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RE^{4} Project

REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction

D4.4

Quality classes and potential applications for recovered CDW-derived materials

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Distribution[2]	PU
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Abstract:	D4.4 reports on RE^{4} materials classification according to the potential use for structural and non-structural applications. The document includes an overview of existing standards relevant for the RE^{4} materials, their classification according to them and it also suggests new quality classes for these materials both for RE^{4} and alternative applications.
File Name	Deliverable D4.4_Quality classes and potential applications for recovered CDW-derived materials_V2.0

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[1] Just mention the partner(s) responsible for the Deliverable
[2] PU: Public, RE: restricted to a group specified by the consortium, CO: Confidential, only for members of the consortium; Commission services always included.
[3] Draft, Revised, Final

TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

ACRONYMS & ABBREVIATIONS

CDW	Construction and Demolition Waste
FL	Floating particles
LW	Lightweight
LWA	Lightweight Aggregates
MF	Mineral Fraction from CDW
N-EU	Northern Europe
NS	Natural sand
OPC	Ordinary Portland Cement
PTFE	Polytetrafluoroethylene
Ra	Bituminous materials
Rb	clay masonry units, calcium silicate units and aerated non-floating concrete
Rc	concrete, concrete products, mortar and concrete masonry
Rg	glass
RP	Mixed Rigid Plastic from CDW
RS	Recycled sand
Ru	unbound aggregate, natural stone and hydraulically bound aggregate
SCM	Supplementary Cementitious Materials
S-EU	Southern Europe
SS	Standard sand
w/c	Water to cement ratio
WP	Mixed Wood and Plastic from CDW
wt	weight
X	clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum

1. EXECUTIVE SUMMARY

This report deals with quality classification and potential applications for recovered sorted CDW-derived materials investigated in RE^4 project, whose characterisation, performance in mortar/concrete and variability (over time and by geographic location) have been reported in previous RE^4-deliverables (D4.2 and D4.3). The CDW-derived sorted materials include mineral fractions (0-2, 2-8, 8-16 mm and silt/clay size-fractions), non-mineral fractions such as LW scraps (rigid plastic, mixed wood/plastic and wood flakes) and timber; the geographic sources of such CDW includes Germany and Norway (Northern Europe/N-EU) and France (Southern Europe/S-EU).

The CDW fraction for which the most elaborated existing quality classing system exists, is the coarse mineral CDW fraction (> 2 mm). In the basic standard (EN 13369:2013) [1], it is specified that the recycled coarse aggregates shall not adversely affect the setting and hardening of the concrete and its durability. In the concrete standard (EN206:2013) [2], classification of mineral CDW of unknown source is carried out according to the concrete aggregate standard (EN 12620+A1:2008) [3] and relies on examination and quantification of the relative proportions of the constituent materials, as specified in the test standard EN 933-11. Based on these, the coarse recycled aggregates shall be quantified in the relative proportions of different constituents and classified in two aggregate quality classes: Type A and Type B. Based on assessment of mineral CDW and its performance in concrete investigated in the RE^4 project in relation to the present quality classes, new classes are suggested: Type A+, Type A, Type B and Type L. The quality of both Type A+ and Type A are sufficient for use in concrete in load-bearing structures, whereas class Type B would be intended, for instance, for applications in concrete masonry units or in non-structural concrete. Type L should be used for mineral CDW which have oven-dry density ≤ 2000 kg/m^3, thereby qualifying as LWA for lightweight concrete.

These classes can also be used for other products, e. g. reconstituted roof tiles (Type A+) and façade panel applications (Type A, B or L), with additional requirements on frost-resistance, when relevant.

When it comes to non-mineral LW CDW, which result from rigid plastic (RP) and mixed wood-plastic (WP) fractions as well as from wood (W) scraps, these could be used as aggregates and flakes for the development of insulating building materials. Even if the available standards do not specifically cover these kind of LW materials, building products (e.g. concretes, panels) incorporating them have showed promising results in terms of crucial properties such as density and thermal conductivity. Materials based on LW CDW resulted suitable for non-structural applications especially where improved thermal insulating performance are required.

Concerning timber and wood products, two main aspects have to be considered for their classification: timber grading and contamination levels. For timber grading, reused elements and products fall under the same set of codes as new elements and products. Contamination is also a crucial parameter for determining the suitability and potential of reuse for timber. However, no unified regulation is in place in Europe. Timber components, in line with what above mentioned, have been classified according to the current norm for virgin materials.

2. INTRODUCTION

Deliverable D4.4 summarises the results obtained by the RE^4 team involved in Task 4.4 – *Quality classes and potential applications for recovered CDW-derived materials*. The work in this task focused on the quality assessment of different sorted CDW fractions (i.e. mineral and non-mineral) obtained by CDE from recycling centres in N-EU and S-EU.

2.1 Relevant Work Package input

This deliverable builds upon the knowledge obtained from D2.1 "CDW specifications and material requirements for prefabricated structures", D4.2 "Characterisation of CDW-derived materials" and D4.3 "Effect of the variability of CDW batches" [4] [5] [6]. The defined classes and related applications will be transferred to WP5 for the development of formulations for robust materials (structural, non-structural, lightweight, insulating) integrating high ratios of CDW.

2.2 WP objectives and limitations

The objective of D4.4 has been to compile the results from Task 4.2 and Task 4.3, in order to define a codification of quality classes for identifying the optimal recycling strategy for each fraction of CDW, maximising the technical and economic value of sorted materials. Reutilisation of timber from CDW has also been classified in a system for defining the best valorisation strategy.

2.3 Deliverable structure

D4.4 includes the following sections:

- *New material data*, which contains additional data for CDW fractions of different typology, treatment and source, not published in any of the previous RE^4 deliverables.
- *Materials and existing standards, rules and guidelines*, which gives a review of the present state when it comes to quality assessment of CDW fractions in construction and building materials.
- *Classification of the RE^4 materials*, in which a quality assessment is conducted on the various CDW fractions - characterized in D4.2, D4.3 and the "New material data" section of this deliverable - using the present standards, rules and guidelines summarized in the previous section.
- *Suggested new quality classes,* in which new and/or modified old quality assessment systems are suggested, for identification of best use of a certain CDW fraction in different materials and building applications.
- *Conclusions and recommendations*, which presents the main achievements of the investigations performed on RE^4 CDW and their potential for different applications.
- *References*, which presents relevant documents used as reference in this study.

3. NEW MATERIAL DATA

This deliverable uses CDW data presented in earlier contributions (D4.2 and D4.3). However, data on improved sorted CDW from RISE where not presented in D4.2. Furthermore, the fourth batch of sorted CDW from Southern Europe received by CDE and analysed by RISE in the end of Task 4.3 were not included in the T4.3 deliverable (D4.3) and, therefore, the results on this batch arepresented here.

3.1 Improved sorted CDW

Sorted CDW from Northern and Southern Europe has been manually sorted, in order to produce a so called "improved sorted" aggregate. Bricks, bituminous material, other clinker materials, gypsum mortar, light weight concrete, concrete with fibres, glass, metals, wood and plastics have been removed from a portion (15 kg) of 8/16 material from Northern and Southern Europe, respectively (Figure 1). Some properties were tested on the new improved sorted 8/16 accordingly produced, whereas some of it was crushed in a lab cone-crusher and sieved in order to produce improved sorted 2/8 and 0/2 fractions. Some properties were tested also on these fractions and mortar tests were conducted on mortars based on the 0/2 fraction. In order to enable comparison between results on the sorted and the improved sorted CDW 2/8 and 0/2 fractions, some sorted 8/16 was crushed and sieved in the same manner as manually sorted 8/16. In all tables and text below, it is assumed but not explicitly written that the improved sorted CDW refers to manually sorted CDW.

Figure 1: Improved sorted CDW of size-fraction 8/16 mm (pile marked with red circle), surrounded by components that have been sorted out. Upper image is from Northern Europe (NE B1), lower image from Southern Europe (SE B1).

Density and water absorption was measured following the method described in EN 1067-6. Details on this test can be found in D4.2. Results are presented in Table 1.

Table 1: Density and water absorption.

Property	Unit	NE Sorted			SE Sorted		
		0/2 mm	2/8 mm	8/16 mm	0/2 mm	2/8 mm	8/16 mm
Water absorption, WA_{24}	%	1.4	3.3	3.0	4.0	8.1	7.7
Apparent density, ρ_a	kg/m³	2650	2690	2510	2640	2680	2530
Particle density on an oven dried basis, ρ_{od}	kg/m³	2550	2470	2340	2390	2200	2120
Particle density on a saturated and surface-dried basis, ρ_{ssd}	kg/m³	2590	2560	2410	2480	2380	2280
Property	**Unit**	**NE Sorted (crushed)**			**SE Sorted (crushed)**		
		0/2 mm*	**2/8 mm***	**8/16 mm**	**0/2 mm***	**2/8 mm***	**8/16 mm**
Water absorption, WA_{24}	%	2.1	3.0	-	3.9	6.1	-
Apparent density, ρ_a	kg/m³	2710	2690	-	2680	2630	-
Particle density on an oven dried basis, ρ_{od}	kg/m³	2560	2490	-	2420	2260	-
Particle density on a saturated and surface-dried basis, ρ_{ssd}	kg/m³	2610	2560	-	2520	2400	-

Property	Unit	NE Improved Sorted			SE Improved Sorted		
		0/2 mm*	2/8 mm*	8/16 mm	0/2 mm*	2/8 mm*	8/16 mm
Water absorption, WA_{24}	%	1.8	2.8	3.0	1.8	4.0	4.9
Apparent density, ρ_a	kg/m³	2710	2700	2660	2710	2680	2360
Particle density on an oven dried basis, ρ_{od}	kg/m³	2580	2510	2460	2580	2450	2330
Particle density on a saturated and surface-dried basis, ρ_{ssd}	kg/m³	2630	2580	2530	2630	2510	2440

*Produced from crushed 8/16

Grading was measured following the method described in EN 933-1. Details on this test can be found in D4.2. Results are presented in the tables (Table 2, Table 3 and Table 4) and figures (Figure 2, Figure 3, Figure 4, Figure 5, Figure 6 and Figure 7) below.

Table 2: Particle-size distribution of size-fraction 0/2 mm.

Aperture size [mm]	Cumulative passing					
	NE Sorted	SE Sorted	NE Sorted (crushed)*	SE Sorted (crushed)*	NE Improved Sorted*	SE Improved Sorted*
	% Average	% Average	% Average	% Average	% Average	% Average
8	100	100	100	100	100	100
5.6	100	100	100	100	100	100
4	100	100	100	100	100	100
2	90	91	100	100	100	100
1	65	70	60	58	61	58
0.5	43	44	39	34	38	34
0.25	23	20	27	21	24	21
0.125	9	8	19	14	16	14
0.063	4	5	14	10	11	10

*Produced from crushed 8/16

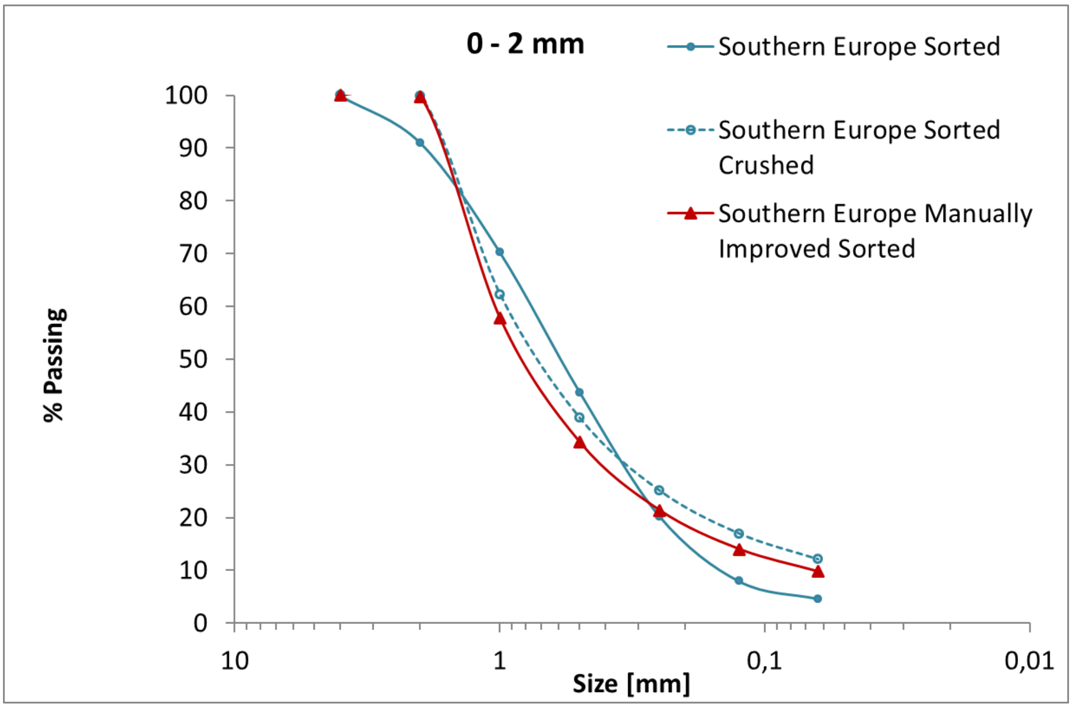

Figure 2: Particle size distribution of SE CDW mineral-fraction 0/2.

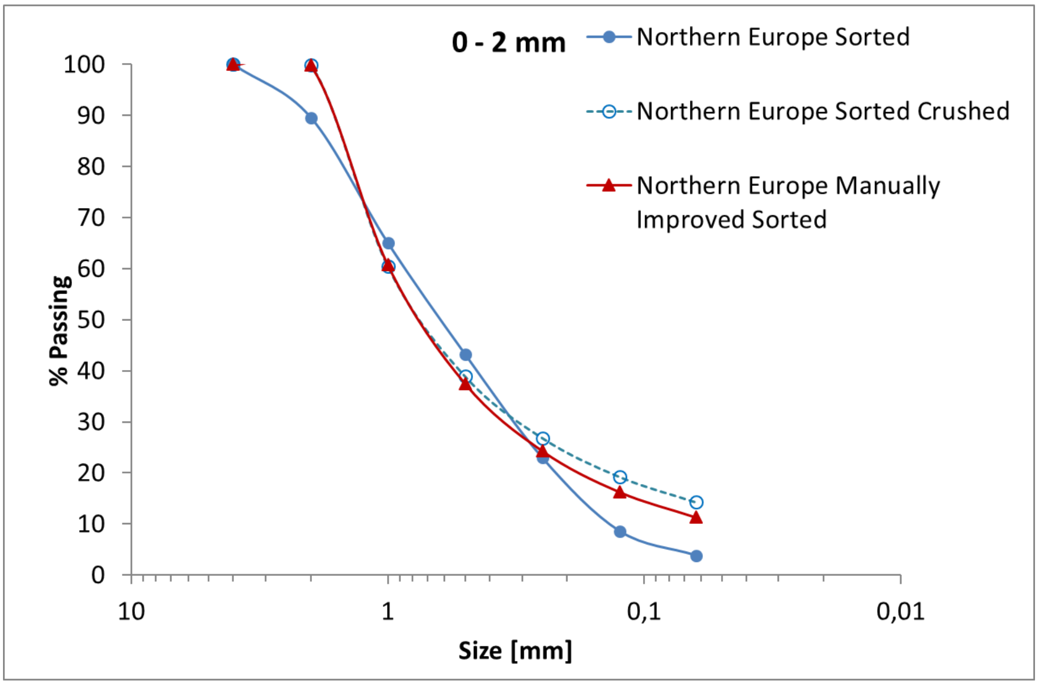

Figure 3: Particle size distribution of NE CDW mineral-fraction 0/2.

Table 3: Particle-size distribution of size-fraction 2/8 mm.

Aperture size [mm]	Cumulative passing					
	NE Sorted	SE Sorted	NE Sorted (crushed)*	SE Sorted (crushed)*	NE Improved Sorted*	SE Improved Sorted*
	% Average	% Average	% Average	% Average	% Average	% Average
10	100	100	100	100	100	100
8	100	99	100	100	100	100
5.6	86	78	96	97	98	96
5	76	62	91	94	95	92
4	54	36	76	81	80	77
2	3	4	5	6	6	5
1	2	3	2	2	2	2
0.5	1	2	1	2	1	1
0.25	1	2	1	2	1	1
0.125	1	1	1	1	1	1
0.063	1	2	1	1	1	1

*Produced from crushed 8/16

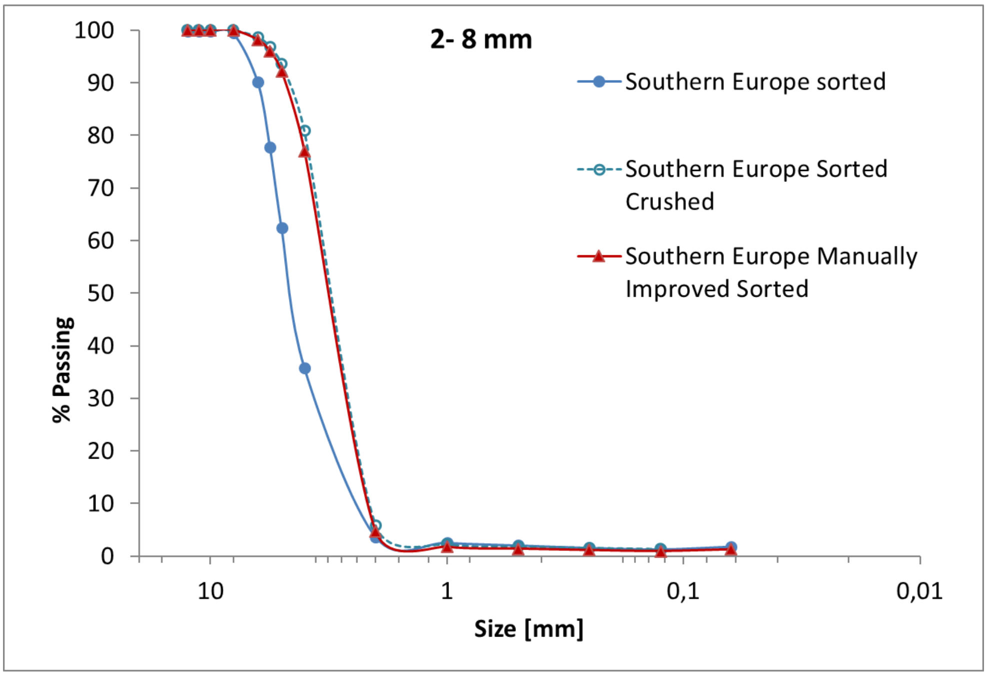

Figure 4: Particle size distribution of SE CDW mineral-fraction 2/8.

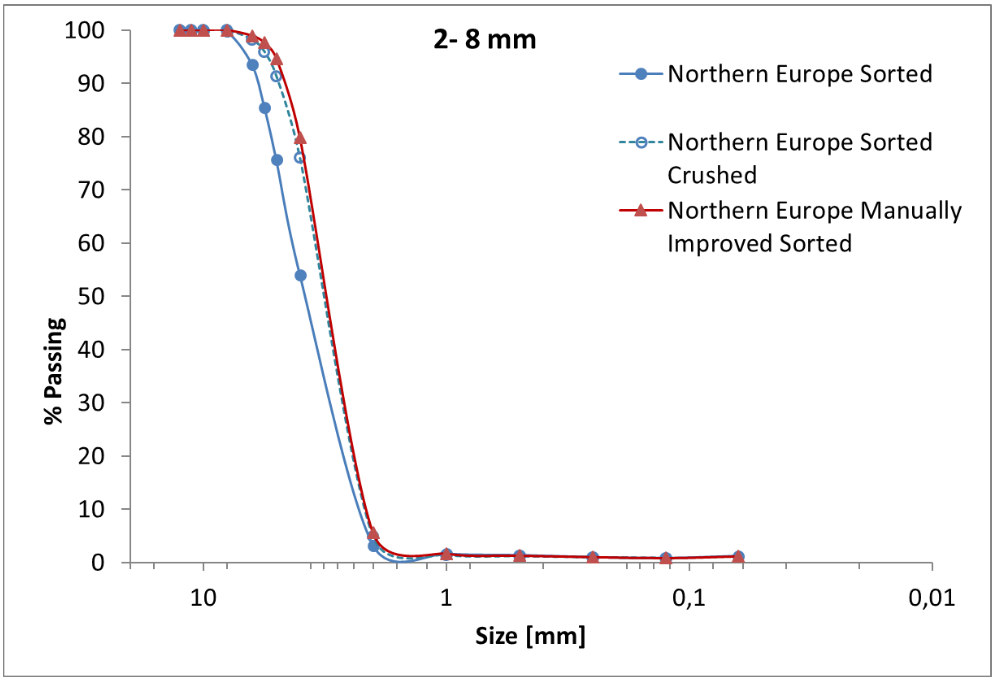

Figure 5: Particle size distribution of NE CDW mineral-fraction 2/8.

Table 4: Particle-size distribution of size-fraction 8/16 mm.

Aperture size [mm]	Cumulative passing			
	NE Sorted	SE Sorted	NE Improved Sorted	SE Improved Sorted
	% Average	% Average	% Average	% Average
20	100	100	100	100
16	100	97	98	97
12.5	73	65	73	64
11.2	59	48	59	46
10	44	31	42	29
8	23	12	19	10
6.3	10	5	5	4
5.6	8	5	3	3
5	8	4	2	3
4	7	4	1	3
2	5	3	1	2
1	4	3	1	2
0.5	4	2	1	2
0.25	3	2	1	1
0.125	2	1	1	1
0.063	2	1	1	1

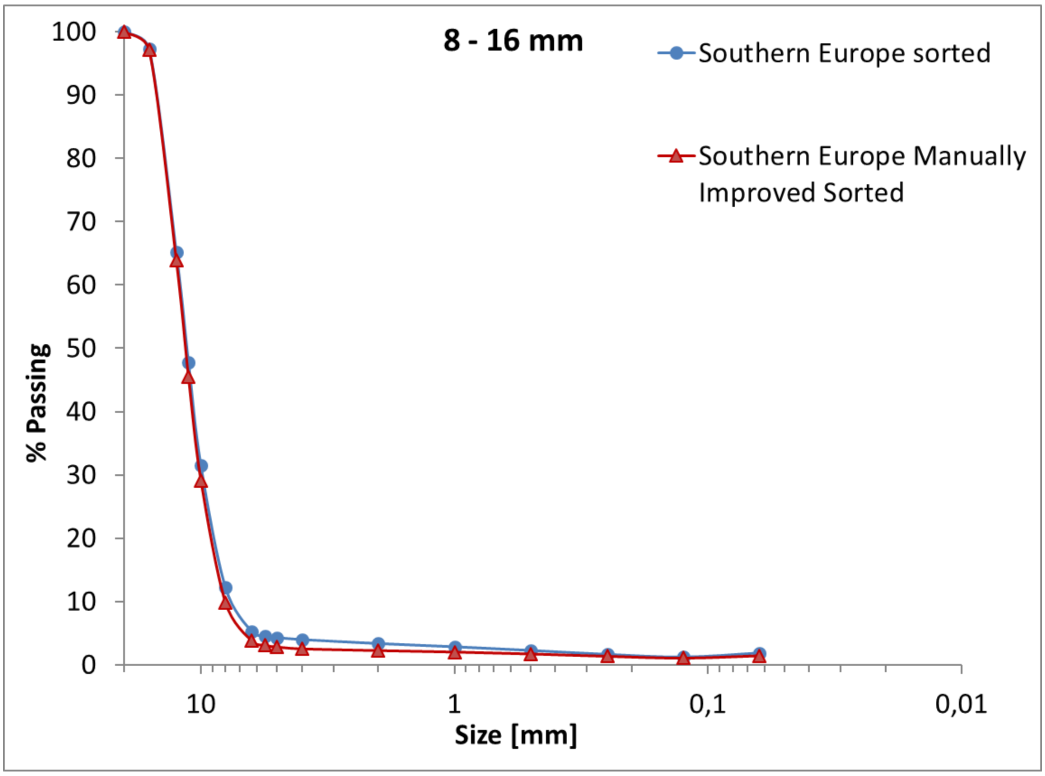

Figure 6: Particle size distribution of SE CDW mineral-fraction 8/16.

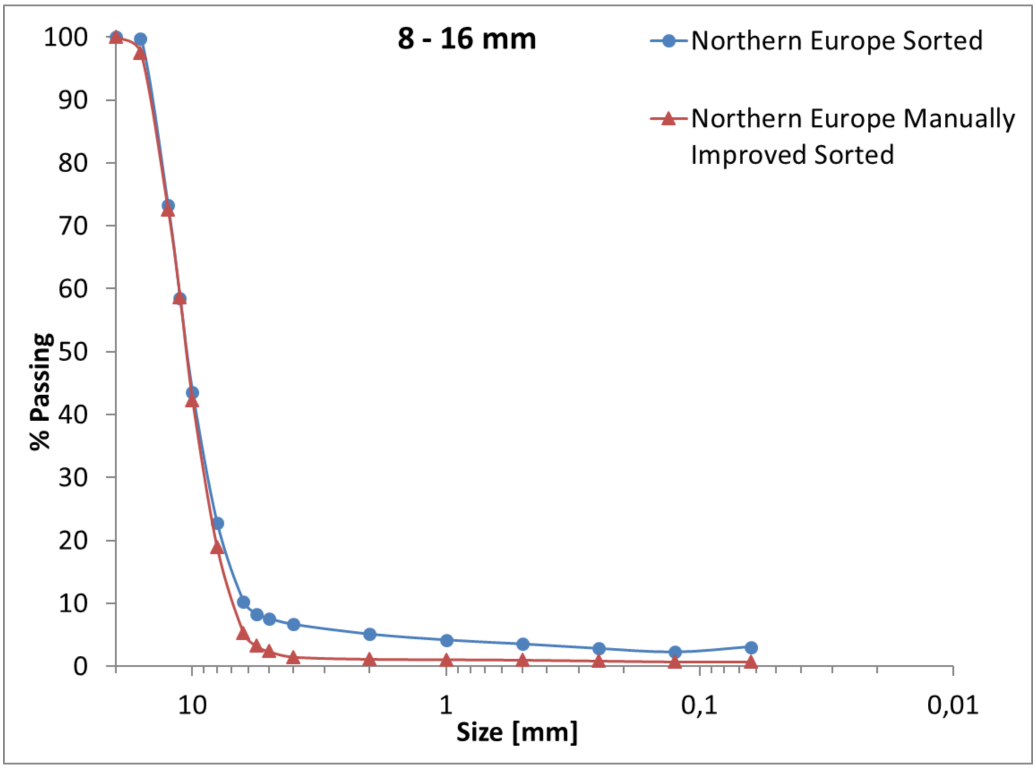

Figure 7: Particle size distribution of NE CDW mineral-fraction 8/16.

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Flow coefficient of fine aggregates was measured following the method described in EN 933-6. Details on this test can be found in D4.2. Results are presented in Table 5.

Table 5: Flow coefficient for fine aggregates.

Property	Unit	NE Sorted	SE Sorted
		0/2 mm	**0/2 mm**
Flow coefficient of Fine Aggregates	s	34	29
		NE Sorted (crushed)	**SE Sorted (crushed)**
		0/2 mm*	**0/2 mm***
		45	52
		NE Improved Sorted	**SE Improved Sorted**
		0/2 mm*	**0/2 mm***
		45	50

*Produced from crushed 8/16

Flakiness Index was measured following the method described in EN 933-3. Details on this test can be found in D4.2. Results are presented in Table 6.

Table 6: Flakiness Index.

Property	Unit	NE Sorted		SE Sorted	
		2/8 mm	**8/16 mm**	**2/8 mm**	**8/16 mm**
Flakiness index		19	9	17	8
		NE Sorted (crushed)		**SE Sorted (crushed)**	
		2/8 mm*	-	**2/8 mm***	-
		18	-	25	-
		NE Improved Sorted		**SE Improved Sorted**	
		2/8 mm*	**8/16 mm**	**2/8 mm***	**8/16 mm**
		18	10	23	10

*Produced from crushed 8/16

Mortar bars were casted from mixes, using 1350 g CDW sand (0/2), 450 g cement (CEM I 52.5 R) and a w/c-ratio of 0.55. Compressive strength was measured on these bars at 1, 7 and 28 days after casting, following the method described in EN 196-1 (see D5.1 for details). Results are presented in Table 7, whereas the strength development is shown in Figure 8.

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Table 7: Compressive strength of mortar bars.

Property	Unit	NE Sorted 0/2		SE Sorted 0/2	
Compressive strength, average value of three specimens	MPa	1d	-	1d	-
		7d	-	7d	-
		28d	-	28d	-
		NE Sorted (crushed) 0/2*		**SE Sorted (crushed) 0/2***	
		1d	16.8	1d	5.2
		7d	31.5	7d	9.8
		28d	33.9	28d	12.1
		NE Improved Sorted 0/2*		**SE Improved Sorted 0/2***	
		1d	20.4	1d	10.6
		7d	37.1	7d	19.4
		28d	39.9	28d	26.5

*Produced from crushed 8/16

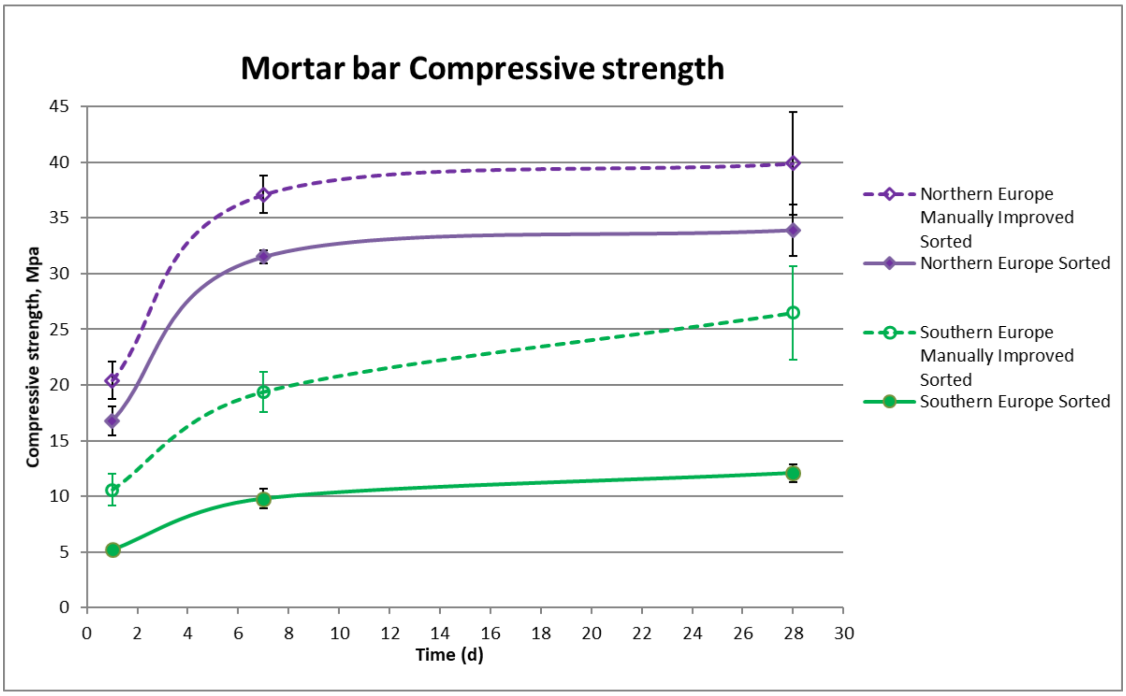

Figure 8: Graphs showing the development of compressive strength of mortar bars, for mortar mixes using Sorted and Improved Sorted CDW (0-2 mm) from Northern and Southern Europe, respectively.

3.2 Sorted CDW from Southern Europe – Batch 4

3.2.1 Introduction

The variability of chemical and physical features of sorted Southern Europe (S-EU) CDW mineral aggregate (0/2 mm, 2/8 mm & 8/16 mm size-fractions), and their effect on fresh and hardened properties when used in OPC concrete, was studied on 4 different batches. Results from batches 1-3 were presented in deliverable D4.3, whereas the results from batch 4 are presented here. For this fourth and last batch, three sub-batches were tested to access the variability within a CDW batch extracted at the same occasion. For this purpose, CDE in charge of material procurement supplied RISE CBI with the materials shown in Table 8. All tests were conducted using methods and conditions specified in D4.3.

Table 8: S-EU CDW batches tested by RISE CBI.

Batch no	Date Received	Date Collected	Composition (seperate size fractions)	Source
4	20th of December 2017	November 2017	0/2 mm, 2/8 mm & 8/16 mm	France

Based on the grading, water absorption and particle density values of S-EU sub-batches 4-1, 4-2 and 4-3, three concrete mix recipes were developed for casting and testing specimens as described in deliverable D4.3 (Table 9). The aim was to keep the mixes as similar to each other as possible, using the same cement type and cement amount in each mix. The amount of different CDW aggregate size-fractions in each mix were determined by calculation of a common total grading curve, designed so that 30 % of material was < 4 mm and 70 % > 4 mm. Note that because the grading and particle density between the sub-batches were so similar, the total grading curve and mix recipes turned out more or less the same. Because the intra-batch properties basically were the same, the three concrete mix tests were instead performed as check of effect of adding extra water. Accordingly, the w/c was varied. The mixing water stated in Table 9 was the amount required for cement hydration, i.e. extra water corresponding to the water absorption of the CDW aggregate was always added to this (107 kg/m^3).

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Table 9: Details of concrete mix recipes.

Mix Recipe 4-1 (Subbatch 4-1)			Mix Recipe 4-2 (Subbatch 4-2)		Mix Recipe 4-3 (Subbatch 4-3)	
Raw Materials	Quantities (kg/m^3)		Raw Materials	Quantities (kg/m^3)	Raw Materials	Quantities (kg/m^3)
w/c	0.57		w/c	0.53	w/c	0.5
CEM I - 52.5 N	500		CEM I - 52.5 N	500	CEM I - 52.5 N	500
Mixing water	283		Mixing water	263	Mixing water	250
Extra water	107		Extra water	107	Extra water	107
0/2 mm aggregate	244		0/2 mm aggregate	244	0/2 mm aggregate	244
2/8 mm aggregate	406		2/8 mm aggregate	406	2/8 mm aggregate	406
8/16 mm aggregate	956		8/16 mm aggregate	956	8/16 mm aggregate	956

3.2.2 Grading

The results of sieving the sorted S-EU CDW aggregate sub-batches 4-1, 4-2 and 4-3 are shown for size-fractions 0/2 mm (Table 10 and Figure 9), 2/8 mm (Table 11 and Figure 10), and 8/16 mm (Table 12 and Figure 11).

Table 10: Particle size distribution of 0/2 mm fraction of S-EU Batch 4.

0/2 mm SIZE FRACTION – S-EU Batch 4			
Aperture Size (mm)	**Cumulative Passing (%)**		
	Batch no 4-1	Batch no 4-2	Batch no 4-3
5.6	100	100	100
4.0	100	100	100
2.0	97	97	98
1.0	74	76	79
0.5	34	35	37
0.25	13	13	13
0.125	6	5	6
0.063	3	2	3
pan	0	0	0

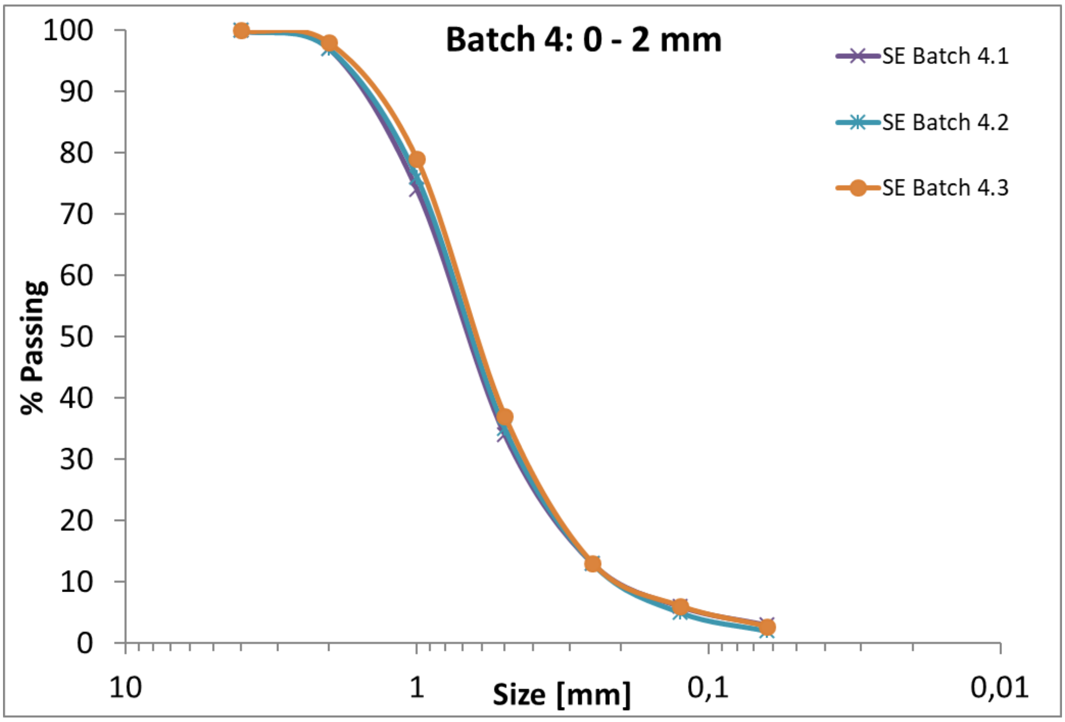

Figure 9: Particle size distribution of 0/2 mm fraction from S-EU Sub-batches 4-1, 4-2 and 4-3.

Table 11: Particle size distribution of 2/8 mm fraction of S-EU Batch 4.

2/8 mm SIZE FRACTION – S-EU SUBBATCHES 4.1, 4.2 & 4.3			
Aperture Size (mm)	Cumulative Passing (%)		
	Subbatch no 4-1	Subbatch no 4-2	Subbatch no 4-3
10.0	100	100	100
8.0	100	100	100
5.6	77	76	78
4.0	55	53	57
2.0	30	27	28
1.0	20	13	13
0.5	9	9	9
0.25	6	5	5
0.063	1	1	1
pan	0	0	0

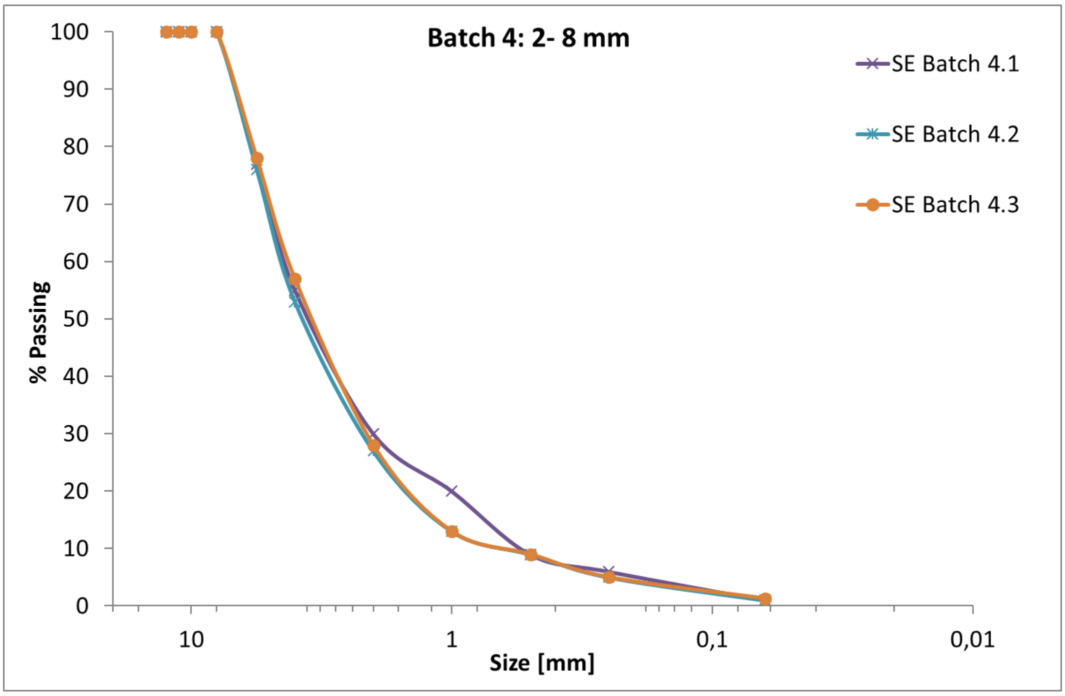

Figure 10: Particle size distribution of 2/8 mm fraction from S-EU Sub-batches 4-1, 4-2 and 4-3.

Table 12: Particle size distribution of 8/16 mm fraction of S-EU Batch 4.

8/16 mm SIZE FRACTION – S-EU SUBBATCHES 4.1, 4.2 & 4.3			
Aperture Size (mm)	Cumulative Passing (%)		
	Subbatch no 4-1	Subbatch no 4-2	Subbatch no 4-3
20.0	100	100	100
16.0	97	97	99
11.2	57	55	55
8.0	15	13	13
5.6	2	1	1
4.0	2	1	1
0.063	1	1	1
pan	0	0	0

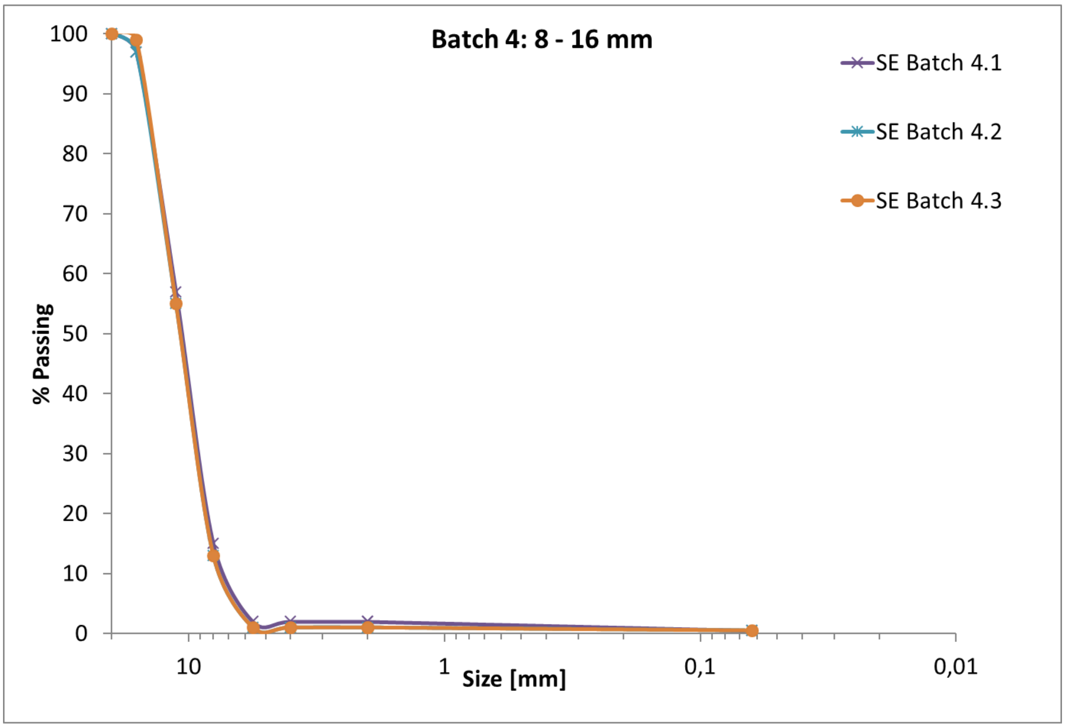

Figure 11: Particle size distribution of 8/16 mm fraction from S-EU Sub-batches 4-1, 4-2 and 4-3.

Good particle size distribution was observed in all three 0/2 mm fractions, whereas in the 2/8 mm fraction the amount of grains < 2 mm was approximately 30 % and thereby way too high. In the 8/16 mm fraction, the amount of grains < 8 mm was 13-15 %, which is a little bit too high.

3.2.3 Constituent Classification of 8/16 mm Size Fraction

The compositions of the different 8/16 mm size fraction of S-EU 8/16 Batch 4 sub-batches were measured following the method described in EN 933-11 (see D4.3 for details). Results are given in terms of tables, diagrams and photographs, for Sub-batch 4-1 in Table 13, Figure 12 and Figure 13, Sub-batch 4-2 in Table 14, Figure 14 and Figure 15, and Sub-batch 4-3 in Table 15, Figure 16 and Figure 17.

Table 13: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-1.

S-EU BATCH 4-1 – SIZE FRACTION 8/16 mm			
Symbol	**Description**	**Amount (kg or ml)**	**Proportion**
M_1	Mass of oven-dried portion	10.9456 kg	n/a
V_{FL}	Volume of floating particles in M_1	0.5 ml	n/a
M_X	Mass of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	0.00215 kg	n/a
M_2	Mass of non-floating particles in M_1	10.7873 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	1.9825 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	1.4128 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	0.53338 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aereated non-floating concrete detected in M_3	0.03356 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0.00058 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0.00078 kg	n/a
FL	Estimated volume of floating particles in M_1	n/a	0.05 cm^3/kg
X	Estimated percentage of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	n/a	0.02%
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	71 %
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	27 %
Rb	Estimated percentage of clay masonry units, calcium silicate units and aereated non-floating concrete detected in M_1	n/a	1.7 %
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	0.03 %
Rg	Estimated percentage of glass detected in M_1	n/a	0.04 %

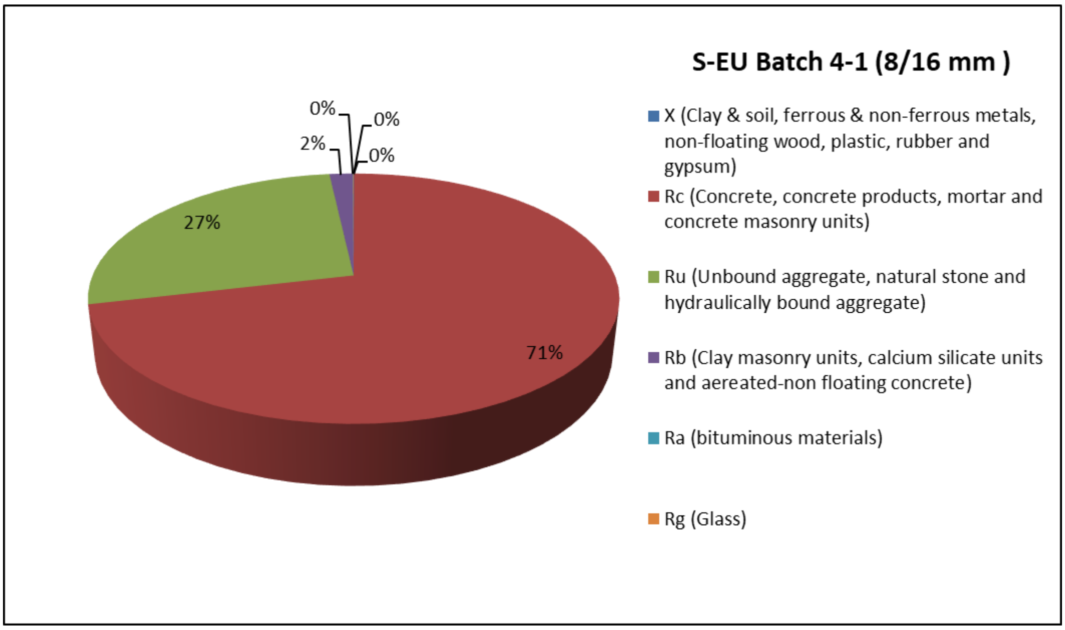

Figure 12: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-1.

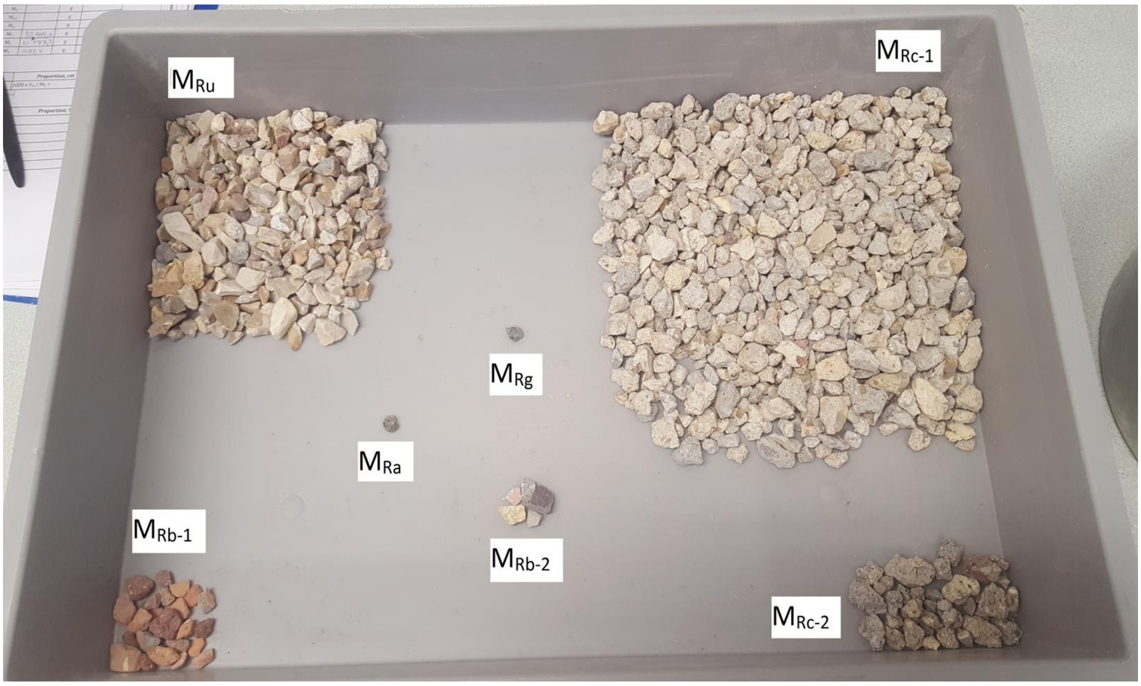

Figure 13: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-1. Note that both the concrete fraction (Rc) and brick fraction (Rb), in the photograph has been subdivided into two sub-groups. Rc-1 is denser and Rc-2 is more porous, wheras Rb-1 is bricks and Rb-2 is clinker.

Table 14: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-2.

S-EU BATCH 4-2 – SIZE FRACTION 8/16 mm			
Symbol	**Description**	**Amount (kg or ml)**	**Proportion**
M_1	Mass of oven-dried portion	9.8076 kg	n/a
V_{FL}	Volume of floating particles in M_1	1.5 ml	n/a
M_X	Mass of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	0.00110 kg	n/a
M_2	Mass of non-floating particles in M_1	9.6774 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	2.0750 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	1.5037 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	0.54486 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aereated non-floating concrete detected in M_3	0.025724 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0 kg	n/a
FL	Estimated volume of floating particles in M_1	n/a	0.2 cm^3/kg
X	Estimated percentage of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	n/a	0.01 %
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	73 %
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	26 %
Rb	Estimated percentage of clay masonry units, calcium silicate units and aereated non-floating concrete detected in M_1	n/a	1.2 %
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	0 %
Rg	Estimated percentage of glass detected in M_1	n/a	0 %

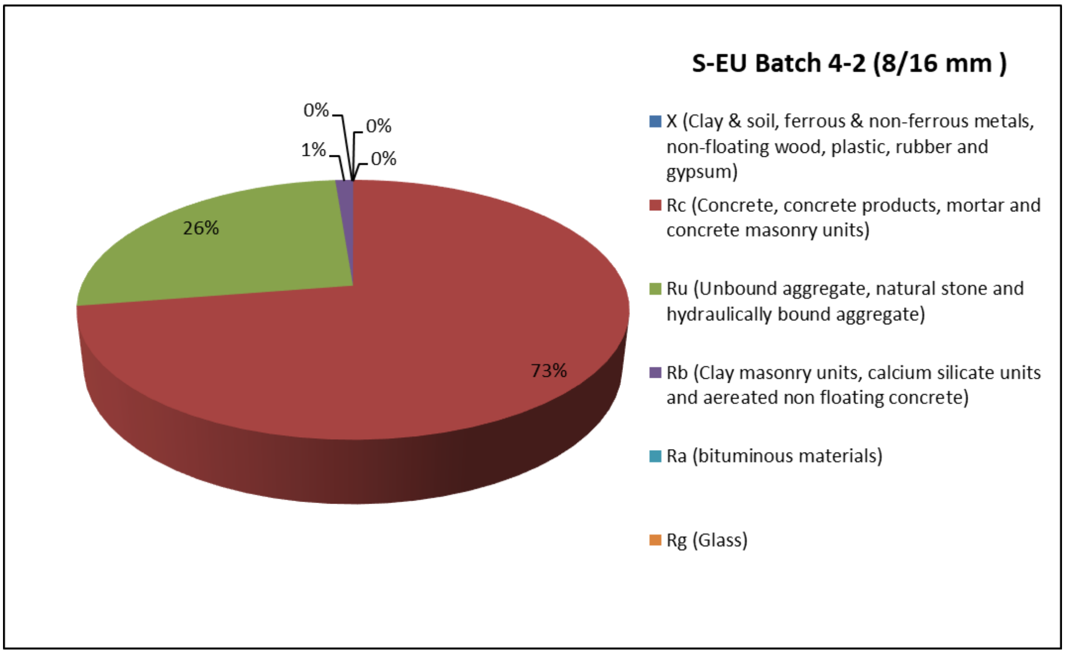

Figure 14: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-2.

Figure 15: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-2. Note that the concrete fraction (Rc) in the photograph has been subdivided into two sub-groups; Rc-1 is denser and Rc-2 is more porous.

Table 15: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-3.

S-EU BATCH 4-3 – SIZE FRACTION 8/16 mm			
Symbol	**Description**	**Amount (kg or ml)**	**Proportion**
M_1	Mass of oven-dried portion	10.2079 kg	n/a
V_{FL}	Volume of floating particles in M_1	0.2 ml	n/a
M_X	Mass of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	0.00118 kg	n/a
M_2	Mass of non-floating particles in M_1	10.0465 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	2.247.3 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	1.5765 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	0.62336 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aereated non-floating concrete detected in M_3	0.038817 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0.005451 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0 kg	n/a
FL	Estimated volume of floating particles in M_1	n/a	0.02 cm^3/kg
X	Estimated percentage of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	n/a	0.01 %
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	70 %
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	28 %
Rb	Estimated percentage of clay masonry units, calcium silicate units and aereated non-floating concrete detected in M_1	n/a	1.7 %
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	0.2 %
Rg	Estimated percentage of glass detected in M_1	n/a	0 %

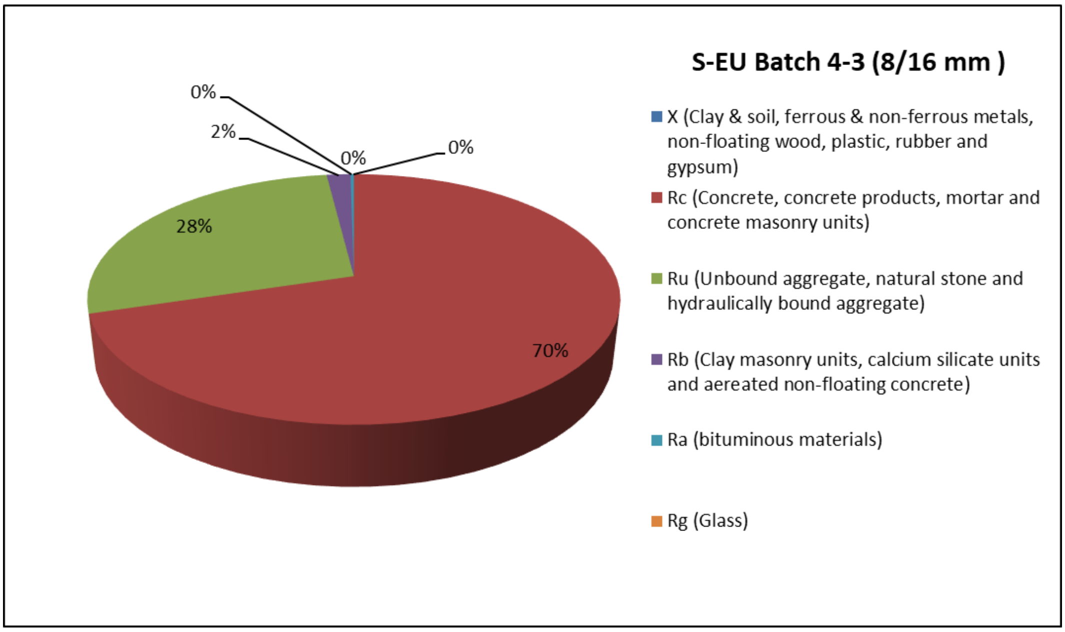

Figure 16: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-3.

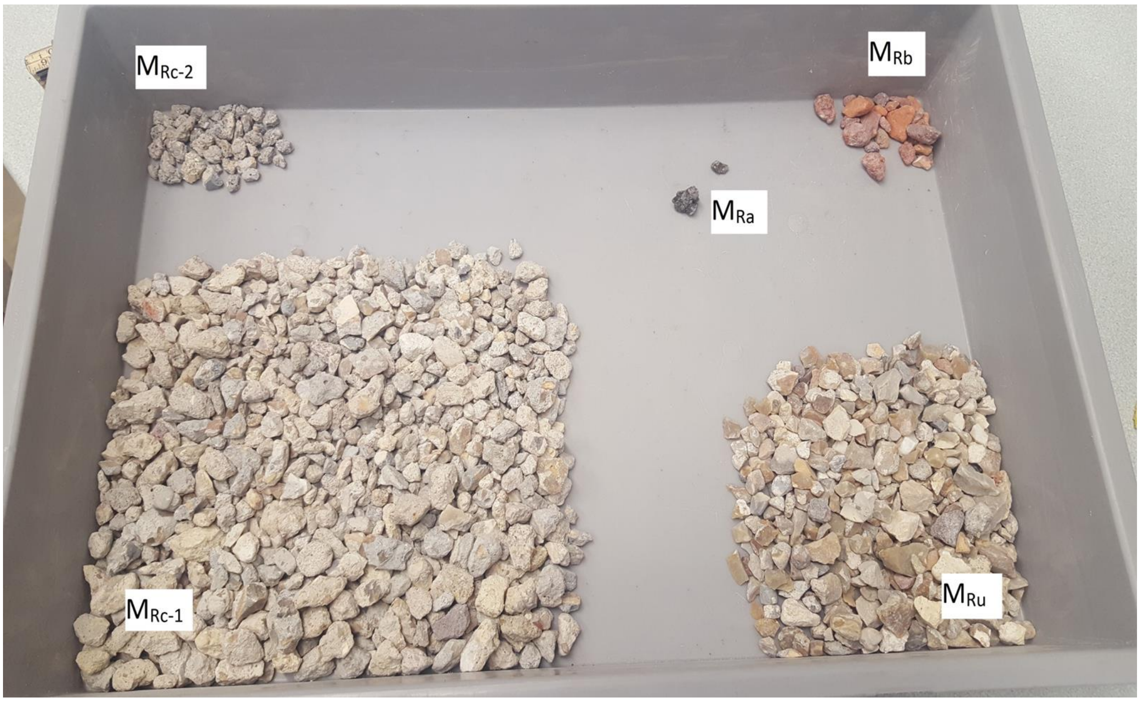

Figure 17: Constituent classification of 8/16 mm sorted S-EU CDW sub-batch 4-3. Note that the concrete fraction (Rc) in the photograph has been subdivided into two sub-groups; Rc-1 is denser and Rc-2 is more porous.

3.2.4 Water Absorption and Particle Density

The water absorption and density (apparent, oven dried and saturated surface dry) of all size fractions (0/2 mm, 2/8 mm and 8/16 mm) of sub-batches 4-1, 4-2 and 4-3 are shown in Table 16.

Table 16: Water absorption and density values of S-EU Batch 4.

Sub-batch	Property*	Size Fraction		
		0/2 mm	2/8 mm	8/16 mm
4-1	WA_{24} (% by mass)	(4.2)**	7.6	6.0
	ρ_a (kg/m^3)	2680	2650	2580
	ρ_{rd} (kg/m^3)	2410	2210	2230
	ρ_{ssd} (kg/m^3)	2410	2370	2370
4-2	WA_{24} (% by mass)	7.9	7.6	6.0
	ρ_a (kg/m^3)	2690	2640	2590
	ρ_{rd} (kg/m^3)	2220	2200	2240
	ρ_{ssd} (kg/m^3)	2390	2370	2380
4-3	WA_{24} (% by mass)	7.1	7.6	6.2
	ρ_a (kg/m^3)	2670	2640	2590
	ρ_{rd} (kg/m^3)	2240	2200	2230
	ρ_{ssd} (kg/m^3)	2400	2380	2370

* WA_{24} = water absorption after 24 hours, ρ_a = apparent density, ρ_{rd} = oven-dried density, ρ_{ssd} = water saturated surface dry density
** Should not be used. See discussion below for justification.

For a certain size-fraction, the apparent density of all three sub-batches is basically the same and in the range of normal virgin aggregates (typically 2550-2750 kg/m^3). Since this is the density of the solid bulk of the material (pore volume excluded), the fact that it is almost in level with virgin materials indicate that the amount of pores accessible to water in the solid bulk is approximately the same as for virgin materials (i.e. corresponding to a water absorption <1 %).

The water absorption value was also the same in all three sub-batches for a specific size-fraction, at least when looking at the coarse size-fractions (2/8 and 8/16 mm). The WA_{24}-values spread more in the sand fraction (0/2 mm), with 4.2 % for Sub-batch 4-1 compared to 7-8 % for Sub-batches 4-2 and 4-3. However, during measurement it was noticed that the material in the 4-1 sample was a bit too dry when weighing for water saturated surface dry mass, so most likely the value at 4.2 % is not correct but should be higher. Nevertheless, as expected the water absorption values were higher than those commonly encountered in virgin aggregates and more in the range usually seen in CDW aggregates. As a final remark, the water absorption for all three sub-batches was higher for the 2/8 mm fraction compared to the 8/16 fraction. This is probably due to a shortcoming of the method used, which is not designed for size-fractions with particles < 4 mm. In the step where particles are wiped surface dry using a cloth, there is a risk of losing particles to the cloth and thereby achieving a lower mass and hence a higher WA value.

3.2.5 Water-Soluble Chloride Content (0/2 mm, 2/8 mm & 8/16 mm fractions)

The water-soluble chloride content of all tested size fractions (0/2 mm, 2/8 mm and 8/16 mm) of S-EU Sub-batches 4-1, 4-2 and 4-3 is shown in Table 17.

Table 17: Water-soluble chloride content of S-EU Batch 4.

Test Method	Sub-batch	Unit	Size Fraction		
			0/2 mm	2/8 mm	8/16 mm
Ion Chromatography	4-1	wt%	0.003	0.001	<0.001
	4-2	wt%	0.003	0.001	<0.001
	4-3	wt%	0.003	0.001	<0.001

As shown in Table 17, all tested mineral fractions of all S-EU sub-batches contain relatively low levels of water-soluble chlorides. This can be attributed to the various washing stages of CDE's processing and sorting equipment, which effectively removes water soluble chlorides.

3.2.6 Water-Soluble Sulfate Content (0/2 mm, 2/8 mm & 8/16 mm fractions)

The water-soluble sulfate content of all tested size fractions (0/2 mm, 2/8 mm and 8/16 mm) of S-EU sub-batches 4-1, 4-2 and 4-3 is shown in Table 18 below. Values were obtained expressed as SO_4 from the analysis, but has also been recalculated to SO_3, using the equation on p. 33 in EN 1744-1:2009.

Table 18: Water-soluble sulfate content of S-EU sorted CDW Batch 4.

Sub-batch	Size Fraction					
	0/2 mm		2/8 mm		8/16 mm	
	wt.% SO_4	wt.% SO_3	wt.% SO_4	wt.% SO_3	wt.% SO_4	wt.% SO_3
4-1	0.061	0.051	0.044	0.037	0.007	0.006
4-2	0.061	0.051	0.044	0.037	0.005	0.004
4-3	0.068	0.057	0.041	0.034	0.008	0.007

The water-soluble sulfate content (by mass of aggregate) of all size fractions in all sub-batches are well below the 0.2% limit set by EN 12620:2002+A1:2008 [3], for use in structural concrete.

3.2.7 Slump Test

The high water absorption values of the used CDW compared to virgin aggregate is a factor that negatively affects workability, because absorption of the mixing water by the aggregates starts more or less immediately upon mixing. Therefore, extra water reflecting 100 % saturation of the used CDW aggregates have been added to the water content stated in the mix recipes (Table 9).
The slump values at 15 and 30 minutes from start of mixing the dry materials with water are shown in Table 19. The water content was too high in all mixes, therefore slump value was not tested until

30 min after mixing (40 min for Mix no 4-1) and was very high for all mixes, corresponding to consistency class S4 for Mix no 4-2 and 4-3. Mix no 4-1 was even outside the S-class system after 40 minutes.

Table 19: Slump test values at 15 and 30 mins for mixes containing 100% sorted CDW from S-EU Batch 4.

Mix no	c/w	Time (min)	Slump Value (mm)
4-1	0.57	15	n.d.
		30 (40)	240
4-2	0.54	15	n.d.
		30	210
4-3	0.50	15	n.d.
		30	210

3.2.8 Fresh Concrete Density

The use of recycled aggregate in concrete generally reduces its fresh density. This is due to the fact that recycled aggregate contains Rc, Rb and Ra particles which are less dense compared to virgin aggregate. The higher the replacement level of virgin aggregate by recycled aggregate, the lower the fresh density of concrete. However, since the apparent density is about equal to the density of virgin aggregate the decrease will not be significant. Fresh density values of S-EU Mixes 4-1, 4-2 and 4-3 are shown in Table 20. The fresh density of all mixes is more or less in the range often assumed for normal concrete mixes containing 100% crushed, gravel or sand virgin aggregate (2300-2400 kg/m^3).

Table 20: Fresh density values of mixes 100% S-EU sorted CDW from S-EU Batch 4.

Mix no	Volume (m^3)	Mass (kg)	Fresh Density (kg/m^3)
4-1	0.0022	5.046	2290
4-2	0.0022	5.071	2310
4-3	0.0022	5.044	2290

3.2.9 Hardened Concrete Density

Hardened concrete density values (water saturated) of S-EU Mixes 4-1, 4-2 and 4-3 are shown in Table 21. As expected, a variation between the mixes is observed, with a slight increase in density with decreasing w/c ratio. One peculiarity is that the hardened density of these water cured specimens is lower than the fresh densities of the same batches, shown in Table 20. Normally a certain amount of water uptake during storage will occur, leading to a slightly higher density in the specimens. This may be an indication of that the concrete on which the density was measured is not the same as the concrete in the specimens. This may be due to differences in degree of compaction used on the fresh concrete sample and the cast specimens, or on stone separation of this fresh very fluid concrete. Insufficient compaction may lead to that some of the air originally in the porous aggregate is not completely replaced by water and evacuated from the cast concrete, leading to a high air content decreasing the density of the specimens.

Table 21: Hardened density values of mixes containing 100% sorted CDW aggregate from S-EU Batch 4.

Mix no (w/c)	Age (days)	Cube no	Water saturated			
			Mass (g)	Density (kg/m³)	Average Density (kg/m³)	Std. dev. (±kg/m³)
4-1 (0.57)	1	1	2054	2070	2090	< 10
		2	2101	2100		
		3	2059	2080		
	7	1	2110	2110	2100	< 10
		2	2090	2090		
		3	2090	2090		
	28	1	2088	2100	2100	< 10
		2	2092	2110		
		3	2061	2100		
4-2 (0.54)	1	1	2131	2170	2120	50
		2	2129	2100		
		3	2122	2090		
	7	1	2133	2130	2120	20
		2	2124	2150		
		3	2113	2120		
	28	1	2167	2190	2170	10
		2	2157	2170		
		3	2162	2160		
4-3 (0.50)	1	1	2093	2100	2120	20
		2	2149	2140		
		3	2114	2100		
	7	1	2173	2130	2130	20
		2	2189	2140		
		3	2149	2130		
	28	1	2118	2140	2140	< 10
		2	2149	2150		
		3	2117	2140		

3.2.10 Compressive Strength

Compressive strength values of S-EU Mixes 4-1, 4-2 and 4-3 are shown in Table 22 and Figure 18. As expected, the compressive strength at 1, 7 and 28 days for each mix increases with decreasing w/c. Since the aggregate used in each mix was of the same type, w/c is most likely the parameter that most strongly influences the compressive strength of these mixes. When comparing with S-EU mixes 1, 2 and 3 presented in D4.3, it is mix 4-3 that has the same mix proportions and should be used. The compressive strengths are rather low, which further strengthens the suspicion drawn from hardened density measurements, that the cast specimens contain too much air caused by insufficient compaction.

Table 22: Compressive strength values of mixes containing 100% sorted CDW aggregates from S-EU Batch 4.

Mix no (w/c)	Age (days)	Cube no	Mass (g)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Standard Deviation (±MPa)
4-1 (0.57)	1	1	2054	5.6	6.0	0.4
		2	2101	6.0		
		3	2059	6.5		
	7	1	2086	16.0	17.0	0.8
		2	2053	17.9		
		3	2068	16.7		
	28	1	2088	24.5	24.0	0.3
		2	2092	23.7		
		3	2061	24.0		
4-2 (0.54)	1	1	2131	9.1	9.1	0.1
		2	2129	9.0		
		3	2122	9.1		
	7	1	2133	23.4	22.8	0.5
		2	2124	22.8		
		3	2113	22.2		
	28	1	2167	29.3	30.2	0.6
		2	2157	30.8		
		3	2162	30.5		
4-3 (0.50)	1	1	2093	8.8	9.0	0.2
		2	2149	9.1		
		3	2114	9.1		
	7	1	2173	23.5	23.9	0.4
		2	2189	23.7		
		3	2149	24.4		
	28	1	2118	34.4	31.0	2.8
		2	2149	31.7		
		3	2117	27.5		

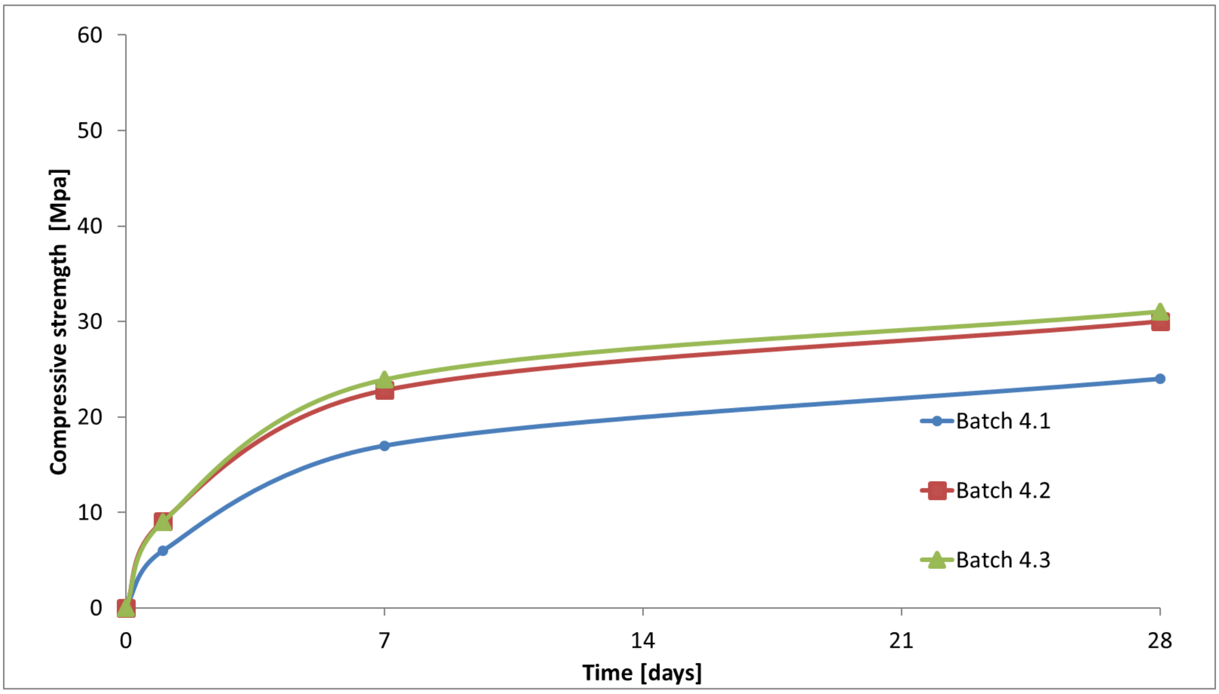

Figure 18: Compressive strength development over time of Mixes 4-1, 4-2 and 4-3, containing 100% sorted CDW aggregates from S-EU Batch 4.

4. MATERIALS AND EXISTING STANDARDS, RULES AND GUIDELINES

4.1 Mineral aggregates in concrete and roads

This topic is more thoroughly treated in D2.1 [4].
For the standards treating prefabricated concrete elements, many of the common features (such as material requirements) are put into a horizontal standard: *EN 13369:2013 - Common rules for precast concrete products* [1]. For the concrete material and its constituents, reference is in this standard made to the concrete standard EN 206-1:2001 [7] in which no requirements for recycled aggregate can be found. EN206-1 is an older version of EN 206:2013 [2]. Recycled aggregate is mentioned in EN 13369:2013, but with the reservation that provisions in EN 206:2013 should be considered.

In both EN 206:2013 and EN 13369:2013, recycled aggregate is defined as "aggregate resulting from processing of inorganic materials previously used in construction" (i.e. CDW), and in both standards only coarse recycled aggregate is mentioned. The lower limit for what is considered coarse aggregate is 2 mm according to the concrete aggregate standard (EN 12620+A1:2008, [3]), but is proposed to be changed to 1 mm. In EN 13369:2013, it is specified that the recycled coarse aggregates shall not adversely affect the setting and hardening of the concrete and its durability. In an informative annex in EN 13369:2013, some non-mandatory guidelines for the use of recycled aggregates from crushed concrete are given. These guidelines are based on the assumption that the source and the composition of the crushed concrete are known, and they do not cover recycled aggregate classified according to EN 12620+A1:2008.

In EN206:2013, the provisions for recycled aggregate are more general. Classification is carried out according to the concrete aggregate standard (EN 12620+A1:2008) and relies on examination and quantification of the relative proportions of the constituent materials of the CDW, as specified in the test standard EN 933-11 (see D4.3 for details). Since EN 12620+A1:2008 is harmonised, the coarse recycled aggregate shall be CE-marked.

For the classification according to EN 12620+A1:2008 and the test method EN 933-11, the coarse recycled aggregates shall be quantified in the relative proportions of the following constituents (by weight):

- FL Floating particles (estimated by volume)
- Rc Concrete and mortar
- Ru Unbound aggregate and natural stone
- Rb Clay and calcium silicate masonry units, aerated non-floating concrete
- Ra Bituminous materials
- Rg Glass
- X Other, such as clay and soil, metals, non-floating wood, plastic and gypsum

Based on the relative content of these constituents, EN 12620+A1:2008 then specifies classes to be used for declaring the constituents of the recycled coarse aggregate. Other properties that should be declared are grading, water soluble chloride content, presence of sulfur containing compounds, influence on the initial setting time of concrete, particle density, water absorption and water soluble sulphates. EN 12620+A1:2008 does not give any maximum or minimum requirements for these properties.

The concrete standard EN 206:2013 recommends that also the fines content, the resistance to fragmentation and the shape of coarse aggregate should be declared when used in concrete.

EN 206:2013 gives recommendations regarding requirements for these properties for recycled coarse aggregates intended for use in concrete. The standard proposes a separation into two classes, Type A and Type B, with different requirements for different uses. These provisions are only recommendations, and it is up to each CEN member state to decide if recycled aggregate may be used in concrete and if so, under what conditions.

In a preliminary version of a survey on national choices regarding open items in EN 206:2013, a table containing the requirements in EN 206:2013 and how these are treated in a number of CEN member states are [8] given. This information is reproduced in Table 23 below. In this preliminary survey, the values for Sweden was not always correct, and therefore the correct values according to SS 137003:2015 [9] (Swedish application standard to EN 206:2013) have been used instead. Since there were incorrect values for Sweden, there may also be mistakes with the values for other countries. Table 23 may thus only be regarded as an indication of the status in the respective countries.

Table 23: National choices with regard to requirements in EN 206:2013.

CEN member state	Name	Rc (concrete)	Rc+Ru (concrete + unbound)	Rb (brick)	Ra (bituminous)	Fl (floating material)	XRg (glass, others)
EN 206 Table E.2	Type A	≥ 90%	≥ 95%	≤ 10%	≤ 1%	≤ 2%	≤ 1%
	Type B	≥ 50%	≥ 70%	≤ 30%	≤ 5%	≤ 2%	≤ 2%
BE	Type A	≥ 90%	≥ 95%	----	≤ 1%	≤ 2%	≤ 1%
	Type B	As EN 206, Table E.2, values for Type B					
CZ	As EN 206, Table E.2 values						
FI	As EN 206, Table E.2 values						
FR	Type 1		≥ 95%	≤ 10%	≤ 1%	≤ 0.2%	≤ 0.5 %
	Type 2		≥ 90%	≤ 10%	≤ 1%	≤ 2%	≤ 1%
	Type 3		≥ 70%	≤ 30%	≤ 10%	≤ 2%	≤ 2%
GR	Not used						
IE	Will adopt EN 206, Table E.2 values, but SR16 not yet published so recycled concrete not yet formally in use. The revised SR16 is to increase the acid soluble sulphate level for this waste stream only. Currently this property is set at such a low level as to only allow for the use of virgin aggregates.						
IT	As EN 206, Table E.2 values						
NO	R_{cu99}		≥ 99%				
PT	As EN 206, Table E.2 values						
RO	As EN 206, Table E.2 values						
SE	As EN 206, Table E.2 values						
CH	RC-C	≥ 25%	≥ 75%	≤ 5%	≤ 1%	≤ 2%	≤ 0,3%
	RC-M	----	≥ 95%	≤ 10%	≤ 1%	≤ 2%	≤ 1%
TR	As EN 206, Table E.2 values						
UK	CCA	≥ 90%	≥ 90%	≤ 10%	≤ 5%	≤ 2%	≤ 1%

As can be seen, several countries have adopted the recommendations in EN 206:2013. In some countries the values are changed to a minor or larger extent. In EN 206:2013 there are also recommendations regarding some other properties of recycled aggregate (Table E.3 in EN 206:2013). These recommendations together with information about adoption/variation of these requirements in some CEN member states are given in Table 24.

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Table 24: National adaptation on recycled aggregate properties in EN 2016:2013.

CEN member country	Type	Fines content	Flakiness index	Resistance to fragmentation	Oven-dry particle density (kg/m³)	Water absorption (%)	Water soluble sulfate (%)	Acid soluble chloride (%)	Influence on setting time
EN 206 Table E.2	Type A and B	Declared	$\leq FI_{50}$ or $\leq SI_{55}$	$\leq LA_{50}$ or $\leq SZ_{32}$	A: ≥2100 B: ≥1700	Declared	$SS_{0,2}$	Declared	$\leq A_{40}$
BE	Type A (BE)	$f_{1,5}$	$\leq FI_{20}$	$\leq LA_{35}$	≥2200	≤ 10 %	Table E.3	Table E.3	Table E.3
	Type B	Table E.3	$\leq FI_{50}$	$\leq LA_{50}$	Table E.3	≤ 10 %	Table E.3	Table E.3	Table E.3
CZ	As EN 206, Table E.3 values								
FI	As EN 206, Table E.3 values								
FR	Type 1	Table E.3	$\leq FI_{35}$	LA_{40}	≥2000	24 h value declared	$SS_{0,2}$	Table E.3	A_{10}
	Type 2			LA_{40}	≥2000		$SS_{0,2}$		Table E.3
	Type 3			LA_{50}	≥1700		$SS_{0,7}$		Table E.3
GR	Not used								
IE	Will adopt EN 206, Table E.2 values, but SR16 not yet published so recycled concrete not yet formally in use. The revised SR16 is to increase the acid soluble sulphate level for this waste stream only. Currently this property is set at such a low level as to only allow for the use of virgin aggregates.								
IT	Type A & B as in EN 206, Table E.2	Table E.3	$FI_{Declared}$ or $SI_{declared}$	---	Table E.3	Table E.3	Table E.3	Table E.3	A_{10}
NO	R_{cu99}	Table E.3	Table E.3	Table E.3	Table E.3	Table E.3	----	Table E.3	Table E.3
PT	Type A & B as in EN 206, Table E.2	f_{4}	$\leq FI_{35}$	A: $\leq LA_{50}$ B: Declared	≥2200	≤ 7%	Table E.3	Table E.3	Declared
RO	As EN 206, Table E.3 values								
SE	Type A & B as in EN 206, Table E.2	Table E.3	A: Declared B:$\leq FI_{40}$	----	Table E.3	Table E.3	$SS_{0,8}$	----	A: ----- B: A_{40}
CH	RC-C & RC-M	$f_{1,5}$	Declared	----	Table E.3	Table E.3	$SS_{0,2}$	Table E.3	A_{10}
TR	As EN 206, Table E.3 values								
UK	CCA	f_{4}	Table E.3	≤ 10%	Table E.3	Table E.3	Table E.3	Table E.3	Table E.3

Additionally, the recycled coarse aggregate shall fulfil requirements when used in concrete for specific uses, for example freeze-thaw resistance, alkali silica reactivity, resistance to wear, polishing, surface abrasion and abrasion from studded tyres, as relevant.

It would be logical to be able to classify parts of CDW as mineral lightweight aggregate (LWA), according to the lightweight aggregate standard EN 13055-1:2016 [9], for use in LWA concrete according to EN 206:2013. The maximum allowed particle density for LWA conforming to EN 13055:2016 is 2000 kg/m^3. According to the scope, one of the recognized LWA sources is LWA manufactured from recycled source materials. However, in the list of accepted source materials in the normative Annex A of EN 13055-1:2016, CDW is not included. The list contains materials with a positive history of use, but recycled CDW is not included. This list should be subject to continual review if other sources, based on routine application on the market by at least one CEN member state, are used and a procedure for how this can be carried out is given (see Section 4.2.1).

Concrete blocks for masonry are covered by the harmonised standard EN 771-3, which only have a general reference to EN standards, when available, and do not have any specific requirements on aggregates. Moreover, the strength requirements on masonry units are normally not as high as on in-situ cast concrete and prefabricated concrete elements. This is a niche where CDW of lower density and strength than Type A and B above would be suitable, and additional classes are needed.

There are no common European standards for the use of CDW in road structures. The Swedish Transport Administration [10] uses the following classification for the use of such materials in their road structures (Table 25). Class 1 or 2 is required for the base course, Class 3 can be used in the subgrade and Class 4 for embankments and other fillings.

Table 25: Classification of CDW for use in road structures by The Swedish Transport Administration.

Class	1	2	3	4
Rc	≥ 90 %	≥ 90 %	≥ 70 %	≥ 50 %
Rcu	≥ 95 %	≥ 95 %	≥ 90 %	≥ 70 %
FL	≤ 2 %	≤ 2 %	≤ 5 %	≤ 10 %
X	≤ 1 %	≤ 1 %	≤ 1 %	≤ 1 %
AVCP-system	2 + [a)]	2 + or 4 [a, b,c)]	4 [b)]	4 [b)]
micro-Deval value	M_{DE25} (M_{DE35}) [d)]	M_{DE25} (M_{DE35}) [d)]	M_{DE40} (M_{DE50}) [d)]	----
[a)] Surveillance of factory production control by notified body [b)] No notified body involved [c)] 2+ for base course and 4 for subbase [d)] Subjected to only few heavy vehicles during construction				

4.2 Mineral aggregates in earthen building materials

Mineral sand aggregates (0/2 mm) from CDW have been used for the development of the following earthen building materials:

- earth plaster
- earth mortar

- rammed earth

The main aim is to offer possibilities for application for the high amount of aggregates that occur as CDW but also to preserve virgin material. In addition, it is intended to demonstrate that the application of these materials offer endless opportunities for reuse if certain aspects are considered, which is an outstanding and quite unique property for a building material.

The following standards make reference with regards to the quality criteria for raw materials for the above-named materials:

- DIN 18947 - Deutsches Institut für Normung (Ed.): DIN 18947:2013-08: Earth plasters - Terms and definitions, requirements, test methods, edition: August 2013. [11]
- Deutsches Institut für Normung (Ed.): DIN 18946:2013-08: Earth mortars - Terms and definitions, requirements, test methods, edition: August 2013. [12]
- Dachverband Lehm e.V. (Ed.): Lehmbau Regeln (earth building rules), 3, revised edition, Vieweg+Teubner / GWV Fachverlage GmbH, Wiesbaden 2009. [13]

For earth plaster and earth mortar the allowance and quality requirements for the raw materials differ only to the extent that plaster require finer grains when brick is added and foam glass is only allowed for earth mortar. The following materials are allowed as suitable aggregate:

- natural aggregate according to EN 12620+A1:2008
- brick dust (plaster) or crushed brick (mortar) made of mortar-free bricks
- expanded perlite, expanded clay, expanded glass, foam glass (only plaster) expanded slate and natural pumice according to EN 13055-1

All substances added to the building material must be declared in full and:

- starting materials must be suitable for production of the respective material
- it must be possible to mix the components homogeneously with the help of suitable mixers
- filling and transport must not result in any significant segregation.

For rammed earth, additional fractions (2/8 mm and 8/16 mm) to the sand have been used. No specific quality criteria are mentioned in [13]. Coarse sand, gravel and grit are considered as suitable aggregates.

4.3 Lightweight aggregates in concrete

4.3.1 Standards on lightweight aggregate for concretes

In RE^4 project the use of non-mineral lightweight aggregates (LWA) from Construction and Demolition Waste (CDW) - such as those resulting from rigid plastic (RP) and mixed wood/plastic (WP) scraps - is specifically intended for production of concretes with improved insulating properties and suitable for specific building applications (e.g. layers of panels, substrates for screeds or roofs insulation). The main purpose is the valorisation of recycled non-mineral LWA, which are currently discarded, through the development of insulating concretes with reduced density and moderate strength.

There a no specific standards available for the specific typologies of LWA investigated in the Project (plastic and mixed wood/plastic from CDW processing). However, the following standards have been identified as useful references:

- EN 13055:2016 *"Lightweight aggregates"* in [9];
- ASTM C332:2017 *"Standard specification for lightweight aggregates for insulating concrete"* in [46].

It should be noted that, for the aim of the classification of RE^4 LWA, the above listed standards can only be used as references since, in both, the considered source materials do not cover the type of non-mineral LW aggregates from CDW investigated in this Project. In the following a brief overview of the standards mentioned above is given. For specific details the referenced documents have to be considered.

EN 13055: 2016 "Lightweight aggregates"

This standard specifies the properties of LWA and fillers obtained by processing natural or manufactured materials as well as mixtures of these aggregates for the following use in concrete, mortar and grout, bituminous mixtures and surface treatments and unbound and hydraulically bound mixtures.

This standard covers LWA of mineral origin having particle densities not exceeding 2000 kg/m^3 or loose bulk densities not exceeding 1200 kg/m^3. According to the scope, one of the recognized LWA sources is LWA manufactured from recycled source materials. A list of source materials and specific materials, which are within the scope of this standard, is given in *Annex A (normative) – Source materials considered in the development of EN 13055 and their status in respect of the scope of the standard.* The list contains materials with a positive history of use, but recycled CDW is not included. This list may however be subject to continual review if other sources, based on routine application on the market by at least one CEN member state, are used and a procedure for how this can be carried out is given. However, even if CDW materials were incorporated in this list, this would only apply to mineral LWA, not to non-mineral LWA from CDW.

Some LWA for specific applications are covered in separate European product Standards and listed in *Annex B (normative) – Standards covering other applications of LWA.* As above, it must be noted that Annex B does not cover non-mineral LW materials coming from CDW. In addition, the standard includes a note on recycled materials from CDW and MIBA (Municipal Solid Waste Incinerator Bottom Ash) which are covered by the following standards: EN 12620+A1:2008, EN 13043, EN 13139 and EN 13242. None of these standards cover non-mineral aggregates.

EN 13055:2016 includes a complete list of tests to assess the product characteristics in accordance with relevant standards. It is not necessary to test and declare all the characteristics specified. Some are only relevant for special applications or origin of the aggregates. From this list, properties and

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tests that could be relevant for non-mineral LWA are given in Table 26. Tests which never would be relevant for non-mineral LWA, or test methods not suitable for non-mineral LWA, have been omitted.

CE-marking of mineral LWA is treated in Annex ZA of EN 13055. Characteristics defined as essential for mineral LWA aggregates which may be relevant for non-mineral LWA of the type used in this project, have been marked in Table 26. Most of the characteristics shall be declared, a few of them are subject to fail/pass criteria. National regulations on *dangerous substances* may require verification and declaration on release and sometimes contents.

Table 26: Properties and test methods (EN 13055:2016) that may be relevant for CDW non-mineral LWA.

Property	Test method	Mandatory or optional	Essential characteristic (EN 13055 Annex ZA)	Comment
Loose bulk density	EN 1097-3	M	X	
Particle density	EN 1097-6	O	X	
Aggregate size		M	X	
Grading	EN 933-1	O	X	
Fines content	EN 933-1	O		
Particle shape		O	X	
Water content	EN 1097-5	O		
Water absorption	EN 1097-6 (coarse aggregate) EN 13055 D (fine aggregate)	O	X	
Bulk crushing resistance	EN 13055/Annex C)	O	X	
Chloride content	EN 1744-1	O	X	*Test methods not directly suitable for organic materials*
Sulphur containing compounds	EN 1744-1	O	X	
Cleanliness (organic contaminators)	EN 1744-1	O	X	

ASTM C332: 2017 "Standard specification for lightweight aggregates for insulating concrete"

This specification covers LWA intended for use in concrete not exposed to the weather, in which the prime consideration is the thermal insulating property of the resulting concrete. Two general types of LWA are covered by this specification as follows:

- Group I – aggregates prepared by expanding products such as perlite or vermiculite.
- Group II – aggregates prepared by expanding, calcining or sintering products such as furnace slag, clay, diatomite, fly ash, shale or slate and aggregates prepared by processing natural materials, such as pumice, scoria or tuff.

Group I aggregate generally produce concrete with density from 240 to 800 kg/m^3 and thermal conductivity from 0.065 to 0.22 W/m·K. Group II aggregates generally produce concrete with density from 720 to 1440 kg/m^3 and thermal conductivity from 0.15 to 0.43 W/m·K. In addition, the standard specifies that the aggregate shall be composed predominantly of LW cellular and granular inorganic material. RE4 LWA is not covered by this group, therefore just some prescriptions are considered from the standard at issue. This can be used just as reference.

With respect to physical properties of concrete made with LWA, the thermal insulating properties shall conform to the maximum average thermal conductivity reported in Table 27.

Table 27: Insulating requirements of concrete made with LWA (adopted by ASTM C332).

Maximum average 28-day oven-dry	Maximum average thermal conductivity
[kg/m^3]	[W/m·K]
800	0.22
1440	0.43

This standard also gives grading and density requirements, including uniformity of grading and density, for LWA typically used for insulating concretes. These requirements are specifically given for aggregates of Group I and II, which do not include materials investigated in RE4 project. The standard also reports a list of tests for the determination of aggregate properties, which includes sampling, grading (fine and coarse aggregate), loose density and fineness modulus including corresponding testing methods. Finally, the standard reports test methods for the determination of insulating concrete properties including specimen preparation, density and thermal conductivity evaluations (ASTM Test Method C177). The LWA have to be sampled, tested and inspected in accordance with this standard and have to meet the requirements. The materials that fail to conform to the requirements of this standard are subject to rejection.

4.3.2 Standards on (precast) concrete products based on lightweight aggregates

As opposed to compact concretes, for which *EN 13369 – Common rules for precast concrete products* can be followed, there are no specific standards for concretes based on (recycled) LWA with reduced density and, therefore, improved insulating performance. EN *13369* applies to compact concrete with no appreciable amount of entrapped air other than entrained air and with dry density ≥ 800 kg/m^3; it does not cover prefabricated reinforced components of LWA concrete with open structure. However, according to *EN 13369*, among the requirements for the finished concrete products, thermal properties shall be declared when relevant for the type of product. In the RE4 project, the use of non-mineral LWA from CDW (i.e. rigid plastic, and wood and plastic) is specifically intended for production of concretes with improved insulating properties, reduced density and suitable for specific building applications (e.g. layers of panels, substrates for screeds or roofs insulation). Therefore, this standard can eventually be considered as reference for what concerns thermal properties.

EN 13369 specifies which thermal properties are required for the material (e.g. thermal conductivity and specific heat capacity) and for the product (e.g. geometry, thermal resistance and heat capacity). Moreover, *EN 13369* specifies which standards that must be applied for the determination of these: *EN 12664* for thermal conductivity of the material, *EN ISO 10456* for the determination of declared properties and their conversion in designed thermal values for dry state, *EN 1745* or *EN*

12524 include tabulated values to obtain the design thermal conductivity and specific heat capacity, and EN ISO 6946 allows the calculation of thermal resistance and thermal transmittance of concrete components which can be also measured in a hot box in accordance with EN ISO 8990 or EN 1934.

In Annex A of *EN 1745* [47], $\lambda_{10,dry}$ values (thermal conductivity in dry state at an average temperature of 10 °C) are reported for different materials used for masonry products, differentiated by material type and its dry density. Annex A also contains values for μ (water vapour diffusion coefficient) and c (specific heat capacity). Tabulated values are available in Annex A which includes Table A.3 on dense aggregate concrete units, Tables from A.4 to A.8 on LWA commonly used for concrete units (e.g. pumice, expanded clay, polystyrene) and Table A.9 on concrete units with other LWA. Table A.9 shall be used for concrete units with LWA where no history for λ exists (e.g. for new products) and the given λ-values are safe values for all different types of aggregates. Table A.9 can be used, at least as reference, for non-mineral lightweight insulating concretes developed in the RE[4] project (see compilation in Table 28).

Table 28: Properties of concrete units with other LWA.

Property	**Density**	**$\lambda_{10,\,dry}$**	**μ**	**c**
Unit	[kg/m^3]	[W/m·K]	[-]	[kJ/kg·K]
	500	0.24	5/15	1.0
	600	0.27	5/15	1.0
	700	0.30	5/15	1.0
	800	0.33	5/15	1.0
	900	0.37	5/15	1.0
	1000	0.41	5/15	1.0
	1100	0.46	5/15	1.0
	1200	0.52	5/15	1.0
	1300	0.58	5/15	1.0
	1400	0.66	5/15	1.0
	1500	0.74	5/15	1.0
	1600	0.83	5/15	1.0
	1800	1.08	5/15	1.0
	2000	1.33	5/15	1.0

EN 12524 [48] reports humidity, water vapour resistance factor and specific heat capacity of concretes incorporating general mineral LWA and with density in the range 500-2000 kg/m^3 (see Table 29 Table 29).

Table 29: Properties of materials for thermal insulation and masonry materials (from table 2 in EN 12524).

Material	**Density**	**ψ**		**F_ψ**	**μ**		**C_p**
		23°C, 50% R.H.	23°C, 80% R.H.		dry	wet	
	[kg/m^3]	[m^3/m^3]	[m^3/m^3]	[-]	[-]	[-]	[J/(kg·K)]
Concrete with other LWA	500-2000	0.03	0.05	4	15	10	1000

4.4 Fine materials (silt and clay) as SCM or AAB

The fine material tested in the RE[4] project is the clay and silt fraction obtained from the washing of the recycling of CDW. To test its conformity, it was treated primarily as clay and tested for its main chemical constituents and water soluble elements (chlorides, sulfates and alkalis). The potential to be used as a binder was limited to assessing its reactivity via calorimetric observations, where it was observed that the material did indeed set.

4.4.1 Fine materials as a pozzolanic addition to OPC

The use of clay as a pozzolanic material in cement is defined in EN 197-1:2011 [14]. The standard provides two classes: *Natural pozzolans* (P), from material of volcanic origin or sedimentary rocks, and *Natural calcined pozzolans* (Q), which come from material of volcanic origin, clays, shales and sedimentary rocks, and that requires thermal activation. Regardless of their class, pozzolanic materials (e.g. clays) are typically made up of reactive SiO_2 and Al_2O_3. The standard further dictates that the reactive SiO_2 content shall not be less than 25% by mass. Several classes of cement containing pozzolans are defined in EN 197-1:2011 [14] and some are summarized in Table 30. If activation is going to be successful, deliverable D4.2 demonstrated that the RE[4] fine material should be thermally activated and treated as a calcined pozzolan (Q), if blended with cement.

Table 30: Pozzolan cement constituents according to EN 197-1:2011 [14].

Type of Cement		Composition by mass (%)						
		clinker	GGBS	(P)	(Q)	silica fume	fly ash	limestone
CEM II	CEM II/A-P	80 - 94	-	6 - 20	-	-	-	
	CEM II/B-P	65 - 79	-	21 - 35	-	-	-	
	CEM II/A-Q		-	-	6 - 20	-	-	
	CEM II/B-Q		-	-	21 - 35	-	-	
	CEM II/A-M	80 - 88	12 - 20					
	CEM II/B-M	65 - 79	21 - 35					
CEM IV	CEM IV/A	65 - 89	-	11 - 35				
	CEM IV/B	45 - 64	-	36 - 55				

The cement type must also comply with the chemical requirements, e.g. sulfate and chloride contents (Table 31). Furthermore, any pozzolanic cement must satisfy the conditions in EN 196-5:2011 [15].

Another possibility to use the finest CDW material in cement production, is if it can be used as the 5 % allowed in all cements for *minor additional constituents* described in section 5.3 in EN 197-1. These should be specially selected, inorganic natural mineral materials, inorganic mineral materials derived from the clinker production process or silica fume, granulated blast furnace slag or fly ash unless they are included as main constituents in the cement.

Table 31: Chemical requirements of cement types (from EN 197-1:2011 [14]).

Property	Reference	Cement Type	Strength Class	Requirements
Loss on ignition	EN 196-2	CEM I CEM III	all	≤ 5 %
Insoluble residue	EN 196-2	CEM I CEM III	all	≤ 5 %
Sulfate content (as SO_3)	EN 196-2	CEM I CEM II CEM IV CEM V	32.5 N 32. 5 R 42.5 N	≤ 3.5 %
			42.5 R 52.5 N 52.5R	≤ 4 %
		CEM III	all	
Chloride content	EN 196-2	all	all	≤ 0.10 %
Pozzolanicity	EN 196-5	CEM IV	all	satisfies test

4.4.2 Fine material as AAB

Currently, no standard focuses specifically on the use of fine material as a precursor in alkali activated binder concrete. In addition, fine material does not conform to any national or international standard for use in OPC concrete [16]. However, Alkali Activated Materials (AAM) provide a greater challenge over Portland cement as AAM can be produced with numerous precursors and activators, of differing chemical compositions.
Despite this, efforts to standardize AAM have been made in the past, notably in the former USSR [17], [18], [19]. Furthermore, standards exist under which AAM, that do set the building blocks to devise standards suitable for AAM [20], [21], [22]. This is the case of the ASTM C1157 [22] which defines only performance targets, but imposes no restrictions on the composition of the binder constituents. A RILEM committee (TC 224-AAM) [16] was set up to review the use of AAM, in which they propose a performance based standard specific for AAM. The report suggests two lines of recommendations, one for alkali activated cement and another for alkali activated concrete, with the main points summarized in Table 32.

Table 32: Recommendations for performance-based standards of AAM.

Alkali Activated Cement	Alkali Activated Concrete
Definition of alkali activated cement	Definition of alkali activated concrete
Suitable precursors and activators	Effect constituents
Classification based on fresh and hardened properties	Fresh and hardened properties which satisfy performance requirements
Information to be shared with customers	Durability tests
Testing method	Health and safety

4.4.3 Fine Material as binder for earthen building materials

The requirements for the silt and clay fraction are fairly limited. If clayey soil should be used as binder for earth plasters it must be cohesive enough. A threshold value of 50 g/cm^2 for the binding force is defined. In addition, the material should not contain any harmful substances or damaging salts, the organic content should be very low and the carbonate content suitable. No threshold values are provided for these parameters in [13].

4.5 Timber – reused timber and wood products

As far as timber and wood products go, two main aspects come into play in terms of classification: timber grading and contamination levels.

For timber grading, reused elements and products fall under the same set of codes as new elements and products. Indeed, as already reported in D4.2, the properties of aged timber have been investigated since the 1950s and evidence suggests that aging has negligible effects [23], as long as the materials have been correctly protected from deterioration (i.e. protected for instance against pest attack and preserved in adequate conditions in terms of humidity and temperature). Once the reclaimed materials and elements have been treated so as to eliminate damaged and irregular parts, their structural capacity remains comparable with that of equivalent new timber element, i.e. no downgrading occurs. Hence, grading according to the European Norm ([24], [25], [26]) applies to reused elements cut and planed into rectangular cross sections as well as lamellas for glue-laminated timber elements.The harmonized European Norm [26] defines the framework for national grading regulations, which rule sorting classes on the basis of strength, stiffness and density. Depending on the national clauses, these parameters might be assessed according to different methodologies and sorting classes follow a different nomenclature. Nevertheless, the sorting categories identified by the national codes correlate to the strength classes listed in [27]; such classes are used Europe-wide in structural calculations and therefore constitute a meaningful parameter for the construction market.

Contamination is also a crucial parameter for determining the suitability and potential of reuse for timber. However, no unified regulation is in place in Europe. Guidelines and recommendations are applied in some European countries, but limit values vary largely, as visible from Table 33. Increasing awareness of the issues connected to contamination, growingly stringent legislation and a larger demand for recycled product entail that contamination will be less of an issue in the future. For the time being, however, the possibility of defining and applying a set of common limits is crucial in order to boost the reusability of timber.

Table 33: Limits of chemicals in recycled wood used for wood based panels.

			Germany	United Kingdom	Italy	Belgium (Flanders)	Austria
	max. concentration in untreated wood	**European Panel Federation** (not obligatory)	**Altholzverordnung** (waste wood directive)	**PAS 111:2012** specification for the requirements and test methods for processing waste wood	**Standard per la certificazione dei prodotti realizzati con materiali da riciclo** (Standard for the certification of products made from recycled materials)	**VLAREM II** Vlaams Reglement betreffende de Milieuvergunning	**Recyclingholzverordnung** (recyclingwood directive)
Elements/ Compounds		**upper limits mg/kg recycled wood**					**80% percentile**
Arsenic (As)	< 1,0	25	2	25	2	2	1,8
Cadmium (Cd)	< 0,8	50	2	50	2	x	1,2
Chromium (Cr)	< 5,0	25	30	25	25	30	15
Copper (Cu)	< 10,0	40	20	40	20	20	x
Lead (Pb)	< 10	90	30	90	30	90	15
Mercury (Hg)	< 0,2	25	0,4	25	0,4	x	0,075
Fluorine (F)	< 100	100	100	100	100	30	20
Chlorine (Cl)	< 100	1000	600	1000	600	600	300
Pentachlorphenol (PCP)		5	3	5	3	3	3
chlorinated diphenyls (PCB)		x	5	x	x	x	x
Creosote (Benzoapyrene)		0,5	x	0,5	0,5	0,5	x

Sources: Column 1 [28], Column 2 [29], Column 3 [30], Column 4 [31], Column 7 [32]

4.6 Lightweight materials for insulating panels

As far as it concerns use of wood based lightweight flakes coming from CDW, neither European nor non-European standards report on quality assessment of this fraction in insulating panels (or construction and materials in general). As already reported in D4.2 [5] and D4.3 [6], the available standards specify the requirements for factory made wood wool (WW; EN 13168+A1:2015) [49] and wood fibre (WF; EN 13171+A1:2015) [50] products, describe product characteristics and include procedures for testing, evaluation of conformity, marking and labelling of the final product. Furthermore, these standards do not specify the required level of a given property to be achieved by a product to demonstrate fitness for purpose in a specific application. The levels and classes required for a given application are to be found in regulations or non-conflicting standards.

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5. CLASSIFICATION OF THE RE4 MATERIALS

5.1 Mineral aggregates in concrete

In the RE^4 project, eight different batches of mineral CDW from CDE recycling centres have been systematically investigated, in order to access the quality variability.

Table 34: Constituents of and concrete performance with the different batches of CDW.

Material	N-EU B1	N-EU B2	N-EU B3	N-EU B4	S-EU B1	S-EU B2	S-EU B3	S-EU B4	EN206 E.2 A/B
Rc [%]	5	6	5	4	38	10	69	71 [1]	≥90/50
Ru [%]	85	89	92	93	39	84	28	27[1]	---
Rc+Ru [%]	90	95	97	97	77	94	97	98[1]	≥95/70
Rb [%]	4	2	1	1	19	1	3	1[1]	≤10/30
Ra [%]	6	4	2	2	0	2	0	0[1]	≤1/5
Fl [cm^3/kg]	0	0	0	0	1.3	0.9	0.05	0.1[1]	≤2/2
XRg [%]	0.1	0.2	0.2	0.2	4.7[3] (0.7)	2.6[3] (0.5)	0.3	0[1]	≤1/2
Oven dry particle density [kg/m^3]	2480	2690	2670	2630	2120	2680	2310	2230[1]	≤2100/ ≤1700
Apparent particle density [kg/m3]	2630	2800	2760	2740	2530	2790	2710	2620[1]	----
Water absorption [%]	2.4	1.5	1.3	1.5	7.7	1.5	6.3	6,0[1]	Decl.
Water soluble chloride [%]	Negl.	Negl.	Negl.	Negl.	0.003	Negl.	0.007	Negl.[1]	Decl.
Water soluble sulphate [%]	0.01	0.02	0.02	0.008	0.1	0.002	0.006	0.2[1]	≤0.2
Performance in concrete									
1 d compressive strength [MPa]	11.5	11.0	10.5	12.5	12.0	19.5	21.0	9.0[2]	---
28 d compressive strength [MPa]	36.0	37.0	36.5	37.5	34.5	47.5	53.0	31.0[2]	---
28 d tensile strength [MPa]	2.65	2.70	3.15	2.75	--	--	--	--	---
Hardened density after 28 days	2270	2380	2390	2390	2150	2410	2190	2140[2]	
Fresh density[kg/m^3]	2260	2360	2360	2370	2090	2340	2150	2290[2]	---
Slump after 15 min. [mm]	110	200	190	210	30	70	75	210 [2, 4]	---

[1] Average of B4-1, B4-2 and B4-3
[2] Value for B4-3
[3] Mostly slag-like particles, number within brackets is percentage of pure glass
[4] Slump after 30 min

Four of these came from a Northern Europe Source – one from Germany (N-EU B1) and three from Norway (N-EU B2, B3 and B4) – and results of the investigations were published in D4.3. Four of the batches came from a Southern Europe Source (southern France) and results for the first three (S-EU B1, B2 and B3) were given in D4.3, whereas results on the last (S-EU B4) are given in this report. In Table 34, the constituents of the 8/16 fraction of these eight different batches are given, together with the EN206:2013 requirements on constituents for Type A and B CDW. Some of the concrete properties obtained with these batches are also included in Table 34. Where the batches does not fulfil the requirements for neither Type A nor Type B, the cell is marked with red. Where the batches does not fulfil the requirements for Type A but fulfils the requirement for Type B, the cell is marked with blue.

As can be seen, not a single batch fulfils the EN 206:2013 requirement on percentage of concrete debris. However, five of the batches meet the requirement on Rc+Ru (i.e. concrete and stone) for Type A and the other three batches meet those for Type B. It must be questioned if there should at all be a requirement on a separate value for Rc, since the critical value is Rc+Ru. Both stone and crushed concrete contribute significantly to the concrete strength. Several of the CEN member countries have omitted the value for Rc and only give values for Rc+Ru (see Table 23). Another resason for not separating the requirement on Rc and Ru is tyhat when CDW is sorted and classified according to EN 933-11, it is not easy to determine whether stone particles come from unbound stone or from stone aggregate incorporated in concrete.

Only one batch has too much masonry material for the Type A requirements. Only three batches passes the limit for type A, as regards bituminous materials, and four batches can be classified as Type B with regard to this property. It is not clear how slag-like particles shall be classified: as "glass", as "other" or could they even be sorted as Rc or Ru. In EN 12620+A1:2008, air-cooled granulated slag is considered as a material that can be used as aggregate. It would therefore be logical to count these particles as belonging to Ru. If the slag-like particles found in S-EU B1 and S-EU B2 are not categorized as glass, but as Rc or Ru, also these two batches fulfil the requirement for Type B.

All batches, irrespective of the composition, has an oven-dry particle density above 2100 kg/m^3 which is the lower limit for Type A. Possibly the same basic value for aggregates according to EN 12620+A1:2008 can be also applied for these types of recycled aggregates, i.e. 2000 kg/m^3.

If the requirement on Rc is disregarded from the constituent levels in Table E.2 of EN 206:2013, only S-EU B3 and S-EU B4 could be classified as type A, and N-EU B2, N-EU B3, N-EU B4 as Type B aggregates. The northern Euopean batches all have rather high amounts of bituminous material, which is the reason why they can not be classified as Type A. How much does the bituminous material influence the performance of the concrete? Is the low limit for Type A (1 %) motivated? Looking at the performance of the concretes made with the batches with higher Rb, a somewhat higher amount of Rb (2%) does not seem to influence the concrete performance significantly. If the limit is raised to 2 % also the N-EU B2, N-EU B3, N-EU B4 can be classified as Type A.

5.2 Mineral aggregates in earthen building materials

As requirements for mineral aggregates are fairly limited, the work carried out for the classification of mineral aggregates is limited to the preparation of sieving curves in addition to a visual inspection. Batches from SE and NE, as well as material being purchased in Berlin due to late arrival of NE batches, have been analysed.

Both the CDW aggregates from NE and those from SE contained a small proportion of oversize grains larger than 4 mm. In spite of this, the particle size distributions of the two batches are similar, as shown by the grain distribution curves; the greatest difference lies in the proportion of grain size >0.25 mm, which was about 8 % higher for deliveries from N-EU than for deliveries from S-EU. The fraction of fine particles < 0.063 mm is very small for both CDW batches and is on the order of 1.4 %.

The particle size distribution of a 0-2 mm "recycling" sand from Berlin differed very clearly from the materials from SE and NE, which can be seen in the course of the grain distribution curve. Thus, the oversize fraction > 4 mm was significantly higher, but also the content of the grain fractions 2, 1 and 0.5 mm was significantly lower. Results for the sieving curves can be found in Figure 19, Figure 20 and Figure 21.

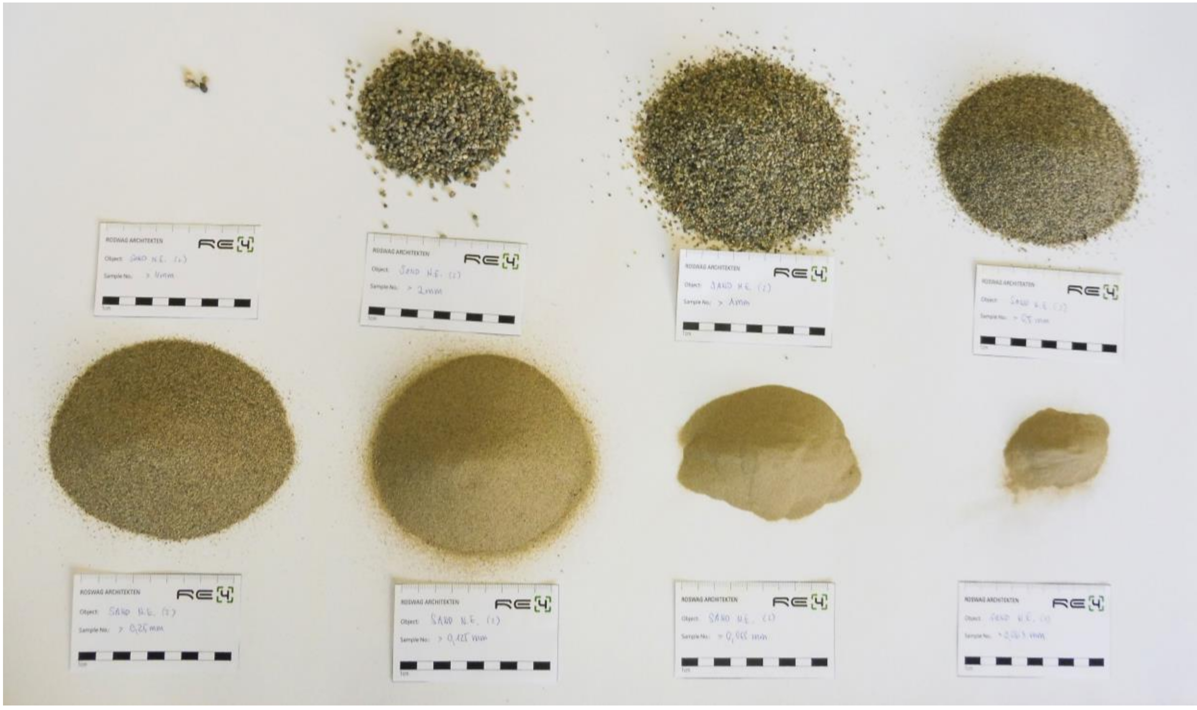

Figure 19: Sieving curve of CDW from N-EU.

Figure 20: Sieving curve CDW S-EU.

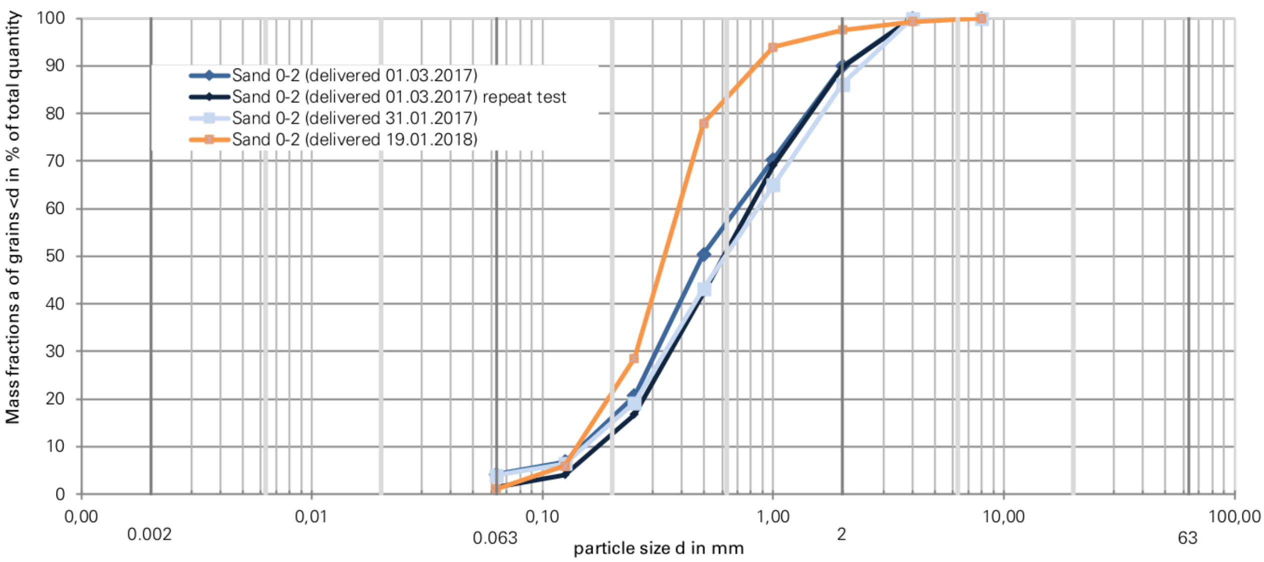

Figure 21: Comparison of particle-size distributions.

As a result, it can be stated that all batches demonstrated the required qualities for mineral aggregates. For rammed earth only a visual inspection and hand sorting has been carried out (Figure 22). Again, all aggregates in the CDW demonstrated the required level of quality.

Figure 22: Hand sorting of aggregates for rammed earth.

5.3 Lightweight aggregates in concrete

As already mentioned, standards on LWA concretes identified and discussed in Section 4.3 cover materials from sources different from those used in the RE^4 project. The LWA investigated here consist of rigid plastics resulting from a grinding process of plastic scraps, and a mixed wood/plastics fraction coming from the discarded CDW processing lightweight by-products. The aim consists in valorisation of these LWA, by incorporation in insulation concrete solutions. Since LWA is not specifically included in the available standards, RE^4 LWA cannot be classified according to them. Nevertheless, some reference standards dealing with LWA used for concretes and insulating concrete based on LWA have been identified. General guidelines included in these standards might be eventually followed for RE^4 LWA classification. In this section, possible approaches for use of these standards as reference are suggested.

EN 13055:2016 standard has been identified as useful reference on LWA for concrete and mortars. This standard does not deal with non-mineral aggregates, but two important notes can be made:

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- ASTM C332:2017 deals with materials different from RE^4 LWA, however, it includes insulating requirements for LW concretes (see Table 27) that can be used as reference.
- EN 13369 refers to EN 1745 and EN 12524 including values of thermal properties of concretes based on general LWA (see Table 28 and Table 29) and can be used as references.

Based on this approach, below is presented a proposal for the classification of RE^4 LWA from CDW according to the existing product standards. The classification is developed on two different levels:

1. With respect to the essential characteristics of the LWA
2. With respect to the insulating performance of concretes incorporating such LWA

Table 35 and Table 36 include some characteristics of RE^4 LWA, assessed according to relevant standards of RP and WP, respectively, according to EN 13055 required for CE marking. As suggested in the standard, the necessity for testing and declaring all the characteristics specified are limited according to the specific application or origin of the aggregates.

Table 35: Characteristics of RE^4 rigid plastic aggregates according to relevant standards.

Clauses of EN 13055 related to essential characteristics	**Results**	
	S-EU source	**N-EU source**
5.2.1 Loose bulk density	RP<4mm: 490 kg/m^3	RP<4mm: 440 kg/m^3
	RP>4mm: -	RP>4mm: 390 kg/m^3
5.2.2 Particle density	RP< 4 mm: ρ_{rd}: 1055 kg/m^3; ρ_{ssd}: 1130 kg/m^3	RP > 4 mm ρ_{rd}: 860 kg/m^3; ρ_{ssd}: 1160 kg/m^3
	RP> 4 mm: 1030 kg/m^3; ρ_{ssd}: 1080 kg/m^3	RP> 4 mm: ρ_{rd}: 930 kg/m^3; ρ_{ssd}: 1000 kg/m^3
5.3 Aggregate size	d= 1 mm; D< 10 mm	d=0.125 µm; D< 10 mm
5.4 Grading	Available (fine, medium, coarse fraction)	Available (fine, medium, coarse fraction)
5.7 Particle shape	Irregular particles with rounded corners	Irregular particles with rounded corners
5.9 Water absorption	RP<4mm: 7%	RP<4mm: 10%
	RP>4 mm: 5%	RP>4 mm: 7%
5.25.3 Chloride	Test method not suitable for organic materials	Test method not suitable for organic materials
5.25.4.1 Acid-soluble sulphate		
5.25.4.2 Total sulphur		
5.25.7 Organic contaminators	Test method not suitable for organic material. No relevant alteration in rate of setting and hardening of concrete observed	Test method not suitable for organic material. No relevant alteration in rate of setting and hardening of concrete observed

Table 36: Characteristics of RE[4] wood/plastic aggregates according to relevant standards.

Clauses of EN 13055 related to essential characteristics	Results	
	S-EU source	N-EU source
5.2.1 Loose bulk density	170 kg/m^3	210 kg/m^3
5.2.2 Particle density	ρ_{rd}: 355 kg/m^3; ρ_{ssd}: 735 kg/m^3	ρ_{rd}: 230 kg/m^3; ρ_{ssd}: 650 kg/m^3
5.3 Aggregate size	d=1 mm; D=4 mm	d= 1 mm; D=4 mm
5.4 Grading	Available (fine fraction)	Available (fine fraction)
5.7 Particle shape	Rounded particles with minor presence of elongated parts	Rounded particles with minor presence of elongated parts
5.9 Water absorption	107%	98%
5.25.3 Chloride 5.25.4.1 Acid-soluble sulphate 5.25.4.2 Total sulphur	Test method not suitable for organic material	Test method not suitable for organic material
5.25.7 Organic contaminators	Test method not suitable for organic material; No relevant alteration in rate of setting and hardening of concrete observed	Test method not suitable for organic material; No relevant alteration in rate of setting and hardening of concrete observed

Additionally, Table 37 and Table 38 propose classification of concretes based on RE[4] LWA (RP and WP, respectively), according to standards dealing with insulating performance. The data are referred to optimised RP/OPC and WP/OPC concrete formulations and take into consideration exclusively the insulating performance. However, mechanical performance was also satisfying (7.0 MPa and 12.0 MPa, respectively). The classification here reported, with the limitations above mentioned (e.g. existing standards only covering LWA with sources different from RP and WP), will support the definition of new quality classes of RE[4] LWA from CDW, reported in Section 6.

Table 37: Classification of RE[4] concrete based on rigid plastic aggregates according to relevant standards.

LW concrete based on RE[4] RP aggregates and OPC					
Materials		**Density**	**λ**	**μ**	**c_p**
Binder	OPC	Kg/m^3	W/m·K	-	J/kg·K
LW aggregates	RP 0/2 mm, RP 2/8 mm, RP 4-10 mm	1220	0.25	15 (dry); 10 (wet)	1000
NW aggregates	MF 0/2 mm				
Requirements adopted by ASTM C332		800-1140	0.22-0.43	/	/
Comments on RE4 LW concrete			Suitable		
Requirements adopted by EN 1745		1200-1300	$\lambda_{10,dry}$ 0.52-0.58	5 (dry); 15 (wet)	1000
Comments on RE4 LW concrete			Not comparable	Suitable	Suitable
Requirements adopted by EN 12524		500-2000	/	15 (dry); 10 (wet)	1000
Comments on RE4 LW concrete				Suitable	Suitable

Table 38: Classification of RE4 LW concretes based on wood/plastic aggregates according to relevant standards.

LW concrete based on RE4 WP aggregates and OPC						
Materials		**Density**	**λ**	**μ**	**c_p**
Binder	OPC	kg/m^3	W/m·K	-	J/kg·K
LW aggregates	WP 0/2, WP 2/8, WP 4-10 mm	1470.0	0.60	15 (dry); 10 (wet)	1000
NW aggregates	MF 0/2 mm				
Requirements adopted by ASTM C332		800-1140	0.22-0.43	/	/
Comments on RE4 LW concrete			Slightly higher		
Requirements adopted by EN 1745		1200-1300	$\lambda_{10,dry}$ 0.52-0.58	5 (dry); 15 (wet)	1000
Comments on RE4 LW concrete			Not comparable	Suitable	Suitable
Requirements adopted by EN 12524		500-2000	/	15 (dry); 10 (wet)	1000
Comments on RE4 LW concrete				Suitable	Suitable

5.4 Fine materials (silt and clay) as SCM or AAB and binders for earth materials

The work carried out on the fine material was very limited based on the outcomes of RE4 regarding its use. The main results collected are summarised in Table 39. The conclusions and recommendations assume that no treatment, other than calcination, is carried out on the fine material. It should be noted that the chloride and sulfate contents were not measured following the procedures set in EN 196-2:2013 [33]. These methods rely on dissolution of the cement by using acid. As such, the values measured according the EN 1744-1:2009 [34], which measure only the water soluble contents, are underestimated.

Table 39: Summary of results from Deliverable 4.2.

Test	Standard	% by mass
Plastic Limit	BS 1377-2:1990 [35]	33
Liquid Limit	BS 1377-2:1990 [35]	66
Plasticity Index	BS 1377-2:1990 [35]	27
Activity Index	N/A	9.05
Water Soluble Chlorides	EN1744-1:2009+A1:2009 [34]	0.19
Water Soluble Sulfates		
2:1 solids ratio at 20 °C		0.274
40:1 solids ratio at 60 °C		3.126
Organic Content		
Fulvo acid		nil
Humus		small quantity
Soluble Alkali		
Na		0.023
K		0.024
XRD Analysis	N/A	
Quartz (SiO_2)		31.7
Calcite ($CaCO_3$)		12.7
Gypsum ($CaSO_4*2H_2O$) / SO_3 equivalent		18.3 / 8.5
Remaining (including XRD amorphous)		37.3

5.4.1 As a SCM to OPC

If fine material is to be blended with Portland cement to form a pozzolanic cement, even after calcination, the amount used will have to remain minimal as to meet the restrictions set in EN 197-1:2000 (Table 31) [14]. It is very unlikely that this material could ever be used as a partial substitute to Portland cement. XRD analysis determined 32% SiO_2 in the form of quartz and is therefore unreactive. This makes up the majority of the SiO_2 present in the fine material (43% according to XRF analysis, see D4.2). EN 197-1:2000 [14] requires that pozzolan contain at least 25% of reactive SiO_2, and this material does not meet this requirement. Even if blended with cement and other additives, for example to prepare CEM IV cement, the high sulfate content (18.3% of gypsum, equivalent to 8.5% of SO_3, while XRF analysis determined 7.9% of SO_3) suggests that its use would be very limited as small additions would quickly increase the overall SO_3 content. However, sulfur in the form calcium sulfate is deliberately added to Portland cement clinker in the production process, in order to control setting of the cement. Could the fine CDW fractions be used, and the sulfate content in it partly substitute some of the needed calcium sulfate?

5.4.2 As an AAB

It is harder to assess the use of the fine material as an alkali activated binder based on the work carried out so far. On a chemical level, the fine material contains low levels of reactive SiO_2 but moderate Al_2O_3 levels. It was found that the calcined fine material had the potential to set. However, strength evolution was not assessed, although manual observations showed that the material was easily scratched and friable when handled after 7 days of curing at 20 °C.

The chloride content is higher than what the industry is used to, compared with Portland cement. However, research shows that alkali activated binders spiked with 2% chloride by mass of binder and exhibited adequate resistance to chloride corrosion of steel reinforcement [36], [37], [38], outperforming equally spiked OPC concrete.

It is harder to assess the impact of the high sulfate reservoir on performance. Alkali activated binders typically show good resistance to sulfate attack but that is not to say that they are immune to damage. Kukko and Mannonen [39] found that alkali activated blast furnace slag cement exposed to 10% by mass of $MgSO_4$ disintegrated. Similarly, Bakharev witnessed the formation of ettringite in fly ash geopolymer concretes [40]. However, the low levels of CaO would suggest that only minute amounts of ettringite could form. However, these two studies relied on external sulfate attack and comparison to internal sulfate attack has its limitations. Blending the fine material with any other precursor, e.g. fly ash, GGBS or metakaolin, could dilute the sulfate and chloride levels to values more akin to the cement industry. The resulting product may very well perform adequately, as all other precursors are known to perform well, but without a standard the class cannot be determined.

Previous work on CDW silt and clay as a binder showed that the material can gain strengths of up to 26 MPa [41]. This strength was achieved on ground silt and clay that were mixed with an activating solution to form wet crumbs that were subsequently pressed into a steel mould at 24 MPa.

Furthermore, the strongest sample was cured at 60 °C with a 9 M NaOH solution as an activator. The authors concluded that such a product could be used as low strength aggregates. Provided the strength is adequate, the alkali activated material could very well be used for non-structural elements.

5.4.3 As a binder for earthen building materials

Work that has been carried out in relation to the requirements set out in section 4.3.3 is presented in Table 40. However, salt content and the occurrence of harmful substances have not been tested as these parameters might differ from batch to batch and do not impact on the technical suitability for the silt and clay for usage as binder.

Table 40: Properties of S-EU and N-EU CDW silt and clay presscake.

Material ID	Standard	Property	Unit	Result
Silt and clay press cake (SE / NE)	EN ISO 14688-1: 2013-12	semi-quantitative determination of calcium carbonate using dilute hydrochloric acid	(-)	strong, long-lasting effervescence (SE) → increased carbonate in different particle sizes
	EN ISO 14688-1: 12-2013	olfactory test - indications of organic components	(-)	humus smell (SE, NE) → contains organic components
	Lehmbau Regeln 2009	average binding force (8-shaped test sample)	g/cm²	157 (SE) → nearly fat, suitable if made leaner by adding aggregates

According to the results of the tests, the silt clay press cake is suitable for the production of clay building materials, as the determined binding force was high enough, the content of organic matter was very low and the carbonate content suitable.

5.5 Timber – reused timber and wood products

According to the review of the technical literature and sample treatment of reclaimed timber carried out in the framework of D4.2, it is possible to say that the most meaningful outcome of this deliverable is not the grading of timber according to codes but rather the assessment of the working procedure prior to grading. Indeed, it has already been discussed that no downgrading of the mechanical properties occurs. A reused timber element or piece, which has been cleared of fasteners and irregular/damaged areas, will perform in line with its behaviour at the beginning of its life cycle. This means, for instance, that mechanical testing of parts of a timber element with strength class C24 will provide results in line with the values set forth for this strength class. If the parts are worked in the form of lamellas and used to build up a glue laminated timber element, this will have a performance in line with the code specifications for the relevant strength class of the lamellas. As such, mechanical testing does not help to gain a better insight in the potential reuse of timber. On the other hand, the issue of obtaining reusable parts prior to grading is crucial; this includes the possibility of cutting out a sufficient number of parts with meaningful size and regularity and yet limit the waste. This has been investigated in the framework of D4.2, where lamellas for glued laminated beams were obtained from timber elements reclaimed from a roof structure in Berlin, Germany.

The experience gained in D4.2 confirms that the procedures such as that set forth by [42] is feasible and yields good results. The issue of chemical contamination remains open: as no clear guidelines are set at a European level and threshold values applied in different countries fluctuate considerably, it is not deemed meaningful to carry out extensive testing, as this would be hard to correlate with technical results or requirements. The definition of appropriate limits should be investigated in future research projects so as to inform a European-wide norm. At the moment, the lack of information and rules in this sense constitutes a main obstacle to a broader implementation of reused timber for timber elements and products.

5.6 Lightweight materials for insulating panels

Different insulating wood-based materials can be classified by category (though there is some overlap): batts and blankets, loose-fill, soft and rigid boards. These categories are based primarily on the material form and installation method. The physical parameter that better characterize each category is density. Batts and blankets have density values in the range 50-100 kg/m^3, loose-fill have a raw density of 35 kg/m^3, and soft and rigid boards have densities in the range 100-300 kg/m^3. For this reason, as reported in D4.3, on the basis of wood based panels realized by a non-optimized fabrication process (Table 41), the hygrothermal performances of wood flakes in the production of insulating panels have been evaluated considering the densities of the panels, according to EN 10456:2008 [51].

Table 41 Hygrothermal properties of wood-based panels.

Material	**Density (kg/m^3)**	**Thermal Conductivity λ (W/m·K)**	**Specific Heat Capacity c_p J/(kg·K)**	**Water Vapour Resistance Factor μ**	
				dry	wet
S-EU wood					
0-4 mm	247	< 0.07	1700	<5	<3
N-EU wood					
0-4 mm sorted by machine	312	0.0822	1700	7.03	3.81
0-4 mm mixed sorted	318	0.0836	1700	7.26	3.90
0-8 mm sorted by machine	324	0.0847	1700	7.45	4.01

6. SUGGESTED NEW QUALITY CLASSES

6.1 For application in the RE4 project

6.1.1 Concrete elements

For normal and heavy weight concrete (oven-dry density > 2000 kg/m^3), the quality classes Type A and Type B in Table E.2 of EN 206:2013 should be modified and complemented with new classes, taking into consideration the following aspects:

- The separate requirement on minimum amount of concrete debris (Rc) is not motivated and the main requirement should be a minimum value on Rc+Ru.
- It would be better to use the same limit on oven-dry density as for natural normal weight aggregate, i.e. 2000 Kg/m^3 for all classes mainly composed by CDW from normal weight.
- It would be preferable to have a class with higher requirements than Type A in EN 206:2013, which may be regarded as almost equal to natural aggregate.

Type A and the new Type A+ should be used for structural concrete. Type B should be mainlyintended for non-structural concrete or concrete subjected to low loads as, for instance, concrete masonry units. For this purpose and for L classes of concrete according to EN 2016:2013 it should also be possible to use lighter fractions of CDW as a LWA aggregate (oven-dry density ≤ 2000 kg/m^3).

Proposal for constituents and properties for modified Type A and Type B classes and for the type A+ and Type L (LWA) classes are given in Table 42.

Table 42: Proposal for properties of new quality classes for mineral CDW aggregate in concrete.

Property	Type A+	Type A	Type B	Type L
Density (oven dry) [kg/m^3]	> 2000	> 2000	> 2000	≤ 2000 (To be declared)
Rc+Ru [%]	≥ 95 %	≥ 90 %	≥ 70 %	---
Rb [%]	≤ 5 %	≤ 10 %	≤ 30	---
Rc+Ru+Rb [%]	---	----	≥ 90 %	≥ 95 %
Ra [%]	≤ 1 %	≤ 5 %	≤ 10 %	≤ 5 %
FL	≤ 0,2 %	≤ 2 %	≤ 2 %	≤ 5 %
X+Rg [%]	≤ 1 %	≤ 5 %	≤ 5 %	≤ 5 %
Shape	≤ FI_{35} or ≤ $SI40$	≤ FI_{50} or ≤ SI_{55}	To be declared	To be declared
Water soluble sulfates	≤ $SS_{0,2}$	≤ $SS_{0,2}$	≤ $SS_{0,2}$	≤ $SS_{0,2}$
Influence on setting time	≤ A_{10}	≤ A_{40}	≤ A_{40}	≤ A_{40}
Water absorption	≤ 5%	≤ 10 %	To be declared	To be delared

With this new quality classification the studied eight batches in the Project will be classified as shown in Table 43.

Table 43: Classification of the RE[4] materials according to the new proposed classes.

Material	N-EU B1	N-EU B2	N-EU B3	N-EU B4	S-EU B1	S-EU B2	S-EU B3	S-EU B4
Type	B	A	A	A	B	A	A+	A+

These classes only refer to coarse aggregate, which according to the current aggregate standard is limited to 2 mm as minimum size. If the new proposed limit of minimum 1 mm is adapted, more of the CDW can be categorized as coarse aggregate. Fractions below 1 mm, can be used if they fulfil the same requirements as smaller fractions of natural aggregate.

If these new quality classes are adopted, the recommendations in EN 206:2013 (Table E.3) regarding how much and under which conditions coarse mineral CDW aggregates can be used is no longer valid and must be revised. The values in the existing table E.3 only concerns the coarse aggregate while nothing is said about finer CDW aggregate. The maximum value is 50% substitution which is stated for the least severe exposure classes. This leads to a maximum substitution level of around 25 %, counted on the total aggregate content. However, as shown in this Project, concrete of rather high strength (up to 40-50 MPa 28 day strength), can be produced when 100 % good quality coarse CDW aggregate is used. These concretes may however not be optimal, since a 100 % replacement level requires rather high cement contents. Thus, the recommended maximum replacement levels for the least severe exposure classes (X0 and perhaps also XC1), where the main issue is to get sufficient strength, could be radically increased (even up to 100%), and also given as percentage of the total aggregate content. The optimum replacement levels will anyhow in practice be governed by the strength and the workability of the concrete and economic factors. For these exposure classes, all the suggested new quality classes (Type A+, Type A, Type B and Type L) could be used.
A very preliminary onset could be that for the other exposure classes the values for the new Type A+ may be as the values for the existing Type A, but counted on the total aggregate content, i.e. maximum 30 % of the total aggregate content for the intermediate exposure classes. For use of up to 30 % in chloride related exposure classes (XD2, XD3, XS2, XS3), the applicability should be determined by the resistance to chloride intrusion of the concrete and for XC3 and XC4 the resistance to carbonation should be verified. Analogically, for use of up to 30 % in the intermediate frost related exposure classes (XF2 - XF3), the aggregate should be tested (with or without salt, respectively) according to the rules in EN 12620+A1:2008 and fulfil the requirement for a relevant freeze-thaw category. For use in the most severe frost resistance class (XF4) the concrete should have an acceptable salt-frost resistance when tested according to the European scaling specification(CEN/TS12390-9). This performance based approach is line in with the ongoing development of exposure resistance classes for concrete within European concrete standardisation.

For the new Type A, the maximum replacement level could be 20 % counted on the total aggregate content, for all exposure classes except X0 and XC1, where much higher contents can be accepted. As for Type A+, the resistance to chloride intrusion of the concrete should decide the applicability of maximum 20 % in XD2, XD3, XS2, XS3 and frost testing of the aggregate for XF2 and XF3 and of the concrete for XF4.

This proposal, for when different types of recycled aggregate from CDW could be used, are summarized in Table 44, substituting Table E.2 in EN 2016:2013.

Table 44: Maximum percentage of replacement with CDW of total amount of aggregate (% by mass).

Type of CDW	Exposure classes					
	X0, (XC1?)	(XC1?), XC2, XS1, XD1, XS1, XA1	XC3, XC4	XS2, XS3, XD2, XD3	XF2, XF3, XF4	XF4
Type A+	100 %	30 %	30 % (1	30 % (2	30 % (3	30 % (4
Type A	100 %	20 %	20 % (1	20 % (2	20 % (3	20 % (4
Type B (5	100 %	20 %	0 %	0 %	0 %	0 %
Type L (5	100 %	20 %	0 %	0 %	0 %	0 %

1) Sufficient carbonation resistance of the concrete shall be verified
2) Sufficient chloride resistance of the concrete shall be verified
3) Sufficient frost resistance of the aggregate shall be verified
4) Sufficient salt-frost resistance of the concrete shall be verified
5) Type B and L is mainly intended for non-structural concrete. They shall not be used in concrete with compressive strength > C30/37.

6.1.2 Concrete blocks

Depending on type of concrete blocks (e.g. strength) and their intended use (loadbearing/non-loadbearing, exposure class, etc.), the Type A+, A, B or L mineral CDW aggregate and the requirements of EN 12620+A1:2008 or EN 13055 relevant for the specific intended use of the concrete blocks could be used when assessing the suitability of use. For many concrete block applications Type B or Type L may be sufficient. To use Type A+ for blocks may be an inefficient use of good material, since this type is primarily intended for more demanding applications.

Non-mineral LWA, e.g. the RP (0-2 mm, 2-4 mm and 4-10 mm) and WP (< 4 mm) worked with in RE^4, have the potential to be used for the production of LW building blocks. The design of concrete, based on such LWA, can be specifically optimised in order to comply with the requirements for blocks production. These building blocks can be used for non-structural applications and, especially, when good thermal insulating performance is required.

6.1.3 Prefab timber elements

Timber components are classified according to the current norm for virgin materials in line with what discussed in the previous sections. Standards [24], [25] and [26] are respectively applied depending on the typology of components, namely solid timber section or glued laminated timber products. Components are then designed according to the requirements of [43] and fire performance is classified according to [44]. No variation in respect to the classification set forth by the current codes is required. The presence and amounts of contaminants remain unknown as extensive testing and uniform classification of contamination levels are missing from the technical literature and European norm.

6.1.4 Reconstituted tiles

For what concern "extruded" reconstituted tiles, a distinction will be needed based on the kind of intended use of the tile:

- For roof tiles, the requirements by the EU Standard (and also from the market – customers) are quite strict and not avoidable. For this reason, if mineral CDW (with coarse aggregate from 2 to maximum 4 mm) are to be used in this application, they need to fulfil requirements in conformance with the Type A+ class, as specified in Section 6.1.1, with additional requirements on frost-resistance, when relevant.
- For facade panel applications (e.g. Marmoroc, ventilated facade tile and floor tile) which generally do not have strict requirements, mineral CDW of Type A, B or L (as specified in Section 6.1.1) can be considered as usable. The only tricky aspect could be the freeze-thaw behaviour, for the intended use in cold climate regions, which can be mastered by additional requirements on frost resistance, when relevant.

6.1.5 Insulation panels

Insulation panels may be produced with LWA concrete made with mineral CDW aggregates, according to Type L in Table 42. The amount of debris from porous masonry products then has to be rather high, and the density should be as low as possible.

When it comes to non-mineral LW CDW, two different solutionscould be considered for insulating panels:

- Lightweight flakes. The available results allow considering the wood lightweight flakes as suitable for the production of boards for thermal insulation composite systems. Different densities can be achieved, depending on the application and the desired thermo-mechanical properties.
- Lightweight aggregates. The RP (0-2 mm, 2-4 mm and 4-10 mm) and WP (< 4 mm) from the RE^4 CDW have the potential to be used for making non-loadbearing layers of insulating building panels. The design of concrete, based on such LWA, can be specifically optimised in order to comply with the requirements for panel layers production, improving the overall thermal insulating performance of the final panel.

6.1.6 Earth plaster, earth mortar, rammed earth

The use of CDW aggregates and silt and clay is in general suitable for the application in earth plaster, earth mortar and rammed earth. The decision is based on two considerations. On one hand the CDW tested meet the technical requirements for all materials. Other requirements not tested in the project such as occurrence of harmful substances or damaging salts must be met in any case not only to meet the quality for the material but also to protect buildings occupants from negative impacts, as developed earthen material are mainly used for interior application.

6.2 For alternative applications

6.2.1 Ready mixed masonry mortars

Ready mixed masonry mortars are covered by EN 998-2, in which there are no specific requirements on the aggregate and no reference to any aggregate standard, not even to EN 13139 *Aggregates for mortar*. EN 13139 does not give any specific provisions regarding recycled aggregates but they are mentioned in a note where it is foreseen that there will be provisions in the future. Until then all provisions in EN 13139 shall apply also to recycled aggregate and specific requirements given on a case by case basis. Mineral CDW aggregates of Type A, B and L, according to Table 42, should also be suitable for mortar. To use Type A+ for blocks may be an inefficient use of good material, since this type is primarily intended for more demanding applications. However, the size of the aggregate is limited by the thickness of the mortar layers, so possibly only gradings up to 4 mm can be used.

The non-mineral CDW fine-graded LWA, consisting of RP (0-2 mm or 0-4 mm) and WP (< 4 mm), have the potential to be used for the preparation of LW mortars. Some experiments were carried out with promising results in terms of density and thermal conductivity, as reported in D4.3. These investigations, however, have to be further extended in order to optimise the design of mortars and then comply with the specific requirements. These mortars can be used for non-structural applications and, especially, when good thermal insulating performance is required.

6.2.2 Aggregate for bituminous products

These aggregates are covered by EN 13043, where no specific requirements on recycled aggregates are given. As in EN 13139, there is a note where it is foreseen that there will be provisions in the future. Until then all provisions in EN 13043 shall apply also to recycled aggregate and specific requirements given on a case by case basis. Due to that bituminous mixtures are subjected to severe abrasion, probably only recycled aggregate corresponding to Type A+ will be suitable. The requirement on influence on setting time should though be replaced by a requirement on bond between the coarse aggregate and bituminous binders. For this application additional requirements to those given in Table 42 should also be fulfilled, such as requirements on frost-resistance, resistance to fragmentation, abrasion, polishing and studded tyres as relevant.

6.2.3 Substrates

Non-mineral CDW LWA, consisting of RP (0-2 mm, 2-4 mm and 4-10 mm) and WP (< 4 mm), have the potential to be used for the production of LW substrates (screeds, roofs). The design of concrete, based on such LWAs, can be specifically optimised in order to comply with the requirements for substrates production. These substrates can be used for applications requiring marked thermal insulating performance.

6.2.4 Ready mixed cement plasters

Ready mixed cement plasters are also covered by EN 998-2, in which there are no specific requirements on the aggregate and no reference to any aggregate standard, not even to EN 13139

Aggregates for mortar. EN 13139 does not give any specific provisions regarding recycled aggregates but they are mentioned in a note where it is foreseen that there will be provisions in the future. Until then all provisions in EN 13139 shall apply also to recycled aggregate and specific requirements given on a case by case basis. Type A+ to Type B as for concrete elements above would probably be technically suitable also for mortar. However, the size of the aggregate is limited by the thickness of the plaster layers, and since it has been shown that the finest fractions of sorted CDW cannot be used in cement mixtures due to chemical reasons, such a small fraction of sorted CDW is usable for this purpose that it is hardly worth wile.

6.2.5 Grading for road construction

Suitable classification may be Class 1 to Class 4 as in the provisions of The Swedish Transport Administration (see section 4.1). However, as for use as aggregate the specific requirement on Rc could be omitted and only the Rc+Ru used for classification. Class 1 or 2 can be used for the base course, Class 3 can be used in the subgrade and Class 4 for embankments and other fillings.

Table 45: Proposed classification of CDW materials for road construction.

Class	1	2	3	4
Rc+Ru	≥ 95 %	≥ 95 %	≥ 90 %	≥ 70 %
FL	≤ 2 %	≤ 2 %	≤ 5 %	≤ 10 %
X	≤ 1 %	≤ 1 %	≤ 1 %	≤ 1 %
micro-Deval value	M_{DE25}	M_{DE25}	M_{DE40}	----

6.2.6 Worst case use

If the CDW fraction is not suitable for any of the uses discussed above, the last options are (in falling priority): i) soil improvement (mix clay in sandy soils etc.), ii) energy recovery, iii) back-fill and iv) land-fill [52].

7. CONCLUSION AND RECOMMENDATIONS

D4.4 completes the work reported in previous WP4 deliverables - D4.2 and D4.3 dealing with the characterization of several CDW-derived materials and the effect of their features on technological properties. . The aim of this document is to report on RE^4 CDW materials classification according to the potential use for structural and non-structural applications. The document includes an overview of existing standards relevant for CDW materials investigated in RE^4 project, the materials have been then classifiedaccording to these standards and, finally, new quality classes have been defined. Different applications for RE^4 CDW have been proposed, some of them specifically intended for RE^4 project but also alternative applications are included. Based on the evaluations carried out, RE^4 CDW - mineral fractions, non-mineral lightweight fractions (e.g. plastic, wood or mixed wood/plastic) and timber can be reused for the development of concrete elements and blocks, prefabricated wood elements, reconstituted tiles, insulating panels as well as plasters and mortars. In addition, as alternative applications for RE^4 CDW, ready mixed masonry mortars, ready mixed plasters, bitumens, substrates or grading for road can be also mentioned. The defined classes and related applications will be transferred to WP5 which focus on the development of robust materials (structural, non-structural, lightweight, insulating etc.) integrating high ratios of CDW and suitable for the production of precast building components and elements.

The main findings of the investigations reported in this document are summarized in the following.

The CDW fraction for which the most elaborated existing quality classing system exists, is the coarse mineral CDW fraction (> 2 mm). Based on the relevant standards, the coarse recycled aggregates shall be quantified in the relative proportions of different constituents and classified in Type A and Type B quality classes. Based on assessment of mineral CDW and its performance in concrete investigated in the RE^4 project in relation to the present quality classes, new classes are suggested: Type A+, Type A, Type B and Type L. The quality of both Type A+ and Type A are sufficient for use in concrete in load-bearing structures, whereas class Type B would be intended for applications in for instance concrete masonry units or in non-structural concrete. Type L should be used for mineral CDW which have oven-dry density ≤ 2000 kg/m^3, thereby qualifying as LWA for lightweight concrete.

These classes can also be used for other products, e. g. reconstituted roof tiles (Type A+) and façade panel applications (Type A, B or L), with additional requirements on frost-resistance, when relevant.

When it comes to non-mineral LW CDW, which result from rigid plastic (RP) and mixed wood-plastic (WP) fractions as well as from wood (W) scraps, these could be used as aggregates and flakes for the development of insulating building materials. Even if the available standards do not specifically cover these kind of LW materials, building products (e.g. concretes, panels) incorporating them have showed promising results in terms of crucial properties such as density and thermal conductivity. Materials based on LW CDW resulted suitable for non-structural applications especially where improved thermal insulating performance are required.

Concerning timber and wood products, two main aspects have to be considered for their classification: timber grading and contamination levels. For timber grading, reused elements and products fall under the same set of codes as new elements and products. Contamination is also a crucial parameter for determining the suitability and potential of reuse for timber. However, no unified regulation is in place in Europe. Timber components, in line with what above mentioned, have been classified according to the current norm for virgin materials.

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