Key Engineering Materials
ISSN: 1662-9795, Vol. 919, pp 28-34
doi:10.4028/p-rf17nl

Submitted: 2021-08-04
Revised: 2022-01-23
Accepted: 2022-01-23
Online: 2022-05-11

Characterisation of Recycled Quarzitic and Plastic Aggregates for Sustainable Lightweight Screeds

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Keywords: lightweight screed, recycled aggregate, mechanical characterisation, quarzitic sand, recycled acrylic composite

Abstract. The present contribution reports the results of the experimental investigation on a sustainable lightweight cementitious composite material, in which virgin sand is partially substituted by a very fine composite powder retrieved from the manufacturing process of kitchen and sanitary ware. In order to obtain lightweight structural concrete suitable for screeds, the mixture is completed by the addition of recycled polyethylene terephthalate aggregates and lightweight glass spherules. First, physical and morphological properties of the raw powder are thoroughly investigated. Then, the mechanical response of the composite is assessed by means of three-point bending tests and uni-axial compression tests. The conglomerates exhibit promising mechanical performance, thus being regarded as possible candidate for innovative and sustainable structural applications.

Introduction

Nowadays both energy conservation and use of low impact materials represent two necessary requirements to engage in a transition towards a sustainable society. In particular, the construction industry produces every year an overwhelming quantity of material with a significant environmental impact and is estimated to be responsible for about 7% of the CO_2 generated worldwide [1]. Therefore, it can greatly benefit from the results of the scientific research, focussing on the development of innovative and sustainable solutions. Alongside the opportunity of adopting industrial by-products, like silica fume and biomass ashes in inorganic conglomerates and composites [2], solutions including a significant portion of recycled materials have been recently investigated and designed: composites reinforced with recycled fibres, like steel [3,4], plastic [5,6,7], or natural fibres [8], structural and nonstructural screeds lightened by the addition of polymers from electric wires [9], cork granules [10,11], cement powder and fly ash [12] represent only some of the promising solutions proposed so far. In this context, the characterisation of the physical and morphological properties of the recycled constituents which largely influence the mechanical performance of the composite [13,14] is essential to achieve an optimal design, also taking advantage of the insulating characteristics of the retrieved components. Thermal and acoustic insulation regulations, in fact, have become stricter [10], such that the innovative products must exhibit excellent performance also in this field.

In the present contribution, we experimentally investigate the mechanical performance of an innovative lightweight screed, in which the ordinary mixture, usually made of cement, water, and virgin aggregates, is partially modified by the substitution of sand with recycled components. Specifically, we adopt a very fine composite powder comprising quarzitic particles coated with acrylic resin retrieved from the manufacturing process of kitchen and sanitary ware, whose composition and characteristics are assessed through leaching test, laser grain size analysis, field emission scanning electron microscope, and Fourier Transform Infrared Spectroscopy. The cementitious mixture is also completed by the addition of both polyethylene terephthalate (PET) recycled aggregates from sandwiched structures for construction and lightweight glass spherules, to further reduce the density and presumably increase the insulating performance, whose determination is out of the scope of the present work. The cementitious composites, characterised by different fractions of powder, are tested under three-point bending and uni-axial compression conditions. This investigation reveals the good mechanical performance of the conglomerate, which turns out to be a promising candidate for structural applications.

Materials and Methods

Raw materials. We assess the mechanical properties of cementitious composites manufactured by mixing virgin sand with recycled aggregates, such as very fine composite powder, in the following referred to as RP (Recycled Powder), comprising quarzitic particles embedded in a acrylic resin, and PET granules. The aggregates at hand are added in different fractions to Ordinary Portland Cement (OPC), silica fume (15% with respect to the OPC only), and lightweight glass spherules, added to further reduce the conglomerate density. The different formulations here investigated are specified in Table 1, whereas the aggregates adopted are illustrated in Figure 1.

Table 1: Experimental programme

Sample ID	Aggregates [wt.%]				OPC [wt.%]	w/c ratio
	Sand	RP	PET	Glass spherules		
RP-20	39.6	14.4	14.4	3.6	28.0	0.70
RP-30	32.4	21.6	14.4	3.6	28.0	0.70
RP-40	25.2	28.8	14.4	3.6	28.0	0.70

(a) (b) (c)

Figure 1: Aggregates: recycled powder (a) and PET granules (b), and glass spherules (c)

Specimen manufacturing. Conglomerate specimens are manufactured according to the prescriptions of UNI-EN 13813 [15] and 196-1 [16], by following the procedure illustrated in Figure 2 and here briefly summarised. OPC, silica fume, and aggregates are mixed with water through low-speed mechanical stirring, and $40 \times 40 \times 160$[mm] prismatic beams are produced out of plastic moulds properly lubricated to ease stripping after 7 days. Specimens (six samples for each mixture) are left curing at laboratory conditions (approximately 20 °C and 70% RH) for 21 days, until complete hardening.

(a) (b) (c)

Figure 2: Specimen manufacturing: mixture (a), casting of prismatic beams (b), and moist curing (c)

Powder characterization methods. In order to determine the physical and morphological properties of the raw RP, several characterisation techniques are adopted. First, we determine the elements constituting the mixture by following the procedure reported in EN 13656 [17], EN 14346 [18], CNR-IRSA 2Q64 [19], and EN 12457 [20] (leaching tests). Second, a laser grain size analysis is conducted (Mastersizer 2000, Malvern UK), then a field emission scanning electron microscope (FE-SEM, Nova NanoSEM 450, Bruker Corporation) session is carried out, by processing the images through Energy Dispersive X-ray (EDX) analysis. Finally, a Fourier Transform Infrared Spectroscopy (FT-IR, FTIR Vertex 70, Bruker Corporation) in attenuated total reflectance (ATR) mode is performed to compare the powder from thermal hydraulic equipment to customary quarzitic sand (Po River, Italy), commonly employed in mortar and screed formulations.

Mechanical tests. Three-point bending (3PB) tests are carried out on an Instron 5567 universal testing machine equipped with a 30 kN load cell. Tests are conducted at a fixed deflection rate of the movable crossbar of 1 [mm/min]. The two halves of failed specimens are then subjected to uni-axial compression tests on a 40× 40 [mm] surface at the same displacement rate set for 3PB tests.

Results and Discussion

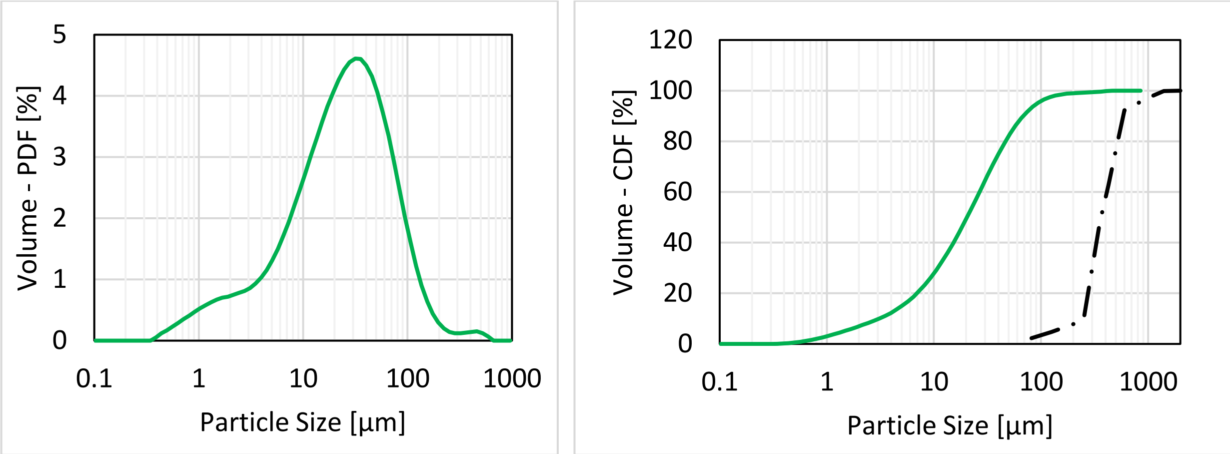
Powder characterisation. Table 2 and Table 3 report the main constituents and some fundamental physical characteristics of the RP, evaluated by following EN 13656 [16], EN 14346 [17], CNR-IRSA 2Q64 [18], and EN 12457 [19]. The analysis of the data leads to the classification of RP as a non-hazardous waste, which can be profitably retrieved for new applications in the construction field. Figure 3 illustrates the output curves of the particle size analysis, comprising both probability density function (PDF - Figure 3a) and cumulative distribution function (CDF - Figure 3b). Specifically, in Figure 3b the CDF curve of RP (green solid line), indicating the average particle sizes weighted by the volume fractions, is compared with that of quarzitic sand (black dash-dotted line) generally employed in screeds. As we can note, the average particle size of the RP turns out to be of approximately 50 μm, being one order of magnitude lower than the one of the sand (470 μm). This extremely fine aggregate size partially influences the workability of the fresh conglomerate, which turns out to be slightly penalised.

Table 2: Constituents of the RP, according to EN 13656:2004 [17]

Metal	Concentration [mg/kg]
Barium (Ba)	12
Copper (Cu)	12
Antimony (Sb)	13
Tellurium (Te)	15
Zinc (Zn)	31

Table 3: Characteristics of RP, according to EN 14346 [17], CNR-IRSA 2Q64 [18], and EN 12457 [19]

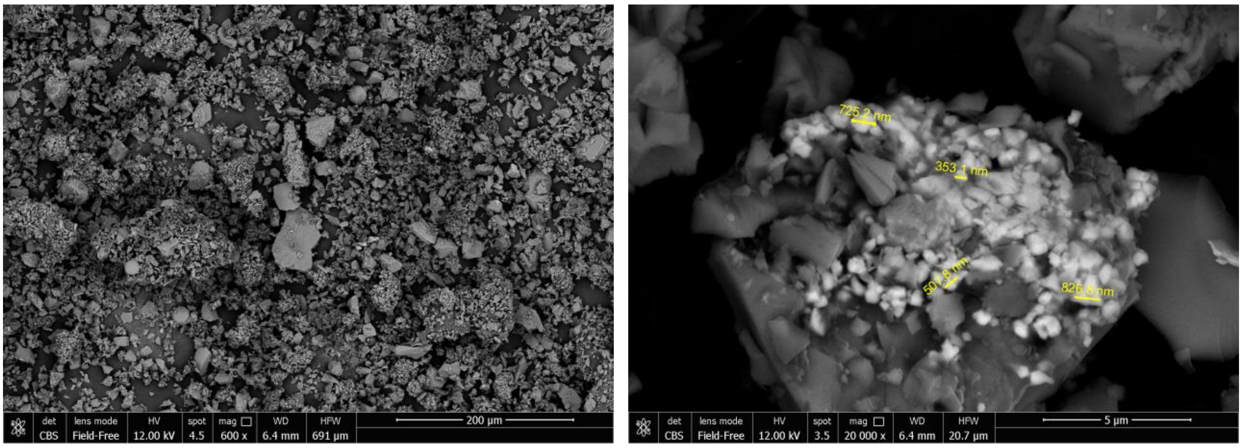
Characteristic	Guideline	Unit	Value
Dry residue at 105°C	EN 14346 [18]	[%]	99.6
Dry residue at 600°C	CNR-IRSA 2Q64 [19]	[%]	70.5
pH	EN 12457 [20]	[-]	7.5
Electrical conductivity at 20°C	EN 12457 [20]	[μS/cm]	30
Chemical Oxygen Demand (COD)	EN 12457 [20]	[mg/l]	28
Nichel (Ni) from leaching test	EN 12457 [20]	[μg/l]	1



(a) (b)

Figure 3: PDF particle size distribution of RP (a) and comparison of the CDF particle size distributions of RP (green solid) and quarzitic sand (black dash-dotted)

Figure 4 reports the results of FE-SEM investigation. We note the presence of a scattered grain size distribution, with particles possessing a pronounced irregular shape. The presence of a polymeric medium (acrylic resin) embedding the quartz particles induces the formation of clusters of sub-micrometric fragments, as clearly shown in the detail of Figure 4b.



(a) (b)

Figure 4: FE-SEM investigation of the RP batch (a) with detail of sub-micrometric fragments (b)

Figure 5 illustrates the comparison between FT-IR spectra of RP (green solid line) and common quarzitic sand (black dashed line). Apart from the wide absorbance peak at approximately 3365 cm^{-1}, which is due to O-H interactions owing to the presence of moisture, the common peaks of silica (quartz) are detected at wavenumbers lower than 1100 cm^{-1}. In particular, asymmetric and symmetric stretching vibrations of Si – O bonds are observed at approximately 1000 cm^{-1} and 775 cm^{-1}, respectively. Finally, Si – O symmetric bending vibrations emerge in the range 690-700 cm^{-1}. The main composition of both powders is indeed quartz, thus making the RP a good candidate to replace a fraction of virgin sand in cementitious materials. Other relevant peaks suggesting the dominant presence of quartz are also located at 1636 cm^{-1} and 1726 cm^{-1}, according to the measurements in [21].

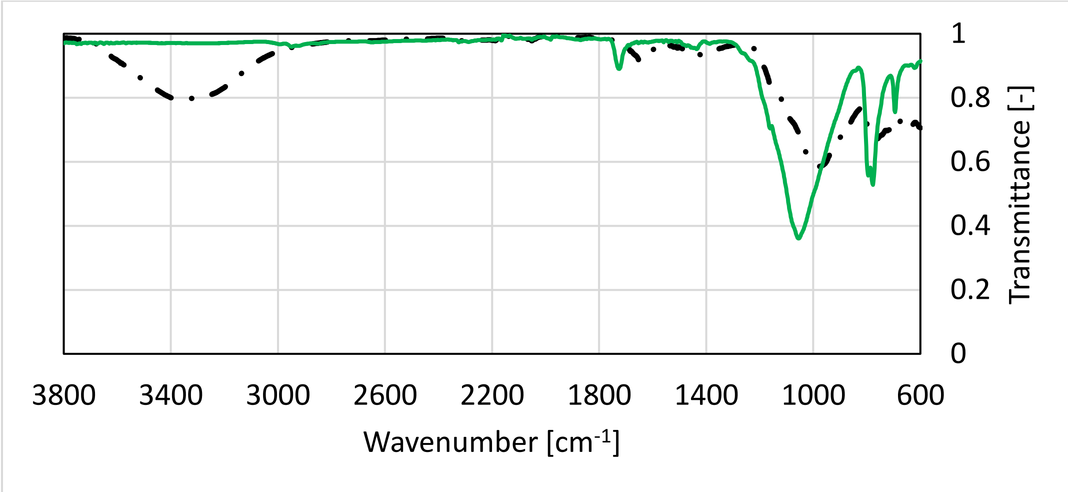
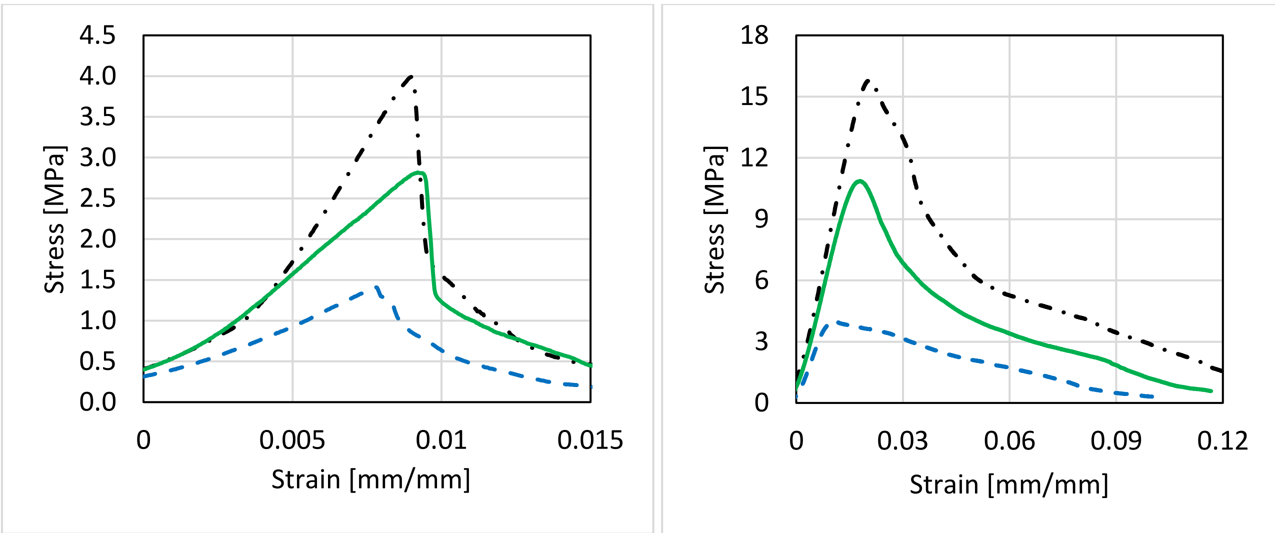


Figure 5: FT-IR spectrum of RP (green solid) compared with quarzitic sand (black dash-dotted)

Mechanical tests. Figure 6 illustrates the mean stress-strain curves of bending (3PB) (Figure 6a) and uni-axial compression tests (Figure 6b), performed on the conglomerates described in Table 1, whose measured densities are 1629 [kg/m^3] (RP20), 1469 [kg/m^3] (RP30), and 1289 [kg/m^3] (RP40).



(a) (b)

Figure 6: Mean strength curves for 3PB (a) and uni-axial compression (b) tests on conglomerates RP20 (black dash-dotted), RP30 (green solid), and RP40 (blue dashed) described in Table 1

Trends exhibited by the concrete mixtures is common regardless of the test type and are well-aligned to the customary behaviour of cementitious materials. A pseudo-elastic branch is observed for low load levels, until a microcracking pattern is triggered near the mid-span cross-section in bending tests and diffusely distributed in compression tests. A reduction of the stiffness is hence obtained in the proximity of the peak load value. Then a softening branch is observed, possessing a slope depending on the peak values. Indeed, weaker conglomerates exhibit a more ductile post-peak behaviour and vice versa. Moreover, the mechanical performance of the cementitious conglomerates presents a monotonic decrease as the RP content increases. This behaviour is confirmed by several previous studies, which suggest that lightweight aggregates strongly penalise the response of cementitious mixtures [22]. However, the performance losses cannot be ascribed to the sole inclusion of RP, and an optimal powder content in terms of both mechanical response and density of the conglomerate can be identified around 25% with respect to the amount of aggregates only.

Summary

In this contribution, we have firstly thoroughly characterised a recycled composite powder, retrieved from the manufacturing process of kitchen and sanitary ware. The powder, containing quarzitic particles, turned out to be inert and suitable for partially replacing virgin quarzitic sand in cementitious screed mixtures, being its chemical composition strictly comparable and affine.

After this assessment, we have mechanically tested prismatic beams manufactured by including the powder at hand and lightening aggregates (polyethylene terephthalate recycled particles and lightweight glass spherules), required to achieve the target density for practical purposes. We have obtained a good mechanical response in terms of bending and compression. This performance is largely affected by both the amount of recycled aggregates added in the mixture, which influences the peak load value, and by the very fine size of the powder, which slightly penalises the workability of the fresh conglomerate.

Future works should focus on the determination of an optimal mix design and on the assessment of the thermal and acoustic insulating performance of the conglomerates, which can find application in the construction field as structural lightweight screeds.

Acknoledgements

Fruitful discussions with Dr. Cesare Signorini and contribution of Desiree Napenas in specimens manufacturing are gratefully acknowledged. The authors also thank Dr. Miriam Hanuskova, Dr. Fabio Bergamini, and Dr. Mauro Zapparoli for their valuable assistance during particle size measurement, E-SEM, and FT-IR analyses. V. Volpini acknowledges financial support from POR FESR 2014–2020 ASSE 1 AZIONE 1.2.2, Project IMPReSA, CUP E81F18000310009.

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