Revista Colombiana de Materiales
ISSN 2256-1013, No 19, pp. 50-63, 2022. https://doi.org/10.17533/RCM/udea.rcm.n19a05

COMPACTED UNCALCINED WASTE FROM GRAVEL AND SAND WASH MUDS OF AN AGGREGATES PLANT AS WASTES VALORIZATION STRATEGY

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KEYWORDS

Sand wash mud
Wastes reuse
Compacted uncalcined waste
Earth constructions.

ABSTRACT

Fine waste management from quarry has been commonly the final disposal in mining tailings and as refilling material for landscape recovery in areas already exploited. However, different uses of these wastes have been studied, highlighting the earth constructions because a new economic benefit is generated and the environmental impact is reduced. Moreover, compared to cement constructions, the earth constructions are environmentally friendly and represent an energy saving, due to their low emission of CO_2 by low or no-cement content in their manufacture in contrast to good physical and mechanical properties obtained. So, in this work, the use of wastes muds from an aggregates plant (as result of crushing and washing process) were evaluated as a circular economy strategy. Raw materials were chemical, mineralogical and physically characterized and were employed in the elaboration of cubic specimens of un-calcined material, which they were hydraulically compacted in metal molds at mixtures of wastes muds, commercial gray cement and washed fine sand. The cubic specimen's performance was evaluated by Simple Compressive Strength (SCS) and water absorption test. In the best of configurations, an increase in SCS of 221.3% (8 MPa) on samples of 20% cement with respect to samples of only waste was found and, in turn, an increase of 517.3% (15 MPa) when these were cured in water was also found. Thus, wastes mixed with small amounts of cement are promising in the Manufacture of Compacted Earth Specimens (MCES), particularly as masonry or structural elements made of un-calcined wastes.

RESIDUOS DE LODOS COMPACTADOS SIN CALCINAR PROVENIENTES DEL LAVADO DE GRAVA Y ARENA DE UNA PLANTA DE ÁRIDOS COMO ESTRATEGIA DE VALORIZACIÓN DE RESIDUOS

PALABRAS CLAVE
Lodo del lavado de arena
Reutilización de residuos
Residuo no-calcinado compactado
Construcciones de tierra.

RESUMEN
El manejo de los residuos finos de cantera ha sido comúnmente la disposición final en relaves mineros y como material de relleno para la recuperación paisajística en áreas que han sido explotadas. Sin embargo, se han estudiado diferentes usos de estos residuos, destacándose las construcciones de tierra debido a que se genera un nuevo beneficio económico y se reduce el impacto ambiental. Además, comparadas con las construcciones de cemento, las construcciones de tierra son amigables con el medio ambiente y representan un ahorro energético, debido a su baja emisión de CO_2 por el bajo o nulo contenido de cemento en su fabricación frente a las buenas propiedades físicas y mecánicas obtenidas. Así, en este trabajo se evaluó el aprovechamiento de los lodos de desecho de una planta de áridos (resultado del proceso de trituración y lavado) como estrategia de economía circular. Las materias primas fueron caracterizadas química, mineralógica y físicamente y fueron empleadas en la elaboración de probetas cúbicas de material no-calcinado, las cuales fueron compactadas hidráulicamente en moldes metálicos en mezclas de lodos de desecho, cemento gris comercial y arena fina lavada. El desempeño de las probetas cúbicas se evaluó mediante la prueba de absorción de agua y la resistencia a la compresión simple (SCS). En la mejor de las configuraciones, se encontró un aumento en SCS de 221.3% (8 MPa) en muestras de 20% de cemento con respecto a muestras de solo residuo y, a su vez, también se encontró un aumento de 517.3% (15 MPa) cuando estas fueron curadas en agua. Así, los residuos mezclados con pequeñas cantidades de cemento son prometedores en la Fabricación de Probetas de Tierra Compactada (MCES), particularmente como elementos de albañilería o estructurales hechos de residuos no-calcinados.

1. INTRODUCTION

The earth has been one of the most widely used primitive construction materials throughout human history, being also a central element in the development of civilizations, cultures and evolution of architectural [1], so much so that by 2006 about 40% of the world population still lived in buildings constructed with this material [2]. These constructions are not only found in underdeveloped or developing countries, but also in developed countries as Australia, The United States, France, Spain, India, among others [2]. This is due to the price of industrial construction materials as commercial cement, energy costs and environmental impacts are higher compared to earth constructions [1,2].

On the other hand, earth constructions (soil, sludge, mud constructions) generally have the following main characteristics [2]: 1) Lower environmental impacts (minimal amount of finite natural resources are used). 2) Manufacturing, storage, distribution, utilization and maintenance costs are fairly low compared to other construction materials (300 times cheaper to produce a block of adobe than a commercial concrete block of the same volume). 3) Geologically, these materials are made up of alluvial sediments or residual soils, which are abundant and widely distributed throughout the planet; in these materials the presence of sand (medium to coarse size) and clay stands out because clays are very fine filling material that unite the largest particles (it gives consistency to the system). 4) Mineralogically, soil is mainly composed of quartz and feldspar, and minimal quantities of calcite, clay minerals and gypsum (physical weathering processes of the parent rocks are preferred over chemical weathering). 5) Despite that percentage of clay-size particles in earth constructions are lower than silt and sand-sized particles, their chemical composition are highly variable (variety of clay and non-clay minerals). Within the clay minerals there are the expandable ones (smectites, illites/smectites interlayered) and the non-expandable ones (kaolinite, illite). This should be considered because, although expandable ones are more effective in the bind of largest particles (silt and sand), their presences cause problems in earth constructions due to they absorb significant amounts of water and so, cracks during drying are caused. However, if drying is gradual and calcite and gypsum are present; the earth constructions will be stronger and no-cracks.

From the investigations carried out in this field (about MCES), some were highlighted in Table 1, and brief summarized (Table 2) according to the main characteristics found.

Different type of wastes had been used both for the production of un-calcined [1], [4–14] and calcined [7, 8, 11, 13, 15, 16] bricks at different temperatures, being commonly between 800-1100 °C. Although wastes came from different geographical places, their mineralogical identification was similar among them with minerals as clay minerals (kaolinite, illite, smectite), plagioclase, calcite and ferrous minerals (hematite). In addition, high Simple Compressive Strength (SCS) and appropriate water absorption (WA) were obtained (generally between 4-20 MPa) with scarcely introduction of stabilizers or additives as cement, lime, fly ash, ground granulated blast furnace slag, rice husk, among others. Furthermore, other properties as thermal conductivity, bending strength, drying shrinkage, freeze-thaw cycle, and ultrasonic pulse velocity, among others were also evaluated.

Among the main features of earth constructions and the effects on their properties, they are highlighted that: the plasticity index of soils increased with the fine particles and smectite [8], drying shrinkage depended on the DTP and mineralogy [8], amount of water and bending strength increased with the clay content [8], the use of paper waste (10 wt.%) made the adobe lighter (increased SCS by 25%, decreased thermal conductivity by 50%) [12], the stability of soil-cement (OPC 5-15 wt.%) depended on gravel, sand, silt and clay content (cement content increased with deficiency of fine particles or with increase of clay content) [3], the increasing of compaction pressure in the MCES increased SCS and decreased WA [4] and, these constructions fulfilled as normal, medium and lightweight masonry units according to ASTM C90 (in spite of the no-existence of international standards that allow their use and manufacture in a massive and industrial way) [11].

Table 1. *Atterberg limits, optimal soil types and quantities of material in the MCES.*

	Calderón [1]	Austin & Holmes [2]	Toirac [3]	Cabo [4]	Arteaga, Medina & Gutiérrez [5]	Seco et al. [6]	Bruno et al. [7]
P.L. (%)	28.1	-	< 18	18.05	0.0	18.0	20.1
L.L. (%)	28.9	-	< 45	25.72	19.2	26.0	33.0
P.I. (%)	0.8	-	-	7.67	NP	8.0	12.9
Type of soil	ML or CL	-	-S or G with 10-35 wt.% of M and C. -S with fine particles deficiency. -ML or CL.	CL (lean clay)	Silt-sandy with low plasticity	ML-CL (clayey silt soil)	CL (lean clay)
Sand (wt.%)	32	27–89 (67 optimal)	55-75	-	-	-	40.4
Silt (wt.%)	29	8–68 (29 optimal)	0-28	-	-	-	42.9
Clay (wt.%)	21	1–15 (6 optimal)	15-18	-	-	-	16.3
Sieve No. 40 (wt.%)	85	-	100	-	-	-	-
Sieve No. 200 (wt.%)	10	-	10-50	-	-	-	-
OM* (wt.%)	-	-	3	-	-	-	-

P.L.: Plastic Limit. L.L.: Liquid Limit. P.I.: Plasticity Index. OM*: Organic matter max. ML: Silty soils with low plasticity. CL: Clayey soils with low plasticity. S: Sandy soils. G: Gravel soils.

Table 2. *Main characteristics in the study of MCES.*

Authors	Soil origin	Minerals	Materials and mixtures	SCS and WA results
Calderón [1]	-	-	Silica sand (1-2 mm, 25-30 wt.%), soil (60, 70, 100 wt.%), lime, OPC, nanosilica, FA	SCS: 5.5-6.1 MPa.
Cabo [4]	Gray loam of Pamplona city (Navarra, Spain)	C, I, Q, K, At, Ak	OPC type II (5, 10, 15 wt.%), NHL-5, RH, RHA	SCS: 12-15 MPa at 90 days. WA: not more than 6 % at 7 days and 3 % at 90 days.
Seco et al. [6]	Gray marl (Pamplona, Spain)	C, I, Q, K, At, Ak	CDW (concrete 50 wt.% max. and ceramics bricks 30 wt.% max.), OPC, CHL, NHL, GGBS	Best configurations at 28 days: SCS: RCB (6-12 MPa). Rcb (8-13 MPa). WA: RCB (11-15 %). Rcb (12-16 %)
Blanco et al. [8]	Residues of the sand and gravel washing process of the Quaternary sediments (Madrid, Spain)	P (SG, KG, I, Ch), Q, F (Pl), C, D, H.	Mixtures between different soil samples	Bending strength: 4-14 MPa (it increases with clay content).

SCS: Compressive Strength. WA: water absorption. OPC: Portland cement. FA: fly ash. RH: rice husk. RHA: rice husk ash. CDW: construction and demolition waste. CHL: calcareous hydrated lime. NHL: natural hydrated lime. GGBS: ground granulated blast furnace slag. RCB: recycled concrete brick. Rcb: recycled ceramic brick. C: calcite. I: illite, Q: quartz. K: kaolinite, At: attapulgite, Ak: ankerite, P: phyllosilicates, Ch: chlorite, F: feldspar, D: dolomite, H: hematite. SG: smectite group. KG: kaolinite group. Pl: plagioclase.

As demonstrated, waste from different industrial processes have been widely studied in the manufacture of calcined bricks and secondly as un-calcined bricks. These materials have come from petrographically homogeneous units and very little from heterogeneous units as alluvial deposits. The same for the use of quarry fines dust as raw material for these bricks. For these reasons, and based on the characterization results obtained in Restrepo et al. [17], this work evaluated the use of fine quarry waste (sludge) from alluvial deposits composed of materials of different compositions in the Manufacture of Compacted Earth Specimens (MCES) by Simple Compression Strength (SCS) and water absorption (WA) tests.

In addition, this investigation pretends to reuse industrial wastes, which is a fundamental pillar of circular economy strategy (wastes from other industries are used as raw material in the generation of a new product for a different industry). Thus, for cement and construction industry, these MCES are construction elements with low or no-cement content, compared to OPC.

Furthermore, these MCES could be used as adobes, due to according to The Clay Minerals Society, adobes are a kind of hardened bricks sun-dried and made from mixtures of water, clay, silt, sand and straw, or other fibrous organic materials. However, from an industrial point of view, these MCES must fulfill with certain physical and dimensional requirements.

2. EXPERIMENTAL METHODOLOGY

2.1. Materials

Materials used in this research were the "washed sand" (commercial product of the aggregates plant), commercial gray cement with low content of mineral addition, and wastes (sludge) passing through mesh sieve No. 200 (0.075 mm) from gravel and sand wash mud of the aggregates plant. Both, washed sand and wastes samples were dried in an electric oven at 110 °C up to constant weight (~24 h) before starting the respective tests and analyses.

Cement and wastes were described and characterized in Restrepo et al. [17]. In addition, the geological origin of wastes was also stablished there.

2.2. Characterization techniques

The cement and wastes were physically, chemically and mineralogically characterized by means of X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD) and, thermal analyzes as Thermogravimetric Analysis (TGA), Differential Thermogravimetric Analysis (DTGA) and Differential Thermal Analysis (DTA). Each of these techniques were described in Restrepo et al. [17].

For cement, the main results of characterization were: 1) chemical composition (% by weight) of 64.12% CaO, 20.29% SiO_2, 4.27% Al_2O_3, 3.44% Fe_2O_3, 2.67% SO_3, 2.01% MgO, 1.07% others oxides and 2.13% loss on ignition (LOI); 2) mineralogical composition of 64.4% alite, 14% belite, 13.2% celite, 3.1% felite, 2.4% gypsum and 2.9% calcite (quantified by Rietveld method with Rwp/Re of 2.26).

For wastes, the main results of characterization were: 1) chemical composition (% by weight) of 50.20% SiO_2, 18.95% Al_2O_3, 8.81% Fe_2O_3, 5.71% MgO, 5.19% CaO, 2.06% Na_2O, 1.11% K_2O, 0.99% Ti_2O, 0.96% SO_3, 0.68% others oxides and

5.34% LOI; 2) mineralogical identification of quartz, albite, actinolite, chlorite, muscovite-illite (clay mineral), anatase, calcite, goethite and dickite (clay mineral) along with four decomposition reactions as dehydroxylation of iron hydroxides (goethite), dehydroxylation of clay minerals, decomposition of organic matter and decarbonation of calcite.

On the other hand, Particle Size Distribution (PSD) of washed sand was determined by means of Particle Size Analysis under ASTM D422-07; meanwhile, wastes were subjected to the Granulometry test using the Hydrometer Method with Deflocculating Agent (sodium hexametaphosphate) under ASTM D422-07 and the Consistency Limits (Atterberg limits) test under ASTM D4318-05, in order to perform the physical characterization of the fine waste material [18, 19].

2.3. Elaboration of MCES specimens

Four types of mixtures were defined for the Manufacture of Compacted Earth Specimens (MCES) specimens as it is shown in Table 3. Here, the percentage of material used in each mixture is shown along with its quantity by mass.

Each mixture was homogenized in a Hobart N-50 mixer for 2 min at speed 1 (140 rpm) followed by 2 min at speed 2 (285 rpm). The moisture used was 10%. Then, samples were compacted in a 50 x 50 x 50 mm metal mold in a Controls Advantest 9Rock model 45-C9842/RCK hydraulic triaxial testing press using solid stainless-steel parallelepipeds with dimensions 1 mm smaller than the cross-sectional area of the mold.

Table 3. *Mixtures for MCES.*

Mixture	Waste (wt.%)	Sand (wt.%)	Cement (wt.%)	Total (%)
M1	100	-	-	100
M2	80	20	-	100
M3	80	-	20	100
M4	80	10	10	100
Mixture	**Waste mass (g)**	**Sand mass (g)**	**Cement mass (g)**	**Total (g)**
M1	1650	-	-	1650
M2	1320	330	-	1650
M3	1320	-	330	1650
M4	1320	165	165	1650
Total (g)	5610	495	495	6600

The load application rate was 0.05 MPa/s until a maximum load of 5 MPa with dwell time in the maximum load of 180 s. The process was repeated (layer pressing) until that a height of 50 mm was obtained. Thus, for each mixture, specimens for SCS and water absorption tests were produced. These tests were carried out 28 days after the manufacture of the specimens.

2.4. Physical tests on MCES

2.4.1 Simple Compressive Strength (SCS) test

For SCS tests the UNE-EN 772-1: 2011+A1 was used [20]. These tests were carried out in a Controls model 50 C7022 hydraulic press, at a load application rate of 0.05 MPa/s, with sensitivity of 0.5 kN and with load application direction parallel to the force applied during the manufacturing of the specimens; in order to the layered manufacturing process would not influence in the results.

2.4.2 Water absorption (WA) test

Water absorption test was performed according to ASTM C140/C140M-18a [21], on mixtures that were open-air cured and then submerged in water for 24 h. This consisted of total immersion of the specimens in water at temperature between 15-27 °C, then they were removed from the water, dried in the open air for 60 s and then weighed (saturated weight). Later, samples were dried in an electric oven at a constant temperature of 110 °C for at least 24 hours until that a constant weight was obtained and the latter value was recorded (oven-dry weight). Thus, the ratio of the difference between the saturated weight and the oven-dry weight corresponds to the amount of water absorbed by specimens.

Furthermore, SCS tests were carried out on specimens that after drying in an electric oven, showed good surface finishes, conserved their dimensions and did not fracture. This was done with the purpose of analyzing and contrasting SCS of the specimens that were cured in open-air and those that were submerged for 24 h in water.

3. RESULTS AND DISCUSSION

3.1. Materials characterization

The washed sand presented a wide variety of particle sizes ranged from 0.07 to 4.76 mm, however, it was within the standard specifications according to ASTM D422-07, where washed sand and standard specification limits corresponded to red line and black dashed lines respectively (Table 4 and Figure 1).

General characteristics of the washed sand and waste (sludge) are presented in Table 5, where it is highlighted that, compared to the waste, washed sand presented only a passing percentage through mesh sieve No. 200 of 2.8 wt.% (in the waste was 75.4 wt.%), which reflects a higher fineness modulus (3.0) compared to the waste (0.1), in other words, waste was finer material than washed sand.

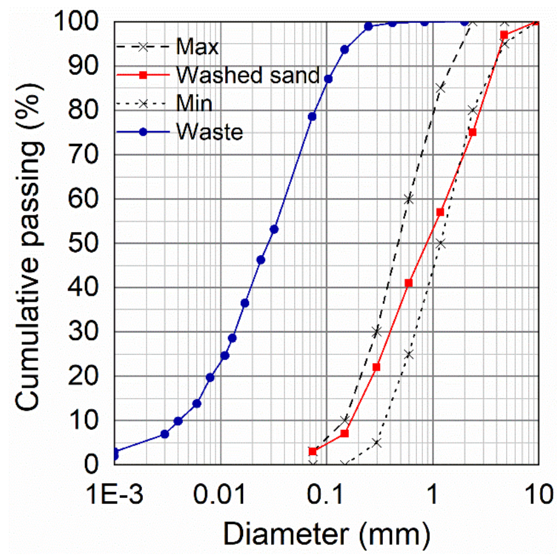

Figure 1. *PSD curve of washed sand (red), waste (blue) and standard specification limits (black dashed lines).*

Table 4. *Granulometric analysis of washed sand.*

Mesh sieve		Retained mass	Cumulative Passing		
			Max*	Sample	Min*
mm	in	g	wt.%	wt.%	wt.%
9.510	3/8"	0.0	100	100	100
4.760	N° 4	29.0	100	97	95
2.380	N° 8	202.1	100	75	80
1.190	N° 16	155.2	85	57	50
0.595	N° 30	153.0	60	41	25
0.297	N° 50	163.9	30	22	5
0.149	N° 100	140.0	10	7	0
0.075	N° 200	37.0	3	3	0
Bottom (g)		1.0		-	
Mass at the start (g)				906.7	
Mass at the end (g)				881.2	
Error (%)				2.81	

*Max and Min: maximum and minimum standard specification limits respectively.

Particle Size Analysis of waste by Hydrometer method with deflocculating agent under ASTM D422-07 showed particle sizes between 0.4-1.0 µm, which that means a smaller size range compared to the washed sand (Figure 1), as previously stated. From these data were possible to estimate the amount of particle size sand (2-0.05 mm), silt (0.05-0.002 mm) and clay (<0.002 mm) as is shown in Table 6.

Table 5. *Characteristics of raw materials.*

Physical Properties		Raw materials	
		Washed sand	Waste (sludge)
Moisture	(%)	10.3	254.53
Passing sieve N° 200	(Wt.%)	2.8	75.4
Fineness modulus	-	3.0	0.1
Dry density	(kg/m^3)	2586	-
Density s.s.s.[a]	(kg/m^3)	2639	-
Pulp Density	(kg/m^3)	-	1260
Solid particles	(wt.%)	-	24.7
Absorption	(wt.%)	2.0	-
L.U.M.[b]	(kg/m^3)	1692	-
C.U.M.[c]	(kg/m^3)	1810	-

a) SSS: Saturated surface dry density. b) LUM: Loose unit mass. c) CUM: Compact unit mass.

Table 6. *Quantities of particles in the waste according to particle size.*

Size (mm)		Quantity (wt.%)
Sand	2.00 – 0.05	34.50
Silt	0.050 – 0.002	65.00
Clay	< 0.002	0.50

A large amount of silty material can be observed (more than sandy material) and a small contribution of the clayey material. Although these amounts were maintained within Austin & Holmes [2] range, the proportionality among sizes were not maintained.

Thus, consistency limits of the waste under ASTM D4318-05 were showed characteristic values of silty soils (Table 7), i.e., low Liquid Limit (L.L.) and very close to its Plastic Limit (P.L.), which indicated low presence of clay minerals (P.I. < 10) (Figure 2).

Finally, according to the consistency limits of Table 7 and the plasticity chart of the Unified Soil Classification System (USCS) (Figure 2), it can be concluded that the waste was an ML soil (silt with low plasticity), which was congruent with the soils used in the investigations shown in the literature review.

Table 7. *Atterberg limits of waste.*

G	L.L. (%)	P.L. (%)	P.I. (%)
2.77	29.5	23.3	6.2

G: Specific gravity. P.L.: Plastic Limit. L.L.: Liquid Limit. P.I.: Plasticity Index.

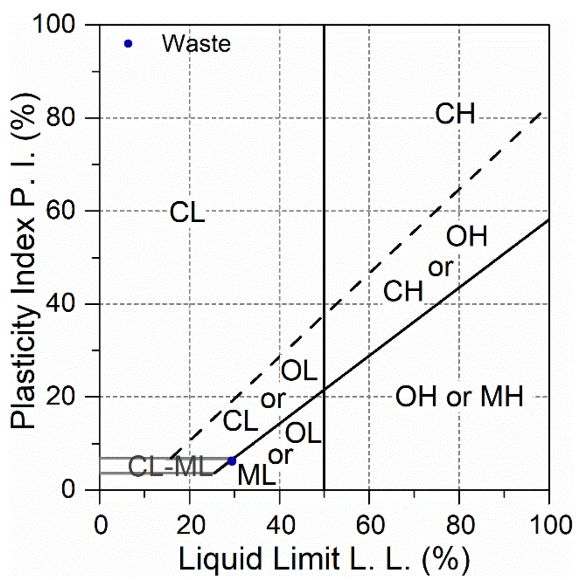

Figure 2. *Soil type according to USCS.*

3.2. SCS test on open air cured specimens

SCS results of mixtures M2, M3 and M4 were compared with respect to mixture M1 (100% waste), in order to visualize the influence of the incorporation of different materials in the MCES (Figure 3, Table 8).

From Figure 3 and Table 8 it was observed that those specimens with cement had the best mechanical responses; around 8 MPa for mixtures with 20% cement (M3) and 6 MPa for mixtures with 10% cement and 10% washed sand (M4). Thus, these results were equal and higher than those found in Calderón [1], which they were between 5-7 MPa.

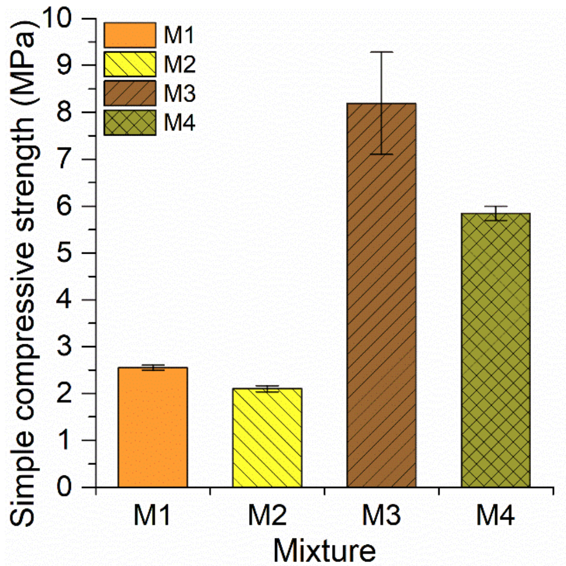

Figure 3. *SCS of mixtures at 28 days of open-air curing age.*

Table 8. *Variation of mixtures with respect to M1 and statistical coefficient of variation (CV).*

Mixture	Variation (%)	CV (%)
M1	-	2.16
M2	-17.41	3.09
M3	221.34	13.31
M4	129.32	2.59

Variation of SCS with respect to M1 and CV of SCS on mixtures at 28 days of open-air curing age.

In contrast, specimens with no-cement in their composition presented the lowest SCS values, being lower in those that had 20% washed sand (M2) compared to those that were only made with waste (M1). Thus, a decrease of around 17% was found when only washed sand was incorporated into the mixture and an increase of 221% and 129% when cement and cement-washed sand were incorporated into the mixture respectively; in other words, an increase of more than 3 times and 2 times the mechanical resistance of M1, for M3 and M4 correspondingly.

A possible explanation for the decrease in SCS presented in M2 (in contrast to the results obtained by the authors in the literature review) were: 1) the sand used had a large particle size distribution (0.07 and 4.76 mm) compared with the silica sand (1-2 mm) used by Calderón [1]; 2) this variability in size, together with the low presence of clay-size material in the waste (0.5%), made that specimens do not have sufficient cohesion and filling in the mixture, leaving empty spaces that reduced final SCS values.

Furthermore, knowing that the coefficient of variation allows evaluate the statistical quality of the estimates (averages and standard deviations) and that if the coefficient is less than 7% the estimates are accurate, if it is between 8-14% the estimates are acceptable, if it is between 15-20% the precisions are regular (they should be used with some caution) and if it is greater than 20% the estimates are imprecise indicating that the average is not representative for the data set analyzed and therefore nothing can be concluded [22]; it can be stated that the estimates of averages in M1, M2, M4 were accurate and for M3 was acceptable (Table 8), in other words, the averages were representative and can be used as continuous quantitative values in the statistical description of the trends.

3.3. Water absorption test

The specimens made from mixtures of M1 (100 wt.% waste) and M2 (80 wt.% waste and 20 wt.% washed sand) did not pass the water absorption test, this means that the specimens were completely destroyed 5 min after immersion in water (intense bubbling). The opposite occurred with M3 (80 wt.% waste and 20 wt.% cement) and M4 (80% waste, 10 wt.% washed sand and 10 wt.% cement), which conserved their shape and cohesion 24 h after immersion in the water. These presented a small bubbling while they were submerged and decreased as time goes by (after 1 h it was practically null). For these reasons, Figure 4 and Table 9 only record values for mixtures M3 and M4.

The water absorption percentages were ~25% for M3 and ~24% for M4. These values were very close to each other and higher than those obtained by Cabo [4], which did not exceed 6%. This was due to the low quantity of clay size material in the waste (increasing voids due to underfilling of specimens), the conditioning process or the compaction pressure used (leaving voids in specimens).

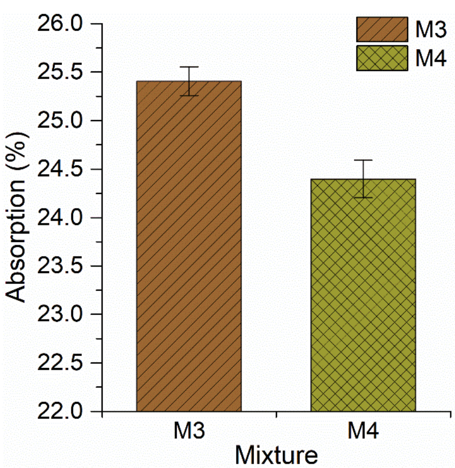

Figure 4. *Percentage of water absorption after 28 days curing for M3 and M4 mixtures.*

Table 9. *Statistical coefficient of variation (CV).*

Mixture	CV (%)
M1	-
M2	-
M3	0.58
M4	0.79

CV of water absorption after 28 days curing for M3 and M4 mixtures.

The coefficient of variation was also calculated (Table 9), which showed measurements below 1% of variation (far below 7%) indicating that the averages are representative for the data set analyzed. So, by improving these results of WA, MCES could be technically implemented as:

- Concrete Paver for Pavement (Colombian Technical Standard NTC 2017: 2018) if the absorption percentage is less than 7% (due to M3 and M4 had highest SCS, of 8 and 6 MPa respectively and, it could be inferred that their modulus of rupture is also higher than the value of 4.2 MPa established by the standard).

- Clay Paver for Pedestrian and Light Vehicle Traffic (Colombian Technical Standard NTC 3829: 2004) or for Heavy Vehicle Traffic (Colombian Technical Standard NTC 5282: 2004) if the absorption percentage is less than 6% (but no specimens obtained the minimum value of 20 and 55 MPa in SCS established by the standards respectively).

- Baked Clay Masonry Units. Bricks and Ceramic Blocks. Part 1: Structural Masonry (Colombian Technical Standard NTC 4205: 1) or Part 3: Facade Masonry (Colombian Technical Standard NTC 4205: 3) or

"Bloquelón" Brick (Colombian Technical Standard NTC 6170: 2016) if the absorption percentage is lower than 16% (due to M3 and M4 had highest SCS, of 8 and 6 MPa respectively and, far exceeded the minimum value of 5.2 and 2 MPa in SCS established by the standards respectively).

- Baked clay masonry units. Bricks and Ceramic Blocks. Part 2: Non-Structural Masonry (Colombian Technical Standard NTC 4205: 2) if the absorption percentage is less than 17% (due to M3 and M4 had highest SCS, of 8 and 6 MPa respectively and, far exceeded the minimum value of 2 MPa in SCS established by the standard).

For these reasons, it is clear that only M3 (residue, cement) and M4 (residue, sand, cement) satisfactorily fulfill the mechanical strength requirements as concrete paver for pavement, structural masonry, facade masonry, "bloquelón" brick and non-structural masonry, as long as the high water absorption decreases (which is detrimental to its stabilization) and they are manufactured with the physical and dimensional requirements established by the standards mentioned above (for their adequate industrial use).

3.4. SCS test on water-cured specimens

SCS tests were performed on the specimens that presented a good physical appearance after having completed of the water absorption test. These were a single specimen for M3 (due to the fact that the others were fractured in the horizontal plane perpendicular to the force applied during specimen manufacture) and all specimens of M4. For this reason, M3 result was not plotted as an average value in Figure 5 and Table 10.

SCS on water-cured specimens followed the trend of open-air drying-cured specimens. Higher values were obtained for M3 followed by M4, these values were around 15 MPa and 11 MPa respectively, showing similar values with those found by Cabo [4] for natural materials. This showed a clear influence of conditioning process (curing), because with only 24 h of immersion in water, the SCS for M3 and M4 was doubled.

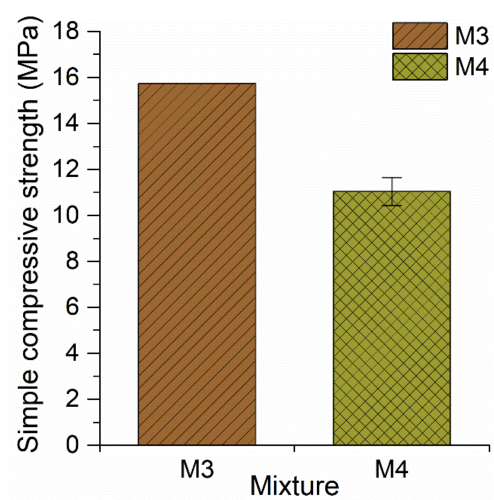

Figure 5. *SCS of the water-immersed and oven-dry specimens of the WA test.*

Table 10. *Variation of SCS for samples of mixtures with respect to M1.*

Mixture	Variation (%)
M1	-
M2	-
M3	517.28
M4	333.12

Variation of SCS with respect to M1 mixture open-air cured, for mixtures that fulfilled the WA test.

If the comparison is made with SCS of M1 open air drying-cured it was found that SCS increased six times for M3 and four times for M4. This may be due to that the open air drying-cured specimens did not have sufficient water for complete hydration of the cement particles; which resulted in lower SCS values compared to the specimens that did have sufficient water (those tested after the absorption test). In addition, the correct hydration of cement was promoted the cohesion between soil particles and cementitious matrix, in contrast with no-cement specimens, which were completely destroyed.

4. CONCLUSIONS

It was possible to manufacture un-calcined compacted earth specimens (MCES) with waste from gravel and sand washing, which obtained well mechanical performances that allow their use as masonry or structural elements with an adequate dosage.

The presence of cement in the compacted waste (MCES) is necessary if excellent mechanical behavior is required, because the SCS obtained reached up to 8 MPa when they were open air drying-cured with only 20 wt.% cement. These results also can be improved if during the curing process, a greater quantity of water or moisture percentage of the mixture is available to guarantee the correct hydration process of the cement. By immersing specimens in water for just 24 h, up to 15 MPa was achieved.

Furthermore, the compaction process must be carried out in a single stage, as this eliminates the risk of fracture in the plane perpendicular to the direction of application force in the manufacture (for adequate industrial scalability). This was evidenced in the fractured samples after oven-drying in the water absorption test.

On the other hand, as the water absorption percentage of the specimens was very high (around 25%, when in industrial applications it should not exceed 6%) it is recommended for future works to study the influence of the variables conditioning process, compaction pressure, moisture content and cement content, as well as the incorporation of some type of waterproofing that allows this absorption percentage to be reduced and simple compressive strength to be maximized.

For now, the possibilities of industrial application of these compacted wastes are as masonry units and coated structural elements, as long as the water absorption is controlled and the adobes are manufactured under the physical and dimensional requirements established in the standards.

5. ACKNOWLEDGMENTS

Authors are grateful to the company Industrial Conconcreto Aggregate Plant for its wide willingness to strengthening academic-company relationships through the realization of researches like this.

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