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Case study

An investigation on the use of coarse volcanic scoria as sand in Portland cement mortar

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ABSTRACT

In this study, the utilization of coarse volcanic scoria CVS as sand in Portland cement mortar was investigated. The aim of this study is to give some physical properties, mechanical properties and durability properties of CVS mortars investigated at short term of curing in comparison with a reference mortar. Investigation was carried out on three groups of mortar samples according to the proportion of fine particles on the coarse volcanic scoria, "low" for the first group MCVS1, "average" for the second group MCVS2 and "high" for the third group MCVS3. The reference mortar has been made with standard sand. The water–cement w/c ratio and sand/cement s/c ratio used in the mixtures were 0.5 and 3, respectively according to European Standard EN 196-1-2005. The particle size of CVS aggregates used to prepare mortar mixtures were between 0.08 mm and 2.00 mm like in the standard sand. Compressive and flexural strengths were tested at mortar age of 28 days. The results revealed improved compressive and flexural strengths, which were maximal for the MCVS3 samples. Unit weight increased with the ratio of fine CVS size between 0.08–1.00 mm. Sorptivity and carbonation depth decrease as the ratio of fine CVS increase. Based on these results, using Cameroonian volcanic scoria in the appropriate particles size ratio composition will improve these mortar characteristics. CVS mortars can be used for more applications for building construction in Cameroon and all over the world, especially in regions where volcanic scoria resources are abundant.

1. Introduction

The use of some wastes or by-products finely ground in mortar and concrete has become increasingly effective because their use can give better results and be successful, especially from the viewpoint of the mechanical properties or durability of material. In the literature, several waste types have been cited such as volcanic ash, volcanic scoria or tuff, natural pozzolan or ground granulated blast furnace slag as addition or aggregate in mortar [1–13].

Mortar is a workable paste typically made from a mixture of fine aggregate, a binder such as cement or lime, and water. Mortar becomes hard when it sets, resulting in a rigid aggregate structure. It is used in masonry to bind bricks and stones, to provide an even bed between joints, and to plaster and point exposed masonry surfaces. Mortar in a thin liquid form (grout) is used to fill empty joints in masonry, to stabilize soil, to solidify porous rock, to make cast-in-situ reinforced concrete membranes, and has many other uses [14,3].

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Natural river and sea sand is mostly using in mortar production. The actual requirements of sustainability in construction promote the use of materials which cause a lower environmental impact than those traditionally used. Natural sand mining from rivers and seashores is causing serious environmental problems in many parts of the world, whereas the fine fraction from volcanic scoria deposit is underutilized as a construction material [1]. Aggregates such as coarse volcanic scoria (CVS) aggregates are used in mortars to replace or combine with cement. By using these aggregates, such diverse properties as weight reduction, thermal insulation and fire resistance or workability may be improved. Thus, many lightweight materials such as expanded perlite, expanded glass, hollow microspheres and expanded polystyrene are used without replacing cement, to improve these characteristics [15,3]. The manufacturing of mortars which replace natural aggregates for those of CVS aggregates obtained by crushing of volcanic scoria is a sustainable alternative. An alternative which can only be considered as beneficial as it reduces the exploitation of the existing sea sand quarries, thus conserving natural resources as well as reducing transport costs and minimizing the environmental impact.

Volcanic scoria deposits are abundant in Cameroon. Cameroon has been affected by a gigantic tectonic accident linking the Sao Tome and would continue until the Tibesti. This accident is observed by the alignment of forty massifs over a distance of more than 500 km, from the Atlantic Ocean to Lake Chad which is called the “Cameroon Volcanic Line”(CVL). The CVL is a suite of volcanic and sub volcanic devices, that are aligned in the direction North 30° East. 1600 km long, it is dotted with volcanic massifs of the Southwest to Northeast. It comprises Gulf of Guinea islands, mostly volcanic: Bioko Pagalu, Sao Tome, Principe and also some seamounts; the region of West Cameroon, with alternating mountains: Mount Cameroon (Altitude: 4100 m), the Manengouba Mountains (shield volcano of 20 km in diameter, with no known historic activity presents some Strombolian cones Bamboutou, Mbam and Oku and grabens (Kumba, Tombel, Mamfe, Mbos, Ndop) and end the Tikar lowland (Foumban in Banyo) (Fig. 1). These massifs located in the western part of the country at the border with Nigeria are dotted with their shallow by many scoria deposits. Especially on the slopes of Mount Cameroon, the slopes of Mount Manengouba, Mount Galim, the plains of Tombel around Djoungo, Kumba plain, the plain of Noun around Foumbot, Lake Nyos area and the plateau of the Adamaroua [18].

The advantages of volcanic scoria and tuff include its highly porous structure, high surface area, and low density. It is available in different types, sizes, and colors, and can reduce mortar or concrete dead weight. Similar to other pozzolanic material, such as silica fumes and fly ash, substitution with zeolite can improve the strength of concrete via the pozzolanic reaction with $Ca(OH)_2$ [3,15,19]. It can prevent the bleeding, segregation, and delamination of fresh concrete, facilitate pumping processes, decrease the permeability of hardened concrete, enhance durability (especially resistance to alkali-aggregate reactions), increase concrete strength, and minimize the cracking in concrete caused by self-shrinkage [3,20]. Many authors have investigated the properties of volcanic scoria or tuff sand and checked its suitability for use in mortar mixes [10–13]. Their results indicated that volcanic scoria and tuff sand increased mortar adhesion, bonding strength, and durability. Therefore, this study aims to investigate characteristics of cement mortar using coarse volcanic scoria aggregates in comparison of mortar with standard sand, with a constant water to cement ratio.

2. Experimental program

2.1. Materials

The main components of the mortars investigated are:

- Cement CEM I 52.5 N;
- Clean water from city of Liège (Belgium);
- CEN Standard sand, consisting of siliceous rounded particles or CVS aggregates from volcanic scoria.

The physical and chemical properties of CVS aggregates used in the present work are highlighted below. The choice of local “Djoungo” Cameroonian volcanic scoria materials was based on their abundant availability and accessibility. The cement used was a local ordinary Portland cement type (CEM I 52.5 N), manufactured by the Heidelberg CBR Cement Company located in Lixhe, Belgium. The cement factory conforms to the European Standard EN 197-1 [21]. Its main mineralogical, chemical and physical features are summarized in Table 1 (data made available by the producer company) [22].

Clean water from the urban tap supply of the city of Liège (Belgium) was used: it doesn’t contain any element that might negatively affect the quality of the hydraulic mixes. A standard sand conform to European Standard EN 196-1 [23] and packaged in polyethylene bags of (1350 ± 5) g content was used. Its physical proprieties were as follows: relative specific density, (2650 ± 5) kg/m^3; water absorption, 1.5 ± 1%; bulk density, (1530 ± 5) kg/m^3 and maximum grain size, 2.00 mm. Volcanic scoria collected in the main “Djoungo” deposits in Tombel (Fig. 2) were used.

2.2. Methods

In this part, different methods using to characterize volcanic scoria to produce CVS aggregates (chemical and mineralogy composition, mechanical process to obtain CVS aggregates) and different mortars obtained (Physical, mechanical properties and durability) have been presented.

2.2.1. Chemical and mineralogical characterization of volcanic scoria

Chemical and mineralogical characterizations were performed analysis by X-ray fluorescence (XRF) and X-ray diffraction (XRD) methods. The result of chemical composition was compare by several results provide by other authors on the same volcanic scoria

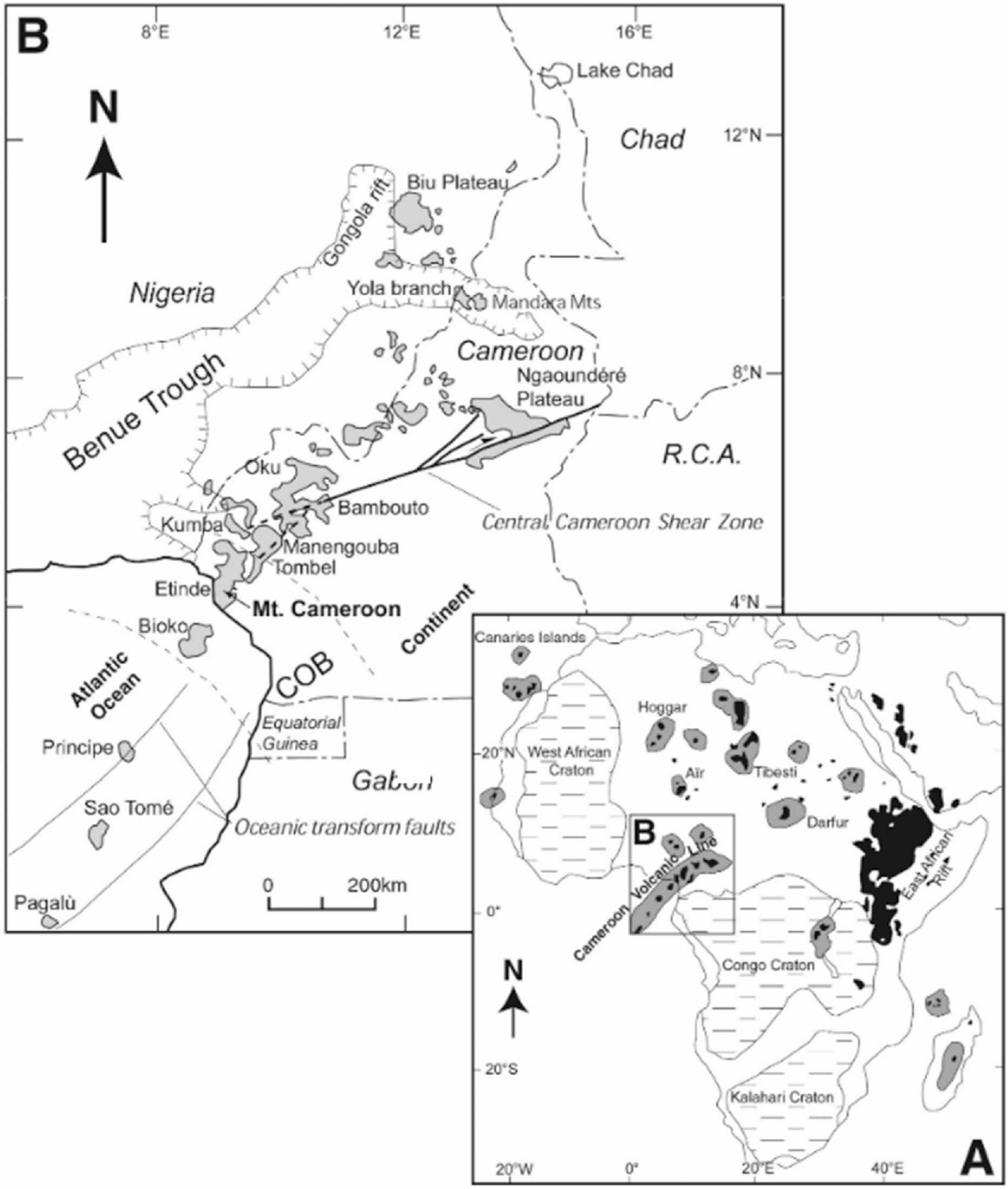


Fig. 1. Location map of the Cameroon Volcanic Line (CVL), Mount Cameroon and other main volcanic centres (grey) along the CVL (after [16], modified according to [17] cited by [18].

deposit. Results of chemical and mineralogy composition was also analysis to show the pozzolanic activity ability level of this material resource.

2.2.2. Preparation of CVS aggregates

The reduction of volcanic scoria samples was performed, in laboratory by crushing and then sieving to classify the different grading sizes. The volcanic scoria samples size reducing was performed on the material dried in open air environment during 24 h

Table 1
Mineralogical, chemical and physical features of the Portland cement (CBR Lixhe).

Oxide	Value
Chemical composition (%)	
SiO_2	21
CaO	64
MgO	–
Al_2O_3	5
Fe_2O_3	4
SO_3	2.9
Cl	0.06
Na_2O	0.85
K_2O	–
LOI	1.3
Physical properties	
Specific gravity	3.1 g/cm^3
Blaine fineness	4400 cm^2/g

Fig. 2. Sample of "Djoungo" volcanic scoria collected in metallic bottle with 25 mm diameter.

and then in oven at 105 °C during 24 h for the removal of moisture in the rocks. For crushing, a jaw crusher was used. After crushing, the volcanic scoria samples are sieved using the 2, 1.6, 1, 0.5, 0.15 and 0.08 mm stainless steel sieves of 20 cm diameter. Each sieving operation is carried out for 20 min. Three coarse volcanic scoria (CVS) aggregates type (CVS1, CVS2 and CVS3) was performed by mass ratio composition using different volcanic scoria sand grading obtained.

2.2.3. *Mix design and production of mortars*

Mixtures were based on absolute mass method. Mortars were prepared with Portland cement as binder and siliceous standard sand or CVS as aggregate. All mortars were prepared with a water content of 225 g and a cement content of 450 g, based on requirements given in EN 196-1 [23]. A laboratory mortar mixer was used for preparation of mixtures (Fig. 3a). CVS aggregates were wetted with half of total water before 1 h from mixing. Firstly, cement was mixed, secondly CVS aggregates wetted were added. Finally, the rest of water added. Mixing time in total was 3 min. After mixing completed, mortar formulations were cast in moulds 40 × 40 × 160 mm with a two-layer compaction on an impact compactor (Fig. 3b).

All the specimens hold in moulds for 24 h at room temperature (20 °C) were demoulded and then cured in water at 23 °C for 27 days. Fig. 4 shows different process and steps of samples production.

2.2.4. *Tests methods*

Two properties were tested to evaluate the fresh mortar: fresh unit weight and flowability. The hardened mortar was characterized by studying six properties: dry unit weight, compactness, porosities, compressive strength, flexural strength, carbonation depth and sorptivity.

Unit weight of fresh mortar was measured according to European Standard EN 1015-6 [24]. The flowability (consistency) of the mortars was determined by flow table tests according to European Standard EN 1015-3 [25]. Diameter of mortar was measured and flow value was expressed as an average of two measurements. The mortar sample spread diameter, measured before and after 15 strokes (1 stroke per second), represented the consistency of a mortar. All specimens were removed from the moulds 1 day after

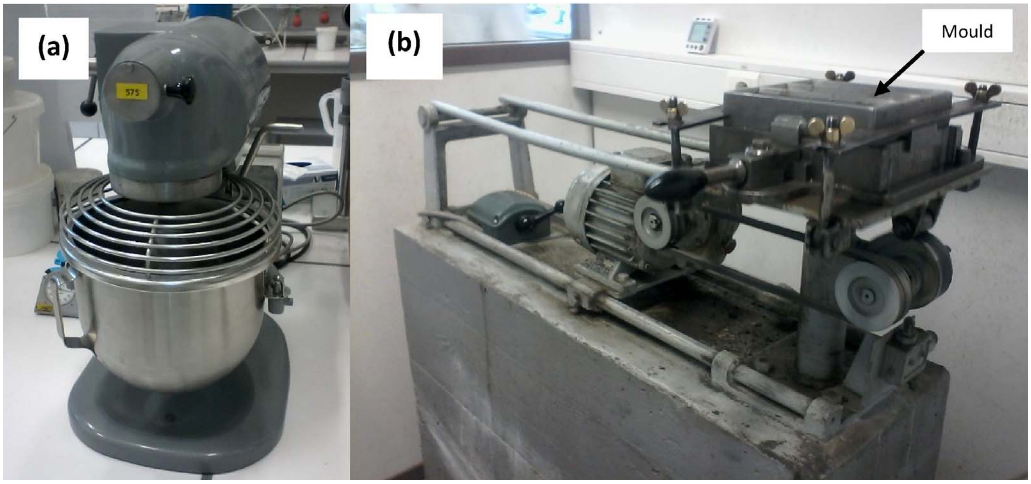


Fig. 3. Production of samples: (a) laboratory mortar mixer and (b) impact compactor used.

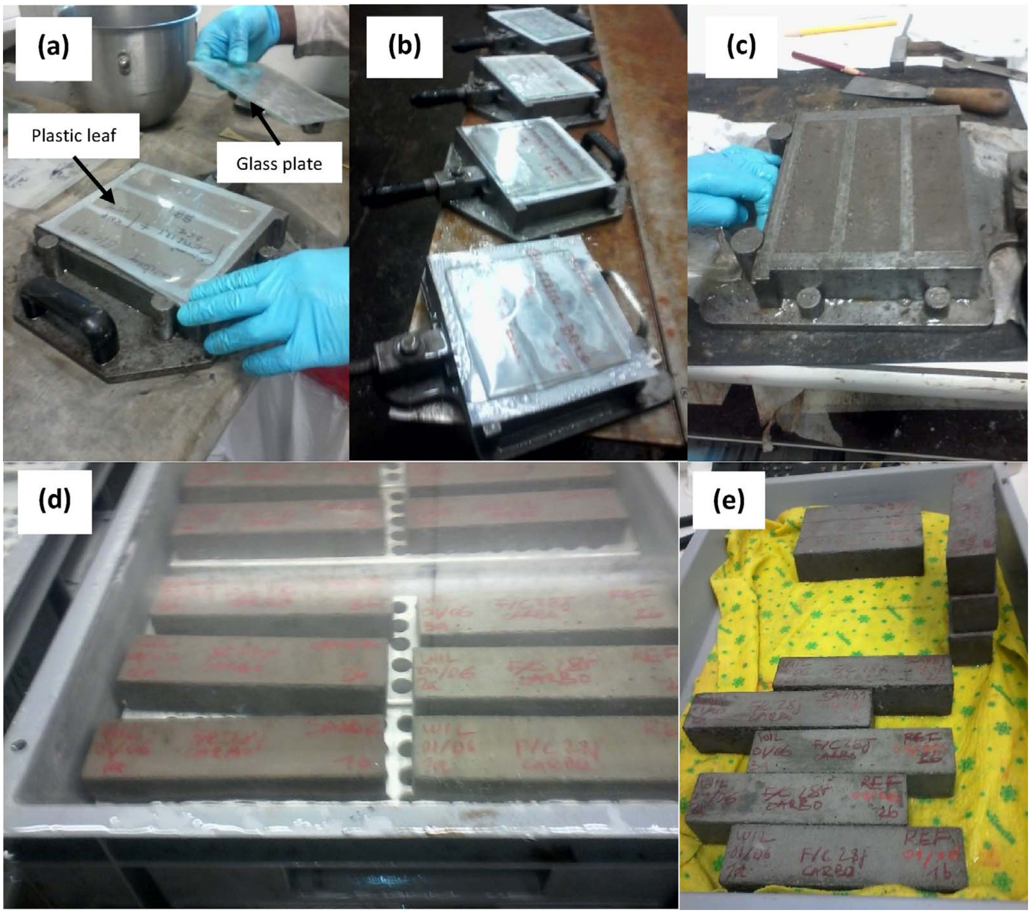


Fig. 4. Production of samples: (a) fresh mortar in mould cover with plastic leaf and glass plate, (b) specimens during 1 day curing in moulds, (c) demoulded of mortar bar after 1 day, (d) 28 days curing in water at chamber of curing, (e) soaked samples after 28 days curing in water before measurements.

casting. Thereafter, they were cured in water at room temperature (20 ± 5 °C).

Unit weight of hardened specimens, porosity and water absorption were determined on the unheated specimens aged 28 days according to Archimedes principle by the weight measurements of saturated specimens in air and in water and dry weight. The difference in weight between in the water-saturated and dry conditions was used to evaluate the porosity of mortars and it was expressed as a percentage of the bulk specimen volume.

To study granular effect of CVS aggregates on mortars, compactness and porosity have been evaluated for each mortar mixture. Moreover, it is proposed to determine the compactness of the granular skeleton in order to verify directly the density of the stack. The compactness of fresh mortars, Φ (Φ_{MREF} or Φ_{MCVS}) expressed in%, shall be calculated from their fresh density (fresh unit weight), measured after placing in the moulds taking into account the absolute density (dry unit weight) of the solid constituents in the mixtures, by the following formula according by Bessa Badreddine [33]:

$$\Phi_{MREF} = 100 \times \left(\frac{M_c}{\rho_c} + \frac{M_s}{\rho_s}\right) \times \left(\frac{M_{fresh\ unit\ weight}}{M_c + M_s + M_w}\right) \tag{1}$$

$$\Phi_{MCVS} = 100 \times \left(\frac{M_c}{\rho_c} + \frac{M_{cvs}}{\rho_{cvs}}\right) \times \left(\frac{M_{fresh\ unit\ weight}}{M_c + M_{cvs} + M_w}\right) \tag{2}$$

where:

$$\frac{M_{cvs}}{\rho_{cvs}} = \frac{M_{cvs1.60/2.00}}{\rho_{cvs1.60/2.00}} + \frac{M_{cvs1.00/1.60}}{\rho_{cvs1.00/1.60}} + \frac{M_{cvs0.50/1.00}}{\rho_{cvs0.50/1.00}} + \frac{M_{cvs0.15/0.50}}{\rho_{cvs0.15/0.50}} + \frac{M_{cvs0.08/0.15}}{\rho_{cvs0.08/0.15}} \tag{3}$$

$$M_{cvs} = M_{cvs1.60/2.00} + M_{cvs1.00/1.60} + M_{cvs0.50/1.00} + M_{cvs0.15/0.50} + M_{cvs0.08/0.15} \tag{4}$$

$M_{fresh\ unit\ weight}$ is the bulk unit weight of fresh mortar after placed in the moulds (kg/m^3);

ρ_c, ρ_s and ρ_{cvs} are respectively the specific density of cement, siliceous sand and CVS aggregates using in the mortar mixture (kg/m^3);

M_c, M_s, M_{cvs} and M_w are respectively the mass of cement, natural pozzolan, siliceous sand and CVS aggregates using in the mortar mixture (kg).

The total porosity (water + air content) of mortars, P_i, expressed in percentage (%), can then be determined to be the complement of the compactness by the relation:

$$P_i = 100 - \Phi \tag{5}$$

The porosity of all mortars was also obtained using this method using these empirical equations (Eqs. (1)–(5)).

For each mix, prisms (40 × 40 × 160) mm^3 were tested to determine compressive strengths and flexural strengths at 28 days (Fig. 5). The results reported are the average of three tests flexural strengths and three tests of compressive strength in accordance with EN 196-1 [23].

Capillary absorption was undertaken on 28 days old cast test specimens, section (40 × 40) mm^2 an approximatively 80 mm length in accordance with standard procedure EN 13057 [26]. The samples were put to dry in a laboratory condition at (21 ± 2)°C until constant mass during 7 days. For the test itself, specimens were placed with moulded face downwards, in a shallow water bath. Water level was adjusted automatically so that the formwork face was constantly dipped to a depth of approximately 3 mm. During the test, water was drawn into the core by capillary forces and weighed at time intervals up to 14 days (Fig. 6). The absorption of water into mortar under capillary action is dependent on the square-root of time and may be modelled by the following equation:

$$A = S.\ t^{1/2} + A_0 \tag{6}$$

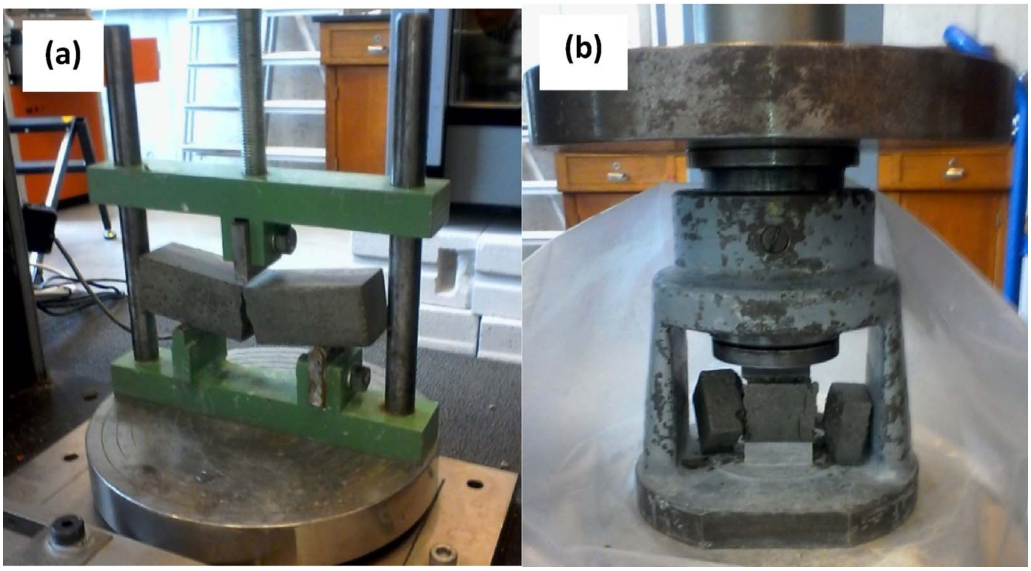


Fig. 5. Tests conducted: (a) compressive strength and (b) flexural strength.

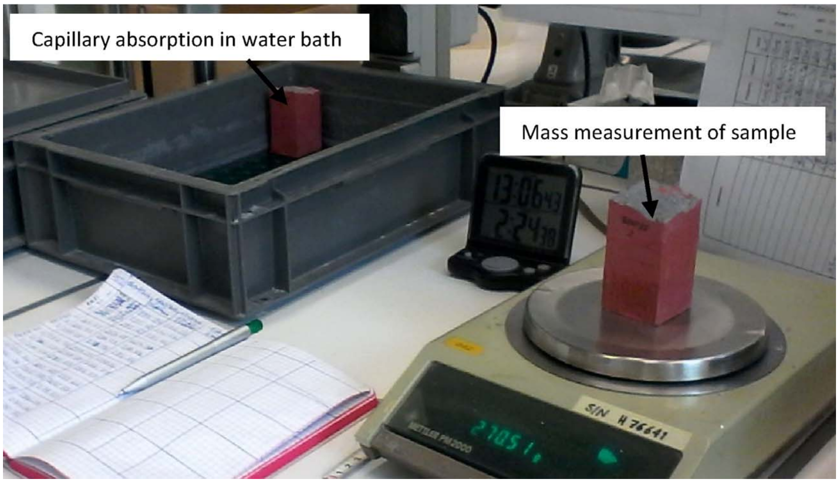


Fig. 6. Capillary absorption test procedure of mortars: process and mass variation measurement.

where:

A (mg/mm^2) is the water absorption by unit area of mortar surface since the moment the core was dipped in water, S is the sorptivity of the material, t is the elapsed time and A_0 (mg/mm^2) is the water absorbed initially by pores in contact with water.

Resistance to carbonation was assessed in accordance with the procedure described by European standard EN 13295 [27] where test specimens were exposed during 56 days to 3% carbon dioxide and temperature of (23 ± 3)°C, in an accelerated carbonation chamber (Fig. 7).

3. Results and discussion

3.1. Chemical and mineralogy composition of volcanic scoria used

Table 2 shows chemical composition of volcanic scoria of “Djoungo” obtain by XRF realized in this study and those giving by several studies. The result is very similar with the results of other authors who used materials from the same site [28–30]. The principal components of volcanic scoria of “Djoungo” are silica, alumina, iron oxide and calcium, with varying amounts of carbon as measured by the loss on ignition (LOI). It presents a low quantity of silica (expressed as SiO_2, around 44%–46%) compared with traditional siliceous sand. The second element is aluminium (expressed as Al_2O_3, around 15% to 17%) and the third is iron (expressed as Fe_2O_3, around 12%–14%) which are typical of volcanic scoria. The presence of calcium is noticeable (expressed as CaO, around 8% to 11%): that’s why, volcanic scoria does not have hydraulic characteristics. Other significant compounds, such as MgO, MnO, Na_2O, SO_3, TiO_2, K_2O and P_2O_5 are also present. A low loss on ignition (LOI) value (0.46%) was obtained in comparison for value of LOI obtain by Billong et al. [29]. For instance, ASTM C 618 [31] recommands a minimum content of 70% in $SiO_2 + Al_2O_3 + Fe_2O_3$, whereas volcanic scoria of “Djoungo” offers around 75% to 76%. However, the importance of ($SiO_2 + Al_2O_3$) content is emphasised by the fact that the active vitreous phases generally are richer in silica and alumina. This volcanic scoria shows a strong acidic character, having a ($SiO_2 + Al_2O_3$) content ranging around 59% to 62%. Pozzolanic activity is related to the total content of $SiO_2 + Al_2O_3 + Fe_2O_3$. So one of the most important factors increasing strength of mortars containing volcanic scoria is the total content of $SiO_2 + Al_2O_3 + Fe_2O_3$. SiO_2 in volcanic scoria can combine with hydrated calcium hydroxide ($Ca(OH)_2$), in the presence of water to form compound like hydrated calcium silicate, CSH, that has cementitious properties and is the principal responsible for

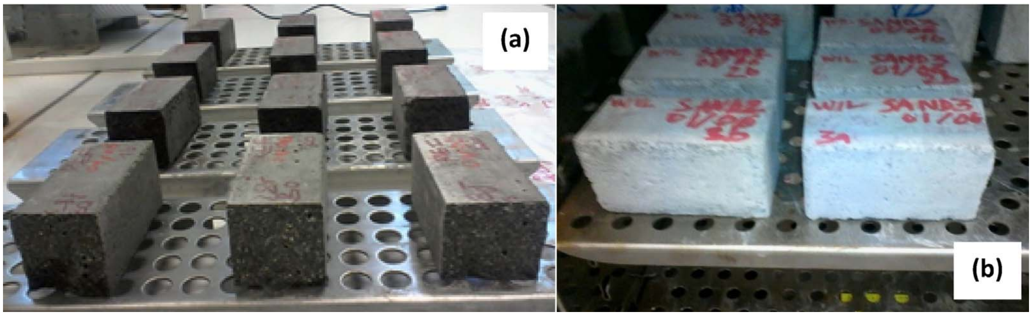


Fig. 7. (a) Constant mass preparation of samples for carbonation test (MREF in first line; MCVS1 in second line; MCVS2 in third line; MCVS3 in last line) and (b) carbonation chamber test samples contain.

Table 2
Chemical composition of volcanic scoria of "Djoungo" by several authors.

Oxide (%)	This study	[28]	[29]	[30]	[31,32]
SiO_2	45.62	45.57	44.04	45.79	43–72
Al_2O_3	16.20	15.94	15.26	15.68	9–20
Fe_2O_3	14.05	12.81	12.77	12.83	1–12
CaO	10.46	8.97	9.29	9.60	1–15
MgO	5.34	5.76	7.00	6.26	0.50–7
MnO	0.25	–	0.17	0.17	/
Na_2O	3.56	3.28	5.64	3.54	0.5–11
K_2O	1.10	1.03	1.35	1.39	0.2–8
SO_3	–	–	0.01	–	0–1.40
TiO_2	3.12	2.11	2.87	2.84	/
P_2O_5	0.37	–	0.53	0.60	/
L.O.I.	0.46	0.20	1.10	0.31	0.20–19

the strength of hydrated cement pastes. It can be used in two ways as a cement replacement in order to save cement and admixture to modify properties of concrete or mortar such as chemical attack, sulfate resistance, alkali–silica reaction, freeze–thaw resistance, abrasion resistance.

XRD data obtain are given in Table 3. The volcanic scoria is primarily glassy in nature, as indicated by the broad amorphous halo in the diffraction pattern. They contain Albite, Augite, Diopside, Hematite and Quartz as principal mineral phases (Table 3). The XRD analysis with standard corundum (Al_2O_3 at 10.87%) was performed to quantify the amorphous phases. XRD results show that "Djoungo" volcanic scoria has both amorphous and crystalline phased: hematite (2.89%), orthoclase (2.68%), andesine AN50 C-1Format (34.78%), Augite (19.22%), siderite (0.59%), forsterite iron (7.74%) and amorphous (21.24%). Regarding chemical and mineralogy of this volcanic scoria, it is sure that using CVS as aggregates in mortar can exhibit pozzolanic activity in long term, but in this study, only short term (Up to 28 days) behaviour was been studied. The long term (up to 1 year) can be carry in previous studies to evaluate pozzolanic activity due of using of CVS as aggregate in mortars on mechanical strengths.

3.2. CVS aggregates preparation and characterization

3.2.1. Particle size distribution of CVS aggregates obtained after crushing and sieving

Fig. 8a shows the CVS aggregates grading obtained after crushing and sieving. Five CVS class was obtained: 1.60/2.00, 1.00/1.60, 0.50/1.00, 0.15/0.50 and 0.08/0.50 mm. Three CVS sand (Sand 1: CVS1, sand 2: CVS2 and sand 3: CVS3) were prepared using different CVS class and particle size distribution of siliceous standard sand as reference. Fig. 8b shows a macroscopic view of all sand used.

The grading sizes composition and physical properties of standard sand and CVS sand used in mortar production are presented in Fig. 9 and Table 4. CVS3 is a CVS sand has a very similar particle size distribution (PSD) like standard sand. CVS1 and CVS3 are obtained by modification of standard sand PSD by the high amount ratio of fine particle (especially class: 0.15/0.50 and 0.08/0.50 mm).

3.3. Properties of fresh mortars

3.3.1. Flowability of mortars

The flowability is often a qualitative assessment of mortar; it is useful to describe the consistency of mortars by the spread diameter obtained by flow table test. Table 5 shows flow value for all mortars tested.

Consistency of control mortar was very similar of consistency of MCVS1, but very different for MCVS2 and MCVS3. For CVS mortars flow increase will fine CVS aggregate ratio contain. CVS aggregate sand particle size distribution have more influence on flowability of CVS mortars. Fig. 10 presents the consistency of MCVS2 and MCVS3. Mortar workability is affected both by CVS shape and porous surface. The porous structure of CVS sand influences workability of fresh mortar due to the absorption of both mixing water and cement paste inside pores. On the contrary, as discussed before, standard sand (natural quartz sand) has a smooth surface and water absorption is close to zero. Moreover, also aggregates shape affects mortar rheology: rounder particles produce a more

Table 3
Major elements present in volcanic scoria of "Djoungo" by XRD.

Compound Name	Chemical Formula	d-spacing [Å]
Albite	$NaAlSi_4O_8$	4.03113, 3.75670, 2.46194
Augite	$CaMgSi_2O_6$	3.33588, 3.21150, 2.99270
Diopside	$CaMgSi_2O_6$	2.56175, 2.51412, 2.13510, 2.03275
Hematite	Fe_2O_3	2.70007, 2.70121, 2.69926, 2.51316
Quartz	SiO_2	4.24753, 4.23745, 4.03632, 3.75063, 3.33690, 1.36997

Fig. 8. (a) Different volcanic scoria sand grading obtained: 1.60/2.00, 1.00/1.60, 0.50/1.00, 0.15/0.50 and 0.80/0.15 and (b) Macroscopic view of different aggregates (a) Standard sand, (b) CVS1 (Sand 1), CVS2 (Sand 2) and CVS3 (Sand 3).

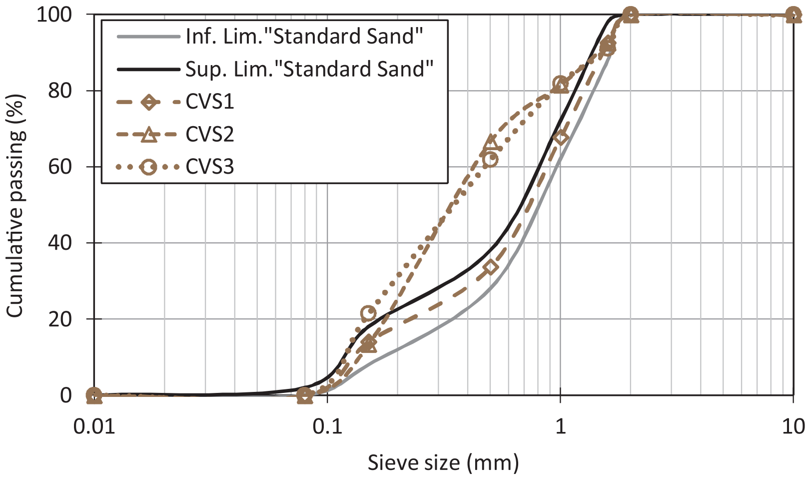


Fig. 9. Particle size distribution of different aggregates used.

Table 4
Physical properties and Particle size range of standard sand and CVS sand.

Sand	Bulk density (kg/m^3)	Specific density (kg/m^3)	Water Absorption (%)	Particle size range (mm)		Composition (%)			
				d_{max}	d_{min}	Standard Sand	CVS1	CVS2	CVS3
Standard sand	1530 ± 5	2650 ± 5	1.5 ± 1						
CVS 1.60/2.00	820 ± 5	2420 ± 5	16.4	2.00	1.60	7 ± 5	7.4	7.4	8.9
CVS 1.00/1.60	880 ± 5	2480 ± 5	11.8	1.60	1.00	26 ± 5	24.8	11.1	9.2
CVS 0.50/1.00	970 ± 5	2610 ± 5	9.8	1.00	0.50	34 ± 5	34.1	14.8	20.0
CVS 0.15/0.50	1560 ± 5	2730 ± 5	–	0.50	0.15	20 ± 5	19.6	53.3	40.4
CVS 0.08/0.15	1640 ± 5	2960 ± 7	–	0.15	0.08	12 ± 5	14.1	13.4	21.5

workable mortar while elongated particles, as CVS sand, give rise to higher friction and reduce consistency. To partially overcome these drawbacks, CVS are be soaked and saturated into part of mixing water before mixtures preparation. It was observed that the flow values of mortars with CVS aggregates is highly depending on the percentage of fine CVS particle size (0.08/0.15).

3.3.2. Fresh unit weight

Measured of fresh unit weight of mortar specimens after putting on mould are presented in Table 5. They are generally increase

Table 5
Properties of fresh mortars.

Mixture	Flow value (mm)	Fresh unit weight (kg/m^3)	Compactness (%)	Total Porosity (%) (water + air content)
MREF	148.15	2342 ± 11.5	75.27 ± 0.51	24.73 ± 0.17
MCVS1	155.30	2208 ± 13.9	71.86 ± 0.45	28.14 ± 0.18
MCVS2	188.39	2261 ± 7.1	72.36 ± 0.23	27.64 ± 0.09
MCVS3	125.51	2361 ± 12.0	75.34 ± 0.38	24.66 ± 0.13

Fig. 10. Flow table tests of MCVS2 and MCVS3.

with fine CVS aggregates ratio (size between 0.80 mm and 1.00 mm). The average fresh density of CVS mortars is ranged from 2208 to 2361 kg/m^3. Table 5 also show estimated compactness and estimated porosity of CVS mortars. The compactness is around of 71–76% and 24–29% for porosity, this show that the fresh mortars have an important quantity of water porosity and air void.

3.3.3. *Compactness and total porosity (water + air content)*

The compactness of all mortars is show in Table 5. The reference mortar (MREF) made with standard siliceous sand present 75.27% of compactness. The compactness little decrease for CVS mortars. The compactness of MCVS3 is very similar with MREF. As expected, Fig. 11 shows that compactness of mortars increases when total porosity decreases with fresh unit weight. The regression coefficient (R^2) is 0.9523. The particle size distribution of CVS aggregates has a different effect on compactness and consistency of mortars. Compactness increase with fine CVS aggregates contain ratio while flowability decreases with large amount of fine CVS aggregates ratio as show in Fig. 11.

3.4. *Properties of hardened mortars*

3.4.1. *Unit weight of mortars*

Measured fresh unit weights and dry unit weights of mortar specimens at 28 days are presented in Table 6. Dry unit weight

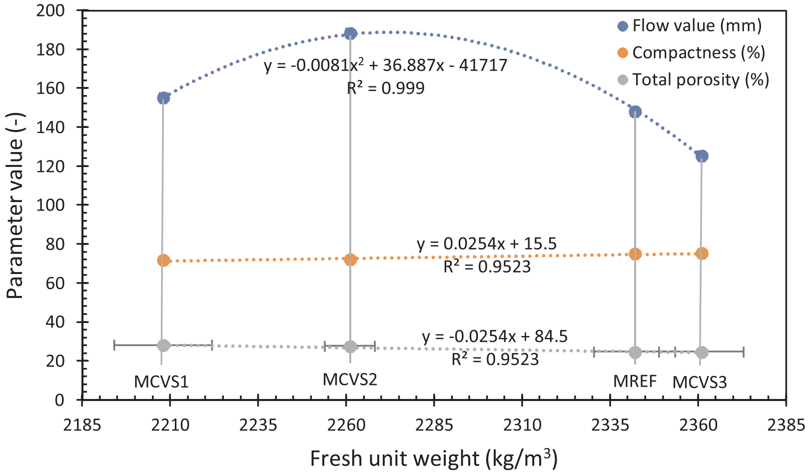


Fig. 11. Relations between fresh unit weight and other properties of fresh mortars (Flowability, compactness and total porosity).

Table 6
Dry unit weights, 24-h water absorption and mechanical strengths of mortars.

Mixture	28 Days			
	Dry unit weight (kg/m^3)	Water Porosity (%)	Compressive strength (MPa)	Flexural strength (MPa)
MREF	2337 ± 11.5	1.42	63.16 ± 1.28	9.44 ± 0.70
MCVS1	2081 ± 12.5	6.65	28.29 ± 0.72	6.41 ± 0.20
MCVS2	2193 ± 8.6	4.43	47.58 ± 1.39	8.09 ± 0.60
MCVS3	2328 ± 12.0	3.35	61.16 ± 1.24	9.80 ± 0.30

decrease is lower due to the porous structure of CVS aggregates which absorb water, reducing the free water respect to the mixtures in which aggregates are saturated. On the contrary, when CVS aggregates are saturated, part of the water contained into pores is given back to the mixture increasing porosity. These assumptions are confirmed by the lower compressive strength and higher porosity (Table 6).

3.4.2. Compressive and flexural strength

The compressive strength and flexural strength values of mortars measured in the laboratory are presented in Table 6. Table 6 shows that the compressive strength values at 28 days of the CVS mortar specimens were quite higher than 28 MPa. When the unit weight and compressive strength values are considered together, MCVS1 and MCVS2 mixtures can be classified as a semi-lightweight mortar. The 28 day's compressive strength values of the mixtures containing coarse volcanic scoria aggregates (MCVS1, MCVS2 and MCVS3) were 28.29, 47.58 and 61.16 MPa. It was seen from these results that the compressive strengths of the mixtures containing coarse volcanic scoria aggregates increase with the proportion of fine volcanic scoria. The compressive strength values of standard control normal weight mortar mixture which is prepared for comparison purposes were 63.16 at 28 days. The 28-day compressive strengths of MCVS3 were compared with the 28-day compressive strength of control mortar. The compressive strength ratio of CVS mortars produced in this investigation to compressive strength of control mortar were 44.79% for MCVS1; 75.33% for MCVS2 and 96.83% for MCVS3 mixtures. From this result, it can be concluded, the CVS mortars produced in this investigation developed about 44% strength of normal mortar.

The flexural strengths of the mortars are also presented in Table 6. It can be seen from Table 6 that, the flexural strength values of MCSV1, MCVS2 and MCVS3 mixtures were 6.41, 8.09 and 9.80 MPa at 28 days. It can be observed that the flexural strength values of mortars containing CVS3 were close to one of the control mortar, which was 9.44 MPa.

Compressive strength decrease for CVS mortars is mainly due to CVS sand as results of lower mechanical properties. Moreover, also porosity increase is responsible for compressive strength decay.

3.4.3. Correlation between compressive and flexural strength

Fig. 12 shows the correlation between the flexural strength and the compressive strength results were calculated for the entire population of test results, and the relation obtained is:

$$f_t = 1.06(f_c)^{0.53}$$

with a correlation factor of 0.92. So, knowing the compressive strength f_c and flexural strength f_t of CVS mortar can be predicted by using this equation.

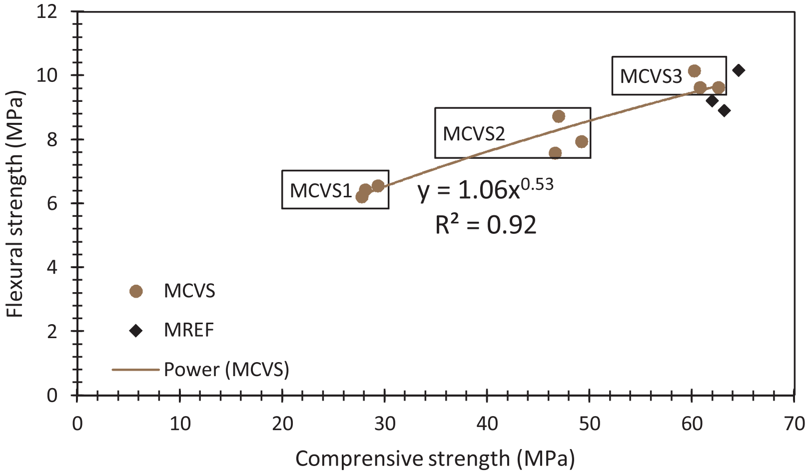


Fig. 12. Relation between compressive and flexural strength of tested mortars.

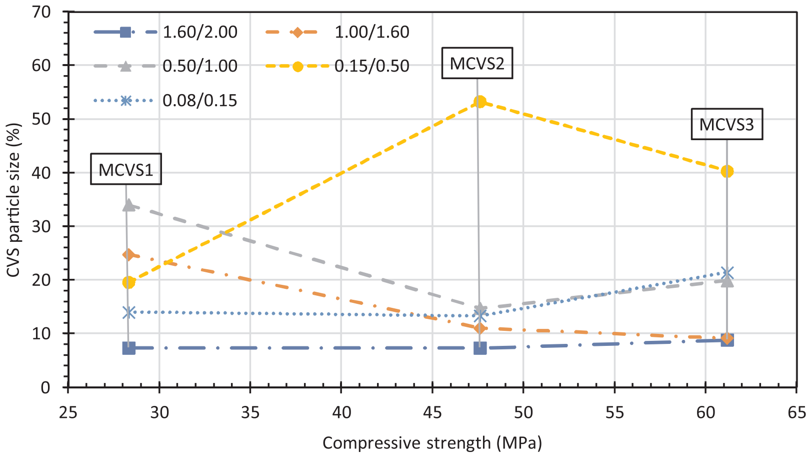


Fig. 13. Influence of coarse volcanic particle size on the compressive strength.

Fig. 13 shows the influence of particle size composition of CVS on the compressive strength. The Compressive strength increase with percentage of fine particle size CVS aggregate (0.08/0.15 grading).

3.4.4. Water porosity of hardened mortars

Fig. 14 shows appearance of mortars after curing during 28 days and after 24 h drying. From visual observation, it is observed that water porosity of CVS mortars decreases with percentage of fine CVS aggregates sand (0.50/1.00, 0.15/0.50 and 0.08/0.15 grading). The approximate value of water porosity was evaluated using water absorption after saturation (Table 6). The water porosity increases with percentage of fines CVS aggregate. This result shows that the water porosity of CVS particle decreases with CVS particle size. The volcanic scoria used have a high scale pores system, and the crushed of large scoria caused a very significant reduction of water porosity.

3.4.5. Correlation between porosity and mechanical strength

Fig. 15 shows mechanical strength of CVS mortars is strongly depending of porosity. Flexural and compressive strength are very correlating to porosity, the exponential decrease of strength as function of MCVS mortars porosity shows correlation coefficient of 0.99 and 0.93 for compression strength and flexural strength respectively.

3.4.6. Absorption by capillarity

The above equation of water absorption by capillarity vs time (Eq. (6)) was found to provide a very good fit to the data with correlation coefficients of over 0.98 (Fig. 16). The average sorptivity value and initial absorption of each mortar type are shown in Fig. 17.

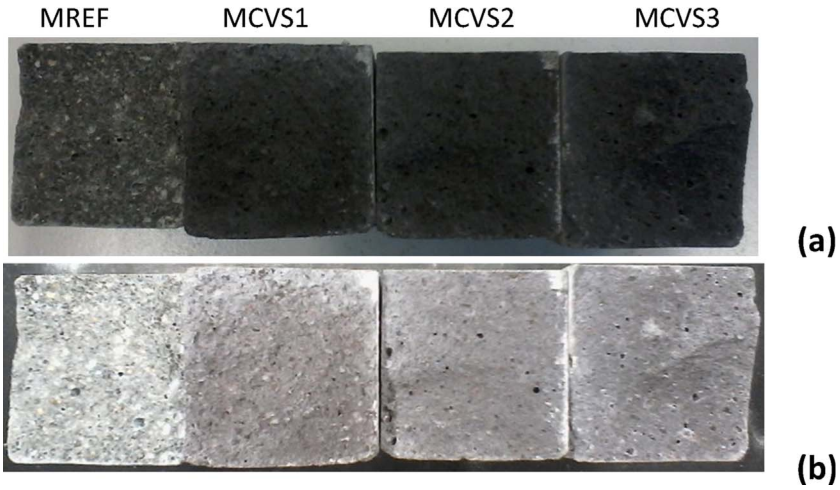


Fig. 14. The section surface appearance of specimens after (a) curing of 28 days (b) 24 h drying.

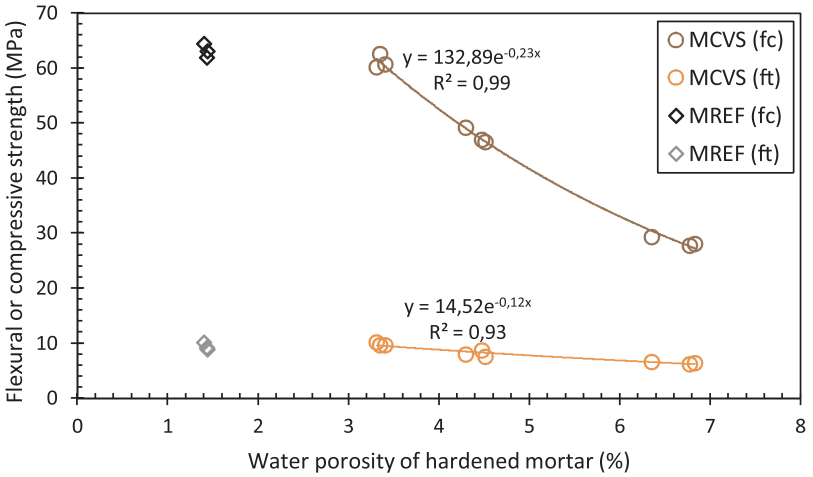


Fig. 15. Relation between mechanical strength and porosity.

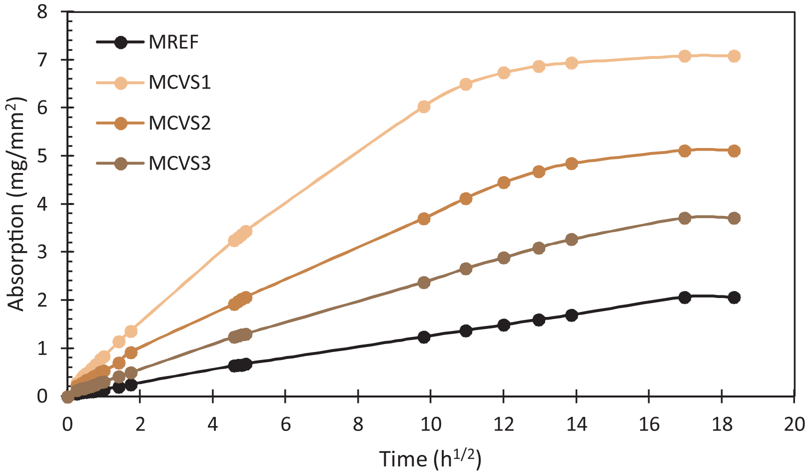


Fig. 16. Evolution of absorption by capillarity during 14 days.

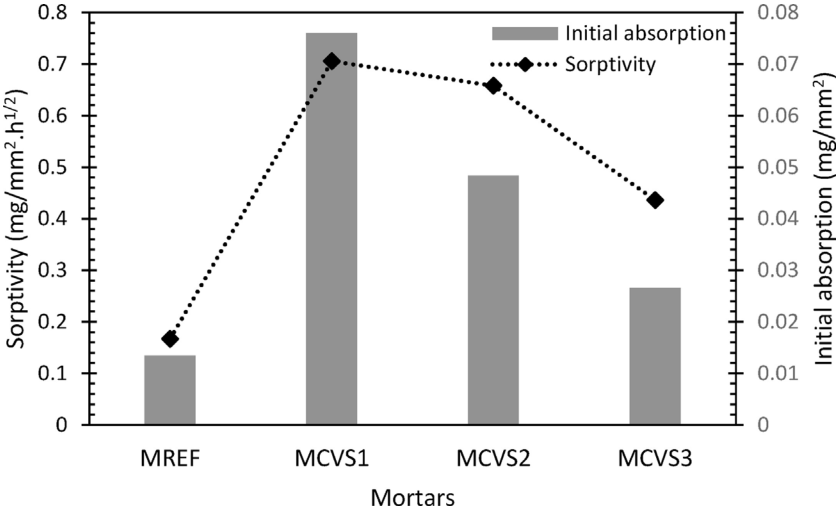


Fig. 17. Sorptivity and Initial absorption of each mortar type.

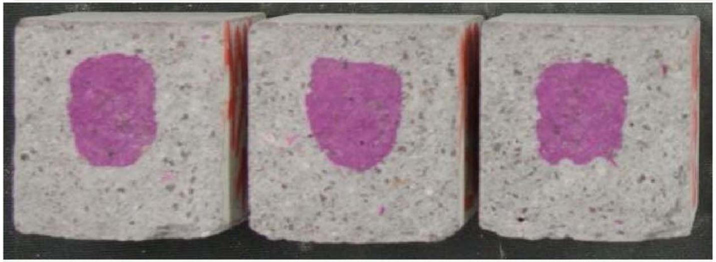
Mortar	Carbonation depth (Phenolphthalein reaction)
MREF	
MCVS1	
MCVS2	
MCVS3	

Fig. 18. Phenolphthalein reaction on carbonated mortars.

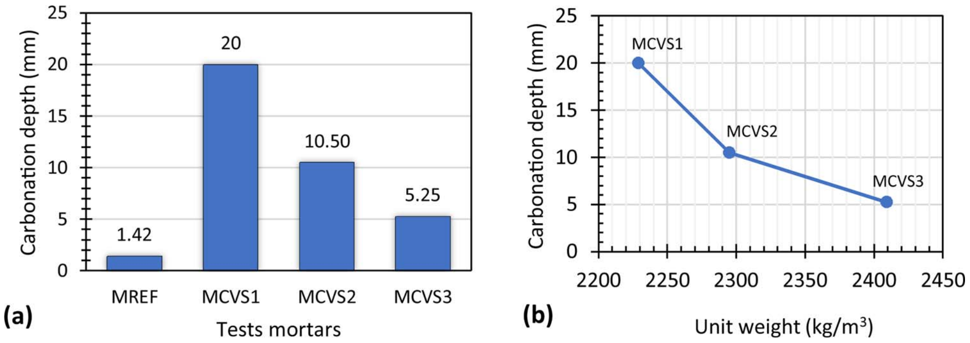


Fig. 19. (a) Carbonation depths (mm) of mortars and (b) Evolution of carbonation depth with unit weight of CVS mortars.

3.4.7. Carbonation depth

During the carbonation process, calcium hydroxide ($Ca(OH)_2$) reacts with carbon dioxide (CO_2) from the atmosphere. Carbonation can be visualized by using phenolphthalein. For measuring the carbonation depths of mortars, phenolphthalein solution was applied on the broken surfaces of the half pieces obtained from flexural-tensile strength test prismatic specimens

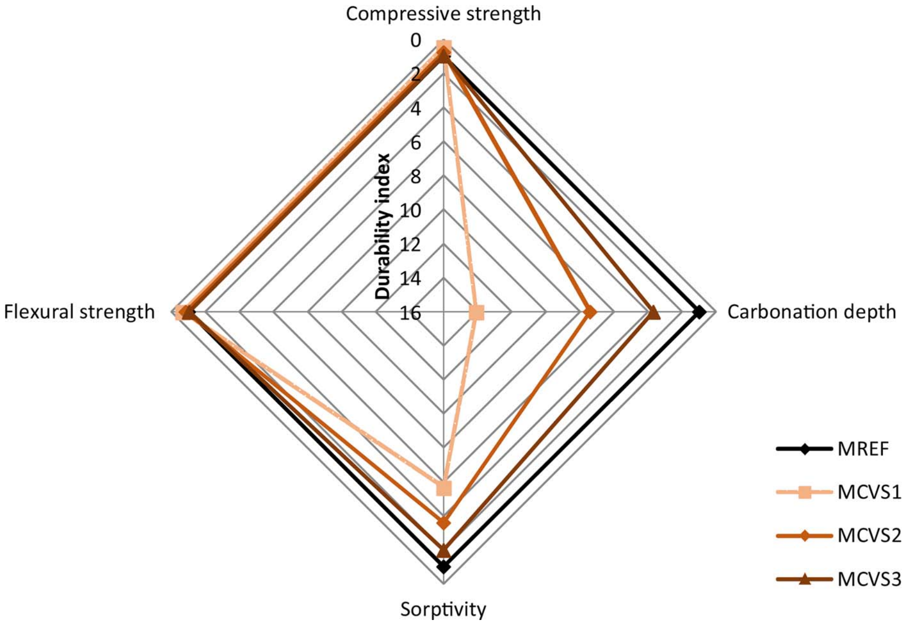


Fig. 20. Relation between mechanical strengths and durability.

(40 × 40 × 160 mm) which were cured in dry laboratory condition. Noncarbonated internal areas turned purple colour while carbonated outside areas remained colourless in the 40 × 40 mm dimensions area after the solution applied (Fig. 18).

Results of carbonation depth measurement of mortars are presented in Fig. 19a. Carbonation depths of mortars increased depending on increasing CO_2 amount penetrated into the samples which increased in time. Fig. 19a shows that, carbonation depths of tests mortars specimens at 56 days were 1.42, 20, 10.50 and 5.25 mm for MREF, MCVS1, MCVS2 and MCVS3 respectively. These values are increased for CVS mortars. The carbonation depth values observed in Fig. 19a are signified in a graph at Fig. 19b. The carbonation depth decreases with unit weight of CVS mortar (Fig. 19b). It can be observed from Fig. 18 that carbonation depths of MCVS1 mortars (CVS sand grading similar for standard sand grading) were higher than MCVS2 and MCVS3 mortars (using more fine CVS aggregates). The results published in the literature were found to be in line with the current study. Carbonation depth of concrete or mortar containing scoria was higher than the carbonation of concrete or mortar made without scoria.

3.4.8. Correlation between mechanical strengths and durability

Fig. 20 illustrates the relationship between mechanical strength (compressive and flexural strengths) after 28 days and durability parameters (sorptivity and carbonation depth after 56 days). Durability index is the ratio of value obtain with a considered mortar by value obtain with control mortar. Durability index is 1 for all parameters for control mortar. The control mortar is considered for the durability reference.

4. Conclusions

Four sets of mortars differing in the main mortars components as sand type and sand grading particle size were evaluated in terms of structural changes, mechanical strength and durability, when CVS sand were added as replacement of standard sand (100 wt.%). Both mortar sets were prepared with fixed water/cement: w/c = 0.5 mass ratio. It was confirmed that:

- CVS grading particle size cause microstructural changes in mortar matrixes.
- Fine CVS, can exhibit pozzolanic activity according of chemical and mineralogy composition obtain by XRF and XRD analysis.

Based on the results of this experimental investigation, the following conclusions can be drawn:

1. Mortars containing standard sand performed better than those prepared with CVS, but the higher content of fine CVS sand (grading 0.08/0.50) in CVS sand (up to 60%) seems to ameliorate mortar mechanical and durability performance.
2. Mortar unit weights showed that semi-lightweight or lightweight mortar can be produced when at least 7% of 1.60/2.00 CSV sand grading and least 26% of 1.00/1.60 CSV sand grading are used. Therefore, only a mortar strength class of 25 MPa is achievable by adding CVS sand by-products for producing lightweight mortars; nevertheless, the addition of fine CVS sand (grading 0.08/0.50) proved to be effective by allowing to reach a mortar strength class of 60 MPa.
3. The addition of CVS sand seems to show negative influence on lowering both resistance to water vapour permeability and carbonation, which resulted until 60% lower in comparison of control mortar; on the other hand, water absorption resulted increased.

Acknowledgments

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