Chapter

The Role of Sand in Mortar's Properties

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Abstract

Mortars are diachronic composite materials used in masonry construction to serve multiple roles. Their durability and esthetic harmonization in constructions of the different eras were the reasons why numerous research works have been realized over recent decades. Each time, the role of the mortars' components revealed significant pieces of information on the technology used. Despite the indisputable role of the binders on the mortar's quality, aggregates of different characteristics had a significant role in the behavior of mortars. The addition of aggregates to a binding system in mortars technology has proved to confer technical advantages as they contribute to volume stability, durability, and structural performance. Apart from the different types of aggregates, as their mineralogy and origin are concerned, the volume content in the mixture, the maximum size, and their gradation influences the structure of a binder—aggregate mixture and the performance of mortars overall. In the present article, the diachronic presence of mortars is presented. The role of aggregates is emphasized to understand their impact on the longevity and durability of the mortars.

Keywords: sand, mortars, composites, mechanical-physical properties

1. Introduction

Mortars are among the first building materials used in constructions, even from prehistoric times. Their study reveals a great source of information regarding the evolution of their technological characteristics and application techniques, the availability and exploitation of raw materials, as well as the wider socioeconomic aspects of each era. In any case, it seems that ancient masons were fully aware of the significant role of mortars in constructions and could exploit the raw materials that were available along with the application techniques [1]. In particular, the role of the quality of aggregates on the properties of old mortars has been known since, at least, Roman times. Natural sands of different origins and nature (river, quarry, sea) and crushed bricks combined with binders which were usually lime-based, were used for many centuries (**Figure 1**). These mortars were of different types and served as bedding, renders or plasters, floors, and mosaics' substates forming masterpieces of the world cultural heritage [2].

It is evident from the classic authors that the Romans preferred sharp sands to rounded sands, as they knew that these would produce stronger mortars; for example,

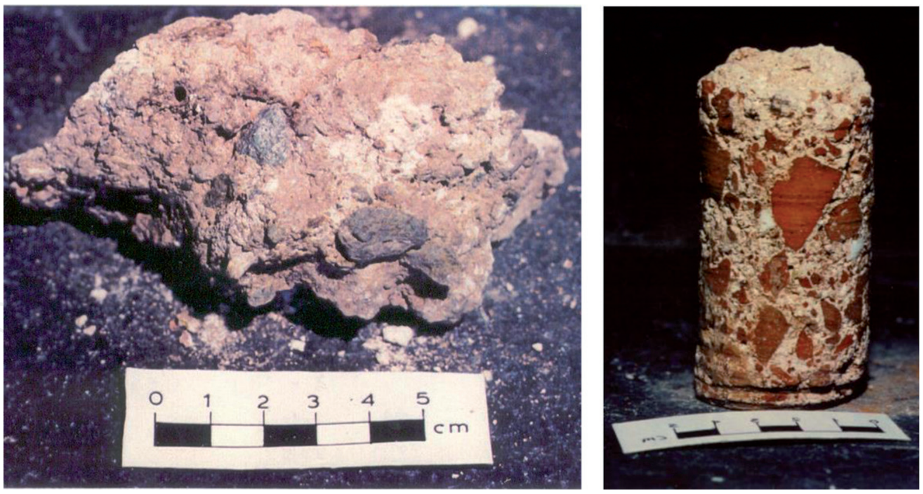

Figure 1.
Coarse aggregates of natural origin in bedding mortars of the fourth century AD (left) and crushed brick as aggregates in a bedding mortar of the sixth century AD (right).

Palladius, Pliny, and Vitruvius refer to recipes and guidelines for criteria that can be used for sand selection in the mixtures [3–5]. Among the requirements they mention, the origin, the shape, and the cleanness of the sand are the ones that prevail. They noticed the direct relation of the sand quality to the setting and strength of the mortars, and they gave precise directions to avoid, for example, sea sand due to salt contamination that can accelerate the weathering of the mortar. Manufacturing mortar was the first milestone in building history which has been continuously evolved up to the modern concrete. The materials used for mortar manufacture since antiquity were binders (clay, lime, pozzolan, brick/tile dust), aggregates (sand, gravel, crushed brick, pumice), and materials that were less frequently found and used (such as chopped straw, egg whites, reeds, blood, palm fibers, milk, and goat hair.). In Akrotiri of Thera, Greece (1700–1400 BC), structural mortars were made of local origin clay, mixed with gravel, charcoal, and straw [6]. In Hellenistic monuments, such as Dilos residences (second century BC), lime-pozzolan mortars were mainly found, with aggregates of natural origin and of granulometry mainly 0–8 mm [7]. During the Roman period (second century BC–third century AD), the use of lime and pozzolan dominated in constructions, while brick dust and crushed brick also started to be used [8]. The systematic and in high proportion use of brick dust and crushed brick in lime or lime-pozzolan mortars were expanded during the Byzantine era fourth–fifteenth century AD [9]. Aggregates (natural origin and crushed brick) were of gradation 0–8 mm to 0–16 mm, with a B/A ratio 1/2–1/3 [10]. The effectiveness of the adhesion between the binder and the crushed brick aggregates achieved in those cases was impressive. During the Ottoman period (fifteenth–nineteenth century AD), structural mortars were manufactured by using the available raw materials [11]. They were mainly lime-based (pure lime or lime with clay), while in specific constructions demanded in resistance to humidity (baths, cisterns), pozzolan and brick dust were also added. Aggregates were of natural origin (in some cases crushed brick was also added), of 0–8 mm granulometry, and of B/A ratio 1/2 [12]. In Medieval times (fifteenth–nineteenth century AD), structural mortars mainly consisted of lime (in some cases pozzolan was added), natural or crushed aggregates, and crushed brick in gradations 0–4 mm to 0–8 mm and B/A ratio 1/1–1/2 [13]. During the nineteenth and beginning of the twentieth century, structural mortars varied depending on the building type and the local constructional tradition. Aggregates were usually of the natural origin of 0–8 mm gradation [14]. Later, scholars such as Lanas [15] referred to the importance of the binder/aggregate interface as a zone that requires special attention. From the historic research of the components of mortars, it is obvious that the presence of sand was catalytic and continuous. In relation to the origin of the sand used, it was mainly local, from streams or rivers, and in special cases, crushed bricks or tiles in different gradation were added [16–17]. Aggregates are the most ubiquitous materials in construction. Nowadays, the building industry uses aggregates as materials for construction, mainly in their bound state with cement to form concrete, bitumen to form asphalt, or as components for composite materials. Nevertheless, the utilization of aggregates has a long history in construction technology and especially in mortars. Over the last decades, due to the increasing cost of raw materials and the continuous reduction of natural resources, the recycling of industrial waste has become an interesting option for the building industry. Nowadays, many large industries use manufactured sand alone for producing mortar by partially replacing river sand. In these complex systems, the aim seems to be first, the utilization of low-cost materials from local resources and second ensuring the quality and performance of materials for specific applications. Therefore, there is still a continuous usage of sand in construction works. Alternative approaches to completely replacing sand in mortars have intensified over the last decades [18]. At the moment, the increasing awareness of society about safeguarding heritage buildings and at the same time protecting the environment promotes strategies of combining principles of restoration with environmental friendly materials and techniques.

2. The influence of sands in mortar's properties

2.1 Mortars as composite materials

Composites are materials made by combining two or more other materials. These materials are important in the construction sector as building technology has been favored by the advanced properties that composites can offer. The development of composite materials along with related design and manufacturing technologies constitute one of the most important advances in the history of materials. Composites are multifunctional materials having unprecedented mechanical and physical properties that can be tailored to meet the requirements of a particular application [19]. Thus, new achievements have been constructed as the innovative composites could add new possibilities to the engineers' imagination.

Mortars are a specific type of composite material, which consists mainly of three phases—paste as the matrix, interface transition zone (ITZ), and aggregates. The properties of mortars are influenced by:

- Aggregates (type, percentage, shape)
- Binders (activity, percentage)
- Their contact surface area
- Mixing water
- The maintenance conditions of the applied specimens

At fresh state, mortar should be workable (do not break and do not flow), plastic (to have consistency to hold and not flow on overload loads) and it should show volume stability (do not cause contractions or expansions). At harden state, it should have the required strength and the required porosity. Aggregates constitute the strongest phase, hold a significant percentage in the volume of mortar and are frequently used in sand size (up to 4 mm). Conditions for the use of aggregates in mortars is the health of both the parent rock and the grains (without breaks, cracks, impurities), low porosity—small absorption index, homogeneous granulometric grade, percentage of the fines (<0.075 mm) should not exceed 5% [20]. The presence of fines in lime-based mortars can cause considerable alterations to the properties of the mortars. Their presence significantly reduces the strength and increases the volume shrinkage of mortars [21]. Furthermore, the porosity can be increased, and the same can also happen with capillarity when fine aggregates are participating in excess. Additionally, the type of fines also seems to play a role in their behavior in relation to the basic binder. For example, the strength is decreased in compositions with clay fines while porosity is affected mainly by limestone fines [22]. Capillarity also seems to be affected by the type of fines as the compositions containing fines 10–15% presented low absorption probably because fines block capillary pores [23].

In the case of mortars, as composite materials and keeping in mind that aggregates retain the inherent properties of the rocks from which they are derived, it can explain that the color, the chemical and physical characteristics of the aggregates directly affect the specific weight, the measure of elasticity, the volume stability, the appearance, and the mechanical and physical properties of mortars. The addition of sand to a binding system in mortars technology has proved to confer technical advantages as they contribute to volume stability, durability, and structural performance [16]. The gradation of the aggregates was wide, but the most adequate part was sand of 0–4 mm. Coarse aggregates up to 1 cm were used in thick joints [10] and also combined with sand for structural mortars while sand or finer aggregates (0–2 mm) are usually the constituents of the renders or plasters [24]. Usually, aggregates are obtained after the gentle grinding and sieving (based on EN1015-1) [25]. Even homogeneous distribution of grains is usually obtained as shown in **Figure 2** in a typical bedding mortar.

The ratio of binder to aggregates (B/A) ranges widely but it could be said that for most of the structural mortars, it is 1:2.5 or 1:3 while for the renders and plasters are

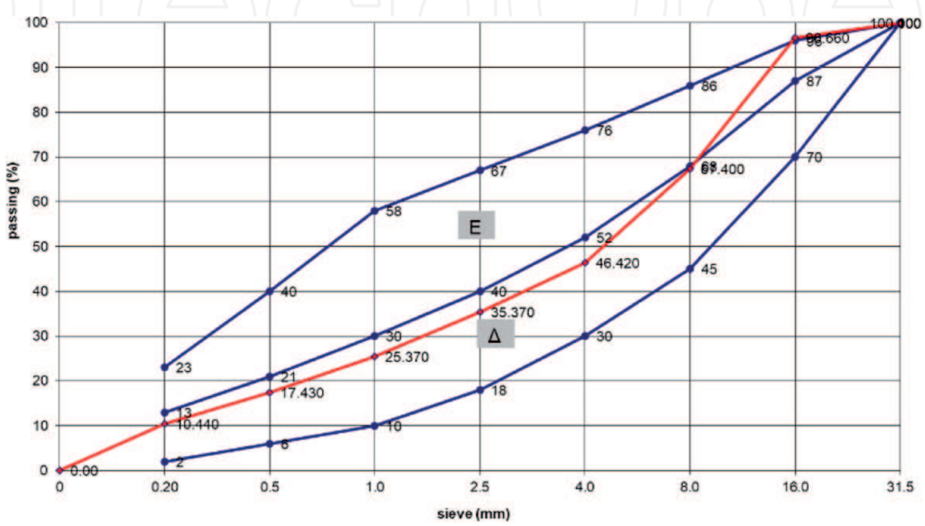

Figure 2.
Typical gradation of old structural mortar.

richer in binder content and the ratio is mostly 1:1 or 1:1.5 [23]. Apart from the different types of aggregates, as their mineralogy and origin are concerned, the volume content in the mixture, the maximum size, and their gradation influences the structure of a binder—aggregate mixture and the performance of mortars overall [10]. The added aggregates strengthen the composite, and the associated interface weakens it. These two opposite effects offset each other, and the combination of them leads to declined strength. Generally, a strong cohesion between the mortar binder and coarse aggregate confirms the good masonry properties. On the other hand, the increase of aggregate content reduces the workability of a mix and thus, reduces the strength as well [26]. It has been mentioned before that aggregate plays a role in restraining the shrinkage of cement paste, and that the shrinkage of the aggregate itself can be neglected [27]. It has been found in various composite materials that a certain amount and proper size of the aggregate are beneficial to the strength and fracture energy of the composite [28]. For mortar specimens, aggregates have a significant influence on both rheological and mechanical properties. Their specific gravity, particle size distribution, shape, and surface texture influence markedly the properties of mortars in the fresh state. On the other hand, the mineralogical composition, toughness, elastic modulus, and degree of alteration of aggregates are generally found to affect the properties of mortars and in the hardened state [29]. The drying shrinkage strains in investigated mortars are changed significantly by different kinds of fine aggregate materials. The water content of the mortar mix proportion is a major factor in drying shrinkage evolution. Increasing the unit water content can result in an increase in the amount of capillary water, and hence more shrinkage strain would be obtained. The bonding stress of the weak interface zone between the coarse aggregate and paste can be improved when a chemical reaction between the aggregates and the paste [30].

More recently, the role of the recycled sand from waste demolition, when examined in mortars, revealed that it was more beneficial in lime mortars rather than in stronger lime-pozzolan or lime-pozzolan and cement mortars as a decrease in their performance were recorded in the latter cases due to the mortars' structure [31]. It seems that two competitive mechanisms acted in these mortars; high porosity (due to high water content and the nature of the aggregates) which assists toward low strength and durability and the chemical reaction due to the presence of reactive components which creates a strong structure. This chemical reaction is a stronger mechanism in the case of lime mortars and prevails in relation to the competitive mechanisms of the higher porosity [32].

In an effort to test different aggregate-related properties to hydraulic lime mortar, Pavia et al. suggested [33] that an increase in the calcite content of the aggregate lowers the flexural and compressive strength of the mortar. At the same time, they proved that sharp aggregate, as well as aggregate with small average particle size, tends to increase the mechanical strength and bulk density of a mortar simultaneously reducing porosity, water absorption, and capillary suction. Additionally, they concluded that aggregates containing particles of a wide size range can increase the mechanical strength and bulk density of the hardened mortar diminishing porosity, water absorption, and capillary suction.

2.2 Different sands in mortars

The role of aggregates on the structure and behavior of lime-based mortars is examined by studying the influence of the aggregate content, type, and grain size on the strength, porosity, and volume stability of the mortars. Trying to understand how

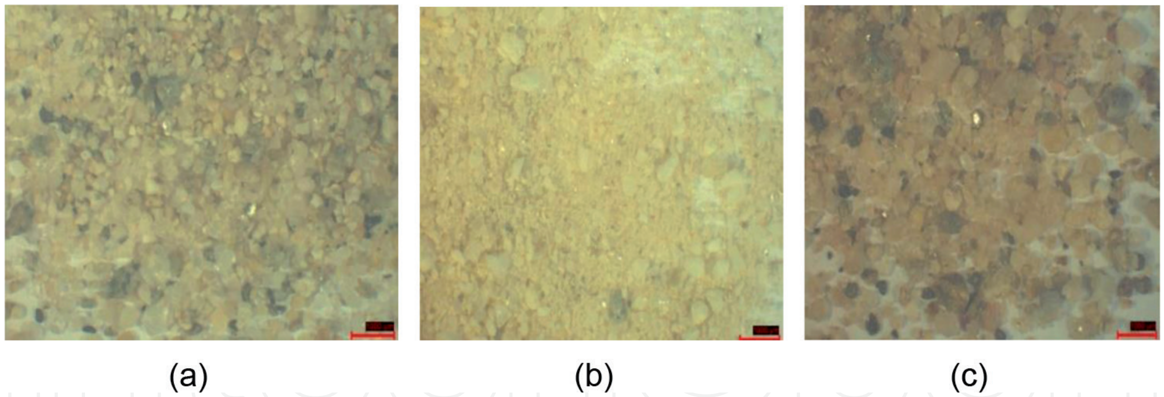

Figure 3.
(a) Black sand, (b) yellow sand, and (c) blonde sand.

the properties of the sands influence important macroscopic properties of pure lime mortar, threes sands that were available in the market were selected and analyzed in the laboratory. All of them were river origins of siliceous content (**Figure 3**).

X-ray diffraction analysis (XRD) using a D2 Phaser 2nd generation, Bruker instruments, indicated that blonde sand was containing quartz, feldspar, magnetite, calcite, hornblende. Yellow sand contained quartz, feldspar, magnetite and black contained quartz, feldspars, biotite, and hornblende. Physical properties, such as water absorption, specific gravity, and sand equivalent (S.E.), are shown in **Table 1** while the chemical analysis revealed the silicic nature of the sands (**Table 2**).

Lime mortars were prepared using lime CL90 (based on EN459) [34] and the compositions were produced, as shown in **Table 3**. The workability was measured with a flow table as described in EN1015-3 [35].

The samples were cured based on EN456 and at 28 days, the compressive strength and the open porosity were recorded (**Table 4**).

The results show that there are different properties recorded in the produced mortars even when siliceous sands are used. The different properties, such as S.E. and the

	Water absorption %	Specific gravity g/cm^3	S.E.
Blonde	0.70	2.36	90.5
Black	1.46	2.35	98.0
Yellow	1.09	2.34	75.0

Table 1.
Physical properties of sands.

	Soluble in acids % b.w.								Soluble salts % b.w.		
Sample	**Na_2O**	**K_2O**	**CaO**	**MgO**	**Fe_2O_3**	**Al_2O_3**	**SiO_2**	**L.I.%**	**Cl^-**	**NO_3^-**	**SO_4^{2-}**
Black sand	3.24	2.63	3.05	1.28	3.66	13.83	68.37	3.45	0.19	0.08	<0.01
Blonde sand	2.97	1.76	3.16	1.87	5.69	14.17	66.00	4.23	0.09	0.11	0.04
Yellow sand	7.82	0.94	0.73	0.46	1.02	18.71	67.14	2.88	0.01	<0.01	0.31

Table 2.
Chemical analysis of sands.

Composition	Lime	Blond sand	Black sand	Yellow sand	W/B	Workability (cm)
L-blond	1	3	—	—	0.758	15.0
L-black	1	—	3	—	0.800	14.5
L-yellow	1	—	—	3	0.750	14.8

Table 3.
Composition of trial mortar mixtures.

Composition	Compressive strength (MPa)	Porosity % (RILEM CPC11.3)
L-blond	1.14	26.42
L-black	1.03	27.11
L-yellow	0.98	30.79

Table 4.
Properties of the produced mortars at 28 days.

water absorption capacity of the sand grains, influence both the fresh (workability) and the hardened properties (porosity, strength) of the produced mortars.

The natural sands can be of similar origin with the crushed but weathering not only rounded the particles but also changed the proportions and removed most of the light minerals, such as the flaky micas. Due to these differences, mixtures with crushed sand often display higher water demand and lower workability than the corresponding composite with glaciofluvial sand. Additionally, crushed sand has a positive impact on long-term strength. It seems that, when rough-grained sand is used, strong cohesion with the binder can be achieved, as shown in **Figure 4**, where mortars with rounded and crushed sand were examined under scanning electron microscopy (SEM) [17].

The mechanical features, particle shape, grading, and physical properties, such as moisture absorption, sand equivalent value, are what can be labeled as properties of interest in the aggregates when used in mortars. Some of these most important properties are shown in **Table 5**.

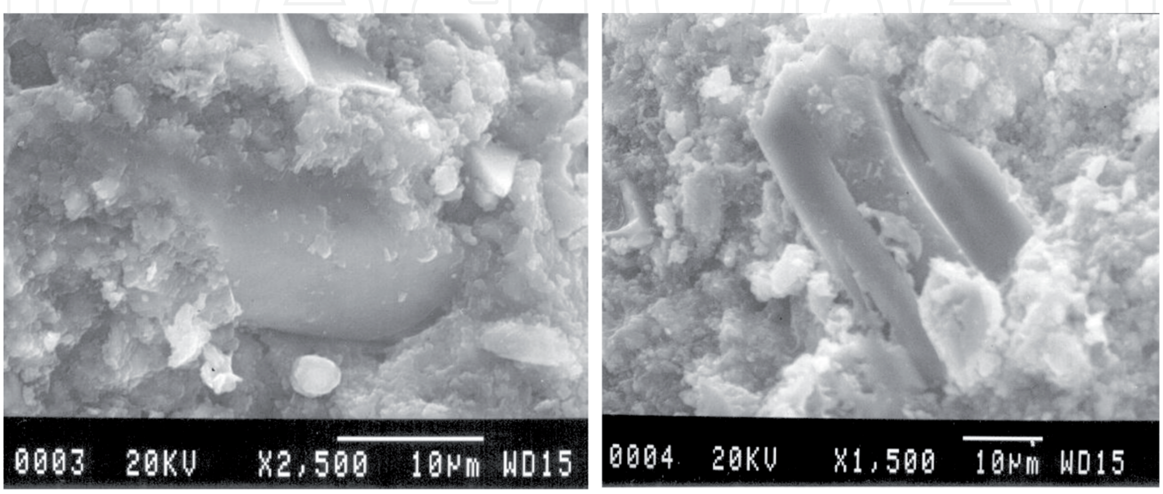

Figure 4.
SEM examination of rounded sand grain (left) where there is a gap in the contact zone and angular grain with strong cohesion (right).

Property	Regulation
Determination of rock compressive strength	ASTM C170
Determination of disintegration resistance (health) of aggregates (sodium sulfate method).	ASTM C88 AASHTO T104)
Determination of mineral hardness	the MOHS scale
Determination of specific gravity of aggregates	BS 812/ AASHTO T 19.
Determination of moisture absorption of aggregates.	AASHTO T85
Determination of granulometric analysis	AASHTO T27/ AASHTO T11/ EN933-1
Determination of ultra-fine crushed material by rinsing	A8TM 0117 (AASHTO T37)
Determination of equivalent sand	AASHTO T176
Determination of abrasion resistance of aggregates	BS 812/75
Determination of wear in aggregate crushing	BS 812/75
Determination of wear on the impact of aggregates	BS 812/75
Determination of plaque index	88,812/75 Section 105.1

Table 5.
Important properties of aggregates to be used in mortar production.

The bond behavior in the interface between the binder and the aggregates has a strong effect on the mortar properties since the effectiveness of the reinforcement provided by the addition of particles depends on the interfacial bond (**Figure 5**). This is since the size, shape, and content of the particles predominantly control the morphological features of the internal structure of the composite.

The test results showed that with increasing volume fraction of aggregate, the compressive strength of the composite decreases, which is different from the prediction of conventional composite theories. The possible explanation of this result is

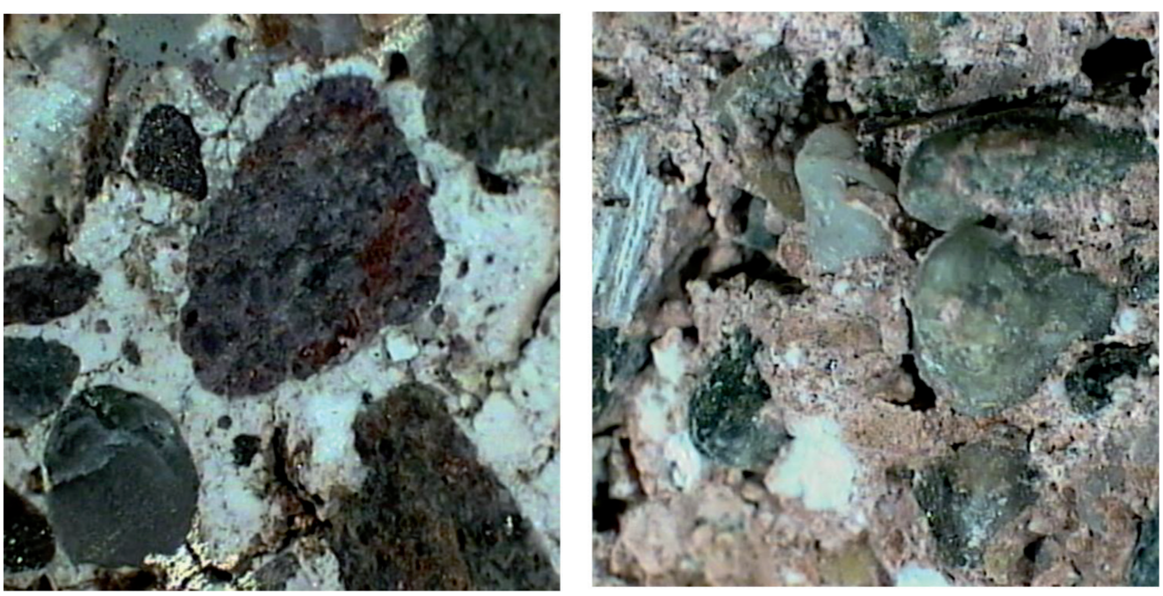

Figure 5.
Macroscopic examination of contact zones of natural aggregates and binders in old mortars. Despite the presence of cracks in the binder in the left image, the cohesion is strong. On the right, there are pores on the interface probably due to the high content in aggregates in relation to the binder.

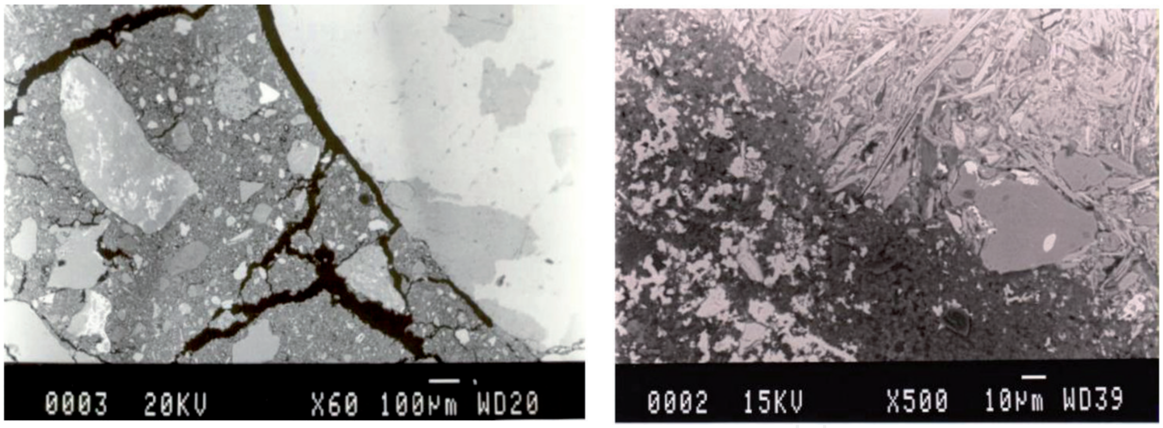

Figure 6.
Examination under SEM of natural aggregate and lime binder with weak ITZ (left) and crushed brick as aggregate and lime-pozzolan binder with strong ITZ (right).

based on the interface transition zone (ITZ) around the aggregate, which is the weak zone in composites (**Figure 6**) [15]. With more aggregate added into the mixtures, more interfaces are formed in the hardened material. The compatibility between the aggregate of the paste affects the development of strong cohesion at the aggregate-matrix interface in many cases and that usually indicates the good performance of the mortar. As aggregates are, by weight or by volume, the major component of mortars, they can be a source of silica, which can react in certain conditions with the binder, leading to the formation of reaction rims at the edge of the grains and recrystallization along with the pre-existing cracks (**Figure 7**).

Apart from the different types of aggregates as their mineralogy is concerned, the volume content in the mixture, the maximum size, and their gradation influences the structure of a binder—aggregate mixture [3, 5]. The analysis of mortars reveals that higher strength values are attained for lime mortars of low binder/aggregate (B/A) ratio (1:1.5, 1:2.5, and 1:3) which contained sand (0–4 mm). Coarse aggregates have

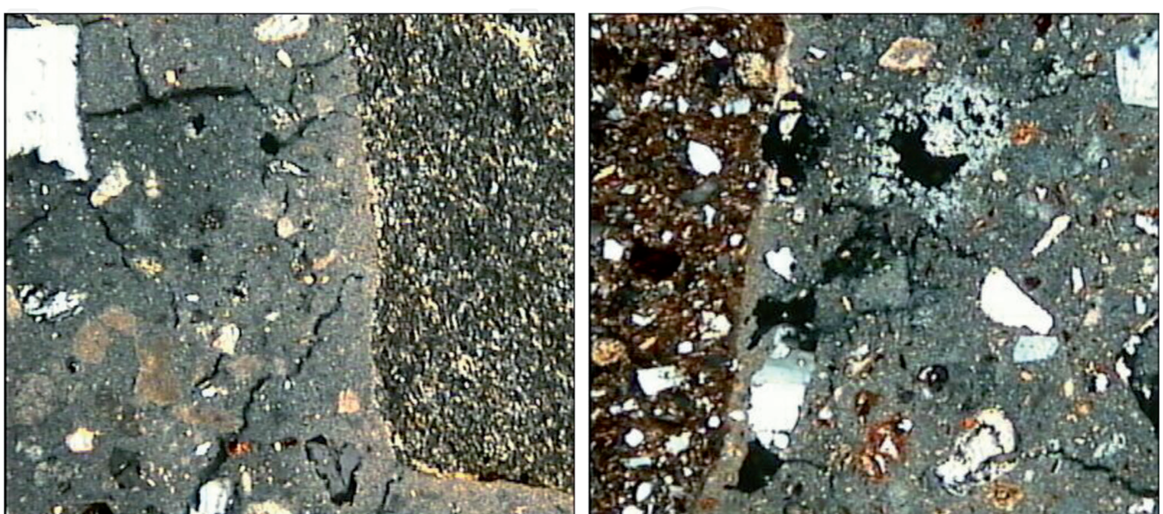

Figure 7.
Old mortars under the polarized microscope (x10). Reaction rim in the interfacial zone of the binders and the aggregates used.

Figure 8.
Pores and cracks in the structure of lime mortar with coarse aggregates (polarized microscope, x15).

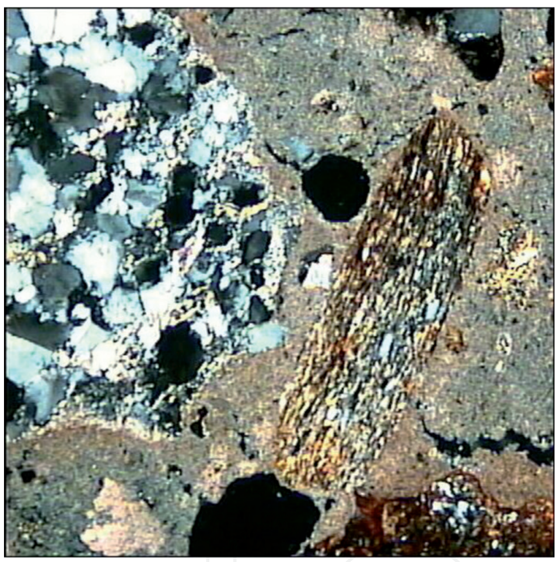

Figure 9.
Cracks inside the binder where they meet the aggregate volume as the obstacle.

contributed positively to the volume stability of lime mortars. The microstructure has recorded the restriction of volume changes in cases where coarse aggregates have been used in the structure of lime mortars (**Figure 8**).

However, it is well recognized that coarse aggregate particles can act as crack arresters, as they restrict the shrinkage of the binder so that under an increasing load, extra energy is absorbed for the formation of a new crack (**Figure 9**) [36].

3. Designing repair mortars

Usually, a detailed analysis of the authentic building materials is performed to establish an opinion about the materials and techniques used during the construction phase [2]. Based on the results of this analysis, the design and laboratory production of some materials follows [14, 37]. The destructive consequences from the use of incompatible repair materials are related to different physical, chemical, and elastic characteristics that many new materials possess in relation to the old lime-based ones. For this reason, the quality of the materials used in intervention works is of primary importance for the longevity and economy of interventions. However, standard test methods and recommendations have not yet been developed despite the effort at the European level.

As river sand remains as one of the most widely used fine aggregates due to its desirable properties an increased tendency to use and it is observed. With an increase in construction activities, the demand for river sand has also been increasing. As a result, it has been mined at a high rate, depleting its natural resources and causing serious environmental issues. Also, owing to the excess cost of transportation, the natural river sand has become expensive. Hence, industries are shifting to other materials, such as crushed sand. But as the demand for building materials will continue to increase, their sources for crushed sand might also get exhausted. Therefore, there is a need to replace the fine aggregate either completely or partially with an alternative material that can satisfy the properties required for concrete, which is cost-effective and at the same time sustainable. Finding an alternative material to river sand has now become imperative.

The incentive to use sand from building demolition in repairing mortars derives from different needs. Natural sand originating from rivers is becoming rare, while the extraction of aggregates from quarries carries an increased administrative cost due to new strict legislations.

Both practices are not considered environmental friendly and, thus, the criteria and legislation for sand extraction are becoming stricter and demanding, while in some places, good quality natural sands are not available. On the other hand, the increased waste production offers the availability of large volumes of recycled materials and public concern about the environment pushes toward their utilization. The possibility of incorporating fine recycled sand originating from construction and demolition waste in lime-based traditional mortars. The study showed that the recycled sand had an even grain distribution, without any hazardous material and low content of soluble salts [38]. The mortars mixtures with recycled sand showed increased water demand and reduced workability compared to mortars with natural sands, even when superplasticizer was used [39]. The mechanical strength measured at 28 and 90 days showed good results as the mortars with lime and recycled sand had higher compressive strength compared to mortars with natural sands [40].

Additionally, several industrial wastes, (fly ash, demolition waste, slag, glass, brick waste, and plastic), have been shown to be suitable as construction materials and readily follow the design requirements. The substitution of the siliceous aggregate with plastic sand leads to a decrease in mechanical properties, opportunities in the use of these materials are not affected, especially for applications that do not require a structural function [41].

4. Conclusions

The mechanical and physical properties of a mortar both at fresh state, but also long-term, depend on multiple factors, including binder type, curing time, binder—aggregate and binder—water ratios, nature, shape, and grading of aggregates, the compaction degree, and also the environment in which they function. As mortars are composite materials, each component has a special role in the ultimate quality of the material. Aggregates, being of great volume in the mortar mass, significantly influence the structure and the properties achieved in all states of mortar production. The analyses of old mortars revealed the continued presence of sand in the mortars from pre-history up to the cement era. Coarser grains were also used in the technology of mortars. Generally, it is accepted that the strongest mortar mixes are produced from well-graded, clean, and angular aggregates. Usually, they were of local origin following principles of ecology and economy.

The same principles should be applied today having the technological evolution as an alley to protect the environment and work on the benefit of the constructions. Understanding the mechanisms of action and the parameters affecting significant properties in mortars, a well-engineered mixture can be achieved utilizing alternative solutions to protect natural resources and at the same time bring to the market high-quality innovative mortars. Recycled sands are promising materials in construction as after specific tests, they can be utilized either in repairing old structures or even in preparing new cement-based mortars.

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