

**CHOOSING THE CONSOLIDANT FOR CARBONATE SUBSTRATES:
TECHNICAL PERFORMANCE AND ENVIRONMENTAL SUSTAINABILITY OF
SELECTED INORGANIC AND ORGANIC PRODUCTS**

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Supplementary Material

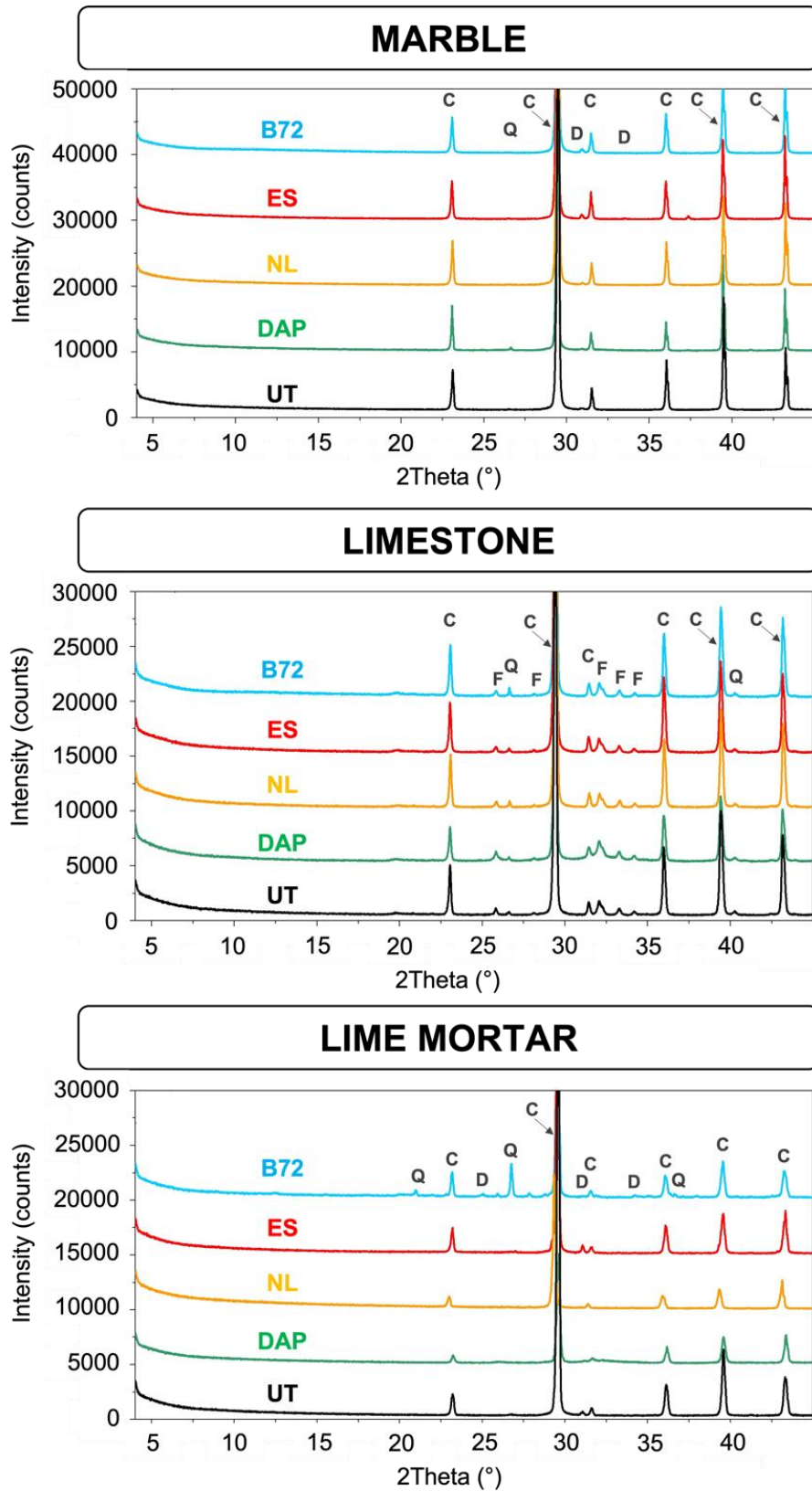


Figure S1: XRD pattern of untreated and consolidated surfaces. Legend indicates: (C) calcite; (D) dolomite; (F) fluorapatite; (Q) quartz.

Table S1: Life cycle inventory for the DAP treatment. Quantities related to application until apparent refusal.

Flow	Unit	Amount for application to:			Assumptions and linked background unit process
		Marble	Limestone	Lime mortar	
Reference product (DAP)	L	0.9	3.9	6.9	Quantities estimated in § 3.1.1 of the paper
Production: consolidant and precursors					
Ammonia	kg	0.09	0.40	0.71	See modelling of DAP production in Dal Pozzo et al. (2023) <i>Ammonia, as 100% NH3 production; technology mix; production mix, at plant; 100% active substance / RER / 2017</i> (Ecoinvent database)
Phosphoric acid	kg	0.26	1.15	2.03	See modelling of DAP production in Dal Pozzo et al. (2023) <i>Phosphoric acid production; technology mix; production mix, at plant; 100% active substance / RER / 2017</i> (Ecoinvent database)
Energy for stirring	kJ	0.03	0.11	0.20	See modelling of DAP production in Dal Pozzo et al. (2023) <i>Electricity grid mix; AC, technology mix; production mix (region specific plants), at consumer; <1kV / IT / 2011</i> (Sphera database)
Production: solvent					
DI water	kg	1.91	8.27	14.64	The amount of DI water includes both its consumption in the synthesis of DAP and its presence as solvent in the final DAP formulation. <i>De-ionised water production, production mix, at plant, technology mix, 100% active substance / RER / 2017</i> (Ecoinvent database)
Transportation and packaging					
Transportation by road	km	500 ^a / 300 ^b	500 ^a / 300 ^b	500 ^a / 300 ^b	^a for the supply of precursors ^b for the delivery of the consolidant product to the site of application <i>Articulated lorry transport, Total weight <7.5 t, mix Euro 0-5, consumption mix, to consumer, diesel driven / EU27 / 2013</i> (Sphera database)
Transportation by plane	km	10,000	10,000	10,000	Only for the supply of Japanese paper <i>Cargo plane; technology mix, kerosene driven, cargo; consumption mix; 65 t payload / GLO / 2013</i> (Sphera database)
Packaging: HDPE buckets	kg	0.05	0.20	0.35	Assumption: product marketed in buckets of 5 L of capacity <i>Polyethylene, HDPE, granulate; production mix, at plant / EU28 / 2013</i> (Sphera database)

Use: application (production of auxiliary materials and rinsing)					
Limewater	kg	7.00	7.00	7.00	Calcium hydroxide production; technology mix; production mix, at plant; 100% active substance / RER / 2017 (Ecoinvent database)
Cellulose pulp	kg	0.60	0.60	0.60	Cellulose (excluding blowing) production; technology mix; production mix, at plant; 100% active substance / RER / 2017 (Ecoinvent database)
Japanese paper	kg	0.01	0.01	0.01	Assumption: negligible impacts of production, considering the small amount of material required. Only transportation by plane is considered
Use: evaporation of volatiles					
Carbon dioxide	kg	0.19	0.82	1.46	Quantitative release of CO ₂ according to the following reactions, involved in the DAP consolidation mechanism on the substrate: i) $10 CaCO_3 + 5 (NH_4)_2HPO_4 \rightarrow Ca_{10}(PO_4, CO_3)_6(OH, CO_3)_2 + 5 (NH_4)_2CO_3 + 3 CO_2 + 2 H_2O$ ii) $(NH_4)_2CO_3 \rightarrow 2 NH_3 + CO_2 + H_2O$

Table S2. Life cycle inventory for the NL treatment. Quantities related to application until apparent refusal.

Flow	Unit	Amount for application to:			Assumptions and linked background unit process
		Marble	Limestone	Lime mortar	
Reference product (NL)	L	1.2	4.8	7.8	Quantities estimated in § 3.1.1 of the paper
Production: consolidant and precursors					
Calcium chloride	kg	0.010	0.038	0.062	See modelling of NL production in Dal Pozzo et al. (2023) <i>Calcium chloride production; technology mix; production mix, at plant; 100% active substance / RER / 2017</i> (Ecoinvent database)
Sodium hydroxide	kg	0.007	0.027	0.045	See modelling of NL production in Dal Pozzo et al. (2023) <i>Sodium hydroxide production; technology mix; production mix, at plant; 100% active substance / RER / 2017</i> (Ecoinvent database)
DI water	kg	0.64	2.57	4.17	See modelling of NL production in Dal Pozzo et al. (2023) <i>De-ionised water production, production mix, at plant, technology mix, 100% active substance / RER / 2017</i> (Ecoinvent database)
Energy for heating	kJ	117.8	471.4	766.0	See modelling of NL production in Dal Pozzo et al. (2023) <i>Electricity grid mix; AC, technology mix; production mix (region specific plants), at consumer; <1kV / IT / 2011</i> (Sphera database)
Energy for stirring	kJ	0.13	0.52	0.84	See modelling of NL production in Dal Pozzo et al. (2023) <i>Electricity grid mix; AC, technology mix; production mix (region specific plants), at consumer; <1kV / IT / 2011</i> (Sphera database)
Production: solvent					
Ethanol	kg	1.24	4.94	8.03	The amount of ethanol includes both its consumption in the synthesis of NL and its presence as solvent in the final NL formulation. <i>Ethanol production; technology mix; production mix, at plant; 100% active substance / RER / 2017</i> (Ecoinvent database)
Transportation and packaging					
Transportation by road	km	500 ^a / 300 ^b	500 ^a / 300 ^b	500 ^a / 300 ^b	^a for the supply of precursors ^b for the delivery of the consolidant product to the site of application <i>Articulated lorry transport, Total weight <7.5 t, mix Euro 0-5, consumption mix, to consumer, diesel driven / EU27 / 2013</i> (Sphera database)

Transportation by plane	km	10,000	10,000	10,000	Only for the supply of Japanese paper <i>Cargo plane; technology mix, kerosene driven, cargo; consumption mix; 65 t payload / GLO / 2013 (Sphera database)</i>
Packaging: HDPE buckets	kg	0.06	0.24	0.39	Assumption: product marketed in buckets of 5 L of capacity <i>Polyethylene, HDPE, granulate; production mix, at plant / EU28 / 2013 (Sphera database)</i>
<i>Use: application (production of auxiliary materials and rinsing)</i>					
Limewater	kg	7.00	7.00	7.00	<i>Calcium hydroxide production; technology mix; production mix, at plant; 100% active substance / RER / 2017 (Ecoinvent database)</i>
Cellulose pulp	kg	0.60	0.60	0.60	<i>Cellulose (excluding blowing) production; technology mix; production mix, at plant; 100% active substance / RER / 2017 (Ecoinvent database)</i>
Japanese paper	kg	0.01	0.01	0.01	Assumption: negligible impacts of production, considering the small amount of material required. Only transportation by plane is considered

Table S3. Life cycle inventory for the ES treatment. Quantities related to application until apparent refusal.

Flow	Unit	Amount for application to:			Assumptions and linked background unit process
		Marble	Limestone	Lime mortar	
Reference product (ES)	L	0.9	2.8	6.4	Quantities estimated in § 3.1.1 of the paper
Production: consolidant and precursors					
Silicon tetrachloride	kg	0.55	1.72	3.94	See modelling of ES production in Sanchez-Ramirez et al. (2018) <i>Silicon tetrachloride, at plant / EU+EFTA / 2015</i> (Env. Footprint RPs database)
Ethanol	kg	0.67	2.07	4.74	See modelling of ES production in Sanchez-Ramirez et al. (2018) <i>Ethanol production; technology mix; production mix, at plant; 100% active substance / RER / 2017</i> (Ecoinvent database)
Energy for heating	kJ	678.6	2111.2	4825.6	See modelling of ES production in Sanchez-Ramirez et al. (2018) <i>Electricity grid mix; AC, technology mix; production mix (region specific plants), at consumer; <1kV / IT / 2011</i> (Sphera database)
Energy for stirring	kJ	0.54	1.68	3.84	See modelling of ES production in Sanchez-Ramirez et al. (2018) <i>Electricity grid mix; AC, technology mix; production mix (region specific plants), at consumer; <1kV / IT / 2011</i> (Sphera database)
Production: solvent					
White spirit	kg	0.23	0.70	1.60	<i>White spirit production, production mix, at plant, technology mix, 100% active substance / RER / 2017</i> (Ecoinvent database)
Transportation and packaging					
Transportation by road	km	500 ^a / 300 ^b	500 ^a / 300 ^b	500 ^a / 300 ^b	^a for the supply of precursors ^b for the delivery of the consolidant product to the site of application <i>Articulated lorry transport, Total weight <7.5 t, mix Euro 0-5, consumption mix, to consumer, diesel driven / EU27 / 2013</i> (Sphera database)
Packaging: HDPE buckets	kg	0.05	0.14	0.32	Assumption: product marketed in buckets of 5 L of capacity <i>Polyethylene, HDPE, granulate; production mix, at plant / EU28 / 2013</i> (Sphera database)
Use: application (production of auxiliary materials and rinsing)					
White spirit	kg	2	2	2	For rinsing of excess product <i>White spirit production, production mix, at plant, technology mix, 100% active substance / RER / 2017</i> (Ecoinvent database)

Table S4. Life cycle inventory for the B72 treatment. Quantities related to application until apparent refusal.

Flow	Unit	Amount for application to:			Assumptions and linked background unit process
		Marble	Limestone	Lime mortar	
Reference product (B72)	L	1.1	3.0	5.4	Quantities estimated in § 3.1.1 of the paper
Production: consolidant and precursors					
Acrylic resin	kg	0.045	0.124	0.223	Industrial production of beads of acrylic resin. It is assumed that beads are dissolved into acetone at the site of application in the proportions mentioned in § 2.2. <i>Silicon tetrachloride, at plant / EU+EFTA / 2015</i> (Env. Footprint RPs database)
Production: solvent					
Acetone	kg	0.86	2.35	4.23	<i>White spirit production, production mix, at plant, technology mix, 100% active substance / RER / 2017</i> (Ecoinvent database)
Transportation and packaging					
Transportation by road	km	300	300	300	For the delivery of the consolidant product to the site of application <i>Articulated lorry transport, Total weight <7.5 t, mix Euro 0-5, consumption mix, to consumer, diesel driven / EU27 / 2013</i> (Sphera database)
Packaging: HDPE buckets	kg	0.06	0.15	0.27	Assumption: product marketed in buckets of 5 L of capacity <i>Polyethylene, HDPE, granulate; production mix, at plant / EU28 / 2013</i> (Sphera database)
Use: application (production of auxiliary materials and rinsing)					
Acetone	kg	3	3	3	For rinsing of excess product <i>White spirit production, production mix, at plant, technology mix, 100% active substance / RER / 2017</i> (Ecoinvent database)

References for Tables S1-S4

Life cycle databases (nodes of the European Life Cycle Data Network):

- **Ecoinvent:** <http://ecoinvent.lca-data.com/> **Env. Footprint RPs:** <http://eplca.jrc.ec.europa.eu/EF-node/> **Sphera:** <http://lcdn.thinkstep.com/>

Literature:

Dal Pozzo, A., Masi, G., Tugnoli, A., Sassoni, E., 2023. Towards Green Materials for Cultural Heritage Conservation: Sustainability Evaluation of Products for Stone Consolidation, RILEM Bookseries 40 (2023) 751-760.

Sanchez-Ramirez, E., Ramirez-Marquez, C., Quiroz-Ramirez, J.J., Contreras-Zarazua, G., Segovia-Gernandez, J.G., Cervantes-Jauregui, J.A., 2018. Reactive Distillation Column Design for Tetraethoxysilane (TEOS) Production: Economic and Environmental Aspects. Ind. Eng. Chem. Res. 57, 5024-5034.