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Research Article

Bricks and Concrete Wastes as Coarse and Fine Aggregates in Sustainable Mortars

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The total substitution by volume of natural coarse calcareous aggregate by coarse recycled brick aggregate (RBA) and coarse recycled concrete aggregate (RCA) has been investigated to produce more sustainable and environment-friendly mortars. Aggregates were also partially substituted by their fines at 12.5% by volume. Mortars have been tested in terms of mechanical, microstructural, and durability properties. Results show that it is feasible to replace a natural calcareous aggregate entirely by recycled aggregates. In particular, the obtained mortars, even if more porous and more prone to the water capillary absorption than that manufactured with natural aggregates, result in less stiffness and thus are less subjected to crack formation, more permeable to water vapour, and less susceptible to sulphate attack.

1. Introduction

The construction sector spends 40% of the planet's energy [1]. At the world level, civil works and building construction consume 60% of raw materials extracted from the lithosphere. Of this volume, building represents 24% of these global extractions [2]. The production of concretes and mortars causes serious environmental pollution and huge consumption of nonrenewable resources such as natural calcareous aggregates.

Meanwhile, the total amount of construction and demolition waste (C&DW) is increasing year by year representing the highest amount of waste generated in Europe: in particular, in 2014, the construction sector produced 871 million tons of C&DW, 33.5% of the total waste generated [3]. Wood, plastic, cardboard, metal, and wires from C&DW can provide a substantial source of raw materials [4].

The long-term goal is to turn Europe into a recycling society, reusing waste whenever possible and minimizing the extraction of natural resources: current European policies aim at reducing the impact of building waste on the environment and on health and improving the efficiency of available resources. Furthermore, from the economic point of view, the recycling of C&DW is considered a cost-effective alternative since, due to the taxes of landfills and/or transport, the cost of waste disposal is higher than the costs of sorting, reusing, and recycling. In the Waste Framework Directive 2008/98/EC, according to which the target of 70% recycling should be achieved by 2020, the recycling of C&DW has been recognized by the European Commission (EC) as an important step towards the sustainability of the construction sector.

Although the construction sector is the largest waste stream in Europe, recycling percentages vary significantly among member states from 90% (Germany, Netherlands) down to 5% (Greece, Cyprus) [5] and the comprehensive utilization rate of construction solid waste is very low. Therefore, it is necessary to solve the problem of C&DW recycling as soon as possible and to develop new green building materials.

Unbound stone, crushed concrete, and crushed bricks are the three main constituents of C&DW [6]. Within these three categories, concrete waste and ceramic materials are the most abundant components and their use as aggregates in the manufacture of concretes/mortars has been addressed in several papers, most of them regarding recycled brick aggregates (RBAs) and recycled concrete aggregates (RCAs) [3].

Depending on their origin, there are two different categories of RBA: the waterproof and semipermeable materials that have undergone vitrification, such as ceramic stoneware and ceramic tiles, with high hardness and low water absorption (5–7%) and the porous ceramic materials, such as fired clay, as bricks, and roof tiles, with low hardness and high water absorption (12–18%). The EC Decision 2000/532/EC defined this waste on the European List of Waste (ELW) as "10.12.08 ceramic, brick, roof tile and construction materials waste (fired)". There is a large availability of this material: in the production of European ceramic industry, 3–7% is represented by waste, which is very homogeneous, free from unwanted materials such as poor quality mortar or plaster [7].

Focusing on porous ceramic materials, in recent years, many scholars have carried out research on waste clay brick [8] as coarse and fine aggregates. Literature agrees that the coarse recycled aggregates from crushed bricks generally increase the porosity of concrete, resulting in the reduction of mechanical strength and durability; for structural purposes, caution is mainly advised when exceeding 30% volume of RBA [3, 9, 10]. de Brito et al. found that, for nonstructural concrete ($R_c < 25\,\mathrm{MPa}$), the higher the percentage of coarse RBA replaced the natural coarse aggregate, the higher the loss in the compressive strength, following a linear correlation. The total substitution implies 45% lower compressive strength compared to the reference concrete mix [11].

The incorporation of fine RBA increases the water requirement of concrete during the mix because of its high water absorption [12]. Moreover, with the full replacement of conventional fine fractions by fine RBA, the loss of resistance in a middle strength concrete (40 MPa) is evaluated about 30% [13]. However, the interfacial transition zone (ITZ) between RBA and cement paste appears relatively compact by morphological observations, thanks to the rough surface of the recycled aggregate and its pozzolanic activity [8]. The pozzolanic effect can even improve the mechanical strength as supposed also by Viera et al. [12] and Colangelo and Cioffi [14].

By contrast, the higher the amount of fine RBA, the higher the shrinkage, probably due to the lower modulus of elasticity of RBA than normal aggregate. The magnitude of this phenomenon could be greater than expected because of the pozzolanic activity, leading to greater self-desiccation resulting in higher autogenous shrinkage strain [12].

Also RCA can be classified into coarse and fine aggregates based upon their particle size. RCA are composed of natural aggregates, hardened cement paste, and other impurities. The different components imply a significant higher heterogeneity than natural aggregate and a nonhomogeneous distribution of these impurities in the different granular classes [15].

The performances of RCA is mainly influenced by the adhered mortar of RCA: the higher the amount of adhered mortar, the higher the porosity and water absorption, implying lower durable mortars and concretes prepared with RCA than those prepared with normal aggregate [16, 17].

The use of coarse RCA can lead to a reduction of up to 40% in compressive strength [18], 24% in split tensile strength, and 45% in modulus of elasticity [19] with higher long-term deformations [19].

Fine RCA has higher quantity of adhered cement paste content than coarse RCA with a consequent increase in water absorption and decrease in density [15]. These negative effects make their utilization very restricted or even banned [20]. These limitations bring to a relative limited literature in using fine RCA [21], whereas there are many studies on the substitution of cement by powders produced from wastes or by-products. The total replacement of fine RCA to the normal aggregate produces a decrease in compressive, splitting tensile, and flexural strengths of about 14, 6, and 23%, respectively. The microstructural investigation of fine RCA concrete reveals more unhydrated cement particles and less dense calcium silicate hydrate gel than in normal fine aggregate concrete [22, 23].

Assuming that there will be a reduction in the quality of the concrete, it is necessary to assess how far this reduction takes place and to ascertain the extent to which recycled aggregates can be incorporated for each specific application [3]. It has been noticed that there is no systematic study on the literature about the comparison of RBA and RCA. Also, the differences induced by using coarse or fine aggregates are still little investigated. Khatib [24] compared the behavior of concrete containing RBA and RCA and observed 30% and 10% lower resistance in case of total content of fine RCA or fine RBA, respectively. A significant loss in mechanical strength of mortars prepared only with RBA and RCA was observed also in [25]. Moreover, up to 50% RBA substitution, no differences have been detected. Losses of strength were found also by Eduardo et al. [26], with the exception in case of fine RBA, where even a slight increase in resistance is observed.

Plaster mortars give to building structures not only decorative effects but also protection against environmental aggressive agents. The ability of mortars to protect building structures is strongly influenced by their ability to transport aggressive agents through porosity. The introduction of fines in the formulation of mortars, thanks to a refinement of microstructure, leads to an increase in mechanical performance and durability. Natural or artificial inorganic fines can improve the physical, chemical, and mechanical properties of cement-based materials, such as workability or water retention. They can be inert or have slightly hydraulic, latent hydraulic, or pozzolanic properties.

In this paper, in order to decrease the environmental impact and the costs of plaster mortars, RBA and RCA coarse aggregates have been introduced in a mortar formulation. Moreover, to investigate the possible improvement of mortar performances by the addition of fines, fine RBA and fine RCA were also added in some mixes to replace the 12.5% by volume of coarse RBA and coarse RCA, respectively. These mortars have been compared with those manufactured with coarse and fine commercial calcareous aggregates in terms of mechanical, microstructural, and durability properties.

2. Materials and Methods

2.1. Characterization of Materials. A Portland cement belonging to class II/A-LL 32.5R with a density of 3.1 g/cm^3 was used as binder.

Coarse calcareous aggregate with a density of 2.65 g/cm^3 was used as reference aggregate (S1). As ceramic wastes, RBA obtained by crushing red clay bricks and RCA coming from a local plant that treats demolition rubble were used. The former (S2) has a density of 1.80 g/cm^3, and the latter (S3) of 2.20 g/cm^3. The three types of aggregate have a grain size lower than 5 mm.

Additionally, also three types of fine aggregates have been used: a calcareous aggregate (F1) with a maximum grain size of 300 μm, a fine RBA (F2) with a maximum diameter of 2 mm, and a fine RCA (F3) with a maximum diameter of 1 mm.

In Figure 1, the granulometric distributions of coarse and fine aggregates are reported, and the visual aspects are shown in Figure 2.

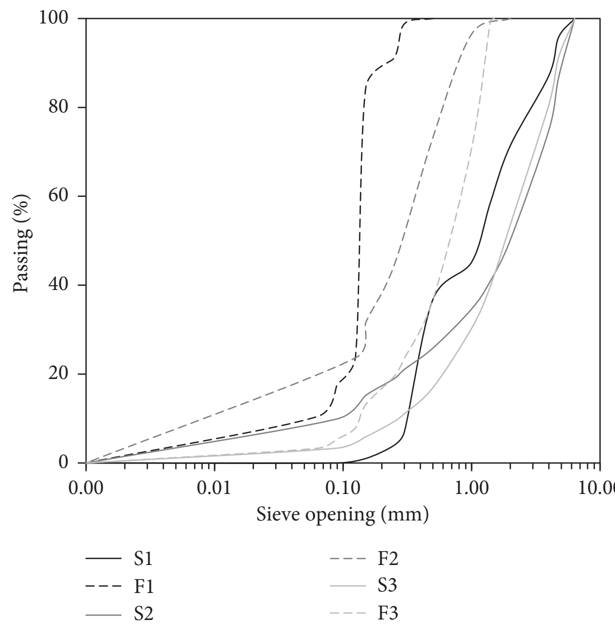

Figure 1: granulometric distribution of coarse and fine aggregates.

2.2. Preparation of Mortars. Mortars were manufactured with an aggregate/binder ratio equal to 4 by volume. The reference mortar was prepared with coarse calcareous aggregate (S1) as aggregate. S1 was substituted with the coarse RBA (S2) and the coarse RCA (S3) at 100% by volume. Additionally, each type of coarse aggregate was partially replaced by a fine aggregate of the same type in an amount equal to 12.5% in volume. Mortars were manufactured in order to reach the same workability, with a slump value between 120 and 130 mm, which corresponds to a stiff consistency (<140 mm, according to UNI EN 1015–3:2007).

The mix proportion of mortars is reported in Table 1.

Mortars were poured in moulds with different geometries depending on the test. Specimens were cured at $T = 20^\circ$C and RH = 90 ± 5% for the first week and then at RH = 50 ± 5% until testing, if not differently specified.

2.3. Characterization of Mortars. The mechanical properties of mortars were investigated after 28 days of curing by means of a "Galdabini" hydraulic press with a precision of 1% at a loading speed of 0.3 (N·mm^2)/s according to UNI EN 1015–11 : 2007 [27]. Compressive strength (R_c) was evaluated on three cubic specimens ($4 \times 4 \times 4$ cm^3), and the average value is reported.

For each mixture, also the dynamic modulus of elasticity (E_d) was calculated after 28 days of curing. Three prismatic specimens of $4 \times 4 \times 16$ cm^3 dimensions were used according to UNI EN 12504–4:2005 [28], and the average result is reported. The methodology used is reported by authors in other studies [29–31]. The equipment used was a portable ultrasonic nondestructive digital indicator tester (PUNDIT), which measures the time value of the ultrasonic pulse through the specimen. Knowing the specimen length (16 cm), the velocity of the ultrasonic pulse can be calculated. The following equation gives the formula for calculating E_d:

$$E_d = \frac{\nu^2 \rho [\, 1 + \gamma_d) \;\, 1 - 2\gamma_d)]}{1 - \gamma_d)}, \qquad (1)$$

where ν is the velocity of the ultrasonic pulse (m/s) and γ_d is Poisson's modulus (equal to 0.2).

The pore structure of mortars was investigated by mercury intrusion porosimetry (MIP) analysis with a Thermo Fisher 240 Pascal, operating between 0.1 MPa and 200 MPa pressures. For each composition, three small fragments were tested after 28 days of curing, and the average results are reported.

The susceptibility to cracking was visually evaluated by an empirical method reported by other authors [32, 33]. The test was carried out on three specimens and consisted on applying a mortar layer of 2 cm to a ceramic brick, which is observed to detect possible cracks at set periods of time. Results at 45 days of curing are reported.

A good water vapour permeability is positive for mortars, since both the proper drying of the internal water and the elimination of water vapour that occurs within buildings can be ensured [34, 35]. Water vapour permeability measurements were carried out on three cylindrical specimens (a diameter of 14 cm and height of 3 cm) after 28 days of curing ($T = 20^\circ$C and RH = 90 ± 5% for the first week and then at RH = 50 ± 5%). The test was performed at RH = 50 ± 5% and $T = 20 \pm 1^\circ$C according to UNI EN 1015–19 : 2007 [36]. The mass loss due to water evaporation through the specimen was measured in time, and the results were expressed in terms of the water vapour diffusion resistance factor (μ).

Water capillary absorption is essential to determine the durability of construction materials, since many aggressive ions, like Cl^- or SO_4^{2-}, can penetrate through water [37–39].

(a) (b) (c) (d) (e) (f)

Figure 2: visual aspect of coarse and fine aggregates: (a) S1; (b) S2; (c) S3; (d) F1; (e) F2; (f) F3.

Table 1: Mix proportions (kg/m^3), water to binder (w/b) ratio, and workability (mm) of mortars.

ID sample	Cement	Coarse calcareous aggregate, S1	Coarse RBA, S2	Coarse RCA, S3	Fine calcareous aggregate, F1	Fine RBA, F2	Fine RCA, F3	Water	w/b	Slump
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	—	mm
M/S1	452	1595	—	—	—	—	—	222	0.49	124
M/S1F1	452	1395	—	—	193	—	—	228	0.50	123
M/S2	452	—	1050	—	—	—	—	236	0.52	124
M/S2F2	452	—	918	—	—	131	—	244	0.54	126
M/S3	452	—	—	1283	—	—	—	213	0.47	122
M/S3F3	452	—	—	1123	—	—	161	218	0.48	127

The water absorbed per unit area (Q_i) was measured according to UNI EN 15801 : 2010 [40]. For each mortar type after 28 days of curing, three cubic specimens ($4 \times 4 \times 4\,cm^3$) were dried at $T = 60 \pm 2^{\circ}C$ until a constant weight was reached and then tested, and the average values obtained were reported.

To determine the durability of mortars in aggressive solutions, after 28 days of curing prismatic specimens ($4 \times 4 \times 16\,cm^3$) were partially immersed (4 cm) in water (one specimen as reference) and in 14 wt.% Na_2SO_4 solution (two specimens) for a period of 45 days. The level of the solution was kept constant by adding only water for replacing the evaporated amount. At first, specimens were dried at $T = 60 \pm 2^{\circ}C$ until constant weight was reached, and the resistance to sulphate attack was then visually investigated by evaluating the formation of possible cracks and efflorescence.

3. Results and Discussion

The total porosity and the pore distribution of mortars are reported in Figure 3. The reference mortar M/S1 has a V_p value of 19%. The substitution by coarse recycled ceramic aggregates always leads to an increase of total porosity. In particular, the mortar manufactured with coarse RCA (M/S3) shows a total porosity of 22%, whereas when coarse

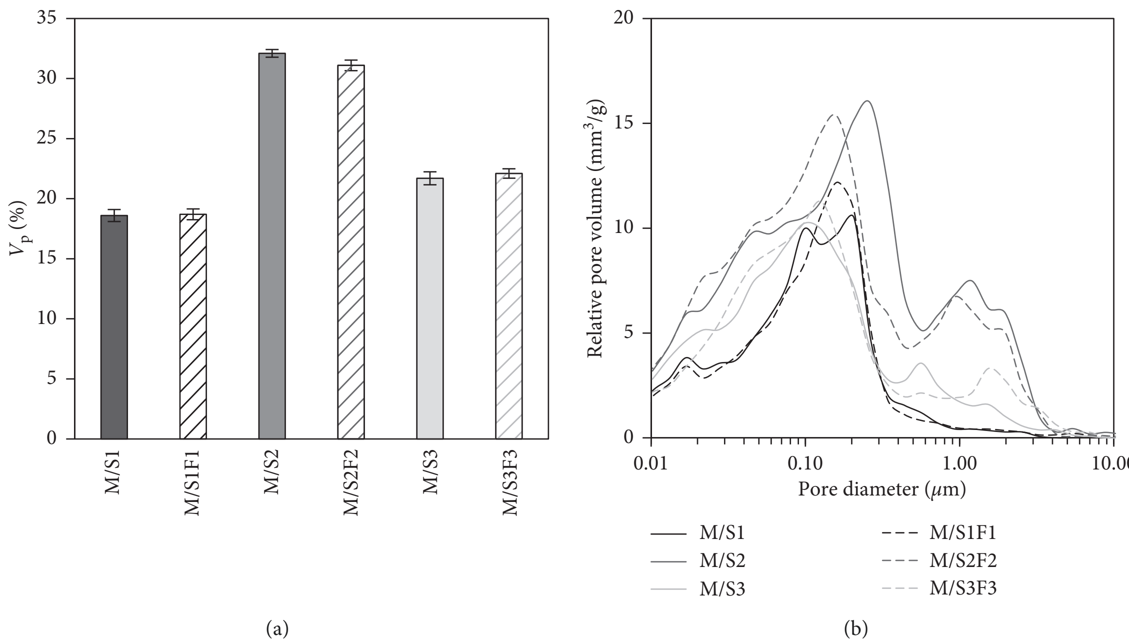

Figure 3: Total porosity (V_p) (a) and pore distribution (b) of mortars after 28 days of curing.

RBA is used (M/S2), V_p reaches a value of 32%, which is 73% higher than the reference mortar. The increase in the total porosity of mortars is due to the use of recycled aggregates much more porous than the calcareous aggregate of the reference mortar M/S1. In fact in literature, RBA has a percentage of the porosity value ranging from 38 to 59% [13] and RCA from 10 to 15% [41, 42].

On the contrary, the partial replacement of each aggregate with its fine fraction does not change the total porosity of mortars regardless of the type of fine fraction used.

Concerning the pore distribution, all mortars show a polymodal curve. The reference mortar M/S1 has two peaks corresponding to the most frequent diameters at 0.08 μm and 0.10 μm. The substitution of coarse calcareous aggregate with both coarse recycled aggregates S2 and S3 increase the number of large pores; in fact, the curves show the presence of pores larger than 1.00 μm and 0.70 μm in M/S2 and M/S3 mortars, respectively. This effect is again related to the higher porosity of S2 and S3 than S1.

The partial substitution of coarse with fine aggregates modifies the pores distribution of mortars. In particular, when F1 is used the most frequent diameter becomes equal to 0.15 μm, whereas for the other two fine aggregates F2 and F3, a shift towards lower and larger diameters is visible, respectively.

The compressive strength after 28 days of curing is reported in Figure 4. The reference mortar registers a compressive strength of 35 MPa, which allows its classification as structural mortar ($R_c \geq 25$ MPa, according to UNI EN 1504–3:2006 [43]). The total substitution of coarse calcareous aggregate (S1) with coarse RBA (S2) and RCA (S3) always worsen the mechanical properties of the hardened mortars. In fact, M/S2 and M/S3 show a R_c value of 31% and 23% lower than that of M/S1 mortar, respectively. The lowering of compressive strength when coarse calcareous aggregate is totally substituted by coarse RBA has been already reported by other authors and related to the increase of the mortar total porosity (Figure 3) owing to the high porosity of RBA [8, 9] and the increased *w*/*b* ratio [13, 44], which moves from 0.49 to 0.52 in the present campaign. On the contrary, the use of coarse RCA causes a reduction of mechanical performance not related to the *w*/*b* ratio, which is higher in M/S3 mortar than in M/S1. Also in this case, the loss of compressive strength is caused by the higher porosity of recycled concrete aggregates [20, 45] than natural calcareous aggregate owing to the presence of adhered mortar on their surface, which causes an increase of the total porosity of mortar (Figure 3) Also, the milling process necessary to obtain recycled aggregates could have introduced microcracks negatively affecting the mechanical performance [46].

The partial substitution of S1 with the fine calcareous aggregate F1 lowers the compressive strength only by 5%, moving from 35 to 33 MPa. This was found also in previous studies where authors found a decrease in compressive strength from 39.6 to 38.7 MPa in concretes with and without limestone addition. The lowering in compressive strength was detected in concrete with limestone filler due to the creation of more nucleation sites that produce smaller portlandite crystals [47].

On the contrary, the use of F2 and F3 partially substituted to S2 and S3, respectively, contributes to an increase in the R_c value. Referring to M/S3F3, the gain is equal to 7%, whereas for M/S2F2, it becomes even 19%. The partial replacement of S3 with F3 enhances the mechanical strength of mortar because the increased amount of fine RCA particles plays an important behaviour on the

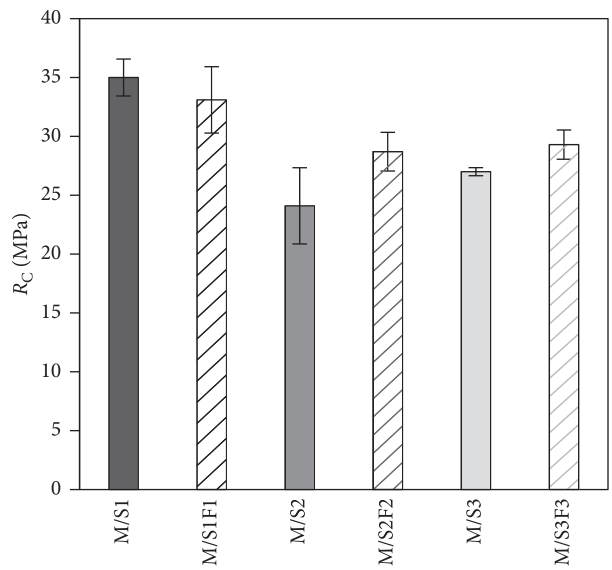

Figure 4: Compressive strength (R_c) of mortars after 28 days of curing.

formation of the ITZ [25]. It is reported that RCA absorbs more water during the mixing process, which is gradually released in time contributing to a continuous hydration mechanism of the cement paste that creates an ITZ with good mechanical properties [48]. Furthermore, a combination of an enhanced physical interlocking mechanism in the ITZ between the recycled aggregate and new cement paste has been detected [49]. For this reason, the larger the surface area of aggregates particles, the larger the ITZ and thus the mechanical strength. Also, recycled aggregates have higher SiO_2 content than calcareous one: it has been already shown that a higher presence of the silicon produces a more homogeneous microstructure in cementitious paste by balancing the Ca/Si molar ratio in the interfacial transition zone relative to that in the bulk paste [50]. Conversely, the partial substitution of coarse RBA with its fine fraction reduces the weak volume of the aggregate: the larger the particle size [8], the bigger the weak volume, related to the microscopic porous structure of the RBA. Moreover, the partial substitution of S2 with F2 enhances the compressive strength of the mortar because of the pozzolanic effect [7, 32] of brick particles diffused within the mortar which contributes to form a compact and dense ITZ with good mechanical properties [8].

The substitution of coarse calcareous aggregate with RCA does not imply a change in mortar strength class (structural R3 strength class, according to UNI EN 1504–3: 2006 [43]). Only the total substitution of S1 with coarse RBA changes the mortar strength class to the R2 nonstructural strength class ($R_c \geq 15$ MPa, according to UNI EN 1504–3: 2006 [43]). However, the partial substitution of S2 with F2 allows to reach again the R3 structural strength class.

The dynamic modulus of elasticity of mortars after 28 days of curing is reported in Figure 5. The reference mortar M/S1 shows an E_d value of 37 GPa. The use of coarse recycled ceramic aggregates instead of natural calcareous aggregate always decreases the modulus of elasticity of mortars, which becomes 18 GPa in case of coarse RBA and 22 GPa in case of coarse RCA, respectively, 51% and 32% lower than the reference mortar. The decrease of the modulus is owed to the reduced density of mortars (Figure 5), caused by the increased total porosity (Figure 3), which was equal to 2437 kg/m^3 for M/S1, whereas 1891 and 2175 kg/m^3 for M/S2 and M/S3, respectively. The use of an aggregate with a lower density and thus a higher porosity than the natural calcareous aggregate is the reason for the decrease of the E_d value. A mortar with a lower modulus of elasticity, thus a lower stiffness, means also a lower probability of cracking caused by tensile (or shear) stresses or expansive reactions because of lower induced tensions at a certain deformation [29, 30]. The addition of recycled fine aggregates, as partial substitution of the coarse aggregate, has slightly modified the values of E_d. In particular, when F1 and F3 are added, the modulus decreases from 37 to 33 GPa and from 25 to 23 GPa, respectively, whereas when F2 is used the modulus moves from 18 to 21 GPa. Again, the modification of stiffness of mortars is related to the modification of density, which decreases in case of F1 and F3 additions (2353 and 2082 kg/m^3, respectively) and increases in case of F2 compared to the mortars with only aggregates (1966 kg/m^3). In general, E_d was found higher in calcareous aggregate mortars than in recycled aggregate mortars because both RBA and RCA are more prone to deformation than natural aggregates. In fact, bricks have lower stiffness than natural aggregate-based concrete [9]. Also, RCA has lower stiffness, in this case mainly due to cement matrix, producing a concrete with a low modulus of elasticity than that produced with natural aggregates [26].

The susceptibility to cracking of mortars applied on a brick substrate is reported in Figure 6. This property is related to drying shrinkage, which depends on many factors, including open porosity, which facilitates water evaporation and pore distribution; the finer the capillary network, the higher the capillary stress that generates shrinkage as well as

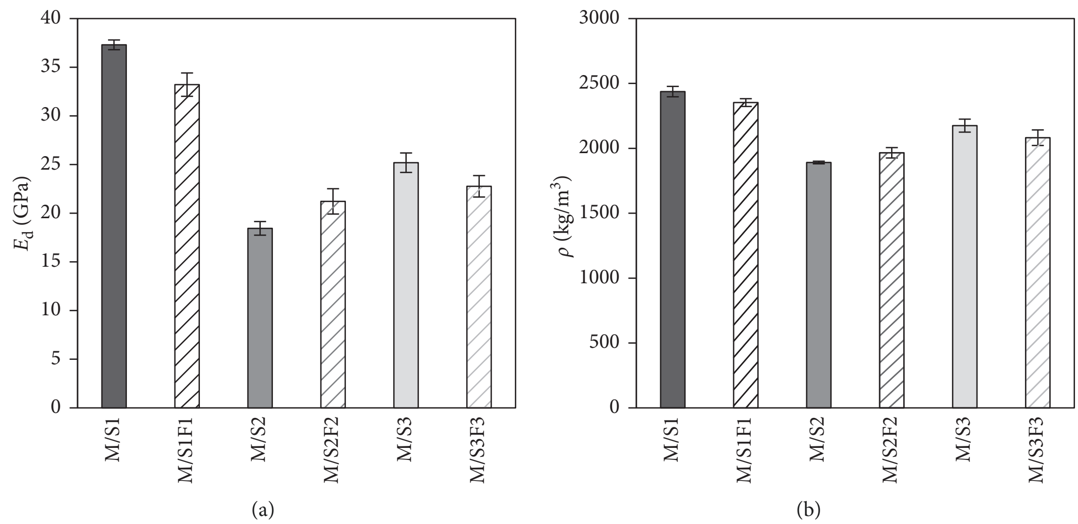

Figure 5: Dynamic modulus of elasticity (E_d) (a) and hardened density of mortars (b) after 28 days of curing.

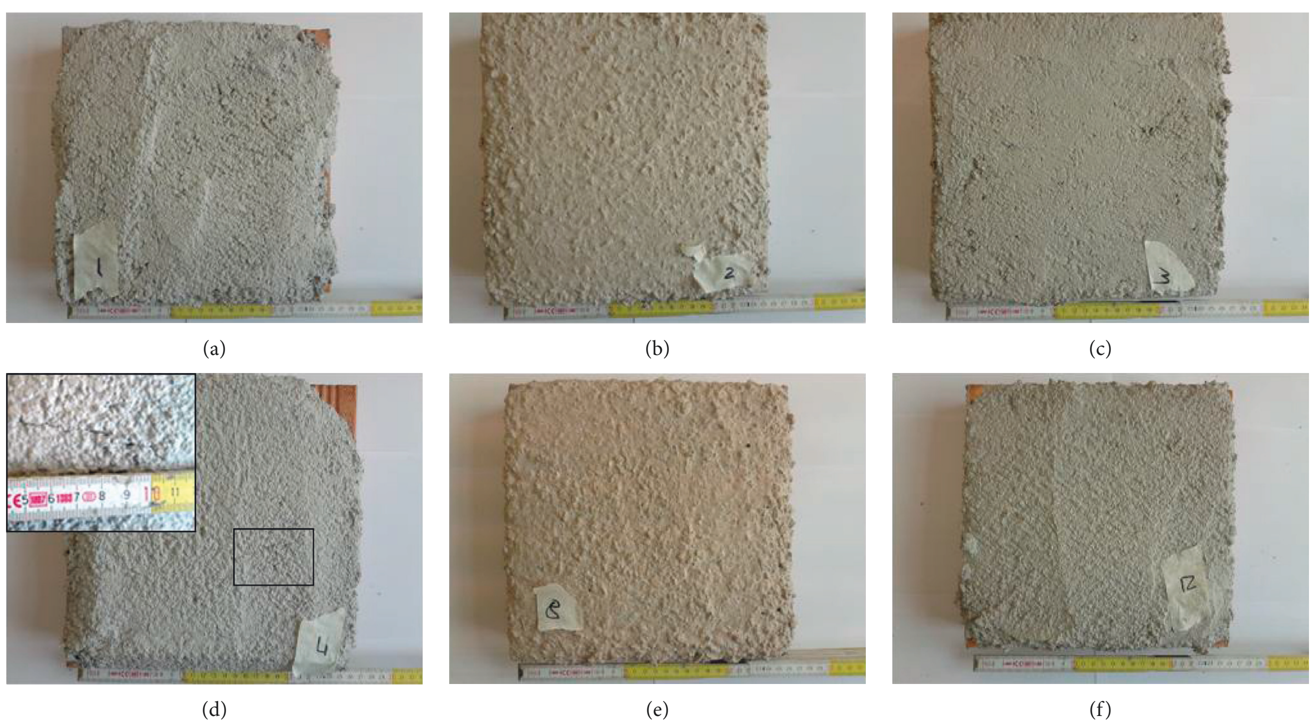

Figure 6: Susceptibility to cracking of mortars on bricks after 45 days of curing: (a) M/S1; (b) M/S2; (c) M/S3; (d) M/S1F1; (e) M/S2F2; (f) M/S3F3.

modulus of elasticity of the mortar; and the lower the stiffness, the higher the shrinkage generated in the presence of the same stress [29, 30]. Figure 6 shows that all mortars manufactured with coarse aggregates, regardless if natural or recycled, are not subjected to crack formation. The only mortar showing crack development is M/S1F1 (zoom in Figure 6(d)) was manufactured with a partial substitution of calcareous coarse aggregate with its fine aggregate. The other two mortars M/S2F2 and M/S3F3 do not show any modification instead. The crack formation in M/S1F1 is due to its modulus of elasticity (33 GPa), much higher than in all the other mortars manufactured with recycled aggregates. If compared to M/S1 with a comparable high E_d value, this behaviour is due to the more water loss during the curing period (10% than 5%, results are not reported for brevity) probably due to the presence of larger pores (Figure 3).

The water vapour permeability of mortars is reported in Figure 7. The M/S1 reference mortar show a μ value of 22. When coarse RBA is used in place of natural calcareous aggregate the μ value becomes 12, 46% more permeable to water vapour than the reference. Also, the use of coarse RCA increases the permeability of mortar of 32% compared to

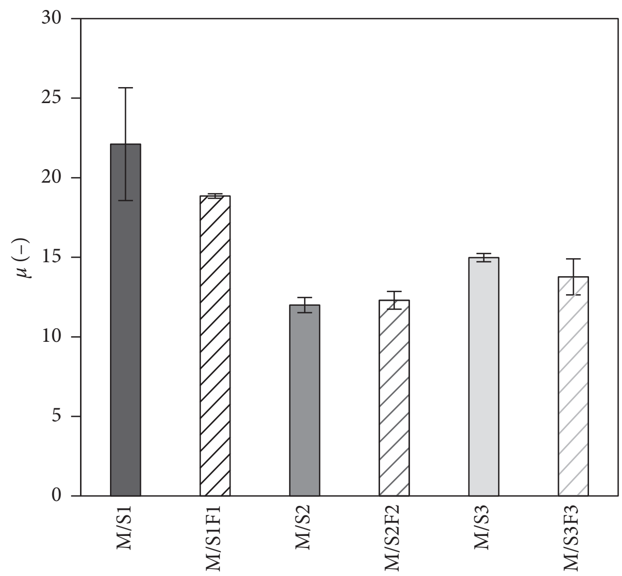

Figure 7: Water vapour diffusion resistance factor (μ) of mortars after 28 days of curing.

M/S1. This result is obviously related to the total porosity of mortars (Figure 3): the higher the total porosity of mortar (as detected in those manufactured with recycled aggregate), the higher the permeability to water vapour [35, 51].

The partial replacement of natural coarse aggregates with natural fine aggregates increases the water vapour permeability of mortar of 18%. This effect is not related to the total porosity of mortars, but to the pore dimensions, in fact, the use of F1 shifts slightly the pore dimension to larger diameters: the larger the pore dimension, the higher the water vapour permeability [52]. The use of F2 aggregate instead does not modify the behaviour of mortar. Even if the use of F2 shifts the pore dimensions to smaller diameters by maintaining similar porosity, the V_p value is so elevated that the behaviour to water vapour does not change. As for M/S1F1, the use of fine RCA slightly increases the water vapour permeability of M/S3F3 by 6% compared to M/S3 because also in this case, the use of fine aggregate increases the number of pores with large diameters.

The water absorbed per unit area (Q_i) of mortars is reported in Figure 8. Results show that the reference mortar M/S1 absorbs the lowest amount of water. When coarse calcareous aggregate is replaced by coarse RCA (M/S3), the mortar absorbs more water, and the highest amount of water absorbed by the capillary action is detected in case of coarse RBA mortar (M/S2). Mortars manufactured with recycled aggregates have a higher capillary absorption capacity than reference mortars, as already shown by other authors [53]. This result is due to the increased total porosity of mortar (Figure 3) [3, 10]; in fact, the higher the porosity, the higher the total water absorbed in time [54, 55]. The partial substitution of S1 with F1 increases the amount of water penetrated in the mortar by the capillary action compared to the reference. The partial replacement of recycled coarse aggregates by their fines instead causes a different result; in fact when F2 is added to the mortar, the capillary suction decreases, whereas when S3 is substituted by F3, the mortar absorbs more water. This result is related to the different pore microstructure of mortars: M/S2F2 is less prone to water absorption than M/S2 because of the lower total porosity and the smaller pore diameters; on the contrary, M/S3F3 is more inclined to the water absorption than M/S3 because its pore size distribution is broader (Figure 3) [56].

Figure 9 shows images of mortar specimens just after the extraction from the containers after 45 days of semi-immersion. The mortar M/S1 shows evident efflorescence formation due to the crystallization of sodium sulphate salt (Figure 9(a)). In the reference specimen (immersed in water), efflorescence is not visible.

The use of RCA and RBA decreases the tendency of efflorescence formation if compared to the mortar prepared with normal calcareous aggregate (Figures 9(b), 9(c), 9(e), and 9(f)). The partial substitution of coarse with fine aggregates in all types of mortar seems to lower the efflorescence formation (Figures 9(d)–9(f)) probably due to a refinement of microstructure with more blocked pores. However, the crystallization of sulphate salts does not lead to disruptive phenomena in any of the mortars tested. It is possible to imagine that sulphate salts cannot reach the extern of the specimens and crystallize inside the mortar manufactured with recycled aggregates. In fact, the presence of macropores (with a dimension higher than 1 μm) in the microstructure of mortars [29] permits to drain better the moisture from the material by also ensuring the salt crystallization inside the specimens and reducing the appearance of efflorescence. In M/S1 mortar, the sulphate crystallization takes place externally because of the reduced pore dimension (Figure 3).

4. Conclusions

In order to manufacture more sustainable mortars, natural calcareous coarse aggregate has been replaced by two types of waste aggregates (coarse recycled brick aggregate, RBA,

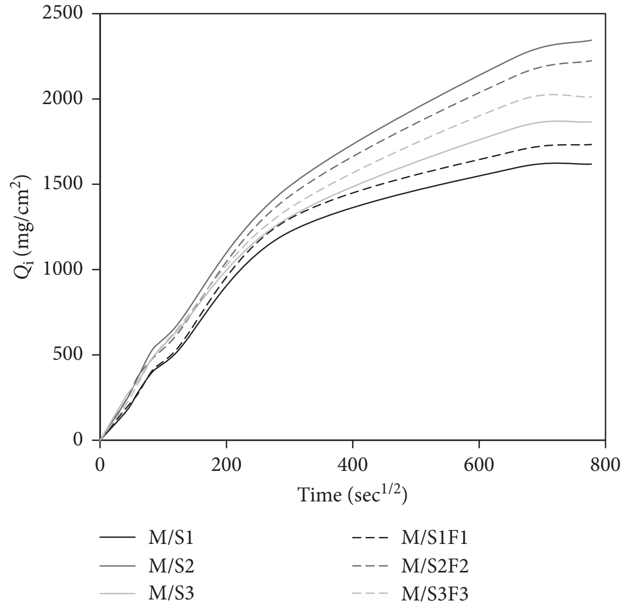

Figure 8: Water absorbed per unit area (Q_i) of mortars after 28 days of curing.

Figure 9: Visual observation of mortars just after the extraction from the semiimmersion test. In each picture, the specimen on the right was exposed in water, as a reference. (a) M/S1; (b) M/S2; (c) M/S3; (d) M/S1F1; (e) M/S2F2; (f) M/S3F3.

and coarse recycled concrete aggregate, RCA) by 100% of volume. Moreover, the partial replacement (12.5% by volume) of coarse with fine aggregates of the same type has been investigated.

Results show that it is feasible to replace a natural calcareous aggregate entirely by recycled aggregates coming from waste bricks and waste concrete in order to contribute in decreasing the depletion of natural quarry and the disposal of waste materials. In particular, using recycled concrete aggregates, the mortars obtained can be classified as structural mortars ($R_c \geq 25$ MPa, according to EN 1504–3: 2006 [43]), and also coarse recycled brick aggregates are replaced by fine recycled brick aggregates at 12.5% in volume. The obtained mortars, besides their higher sustainability, even if more porous and more prone to the water capillary absorption than the reference, result in less stiffness and thus are less subjected to crack formation, more permeable to water vapour, and less susceptible to salts crystallization.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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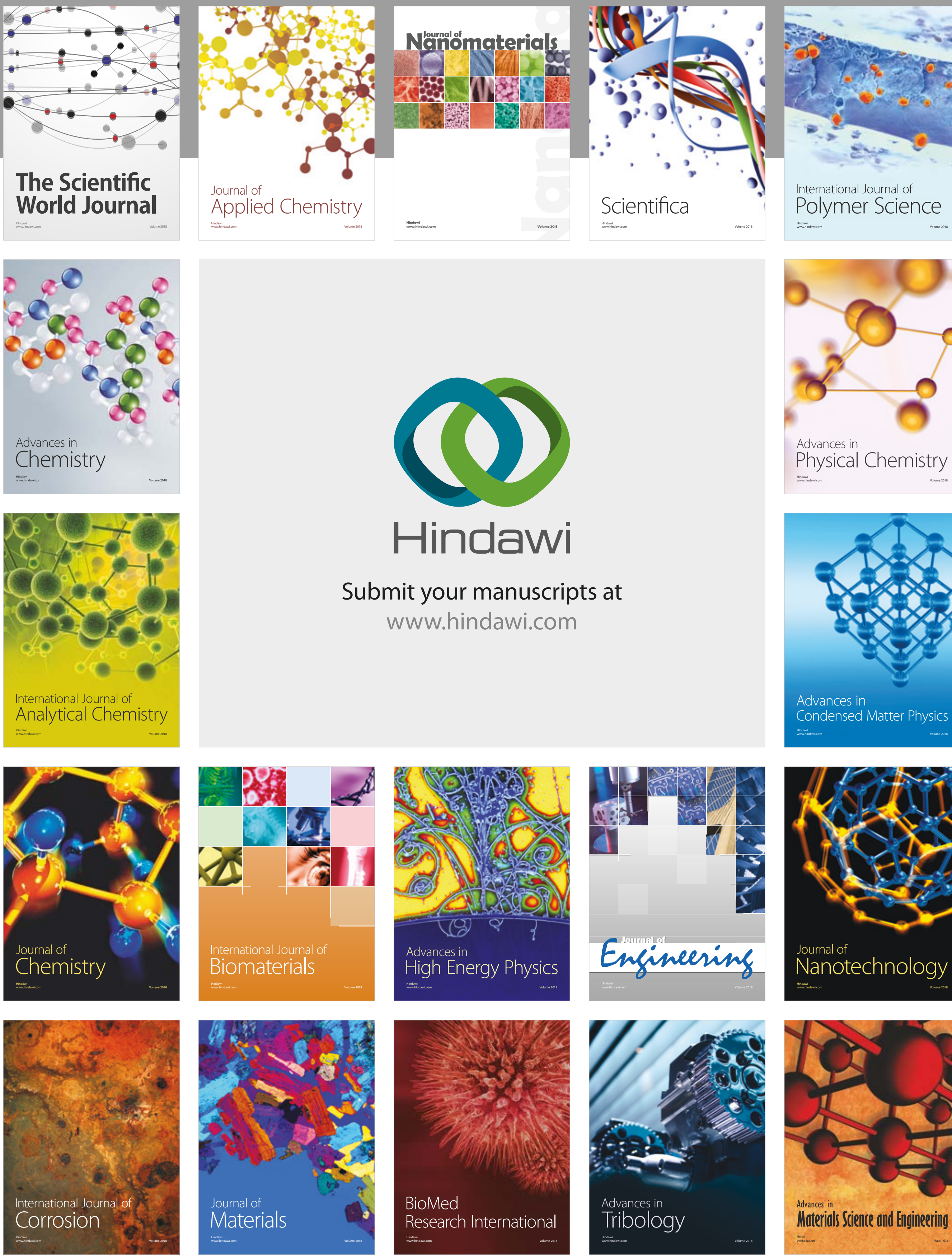
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