

Technical and environmental characterisation of recycled aggregate for reuse in bricks

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Abstract. Waste mud coming from an aggregate washing plant was formerly used as filling material for a pond, aimed at the recovery of an abandoned quarry. Once completed the filling capacity of the pond, the need for identifying a possible reuse of mud produced by the plant arose in order to avoid landfill disposal. Therefore, mud has been geometrically, physically and chemically characterised for its recovery as construction material. A variety of tests was carried out on mud samples as required by EN technical specifications and by Italian environmental standards, focusing particularly on leaching behaviour. The tested material showed satisfactory physical and chemical properties and a release of pollutants below the limits set by the Italian code. Many mix-designs for the production of unfired bricks made of waste mud, sand and straw, stabilised and non-stabilised with lime, gypsum or cement, were developed. The bricks were tested in order to evaluate mechanical properties and leaching behaviour. Mud bricks provided remarkable compressive strength, even if not suitable for structural elements. The use as interior design to minimise humidity changes and to facilitate a thermal insulation is fostered, thus strengthening the so-called green building economy.

1 Introduction

The construction industry is a main issue for environmental sustainability because it produces large amounts of carbon dioxide, exploits natural resources and produces but rarely reuses/recovers wastes. A growing spread of the green building economy appears to be the only solution able to ensure sustainable development. Although in recent years the green building economy and the popular environmental awareness were mainly focused on energy, material (i.e. natural resources) saving and waste recycling have probably the most significance for green economic transformation. Following this idea, it will be possible to decrease quarrying activities (considering that natural aggregates are not a renewable resource) and amount of wastes to dispose of in landfills, thus avoiding environment degradation and pollution. For instance, in Italy, quarrying activities still represent the main source for aggregate supply in the construction sector, with an amount of natural resources extracted that was stated at about 120 million m³ in 2012 [1]. In the late years, industrial

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waste management became an increasing problem, due to the restrictions in landfill disposal prescribed by international regulations. Therefore, waste recovery is considered as an increasingly necessary option, especially the reuse as recycled aggregate in construction can reduce the exploitation of natural quarries. Several types of waste can be recovered in this field, like steel slags, municipal solid waste incineration (MSWI) slags, construction and demolition (C&D) waste, mud from natural aggregate washing etc. Italian regulation on waste recovery allows the use of these materials both directly in the environment (road and railway basements, excavation filling etc.), and indirectly, through the production of concrete and bitumen [2, 3].

Several experimental researches investigated the opportunity to use waste mud or dredged sediments specifically for the production of bricks [4, 5, 6, 7]. Other investigations of mud properties covered the recovery as material for geopolymers production, as containment barrier or protection of groundwater and as wastewater treatment material [8, 9, 10].

This study aims at investigating the possible recovery of waste mud obtained from an aggregate washing plant as unfired bricks. An extensive experimental campaign was carried out in order to determine geometrical, physical and chemical characteristics of mud, according to [11]. Leaching behaviour was also carefully investigated. Bricks produced using only mud and fibre/lightening or stabilised with lime, gypsum or cement were designed and tested in order to determine mechanical properties and to verify the environmental suitability.

2 Experimental program

2.1 Recycled mud

The material employed in this research was mud obtained from an aggregate washing plant located in northern Italy (Bergamo, Italy). The plant treats, by means of crushing and sieving systems, inert material coming from quarries, construction and demolition waste and excavation of construction sites. The product obtained from this plant is an aggregate used in the construction sector (Fig. 1).

In order to optimize the aggregate granular separation, the raw materials are regularly washed with water in the sieving devices. The residue resulting from washing operations consists of wet fine aggregates, which is about 2-10% (w/w) with respect to the raw material treated in the plant. This mixture of fine aggregate and water is then treated by means of a sedimentation and a filter press system. In the settler, an anionic polyelectrolyte DRYFLOC PCP 1® based on polyacrylamide, soluble in water and insoluble in solvents, is added in order to facilitate the liquid-solid separation. The final fine aggregate (named "recycled mud") is mainly composed of silt, and in slight percentages of sand and clay.

Originally the mud was used as filling material for a pond, aimed at the recovery of an abandoned quarry. This study was aimed at researching an alternative solution for mud reuse in the construction sector in order to avoid landfill disposal.

A comprehensive characterisation was carried out on different waste mud samples, hereinafter named "S1", "S2", "S3", and "S4".

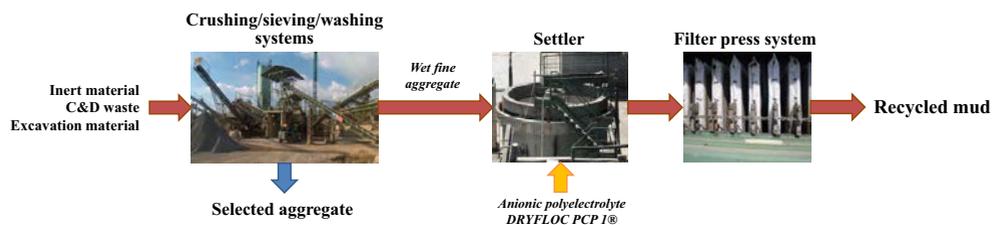


Fig. 1. Scheme of the aggregate washing plant producing the mud investigated in this research.

2.2 Recycled mud characterisation

Technical properties of mud samples (geometrical, physical and chemical) were determined in accordance with the UNI Norm for “Aggregates for mortar” [11] and its Italian accomplishment [12]. The latter provides, for several requirements, limit values in accordance with the different final destinations. The environmental characterisation of mud (chemical composition and leaching behaviour) was carried out in accordance with the Italian Norm [2], which rules over the waste characterisation, reuse and recovery, and the Italian Ministerial Decree that is the specific reference for the leaching test [3].

2.2.1 Geometrical and physical properties

The geometrical properties investigated in this study were the particle size distribution and the quality of fines. The granulometric composition was determined through the testing method [13] specifically addressed to aggregates characterised by particles with grain size lower than 75 μm . The quality of fine particles was carried out by means of two tests: sand equivalent and methylene blue value.

Regarding physical properties, the Atterberg limits were firstly determined for the assessment of mud plasticity behaviour, since materials mainly composed by fine particles (as silt and clay) are strongly influenced by the interaction between grains (and their mineralogical composition) and water. Particle density and water content tests were also carried out in order to acquire important values for the optimal design of final mixtures. The alkali-silica reactivity was investigated in compliance with [14], in order to evaluate the possible decay of mud bricks (in terms of cracks).

Each testing method is defined by [11] and refers to specific technical standards.

2.2.2 Chemical properties

The chemical characterisation of mud was carried out according to [11]. Water-soluble constituents, water-soluble chloride, water-soluble and acid-soluble sulphate, total sulphur, presence of humus and lightweight contaminants were the main properties investigated. Moreover, the organic contaminant content was determined (in compliance with [15]), in order to verify the presence of organic matter able to influence mechanical performances of mud bricks. Mortar samples of 40 x 40 x 160 mm with non-treated and pre-treated (by an incineration process at 480°C for 4 hours) mud samples were designed and tested to measure initial setting time and compressive strength.

Regarding the environmental suitability of mud samples, oxides content, chemical composition and release of pollutants tests were carried out. The X-Ray Diffraction analysis (XRD) was applied to determine the content of oxides, in compliance with [16]. The

leaching test was carried out according to [17] based on contaminants extraction in a single stage in demineralised water (liquid/solid ratio, L/S = 10) for a period of 24 h [3].

2.3 Mud bricks production and characterisation

Several mixtures based on waste mud (dried at 105°C for 3 hours), binder, lightening and fibre (saturated with water in order to hinder its absorption during the mixture realisation) were produced and tested to identify a final product with mechanical properties suitable for the intended use. Table 1 lists all the mixtures performed.

Table 1. Mixtures performed for the mud brick production.

Mixture	Binder (w/w)	Lightening (v/v)	Fibre (v/v)
RM	-	-	-
RM-L6	L 6%	-	-
RM-L5-G5	L 5% + 5% G	-	-
RM-C6	C 6%	-	-
RM-L6-RH1:1	L 6%	-	RH 1:1
RM-L6-EV1:1	L 6%	EV 1:1	-
RM-L6-SD1:1	L 6%	-	SD 1:1
RM-L6-S1:1	L 6%	-	S 1:1
RM-L6-S1:0.5	L 6%	-	S 1:0.5
RM-L10-S1:0.5	L 10%	-	S 1:0.5
RM-G6-RH1:1	G 6%	-	RH 1:1
RM-G6-EV1:1	G 6%	EV 1:1	-
RM-G6-SD1:1	G 6%	-	SD 1:1
RM-C6-RH1:1	C 6%	-	RH 1:1
RM-C6-EV1:1	C 6%	EV 1:1	-
RM-C6-S1:1	C 6%	-	SD 1:1
RM-SA1:1-S1:1	-	S 1:1	-
RM-SA1:1-S1:1-EP1:0.5	-	EP 1:0.5	S 1:1
RM-SA1:1-S1:1-EP1:1	-	EP 1:1	S 1:1
RM-SA1:1-S1:1-SD1:1	-	SD 1:1	S 1:1
RM-SA1:1-L6-S1:1	L 6%	-	S 1:1
RM-SA1:1-L10-S1:1-EP1:1	L 10%	EP 1:1	S 1:1
RM-SA1:1-C3-S1:1	C 3%	-	S 1:1
RM-SA1:1-C6-S1:1	C 6%	-	S 1:1
RM-SA1:1-C6-S1:1.5	C 6%	-	S 1:1.5
RM-SA1:1-C10-S1:1	C 10%	-	S 1:1
RM-SA1:1-C10-S1:1-EP1:1	C 10%	EP 1:1	S 1:1

Legend: Recycled Mud (RM), Sand (SA), Lime (L), Gypsum (G), Cement (C), Expanded Vermiculite (EV), Expanded Perlite (EP), Rice Husk (RH), Saw Dust (SD), Straw (S).

In order to increase mechanical performances, lime (L), gypsum (G) and Portland cement 42.5 R (C) in different percentages were adopted as binder materials, whereas expanded vermiculite (EV) and expanded perlite (EP) were used as lightening to decrease the specific weight of mixtures. Finally, rice husk (RH), sawdust (SD) and straw (S) were adopted as fibre to increase strength, improve the lightening of the final mixtures and drain the moisture during the drying stage. Some mixtures were designed adding sand (in a weight ratio 1:1 compared to mud) in order to improve strength and geometric stability of bricks. Binders were added in different percentages relative to dried mud weight (w/w), whilst lightening and fibre relative to dried mud volume (v/v).

Mixtures without sand were prepared in cubes of 10 x 10 x 10 cm (handmade), whilst mixtures containing sand both in cubes of 10 x 10 x 10 cm (handmade) and in bricks with 5 x 10 cm cross section and variable length (extruded with a machine developed specifically to produce mud bricks [18].

Moisture, specific weight and compressive strength were determined for the different mixtures, then the best performing ones were subjected to a deeper investigation focused on direct tensile strength [19] and leaching behaviour [17].

3. Results and discussion

3.1 Recycled mud properties

3.1.1 Geometrical requirements

The results of the grain size distribution analyses are provided in Fig. 2. The tested material was composed by 80% silt, about 10% sand and 10% clay. Significant differences in the granulometric distribution amongst S1 and S2 samples were not highlighted, whilst a greater discrepancy could be noted relative to the ideal distribution curves for rammed earth and brick production [20]. The low sand content suggested the need for a particle size correction during the production of mud bricks, in order to guarantee a higher compressive strength.

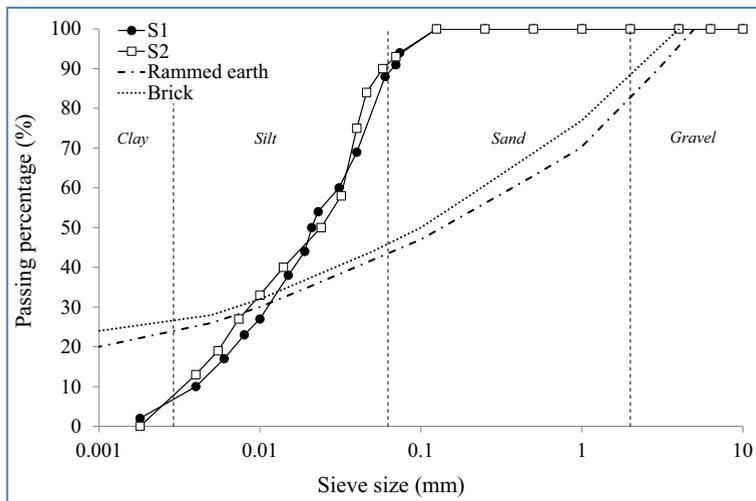


Fig. 2. Grain size distribution curves of recycled mud samples, in compliance with ASTM D 422-63, and ideal curves for rammed earth and brick production.

Test results for the assessment of fines quality (conducted on sample S1) indicated, as expected, the suitability of the material to adsorb ions or other elements in solution. Methylene blue test provided a high value of adsorption (3.1 mg/kg) considering that for the use of aggregates in concrete, the specific standard [21] fixes a value lower than 1.2 mg/kg. Sand equivalent resulted equal to 0.09% (the reference value for aggregates in concrete is set higher than 70%), meaning that the amount of ultrafine particles represented all the material analysed, whilst the sand component was almost no measurable.

3.1.2 Physical requirements

Mud particle density was measured to be $2,728 \text{ kg/m}^3$. This value seemed slightly high, but suitable if typical values of bulk density (in the range $1,600\text{-}2,100 \text{ kg/m}^3$) are considered. As specified in [11], an aggregate with these characteristics (particle density higher than $2,400 \text{ kg/m}^3$) does not provide durability problems in mortars when subjected to phenomena of freezing and thawing. Water content was evaluated according to the testing method [22] and provided a value of 12% for S1 and S2 sample. These results were comparable to the ones obtained in a previous characterisation made on samples S3 and S4, where water contents were equal to 12 and 14% respectively. Even if water content strictly depends on the compression rate set in the filter press, these values permit a suitable recovery of waste mud in unfired bricks, since they are close to the optimum water content range (between 15 and 25%) that maximises plasticity and workability, as confirmed by [23].

Mud samples were analysed in order to determine the Atterberg limits, which provide important information on plasticity behaviour. Results indicate that waste mud samples were characterised by low plasticity (Fig. 3), thus a poor ability to permanently deform under stress conditions, and low compressibility, thus a poor attitude to volume reduction if subjected to compression. S1, S2 and S3 did not show an appropriate behaviour in terms of optimal extrusion (since they are located outside the grey reference area pointed out in Fig. 3), probably owing to the low clay fraction content. The presence of clay minerals, in fact, makes possible for particles to slide over each other due to the water retained in the interstitial spaces, thus favouring the extrusion [24].

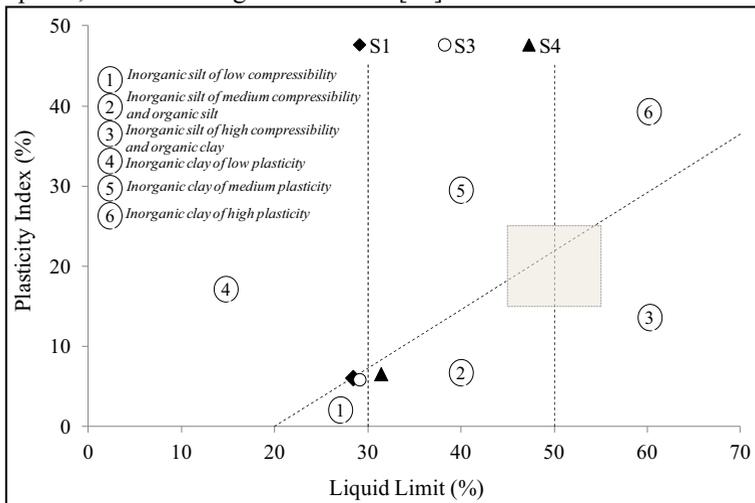


Fig. 3. Representation of mud samples in Casagrande's diagram. Grey rectangular area marks the optimal field for extrusion moulding, as highlighted in [25].

Alkali-silica reactivity was investigated in compliance with accelerated test proposed by [14]. After 14 days testing, the expansion of mud mortar samples was equal to 0.072%. This value was lower than the reference limit of 0.1%, thus avoiding the long-term expansion test and assuring the absence of cracking phenomena when waste mud is recovered in unfired bricks.

3.1.3 Chemical requirements

The mineralogical composition of mud sample S1 was investigated through the XRD analysis. Table 2 shows that the material was mainly composed of quartz and muscovite.

High concentrations of sulphates, chlorides, barium, total chromium, arsenic and zinc were found in the chemical composition of mud samples (Table 3).

Table 2. Mineralogical composition of sample S1 carried out by means of XRD test [16].

Parameter	Unit	S1
Quartz	% SiO ₂	30
Muscovite	% K ₂ Al ₄ (Si, Al) ₈ O ₂₀ (OH) ₄	27
Plagioclase	% CaAl ₂ Si ₂ O ₈ -NaAlSi ₃ O ₈	14
Dolomite	% CaMg(CO ₃) ₂	13
Calcite	% CaCO ₃	13
Chlorite	% (Mg,Fe,Al) ₆ (Si, Al) ₄ O ₁₀ (OH) ₈	3

Table 3. Waste mud chemical composition and percentage of oxides content.

Parameter	Unit	Waste mud sample				Limits [2]
		S1	S2	S3	S4	
Sulphates	mg/kg	55.7	-	-	-	-
Chlorides	mg/kg	57.4	-	-	-	-
Antimony	mg/kg	5.8	< 5.0	-	-	10.0
Arsenic	mg/kg	35.6	18.2	13.9	-	20.0
Barium	mg/kg	237	237	-	-	-
Total chromium	mg/kg	16.8	28.4	5.8	35.2	20.0
Cobalt	mg/kg	7.6	-	-	-	150.0
Nickel	mg/kg	16.7	-	14.2	13.0	120.0
Lead	mg/kg	24.3	44.7	15.2	11.4	100.0
Copper	mg/kg	24.3	21.9	17.8	14.3	120.0
Vanadium	mg/kg	31.1	< 0.5	27.9	-	90.0
Zinc	mg/kg	128	279	88	50	150
Total silicon (SiO ₂)	%	-	52.3	40.0	48.0	-
Iron oxide (FeO)	%	-	2.3	-	-	-
Calcium oxide (CaO)	%	-	< 1.0	-	-	-
Aluminium oxide (Al ₂ O ₃)	%	-	2.7	-	-	-
Magnesium oxide (MgO)	%	-	5.9	-	-	-
Manganese oxide (MnO)	%	-	0.1	-	-	-

Note: in all the samples tested, the following pollutants had concentrations under the detection limit: F-, CN-, Be, Cd, Cr VI, Hg, Tl, Se, Sn, C<12, C>12, asbestos.

Regarding the latter three contaminants, in particular S1, S2 and S4 samples provided concentrations above the limit set by [3] that states a list of pollutant concentration limits above which a soil in a green residential, public and private area needs to be reclaimed. This means that these mud samples are not suitable for reuse in soil with this type of use. A slightly high variability in arsenic, total chromium, lead, vanadium and zinc content was highlighted amongst samples. This was probably due to the variability of the raw material fed and treated in the plant (construction and demolition waste, excavated soil and quarried aggregate).

The content of oxides characterising the inert materials was also evaluated (Table 3). S2 sample was characterised by a higher content of total silicon, as compared to sample S1 (analysed by means of XRD test). The comparison between values obtained in this study and results from other researches, where dredged sediments or sludge from aggregate washing plant were analysed [25, 5, 7], highlighted the same content of total silicon (average value of 55%), a lower content of aluminium oxide (average value of 13%) and a higher content of magnesium oxide (average value of 1.5%).

Chemical properties were determined [11, 13]. Table 4 provides the results of each parameter investigated and the related more restrictive limits (since different limits are proposed by the standards, in function of the different final destinations which the use of the mortar can be addressed to).

Table 4. Chemical properties of waste mud samples, in compliance with [15].

Parameter	Unit	S1	S2	Limits of UNI EN 13139 and UNI 11320
Water-soluble constituents	%	0.10	0.12	< 1.00
Water-soluble chloride	%	< 0.01	< 0.01	< 0.06 ^a
Water-soluble sulphate	%	< 0.01	< 0.01	-
Acid-soluble sulphate	%	< 0.01	< 0.01	< 0.20 ^a
Total sulphur	%	0.03	0.07	< 0.10 ^a
Presence of humus	-	Colourless	Colourless	Colourless
Lightweight contaminants	%	0.02	0.03	< 0.25 ^a

^a: more restrictive limit

Acid-soluble and water-soluble sulphate content, water-soluble chloride content, water-soluble constituents and lightweight contaminants were in compliance with the reference limits and, in some cases, even under the detection limit for both samples. Total sulphur content test provided values below the limit, even if S2 sample (0.07%) was quite close to the reference limit (0.10%). Presence of humus was also detected, in order to verify if organic matter can influence the mechanical behaviour of mud when recovered in unfired bricks. The analysis carried out on samples S1 and S2 provided negative results, thus avoiding to further look for organic matter by means of fulvo acid content test, as specified by the reference standards.

Mortar samples produced with Portland cement (CEM I) and untreated or pre-treated (by an incineration process at 480°C for 4 hours) S1 specimen were analysed after 28 days of curing, in order to evaluate the possible influence of organic contaminants on compressive strength and initial setting time. This latter property was not evaluated owing to the low plasticity of silt that did not permit to correctly carry out the test. Compressive strength resulted to be equal to 16.0 MPa and 17.3 MPa for mortar samples, respectively made by using untreated and pre-treated waste mud, thus strengthening the slight influence of organic matter on mortar mechanical resistance.

Table 5 summarises results of leaching tests carried out in this research (samples S1 and S2) and in the previous characterisations of mud (samples S3 and S4).

Table 5. Concentrations of the pollutants in the leachate, obtained in compliance with [17].

Parameter	Unit	Waste mud sample				Limits [3]
		S1	S2	S3	S4	
Fluorides	mg/L	0.22	0.31	0.14	0.24	1.50
Sulphates	mg/L	4.88	4.58	4.65	3.48	250.00
Chlorides	mg/L	3.64	4.47	2.41	1.86	100.00

Arsenic	µg/L	< 5	< 1	35	< 5	50
Barium	mg/L	0.01	0.01	< 0.02	0.06	1.00
Beryllium	µg/L	< 5.00	< 5.00	6.55	< 5.00	10.00
C >12	mg/L	-	< 0.1	-	-	-
C <12	mg/L	-	< 0.1	-	-	-
PAHs	mg/L	-	< 0.05	-	-	-
DOC	mg/L	17.2	23.1	12.9	3.2	30.0
pH	-	6.5	7.4	-	-	5.5-12.0

Note: in all the samples tested, the following pollutants had concentrations under the detection limit: NO₃⁻, CN⁻, Cd, Co, Cr, Hg, Ni, Pb, Cu, Se, V, Zn, asbestos.

All the parameters analysed provided concentrations below the limits indicated by [2]. A quite significant variability (from a minimum value of 3.2 to a maximum of 23.1 mg/L) was observed for the release of DOC, comparing the results obtained in this and in the previous experimental campaign. In S2 sample, the release of Polycyclic Aromatic Hydrocarbons (PAHs) and heavy (C >12) and light (C <12) hydrocarbons was also investigated even if not required by [2]. The aim of these additional analyses was to verify the release of substances potentially present in excavated soils or construction and demolition waste treated inside the plant.

3.2 Unfired bricks performances

3.2.1 Mechanical strength

The production of brick characterised by different mix-design aimed at providing the best mechanical performances and the most eco-friendly product. The objective of the research was to define a mix-design with the higher compressive strength (in the range 1-2 MPa) accompanied by a low weight (specific weight from 1200 to 1500 kg/m³).

The first mixture was composed only of waste mud. Then, mud brick composition was varied each time using different amounts and types of binder, lightening and fibre. The inadequacy of the waste mud particle size distribution required a correction of the mixtures with the addition of sand, in order to improve mud brick geometrical stability, reduce shrinkage and increase compressive strength. Table 6 shows results concerning physical-mechanical properties of different mud brick mixtures.

Mixtures prepared only with recycled mud and binder (RM, RM-L6, RM-L5-G5, RM-C6) demonstrated interesting compressive strength values (from a minimum of 0.95 to a maximum of 4.16 MPa), but related to high specific weight (from a minimum of 1570 to a maximum of 1710 kg/m³).

For this reason, lightening and fibre were added in order to decrease final density, even if these elements brought to decrease mechanical resistance under the 1 MPa originally set as research goal. Amongst this second mixture category, indeed, only RM-C6-EV1:1 provided suitable results regarding both specific weight (1.42 kg/dm³) and compressive strength (1.76 MPa).

Table 6. Values of moisture, specific weight and compressive strength for the different mixtures.

Mixture	Moisture (%)	Specific weight (kg/dm ³)	Compressive strength (MPa)
RM	29.6	1.71	1.61
RM-L6	44.1	1.65	1.57
RM-L5-G5	34.6	1.57	0.95
RM-C6	35.3	1.71	4.16

RM-L6-RH1:1	67.5	1.11	0.40
RM-L6-EV1:1	89.9	0.97	0.24
RM-L6-SD1:1	60.4	1.41	0.67
RM-L6-S1:1	58.9	1.17	0.48
RM-L6-S1:0.5	50.4	1.33	0.55
RM-L10-S1:0.5	54.6	1.34	0.79
RM-G6-RH1:1	50.6	1.51	0.56
RM-G6-EV1:1	55.6	1.33	0.69
RM-G6-SD1:1	56.9	1.64	0.71
RM-C6-RH1:1	56.5	1.41	0.42
RM-C6-EV1:1	52.4	1.42	1.76
RM-C6-S1:1	57.0	1.47	0.87
RM-SA1:1-S1:1	25.4	1.50 (CU) - 1.58 (BR)	0.48 (CU) - 2.08 (BR)
RM-SA1:1-S1:1-EP1:0.5	44.0	1.44 (CU) - 1.32 (BR)	0.57 (CU) - 2.17 (BR)
RM-SA1:1-S1:1-EP1:1	n.a.	1.38 (CU) - 1.22 (BR)	0.47 (CU) - 1.45 (BR)
RM-SA1:1-S1:1-SD1:1	41.0	1.37 (CU) - 1.33 (BR)	0.80 (CU) - 2.06 (BR)
RM-SA1:1-L6-S1:1	49.0	1.42 (CU) - 1.37 (BR)	0.67 (CU) - 1.47 (BR)
RM-SA1:1-L10-S1:1-EP1:1	n.a.	1.35 (CU) - 1.32 (BR)	0.82 (CU) - 1.29 (BR)
RM-SA1:1-C3-S1:1	29.0	1.50 (CU)	0.43 (CU)
RM-SA1:1-C6-S1:1	n.a.	1.52 (CU)	1.01 (CU)
RM-SA1:1-C6-S1:1.5	40.0	1.48 (CU)	0.99 (CU)
RM-SA1:1-C10-S1:1	49.0	1.51 (CU) - 1.43 (BR)	1.81 (CU) - 3.86 (BR)
RM-SA1:1-C10-S1:1-EP1:1	n.a.	1.50 (CU)	1.85 (CU)

Legend: Recycled Mud (RM), Sand (SA), Lime (L), Cement (C), Gypsum (G), Rice Husk (RH), SawDust (SD), Straw (S), Expanded Vermiculite (EV), Expanded Perlite (EP), Cubes (CU), Bricks (BR), data not available (n.a.).

The addition of sand was the key element in order to gain the performance objectives. Moreover, the production of both cubes and bricks highlighted that the latter ones had better properties in terms of compressive strength and specific weight, as expected, due to a favourable aspect ratio and to the production via mechanical extrusion. Comparing same mixtures, in fact, extruded bricks showed a higher compressive resistance (up to about 4) with respect to handmade cubes, owing to the lower slenderness and to the reduction of eigenstresses during curing.

Adding a more eco-friendly binder as lime, mechanical properties of mixtures did not significantly vary. Longer curing in wet (or with high relative humidity) environment of specimen containing lime should however be considered to obtain adequate performances in terms of compressive strength.

Finally, the dosage of cement clearly increased the compressive resistance (on average equal to 1.42 MPa for cubes compared to the previous 0.61 MPa for mixtures without cement), as expected, but with a subsequent increase of specific weight (from an average value of 1.42 kg/dm³ of previous mixtures to 1.50 kg/dm³ of the latter ones containing cement).

Three out of all the mixtures tested were then considered for a deeper investigation. Table 7 shows the composition of mud bricks specifically produced for further analyses.

Table 7. Composition of mud bricks produced for deeper characterisation.

Mud brick	Silt and sand (g)	Straw (g)	Water (g)	Cement (g)
A (stabilised)	7,800	224	1,800	0
B1 (non-stabilised)	8,000	226	2,300	400
B2 (non-stabilised)	8,000	227	2,500	800

Mixture A was not stabilised with any binder, whereas mixtures B1 and B2 were stabilised with cement in percentages of 5 and 10% respectively. All of these three new mixtures were designed in bricks of 40 x 40 x 160 mm side, according to the requirements set by [19]. Table 8 exhibits the obtained results, indicating that the three proposed mixtures might be considered a good basis for the realisation of non-structural masonry elements.

Table 8. Mechanical properties of the three new mixtures.

Mud brick	Specific weight (kg/dm ³)	Compressive strength (MPa)	Direct tensile strength (MPa)
A	1.65	1.20	0.31
B1	1.62	1.36	0.57
B2	1.63	1.54	1.03

The non-stabilised mud brick, owing to the lower values of compressive and tensile strength, can be used for specific architectural solutions (if subject to limited stress), in combination, for example, with load bearing timber structures. In addition, it can be useful as hygrometric stabiliser in environments exposed to significant moisture variations and as soundproofing element. Conversely, stabilised solutions can be used for the same purposes mentioned above, but even for outdoors and structural elements subjected to higher loads.

3.2.2 *Environmental suitability*

Stabilised (B2) and non-stabilised (A) mud brick samples were analysed by means of leaching test, in order to verify the environmental suitability.

The release of pollutants from the experimental bricks [17] was below the limits [3] for almost all samples (Table 9). Unexpected concentrations above the limits were provided by copper (0.09 with a limit of 0.05 mg/L), nickel (66 and 17, respectively for stabilised and non-stabilised mud bricks, with a limit of 10 µg/L), total chromium (71 with a limit of 50 µg/L) and DOC (156 and 65, respectively for B2 and A mud brick specimens, with a limit of 30 mg/L). Since waste mud samples did not provide releases of those pollutants higher than the reference limits (as reported in Table 5), the exceedance of the maximum concentrations allowed [2] was probably due to the materials mixed to the recycled mud for unfired brick production. In particular, the high concentration of DOC can be traced back to straw, whilst metals to cement. Nevertheless, limits set by the Italian legislation are referred to aggregates (i.e. waste mud) and not to final products (i.e. unfired bricks).

Table 9. Major concentrations of the pollutants released through the leaching test, in compliance with

Parameter	Unit	Mud brick		Limits [3]
		A	B2	
Fluorides	mg/L	< 0.2	0.9	1.5
Sulphates	mg/L	15.7	31.1	250.0
Chlorides	mg/L	8.9	15.3	100.0
Cyanide	µg/L	< 0.02	7.90	50.00
Arsenic	µg/L	14.8	< 5.0	50.0
Barium	mg/L	0.07	0.10	1.00
Copper	mg/L	0.02	0.09	0.05
Zink	mg/L	0.010	< 0.005	3.000
Nickel	µg/L	17	66	10
Total chromium	µg/L	< 5	71	50
DOC	mg/L	65	156	30
pH	-	8.9	11.5	5.5-12.0

Note: in all the samples tested, the following pollutants had concentrations under the detection limit: NO₃, Be, Co, V, Cd, Pb, Se, Hg, C<12, C>12, PAHs, asbestos.

4. Concluding remarks

The possibility of making unfired bricks using recycled mud coming from an aggregate washing plant was investigated in this study. The conclusions derived from this research are as follows:

- The geometrical characterisation of recycled mud highlighted, as expected, a lack of sand in the grain size distribution analysis. In order to guarantee higher compressive strength to mud bricks, a particle size correction adding a coarser fraction (i.e. sand) is therefore required.
- The evaluation of waste mud physical requirements provided suitable results. Mud particle density was higher than 2,400 kg/m³, thus guaranteeing (according to EN 13139 standard) mortars durability if subjected to freeze-thaw phenomena. The determination of Atterberg limits indicated that the recycled mud was characterised by low plasticity and low compressibility. Finally, alkali-silica reactivity was not detected, thus assuring the absence of cracking phenomena in unfired bricks.
- The evaluation of chemical requirements [11] provided, for all waste mud samples and parameters investigated, values below the more restrictive limits set by the reference standard.
- Concerning chemical properties, recycled mud samples highlighted a slightly high variability in chemical composition (mostly in arsenic, total chromium, lead, vanadium and zinc content), probably due to the variability of the material treated in the aggregate washing plant and for which an accurate selection should be carried out. The leaching test provided concentrations well below the limits [3] for all the parameters.
- Unfired bricks made by using recycled mud provided remarkable compressive resistances, even if not suitable for load-bearing structural elements. For being suitable for structural elements, mud bricks should however be designed adding lime or cement.
- Non-stabilised mud bricks can be used for plastic and creative architectures, featuring natural colours and by an inherent sense of warmth. The high hygroscopic adjustment

capacity makes mud bricks suitable for the use in areas subjected to high daily variations in moisture. Finally, they can be even employed as soundproofing elements.

- Stabilised (using lime or cement) mud bricks can be used for the same purposes mentioned above, but even for outdoors and structural elements subjected to higher loads. These mud bricks, however, lack in hygroscopic adjustment capacity, compared to the non-stabilised ones.

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