	0.2	0.1	0.1			<0.1
Na_2O	1.7	2.2	1.7	3.1	1.5	2.5	1.3	0.6	3.8	2.0	2.0
K_2O	0.1	2.4	0.9	0.9	1.7	0.9	0.7	0.4	1.5	1.0	0.9
Cl	0.3	0.6	<0.1	0.2	0.4	n.d.	0.3				
SO_3	4.7										
L.o.I.	30.8	5.9	11.0	1.8	8.8	10.3	11.4	1.7	2.7		

Table 6
Chemical composition of fluxing wastes [mass-%]

has decreased. There are often traces of Cr, Co, Ni, Cd, Cu, etc. (Table 6). These wastes have a mainly "fluxing" effect, which occurs with a substantial reduction of the porosity where the body firing temperature is the same. One of the advantages of this fluxing effect is the possible energy savings as a consequence of the reduction of the firing temperatures.

Focusing on glazing line sludge, the usable quantities vary in relation to the characteristics of the raw materials with which they are mixed, and the type of product to be obtained. Tests were conducted on percentages of up to 80 mass-% [68], but the optimum addition generally does not exceed 20 mass-% (Table 7).

The "fluxing" waste additions have positive effects on the bodies during the extrusion and drying phases. Dry shrinkage remains unchanged or tends to decrease slightly, while there is a reduction in laminations and cracks. The main negative point in these phases of the working process, is a decrease in dry strength of around 15 to 40 % [69].

For fired products there is an increase of the mechanical properties. Moreover, there is a slight decrease in water

Table 7
Technological properties of bricks containing fluxing wastes

Reference		[67]	[69]	[69]	[69]	[70]	[71]	[74]	[75]	[76]
Waste addition to the body	[mass-%]	5–30	80	10–30	50	5–10	1–7	0.5–5	2–20	2–50
Shaping technique		P E	M	E	E	P	E	M	E	P E
Dry bending strength	[MPa]	–	–	4–8	3–6	–	–	–	3–4	–
Drying shrinkage	[%]	–	–	–	–	–	6–7	–	6–7	–
Firing temperature	[°C]	950–1100	550–620	900–950	900–950	900–1000	900–1000	1000	920–1050	950
Water absorption	[%]	13–19	5–18	5–17	2–9	19–24	16–23	11–15	0–15	17–52
Linear firing shrinkage	[%]	1–3	<1	0–1	9	0	2–4	9–15	3–9	0–2
Bending strength (fired)	[MPa]	–	–	15–24	24–31	–	12–22	–	18–46	–
Compressive strength (fired)	[MPa]	30–46	–	–	–	–	–	22–32	–	–

P = pressing, E = extrusion, M = moulding

[Mass-%]	Plasticity Reducing Wastes									Plastifying Wastes						
Reference	[80]	[81]	[82]	[83]		[88]			[89]	[77]	[79]	[84]		[86]		[90]
Type of Waste	Basalt Dust	Brick Chamotte	Cement Dust	Gravel Washing Sludge	Refractory Chamotte	Exhausted Diatomite	Cement Waste		Cu-Ore Dressing Slime	Drilling Muds	Sand Washing Sludge	Mining Wastes		Wastes from Bauxite Processing		
SiO_2	49.6	66.3	14.2	23÷50	58.6	66.0	46.1	53.4 51.2	53.6	19.9	43÷45	74.6	65.4	0.7	3.3	13.5
TiO_2	2.6		n.d.	0.3÷0.5	2.1	1.4	0.8	0.2 2.0	1.0	0.3	1.0					4.0
Cr_2O_3										0.2						
Al_2O_3	15.2	8.7	5.6	7÷12	31.4	24.5	11.6	7.1 20.2	13.1	9.0	30.0	9.3	18.2	53.1	28.0	20.2
Fe_2O_3	5.1	12.3	0.9	1.5÷5	4.1	1.8	6.7	0.9 4.7	12.5	4.0	5.8÷7.2		1.4	1.8	4.6	35.0
FeO	7.8										0.4÷1.1	1.2				
MnO	0.1		n.d.	0.1												<0.1
MgO	5.4	4.0	1.8	1.6÷6.9	0.5	0.4	0.5	0.9 1.0	4.8	2.6	0.4		1.4	2.2	1.9	0.3
CaO	9.1	6.0	42.1	13÷33	0.5	1.7	11.2	19.2 9.3	6.3	7.0	0.1			1.2	15.0	5.3
BaO										26.7						
Na_2O	3.1	1.5	4.5	0.5÷1.6	<0.1	0.2	0.5	1.3 0.9	5.1	0.8	0.1		12.9	8.3	2.4	9.4
K_2O	0.9		4.5	0.7÷2.3	0.8	1.4	0.8	0.7 1.3		1.4	0.7					0.4
P_2O_5	0.4			0.1							0.1					
SO_3	0.2	0.5	3.7		0.7	1.4	6.2	4.0 3.7		13.9				2.0	3.9	0.1
L.o.I.	1.3	0.3	27.5	13÷30	1.4	1.1	15.9	12.3 6.0	4.2	13.4	12÷15	2.7	0.7	30.8	41.0	8.4
CaF_2												10.8				

n.d. = not detected

Table 8 Chemical composition of plasticity reducing and plastifying wastes

absorption with an increase in the sludge content, shrinkage remains the same or increases slightly. In addition, there was also a strong reduction in efflorescence for additions of sludge limited to 2.5 mass-% [69 – 71].

The addition of sludge coming from the glazing lines of ceramic tile manufacturers can be seen as positive, especially in terms of the environmental impact as the potentially toxic sludge, for which disposal is rather difficult, can be neutralised. Some doubts were raised about the real effectiveness of the inertisation processes, since firing might lead to the formation of soluble lead salts [72]. At the present time, this sludge is reused in most tile-making plants and there is no information about reuse in brickmaking.

In regards to plating plant sludge, it was proposed to use it in percentages of < 5 mass-% of the body. However, the use of such wastes requires a preliminary inertisation treatment due to the high contents of heavy metals. The tests performed have shown an improvement of the mechanical properties and the frost resistance of the bricks [23, 73 – 75].

Some experiments were performed on industrial wastes from various sources, and characterised mainly by the presence of toxic and noxious elements which make them particularly difficult to reuse [76]. Such materials were added to the normal raw materials used in the brick industry in percentages ranging from 2 – 50 mass-%. The characteristics of the fired products were acceptable only for small additions (in general < 5 mass-%). In any case, there are generalised increases of water absorption and, in some cases, efflorescence also occurs.

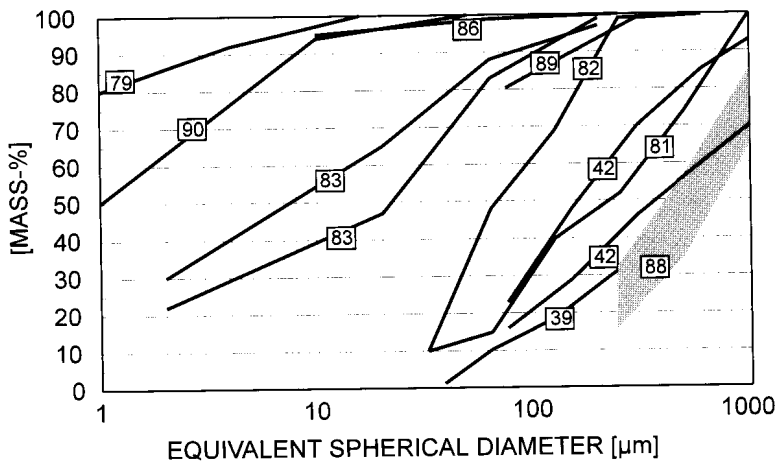


Fig. 2 Grain size distribution of plasticity reducing and plastifying wastes. Reference numbers are indicated

5 Plasticity Reducing and Plastifying Wastes

During the clay working process, waste materials from the mining and metallurgical industries may have a plasticity reducing or plastifying effect. In any case, it is difficult to make a clear distinction, since one of the two effects often occurs in relation to the grain size distribution of the wastes and/or to the characteristics of the clay with which they are mixed [77]. Overall, the chemical compositions of these wastes vary greatly (Table 8) in relation to their origin from different types of processes in the mining, cement, thermal power plant industry or others [77 – 91].

Due to what tends to be a coarse grain size distribution (Fig. 2), some materials are used to attenuate the plasticity of the clay raw materials (plasticity reducing wastes). Therefore, the bodies obtained need less water to acquire

good workability and are characterised by slight reductions in shrinkage and less drying sensitivity.

The quantities of wastes used are 10 – 60 mass-% (Table 9). Such contributions cause slight reductions in mechanical strength and shrinkage, of the fired products, while the other parameters do not appear to be effected. For example, water absorption seems to increase following the use of cement dust [82, 88], chamotte [81, 88], gravel washing wastes [83] and exhausted diatomite [88], while it decreases with the use of copper-ore flotation wastes [85, 89].

Inserting basalt mining wastes [80] into the bodies increases shrinkage and decreases water absorption for contents < 10 mass-%, until reaching a limit value beyond which the effects become diametrically opposite (additions ranging from 10 – 30 mass-%). Finally, some efflorescence [82] may occur, due to the high Ca content of some of these products, even if *Probst* [83] observed a significant reduction. In conclusion, it seems to be confirmed that these waste materials can be used as a plasticity reducing raw material to partially replace clay for producing bricks.

Other mining and metallurgical industry wastes can be used as plastifying materials since they can give the body plasticity, making shaping easier and therefore ensuring savings of clay raw materials. These materials have a fine grain-size distribution (Fig. 2) and consist mainly of clay minerals plus quartz, feldspars and carbonates. The chemical compositions are reported in Table 8.

These wastes generally come from rock and mineral processes, such as bauxite, feldspar, quartz sand, fluorite and gravel. They are commonly added in quantities ranging from 5 – 15 mass-%, with peaks of even 60 – 100 mass-% [84,90]. The most significant effect of such additions is the increase in plasticity, with a consequent slight increase in dry shrinkage. This makes it possible to use certain materials, which initially are not very plastic, that would otherwise create problems [84]. Quantities > 15 mass-% of sand or bauxite processing residues have a negative effect on the final product [79, 86].

The fired products feature generalised and even considerable increases in mechanical resistance, while porosity and shrinkage appear to vary depending on the specific case. Water absorption is reduced, sometimes considerably, for cases involving the use of feldspar and fluorite [84] or carbonaceous clay washing wastes [42]; it increases for those involving bauxite processing wastes [86].

Finally, it was proposed to add < 10 mass-% of materials containing asbestos obtained from the demolition of brake linings. Firing, which converts the asbestos into harmless substances, such as forsterite, has important advantages in terms of human health, thus avoiding environmental pollution, and does not compromise the quality of the finished products. In fact, there is a reduction in shrinkage and a slight increase in water absorption, with a simultaneous reduction in mechanical strength. A small amount of energy savings [87] has also been reported.

6 Conclusions

Over the last twenty years many works have been written about the reuse, in the brick industry, of a wide range of urban and industrial wastes. Most of the research is concentrated in the eighties. This research has demonstrated the practical application of this type of reuse with environmental and technological advantages. Research activities then decreased, and were limited to new types of wastes or more in-depth studies of particular aspects.

Table 9 Technological properties of bricks containing plasticity reducing and plastifying wastes

		Plasticity Reducing Wastes								Plastifying Wastes					
Reference		**[80]**	**[81]**	**[82]**	**[83]**	**[85]**	**[87]**	**[88]**	**[89]**	**[42]**	**[77]**	**[79]**	**[84]**	**[86]**	**[86]**
Waste addition to the body	[mass-%]	10–30	20–60	10–30	~25	10–50	5–10	10	10–30	90	2–10	5–15	60–80	5–15	5–15
Shaping technique		E	E	E	E	M	M	E	M	P	E	E	M	M	?
Dry bending strength	[MPa]	–	–	–	5–6	–	4–7	4–6	1–2	–	4–12	2–3	–	–	–
Drying shrinkage	[%]	8–10	9–12	10–11	~6	7–8	7–8	6–8	5–8	–	4–6	3–5	–	–	8–11
Firing temperature	[°C]	900–1000	900–1000	900–1000	950–1050	950	900–1000	980	950	820	920–960	1000–1100	1000	1000	1000–1075
Water absorption	[%]	10–15	6–11	17–25	17–19	19–20	22–27	10–13 19–24 <1	17–18	17–20	10–16	–	12–16	12–15	12–16
Linear firing shrinkage	[%]	1–2	3–6	1–2	0–1	0–2	<0.5	3–5	1–2	~0	<1	2–7	–	–	3–4
Bending strength (fired)	[MPa]	–	–	–	–	4–9	6–12	7–10 12–16	11–15	–	13–35	–	–	–	2–4
Compressive strength (fired)	[MPa]	–	20–50	–	60–83	16–35	–	–	–	10–18	–	22–59	10–18	4–10	14–20

P = pressing, E = extrusion, M = moulding

The best prospects concern the materials which are rich in organic and/or carbonaceous substances, since their combustion during the firing phase provides significant energy savings, even if used in limited quantities (< 10 mass-%). The technological properties of the products vary within what are generally tolerable ranges, and they are often positive, such as creating lightweight bricks and thus providing additional economic benefits during transport and installation and giving the product better heating insulation properties. Therefore, it is not by chance that about 2/3 of the works examined refer to wastes which can release heat during the brick firing phase. Because of the great variety of waste composition, in each case a series of specific experiments must be carried out before it is possible to use specific type of wastes in industrial applications. In addition, frequent checks are required on the characteristics of the wastes already used in the production process, to prevent negative effects related to the excessive variability.

The use of other waste materials has an influence, in particular, on the plasticity of the bodies and the porosity and the mechanical strength of the fired products, but not always in a positive manner.

In conclusion, it can be stated that the recycling of industrial and urban wastes in clay raw materials is theoretically useful for those who produce them (correct disposal of bulky and polluting materials) and for brick manufacturers (reduction of the supply costs of raw materials, energy savings, improved technological performances in some cases). However, often the reuse of the wastes is not economically advantageous, due to the high transport costs which have a very heavy influence on the global production costs (without forgetting additional costs related to the need to perform controls, for some types of wastes, on the flue gas emissions generated during the firing phase and on the presence of toxic and polluting elements).

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Kurzfassung

Ein Überblick über die Wiederverwertung von Abfällen in der Ziegelherstellung

Die Arbeit gibt anhand von Studien der Literatur der letzten 20 Jahre einen Überblick über den derzeitgen Stand des Wissens zur Wiederverwertung von Industrie- und Siedlungsabfällen in der Ziegelherstellung. Die Untersuchungen stammen von Autoren aus Italien, Rußland, Großbritannien, Spanien, Deutschland und den USA. Behandelt werden die Abfallstoffe: Brennstoffabfälle (53 Arbeiten), Flugaschen (16 Arbeiten), Flußmittel (10 Arbeiten) und plastizitätssenkende und -steigernde Abfallstoffe (12 Arbeiten).

Résumé

Une revue du recyclage des déchets industriels et urbains dans l'industrie des briques.

L' article fait le point sur l'état actuel des connaissances sur le recyclage de déchets industriels et urbains dans l'industrie des briques, à partir des données de la littérature de ces 20 dernières années. Les travaux rapportés sont en provenance d'Italie, de Russie, de Grande Bretagne, d'Espagne, d'Allemagne et des Etats-Unis. 53 publications portent sur les déchets comme combustibles, 16 sur les cendres volantes, 10 sur les déchets à action de fondants, 12 sur les déchets à action de plastifiant ou réduisant la plasticité.

Resumen

Resumen referente al reciclado de desechos industriales y urbanos en la producción de ladrillos.

Este artículo presenta un resumen del estado actual de los conocimientos sobre el reciclado de desechos industriales y urbanos en la producción de ladrillos. Las investigaciones provienen de Italia, Rusia, Gran Bretaña, España, Alemania y de los Estados Unidos. Se tratan residuos de combustibles (53 trabajos), cenizas (16 trabajos), fundentes (10 trabajos) y productos de desecho degrasantes y plastificantes (12 trabajos).

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