



## Research article

# Recycling thermally deactivated asbestos cement in mortar: A possible route towards a rapid conclusion of the “asbestos problem”

Giancarlo Capitani<sup>a,\*</sup>, Michele Dalpiaz<sup>b</sup>, Fabrizio Vergani<sup>a</sup>, Fabrizio Campanale<sup>a</sup>, Roberto Conconi<sup>a</sup>, Stefano Odorizzi<sup>b</sup>

<sup>a</sup> Department of Earth and Environmental Sciences, University of Milan-Bicocca, Italy

<sup>b</sup> RALLK S.R.L., Via Pastrengo 21, Milano, Italy



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## ABSTRACT

The “asbestos problem” arises from the fact that asbestos is still abundant in many buildings and represents a hazard for human health. Current strategies adopted by law aiming at mitigating this hazard are far from being ideal. A smarter solution would be an energy sustainable detoxification treatment followed by recycling. If adopted, it would preserve the environment from pollution, natural resources from depletion and human health from hazard. Asbestos-cement slates were thermally deactivated through a sustainable process and reused in mortar for plaster applications. We found that the addition up to 7 wt% of the deactivated product does not affect significantly the water demand; does not affect thixotropy, stickiness and spreadability of the plastic mixture; slightly increases the strength of the mortar; does not compromise mechanical properties after aging. Considering the huge amount of traditional mortar employed worldwide, a rapid end of the “asbestos problem” is envisaged.

## 1. Introduction

Asbestos is a fibrous material widely used in the past because of its excellent physical properties such as heat and chemical resistance, acoustic and electrical insulation properties and great tensile strength. Because of such properties, asbestos has been used in a variety of applications, but mostly as building and insulation material in sprays, plasters, paints, flooring products, panels, tiles, corrugated sheets for roofing, rainwater and pressure pipes.

Asbestos comprises a group of six mineral species belonging to the serpentine and amphibole groups. Chrysotile, commercially known as *white asbestos*, accounts for more than 90% of the total asbestos employment. Amphibole asbestos has been much less employed but has comparatively longer persistence time in human alveoli (Di Giuseppe et al., 2019), which may suggest higher toxicity than chrysotile. The “asbestos problem” arises from the fact that asbestos has been classified carcinogen and banned in 67 countries around the world since the 1983 (Magnani et al., 2023), but asbestos containing materials (ACM) are still abundant in many buildings and represents a hazard for the human health.

The current strategies adopted by law aiming at mitigating health

hazard from ACM are: i) confinement; ii) encapsulation and iii) land-filling. Confinement refers to the insulation of the ACM from the exterior through a physical barrier. This solution, however, does not eliminate the risk of exposing again the environment to asbestos, as in the unfortunate cases of careless maintenance operations, extreme natural phenomena, or terrorist attacks. Encapsulation consists in the application of special fixative resins to the ACM aiming at keeping the fibres within their matrix, impeding their release into the environment. However, resins are inexorably subject to degradation over time, requiring periodic maintenance. Landfilling, which follows encapsulation and removal, is the most practised solution because cost-effective, but as for the other solutions, it does not eliminate the risk that asbestos fibres could be released over time into the environment, especially in the water table. Moreover, suitable sites for toxic waste confinement are increasingly rarer to find in developed countries where free soil is disappearing (Strollo et al., 2020) and construction and demolition waste increases exponentially (Laurent et al., 2014; Tang et al., 2020).

None of the aforementioned solutions is therefore ideal. A smarter solution would be an energy sustainable detoxification treatment coupled with a clear recycling route, as recommended by the European

\* Corresponding author.

E-mail addresses: [giancarlo.capitani@unimib.it](mailto:giancarlo.capitani@unimib.it) (G. Capitani), [michele.dalpiaz@rallk.com](mailto:michele.dalpiaz@rallk.com) (M. Dalpiaz), [fabrizio.vergani@unimib.it](mailto:fabrizio.vergani@unimib.it) (F. Vergani), [fabrizio.campanale@unimib.it](mailto:fabrizio.campanale@unimib.it) (F. Campanale), [r.conconi@campus.unimib.it](mailto:r.conconi@campus.unimib.it) (R. Conconi), [stefano.odorizzi@rallk.com](mailto:stefano.odorizzi@rallk.com) (S. Odorizzi).

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Parliament resolution of March 14, 2013 on “Asbestos related occupational health threats and prospects for abolishing all existing asbestos (2012/2065(INI))”. This would preserve the natural environment from pollution, natural resources from depletion and human health from hazards.

On the other hand, processes for the detoxification of ACM still suffer from critical issues that need to be solved. For instance, thermal or thermomechanical treatments are effective but energy intense; biological methods are not very effective; chemical methods consume large amounts of reagents and produce highly acidic fluids that require careful disposal (Spasiano and Pirozzi, 2017; Paolini et al., 2019).

Thanks to a recent patent on the thermal inertization of asbestos cement slates (CAS), the process seems more sustainable than in the past (Marian et al., 2021) and, in terms of recycling, many promising fields have been investigated, mostly ceramics (e.g., Gualtieri and Tartaglia, 2000; Leonelli et al., 2006; Pérez-Estébanez et al., 2014; Ligabue et al., 2020; Bernasconi et al., 2023), but also clinker (e.g., Gualtieri and Boccaletti, 2011; Viani and Gualtieri, 2013; Kusiorowski et al., 2015), epoxy resins (e.g., Campanale et al., 2023) and many others (for an overview see Gualtieri et al., 2011), and several patents have been produced (e.g. Belardi et al., 1998).

In the present paper, we investigate the addition of deactivated asbestos cement powder (DACP) to a very common mortar for plaster applications. Since DACP is a mixture of calcium-magnesium silicates, calcium silicates and aluminates and glass close to cement composition, we believe this could be a very promising route. Actually, the use of ACM as a raw material for clinker production has been already proposed (Ambrosius et al., 1996; Sprung et al., 1998) and a process for the use of ground asbestos cement as a raw material for the production of cement has been patented (Gleichmar et al., 1997). Although the results appear satisfactory, there is a major problem to solve before any industrial application, which is the health hazard the workers are exposed to during manufacturing. This risk can be eliminated using DACP (i.e. a non-hazardous material) instead of ACM.

Recycling secondary raw materials (SRMs) in concrete (or mortar) is one of the basic ideas of the green concrete concept, which is becoming a field of research that has growing interest worldwide, due to the environmental impact of the concrete industry (Bertolini et al., 2004; Yvon and Sharrock, 2011). In particular, it has the advantages that it could help saving primary raw materials and decreasing the overall emission of CO<sub>2</sub>. Indeed, unlike other industrial by-products, like fly ash or red mud, this substitution supplies CaO (see Table 1) that otherwise should be supplied by limestone rocks, which implies large CO<sub>2</sub> emissions during cement manufacturing.

The recycling of construction and demolition waste (CDW) has become a socioeconomic priority within the European Union and a considerable amount of research has been undertaken within the frame of RILEM (the international union of testing and research laboratories for materials and structures) (Hansen, 1985). In this scenario, there are several examples of recycling SRMs for the production of concrete. A few notable examples are: i) recycling demolished masonry rubble to create coarse aggregate (Khalaf and DeVenny, 2004); ii) production of concrete bricks and paving blocks using recycled aggregates from CDW (Poon et al., 2002); iii) mineral stone slurry used to replace fine aggregates

(Almeida et al., 2007); iv) ground tire rubbers used as concrete reinforcement (Bignozzi and Sandrolini, 2006); v) fly and bottom ash recovered from municipal solid waste incinerators used to replace part of the Portland cement (Ferreira et al., 2003; Bertolini et al., 2004); vi) ground plastics and glass used in place of fine aggregates (Batayneh et al., 2007); vii) glass fibre reinforced plastics waste used in concrete and cement composites (Asokan et al., 2009); viii) and recycling marble cutting wastes (Mashaly et al., 2012).

In the present work, we used two different DACPs, one obtained from a common inertization process at 1100 °C in oxidizing atmosphere, and one from an inertization process at 1150 °C in reducing conditions, respectively. We found that recycling DACP in mortar is a very promising route since the main mechanical properties of the final products are not negatively affected. Moreover, considering the large volume of annually employed mortar in the construction industry, we could envisage a rapid conclusion of the ACM problem.

## 2. Materials and methods

### 2.1. Deactivated asbestos cement slates

Asbestos cement slates, originally containing calcite as major mineral followed by quartz, chrysotile (up to 17 wt%) and minor (<1 wt%) mica, crocidolite, portlandite, zircon and barite (Marian et al., 2021; Vergani et al., 2022), have been thermally treated according to two different processes, briefly: i) under reducing atmosphere at 1150 °C and ii) in air at 1100 °C (more details in the Supplementary Material). After the thermal treatment, CAS annealed in air acquire a reddish-brown colour (hereafter “Red sample”), whereas those annealed under reducing atmosphere are greenish grey (“Green sample”). Both materials maintain their physical aspect after the treatment, i.e. are still self-sustaining, therefore they require to be powdered before being employed as secondary raw material (Fig. 1). Powdered samples (DACP) were achieved by ball milling for 10 min batches of ~100 g of CAS fragments (Fig. 2); their grain size distribution obtained by dynamic laser scattering (DLS) is plotted in Fig. 3. Although the two curves are similar, significant differences may originate from the two different thermally-driven recrystallization processes, and may be also from any texture difference of the original CAS.

The chemical and mineralogical compositions of the two DACPs used in the experiment are reported in Tables 1 and 2, respectively. Major chemical differences are in the CaO/SiO<sub>2</sub> (C/S) ratio and total iron, both probably inherited from the original CAS, since only volatile components (H<sub>2</sub>O, CO<sub>2</sub>) are supposed to evolve during the thermal treatment. The higher water content of the Green sample may be due to water resorbed during storage. Major differences also exist in the recrystallized phases: mostly Ca–Mg-silicates with lower C/S ratio for the Red sample (akermanite, bredigite, merwinite); mostly Ca-silicates with higher C/S ratio (jasmundite, larnite) and lime for the Green sample, reflecting the different C/S ratio of the original CAS. The MgO component seems sucked up by periclase and minor monticellite in the Green sample. The glass content is high, the most abundant phase in both DACPs. Overall, the two DACPs in the CaO–SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub> diagram collocate between the Slag cement and the Portland cement compositions, the Red closer to the Slag and the Green closer to the Portland, respectively (Fig. 1S in supplementary materials). The magnesium content of both DACPs, however, is significantly higher than in the two mentioned cement classes (Álvarez-Pinazo et al., 2012). Both DACPs can be assimilated to Mg-rich clinkers.

As said, the material is self-sustaining after the thermal treatment and the original asbestos fibres can be still recognised through optical and electron microscopy. However, detailed X-ray powder diffraction (XRPD) experiments, scanning (SEM) and transmission (TEM) electron microscopy observations (Marian et al., 2021; Vergani et al., 2022), certify that the original fibres are completely recrystallized into microscopic and sub-microscopic particles of non-toxic minerals, such as

**Table 1**  
Chemical compositions (wt%) of Red and Green DACPs used in the experiments.

	Red	Green		Red	Green
Na <sub>2</sub> O	0.17	–	Cr <sub>2</sub> O <sub>3</sub>	–	0.04
MgO	7.68	7.43	MnO	0.43	0.39
Al <sub>2</sub> O <sub>3</sub>	3.90	3.09	Fe <sub>2</sub> O <sub>3</sub>	5.94	2.61
SiO <sub>2</sub>	30.41	20.01	NiO	–	0.03
SO <sub>3</sub>	3.11	3.78	SrO	–	0.13
Cl	–	0.06	ZrO <sub>2</sub>	–	0.01
K <sub>2</sub> O	0.42	0.22	SnO <sub>2</sub>	–	0.02
CaO	47.38	59.72	H <sub>2</sub> O	0.32	2.25
TiO <sub>2</sub>	0.23	0.23	Total	99.99	100.02

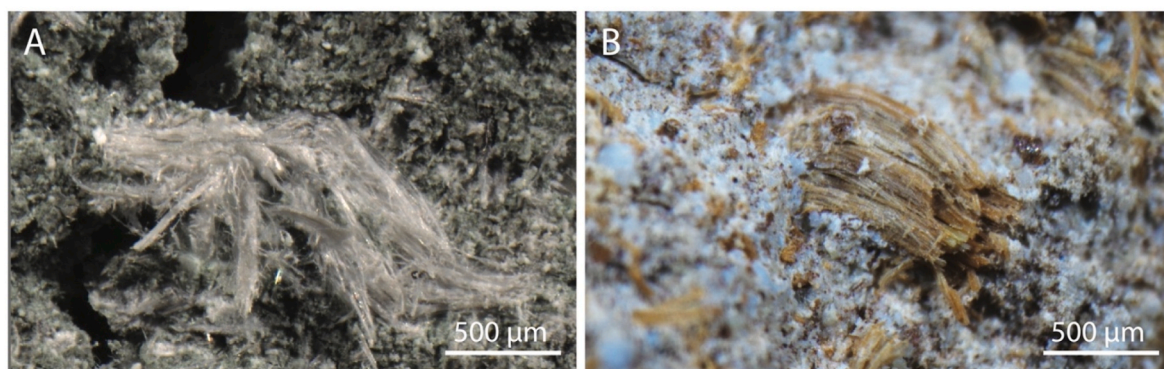


Fig. 1. Asbestos fibres pseudomorphs in thermally treated CAS: A) “Green sample”; B) “Red sample”. Images taken with a stereomicroscope Nikon SMZ25.

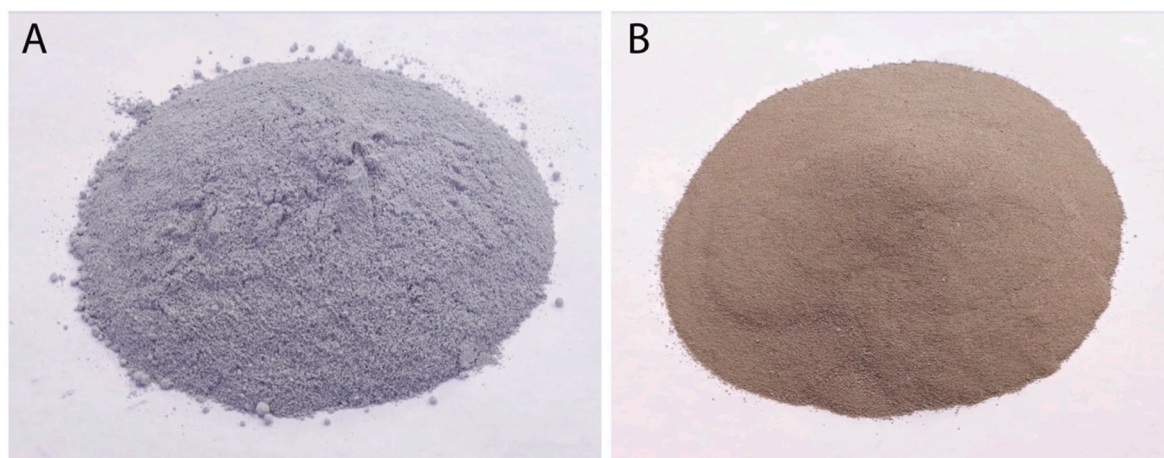


Fig. 2. Powdered samples of thermally treated CAS (DACP): A) “Green sample”; B) “Red sample” (photographs about 12 cm wide).

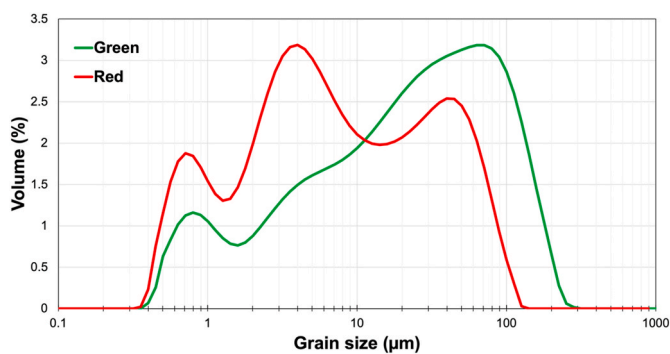


Fig. 3. Grain size distribution of the DACPs employed in the experiments.

**Table 2**  
Mineralogical compositions of Red and Green DACPs used in the experiments.

Phase	Ideal chemical formula	C/S	Red	Green
Akermanite	$\text{Ca}_2\text{Mg}(\text{Si}_2\text{O}_7)$	1:1	19.33	–
Bredigite	$\text{Ca}_{13.5}\text{Ba}_{0.3}\text{Mg}_{1.8}\text{Mn}_{0.4}\text{Si}_9\text{O}_{32}$	3:2	19.25	–
Jasmondite	$\text{Ca}_{11}(\text{SiO}_4)_4\text{O}_2\text{S}$	~3:1	–	17.49
Larnite	$\text{Ca}_2\text{SiO}_4$	2:1	3.67	19.08
Lime	CaO	–	–	8.51
Mayenite	$\text{Ca}_{12}\text{Al}_{14}\text{O}_{32}\text{Cl}_2$	–	–	3.73
Merwinite	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	3:2	17.84	–
Monticellite	$\text{CaMgSiO}_4$	1:1	–	1.51
Periclase	MgO	–	–	5.58
Glass	–	–	39.9	44.1

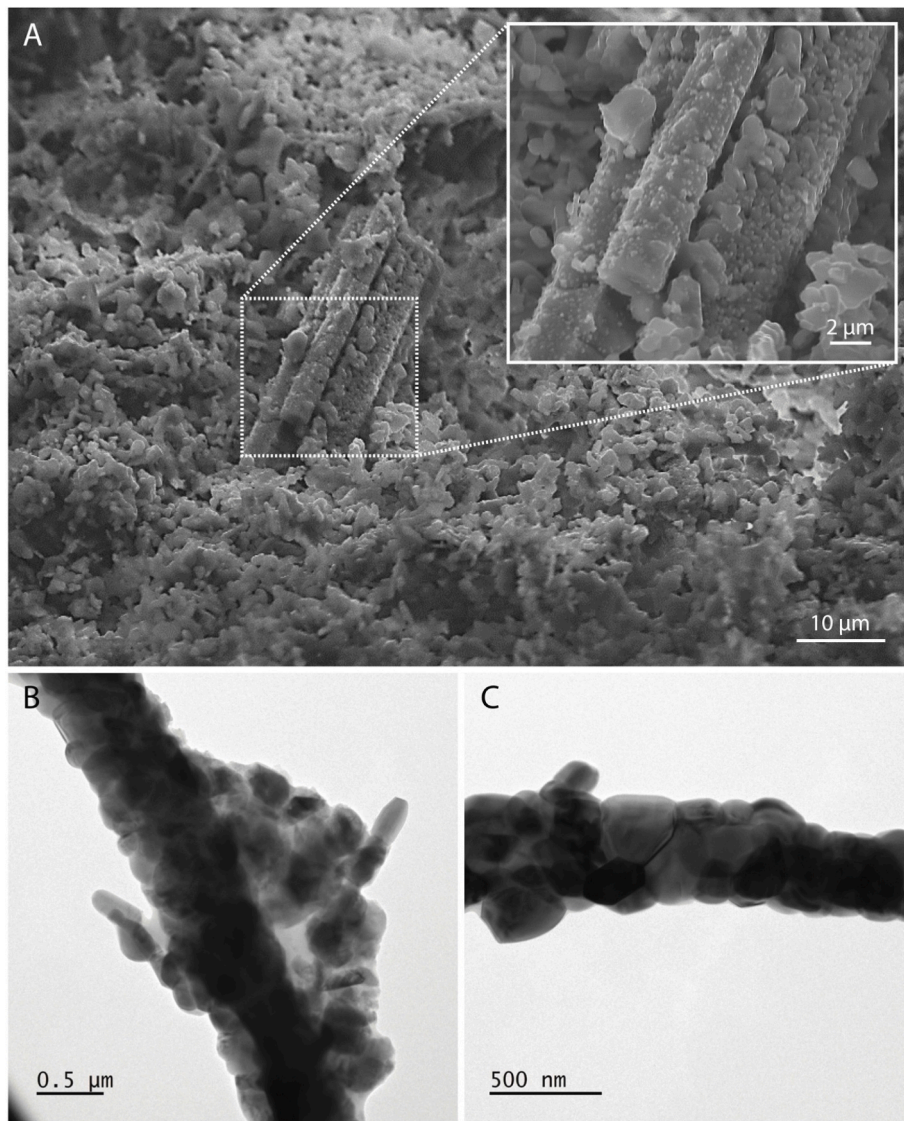
olivine ( $(\text{Mg,Fe})\text{SiO}_4$ ) and orthopyroxene ( $(\text{Mg,Fe})\text{SiO}_3$ ), glass and some Ca-bearing silicates, such as akermanite ( $\text{Ca}_2\text{MgSi}_2\text{O}_7$ ) and kirschsteinite ( $\text{CaFeSiO}_4$ ), these latter probably due to a reaction involving the calcite-rich matrix (Fig. 4).

## 2.2. Premixed mortar

The mortar employed in the experiments was a traditional premixed mortar formulation widely used in construction industry for the bedding of brick walls or for traditional plasters. Two different dosage, 4 wt% and 7 wt% of DACP for each DACP type (Red and Green) were added to the basic mix, as to obtain six different test samples (Table 3). The respective quantities of powdered components were weighted to get batches of 3 kg each, placed in plastic bags and subjected to manual homogenization for 5 min. In the basic mix, Lime 1 to 3 are limestone grounded in a hammer crusher and selected by sieving in the grain size range indicated in the table; Silica 1 and 2 are river silica (quartz) sand selected by sieving in the range indicated in the table. Their quantities were determined in order to obtain a balanced and continuous grain size curve between 0 and 3 mm in compliance with the rules of the art of traditional masonry and plaster mortars. The ligand is a type 2 Portland cement, with 6–20% of limestone and secondary constituents <5%.

## 2.3. Experimental

In order to obtain the chemical and mineralogical composition and the grain size distribution of the DACP, a number of mineralogical techniques has been employed, including energy dispersive X-ray fluorescence (EDXRF), XRPD, SEM, TEM and dynamic laser scattering (DLS).



**Fig. 4.** A) SEM image of deactivated Red sample showing fully recrystallized fibre pseudomorphs (inset) within a recrystallized matrix; B) and C) TEM images of fully recrystallized fibre pseudomorphs from the Green sample.

**Table 3**

Composition (in g) of the tested mixture samples.

Components	Red-0	Red-4	Red-7	Green-0	Green-4	Green-7
Lime 1 (1.2–3.0 mm)	100	100	100	100	100	100
Lime 2 (0.6–1.2 mm)	160	160	160	160	160	160
Lime 3 (0.0–0.15 mm)	260	220	190	260	220	190
Silica 1 (0.0–0.6 mm)	200	200	200	200	200	200
Silica 2 (0.3–1.0 mm)	150	150	150	150	150	150
PTL-II/AL 42.5 R (ligand)	90	90	90	90	90	90
Hydrated lime	40	40	40	40	40	40
DACP	0	40	70	0	40	70
Silipon RN 6031 <sup>a</sup>	0.26	0.26	0.26	0.26	0.26	0.26
Total	1000.26	1000.26	1000.26	1000.26	1000.26	1000.26

<sup>a</sup> Air-entraining.

Detailed information on the instrumentations and of the operating conditions are reported in [Marian et al. \(2021\)](#) and [Vergani et al. \(2022\)](#). The DACP enhanced mixtures have been subjected to physical and mechanical tests to gather information on their workability and strength and by SEM and XRPD for the mineral assemblage and microstructure.

Mechanical tests were performed with a Controls press model 65-L27P12 Pilot Pro. That is a four-column automatic press with a 15/

300 kN double chamber with incorporated devices for bending tests on 40 × 40 × 160 mm samples and for compression tests on 40 × 40 mm based prisms, according to UNI EN 196-1 standard.

Thermal cycles were performed with a Controls H series oven model 10-D1390/10H, with forced ventilation, capacity of 100 L and closed loop temperature control.

### 3. Results and discussion

#### 3.1. Technical and mechanical properties

The effects of the addition of DACP to the premixed mortar formulation were evaluated according to the UNI EN 1015–1,3,6,11 protocol. The following properties were determined: i) change in water demand; ii) variation of the plastic characteristics of the mixture; iii) influence on strength development after 7, 14, 28 days of maturation (all samples). The strength development was also evaluated after 60 and 90 days for the Green samples. All samples were preserved for the first 28 days at 20 °C and 95% of relative humidity (r.h.), then in a close laboratory environment. For the Red samples, thermal treatment cycles consisting in keeping the sample 24 h at 80 °C, two cycles per week, and wetting cycles with immersion in water for 24 h at 20 °C, followed by drying at 20 °C and 50% of r.h. (two cycles per week), were also carried out, after 28 days of normal maturation, for a total experimental duration of 220 days. Test samples were prepared as parallelepipeds 4 × 4x16 cm in size.

In Table 4 we report the main technical properties of the slurry. The addition of Red DACP does not affect the water demand of the original mix, whereas the addition of the Green one slightly increases the water demand. An acceptable water demand is a positive aspect since it excludes the use of additives to contain it, which could deteriorate the workability of the mortar. Differences in the water demand between the reference Red-0 and Green-0 samples, which should be equal in principle, may be due to minor differences in the calcareous and siliceous aggregates used, in terms of grain size and/or humidity, since the tests on the Red series and on the Green series were done at a distance of eight months each other, using nominally equal products, but actually different batches. The water demand, while being unaffected by the Red DACP content, increases with increasing DAP content in the Green series. This may be due to the presence of CaO (lime) in the Green DACP, absent in the Red DACP, which has a strong hydration tendency, and in general to the higher C/S ratio of the Green DACP. The addition of DACP, either Red or Green, does not affect the characteristics of the plastic mixture (e.g., thixotropy, stickiness, spreadability). This is also a very positive aspect as the addition of DACP, at least in the measure of up to 7 wt%, does not affect the original properties of the plastic body.

In Table 5 we report the flexural and compressive strengths and the weight at rupture of the test samples after varying maturation times and thermal and wetting cycles. The flexural and compressive strengths are also graphically reported in Fig. 5 for the non-treated samples. The addition of DACP slightly increases the strength of the mortar for both types of mixture. The addition of 4 wt% of DACP (Red-4) seems the optimal formulation for the Red samples, whereas 7 wt% seems the optimal for the Green (Green-7). The markedly higher strength of the Green samples compared to the Red ones at shorter maturation times is probably due to the difference in the starting DACP composition, i.e. the higher C/S ratio of the former. Indeed, higher C/S ratio components speed up the kinetics of hydration and therefore shorten the hardening

**Table 4**  
Technical properties of the slurry for the Red and Green mixtures (Red-0 and Green-0 = reference samples).

Evaluated property	Red-0	Red-4	Red-7	Green-0	Green-4	Green-7
Mixing water (g/kg)	196.6	195.5	195.4	164.3	177.7	186.4
Water/cement	2.18	2.17	2.17	1.82	1.97	2.07
Volumetric mass (kg/m <sup>3</sup> )	1834	1870	1813	1879	1829	1799
Thixotropy	+++	+++	+++	+++	+++	+++
Stickiness	++	+	+++	+	++	++
Solidity after 48 h	++	++	++	++	++	++
Vertical applicability	+++	+++	++	+++	+++	++

Note: + = good; ++ = very good; +++ = excellent.

time (Gualtieri and Boccaletti, 2011). On the other hand, calcium-magnesium-silicates, which are more abundant in the Red samples, are essentially unreactive to water (Viani and Gualtieri, 2013). The systematically higher strengths of the sample added with DACP (both Red and Green) respect to the reference samples, are due to the ligand properties of the DACP, which therefore generally acts as pozzolanic addendum. Finally, the Red samples subjected to thermal and wetting cycles for 25 weeks, two cycles per week, do not show any deterioration of the mechanical properties, but rather slightly higher values with respect to the reference sample.

#### 3.2. Mineral association microstructure

XRPD patterns for the Green-0, Red-7 and Green-7 samples look very similar, dominated by the calcite and quartz peaks, although with different relative abundances. Minor peaks relating to feldspar and mica can be recognised (Fig. 2S in supplementary materials). Rietveld quantitative phase analyses are reported in Table 1S of the supplementary materials. Calcite and quartz are major constituents of the premixed mortar and therefore also of the mixtures with DACP addition. Calcite, however, is 5–8% higher in the samples with DACP. A possible explanation is that the cement phases detected in the DACP (Table 2) and any other hydraulic ligand (calcium hydroxides) inverted to calcite, as systematically observed in asbestos cement slates (Vergani et al., 2022). This is also consistent with the paucity of cement phases detected. Portlandite, the only cement phase that could be refined at significant levels, comes from the ligand since it is higher in the reference sample. Among the minor phases there are plagioclase and mica. These probably are present as impurities in the sands of the premixed mortar. The higher content of mica in the reference sample than in the DACP bearing samples may be due to a dilution effect caused by the addition of DACP or due to heterogeneities in the starting materials. Finally, gismondine, a zeolite typical of low temperature alteration of calcium silicates, may be an alteration product of the cement phases. It should be remarked that the DACP and the ligand contain some amorphous material that it is not taken into account in Table 1S. The Red and Green DACP contain 40% and 44% of glass, respectively (Table 2). The amount of amorphous in the ligand is not known, but according to some literature data (e.g. Álvarez-Pinazo et al., 2012), the amorphous in cement may vary between 7 and 28 wt%. Therefore, a maximum amount of ~5.5 wt% of amorphous material is expected in the Red-7 and Green-7 samples. However, attempts to refine the amorphous fraction in these samples were unsuccessful.

The same samples investigated by XRPD were further investigated by SEM coupled with energy dispersive X-ray spectroscopy (EDS). As shown in Fig. 6, all samples are made of large grains (here <100 μm) of calcite, quartz, and feldspar in a microcrystalline matrix (Fig. 6A). At higher magnification, both the reference and DACP-bearing samples show pores in the matrix (Fig. 6C and F) with nanometre-size acicular crystals (Fig. 6B and D). An expeditious EDS survey on these crystals reveals an enrichment in SO<sub>3</sub>, CaO, and Al<sub>2</sub>O<sub>3</sub>. This phase might be identified as ettringite, i.e. a common hydration product in concrete and mortar, especially when enriched in C<sub>2</sub>S (Ftikos and Philippou, 1990). This hypothesis is further supported by their peculiar acicular shape and nanometre size, as already reported by Gualtieri and Boccaletti (2011). However, XRPD did not detect the presence of ettringite or any S-rich phase, probably due to its weight content below the detection limit (~1 wt%). Other minerals sometimes detected by SEM-EDS were Fe-rich oxides (Fig. 6E).

### 4. Conclusions

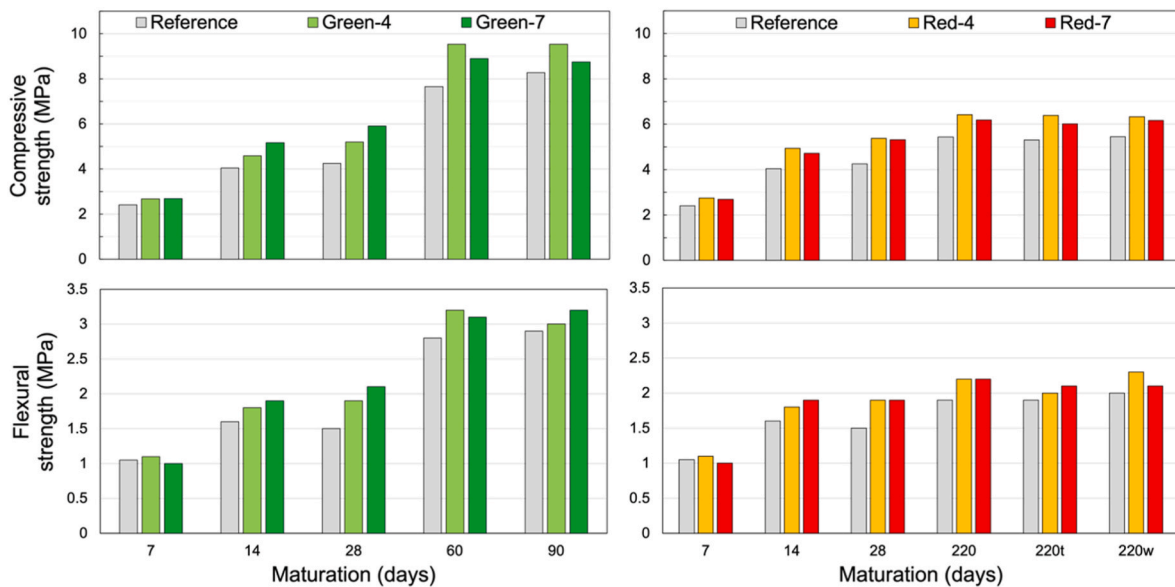
The thermal inertization of asbestos cement is a viable route and, according to recent patents, sustainable. Thermally treated slates contain only non-toxic minerals that can be re-introduced in the productive cycle. Among the most promising industrial applications, the

**Table 5**

Mechanical resistance presented by the test samples at different maturation times and after thermal and wetting durability tests (standard deviations referring to the last digits in brackets).

Maturation (days)	Measured property	Red-0	Red-4	Red-7	Green-0	Green-4	Green-7
7	$\sigma_f$ (MPa)	1.05 (10)	1.10 (13)	1.00 (9)	1.05 (9)	1.10 (10)	1.00 (5)
	$\sigma_c$ (MPa)	2.46 (14)	2.75 (10)	2.69 (8)	2.41 (15)	2.68 (21)	2.69 (14)
	Wt (g)	445 (5)	455 (9)	440 (10)	445 (5)	465 (15)	450 (15)
14	$\sigma_f$ (MPa)	1.60 (13)	1.80 (5)	1.90 (9)	1.60 (9)	1.80 (9)	1.90 (10)
	$\sigma_c$ (MPa)	4.53 (30)	4.94 (13)	4.72 (19)	4.04 (16)	4.58 (23)	5.16 (21)
	Wt (g)	415 (5)	425 (13)	415 (5)	455 (0)	450 (9)	435 (10)
28	$\sigma_f$ (MPa)	1.70 (5)	1.90 (5)	1.90 (9)	1.50 (9)	1.90 (9)	2.10 (13)
	$\sigma_c$ (MPa)	5.09 (12)	5.38 (22)	5.31 (15)	4.25 (26)	5.19 (32)	5.91 (35)
	Wt (g)	410 (5)	415 (10)	410 (5)	480 (18)	485 (9)	475 (15)
60	$\sigma_f$ (MPa)	–	–	–	2.80 (13)	3.20 (9)	3.10 (13)
	$\sigma_c$ (MPa)	–	–	–	7.65 (39)	9.53 (21)	8.90 (58)
	Wt (g)	–	–	–	440 (5)	435 (5)	420 (13)
90	$\sigma_f$ (MPa)	–	–	–	2.90 (13)	3.00 (9)	3.20 (15)
	$\sigma_c$ (MPa)	–	–	–	8.28 (43)	9.53 (30)	8.75 (41)
	Wt (g)	–	–	–	440 (9)	435 (9)	415 (5)
220	$\sigma_f$ (MPa)	1.90 (13)	2.20 (13)	2.20 (9)	–	–	–
	$\sigma_c$ (MPa)	5.44 (37)	6.42 (19)	6.19 (31)	–	–	–
	Wt (g)	400 (9)	405 (5)	405 (0)	–	–	–
220t	$\sigma_f$ (MPa)	1.90 (13)	2.00 (15)	2.10 (10)	–	–	–
	$\sigma_c$ (MPa)	5.30 (32)	6.39 (41)	6.01 (28)	–	–	–
	Wt (g)	405 (9)	400 (9)	405 (5)	–	–	–
220w	$\sigma_f$ (MPa)	2.00 (9)	2.30 (5)	2.10 (10)	–	–	–
	$\sigma_c$ (MPa)	5.45 (22)	6.33 (35)	6.17 (31)	–	–	–
	Wt (g)	410 (0)	415 (5)	400 (5)	–	–	–

Note: the reported flexural strength ( $\sigma_f$ ) values are the average of 3 tests, whereas those of the compressive strength ( $\sigma_c$ ) are the average of 6 tests; Wt is the average weight of the test sample before rupture (3 tests).



**Fig. 5.** Compressive (upper) and flexural (lower) strengths as function of maturation time for the Red and Green samples (220t = maturation after thermal cycle; 220w = maturation after wetting cycle).

addition of DACP to a common mortar for plaster applications has been investigated here. Both, DACP obtained from a classical thermal process operating under oxidizing conditions (Red samples) and according to a recent process operating under controlled atmosphere (Green samples), were used. The results show that: i) the addition of DACP (up to 7 wt%) does not affect (Red) or slightly increases (Green) the water demand of the original mix; ii) the addition of DACP (either Red or Green) does not affect the characteristics of the plastic mixture in terms of thixotropy, stickiness, and spreadability; iii) the addition of DACP slightly increases the strength of the mortar; optimal values of 4 and 7 wt% of DACP were determined for the Red- and Green-bearing samples, respectively; iv) Red-bearing samples subjected to aging tests show a slightly better behaviour than the reference, DACP-free sample.

Overall, these tests demonstrate that the recycling of thermally deactivated ACM is possible in traditional mortars for plaster applications. The safe recycling of deactivated ACM can partly compensate for the heat treatment cost and be beneficial for the environment. Indeed, any economical treatment with a safe re-use scenario is worthwhile if it can prevent landfilling, encapsulation and confinement of ACM with the consequent perpetuation of the health hazard. Given the large amount of mortars used worldwide, a quick end of the “asbestos problem” is envisaged if a such a strategy were adopted by decision makers.

**CRedit authorship contribution statement**

**Giancarlo Capitani:** Writing – original draft, Supervision, Project

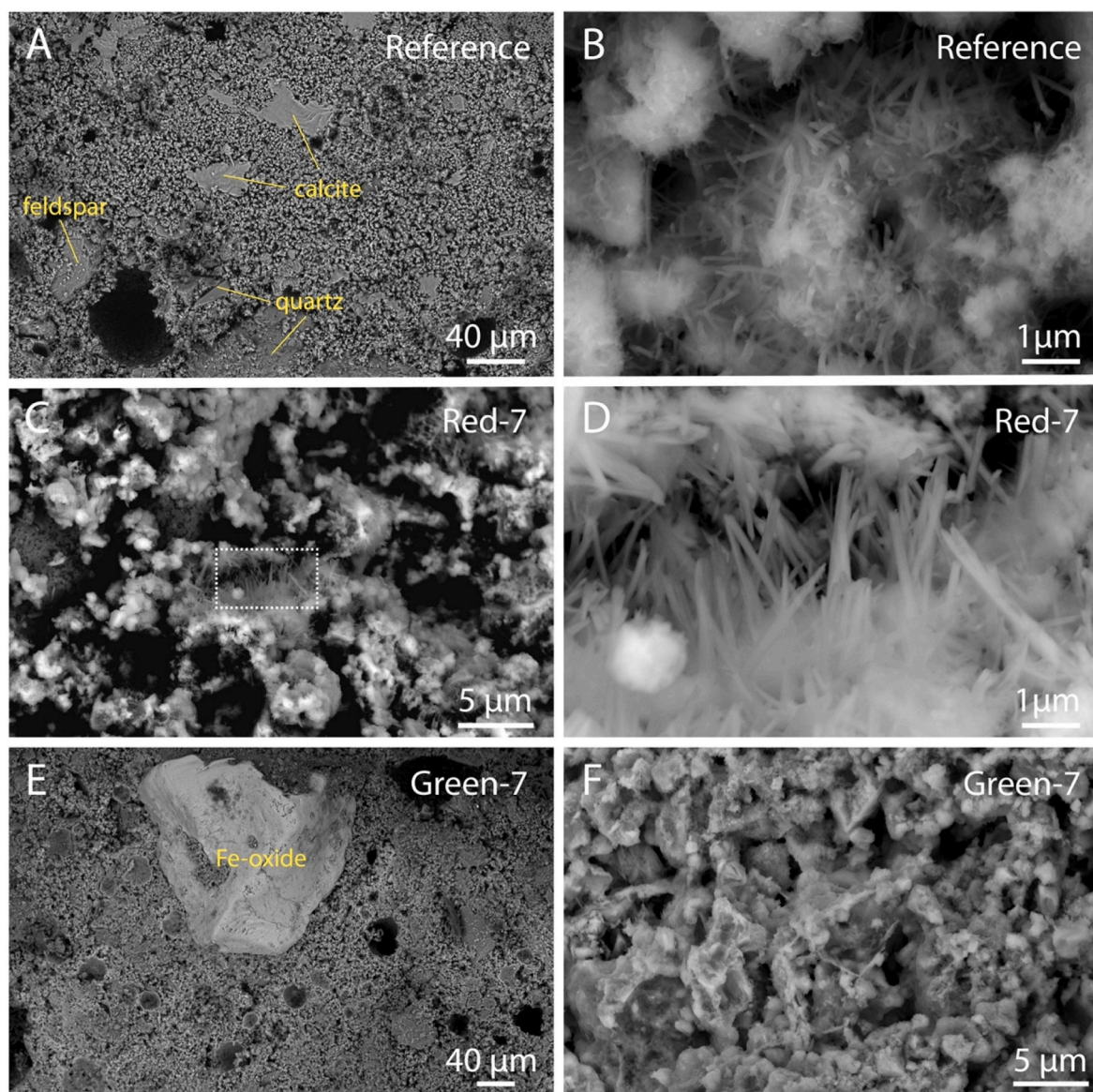


Fig. 6. SEM images of Reference (A and B), Red-7 (C and D), and Green-7 (E and F) samples.

administration, Methodology, Funding acquisition, Conceptualization. **Michele Dalpiaz**: Validation, Resources, Methodology, Data curation. **Fabrizio Vergani**: Software, Data curation. **Fabrizio Campanale**: Visualization, Data curation. **Roberto Conconi**: Writing – review & editing, Data curation. **Stefano Odorizzi**: Resources, Methodology.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2024.120507>.

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