Open Access

Recent Progress in Materials

Research Article

Utilization of Upgraded Recycled Concrete Aggregates and Recycled Concrete Fines in Cement Mortars

Athanasia Soultana *, Michael Galetakis, Anthoula Vasiliou, Konstantinos Komnitsas, Despina Vamvuka

School of Mineral Resources Engineering, Technical University of Crete, 73100, Chania, Greece; E-Mails: asoultana@isc.tuc.gr; galetaki@mred.tuc.gr; avasil@mred.tuc.gr; komni@mred.tuc.gr; vamvuka@mred.tuc.gr

* **Correspondence:** Athanasia Soultana; E-Mail: asoultana@isc.tuc.gr

Academic Editor: Hossein Hosseinkhani

Special Issue: Wastes, Residues and Byproducts for the Production of Construction Materials

Recent Progress in Materials
2021, volume 3, issue 3
doi:10.21926/rpm.2103035

Received: February 11, 2021
Accepted: August 08, 2021
Published: August 17, 2021

Abstract

Waste concrete is the most predominant constituent material among construction and demolition waste. Current waste concrete recycling is limited to the use of recycled concrete aggregates as a road-base material and less as aggregates in new concrete mixes. Further, the production of recycled concrete aggregates results in the generation of a high amount of fines, consisting mainly of cement paste particles. Hence, this study aims to produce the cement mortars using the upgraded recycled concrete aggregates (sand granulometry) for the total replacement of natural aggregates and recycled concrete fines activated through a thermal treatment method as a partial cement substitution material. Cement mortar specimens were tested for their compressive and flexural strength, density and water absorption performance. The results showed that the combined usage of upgraded recycled concrete sand for total replacement of primary crushed sand and recycled concrete fines as partial cement replacement material is a promising option to produce cement mortars.

Keywords
Concrete waste; recycled aggregates; thermal activation; cement mortars

1. Introduction

Construction and demolition wastes (CDW), derived from excavation, construction, and demolition activities, mainly contain mineral waste (concrete, masonry), asphalt, wood, metals and other materials in smaller quantities. These wastes are identified by the EU as a priority stream because of the large amounts that are generated and their high potential for reuse and recycling [1]. Due to the limited landfill capacity and environmental impacts of waste disposal, sustainable management of these waste streams is required. It is estimated that up to 90% of CDW ending up as landfills can be recycled and reused, thus, minimizing the landfilled wastes and mineral resources depletion [2].

Current waste concrete recycling includes the use of recycled concrete as a road-base material or as aggregate in new concrete mixes. More specifically, to produce new concrete, recycling is limited to the use of the coarser recycled concrete aggregate (RCA) fraction (4-8 mm). RCA quality is usually lower than that of the natural aggregates due to the adhered porous cement mortar; thus, it results in reduced workability and mechanical properties of the produced new concrete [3, 4]. For producing recycled aggregates of higher quality, waste concrete is subjected to several crushing stages (selective size reduction). Ordinary crushers cannot effectively separate the concrete from its constituents. Therefore, it results in a mixture of hydrated cement paste and aggregates. Selective crushing and autogenous milling of concrete can be used to remove more hydrated cement paste fines and liberate aggregates. Recycled concrete fines (RCF) (0-4 mm) produced from waste concrete through ordinary crushing processes are rarely used in construction applications [5-9].

Evangelista and De Brito [7] produced concrete using recycled fine concrete aggregates for about 100% replacement of fine natural aggregates. The results showed that about 30% of the replacement ratio is feasible in concrete production with fine natural aggregates. Zega and Di Maio [8] studied the mechanical and durability properties of the concrete produced using the fine recycled concrete aggregates with 0, 20, and 30% replacement of fine natural aggregates. Their results indicated that the concrete produced with the incorporation of recycled concrete fines showed similar mechanical and durability behavior to the conventional concrete. Jesus et al. [9] produced cement mortars using recycled concrete filler (finer than 0.149 mm) and mixed with the recycled aggregates derived from construction and demolition waste at various proportions. They showed that mortars produced with 20% of recycled concrete filler and 15% of mixed recycled aggregates had the best performance.

Recycled concrete fines have a high amount of residual hydrated cement paste (25% of fine concrete powder) [7]. The production of activated cementitious material through thermal activation of hydrated cement paste appears to be a feasible option for recycling these fines since this treatment leads to the formation of unhydrated (anhydrous) compounds with cementitious properties [10]. Thermal activation includes the gradual heating of hydrated cement paste, which results in the decomposition of hydrated clinker minerals. During thermal treatment, a sequence of physical and chemical processes occurs. More specifically, at temperatures up to 100 °C, loss of physically bound water and dehydration of ettringite take place. At temperatures from 100 °C to 450 °C, partially dehydrated C-S-H and modified C-S-H coexist. Above 450 °C, portlandite decomposes to CaO, while at 500 °C, the hardened cement paste mainly consists of dehydrated C-S-H, CaO, partially CH, and non-crystalline dehydrated phases. The hydration of these non-crystalline dehydrated phases results in the formation of the initial hydration products, such as the C-S-H gel, ettringite and CH. At 750 °C, decarbonization of $CaCO_3$ and C-S-H transformation to near C_2S (larnite) structure occurs, while the initial anhydrous phases remain unaltered. At temperatures over 800 °C, mainly free CaO, C_2S, CS (wollastonite), C_4AF (brownmillerite), and C_2AS (gehlenite) exist [11, 12].

The existing studies show that the thermal activation of RCF is generally performed on samples prepared from pure cement paste [3, 10, 13]. However, RCF produced in CDW recycling plants contain significant amounts of fines originated from the sand used in the production of concrete. Furthermore, during concrete crushing and sieving (used to produce the recycled aggregates), additional fine material is generated from the breakage and attrition of the aggregate particles. The effect of these fines on the thermal activation of RCF has not been studied so far.

Hence, in this study, the production of upgraded recycled concrete sand by means of selective crushing and autogenous milling of waste concrete is studied. The thermal activation of RCF, which is generated during the production of the upgraded recycled concrete aggregates, is also investigated. Cement mortars are manufactured by using the upgraded recycled concrete sand for total replacement of natural aggregates and thermally treated RCF for partial replacement of cement. The produced specimens are tested for their compressive and flexural strength, density, and water absorption performance.

2. Materials and Methods

2.1 Waste Concrete Characterization and Sand Production

Waste concrete used in this study was derived from a CDW processing plant located on the island of Crete (Greece). The size fraction of the initial sample was +32 mm. The initial sample was crushed using a Fritsch type jaw crusher to -16 mm. A representative subsample was then taken for the mineralogical analysis. X-ray diffraction (XRD) was performed using an X-ray diffractometer (Bruker AXS, D8-Advance) with a Cu tube. The selected scanning range was from 4° to 70° of 2θ with the step size of 0.02° and a measuring time of 0.2 s/step. The qualitative analysis was performed using the DIFFRACplus EVA v. 2006 software and the Powder Diffraction File (PDF-2) database [1]. The mineralogical analysis indicated that the crystalline waste concrete material was composed of calcite (84.5%), dolomite (13.0%), quartz (1.5%), and brucite (1.0%). This result showed a close association with the composition of the concrete aggregates. In Greece, the majority of ready-mix concrete producers use crushed aggregates extracted from limestone deposits [14, 15].

Following the initial crushing, a part of the crushed sample was subjected to a further size reduction to -4 mm using a Fritsch type jaw crusher and a Sepor type rod mill so as to produce the simple recycled concrete sand of size fraction 0-4 mm coded as RCS.

The remaining quantity of the initially crushed sample was sieved, and the size fraction -0.125 mm was removed. A part of this size fraction (0.125-16 mm) was further crushed using the jaw crusher and the rod mill to produce the first stage upgraded recycled concrete sand of size fraction 0-4 mm coded as URCS1.

The rest of the 0.125-16 mm fraction was subjected to autogenous milling using the Sepor type rod mill for 16 min. The resulting material was sieved, and a -0.125 mm size fraction was removed, while the remaining sample (0.125-16 mm) was further crushed using the rod mill so as to produce the second stage upgraded recycled concrete sand of size fraction 0-4 mm coded as URCS2.

The Sepor type rod mill used for the autogenous milling had a 0.204 m x 0.235 m mill chamber, while the rotation speed was 67 rpm. The autogenous milling time was calculated based on a series of tests where the change in the amount of liberated aggregates from hydrated cement paste with varying milling duration (0, 2, 4, 8, 16, 32, and 64 min) was studied.

Crushing the aggregates using the rod mill was performed to produce sand that meets the requirements of EN 13139 [16] standard. A simple and upgraded recycled concrete sand production procedure is shown in Figure 1.

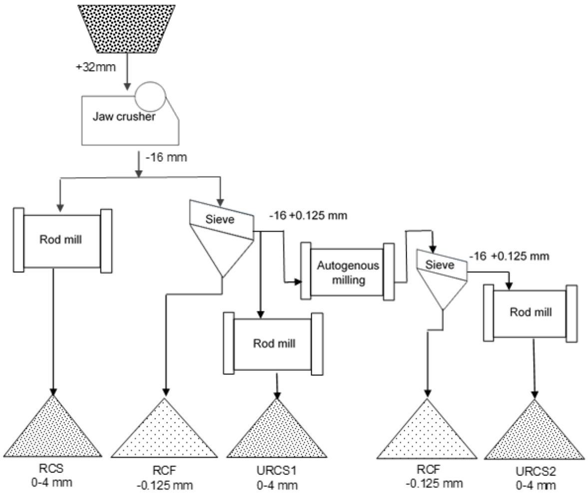

Figure 1 Simple and upgraded recycled concrete sand production procedure.

Particle size analysis of simple and recycled concrete sand, as well as of crushed primary limestone sand (CPLS) used for the production of control specimens, was performed according to EN 933-1 [17]. Besides particle size analysis, water absorption according to EN 13755 [18] and the grain angularity according to EN 933-6 [19] were also determined. A Matest type efflux index apparatus was used to calculate the time required for a specific amount of sand to flow through a funnel of 16 mm with 60^{o} opening. The morphology of the produced sands was optically examined using an Optika type SZM-2 stereomicroscope, and microphotographs were taken by using the mounted Optikam B3 digital camera.

2.2 Characterization and Thermal Treatment of Recycled Concrete Fines

The recycled concrete fines (-0.125 mm) coded as RCF, which resulted as a byproduct during sand production procedure, was 5 wt.% of the initial waste concrete sample. RCF was characterized for its chemical composition by using an X-ray fluorescence energy dispersive spectrometer (XRF-EDS) Bruker-AXS S2Range type. The loss on ignition (LOI) was determined by heating the material at 1050 °C for 4 h. The chemical composition of the studied RCF is given in Table 1. RCF sample was also subjected to mineralogical analysis. Its mineralogical analysis indicated that the crystalline material is composed of calcite (83.3%), dolomite (14.3%), and minor quantities of quartz (2.4%). Chemical and mineralogical analysis results indicated that RCF also contains high amounts of calcite. The enrichment of RCF in calcite agrees with the results obtained by the mineralogical analysis of the initial waste concrete sample, which is closely related to the composition of concrete aggregates in Greece [14]. Thus, the collected RCF, apart from the hydrated cement paste, also contains significant amounts of limestone dust.

Table 1 Chemical composition of RCF (%wt.)

CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	K_2O	MnO	SO_3	*LOI**
35.8	24.9	3.6	4.0	2.1	1.4	0.1	0.2	27.6

*LOI: Loss on ignition

Particle size analysis of RCF was determined by a laser particle size analyzer (Malvern Instruments, Mastersize-S) and is given in Figure 2, which shows the comparison of the particle size analysis of Portland cement type CEM I 42.5N, with RCF, according to EN 197-1 [20]. This analysis was used in this study to produce cement mortars. Table 2 presents the characteristic sizes ($d_{10\%}$, $d_{50\%}$, $d_{90\%}$) and the span of the particle size distribution of used RCF and CEM I 42.5N. As seen in Table 2 and Figure 2, the particle size distribution of RCF is wider than that of the CEM I 42.5N. For size fractions smaller than 15 µm, RCF is finer than CEM I 42.5N. Correspondingly the fineness of RCF, as measured by the Blaine method, is 5050 cm^2/g and is higher than CEM I 42.5N, which is 3454 cm^2/g.

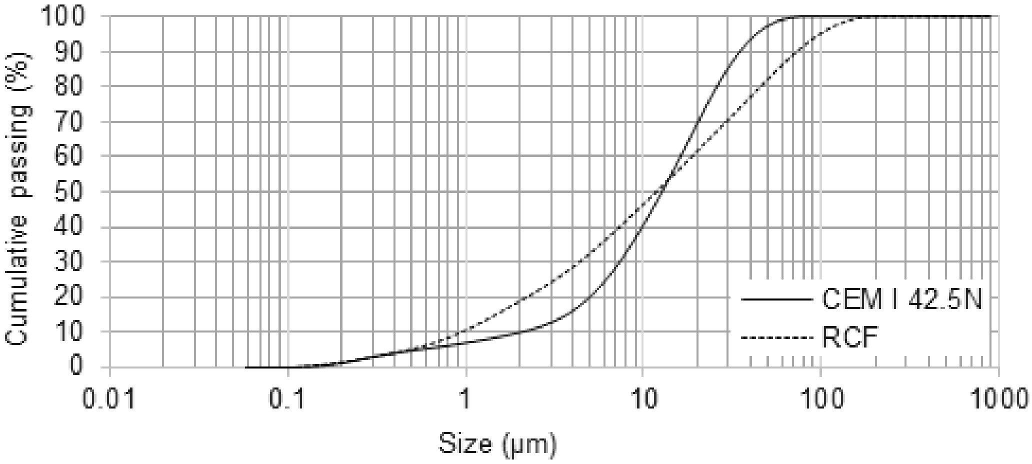

Figure 2 Particle size distribution of RCF and CEM I 42.5N.

Table 2 Particles mean diameter and specific surface area of RCF and CEM I 42.5N.

	$d_{10\%}$ (µm)	$d_{50\%}$ (µm)	$d_{90\%}$ (µm)	*Span**	*Blain value* (cm^2/g)
RCF	0.9	11.6	71.6	6.1	5050
CEM I 42.5N	2.0	12.5	34.4	2.6	3454

*Span = ($d_{90\%}$-$d_{10\%}$)/$d_{50\%}$

Thermogravimetric analysis (TGA) was also performed in a differential thermogravimetric analyzer TGA-6/DTG (Perkin Elmer) on the RCF sample (Figure 3). The thermal analysis was performed up to a maximum temperature of 900 °C, with a heating rate of 10 °C/min, under nitrogen ambiance at atmospheric pressure with a flow rate of 100 mL/min. As seen in Figure 3, at temperatures between 100 °C and 200 °C, mass loss occurs due to the evaporation of pore water and physically bound water from cement hydration products, such as ettringite. The C-S-H gel dehydration effect is visible over 400 °C [10, 11]. The visible mass loss effect between 500 °C and 600 °C is also due to the dissociation of portlandite. The greatest effect appears between 700 °C and 800 °C due to the decomposition of calcium carbonate through CO_2 release.

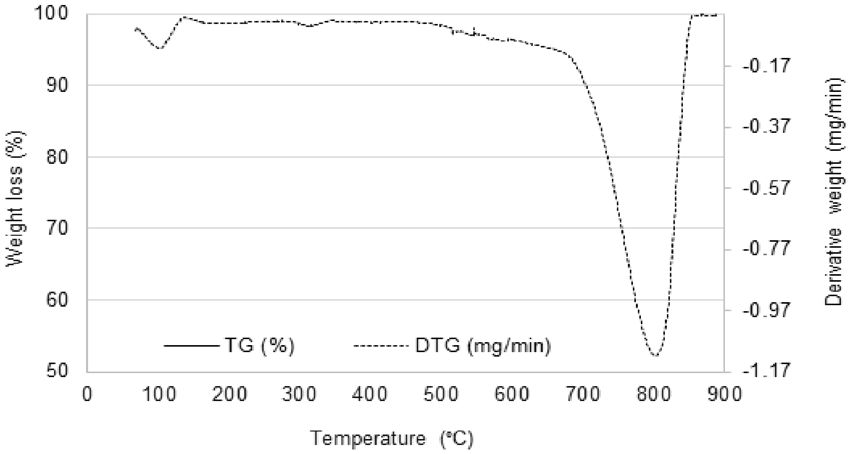

Figure 3 TGA results of RCF.

The RCF, mainly composed of dehydrated C-S-H, was heated up to 600 °C (RCF600) for 120 min at 10 °C/min heating rate. The heated RCF sample was subjected to FTIR analysis. FTIR analysis was performed using a PerkinElmer 1000 spectrometer in the range of 400-4000 cm^{-1} of wavenumber. Figure 4 shows the FTIR spectra of RCF and RCF600 samples. The identified IR characteristic absorption bands are summarized in Table 3.

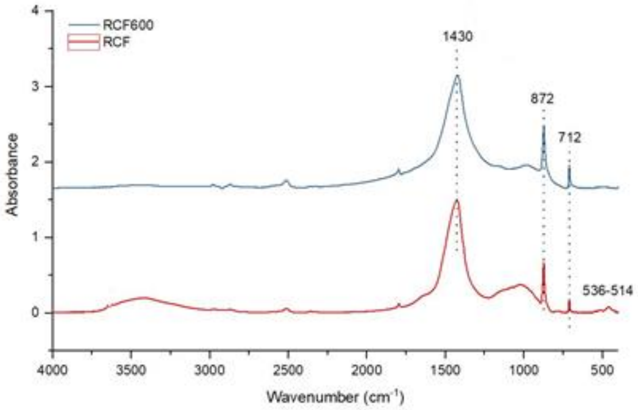

Figure 4 FTIR spectra of RCF and RCF600.

Table 3 FTIR characteristic bands identified in RCF and RCF600.

Wavenumbers (cm^{-1})	*Possible assignments*
1430, 872, 712	vibrations of CO_3-group

536-514	Si-O stretching vibrations

The bands at 872 cm^{-1}, 712 cm^{-1} and 1430 cm^{-1} represent CO_3 vibrations due to $CaCO_3$. Si-O bonds are represented by peaks at 536-514 cm^{-1} [21, 22].

2.3 Mortars Production and Laboratory Tests

Cement mortars were manufactured and tested according to EN 196-1 [23] to examine the quality of the produced sands. The CEM I 42.5N type cement was used, and four different series of specimens were manufactured (Table 4) with the use of:

-recycled concrete sand (RCS),
-first stage upgraded recycled concrete sand (URCS1),
-second stage upgraded recycled concrete sand (URCS2) and
-crushed primary limestone sand (CPLS).

Table 4 Produced cement mortars compositions (kg/m^3).

	Compositions			
	RCS	*URCS1*	*URCS2*	*CPLS*
CEM I 42.5N	586	586	586	586
RCS	1758	-	-	-
URCS1	-	1758	-	-
URCS2	-	-	1758	-
CPLS	-	-	-	1758
Water	375	369	369	293
Water-to-binder ratio	0.64	0.63	0.63	0.50
Corrected water-to-binder ratio*	0.49	0.48	0.48	0.48

*Calculated after subtracting the water absorbed by the aggregates

Due to the higher water absorption of the recycled sands compared to the primary limestone sand, the water-to-binder ratio was determined for the mixtures manufactured using recycled sands to achieve similar workability to the mixture produced with CPLS. The amount of water used to produce recycled sands mixtures was higher than the water amount required by the CPLS mixtures, and it did not contribute to cement hydration. The corrected water-to-binder ratio was calculated based on the water absorption of recycled sands and primary limestone sand (Table 4).

Mortars were prepared according to the proportions given in Table 4 using a Matest type laboratory mortar mixer. The fresh mixture was poured into the prismatic molds (40 × 40 × 160 mm^3), and the produced specimens were cured for 28 days in a curing chamber (at 20 ±2 °C and relative humidity of at least 95%) according to EN 196-1 [23]. Laboratory testing of hardened specimens included measur-ing compressive and flexural strength by the same standard using compression and flexural testing machine (MATEST E161-03N) with dual range 500/15 kN, and measuring density and water absorption was done according to EN 13755 [18].

A series of specimens were also manufactured using URCS1 and 10 wt.% cement substitution either by the untreated RCF (CEMIRCF_90:10) or by the thermally treated one (CEMIRCF600_90:10). Control specimens (no RCF addition, CEMI_Control) were manufactured to compare the performances. The water-to-binder ratio ranged from 0.63 to 0.65. Fabricated specimens were also tested for their compressive and flexural strength, density and water absorption.

3. Results

3.1 Recycled Sands

Figure 5 illustrates the particle size distribution of simple recycled concrete sand and first and second stage recycled concrete sands. It can be seen that the particle size curves of URCS1 and URCS2 are almost identical. Moreover, the particle size curve of RCS shows a relatively higher percentage of the fine fraction 0-0.5 mm and a smaller percentage of 0.5-4 mm fraction. This can be attributed to the selective crushing procedure followed (Figure 1).

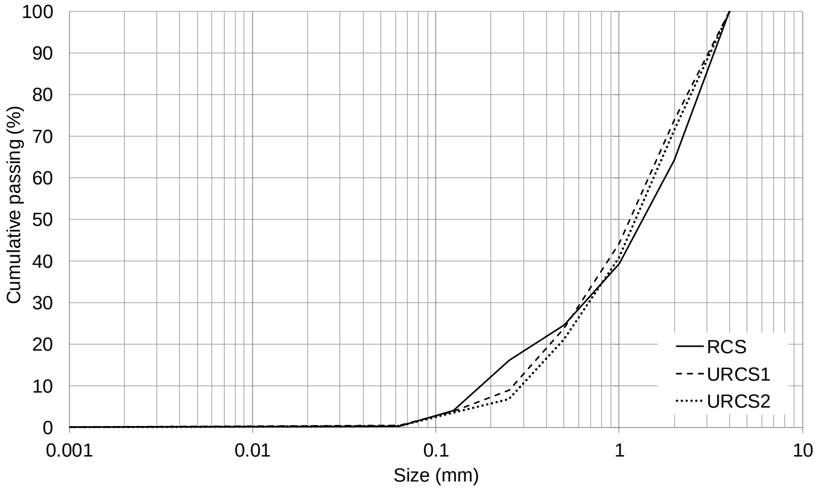

Figure 5 Particle size distribution of the types of recycled sands produced (RCS, URCS1, and URCS2)

Morphological examination through the stereoscope (Figure 6) shows that the grains of recycled concrete sands are more angular than those of the crushed primary limestone sand. Moreover, several grains of recycled concrete sand have adhered cement paste on them. This resulted in a higher flow time of RCS, URCS1, and URCS2 compared to CPLS (Table 5). Moreover, water absorption of recycled concrete sands ranges between 5.0-5.7% and is significantly higher than the water absorption of primary limestone sand (0.7%).

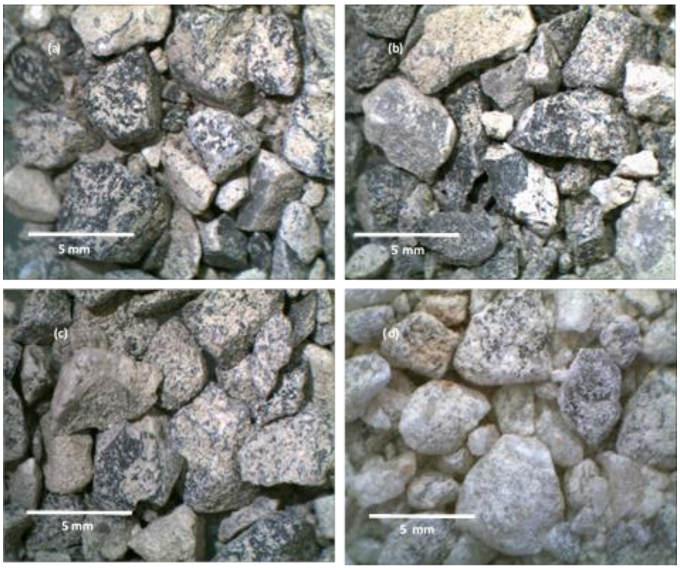

Figure 6 Stereoscopic images of (a) recycled concrete sand (RCS), (b) first stage recycled concrete sand (URCS1), (c) second stage recycled concrete sand (URCS2), and (d) crushed primary limestone sand (CPLS).

Table 5 Flow time and water absorption of recycled concrete sands and primary limestone sand.

	RCS	*URCS1*	*URCS2*	*CPLS*
Flow time (s)	20	19	19	18
Water absorption (%)	5.7	5.1	5.0	0.7

3.2 Cement Mortars

Measured properties of the specimens produced with RCS, URCS1, URCS2, and CPLS are given in Table 6. The compressive and flexural strength values of the examined specimens are shown in Figure 7.

Table 6 Water absorption and density of the produced specimens.

Compositions	*Density (kg/m^3)*	*Water absorption (%)*
RCS	2135	11.6
URCS1	2146	11.3
URCS2	2168	11.2
CPLS	2540	7.5

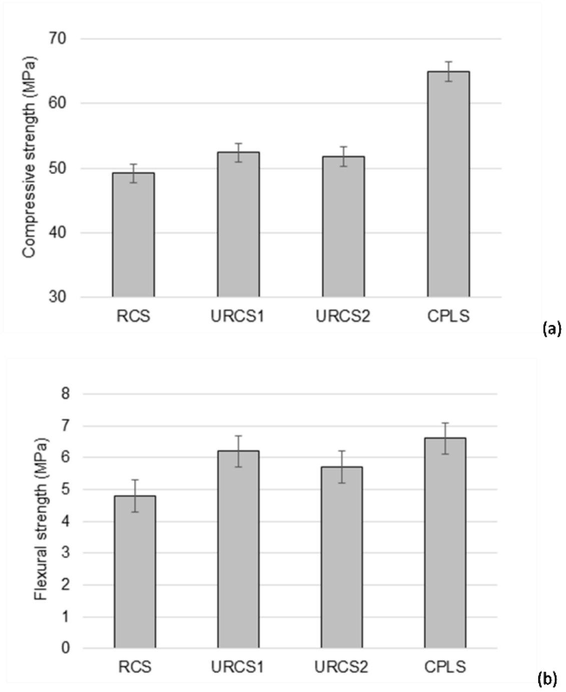

Figure 7 (a) Compressive strength and (b) flexural strength of specimens produced with RCS, URCS1, URCS2, and CPLS. Measurement error was calculated to 1.5 MPa and 0.5 MPa for compressive and flexural strength, respectively.

From Figure 7, it can be seen that the specimens produced using CPLS have the highest compressive and flexural strength values than the specimens produced with the recycled sands (64.9 MPa and 6.6 MPa, respectively). Compressive strength reduction of mortars produced with recycled concrete sands ranges from 19.4% (composition URCS1) to 24.2% (composition RCS) than that of the CPLS samples. The respective reduction in flexural strength is significantly lower for the composition URCS1 (5.0%) and composition URCS2 (13.1%), whereas it is relatively high for the composition RCS (26.5%).

CPLS specimens also show the highest density and the lowest water absorption value (Table 6). The density of the specimens produced with recycled concrete sands ranges between 2135-2168 kg/m^3 and is significantly lower than the density of CPLS mortars (2540 kg/m^3). The water absorption of the specimens produced with recycled concrete sands ranges between 11.2-11.6% and is significantly higher than the one obtained by the CPLS mortars (7.5%). Compressive and flexural strength values of specimens produced with RCS are lower than the mortars produced with the upgraded recycled concrete sands (URCS1, URCS2). In addition, the strength values of the specimens prepared with URCS1 and URCS2 show no significant difference. Therefore, it can be concluded that the first upgrading stage is sufficient to improve the quality of the recycled aggregates and to enhance the mechanical and physical properties of the produced mortars, whereas the second stage did not result in any further improvement.

Measured properties of the specimens produced with the thermally treated (CEMIRCF600_90:10) and untreated RCF (CEMIRCF_90:10), as well as without RCF (CEMI_Control), are shown in Table 7.

Table 7 Properties of the fabricated specimens.

Compositions	*Compressive strength (MPa)*	*Flexural strength (MPa)*	*Density (kg/m^3)*	*Water absorption (%)*
CEMI_Control	52.4	6.2	2146	11.3
CEMIRCF_90:10	50.3	5.2	2152	11.1
CEMIRCF600_90:10	51.6	5.5	2135	11.5

Not much difference is seen in the density and water absorption values of the fabricated specimens since measured values are close to those of the control specimen. According to Table 7, density ranges from 2135 to 2152 kg/m^3 and water absorption from 11.1 to 11.5%. Regarding strength measurements, specimens produced with 10 wt.% of cement RCF show lower compressive and flexural strength compared to RCF600, but all values are similar to the control specimen value.

Table 8 shows the comparison of properties obtained in this study of cement mortars produced with 100% (by weight) replacement of natural aggregates with recycled aggregates (-4.75 mm) with those derived from other selected studies. As seen in Table 8, the properties of the produced specimens (RCS) measured in this study are better than those reported earlier. This could be attributed to upgraded recycled concrete aggregates and the higher strength of cement used in this case.

Table 8 Comparison of measured properties of cement mortars produced with 100% (by weight) replacement of natural aggregates with recycled aggregates.

Raw materials	*Compressive strength (MPa)*	*Flexural strength (MPa)*	*Density (kg/m^3)*	*Water absorption (%)*	*Reference*
CEM II (CPII-E32), HL type III (CH-III), RCA	3.8	-	1699	18.0	Azevedo et al. [24]
Brazilian Pozzolanic Portland cement (PC), MCDW	7.8	1.8	2030	17.0	Ferreira et al. [25]
CEM II (CPII-E32), HL type I (CH-I), MCDW	7.5	1.7	-	-	Miranda and Selmo [26]
CEM II/B-L 32.5N, RCA	7.4	2.1	1570	-	Neno et al. [27]
CEM I 42.5N, RCA	49.2	4.8	2135	11.6	This study

*HL: hydrated lime, RCA: recycled concrete aggregates, MCDW: mixed construction and demolition wastes

4. Conclusions

In this study, the cement mortars were produced using the upgraded recycled concrete aggregates (sand granulometry) as a total replacement of natural aggregates and by using the thermally activated recycled concrete fines as a partial cement substitution material. Cement mortar specimens were tested for their compressive and flexural strength, density and water absorption performance, and the following conclusions were drawn.

Results showed that the first upgrading stage is sufficient to improve the quality of the recycled aggregates and to improve the mechanical and physical properties of the produced mortars.

Upgraded recycled concrete sands produced through the selective crushing procedures had an improved quality compared to the simple recycled concrete sand. Although, the quality of the primary limestone sand was higher than the upgraded recycled concrete sand.

Both untreated and thermally treated recycled concrete fines were suitable as a replacement of cement by 10 wt.%. Regarding density, water absorption and mechanical strength of the specimens produced with 10 wt.% of cement RCF, results showed that the obtained values were similar to the control specimen value.

Further research is needed to study the autogenous grinding process by altering the granulometry of feed material. Additionally, cement mortars production using recycled concrete fines at higher cement replacement percentages should also be investigated. Finally, it should be stated that the combined usage of upgraded recycled concrete sand for total replacement of primarily crushed sand and recycled concrete fines as partial cement replacement material is a promising option to produce cement mortars.

Author Contributions

Michael Galetakis conceived of the idea, designed the experiments and reviewed the paper. Athanasia Soultana and Anthoula Vasiliou performed the experiments, analyzed the results and wrote the first draft of the paper. Konstantinos Komnitsas and Despina Vamvuka reviewed the paper.

Funding

This work was performed within the framework of the funded project “National Contribution to European competitive projects - BEWEXMIN” managed by the Research Committee of the Technical University of Crete (Code 81281).

Competing Interests

The authors have declared that no competing interests exist.

References

1. Zaharaki D, Galetakis M, Komnitsas K. Valorization of construction and demolition (C&D) and industrial wastes through alkali activation. Constr Build Mater. 2016; 121: 686-693.

2. Tam VW, Soomro M, Evangelista AC. A review of recycled aggregate in concrete applications (2000-2017). Constr Build Mater. 2018; 172: 272-292.
3. Gastaldi D, Canonico F, Capelli L, Buzzi L, Boccaleri E, Irico S. An investigation on the recycling of hydrated cement from concrete demolition waste. Cem Concr Compos. 2015; 61: 29-35.
4. Thomas J, Thaickavil NN, Wilson PM. Strength and durability of concrete containing recycled concrete aggregates. J Build Eng. 2018; 19: 349-365.
5. Serpell R, Lopez M. Reactivated cementitious materials from hydrated cement paste wastes. Cem Concr Compos. 2013; 39: 104-114.
6. Serpell R, Lopez M. Properties of mortars produced with reactivated cementitious materials. Cem Concr Compos. 2015; 64: 16-26.
7. Evangelista L, de Brito J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cem Concr Compos. 2007; 29: 397-401.
8. Zega CJ, Di Maio AA. Use of recycled fine aggregate in concretes with durable requirements. Waste Manag. 2011; 31: 2336-2340.
9. Jesus S, Maia C, Farinha CB, de Brito J, Veiga R. Rendering mortars with incorporation of very fine aggregates from construction and demolition waste. Constr Build Mater. 2019; 229: 116844.
10. Florea MV, Ning Z, Brouwers HJ. Activation of liberated concrete fines and their application in mortars. Constr Build Mater. 2014; 50: 1-12.
11. Sui Z, Xuan D, Chen W, Yu R, Zhang R. Cementitious characteristics of hydrated cement paste subjected to various dehydration temperatures. Constr Build Mater. 2009; 23: 531-537.
12. Vyšvaril M, Bayer P, Chromá M, Rovnaníková P. Physico-mechanical and microstructural properties of rehydrated blended cement pastes. Constr Build Mater. 2014; 54: 413-420.
13. Kwon E, Ahn J, Cho B, Park D. A study on development of recycled cement made from waste cementitious powder. Constr Build Mater. 2015; 83: 174-180.
14. Galetakis M, Soultana A. A review on the utilization of quarry and ornamental stone industry fine by-products in the construction sector. Constr Build Mater. 2016; 102: 769-781.
15. Galetakis M, Piperidi C, Vasiliou A, Alevizos G, Steiakakis E, Komnitsas K, et al. Experimental investigation of the utilization of quarry dust for the production of microcement-based building elements by self-flowing molding casting. Constr Build Mater. 2016; 107: 247-254.
16. Aggregates for mortar. London, UK: British Standards Institution; 2013; EN 13139.
17. Tests for geometrical properties of aggregates. Determination of particle size distribution. Sieving method. London, UK: British Standards Institution; 2012; EN 933-1.
18. Natural stone test methods. Determination of water absorption at atmospheric pressure. London, UK: British Standards Institution; 2008; EN 13755.
19. Tests for geometrical properties of aggregates. Assessment of surface characteristics. Flow coefficient of aggregates. London, UK: British Standards Institution; 2014; EN 933-6.
20. Cement. Composition, specifications and conformity criteria for common cements. London, UK: British Standards Institution; 2011; EN 197-1.
21. Horgnies M, Chen JJ, Bouillon C. Overview about the use of Fourier Transform Infrared Spectroscopy to study cementitious materials. WIT Trans Eng Sci. 2013; 77: 251-262.

22. Ylmén R, Jäglid U, Steenari BM, Panas I. Early hydration and setting of Portland cement monitored by IR, SEM and Vicat techniques. Cem Concr Res. 2009; 39: 433-439.
23. Methods of testing cement. Determination of strength. London, UK: British Standards Institution; 2016; EN 196-1.
24. Azevedo AR, Cecchin D, Carmo DF, Silva FC, Campos CM, Shtrucka TG, et al. Analysis of the compactness and properties of the hardened state of mortars with recycling of construction and demolition waste (CDW). J Mater Res Technol. 2020; 9: 5942-5952.
25. Ferreira RL, Anjos MA, Nóbrega AK, Pereira JE, Ledesma EF. The role of powder content of the recycled aggregates of CDW in the behaviour of rendering mortars. Constr Build Mater. 2019; 208: 601-612.
26. Miranda FR, Selmo SM. CDW recycled aggregate renderings: Part I – analysis of the effect of materials finer than 75 µm on mortar properties. Constr Build Mater. 2006; 20: 615-624.
27. Neno C, de Brito J, Veiga R. Using fine recycled concrete aggregate for mortar production. Mater Res. 2014; 17: 168-177.