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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

D4.3 Effect of the variability of CDW batches	
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[2] *PU: Public, RE: restricted to a group specified by the consortium, CO: Confidential, only for members of the consortium; Commission services always included.*
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ACRONYMS & ABBREVIATIONS

CDW	Construction and Demolition Waste
FL	Floating particles
LW	Lightweight
MF	Mineral Fraction from CDW
N-EU	Northern Europe
NS	Natural sand
OPC	Ordinary Portland Concrete
PTFE	Polytetrafluoroethylene
Ra	Bituminus 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
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 the variability (over time and geographic location) of sorted CDW fractions (mineral and lightweight aggregate) and its effect on technological properties of developed products. The various sorted CDW fractions originate from two different regional sources: Northern Europe (N-EU) and Southern Europe (S-EU).

The variability of mineral aggregate (size fractions 0/2 mm, 2/8 mm & 8/16 mm) and its effect on the performance of OPC concrete was assessed by testing (a) its key physical and chemical properties and (b) important fresh and hardened properties of OPC concrete made using the above mineral aggregate as raw material. For this reason 4 N-EU batches and 3 S-EU batches were collected at different time intervals from recycling plants in N-EU (Germany and Norway) and S-EU (France), respectively.

When it comes to physical and chemical properties of mineral aggregate, significant variation in terms of grading, constituent classification (8/16 mm), water absorption and particle density was observed between various batches from S-EU and between different geographic sources. As a result, fresh and hardened properties of OPC concrete were considerably affected.

The variability of the chemical and physical features of lightweight fractions (Wood&Plastic, Rigid Plastic and Wood Flakes) on (a) consistency, mechanical and hygrothermal properties of insulating mortars and (b) physical and hygrothermal properties of wood-based panels was investigated. In more detail, Wood&Plastic and Rigid Plastic fractions were used for making insulating mortars, whereas Wood Flakes were used in the manufacture of wood-based panels. The variability was studied on two batches from recycling plants in N-EU (Germany and Norway) and S-EU (France), respectively.

No significant variations in terms of hygrotermal properties were observed for the lightweight fractions between the different batches.

2. INTRODUCTION

The Deliverable D4.3 summarises the results obtained by the RE^4 team involved in Task 4.3 – Variability of the chemical-physical features of CDW-derived materials and effect on technological properties of developed products (QUB, CBI and CETMA).

The work in this task focused on the variability of the chemical-physical features of different sorted CDW fractions (i.e. mineral aggregate and lightweight fractions) obtained by CDE from recycling centres in Northern and Southern Europe.

In addition, the variability of the chemical and physical features of mineral aggregate fractions on fresh and hardened properties of OPC concrete was investigated.

Finally, the variability of the chemical and physical features of lightweight fractions (Wood&Plastic, Rigid Plastic and Wood Flakes) on (a) fresh, hardened and hygrothermal properties of insulating mortars and (b) physical and hygrothermal properties of wood-based panels was investigated.

The variability of the chemical-physical features of mineral aggregate fractions (0/2 mm, 2/8 mm & 8/16 mm) and its effect on fresh and hardened properties of OPC concrete was investigated by performing the following tests:

- Grading (0/2 mm, 2/8 mm & 8/16 mm)
- Constituent classification (8/16 mm)
- Water absorption and particle density (0/2 mm, 2/8 mm & 8/16 mm)
- Water-soluble chloride content (0/2 mm & 8/16 mm)
- Water-soluble sulfate content (0/2 mm & 8/16 mm)
- Slump measurement of fresh OPC concrete
- Density of fresh OPC concrete
- Density of hardened OPC concrete
- Compressive strength of hardened OPC concrete
- Tensile strength of hardened OPC concrete

The variability of the chemical-physical features of Wood&Plastic and Rigid Plastic fractions (0/4 mm) and its effect on fresh, hardened and hygrothermal properties of insulating mortars was investigated by performing the following types of tests:

- Grading (0/4 mm)
- Water absorption and particle density (0/4 mm)
- Consistency of fresh insulating mortars
- Density of fresh insulating mortars
- Density of hardened insulating mortars
- Flexural strength of hardened insulating mortars

- Compressive strength of hardened insulating mortars
- Thermal conductivity of hardened insulating mortars
- Specific heat capacity of hardened insulating mortars
- Water vapour resistance factor of hardened insulating mortars

The variability of the chemical-physical features of Wood Flake fractions (0/4 mm and 0/8 mm) and its effect on physical and insulation properties of wood-based panels was investigated by performing the following types of tests:

- Grading (0/4 mm and 0/8 mm)
- Water absorption and particle density (0/4 mm and 0/8 mm)
- Density of wood-based panels
- Thermal conductivity of wood-based panels
- Specific heat capacity of wood-based panels
- Water vapour resistance of wood-based panels.

2.1 Relevant Work Package Input

This deliverable builds upon the knowledge obtained from D4.1 – Composition of materials from demolition and available volumes of sorted fractions and D4.2 – Characterisation of CDW-derived materials. D4.1 dealt with the assessment of unsorted CDW delivered to CDE recycling centres based in both Northern and Southern Europe, whereas D4.2 dealt with the assessment of sorted CDW after processing in the above plants. D4.3 on the other hand, deals with the assessment of sorted CDW fractions over time.

2.2 WP Objectives and Limitations

The physical properties and chemical composition of the various sorted CDW fractions can significantly vary over time and geographic location as opposed to virgin material coming from the same source. This, in turn, can have a major impact on the various physical, mechanical and hygrothermal properties of prefabricated building elements (such as structural and non-structural concrete, insulating mortars and panels) made using CDW materials. Depending on their intended use, prefabricated building elements can only be used in new construction provided they meet certain requirements as stated in European and national structural design and building codes.

The objective of Deliverable D4.3 is to present the results of the investigation performed on the variability of the physical and chemical features of different sorted CDW fractions and their effect on the various physical, mechanical and hygrothermal properties of prefabricated building elements. Based on these results, an assessment of the quality of the various sorted CDW fractions can be made. A decision can then be reached regarding the procurement and use of such materials in new prefabricated building elements.

3. DESCRIPTION OF WORK UNDERTAKEN

3.1 Methods for Mineral Aggregates (N-EU & S-EU)

3.1.1 Introduction

Table 1 and Table 2 provide details of all tests performed for assessing the variability of the physical and chemical features of sorted mineral aggregates (N-EU and S-EU) and their effect on the various physical and mechanical properties of OPC concrete. A detailed description of all testing methods used is provided in **Sections 3.1.2 – 3.1.11**.

Table 1: Test methods for CDW mineral fractions (N-EU & S-EU)

Property	Standard	Laboratories
Chemical and physical testing of CDW mineral aggregates		
Grading (0/2 mm, 2/8 mm & 8/16 mm fractions)	EN 933-1:2012	QUB/CBI
Constituent classification of 8/16 mm fraction	EN 933-11:2009	QUB/CBI
Water absorption and particle density (0/2 mm, 2/8 mm & 8/16 mm fractions)	EN 1097-6:2000 or ASTM C 127-15	QUB/CBI
Water-soluble chloride content (0/2 mm & 8/16 mm fractions)	EN 1744-1:2009+A1:2012 or Ion chromatography	QUB/CBI
Water-soluble sulfate content (0/2 mm & 8/16 mm fractions)	EN 1744-1:2009+A1:2012 or Ion chromatography	QUB/CBI
Fresh properties of OPC concrete made using CDW mineral aggregate		

Slump (at 15 and 30 min)	EN 12350-2:2009	QUB/CBI
Hardened properties of OPC concrete made using CDW mineral aggregate		
Compressive strength (at 1, 7 & 28 days)	EN 12390-3:2009	QUB/CBI

Table 2: Additional test methods for CDW mineral fractions (N-EU & S-EU)

Property	**Standard**	**Laboratories**
Fresh OPC concrete properties made using CDW mineral aggregate		
Fresh density	EN 12350-6:2009	QUB/CBI
Hardened OPC concrete properties made using CDW mineral aggregate		
Hardened density	EN 12390-7:2009	QUB
Tensile splitting strength at 28 days	EN 12390-6:2009	QUB

When it comes to concrete mixes, CEM I 52.5 N Ordinary Portland Cement (OPC) was used. The mixing water and OPC contents were fixed at 250 kg/m^3 and 500 kg/m^3 (water/cement ratio of 0.5), respectively.

Use of recycled aggregates in concrete (especially when high levels of virgin aggregate are replaced by recycled aggregate) significantly reduces its workability. This is due to the old mortar attached to them which creates a rougher surface and a more irregular shape. These characteristics in turn, hamper the mobility of the aggregates in the mix. Consequently, a higher amount of cement paste and vibration energy is required for the mix to be cast and compacted [1], [2], [3].

Higher water absorption of recycled aggregate (caused by the attached old mortar) compared to virgin aggregate is another factor which leads to reduced workability. According to published data, concrete mixes which contain recycled aggregate experience a decrease of 5-10% in the amount of free water [2].

However, the amount of old mortar in recycled aggregate can vary significantly. Hence, a decision was made between involved partners (QUB and CBI) to use a high cement content. This in turn, lead to high paste volume which allowed capturing the full variation in workability (slump value) due to the use of 100% recycled aggregate in the mix (mineral fractions 0/2 mm, 2/8 mm and 8/16 mm).

3.1.2 Grading – following EN 933-1:2012

Grading is performed using the procedure described in EN 933-1:2012 [4].The aggregate test portion to be analysed is oven-dried at 40 °C (instead of 110 ± 5 °C, due to presence of bitumen in the aggregates) to constant mass. The sample is then allowed to cool and its mass is recorded as M_1. Next, the aggregate sample is poured into a sieving column. The column is comprised of a number of sieves fitted together and arranged, from top to bottom, in order of decreasing aperture sizes. At the bottom of the column a pan is placed, whereas, its top is covered using a lid. The column is then placed in a sieving machine. After approximately 15 minutes of sieving, the column is removed from the sieving machine and the material retained on each sieve is weighed and related to M_1 as follows:

The mass of the aggregate retained by the sieve with the largest aperture size is recorded as R_1, whereas the mass of the aggregate retained by the sieve with the second largest aperture size is recorded as R_2. The above procedure is repeated in order to obtain the masses of the aggregate retained by the rest of the sieves and record them as R_3, R_4,...R_n.

Next, the cumulative percentage of the original aggregate mass M_1 passing each sieve down to the 0.063 mm sieve (smallest aperture size sieve) is calculated.

Any material passing the 0.063 mm sieve (smallest aperture size sieve) and retained by the pan at the bottom of the sieving column is recorded as P.

In order to avoid overloading of sieves, the fraction of aggregates retained at the end of the sieving process on each sieve should not exceed

$$\frac{A\sqrt{d}}{200} \qquad (1)$$

Where:

A is the area of the sieve (mm)

d Is the aperture size (mm)

3.1.3 Constituent Classification – following EN 933-11:2009

Constituent classification of coarse 8/16 mm aggregate is performed using the procedure described in EN 933-11:2009 [5]. Initially, a test portion is oven dried at 40 ± 5 °C to constant mass. The oven-dried mass of the test portion is then recorded as M1 (M1 minimum mass to be analysed is 20 kg). The test portion is immersed in a filled watertight tank in order to wash the particles and release the floating ones. The floating particles are collected and their volume V_{FL} is determined by placing them inside a graduated cylinder filled with a known volume of water. The non-floating particles are collected and oven-dried at 40 °C to constant mass. Next, they are spread on a flat disc and all clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum particles are removed by hand. The above removed particles are weighed and their mass is recorded as M_x. The remaining non-floating particles are weighed and their mass is recorded as M_2. Next, a sample is taken from M_2 and manually sorted into Rc (concrete, concrete products, mortar and concrete masonry units), Ru (unbound aggregate, natural stone and hydraulically bound aggregate), Rb (clay masonry units, calcium silicate units and aerated non-floating concrete), Ra (bituminous materials) and Rg (glass). The mass of the sample taken from M_2 is recorded as M_3 (M_3 minimum mass to be manually sorted is 2 kg [5]). Next, the masses of the above constituents of M_3 sample are recorded as M_{Rc}, M_{Ru}, M_{Rb}, M_{Ra} and M_{Rg}, respectively. Finally, the proportion of each constituent of M_1 test portion is determined by the following expressions:

$$\mathrm{FL}\left(\frac{\mathrm{cm}^3}{\mathrm{kg}}\right) = (1000)\left(\frac{\mathrm{V_{FL}}}{\mathrm{M_1}}\right) \quad (2)$$

$$\mathrm{X}(\%) = (100)\left(\frac{\mathrm{M_X}}{\mathrm{M_1}}\right) \quad (3)$$

$$\mathrm{Rc}(\%) = (100)\left(\frac{\mathrm{M_2}}{\mathrm{M_1}}\right)\left(\frac{\mathrm{M_{Rc}}}{\mathrm{M_3}}\right) \quad (4)$$

$$\mathrm{Ru}(\%) = (100)\left(\frac{\mathrm{M_2}}{\mathrm{M_1}}\right)\left(\frac{\mathrm{M_{Ru}}}{\mathrm{M_3}}\right) \quad (5)$$

$$\mathrm{Rb}(\%) = (100)\left(\frac{\mathrm{M_2}}{\mathrm{M_1}}\right)\left(\frac{\mathrm{M_{Rb}}}{\mathrm{M_3}}\right) \quad (6)$$

$$\mathrm{Ra}(\%) = (100)\left(\frac{\mathrm{M_2}}{\mathrm{M_1}}\right)\left(\frac{\mathrm{M_{Ra}}}{\mathrm{M_3}}\right) \quad (7)$$

$$\mathrm{Rg}(\%) = (100)\left(\frac{\mathrm{M_2}}{\mathrm{M_1}}\right)\left(\frac{\mathrm{M_{Rg}}}{\mathrm{M_3}}\right) \quad (8)$$

3.1.4 Water Absorption and Particle Density – following EN 1097-6:2000 or ASTM C 127-15

Water absorption and particle density (apparent, saturated surface dry and oven-dried) are determined in accordance with either EN 1097-6:2000 [6] or ASTM C 127-15 [7].

EN 1097-6:2000

Particle density (apparent, saturated surface dry and oven-dried) and water absorption are measured using the pyknometer method on 8/16 mm and 2/8 mm (Clause 8), and 0/2 mm (Clause

9) fractions. Air bubbles are removed by gently jolting/rolling the pre-calibrated pyknometer, before and after soaking the aggregate in water for 24 h. Saturated 8/16 and 2/8 mm aggregates are surface dried using a Wettex cloth (Clause 8), until they look matte but still moist.

In addition to measuring the water absorption after 24 h of water soaking time using a drying temperature of 110 °C (both according to standard), measurements are conducted for long-time water absorption (at intervals from 1 h up to 14 days) as well as using drying temperature of 40 °C (due to presence of bituminous materials in the CDW).

For size-fraction 0/2 mm (Clause 9), instead of a Wettex cloth, a metal cone is used in order to determine when the aggregates become water saturated but surface dry. The metal cone is filled with the specified amount of aggregate and gently stamped 25 times. The cone is lifted and the shape of the unsupported aggregate pile is compared with the pictures in EN 1097-6:2000 Annex F [6], showing different sand pile shapes in relation to drying status. If the sand is considered to still be wet (i.e. not surface dry), the sand is again placed in the oven for further drying, before repeating the above procedure.

ASTM C127-15

Specific gravity (apparent, saturated surface dry and oven-dried) and water absorption of 0/2 mm, 2/8 and 8/16 mm fractions are measured using the method described in ASTM C127-15. A sufficient quantity of aggregate (0/2 mm, 2/8 mm or 8/16 mm) is oven-dried at 40 °C for 72 hours (instead of 110 ± 5 °C, due to presence of bitumen in the aggregates) to constant mass.

Then 500 grams of oven-dried aggregate are placed inside a glass vessel. The vessel is partly filled with tap water (tap water is used instead of distilled water since this type of water is used in all mortar and concrete mixes). A soaking period of 24 hours is used, at the end of which the aggregate is considered to be fully saturated. At the end of the soaking period, entrapped air is removed by gently shaking the glass vessel. The vessel is then fully filled with water. Finally, the vessel is covered with a glass plate disc to ensure that no air is trapped in the vessel.

The weight of the vessel + aggregate sample + water is taken using a digital scale (accurate to ± 1 g) and recorded as A.

The water of the vessel is removed and the aggregates are placed on top of a dry piece of cloth until a saturated surface dry state is achieved (excess water is removed from the surface of the aggregates by gently wiping them using a dry piece of cloth). After approximately twenty minutes, the aggregates are placed on top of a tray, which in turn, is placed on top of a scale. The weight of the aggregates is monitored for a period of 10 minutes. At the end of this period the Saturated Surface Dry (SSD) weight of the aggregate is recorded as C.

The vessel is refilled with tap water and is covered with the glass plate disc to ensure that no air is trapped in the vessel. Next, the weight of the vessel + water is recorded as B.

Next, the aggregates are placed inside the above described oven and oven-dried for 72 hours at 40 ˚C. At the end of this period the aggregates are taken from the oven and conditioned by placing them inside an air tight container. Finally, their oven-dried (OD) weight is recorded as D.

Specific Gravity (OD), Specific Gravity (SSD), Apparent Specific Gravity and Water Absorption are calculated by the following formulae:

$$\text{Specific Gravity (OD)} = \frac{D}{C-(A-B)} \tag{9}$$

$$\text{Specific Gravity (SSD)} = \frac{C}{C-(A-B)} \tag{10}$$

$$\text{Apparent Specific Gravity} = \frac{D}{D-(A-B)} \tag{11}$$

$$\text{Water Absorption}(\%) = \frac{C-D}{D}(100) \tag{12}$$

Where:

A is the weight of the vessel + aggregate sample + water
B is the weight of the vessel + water
C is the saturated surface dry weight of the aggregate
D is the oven-dried weight of the aggregate

3.1.5 Water-Soluble Chlorides following – EN 1744-1:2009+A1:2012 or Ion Chromatography

Water-soluble chloride content of coarse (8/16 mm) and fine (0/2 mm) recycled aggregate is measured using either the potentiometry method described in EN 1744-1:2009+A1:2012 [8] or ion chromatography.

EN 1744-1:2009+A1:2012 Potentiometry

An aggregate sample of 2 kg (8/16 mm size fraction) or 0.5 kg (0/2 mm size fraction) is placed in a PTFE bottle together with an equal amount of water. The bottle is then placed on a rotating table and shaken for 1 hour to extract the chlorides present in the aggregates. Thereafter, the water is extracted by filtering through a medium grade filter paper.

Using a pipette, 50 ml of the filtered extract is transferred to a 250 ml PTFE bottle. The content of the beaker is acidified using HNO_3 to a pH value of 2-3. Next, 5 ml NaCl solution (0.01 M) are added. The content of the bottle is titrated with $AgNO_3$ solution (0.01 M) by using a potentiometric titrator. Finally, the amount of chlorides present in the aggregate sample is determined by the expression:

$$C = 0.000709\, V_{AgNO_3}\, W \quad (\%) \qquad (13)$$

Where:

C is expressed as a % by mass of the aggregate
V_{AgNO3} is the consumption of $AgNO_3$ solution (ml), subtracting 10 ml for the added chloride solution
W is the water/aggregate ratio (g/g)

It should be noted that the amount of coarse (8/18 mm) aggregate specified in EN 1744-1:2009+A1:2012 [8] was reduced from 2 to 1 kg (see Table 3 below).

Table 3: Amount of aggregate and water used for the potentiometry method

Required Quantities	Size Fraction	
	0/2 mm	8/16 mm
Mass of aggregate (g)	500	1000
Mass of deionised water (g)	500	1000

Ion Chromatography

An aggregate sample of 2 kg (8/16 mm size fraction) or 0.5 kg (0/2 mm size fraction) is placed in a PTFE bottle together with an equal amount of water. The bottle is then placed on a rotating table and shaken for 1 hour to extract the chlorides present in the aggregates. Thereafter, the water is extracted by filtering through a medium grade filter paper.

Next, a sample of the filtered extract is inserted into the upper end of an anion exchange column, which performs the separation of F^-, Cl^-, Br^-, I^-, NO_3^- and SO_4^{2-}. Results are initially obtained in µS using a conductivity detector. Equipment software and calibration runs of reference solutions are then used to obtain the concentration in mg/l. Finally, the concentration as a percentage by mass of the aggregate is obtained using the following equation:

$$C_i = \frac{C_{IC,i}}{10000} W \qquad (14)$$

Where:

C_i is the concentration of anion i (e.g. chloride) expressed as a % by mass of the aggregate
$C_{IC,i}$ is the concentration of anion i (e.g. chloride) (mg/l)
W is the water/aggregate ratio (g/g)

3.1.6 Water-Soluble Sulfates – following EN 1744-1:2009+A1:2012 or Ion Chromatography

EN 1744-1:2009+A1:2012

Water-soluble sulfate content of coarse (8/16 mm) and fine (0/2 mm) recycled aggregate is measured using the procedure described in EN 1744-1:2009+A1:2012 [8]. This method is based on extracting the amount of water-soluble sulphates (SO_3) present in the aggregates by mixing them with deionized water. The water is filtered and the amount of sulfate leached into the water is determined by barium sulfate ($BaSO_4$) gravimetry. A barium chloride ($BaCl_2$) solution is added in excess to the sulfate-laden water to precipitate barium sulfate. The amount of sulfate present is determined from the amount of barium sulfate having formed, according to the equation:

$$Ba^{2+} + SO_4{}^{2-} \rightarrow BaSO_4 \qquad (15)$$

For the fine (0/2 mm) fraction, 500 g of aggregates are mixed with 1000 g of deionised water, whereas for the coarse (8/16 mm) fraction, 1000 g of aggregate are mixed with 2000 g of deionised water. The test portions are continuously mixed on a rotating table for 24 hours, after which the sulfate-laden water is filtered.

Next, 50 ml of the sulfate rich filtered extract is transferred to a 500 ml beaker and the test portion is diluted with additional 250 ml of water. Following this, 10 ml of HCl solution (prepared by adding 200 ml concentrated HCl to 800 ml of H_2O) are added to the test portion. The solution is heated to the boiling point after which 5 ml of $BaCl_2$ solution (prepared by dissolving 100 g $BaCl_2 \cdot 2H_2O$ in 1 l of H_2O and filtered through a medium grade filter paper before use) are added drop by drop using a burette. As $BaSO_4$ precipitate forms, the solution turns white opalescent. The solution is maintained at a temperature just below boiling point for 15 minutes after which it is allowed to cool to room temperature.

The $BaSO_4$ precipitate is collected by filtering the solution through an ashless fine filter paper. The filter paper containing the barium sulfate is placed in a ceramic crucible and ignited in a furnace initially set at 110 °C. Next, the temperature of the furnace is gradually increased to 925 °C during a period of 60 minutes. The amount of barium sulfate is then weighed and the amount of sulfate present in the aggregates is determined by the expression:

$$SO_3 = (2W)\left(0.343 m_{BaSO_4}\right) \ (\%) \qquad (16)$$

Where:

m_{BaSO4} is the mass of the precipitate $BaSO_4$ (g)
W is the water aggregate ratio (g/g)

It should be noted, that no active gypsum (e.g. gypsum plaster) was detected in the recycled aggregates. Consequently, the testing procedures of EN 1744-1:2009+A1:2012 [8] referring to virgin aggregates were used.

Ion Chromatography

Please refer to **Section 3.1.5**

3.1.7 Fresh Density – following EN 12350-6:2009

The density of fresh concrete is measured using the method described in EN 12350-6:2009 [9]. A water proof, rigid container of known volume and mass is filled with the fresh concrete sample. The container is then compacted using a vibrating table for approximately 5 s. Next, the top surface is levelled out and excess material removed. In addition, the sides of the container are wiped clean in order to remove any concrete spillage. Finally, the container with the fresh concrete sample is weighed.

The fresh density is calculated using the following expression:

$$D = \frac{m_2 - m_1}{V} \qquad (17)$$

Where:

D is the density of fresh concrete (kg/m3)
m_1 is the mass of the empty container (kg)
m_2 is the mass of the filled container (kg)
V is the volume of the container (m3)

3.1.8 Slump Test – following EN 12350-2:2009

Slump is measured using the method described in EN 12350-2:2009 [10], in which a sample of fresh concrete is placed and compacted inside a mould in the shape of a frustum of a right circular cone. The base and top of the mould are open and parallel to each other. The dimensions of the mould are as follows:

Base diameter:	200 ± 2 mm
Top diameter:	100 ± 2 mm
Height:	300 ± 2 mm

The mould is filled in 3 layers, each approximately one-third of the height of the mould when compacted. Compaction is achieved by using a tamping rod. Each layer is compacted by striking it 25 times using the tamping rod.

The mould is then removed by lifting it carefully upwards in the vertical direction. Immediately after lifting the mould, the slump of the fresh concrete is measured as the difference between the height of the mould and the highest point of the slumped concrete.

3.1.9 Hardened Density – following EN 12390-7:2009

The density of hardened concrete is measured using the procedure described in EN 12390-7:2009 [11]. For this purpose, 100 mm cubes are cast and cured for 28 days in accordance with EN 12390-2:2009 [12]. When 28 days old, the cubes are saturated in water and their volume is determined using either method A or B described in EN 12390-7:2009 (i.e. either by using volume displacement or by using checked, designated dimensions of the cubes).

The hardened concrete density is then calculated using the following expression:

$$D_s = \frac{m_s}{V} \tag{18}$$

Where:

D_s is the density of the water saturated hardened concrete (kg/m3)
m_s is the water saturated mass of the specimen (kg)
V is the volume of the specimen (m3)

3.1.10 Compressive Strength – following EN 12390-3:2009

Compressive strength is measured using the procedure described in EN 12390-3:2009 [13]. For this purpose, 100 mm cubes are cast and cured in accordance with EN 12390-2:2009 [12]. In order to perform the test, an automatic hydraulic press is used capable of applying a constant loading rate of 0.6 ± 0.2 MPa/s.

Three specimens are tested at each age (in days) after casting. The result is expressed as the mean value of the three individual results, calculated using the following expression:

$$f_c = \frac{F}{A_c} \tag{19}$$

Where:

f_c is the compressive strength (MPa)

F is the maximum load at failure (N)
A_c is the cross sectional area on which the force is applied (mm2)

3.1.11 Tensile Splitting Strength – following EN 12390-6:2009

Tensile splitting strength is measured using the procedure described in EN 12390-6:2009 [14]. For this purpose, cylindrical specimens (100 mm in diameter and 200 mm in height or 150 mm in diameter and 300 mm in height) are cast and cured for 28 days in accordance with EN 12390-2:2009 [12]. In order to perform the test, an automatic hydraulic press is used which exerts a compressive force to a narrow region along the longitudinal axis of the cylinder. A constant loading rate between 0.04 and 0.06 MPa/s is used. The resulting orthogonal tensile force causes the cylinder to fail in tension.

Three cylinders are tested at the age of 28 days using the above procedure. The tensile splitting strength is expressed as the mean value of the three individual results, calculated using the following expression:

$$f_{ct} = \frac{2F}{\pi L d} \quad (20)$$

Where:

f_{ct} is the tensile splitting strength (MPa)
F is the maximum load (N)
L is the length of the cylinder (mm)
d is the diameter of the cylinder (mm)

3.2 Methods for Lightweight Aggregates

3.2.1 Introduction

The following lightweight fractions are used in this study:

- Wood&Plastic
- Rigid Plastic
- Wood Flakes

Wood&Plastic and Rigid Plastic fractions are used for making insulating mortars, whereas Wood Flakes are used in the manufacture of wood-based panels.

Consequently, the variability of the chemical and physical features of the first two lightweight fractions and its effect on fresh, hardened and hygrothermal properties of insulating mortars is investigated.

When it comes to Wood Flakes, the variability of their chemical and physical features and its effect on the hygrothermal properties of wood-based panels is investigated.

3.2.2 Lightweight Aggregates for Insulating Mortars

3.2.2.1. Introduction

The variability of chemical and physical features of N-EU and S-EU Wood&Plastic and Rigid Plastic fractions and their effect on fresh, hardened and hygrothermal properties of insulating mortars is investigated by testing 2 different batches. For this purpose, CDE in charge of material procurement supplied CETMA with the following materials as shown in Table 4:

Table 4: N-EU and S-EU Wood&Plastic and Rigid Plastic fractions tested by CETMA

Batch no	Date Received	Composition (separate size fractions)	Source
1	26/06/2017 26/06/2017	Wood&Plastic 0/4 mm Rigid Plastic 0/4 mm	N-EU (Germany)
2	25/01/2017 23/03/2017	Wood&Plastic 0/4 mm Rigid Plastic 0/4 mm	S-EU (France)

Table 5 provides details of all tests performed on N-EU and S-EU Wood&Plastic and Rigid Plastic fractions. A detailed description of all testing methods used is provided in **Sections 3.2.2.2 – 3.2.2.9**.

Table 5: Test methods for CDW lightweight aggregates (N-EU & S-EU) used for insulating mortars

Property	Standard	Laboratories
Physical testing of lightweight aggregates (Wood&Plastic, Rigid Plastic)		
Grading (0/4 mm fractions)	EN 933-1:2012	CETMA
Water absorption and particle density (0/4 mm fractions)	EN 1097-6	CETMA

Fresh properties of insulating mortars made using Wood&Plastic or Rigid Plastic fractions		
Consistency	EN 1015-3	CETMA
Fresh density	EN 1015-6	CETMA
Hardened properties of insulating mortars made using Wood&Plastic or Rigid Plastic fractions		
Hardened density (at 7, 14 and 28 days)	EN 1015-10	CETMA
Flexural strength (at 7, 14 and 28 days)	EN 196-1 (Clause 9.1)	CETMA
Compressive strength (at 7, 14 and 28 days)	EN 196-1 (Clause 9.2)	CETMA
Hygrothermal properties of hardened insulating mortars made using Wood&Plastic or Rigid Plastic fractions		
Thermal conductivity (at 28 days)	EN ISO 10456	CETMA
Specific heat capacity (at 28 days)	EN ISO 10456	CETMA
Water vapour resistance factor (at 28 days)	EN ISO 10456	CETMA

3.2.2.2. Grading – following EN 933-1:2012

Please refer to **Section 3.1.2**. This standard is suitable for determining the particle size distribution of either natural or artificial aggregate including lightweight aggregates.

3.2.2.3. Water Absorption and Particle Density – following EN 1097-6

Please refer to **Section 3.1.4**. For lightweight aggregate size fractions of 0/4 mm, Clause 9 referring to normal-weight aggregates together with Annex C referring to lightweight aggregates are used. It should be noted that oven drying at 80 °C (as opposed to 105 ± 5 °C) to constant mass is performed due to the presence of plastics.

3.2.2.4. Consistency (Flow Table) – following EN 1015-3:1999

Consistency (flow value) is measured using the method described in EN 1015-3:1999 [15], in which a sample of fresh mortar is placed and compacted on a flow table disc by means of a mould in the shape of a frustum of a right circular cone. The dimensions of the mould are as follows:

Base diameter: 100 ± 0.5 mm

Top diameter: 70 ± 0.5 mm

Height: 60 ± 0.5 mm

The mould is filled in two layers. Compaction is achieved by using a tamping rod. Each layer is compacted by striking it at least 10 times using the tamping rod.

Next, any excess mortar is skimmed off using a palette knife and the outer surface of the cone is wiped clean and dry. Any excess water from around the bottom edge of the mould should also be removed.

The mould is then raised slowly upwards in the vertical direction. Immediately after lifting the mould, the mortar is subjected to 15 vertical impacts by raising the flow table and allowing it to fall freely through a given height at a rate of 1 impact/s.

Finally, the diameter of the mortar in two directions at right angles to one another is measured and recorded to the nearest mm.

3.2.2.5. Fresh Density – following EN 1015-6:1999

The density of fresh mortar is measured using the procedure described in EN 1015-6:1999 [16]. A waterproof, rigid container of known volume and mass is filled with the fresh mortar sample. The container is then compacted using a vibrating table until no further settling can be observed. Next, the top surface is levelled out and excess material is removed. In addition, the sides of the container are wiped clean in order to remove any mortar spillage. Finally, the container with the fresh mortar is weighed.

The bulk density of fresh mortar is calculated using the following expression:

$$\rho_m = \frac{\mathrm{m_2 - m_1}}{\mathrm{V_v}} \qquad (21)$$

Where:

ρ_m is the bulk density of fresh mortar (kg/m3)
m_1 is the mass of the empty container (g)
m_2 is the mass of the container filled with mortar (g)
V_v is the volume of the container (l)

3.2.2.6. Hardened Density – following EN 1015-10:1999

The dry bulk density of hardened mortar is measured on specimens using the procedure described in EN 1015-10:1999 [17]. The specimens are oven-dried at 60 ± 5 °C to constant mass. Next, their mass is recorded as $m_{s,dry}$. Following this, their volume is determined by using the volume displacement method.

The dry bulk density of hardened mortar is then calculated using the following expression:

$$\rho_{m,dry} = \frac{m_{s,dry}}{V_{v,dry}} \quad (22)$$

Where:

$\rho_{m,dry}$ is the dry bulk density of the hardened mortar specimen (kg/m3)
$m_{s,dry}$ is the mass of the hardened mortar specimen (kg)
$V_{v,dry}$ is the volume of the hardened mortar specimen (m3)

3.2.2.7. Flexural Strength – following EN 196-1:2016

Flexural strength is measured on mortar prism specimens 40 x 40 x 160 mm according to the procedure described in EN 196-1:2016 [18]. Each prism is subjected to a bending moment by the application of load through one upper and two supporting rollers until failure occurs. The upper roller is positioned at mid-span of the prism, whereas the two supporting rollers are placed 30 mm from each end of the prism. The flexural strength is then calculated from the maximum sustained load. The test is conducted using an automatic hydraulic press capable of applying a constant loading rate of 50 ± 10 N/s.

Three prisms are tested at 28 days old using the above described procedure. The flexural strength is expressed as the mean value of the three individual results, calculated using the following expression:

$$R_f = 1.5\frac{F_f\, l}{b^3} \quad (23)$$

Where:

R_f is the flexural strength (MPa)
F_f is the maximum load applied to the middle of the prism at failure (N)
l is the distance between the supporting rollers (mm)
b is the side of the square section the prism (mm)

3.2.2.8. Compressive Strength – following EN 196-1:2016

Compressive strength is measured on prism halves according to the procedure described in EN 196-1:2016 [18]. The prism halves are obtained either by following the procedure of **Section 3.2.2.7** or by using a suitable method which does not subject the prism halves to harmful stresses. In order to perform the test, an automatic hydraulic press is used capable of applying a constant loading rate of 2400 ± 200 N/s.

The compressive strength is calculated using the following expression:

$$R_c = \frac{F_c}{1600} \tag{24}$$

Where:

R_c is the compressive strength (MPa)
F_c is the maximum load at failure (N)
1600 is the area of the platens of the automatic hydraulic press (40 mm x 40 mm) (mm2)

3.2.2.9. Hygrothermal Properties – following EN ISO 10456:2007

The determination of hygrothermal properties such as thermal conductivity, specific heat capacity and water vapour resistance factor are determined based on the guidelines of EN ISO 10456:2007 [19]. This standard provides methods for determining either the declared or the design value of thermal (thermal conductivity and specific heat capacity) and moisture (water vapour resistance factor) properties.

Declared value of a thermal or moisture property is defined as the value of a building material or product obtained from measured data and corresponds to a reasonable expected service lifetime under normal conditions.

Design value of a thermal or moisture property is defined as the value of a building material or product obtained from either:

- Declared value
- Measured value
- Tabulated value (provided by EN ISO 10456:2007 [19])

For the purpose of this research exercise, the design values of hygrothermal properties of lightweight aggregate insulating mortars are determined. These are obtained from Table 6 adopted from EN ISO 10456:2007 [19]. Linear interpolation is used to obtain the thermal conductivity of lightweight aggregate insulating mortars having density values between 600 and 1800 kg/m^3. Specific heat capacity and water vapour resistance factor on the other hand, are constant within this density range (600-1800 kg/m^3) and equal to 1000 J/(kg·K) and 6 or 10, respectively.

Table 6: Design hygrothermal values for materials used in plasters and renders adopted from EN ISO 10456:2007 [19]

Material Group or Application		Density ρ Kg/m³	Design Thermal Conductivity λ W/(m·k)	Specific Heat Capacity c_p J/(kg·K)	Water Vapour Resistance Factor μ	
					dry	wet
Plasters and Renders	Gypsum insulating plaster	600	0.18	1000	10	6
	Gypsum plastering	1000	0.40	1000	10	6
	"	1300	0.57	1000	10	6
	Gypsum sand	1600	0.80	1000	10	6
	Lime, sand	1600	0.80	1000	10	6
	Cement, sand	1800	1.00	1000	10	6

3.2.3 Lightweight flakes for Insulating Panels

3.2.3.1. Introduction

The variability of physical features of N-EU and S-EU Wood Flake fractions and its effect on physical and hygrothermal properties of wood-based insulation panels is studied on two different batches. For this purpose, CDE, in charge of material procurement, supplied CETMA with the following materials as shown in Table 7:

Table 7: N-EU and S-EU Wood Flakes fractions tested by CETMA

Batch no	Date Received	Composition (separate size fractions)	Source
1	25/05/2017	Wood Flakes (0/4 mm and 0/8 mm)	N-EU (Germany)
2	23/03/2017	Wood Flakes (0/4 mm and 0/8 mm)	S-EU (France)

Table 8 provides details of all tests performed on N-EU and S-EU Wood&Plastic and Rigid Plastic fractions. A detailed description of all testing methods used is provided in **Sections 3.2.3.2 – 3.2.3.5**.

Table 8: Test methods for CDW lightweight wood flakes (N-EU & S-EU) used for insulation panels

Property	Standard	Laboratories
Physical testing of lightweight aggregates (Wood Flakes)		
Grading (0/4 mm & 0/8 mm fractions)	EN 933-1:2012	CETMA

Water absorption (0/4 mm & 0/8 mm fractions)	Test method developed by CETMA	CETMA
Physical and hygrothermal properties of wood-based panels		
Density	EN 323:1993	CETMA
Thermal conductivity	EN ISO 10456	CETMA
Specific heat capacity	EN ISO 10456	CETMA
Water vapour resistance factor	EN ISO 10456	CETMA

3.2.3.2. Grading – following EN 933-1:2012

Please refer to **Section 3.2.2.2**.

3.2.3.3. Water Absorption – following a test method developed by CETMA

Water absorption is determined by soaking sieved and graded wood flakes in water. For each batch, three 1 l and two 2 l graduated containers are used. The weight of each empty container is measured and recorded. Next, a sample of 100 g of wood flakes is placed on each 1 l container, whereas a sample of 200 g is placed on each 2 l container. The containers are then filled with water. After 24 hours of soaking time, the water is removed from the containers and the weight of the wood flakes is measured and recorded. The containers which hold the wood flakes are then re-filled with water. After a further 24 hours the water is removed from the containers and a new weight measurement of the wood flakes is taken. The above procedure is repeated for a total period of 6 days.

3.2.3.4. Density – following EN 323:1993

The density of particles used in wood-based panels is measured by following the procedure described in EN 323:1993 [20]. For this purpose, a micrometer having flat and parallel circular measuring surfaces of 16 ± 1 mm, an operation force of 4 ± 1 N and accurate to 0.01 mm is used. The dimensions of each test particle are measured in accordance with EN 325:2012 [21] as follows:

First the thickness t of the particle is measured to an accuracy of 0.05 mm. Next, the horizontal and lateral dimensions b_1 and b_2 are measured to an accuracy of 0.1 mm. The density ρ of each particle is the obtained using the following formula:

$$\rho = \frac{m}{b_1 b_2 t} 10^6 \qquad (25)$$

Where:

ρ is the density of the test particle (kg/m3)
m is the mass of the test particle (g)
b_1 is the horizontal dimension of the particle (mm)
b_2 is the horizontal dimension of the particle (mm)
t Is the thickness of the particle (mm)

3.2.3.5. Hygrothermal Properties – following EN ISO 10456:2007

Please refer to **Section 3.2.1.9**. The design values of hygrothermal properties of wood-based panels are obtained from Table 9 (adopted from EN ISO 10456:2007 [19]) shown below.

Table 9: Design hygrothermal values of wood-based panels adopted from EN ISO 10456:2007 [19]

Material Group or Application	Density ρ Kg/m³	Design Thermal Conductivity λ W/(m·k)	Specific Heat Capacity c_p J/(kg·K)	Water Vapour Resistance Factor μ	
				dry	wet
Wood-based panels					
Plywood	300	0.09	1600	150	50
	500	0.13	1600	200	70
	700	0.17	1600	220	90
	1000	0.24	1600	250	110
Cement-bonded particleboard	1200	0.23	1500	50	30
Particleboard	300	0.10	1700	50	10
	600	0.14	1700	50	15
	900	0.18	1700	50	20
Oriented strand board (OSB)	650	0.13	1700	50	30
Fibreboard, including MDF	250	0.07	1700	5	3
	400	0.10	1700	10	5
	600	0.14	1700	20	12
	800	0.18	1700	30	20

4. DESCRIPTION OF RESULTS

4.1 N-EU Mineral Aggregate

4.1.1 Introduction

The variability of chemical and physical features of N-EU CDW mineral aggregate (0/2 mm, 2/8 mm & 8/16 mm sorted fractions) and their effect on fresh and hardened properties of OPC concrete was studied on 4 different batches. For this purpose, CDE in charge of material procurement supplied QUB with the following materials as shown in Table 10:

Table 10: N-EU mineral aggregate batches tested by QUB

Batch no	Date Received	Composition (separate size fractions)	Source
1	March 2017	0/2 mm, 2/8 mm & 8/16 mm	Germany
2	September 2017	0/2 mm, 2/8 mm & 8/16 mm	Norway
3	October 2017	0/2 mm, 2/8 mm & 8/16 mm	Norway
4	November 2017	0/2 mm, 2/8 mm & 8/16 mm	Norway

Based on the grading, water absorption and particle density values of N-EU Batches 1, 2, 3 and 4 obtained in **Sections 4.1.2** and **4.1.4**, two concrete mix recipes were used for casting and testing all specimens of **Sections 4.1.9**, **4.1.10** & **4.1.11**. Details of both mix recipes are shown in Table 11 below.

Table 11: Details of concrete mix recipes 1 and 2

MIX RECIPE DETAILS			
Mix Recipe 1 (Batch 1)		Mix Recipe 2 (Batches 2, 3 and 4)	
Raw Materials	Quantities (kg/m^3)	Raw Materials	Quantities (kg/m^3)

CEM I - 52.5 N	500	CEM I - 52.5 N	500
Mixing water	250	Mixing water	250
0/2 mm aggregate	304	0/2 mm aggregate	328
2/8 mm aggregate	152	2/8 mm aggregate	164
8/16 mm aggregate	1064	8/16 mm aggregate	1148

Using the above two mix recipes 4 OPC concrete mixes were cast for evaluating the effect of recycled aggregate variability (chemical-physical features) on the fresh and hardened properties of OPC concrete. Batch 1 recycled aggregate was only used together with Mix Recipe 1 for casting Mix 1, whereas Batches 2, 3 and 4 were used together with Mix Recipe 2 for casting Mixes 2, 3 and 4, respectively.

4.1.2 Grading

The results of sieving N-EU 0/2 mm, 2/8 mm and 8/16 mm fractions (Batches 1, 2, 3 and 4) are shown in Table 12 and Figure 1, Table 13 and Figure 2 and Table 14 and Figure 3, respectively.

Good particle size distribution was observed in most cases. More specifically, for the four 0/2 mm size fractions tested, the amount of particles greater than 2 mm varied between 4.6% (Batch 2) and 10% (Batch 1) by mass.

When it comes to all four 2/8 mm size fractions tested, no particles greater than 8 mm were found. However, the amount of particles less than 2 mm varied between 1.3% (Batch 2) and 7.4% (Batch 4).

Finally, in all four 8/16 mm size fractions tested, the amount of particles greater than 16 mm varied between 0% (Batches 1 and 3) and 4% (Batch 4) by mass. However, the amount of particles less than 8 mm was quite significant and varied between 14.2% (Batch 4) and 23% (Batch 1).

Table 12: Particle size distribution of 0/2 mm fraction (N-EU Batches 1, 2, 3 and 4)

0/2 mm SIZE FRACTION – N-EU BATCHES 1, 2, 3 & 4				
Aperture Size (mm)	**Cumulative Passing (%)**			
	Batch no 1	Batch no 2	Batch no 3	Batch no 4
4.0	100.0	100.0	100.0	100.0

2.0	90.0	95.4	91.6	94.6
1.0	65.0	75.2	65.2	73.0
0.5	43.0	54.2	41.6	51.9
0.25	23.0	33.6	21.4	30.8
0.125	9.0	15.4	7.4	13.5
0.063	4.0	1.0	1.1	2.0
pan	0	0	0	0

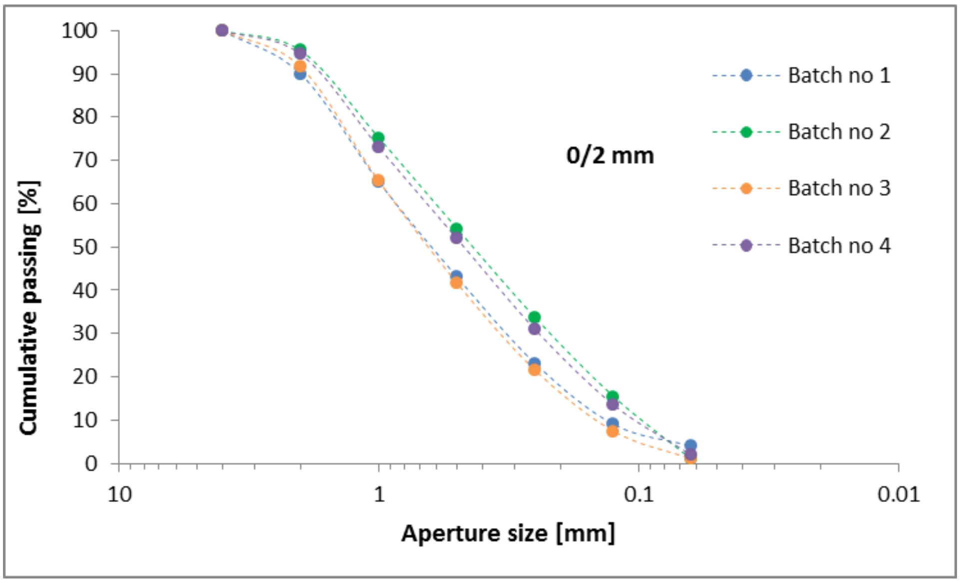

Figure 1: Particle size distribution of 0/2 mm fraction (N-EU Batches 1, 2, 3 and 4)

Table 13: Particle size distribution of 2/8 mm fraction (N-EU Batches 1, 2, 3 and 4)

2/8 mm SIZE FRACTION – N-EU BATCHES 1, 2, 3 & 4	
Aperture Size (mm)	**Cumulative Passing (%)**

	Batch no 1	Batch no 2	Batch no 3	Batch no 4
12.5	100.0	100.0	100.0	100.0
11.2	100.0	100.0	100.0	100.0
10.0	100.0	100.0	100.0	100.0
8.0	100.0	100.0	100.0	100.0
6.3	94.0	97.1	95.3	96.8
5.0	76.0	81.8	88.2	90.1
4.0	54.0	5.4	79.2	82.8
2.0	3.0	1.3	4.5	7.4
1.0	2.0	1.1	0.1	0.5
0.5	1.0	1.0	0.1	0.2
0.25	1.0	0.9	0.1	0.1
0.125	1.0	0.8	0.1	0.1
0.063	1.0	0.0	0.1	0.1
pan	0	0	0	0

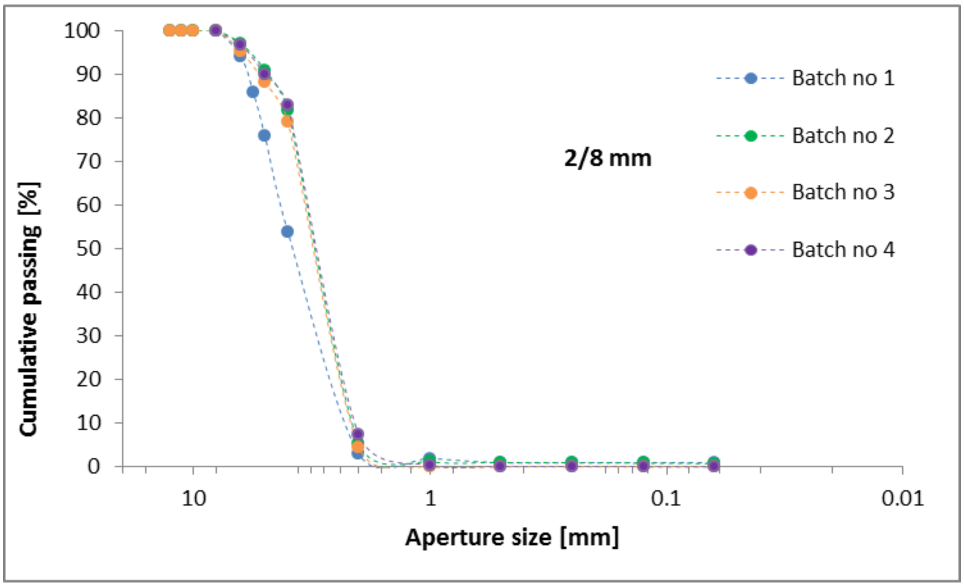

Figure 2: Particle size distribution of 2/8 mm fraction (N-EU Batches 1, 2, 3 and 4)

Table 14: Particle size distribution of 8/16 mm fraction (N-EU Batches 1, 2, 3 and 4)

8/16 mm SIZE FRACTION – N-EU BATCHES 1, 2, 3 & 4				
Aperture Size (mm)	Cumulative Passing (%)			
	Batch no 1	Batch no 2	Batch no 3	Batch no 4
20.0	100.0	100.0	100.0	100.0
16.0	100.0	99.8	100.0	96.0
14.0	73.0	91.4	96.8	90.6
10.0	44.0	53.0	48.8	46.1
8.0	23.0	18.6	14.5	14.2
6.3	10.0	2.5	1.7	2.1
5.0	8.0	0.7	0.3	0.5
4.0	7.0	0.4	0.1	0.2
2.0	5.0	0.3	0.0	0.1
1.0	4.0	0.3	0.0	0.0
0.5	4.0	0.2	0.0	0.0
0.25	3.0	0.2	0.0	0.0
0.125	2.0	0.2	0.0	0.0
0.063	3.1	0.1	0.0	0.0
pan	0	0	0	0

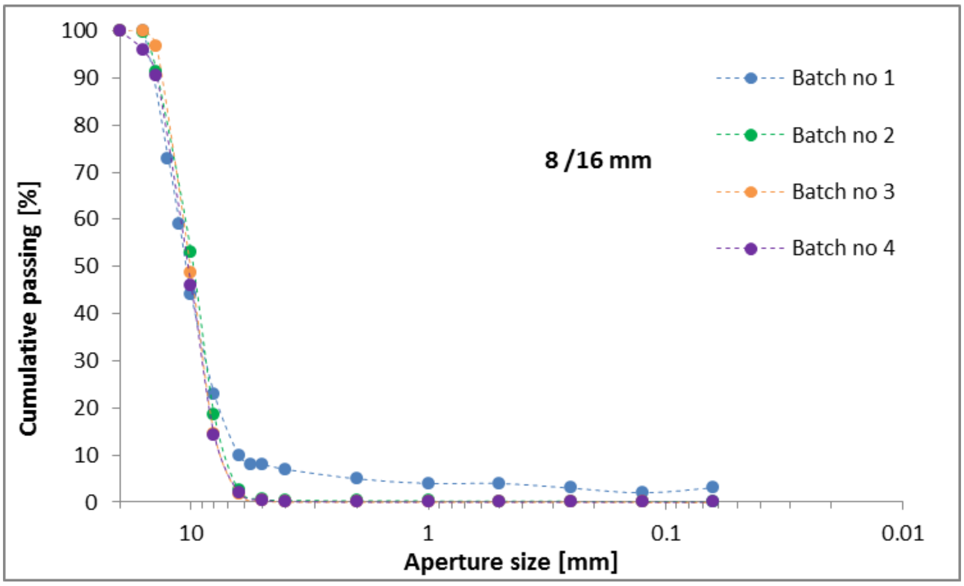

Figure 3: Particle size distribution of 8/16 mm fraction (N-EU Batches 1, 2, 3 and 4)

4.1.3 Constituent Classification of 8/16 mm Size Fraction

The estimated composition of N-EU Batches 1, 2, 3 and 4 (8/16 mm size fraction) in terms of FL, X, Rc, Ru, Rb , Ra and Rg are given in Table 15 and Figure 4, Table 16 and Figure 5, Table 17 and Figure 6 and Table 18 and Figure 7, respectively.

Table 15: Constituent classification of 8/16 mm size fraction – N-EU Batch 1

8/16 mm SIZE FRACTION – N-EU BATCH 1			
Symbol	**Description**	**Mass or Volume**	**Percentage**
M_1	Mass of oven-dried portion	19.981 kg	n/a
M_{FL}	Mass of floating particles in M_1	0.002 kg	n/a
M_X	Mass of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	0.016 kg	n/a
M_2	Mass of non-floating particles in M_1	19.963 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	5.082 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	0.275 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	4.328 kg	n/a

M_{Rb}	Mass of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_3	0.184 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0.287 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0.004 kg	n/a
FL	Estimated volume of floating particles in M_1	negligible	0%
X	Estimated percentage of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	n/a	0.1%
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	5.4%
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	85.0%
Rb	Estimated percentage of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_1	n/a	3.6%
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	5.6%
Rg	Estimated percentage of glass detected in M_1	n/a	0.1%

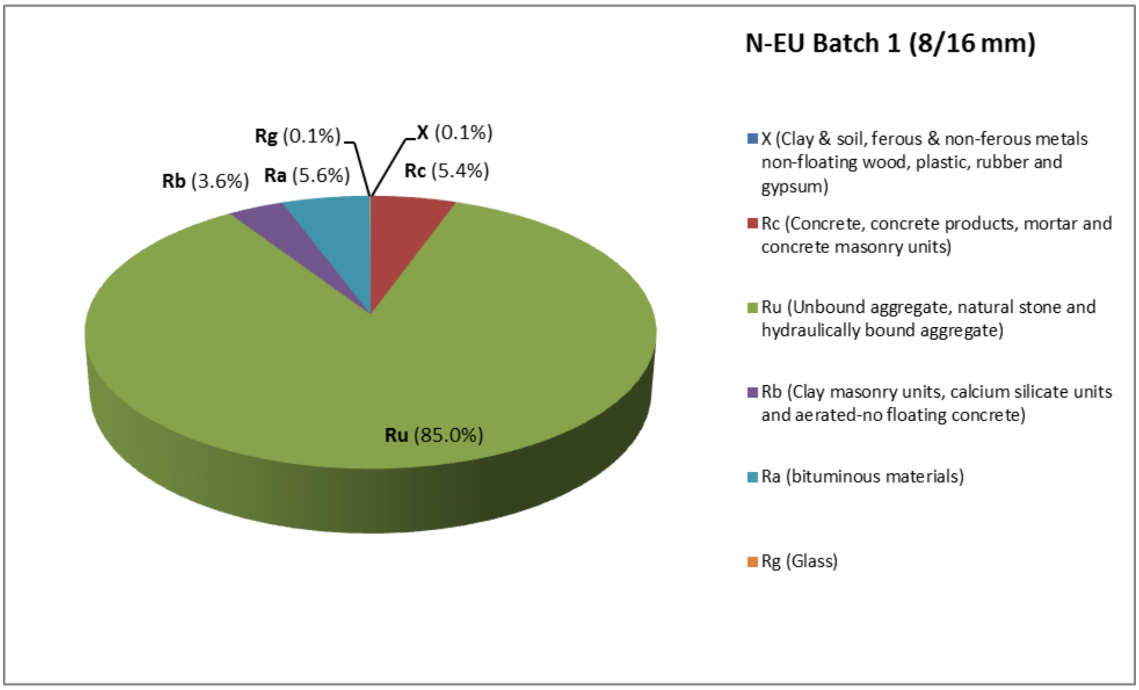

Figure 4: Constituent classification of 8/16 mm size fraction – N-EU Batch 1

Table 16: Constituent classification of 8/16 mm size fraction – N-EU Batch 2

8/16 mm SIZE FRACTION – N-EU BATCH 2			
Symbol	**Description**	**Mass or Volume**	**Percentage**
M_1	Mass of oven-dried portion	19.924 kg	n/a
M_{FL}	Mass of floating particles in M_1	0.006 kg	n/a
M_X	Mass of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	0.012 kg	n/a
M_2	Mass of non-floating particles in M_1	19.918 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	5.935 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	0.337 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	5.279 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_3	0.090 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0.207 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0.010 kg	n/a

FL	Estimated volume of floating particles in M_1	negligible	0%
X	Estimated percentage of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	n/a	0.2%
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	5.7%
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	88.9 %
Rb	Estimated percentage of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_1	n/a	1.5%
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	3.5%
Rg	Estimated percentage of glass detected in M_1	n/a	0.2%

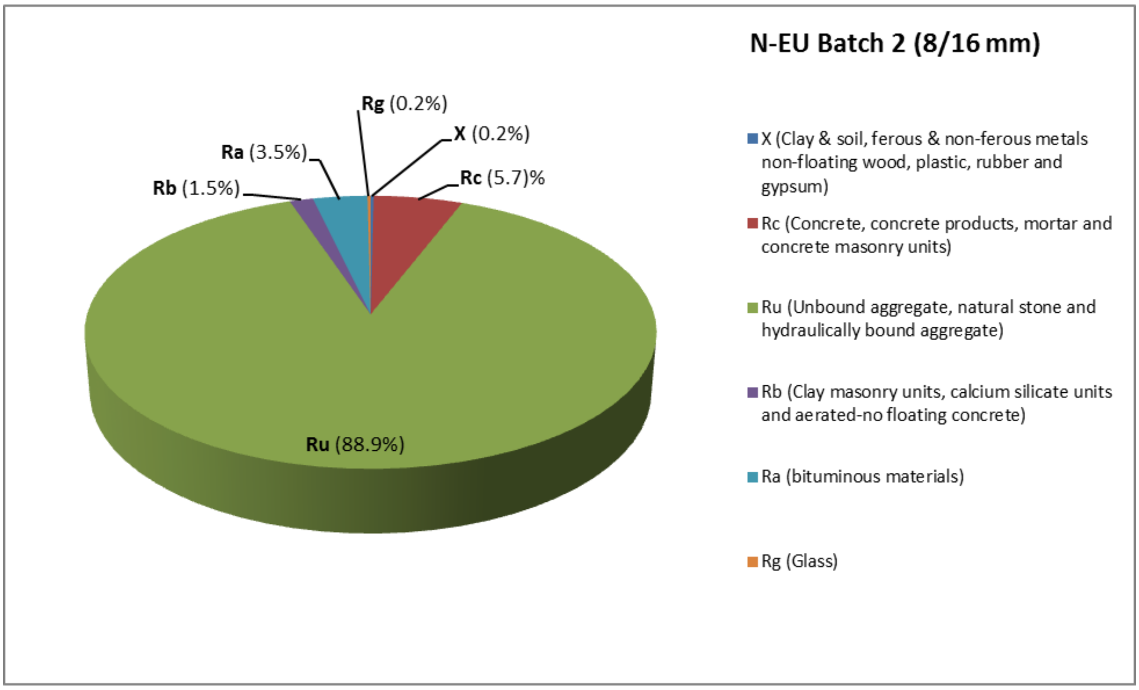

Figure 5: Constituent classification of 8/16 mm size fraction – N-EU Batch 2

Table 17: Constituent classification of 8/16 mm size fraction – N-EU Batch 3

8/16 mm SIZE FRACTION – N-EU BATCH 3			
Symbol	**Description**	**Mass or Volume**	**Percentage**
M_1	Mass of oven-dried portion	20.556 kg	n/a
M_{FL}	Mass of floating particles in M_1	0.006 kg	n/a
M_X	Mass of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	0.023 kg	n/a
M_2	Mass of non-floating particles in M_1	20.550 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	5.989 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	0.274 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	5.495 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_3	0.056 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0.128 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0.013 kg	n/a

FL	Estimated volume of floating particles in M_1	negligible	0%
X	Estimated percentage of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	n/a	0.4%
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	4.6%
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	91.7%
Rb	Estimated percentage of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_1	n/a	0.9%
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	2.1%
Rg	Estimated percentage of glass detected in M_1	n/a	0.2%

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

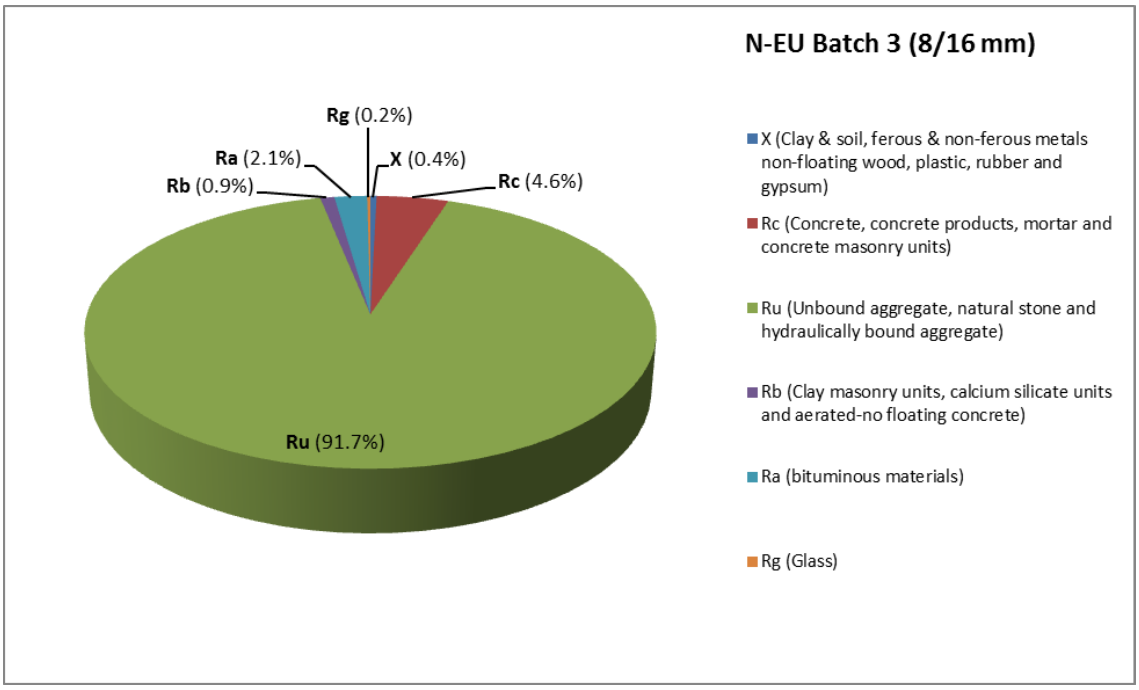

Figure 6: Constituent classification of 8/16 mm size fraction – N-EU Batch 3

Table 18: Constituent classification of 8/16 mm size fraction – N-EU Batch 4

8/16 mm SIZE FRACTION – N-EU BATCH 4			
Symbol	**Description**	**Mass or Volume**	**Percentage**
M_1	Mass of oven-dried portion	20.004 kg	n/a
M_{FL}	Mass of floating particles in M_1	0.003 kg	n/a
M_X	Mass of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	0.032 kg	n/a
M_2	Mass of non-floating particles in M_1	19.885 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	5.987 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	0.224 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	5.541 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_3	0.059 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0.120 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0.011 kg	n/a

FL	Estimated volume of floating particles in M_1	negligible	0%
X	Estimated percentage of clay and soil, ferrous and non-ferrous metals, non-floating wood, plastic, rubber and gypsum in M_1	n/a	0.5%
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	3.7%
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	92.5%
Rb	Estimated percentage of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_1	n/a	1.0%
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	2.0%
Rg	Estimated percentage of glass detected in M_1	n/a	0.2%

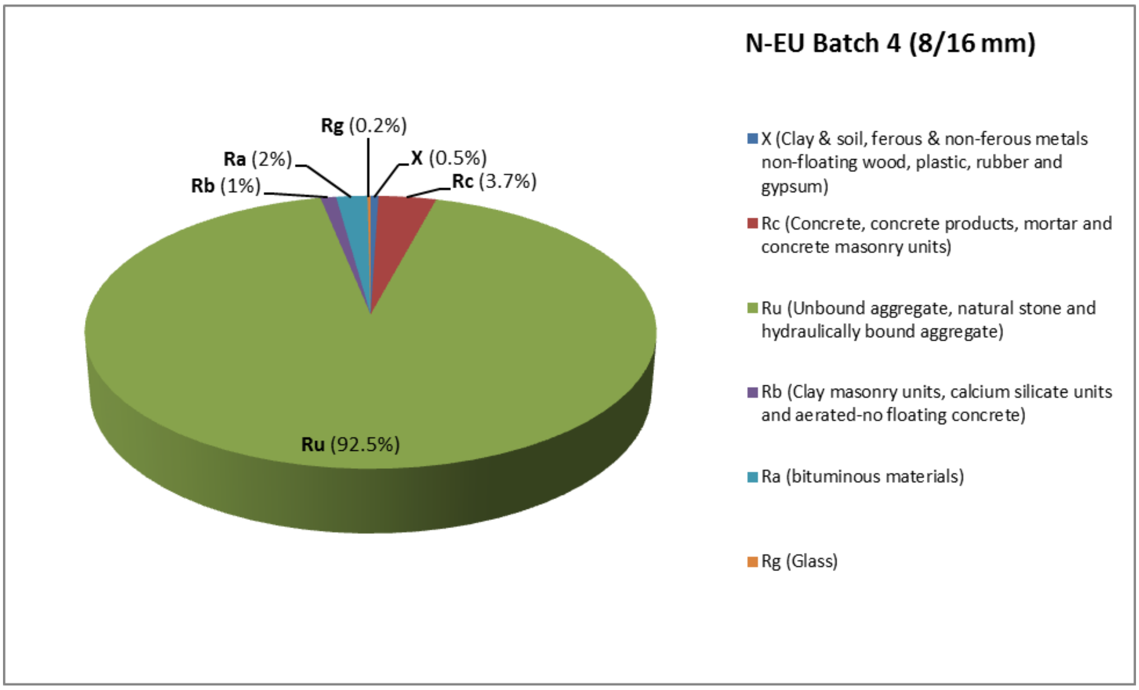

Figure 7: Constituent classification of 8/16 mm size fraction – N-EU Batch 4

Based on the above results, all 4 batches comply with the requirements set by EN 206:2013+A1:2016 [22] and BS 8500-2:2015+A1:2016 [23] with the exception of Ra content of Batch 1 (5.6% as opposed to 5%).

More specifically, for the four 8/16 mm size fractions tested, the amount of X + Rg (clay & soil, ferrous & non-ferrous metals, non-floating wood, plastic, rubber, gypsum and glass) particles varied between 0.2% (Batch 1) and 0.7% (Batch 4) compared to a maximum allowable limit of 1%.

The amount of Rc (concrete, concrete products, mortar and concrete masonry units) particles varied between 3.7% (Batch 4) and 5.4% (Batch 1), whereas the amount of Ru (unbound aggregate, natural stone, and hydraulically bound aggregate) varied between 85% (Batch 1) and 92.5% (Batch 4). Consequently, the Rc + Ru particles varied between 90.4% (Batch 1) and 96.2% (Batch 4) compared to a minimum allowable limit of 90%.

When it comes to the amount of Rb (clay masonry units, calcium silicate units and aerated-no floating concrete) particles, this varied between 0.9% (Batch 3) and 3.6% (Batch 1) compared to a maximum allowable limit of 10%.

Finally, the content of Ra (bituminous materials) particles for Batches 2, 3 and 4 was measured at 3.5%, 2.1% and 2%, respectively.

In conclusion, all 4 N-EU tested batches are quite clean and contain high amounts of good quality Ru particles as opposed to defective ones such as X, Rb, Ra and Rg.

4.1.4 Water Absorption and Particle Density

The water absorption, apparent, oven dried and saturated surface dry density values of all size fractions (0/2 mm, 2/8 mm and 8/16 mm) of Batches 1 to 4 are shown in Table 19.

Very low water absorption values (% by mass) were recorded for all 4 batches tested. More specifically, the absorption value of 0/2 mm size fractions varied between 1.2% (Batches 2 and 4) and 2% (Batch 1). The absorption value of 2/8 mm size fractions varied between 1.1% (Batch 3) and 2.8% (Batch 1), whereas those of 8/16 mm size fractions varied between 1.3% (Batch 3) and 2.4% (Batch 1). The above results are in agreement with the ones obtained in **Section 4.1.3** (constituent classification of 8/16 mm size fraction) i.e. high levels of good quality virgin aggregate as part of Ru coupled with low levels of porous particles such as Rc and Rb.

By comparison, published literature suggests that water absorption of coarse recycled aggregate can be as high as 10% by mass [24], [25], [26]. In the case of fine recycled aggregate, water absorption performance can be even worse due to higher cement paste content [3].

Bearing in mind that typical water absorption values of virgin aggregate are in the region of 0.5% and 1.5% [27], the values recorded for all 4 N-EU batches (0/2 mm, 2/8 mm and 8/16 mm size fractions) are very good.

Finally, when it comes to aggregate saturated surface dry density, results are very close to the ones assumed by BRE [28] for either crushed or uncrushed virgin aggregate.

Table 19: Water absorption, apparent, oven-dried and saturated surface dry density values of N-EU Batches 1, 2, 3 and 4

Batch	Property	Size Fraction		
		0/2 mm	2/8 mm	8/16 mm
1	WA_{24} (% by mass)	2	2.8	2.4
	ρ_a (kg/m^3)	2700	2410	2630
	ρ_{rd} (kg/m^3)	2560	2250	2480
	ρ_{ssd} (kg/m^3)	2610	2320	2540
2	WA_{24} (% by mass)	1.2	1.6	1.5
	ρ_a (kg/m^3)	2650	2810	2800
	ρ_{rd} (kg/m^3)	2570	2690	2690
	ρ_{ssd} (kg/m^3)	2600	2740	2730
3	WA_{24} (% by mass)	1.4	1.1	1.3
	ρ_a (kg/m^3)	2660	2760	2760

	ρ_{rd} (kg/m^3)	2560	2680	2670
	ρ_{ssd} (kg/m^3)	2600	2710	2700
4	WA_{24} (% by mass)	1.2	1.8	1.5
	ρ_a (kg/m^3)	2660	2780	2740
	ρ_{rd} (kg/m^3)	2570	2650	2630
	ρ_{ssd} (kg/m^3)	2610	2690	2670

Where:

ρ_a is the apparent density
ρ_{rd} is the oven-dried density
ρ_{ssd} is the saturated surface dry density

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

The water-soluble chloride content of all tested size fractions (0/2 mm and 8/16 mm) of N-EU Batches 1 to 4 is shown in Table 20 below.

Table 20: Water-soluble chloride content of 0/2 mm and 8/16 mm size fractions – N-EU Batches 1 to 4

Test Method	Batch no	Unit	Size Fraction	
			0/2 mm	8/16 mm
Potentiometry	1	wt%	0.00091	0.00091
	2	wt%	0.000012	0.0000045
	3	wt%	0.000013	0.0000070
	4	wt%	0.0000077	0.0000041

As shown in Table 20, all tested mineral fractions of all N-EU Batches contain very 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. However, requirements in EN 206:2013+A1:2016 [22] set a limit on chloride ion content at either 0.2% or 0.4% by mass of cement for reinforced concrete. Referring to the mix designs used for casting concrete specimens containing 100% coarse and 100% fine N-EU recycled aggregate (**Section 4.1.1**), the amount of chlorides expressed as a % by mass of cement is still well below the 0.2% limit.

4.1.6 Water-Soluble Sulfate Content

The water-soluble sulfate content of all tested size fractions (0/2 mm and 8/16 mm) of N-EU Batches 1 to 4 is shown in Table 21 below.

Table 21: Water-soluble sulfate content of 0/2 mm and 8/16 mm size fractions – N-EU Batches 1 to 4

Batch no	Size Fraction	
	0/2 mm (wt% water soluble SO_3)	8/16 mm (wt% water soluble SO_3)
1	0.025	0.014
2	0.013	0.024
3	0.021	0.021
4	0.015	0.008

Based on Table 21, the water-soluble sulfate content (by mass of aggregate) of all coarse size fractions is well below the 0.2% limit set by EN 12620:2002+A1:2008 [29] for use in structural concrete. The same can be said for all fine fractions tested.

4.1.7 Slump Test

Recycled aggregate typically contains significant levels of Rc particles. These particles create more friction due to their rough surface texture and irregular shape which significantly reduces the workability of concrete. Consequently, higher levels of cement paste and vibration energy are required to compact concrete which contains high replacement levels of recycled aggregate [1], [2], [30], [31], [32].

Higher water absorption values of recycled aggregate compared to virgin aggregate is another factor that negatively affects workability. Typically, recycled aggregate concrete requires 5-10% more free water than virgin aggregate concrete in order to maintain the same workability [2], [33], [34].

The workability (slump value) of N-EU Mixes 1, 2, 3 and 4 at 15 and 30 minutes from the start of mixing the raw materials with water is shown in Table 22 below.

Table 22: Slump test values at 15 and 30 mins for Mixes 1, 2, 3 & 4 containing 100% N-EU aggregate (Batches 1, 2, 3 & 4)

Mix no	Recycled Aggregate Batch no	Time (min)	Slump Value (mm)
1	1	15	110
		30	90
2	2	15	200
		30	200
3	3	15	190
		30	190
4	4	15	210
		30	180

Based on the above results, high and stable workability values were obtained for all 4 mixes. This can be attributed to high levels of good quality virgin aggregate as part of Ru together with very low levels of Rc particles, especially when it comes to Mixes 2, 3 and 4.

4.1.8 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. Clearly, the higher the replacement level of virgin aggregate by recycled aggregate, the lower the fresh density of concrete.

Fresh density values of N-EU Mixes 1, 2, 3 and 4 are shown in Table 23 below.

Table 23: Fresh density values of Mixes 1, 2, 3 & 4 containing 100% N-EU aggregate (Batches 1, 2, 3 & 4)

Mix no	Recycled Aggregate Batch no	Sample no	Fresh Density (kg/m^3)	Average Fresh Density (kg/m^3)
1	1	1	2247	2260
		2	2277	
		3	2237	
		4	2249	
		5	2268	
		6	2255	
2	2	1	2383	2360
		2	2360	
		3	2364	
		4	2338	
		5	2350	
		6	2339	
3	3	1	2340	2360
		2	2356	
		3	2353	
		4	2365	
		5	2368	
		6	2358	
4	4	1	2385	2370
		2	2342	

		3	2364	
		4	2337	
		5	2414	
		6	2404	

Based on the above results, the fresh density of Mixes 2 (2360 kg/m^3), 3 (2360 kg/m^3) and 4 (2370 kg/m^3) is very similar to the one assumed by BRE [28] for normal concrete mixes containing 100% crushed or uncrushed virgin aggregate (2300-2400 kg/m^3).

The fresh density of Mix 1 (2260 kg/m^3) on the other hand, is lower by approximately 4-5% when compared to the density of Mixes 2, 3 and 4. This is mainly due to the higher Rc + Rb + Ra content of Mix 1 (14.6% by mass) as opposed to Mix 2 (10.7% by mass), Mix 3 (7.6% by mass) and Mix 4 (6.7% by mass).

4.1.9 Hardened Concrete Density

Hardened density values of N-EU Mixes 1, 2, 3 and 4 are shown in Table 24

Table 24: Hardened density values of Mixes 1, 2, 3 & 4 containing 100% N-EU aggregate (Batches 1, 2, 3 & 4)

Mix no	Cube no	Water Saturated		Volume of cube (l)	Oven-Dried Mass (g)	Oven-dried Density (kg/m^3)	Saturated Density (kg/m^3)
		Mass in air (g)	Mass in Water (g)				
1	1	2284	1282	1.004	2136	2127	2275
	2	2256	1261	0.997	2108	2114	2263
	3	2270	1272	1.000	2122	2122	2270
					average	**2120**	**2270**
2	1	2334	1351	0.985	2199	2232	2370
	2	2361	1375	0.988	2233	2260	2390
	3	2348	1366	0.984	2219	2255	2386
					average	**2250**	**2380**
3	1	2349	1360	0.991	2193	2213	2370
	2	2331	1351	0.982	2178	2218	2374
	3	2376	1392	0.986	2233	2265	2410
					average	**2230**	**2390**
4	1	2386	1396	0.992	2237	2255	2405

	2	2350	1365	0.987	2192	2221	2381
	3	2376	1387	0.991	2225	2245	2398
					average	**2240**	**2390**

As expected, the hardened density (oven-dried and water saturated) of Mixes 2, 3 and 4 is very similar. The oven-dried density ranges between 2230 kg/m^3 (Mix 3) and 2250 kg/m^3 (Mix 2), whereas the water saturated ranges between 2380 kg/m^3 (Mix 2) and 2390 kg/m^3 (Mixes 3 and 4).

When it comes to Mix 1 lower oven-dried (2120 kg/m3) and water saturated (2270 kg/m^3) hardened density values were obtained. These are in line with the fresh density values obtained for Mix 1.

4.1.10 Compressive Strength

Compressive strength values of N-EU Mixes 1, 2, 3 and 4 are shown in Table 25 and Figure 8, Figure 9, Figure 10 and Figure 11.

Table 25: Compressive strength values of Mixes 1, 2, 3 & 4 containing 100% N-EU recycled aggregate (Batches 1, 2, 3 & 4)

Mix no	Age (days)	Cube no	Mass (g)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Standard Deviation (MPa)
1	1	1	2206	11.46	11.5	0.20
		2	2246	11.72		
		3	2224	11.33		
	7	1	2274	28.12	29.0	0.68
		2	2268	29.30		
		3	2256	29.32		
	28	1	-	36.81	36.0	1.17
		2	-	34.88		
		3	-	37.00		
2	1	1	2308	11.43	11.0	0.39
		2	2359	10.82		
		3	2345	11.53		
	7	1	2348	29.98	29.0	1.21
		2	2364	29.69		
		3	2376	27.72		
	28	1	-	37.55	37.0	0.51
		2	-	36.81		

		3	-	36.57		
3	1	1	2329	10.61	10.5	0.08
		2	2341	10.66		
		3	2356	10.51		
	7	1	2369	27.92	28.0	0.17
		2	2381	27.74		
		3	2362	28.07		
	28	1	2371	35.95	36.5	1.39
		2	2354	38.12		
		3	2408	35.54		
4	1	1	2333	13.51	12.5	0.80
		2	2372	12.18		
		3	2317	12.06		
	7	1	2394	29.57	31.5	1.65
		2	2333	32.04		
		3	2351	32.70		
	28	1	2425	36.90	37.5	5.95
		2	2402	32.12		
		3	2338	43.96		

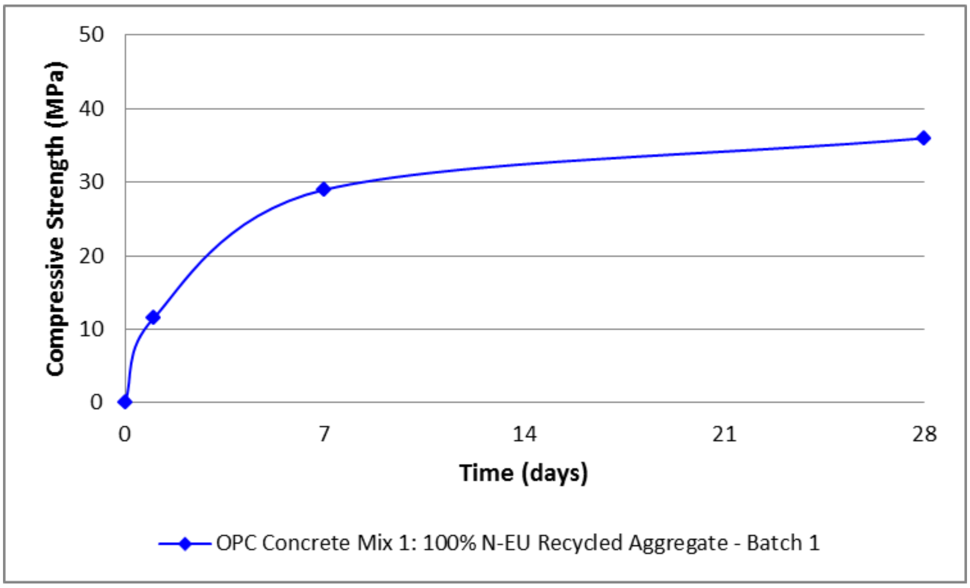

Figure 8: Compressive strength development over time of Mix 1 containing 100% N-EU recycled aggregate – Batch 1

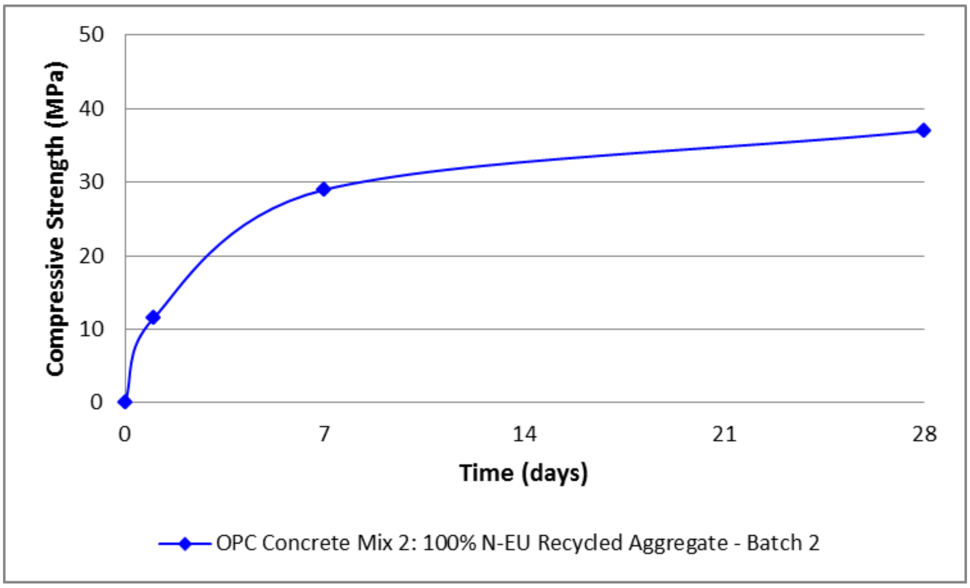

Figure 9: Compressive strength development over time of Mix 2 containing 100% N-EU recycled aggregate – Batch 2

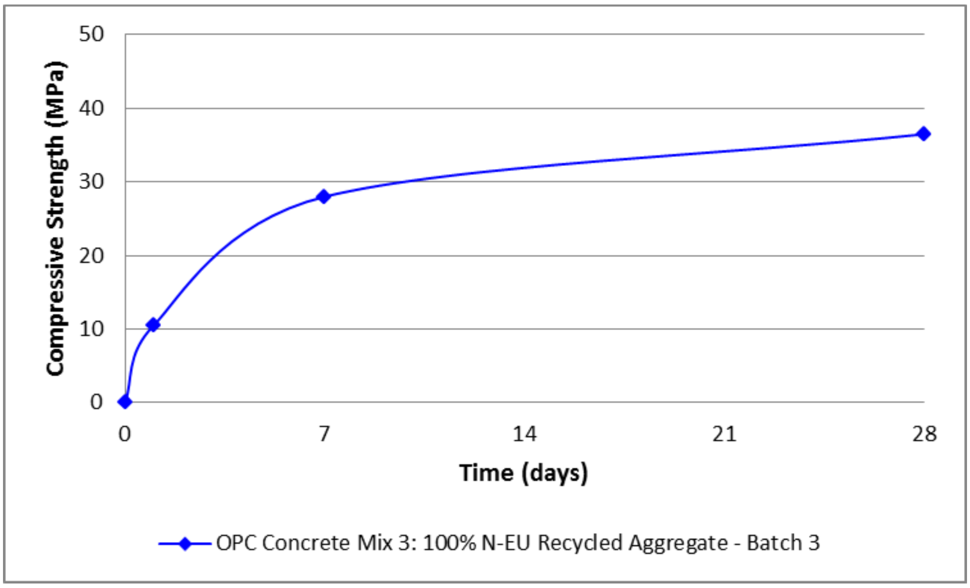

Figure 10: Compressive strength development over time of Mix 3 containing 100% N-EU recycled aggregate - Batch 3

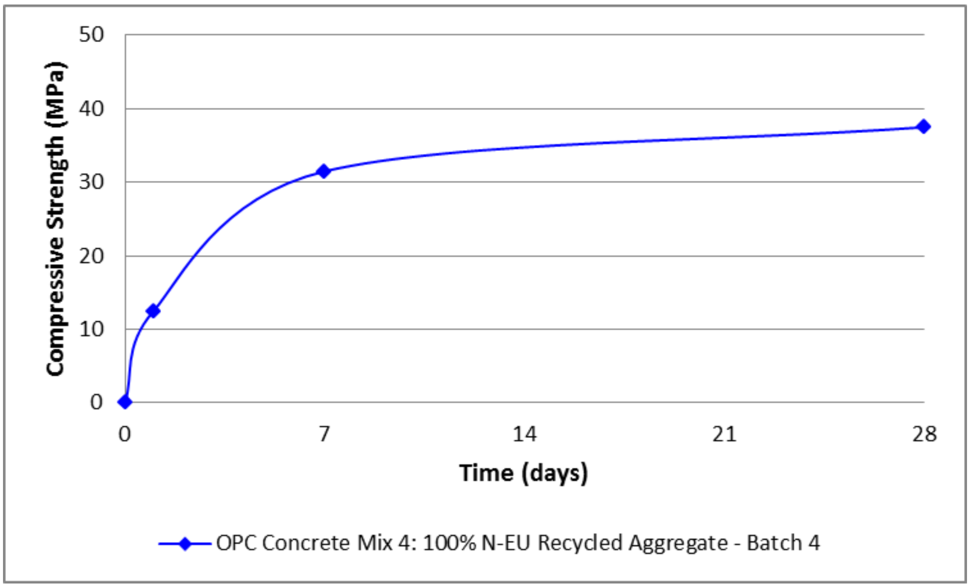

Figure 11: Compressive strength development over time of Mix 4 containing 100% N-EU recycled aggregate - Batch 4

All 4 mixes made using N-EU recycled aggregate achieved very similar 28-day compressive strength values ranging between 36 MPa (Mix 1) and 37.5 MPa (Mix 4). This is mainly due to the fact that all four coarse aggregate batches were very clean i.e. the amount of Ru was very high ranging between 85% (Batch 1) and 92.5% (Batch 4).

4.1.11 Tensile Strength

Tensile strength values of N-EU Mixes 1, 2, 3 and 4 are shown in Table 26 below.

Table 26: Tensile splitting strength values of Mixes 1, 2, 3 & 4 containing 100% N-EU recycled aggregate (Batches 1, 2, 3 & 4)

Mix	Age (days)	Cylinder no	Mass (g)	Tensile Splitting Strength (MPa)	Average Tensile Splitting Strength (MPa)	Standard Deviation (MPa)
1	28	1	3536	2.41	2.65	0.46
		2	3603	2.31		
		3	3548	3.16		
2		1	3740	2.75	2.70	0.26
		2	3708	2.41		
		3	3714	2.91		
3		1	3708	3.17	3.15	0.03
		2	3728	3.18		
		3	3730	3.12		
4		1	3790	2.82	2.75	0.15
		2	3766	2.81		
		3	3752	2.56		

All 4 mixes made using N-EU recycled aggregate achieved very similar 28-day tensile strength values ranging between 2.65 MPa (Mix 1) and 3.15 MPa (Mix 3). These results are in line with the ones obtained for compressive strength. As a material, OPC concrete is very strong in compression but very weak in tension. Typically, its tensile strength is assumed to be approximately equal to 10% of its compressive strength. Tensile strength results confirm the above assumption.

4.2 S-EU Mineral Aggregate

4.2.1 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 3 different batches. For this purpose, CDE in charge of material procurement supplied RISE CBI with the following materials as shown in Table 27:

Table 27: S-EU CDW batches tested by RISE CBI

Batch no	Date Received	Date Collected	Composition (seperate size fractions)	Source
1	13th of January 2017	January 2017	0/2 mm, 2/8 mm & 8/16 mm	France
2	20th of September 2017	September 2017	0/2 mm, 2/8 mm & 8/16 mm	France
3	13th of December 2017	October 2017	0/2 mm, 2/8 mm & 8/16 mm	France

Based on the grading, water absorption and particle density values of S-EU Batches 1, 2 and 3 reported in **Sections 4.2.2** and **4.2.4**, three concrete mix recipes were developed for casting and testing specimens as described in **Section 4.2.9**. Details of mix recipes are shown in Table 28 below. The aim was to keep the mixes as similiar to each other as possible, hence the same cement type, cement amount and vct were used 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.

Table 28: Details of concrete mix recipes 1, 2 and 3

MIX RECIPE DETAILS					
Mix Recipe 1 (Batch 1)		Mix Recipe 2 (Batch 2)		Mix Recipe 3 (Batch 3)	
Raw Materials	Quantities (kg/m^3)	Raw Materials	Quantities (kg/m^3)	Raw Materials	Quantities (kg/m^3)
CEM I - 52.5 N	500	CEM I - 52.5 N	500	CEM I - 52.5 N	500
Mixing water	250	Mixing water	250	Mixing water	250
0/2 mm aggregate	289	0/2 mm aggregate	243	0/2 mm aggregate	243
2/8 mm aggregate	519	2/8 mm aggregate	405	2/8 mm aggregate	405
8/16 mm aggregate	798	8/16 mm aggregate	952	8/16 mm aggregate	952

4.2.2 Grading

The results of sieving Batch 1, 2 and 3 of the sorted S-EU CDW aggregate fractions are shown for size-fractions 0/2 mm (Table 29 and Figure 12), 2/8 mm (Table 30 and Figure 13), and 8/16 mm (Table 31 and Figure 14).

Table 29: Particle size distribution of 0/2 mm fraction (S-EU Batches 1, 2 and 3)

0/2 mm SIZE FRACTION – S-EU BATCHES 1, 2 & 3			
Aperture Size (mm)	**Cumulative Passing (%)**		
	Batch no 1	Batch no 2	Batch no 3
5.6	100.0	100.0	100.0
4.0	99.9	100.0	99.8
2.0	91.0	95.1	98.1
1.0	70.2	73.9	78.6
0.5	43.7	51.0	36.3
0.25	20.2	28.9	15.3
0.125	7.9	13.4	5.3
0.063	4.6	3.8	2.6
pan	0	0	0

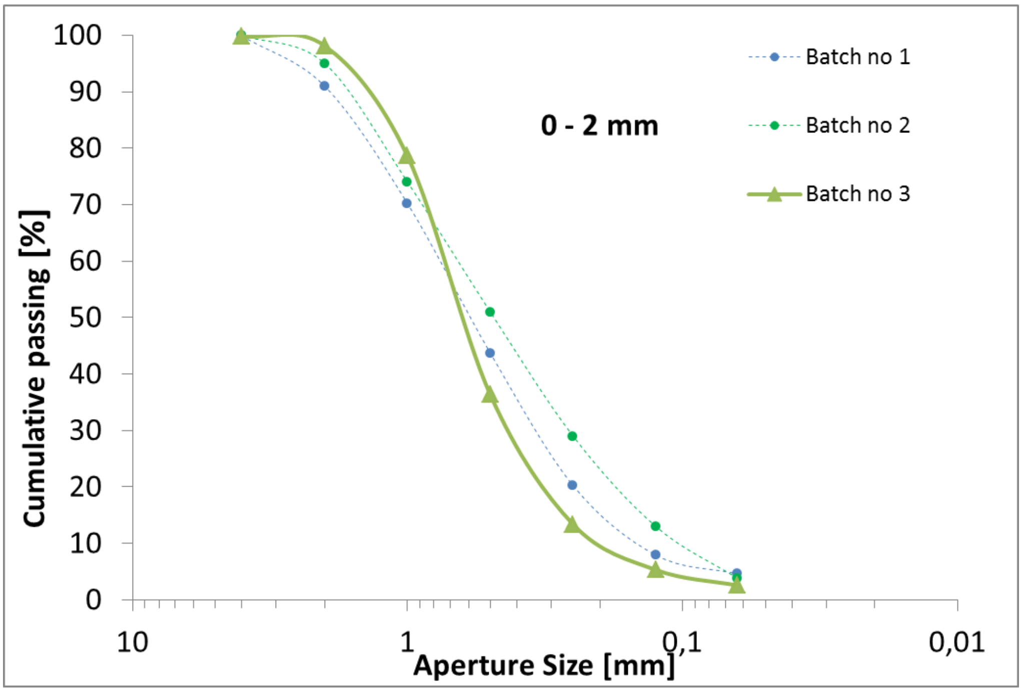

Figure 12: Particle size distribution of 0/2 mm fraction (S-EU Batches 1, 2 and 3)

Table 30: Particle size distribution of 2/8 mm fraction (S-EU Batches 1, 2 and 3)

2/8 mm SIZE FRACTION – S-EU BATCHES 1, 2 & 3			
Aperture Size (mm)	Cumulative Passing (%)		
	Batch no 1	Batch no 2	Batch no 3
12.5	100.0	100.0	100.0
11.2	99.9	100.0	100.0
10.0	99.8		
8.0	99.5	99.9	99.8
6.3	90.2		
5.6	77.8	83.4	75.0
5.0	62.4		
4.0	35.8	61.3	53.4
2.0	3.7	4.4	25.0
1.0	2.6	0.6	12.4
0.5	2.1	0.4	8.8
0.25	1.6	0.3	5.5
0.125	1.3		
0.063	1.8	0.2	1.4

pan	0	0	0

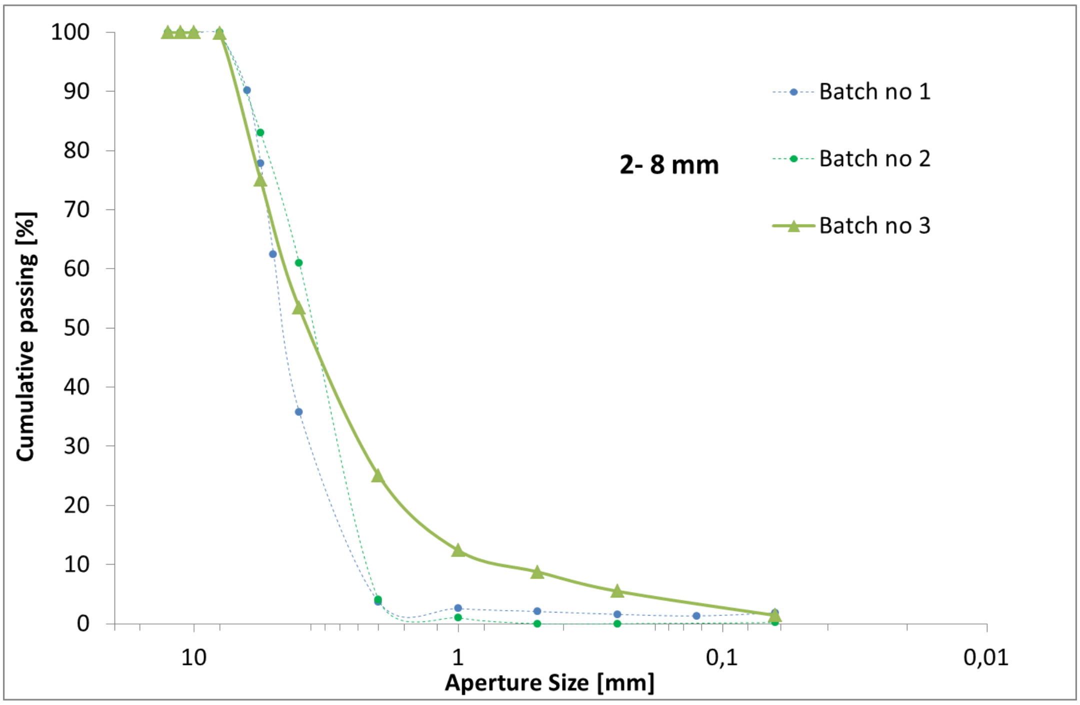

Figure 13: Particle size distribution of 2/8 mm fraction (S-EU Batches 1, 2 and 3)

Table 31: Particle size distribution of 8/16 mm fraction (S-EU Batches 1, 2 and 3)

8/16 mm SIZE FRACTION – S-EU BATCHES 1, 2 & 3			
Aperture Size (mm)	Cumulative Passing (%)		
	Batch no 1	Batch no 2	Batch no 3
20.0	100.0	100.0	100.0
16.0	97.3	100.0	97.5
12.5	65.2		
11.2	47.2	70.9	53.5
10.0	31.5		
8.0	12.2	20.2	14.3
6.3	5.3		
5.6	4.6	1.4	2.3
5.0	4.3		

4.0	4.0	0.8	2.1
2.0	3.4	0.8	1.7
1.0	2.9		
0.5	2.3		
0.25	1.7		
0.125	1.2		
0.063	1.9	0.4	0.6
pan	0	0	0

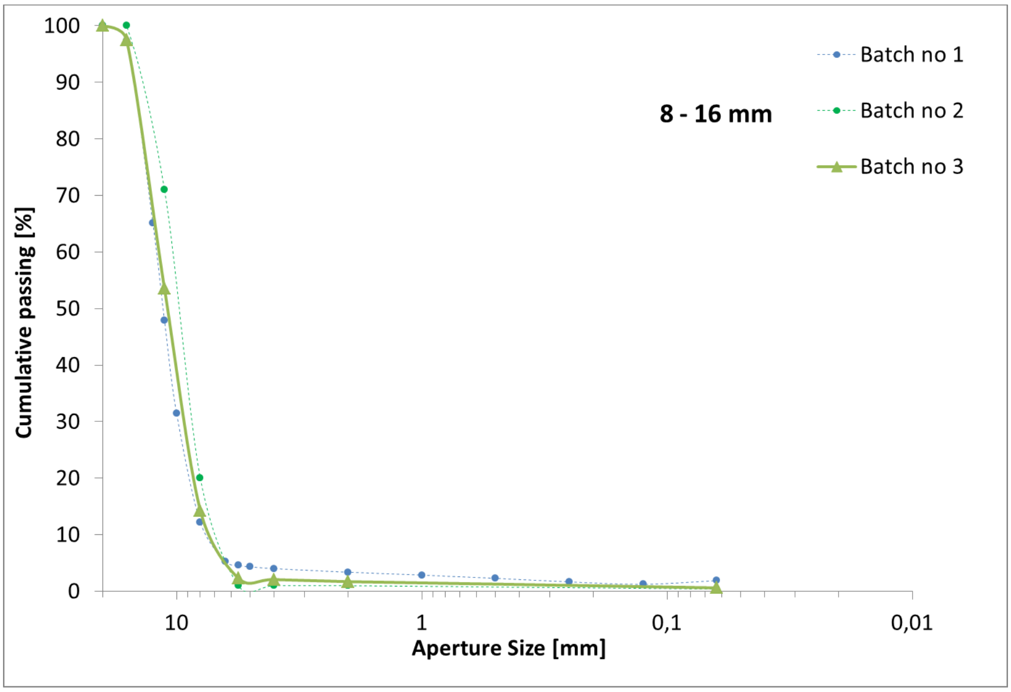

Figure 14: Particle size distribution of 8/16 mm fraction (S-EU Batches 1, 2 and 3)

Good particle size distribution was observed in all three 0/2 mm fractions. However, the amount of particles greater than 2 mm was relatively high, 9 % by mass, in Batch 1.

The size-distribution of all three 2/8 mm S-EU batches was very good when looking on the upper limit, with only up to 0.5% of the material > 8 mm. When looking on the lower limit, ca 4% of the material is < 2 mm in Batch 1 and 2. However, Batch 3 deviates heavily with 25% < 2 mm.

In all three 8/16 mm size fractions, the amount of particles > 16 mm was relatively low. In Batch 1 and 3 it was (2%-3%) and basically 0% in Batch 2. However, the amount of particles < 8 mm was relatively high in all fractions, from 12% and 14% in Batch 1 and 3 respectively, to 20% in Batch 2).

4.2.3 Constituent Classification of 8/16 mm Size Fraction

The estimated composition of the different batches of S-EU 8/16 mm size fraction are given in terms of FL, X, Rc, Ru, Rb , Ra and Rg in Table 32 and Figure 15 and Figure 16 (Batch 1), Table 33 and Figure 17 and Figure 18 (Batch 2), and Table 34 and Figure 19 and Figure 20 (Batch 3), respectively.

Table 32: Constituent classification of 8/16 mm size fraction – S-EU Batch 1

8/16 mm SIZE FRACTION – S-EU BATCH 1			
Symbol	**Description**	**Amount (kg or ml)**	**Proportion**
M_1	Mass of oven-dried portion	23.124 kg	n/a
V_{FL}	Mass of floating particles in M_1	31 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	0.011 kg	n/a
M_2	Mass of non-floating particles in M_1	22.596 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	2.586 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	0.971 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	1.008 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_3	0.484 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	0.123 kg	n/a
FL	Estimated volume of floating particles in M_1	n/a	1.3 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	0.1%
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	38 %
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	39 %
Rb	Estimated percentage of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_1	n/a	19 %
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	0%
Rg	Estimated percentage of glass detected in M_1	n/a	5 %

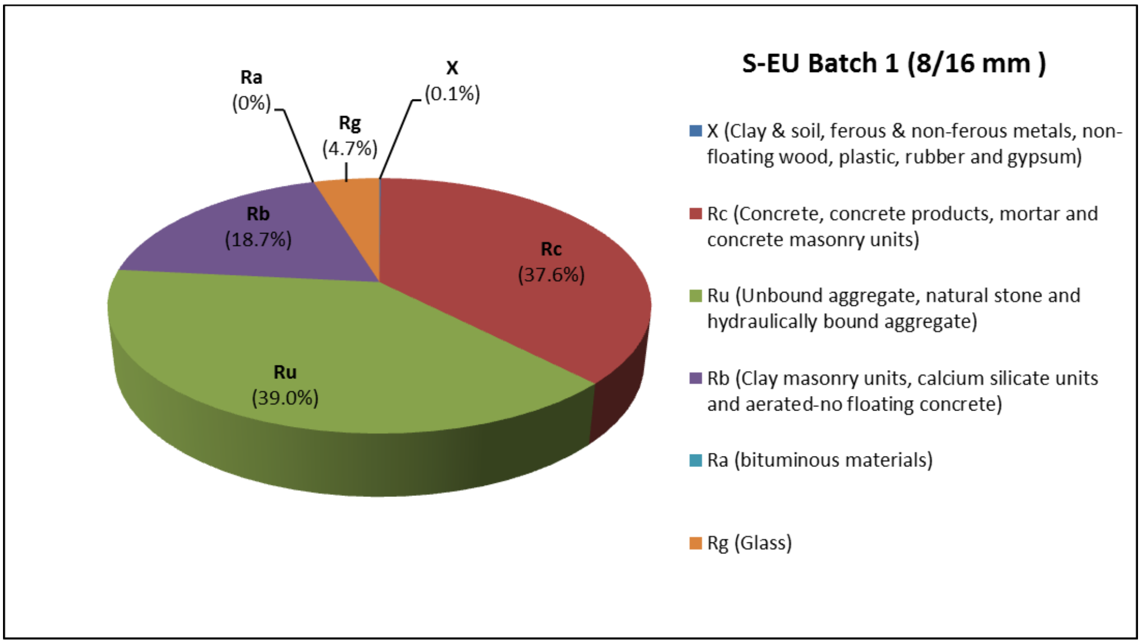

Figure 15: Constituent classification of 8/16 mm size fraction – S-EU Batch 1

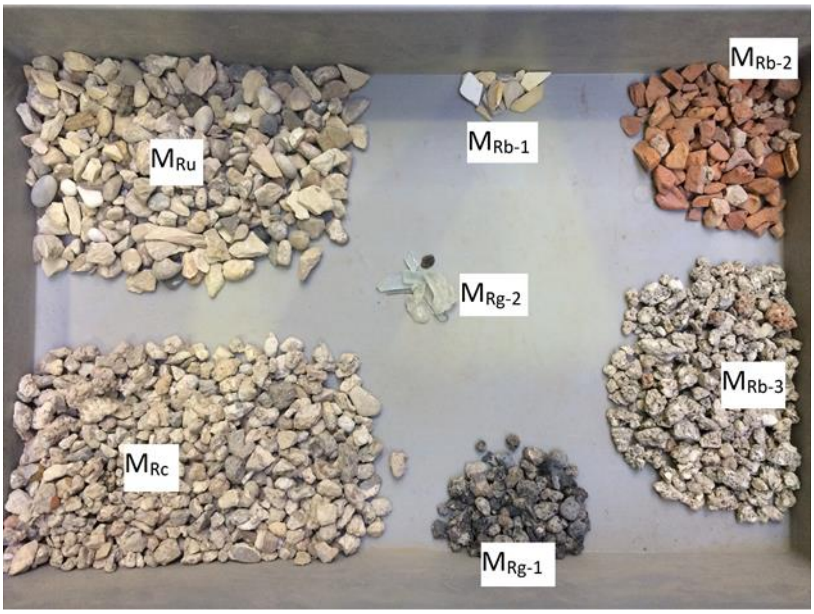

Figure 16: Constituent classification of 8/16 mm size fraction – S-EU Batch 1

Note: The Rb fraction has been divided into three subtypes (Rb-1, Rb-2 and Rb-3) and the Rg fraction into two (Rg-1 and Rg-2). However, in Table 32 the entire content of Rb and Rg fractions is given.

Table 33: Constituent classification of 8/16 mm size fraction – S-EU Batch 2

8/16 mm SIZE FRACTION – S-EU BATCH 2			
Symbol	**Description**	**Amount (kg or ml)**	**Proportion**
M_1	Mass of oven-dried portion	20.288 kg	n/a
V_{FL}	Mass of floating particles in M_1	18 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	0.030 kg	n/a
M_2	Mass of non-floating particles in M_1	20.126 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	2.377 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	0.377 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	2.001 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_3	0.026 kg	n/a
M_{Ra}	Mass of bituminous materials detected in M_3	0.045 kg	n/a
M_{Rg}	Mass of glass detected in M_3	0.062 kg	n/a
FL	Estimated volume of floating particles in M_1	n/a	0.9 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	0.2 %
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	10 %
Ru	Estimated percentage of unbound aggregate, natural stone and hydraulically bound aggregate in M_1	n/a	84 %
Rb	Estimated percentage of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_1	n/a	1 %
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	2 %
Rg	Estimated percentage of glass detected in M_1	n/a	3 %

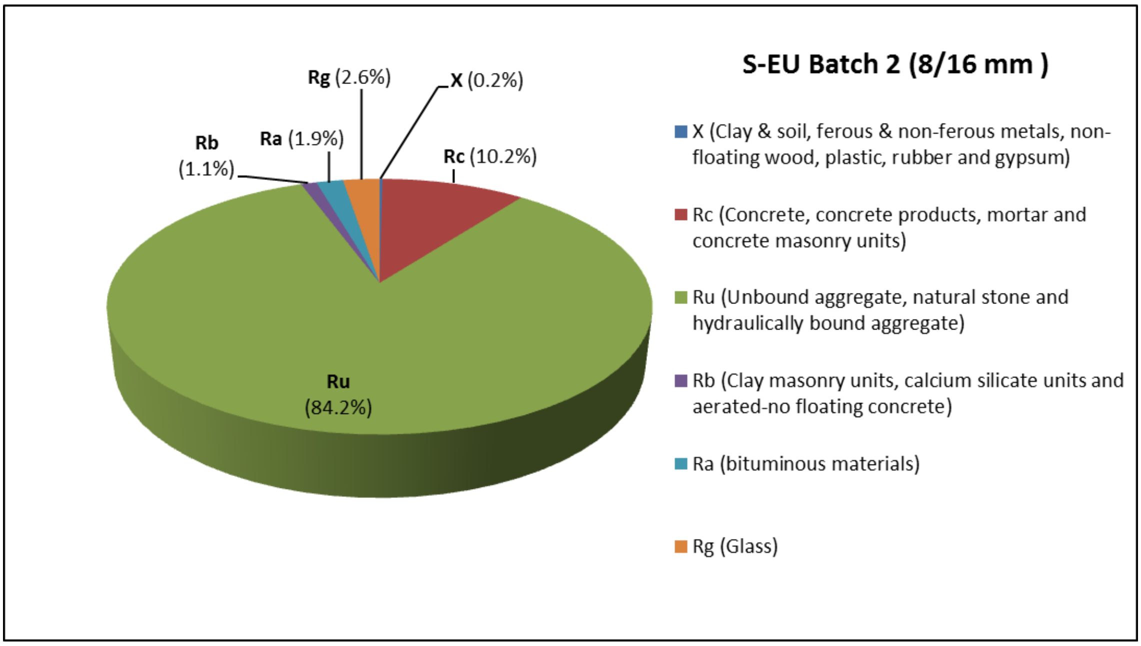

Figure 17: Constituent classification of 8/16 mm size fraction - S-EU Batch 2

Figure 18: Constituent classification of 8/16 mm size fraction - S-EU Batch 2

Note: The Rb fraction has been divided into three subtypes (Rb-1, Rb-2 and Rb-3) and the Rg fraction into two (Rg-1 and Rg-2). However, in Table 33 the entire content of Rb and Rg fractions is given.

Table 34: Constituent classification of 8/16 mm size fraction – S-EU Batch 3

8/16 mm SIZE FRACTION – N-EU BATCH 3			
Symbol	**Description**	**Amount (kg or ml)**	**Proportion**
M_1	Mass of oven-dried portion	20.642 kg	n/a
V_{FL}	Mass of floating particles in M_1	1 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	0.015 kg	n/a
M_2	Mass of non-floating particles in M_1	20.194 kg	n/a
M_3	Mass of test sample obtained from M_2 and analysed	1.683 kg	n/a
M_{Rc}	Mass of concrete, concrete products, mortar and concrete masonry units detected in M_3	1.168 kg	n/a
M_{Ru}	Mass of unbound aggregate, natural stone and hydraulically bound aggregate detected in M_3	0.470 kg	n/a
M_{Rb}	Mass of clay masonry units, calcium silicate units and aerated non-floating concrete detected in M_3	0.044 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	0.006 kg	n/a
FL	Estimated volume of floating particles in M_1		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	0.1 %
Rc	Estimated percentage of concrete, concrete products, mortar and concrete masonry units in M_1	n/a	69 %
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 aerated non-floating concrete detected in M_1	n/a	3 %
Ra	Estimated percentage of bituminous materials detected in M_1	n/a	0 %
Rg	Estimated percentage of glass detected in M_1	n/a	0.3 %

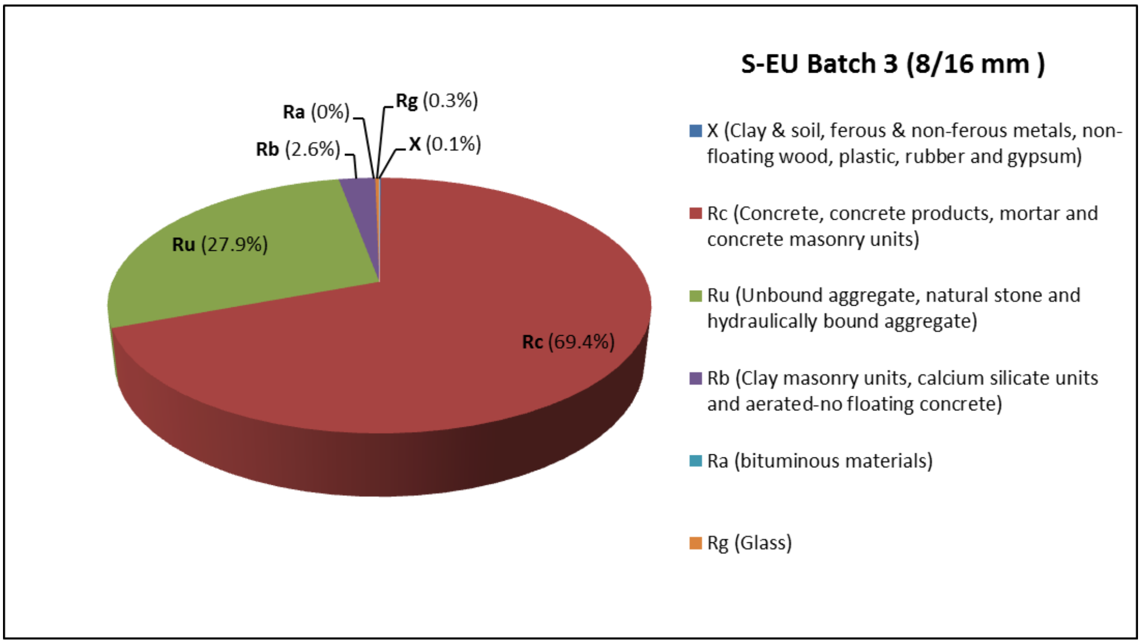

Figure 19: Constituent classification of 8/16 mm size fraction - S-EU Batch 3

Figure 20: Constituent classification of 8/16 mm size fraction - S-EU Batch 3

Note: The Rb fraction has been divided into three subtypes (Rb-1 and Rb-2) and the Rc fraction into two (Rc-1 and Rc-2). However, in Table 34 the entire content of Rb and Rc fractions is given.

Based on the above results, Batch 1 does not comply with the requirements set by EN 206:2013+A1:2016 [22]. One good thing is that Batch 1 does not contain bituminous material and it contains sufficient concrete and unbounded aggregate (Rc + Ru) to be classified as Type B CDW aggregate. But, it has more glass and other materials (Rg + X) than the maximum allowed even for a Type B aggregate. However, it should be mentioned that about two thirds of the glass fraction (Rg), consist of glassy, void rich industry slag, and not real glass (see fraction labelled Rg-1 in Figure 16). If this slag is not considered as Rg, Batch 1 actually succeeds to meet the requirements for Type B CDW aggregates.

In contrast, Batch 2 contains a high proportion of unbound aggregates and concrete materials (Ru + Rc), touching the limit for Type A CDW aggregates and easily managing the limit for Type B CDW aggregates. Also clay masonry materials (Rb) and bituminous materials (Ra) are well below the limit for Type B. However, the high glass content of 2.6% by mass is above the Type B limit of 2%. Thus, Batch 2 also fails to fulfil the requirements for use as CDW aggregate according to the present standard. However, also in this case, it should be mentioned that around two thirds of the glass fraction (Rg) consist of glassy, void rich industry slag, and not real glass (see fraction labelled Rg-1 in Figure 18). If the slag is not counted as Rg, Batch 1 succeeds to meet the requirements for Type B CDW aggregates.

Finally, Batch 3 was the most homogenous batch investigated and meets the requirements set up for Type A CDW aggregates, with a total proportion of concrete material and unbounded aggregates (Rc+Ru) at 97%. The remaining part is basically made of masonry unit materials (2.6%) and glass (0.3%), which both are below limits required for Type A.

4.2.4 Water Absorption and Particle Density

The water absorption and density (apparent, oven dried and saturated surface dry) values of all size fractions (0/2 mm, 2/8 mm and 8/16 mm) of Batches 1 to 3 are shown in Table 35.

Table 35: Water absorption, apparent, oven-dried and saturated surface dry density values of S-EU Batches 1, 2 and 3

Batch	Property*	Size Fraction		
		0/2 mm	2/8 mm	8/16 mm
1	WA_{24} (% by mass)	4.0	8.1	7.7
	ρ_a (kg/m^3)	2640	2680	2530
	ρ_{rd} (kg/m^3)	2390	2200	2120
	ρ_{ssd} (kg/m^3)	2480	2380	2280
2	WA_{24} (% by mass)	0.1	1.6	1.5
	ρ_a (kg/m^3)	2680	2810	2790

	ρ_{rd} (kg/m^3)	2670	2690	2680
	ρ_{ssd} (kg/m^3)	2670	2730	2720
3	WA_{24} (% by mass)	5.7	9.0	6.3
	ρ_a (kg/m^3)	2670	2770	2710
	ρ_{rd} (kg/m^3)	2320	2210	2310
	ρ_{ssd} (kg/m^3)	2450	2410	2460

* WA_{24} = water absorption after 24 hours, ρ_a = apparent density, ρ_{rd} = oven-dried density, ρ_{ssd} = water saturated surface dry density

Unexpectedly low water absorption values (% by mass) were recorded for all size-fractions from Batch 2. Actually, the values were more in line with those of virgin aggregates [27]. Since Batch 2 contains almost 85% unbounded aggregate and only minor amounts of concrete, bricks and other material, the measured values make sense. However, the values of Batch 1 and 3 were higher and more in the range expected from CDW aggregates [24], [25], [26]. These Batches both contained more concrete, bricks and other materials, why it is logical that the water absorption values are in the range they are.

The water absorption is for all three batches a bit higher for the 2/8 mm fraction compared to the 8/16 fraction, which can be explained by the method used. One step in the laboratory procedure is to wipe the aggregates surface dry with a cloth, before weighing and registration of "water saturated surface dry" mass, an operation that is quite difficult when handling aggregate grains as small as 2 mm. Because of these difficulties, the method is actually intended only for aggregates > 4 mm. When wiping the 2/8 mm fraction there is a risk of losing some material to the cloth, in the end resulting in a "measured" water absorption that is slightly higher than the "real".

Finally, when it comes to the apparent density, results are in the range of normal virgin aggregates from crushed rock, gravel and sand. These are typically in the range 2600-2800 kg/m^3, but can be as high as 3000 kg/m^3 for mafic aggregates like diabase, amphibolite and gabbro.

4.2.5 Water-Soluble Chloride Content (0/2 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 Batches 1 to 3 is shown in Table 36.

Table 36: Water-soluble chloride content of 0/2 mm, 2/8 mm and 8/16 mm size fractions – S-EU Batches 1 to 3

Test Method	Batch no	Unit	Size Fraction		
			0/2 mm	2/8 mm	8/16 mm
Ion Chromatography	1	wt%	0.003	0.003	0.003
	2	wt%	<0.001	<0.001	<0.001
	3	wt%	0.003	0.001	0.007

As shown in Table 36, all tested mineral fractions of all S-EU 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.

4.2.6 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 Batches 1 to 3 is shown in Table 37 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 37: Water-soluble sulfate content of 0/2 mm, 2/8 mm and 8/16 mm size fractions – S-EU Batches 1 to 3

Batch no	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
1	0.4	0.3	0.2	0.2	0.1	0.1
2	0.004	0.003	0.005	0.004	0.003	0.002
3	0.05	0.04	0.04	0.03	0.007	0.006

Note
Water-soluble sulfate values are given in terms of SO_3 and SO_4

The water-soluble sulfate content (by mass of aggregate) of all size fractions in Batch 2 and 3 are well below the 0.2% by mass limit set by EN 12620:2002+A1:2008 [29] for use in structural concrete. The coarse size fractions of Batch 1 are at that limit or just below, whereas the fine size fraction (0/2 mm) of Batch 1 is well above.

4.2.7 Slump Test

Recycled aggregate typically contains significant levels of Rc particles. These particles create more friction due to their rough surface texture and irregular shape which significantly reduces the workability of concrete. Consequently, higher levels of cement paste and vibration energy are required to compact concrete which contains high replacement levels of recycled aggregate [1], [2], [30], [31], [32].

Higher water absorption values of recycled aggregate compared to virgin aggregate is another factor that negatively affects workability. Typically, recycled aggregate concrete requires 5-10% more free water than virgin aggregate concrete in order to maintain the same workability [2] [33], [34].

The workability (slump values) of S-EU Mixes 1, 2 and 3, at 15 and 30 minutes from the start of mixing the raw materials with water, are shown in Table 38 below.

Table 38: Slump test values at 15 and 30 mins for Mixes 1, 2 and 3 containing 100% S-EU recycled aggregate (Batches 1, 2 and 3)

Mix no	Recycled Aggregate Batch no	Time (min)	Slump Value (mm)
1	1	15	30
		30	60
2	2	15	70
		30	65
3	3	15	75
		30	55

Based on the above results, high and stable workability values were obtained for all three mixes at both times measured after mixing, corresponding to S2 consistency class. The exception was Mix 1 that at the first measurement was very stiff corresponding to S1 class, but was actually improved after 30 minutes, reaching S2 consistency class.

4.2.8 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. Clearly, the higher the replacement level of virgin aggregate by recycled aggregate, the lower the fresh density of concrete.

Fresh density values of S-EU Mixes 1, 2 and 3 are shown in Table 39 below.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

Table 39: Fresh density values of Mixes 1, 2 & 3 containing 100% S-EU aggregate (Batches 1, 2 & 3)

Mix no	Volume (m^3)	Mass (kg)	Fresh Density (kg/m^3)
1	0.008	16.727	2090
2	0.008	18.755	2340
3	0.0059	12.691	2150

Based on the above results, the fresh density of Mix 2 (2344 kg/m^3) is in the range often assumed for normal concrete mixes containing 100% crushed or uncrushed virgin aggregate (2300-2400 kg/m^3), which is logical considering that Batch 2 contains almost 85% by mass unbound aggregate/stone. However, the density of Batch 1 and 3 are lower, reflecting the higher amounts of constituents other than stone/unbounded aggregates (concrete, masonry units, glass, etc.).

4.2.9 Hardened Concrete Density

Hardened concrete density values of S-EU Mixes 1, 2 and 3 are shown in Table 40 below.

Table 40: Hardened density values of Mixes 1, 2 & 3 containing 100% S-EU aggregate (Batches 1, 2 & 3)

Mix no	Age (days)	Cube no	Water saturated			
			Mass (g)	Density (kg/m^3)	Average Density (kg/m^3)	Std. dev. (±kg/m^3)
1	1	1	2134	2130	2130	< 10
		2	2114	2140		
		3	2109	2130		
	7	1	2166	2170	2160	10
		2	2144	2140		
		3	2159	2160		
	28	1	2179	2140	2150	20
		2	2129	2130		
		3	2194	2170		
2	1	1	2399	2400	2410	10
		2	2422	2420		
		3	2408	2410		
	7	1	2415	2420	2420	30
		2	2395	2400		
		3	2449	2450		

	28	1	2396	2400	2410	10
		2	2436	2410		
		3	2410	2410		
3	1	1	2221	2210	2210	10
		2	2262	2230		
		3	2199	2200		
	7	1	2244	2160	2190	30
		2	2233	2210		
		3	2233	2210		
	28	1	2187	2190	2190	< 10
		2	2255	2190		
		3	2224	2180		

As expected, significant variation in the hardened density (water saturated) of Mixes 1, 2 and 3 is observed. Based on the above table the 28 days hardened density ranges between 2150 kg/m^3 (Mix 1) and 2410 kg/m^3 (Mix 2). These results are in line with the ones obtained for fresh density.

4.2.10 Compressive Strength

Compressive strength values of S-EU Mixes 1, 2 and 3 are shown in Table 41 and Figure 21.

Table 41: Compressive strength values of Mixes 1, 2 & 3 containing 100% S-EU recycled aggregate (Batches 1, 2 & 3)

Mix no	Age (days)	Cube no	Mass (g)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Standard Deviation (±MPa)
1	1	1	2134	11.8	12.0	0.2
		2	2114	12.2		
		3	2109	11.9		
	7	1	2166	26.9	27.5	0.6
		2	2144	28.0		
		3	2159	27.8		
	28	1	2179	33.5	34.5	1.0
		2	2129	34.6		
		3	2194	35.4		
2	1	1	2399	20.1	19.5	0.5
		2	2422	19.2		
		3	2408	19.1		
	7	1	2415	40.3	40.5	0.2
		2	2395	40.2		
		3	2449	40.6		
	28	1	2396	47.6	47.5	0.1
		2	2436	47.6		
		3	2410	47.7		
3	1	1	2221	21.3	21.0	0.2
		2	2262	21.0		
		3	2199	21.0		
	7	1	2244	45.6	46.0	0.8
		2	2233	47.1		
		3	2233	45.4		
	28	1	2187	52.2	53.0	0.7
		2	2255	53.6		
		3	2224	52.7		

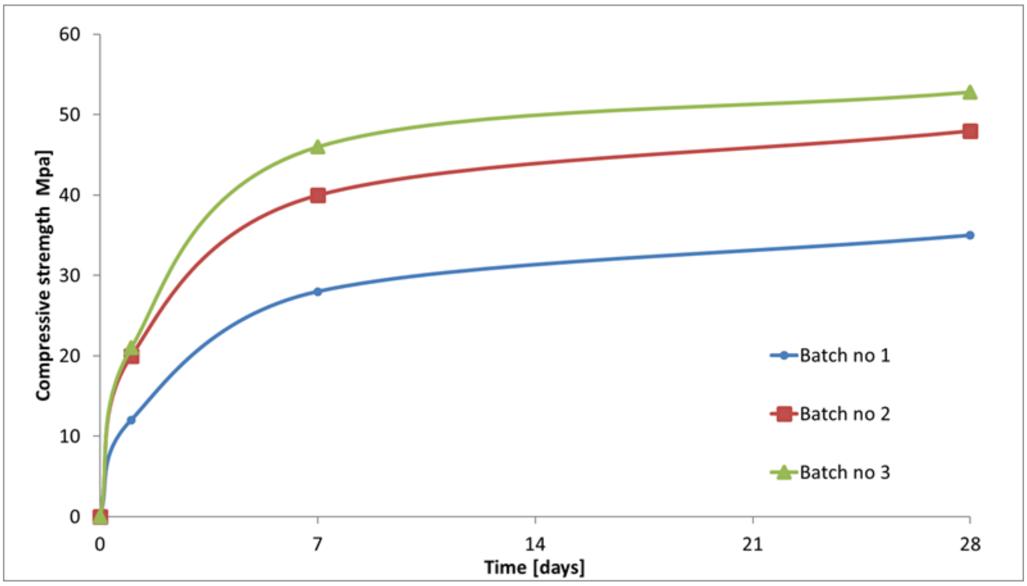

Figure 21 Compressive strength development over time of Mixes 1-3 containing 100% S-EU recycled aggregate - Batches 1-3

Based on the above results, the 28 days compressive strength of Mixes 1, 2 and 3 varies between 34.5 MPa and 53.0 MPa. The above quite significant variation in strength is strongly linked to the Ru + Rc content of coarse aggregate. As the combined amount of Ru and Rc increases, a significant improvement of strength is observed. This is quite evident by the following 28 days compressive strength values of 34.5 MPa, 47.5 MPa and 53.0 MPa of Batches 1, 2 and 3 having Ru + Rc contents of 77%, 94% and 97%, respectively. This could be due to the fact that, although Ru aggregate normally has higher strength than Rc aggregate, the bond between the fresh concrete paste and the aggregate will most likely be stronger due to the more rough surface of the Rc aggregate compared to the clean and smooth Ru surface. Thus there will be less weak interfacial zones between aggregate and paste when the Rc content increases, which is favourable for the concrete strength. Moreover such result is supported by the Type A and B assessment of coarse recycled aggregates in EN 206, according to which it is positive to have high content of Rc and Rc+Ru, and low content of Rb, Ra and X+Rg.

4.3 Lightweight Aggregates for Insulating Mortars

4.3.1 Introduction

To the aim of this study, mortar formulations were designed and developed according to EN 196 -1 [18]. This reference standard gives guidelines for mixing, casting and curing mortars. It also reports on mechanical testing procedures (flexural and compressive strength). According to this standard, the proportions by mass for mortar preparation include: one part of cement, three parts of CEN standard sand (a natural sand with a minumum silica content of 98%, consisting in rounded particles with a specific particle size distribution) and half part of water (water/cement ratio 0.50). The first step of the mixing procedure is to add water to cement after which the sand is added. Specific prescriptions in terms of mixing time and mixing speed are also given for mortar preparation.

In this specific study, the materials used for the mortars preparation consist of CEM I 42.5 R, water and - depending on the mix in question - different aggregate typologies (both normal- and light-weight):

- standard sand (SS) 0/2 mm and commercially available;
- natural sand (NS) 0/2 mm from local sources
- recycled sand (RS) 0/2 mm from local sources
- RE^4 mineral fractions (sand recycled from CDW) with size 0/2 mm
- RE^4 lightweight (LW) fractions recycled from CDW such as:
    A. Rigid Plastic (RP) fine fractions (Figure 22a)
    B. Wood and Plastic (WP) fine fractions (Figure 22b).

RP material consists of heterogeneous rigid plastics, it needs to be groud and sieved to become fine fractions suitable as fine aggregate for mortars. WP material is a by-product from CDW processing (without any specific application and currently discarded) whch is suitable as fine aggregate for mortars without any size reduction process.

a) Rigid Plastic fraction

b) Wood&Plastic fraction

Figure 22: Lightweight (Rigid Plastic and Wood&Plastic) fractions used as aggregate in the development of insulating mortars

The approach followed in this study consisted of the following steps:

- Preliminary tests on normal-weight mortars based on SS, NS and RS;
- Investigations on normal-weight mortars using RE^4 mineral fractions (sand), assessment of their suitability and identification of the best performing sand for the next activities;
- Replacement of RE^4 mineral fractions (above selected) with different dosages of RE^4 lightweight fractions (e.g. RP and WP) to produce light-weight mortars, definition of the maximum amount of RP and WP that can be incorporated once the binder (cement, water) is fixed;
- Replication of light-weight mortars formulations using LW materials from two different batches, more specifically:
    a) RP N-EU (from a N-EU recycling plant);
    b) RP S-EU (from a S-EU recycling plant);
    c) WP N-EU (from a N-EU recycling plant);
    d) WP S-EU (from a S-EU recycling plant);
- Assessment of the effect of LW materials variability on the technological performance of mortars, specifically density and corresponding insulation properties but also mechanical ones.

For each tested mortar the dosage of cement (450 g), water (225 g) and total amount of aggregate (1350 g) were kept fixed. In addition, depending on the specific aggregates used for each mortar, additional water was added to allow for the aggregate saturation (taking into consideration water absorption and moisture content). No additives were used for mortars preparation. The dosages above mentioned were enough for the preparation of 3 prisms (40 mm x 40 mm x 160 mm) used to assess hardened properties (e.g. density) and hygrothermal performance (e.g. thermal conductivity) of the produced mortars.

4.3.2 Grading, Water Absorption & Particle Density of Wood&Plastic and Rigid Plastic Fractions

Among other properties, differences in physical properties (e.g. grading size distribution, water absorption and particle density) of aggregates used for mortars might affect the performance of the final product (e.g. quality of the mix, workability, density, mechanical and thermal behaviour).

A comparison of the size distribution of RP fractions, from N-EU and S-EU sources respectively, is shown in Figure 23. It can be observed that in both cases the material is below 4 mm but grading distributions are different, possibly due to varying composition of constituent materials (plastic heterogeneity might result in different size distribution in the grinding process).

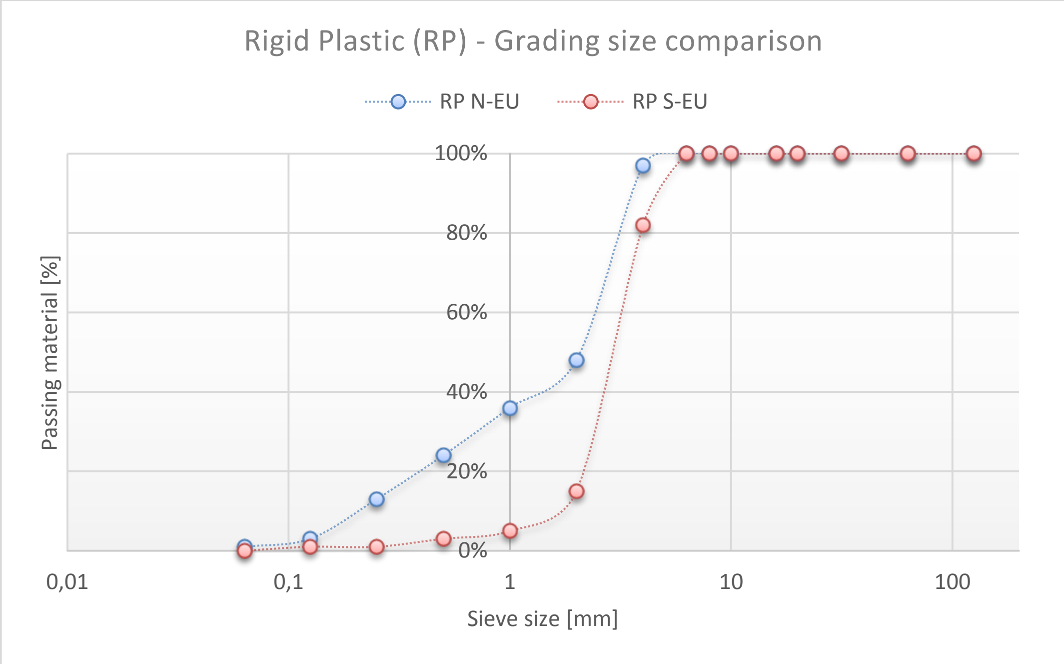

Figure 23: Grading size distribution of Rigid Plastic (RP) from N-EU and S-EU (EN 933-1)

A comparison of size distribution for WP fractions, from N-EU and S-EU sources respectively, is shown in Figure 24. It can be observed that in both cases the material is approximately below 4 mm but grading distributions are not similar, possibly due to variations in the composition of constituent materials (wood and plastic heterogeneity may result in different size distributions).

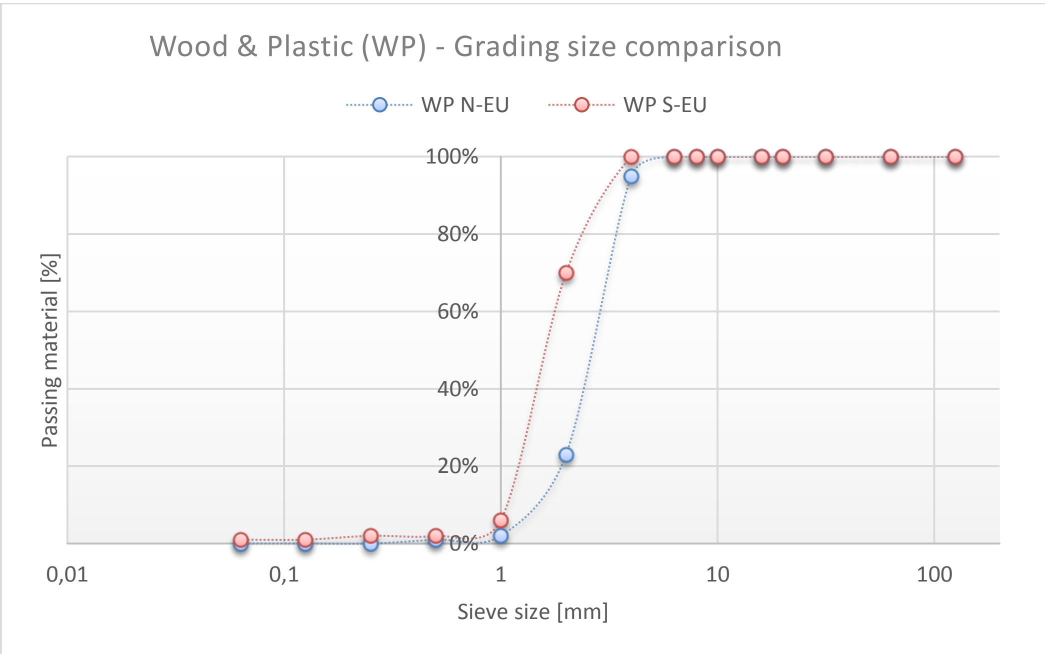

Figure 24: Grading size distribution of Wood and Plastic (WP) from N-EU and S-EU (EN 933-1)

Table 42 reports a comparison of densities and water absorption of RP and WP fractions, from N-EU and S-EU sources respectively. It can be observed that there are no significant differences in terms of density and water absorption among RP from N-EU and S-EU. Consequently, it can be reasonably assumed that the average composition of plastics from CDW is similar, regardless of the source (N-EU or S-EU). Concerning WP, comparing N-EU and S-EU materials, a slight difference in terms of density can be observed possibly due to the intrinsic heterogeneity of this mixed material (wood/plastic relative percentage). On the other hand, water absorption is comparable in both cases. Irrespective of the source, WP has a much lower density and higher water absorption compared to RP. These differences, clearly related to a different composition of the investigated materials, might affect the properties of the mortars prepared with them. It is expected that lower density of the constituent materials results in lower density of the mortar and, in turn, a higher insulating performance.

Table 42: Density and water absorption values for Rigid Plastic (RP) and Wood and Plastic (WP) from N-EU and S-EU (EN 1097-6)

Property		Unit	N-EU	S-EU
Rigid Plastic (RP) fine fractions used as LW aggregate for mortars				
Particle density on a saturated and surface-dried basis	ρ_{ssd}	kg/m³	1156.6	1130.4
Water absorption at 24h	WA_{24h}	%	9.9	7.2
Wood and Plastic (WP) fine fractions used as LW aggregate for mortars				
Particle density on a saturated and surface-dried basis	ρ_{ssd}	kg/m³	650.5	734.1
Water absorption at 24h	WA_{24h}	%	98.4	107.1

Another physical property of the aggregate which was taken into consideration for the mortar preparation, was its moisture content. In order to evaluate the moisture content, RP and WP aggregates were oven dried at 80°C to constant mass. RP showed a moisture content below 1% by mass, irrespective of the source (N-EU or S-EU) or storage conditions, which is mainly related to the high hydrophobic nature of rigid plastics. WP when stored in laboratory conditions showed a moisture content around 30% wt, irrespective of the source (N-EU or S-EU). The highly hydrophilic nature of WP, mainly related to the presence of wood and expanded polystyrene with high tendency to absorb water, has to be duly considered before the mix preparation.

4.3.3 Mortars based on normal-weight aggregates (sand)

Reference tests on sand based mortars were carried out as shown in Figure 25. Table 43 reports the mortar mix recipes for the different types of sand: standard sand (SS), natural sand (NS), recycled sand (RS) and RE[4] mineral fractions (recycled sand) from S-EU (density 2280.0 kg/m^3) and N-EU (density 2270.0 kg/m^3).

Table 43: Details of mortar mix recipes

Mortar ID	Aggregate			Cement		w/c	a/c
	Typology	wt [%]	Dosage [g]	Class	Dosage [g]		
Mix 1_SS	Standard sand	100 %	1350	CEM I 42.5 R	450	0.5	3
Mix 2_NS	Natural sand	100 %	1350	CEM I 42.5 R	450	0.5	3
Mix 3_RS	Recycled sand	100 %	1350	CEM I 42.5 R	450	0.5	3
Mix 4_MF/S-EU	RE[4] recycled sand S-EU	100 %	1350	CEM I 42.5 R	450	0.5	3
Mix 5_MF/N-EU	RE[4] recycled sand N-EU	100 %	1350	CEM I 42.5 R	450	0.5	3

Fresh, hardened and hygrothermal properties of sand based mortars are shown in Table 44 and Table 45. Although the use of RE[4] recycled sand in mortars slightly reduces their workability and mechanical performance compared to standard and natural sand, they are still suitable for making insulating mortars. Comparing the behaviour of these recycled sands, S-EU sand required additional water to reach similar workability as N-EU sand and resulted in reduced mechanical performance. Based on these outcomes, mineral fractions from N-EU source was selected for the next experimental activities, where this sand was tested in combination with RP and WP aggregates aiming at the development of lightweight mortars.

Table 44: Fresh and hardened properties of sand-based mortars

Mortar ID	Fresh mortar		Mechanical properties of hardened mortar								
	Slump [mm]	Density ρ_m [kg/m^3]	Density $\rho_{m, dry}$ [kg/m^3]			Flexural strength R_f [MPa]			Compressive strength R_c [MPa]		
			7 dd	14 dd	28 dd	7 dd	14 dd	28 dd	7 dd	14 dd	28 dd
Mix 1_SS	160.0	2212.2	2203.1	2097.7	2072.3	1.6	1.3	1.8	27.9	34.4	33.3
Mix 2_NS	180.0	2134.1	1996.1	2029.3	1951.2	1.4	1.7	1.7	30.4	39.9	38.1
Mix 3_RS	190.0	2118.5	1955.1	1949.2	1914.1	1.1	1.4	1.7	29.2	31.9	31.9
Mix 4_MF/S-EU	150.0	1964.2	1843.8	1796.9	1761.7	0.8	1.3	1.1	20.1	23.2	23.1
Mix 5_MF/N-EU	150.0	2150.4	2050.8	2027.3	1998.1	1.2	1.5	1.6	26.7	30.2	28.9

Table 45: Hygrothermal properties of sand-based mortars

Mortar ID	Hygrothermal properties of hardened mortar				
	Density $\rho_{m, dry}$ [kg/m^3]	Design thermal conductivity λ [W/m·K]	Specific heat capacity c_p [J/kg·K]	Water vapour resisance factor	
				μ (dry)	μ (wet)
	28 dd	28 dd	28 dd	28 dd	
Mix 1_SS	2072.3	1.20	-	-	-
Mix 2_NS	1951.2	1.11	-	-	-
Mix 3_RS	1914.1	1.08	-	-	-
Mix 4_MF/S-EU	1761.7	0.98	1000	10	6
Mix 5_MF/N-EU	1998.1	1.14	-	-	-

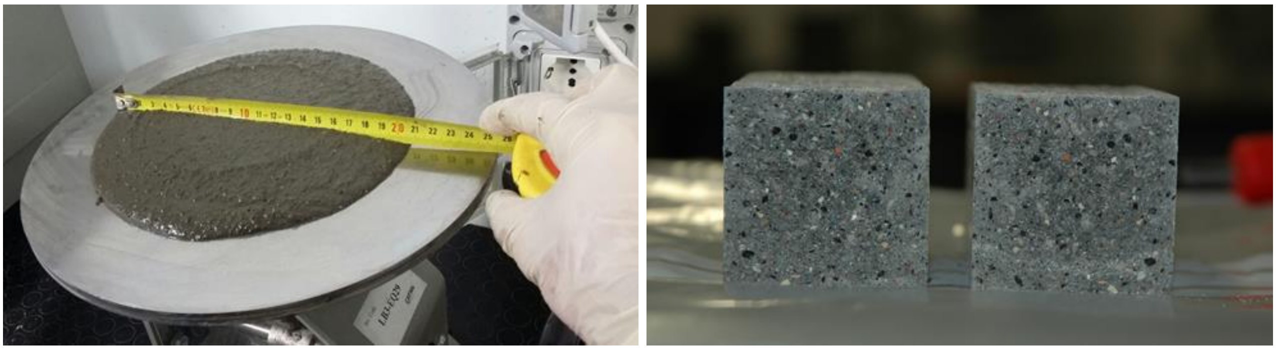

Figure 25: Mortars based on RE^4 mineral fractions (recycled sand).

4.3.4 Mortars based on N-EU lightweight aggregates

Tests on mortars were carried out combining RE^4 mineral fraction (from N-EU, selected in the previous step) with Rigid Plastic (RP) and Wood and Plastic (WP) lightweight (LW) aggregates. The aim was the reduction of the mortar density through the incorporation of different dosages of LW aggregate. Table 46: Details of mix recipes for mortars with gives mix recipes for the mortars based on RP, in which 15%, 20%, 30% and 40% (weight percentages) of the sand was replaced by RP.

Table 47 gives mix recipes for the mortars based on WP, in which 15%, 20% and 30% (weight percentages) of the sand was replaced by WP.

Table 46: Details of mix recipes for mortars with RP (N-EU) based mortars

Mortar ID	Aggregate			Cement		w/c	a/c
	Typology	wt [%]	Dosage [g]	Class	Dosage [g]		
Mix 6_15%RP	RP/N-EU, MF/N-EU	15 %, 85%	1350	CEM I 42.5 R	450	0.5	3
Mix 7_20%RP	RP/N-EU, MF/N-EU	20%, 80%	1350	CEM I 42.5 R	450	0.5	3
Mix 8_30%RP	RP/N-EU, MF/N-EU	30%, 70%	1350	CEM I 42.5 R	450	0.5	3
Mix 9_40%RP	RP/N-EU, MF/N-EU	40%, 60%	1350	CEM I 42.5 R	450	0.5	3

Table 47: Details of mix recipes for mortars with WP (N-EU) based mortars

Mortar ID	Aggregate			Cement		w/c	a/c
	Typology	wt [%]	Dosage [g]	Class	Dosage [g]		
Mix 10_15%WP	WP/N-EU, MF/N-EU	15%, 85%	1350	CEM I 42.5 R	450	0.5	3
Mix 11_20%WP	WP/N-EU, MF/N-EU	20%, 80%	1350	CEM I 42.5 R	450	0.5	3
Mix 12_30%WP	WP/N-EU, MF/N-EU	30%, 70%	1350	CEM I 42.5 R	450	0.5	3

The fresh, hardened and hygrothermal properties of mortars made using either RP or WP aggregates from N-EU source are given in Table 48, Table 49, Table 50 and Table 51. When RP aggregate is used to replace recycled sand it leads to a reduction in density (< 1860 kg/m^3) and mechanical performance of the final product. Moreover, the higher the RP amount is, the lower the mortar workability. Based on this, the maximum dosage of RP that can be incorporated with this binder is around 30 % by weight. With this dosage, a good compromise between workability and mechanical performance is achieved. As regards WP aggregate, when used to replace recycled sand it results in a significant density reduction (< 1300 kg/m^3) and a decreased mechanical performance. The workability is similar in all the tests carried out. The main limiting factor for WP aggregate is its high volume (its low density corresponds to a high aggregate volume, which is difficult to incorporate in the fixed binder mix). In this case, similarly to the procedure applied for concretes, a volumetric approach should be followed instead of a mass approach. Overall, the maximum dosage of WP that can be incorporated in this fixed mortar mix is around 15 % by weight. With this dosage, acceptable mechanical performance are achieved and the its volume can be managed. Moving to thermal conductivity, from RP N-EU based mortars it ranges from 1.04-0.76 W/mK, depending on the density which ranges from 1857.4 kg/m^3 (15% RP) up to 1447.3 (40% RP). With respect to thermal conductivity of WP N-EU based mortars it ranges from 0.65-0.40 W/mK, depending on the density which ranges from 1289.1 kg/m^3 (15% WP) up to 941.4 kg/m^3 (30% WP).

Table 48: Fresh and hardened properties of RP (N-EU) based mortars

Mortar ID	Fresh mortar		Mechanical properties of hardened mortar								
	Slump [mm]	Density ρ_m [kg/m^3]	Density $\rho_{m, dry}$ [kg/m^3]			Flexural strength R_f [MPa]			Compressive strength R_c [MPa]		
			7 dd	14 dd	28 dd	7 dd	14 dd	28 dd	7 dd	14 dd	28 dd
Mix 6_15%RP	230.0	2039.7	1910.2	1904.3	1857.4	0.9	0.9	1.2	15.9	19.6	22.0
Mix 7_20%RP	195.0	2038.4	1828.1	1853.5	1812.5	0.9	0.8	1.0	14.7	18.6	20.4
Mix 8_30%RP	160.0	1779.3	1615.2	1672.7	1638.7	0.7	0.8	0.9	11.4	12.3	12.5
Mix 9_40%RP	135.0	1589.2	1427.7	1403.5	1447.3	0.6	0.7	0.7	7.9	9.9	10.9

Table 49: Hygrothermal properties of RP (N-EU) based mortars

Mortar ID	Hygrothermal properties of hardened mortar				
	Density $\rho_{m, dry}$ [kg/m^3]	Design thermal conductivity λ [W/m·K]	Specific heat capacity c_p [J/kg·K]	Water vapour resistance factor	
				μ (dry)	μ (wet)
	28 dd	28 dd	28 dd	28 dd	
Mix 6_15%RP	1857.4	1.04	-	-	-
Mix 7_20%RP	1812.5	1.01	-	-	-
Mix 8_30%RP	1638.7	0.89	1000	10	6
Mix 9_40%RP	1447.3	0.76	1000	10	6

Table 50: Fresh and hardened properties of WP (N-EU) based mortars

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Mortar ID	Fresh mortar		Mechanical properties of hardened mortar								
	Slump [mm]	Density ρ_m [kg/m^3]	Density $\rho_{m, dry}$ [kg/m^3]			Flexural strength R_f [MPa]			Compressive strength R_c [MPa]		
			7 dd	14 dd	28 dd	7 dd	14 dd	28 dd	7 dd	14 dd	28 dd
Mix 10_15%WP	160.0	1551.8	1308.6	1214.8	1289.1	0.3	-	0.3	3.3	3.6	3.3
Mix 11_20%WP	160.0	1291.0	1060.5	1021.9	1015.6	0.7	-	0.2	1.3	-	1.6
Mix 12_30%WP	165.0	1281.3	1000.0	961.9	941.4	-	-	0.1	1.5	1.2	1.6

Table 51: Hygrothermal properties of WP (N-EU) based mortars

Mortar ID	Hygrothermal properties of hardened mortar				
	Density $\rho_{m, dry}$ [kg/m^3]	Design thermal conductivity λ [W/m·K]	Specific heat capacity c_p [J/kg·K]	Water vapour resistance factor	
				μ (dry)	μ (wet)
	28 dd	28 dd	28 dd	28 dd	
Mix 10_15%WP	1289.1	0.65	1000	10	6
Mix 11_20%WP	1015.6	0.46	1000	10	6
Mix 12_30%WP	941.4	0.40	1000	10	6

Figure 26: Mortars based on RE[4] lightweight fractions, Rigid Plastic and Wood and Plastic from N-EU.

4.3.5 Mortars based on S-EU lightweight aggregates

Tests on mortars with Rigid Plastic (RP) and Wood and Plastic (WP) aggregates (from N-EU source) were replicated but using equivalent materials from S-EU source. The aim of this comparative study was to assess the effect of LW aggregates variability on the technical performance of mortars. Table 52 reports the design parameters of RP based mortars while Table 53 reports WP based mortars, in both cases the percentage of lightweight aggregate were 15%, 20% and 30%.

Table 52: Design parameters of RP (S-EU) based mortars

Mortar ID	Aggregate			Cement		w/c	a/c
	Typology	wt [%]	Dosage [g]	Class	Dosage [g]		
Mix 13_15%RP	RP/S-EU, MF/N-EU	15%, 85%	1350	CEM I 42.5 R	450	0.5	3
Mix 14_20%RP	RP/S-EU, MF/N-EU	20%, 80%	1350	CEM I 42.5 R	450	0.5	3
Mix 15_30%RP	RP/S-EU, MF/N-EU	30%, 70%	1350	CEM I 42.5 R	450	0.5	3

Table 53: Design parameters of WP (S-EU) based mortars

Mortar ID	Aggregate			Cement		w/c	a/c
	Typology	wt [%]	Dosage [g]	Class	Dosage [g]		
Mix 16_15%WP	WP/S-EU, MF/N-EU	15%, 85%	1350	CEM I 42.5 R	450	0.5	3
Mix 17_20%WP	WP/S-EU, MF/N-EU	20%, 80%	1350	CEM I 42.5 R	450	0.5	3
Mix 18_30%WP	WP/S-EU, MF/N-EU	30%, 70%	1350	CEM I 42.5 R	450	0.5	3

The fresh, hardened and hygrothermal properties of mortars with RP and WP aggregates from S-EU source are given in Table 53, Table 53 Table 536 and Table 57. Similarly to RP from N-EU also in the case of RP S-EU a reduction of density was observed by replacing sand with the lightweight aggregate. The density in this case is slightly reduced (< 1735 kg/m^3) and, in turn, the mechanical performance of the final product. On the other side the density reduction results in lower insulating performance with ranges from 0.96-0.81 W/mK, depending on the density which ranges from 1734.0 kg/m^3 (15% RP) up to 1527.0 kg/m^3 (30% RP). With respect to WP also in the case of WP S-EU a reduction of density was observed by replacing sand with the lightweight aggregate. The density in this case is slightly higher (< 1431.6 W/mK) and, in turn, the mechanical performance of the final product (except for 30% replacement which, as observed, it difficult to manage due its high volume). With respect to insulating performance these ranges from 0.68-0.35 W/mK, depending on the density which ranges from 1331.6 kg/m^3 (15% WP) up to 865.6 kg/m^3 (30% WP).

Table 54: Fresh and hardened properties of RP (S-EU) based mortars

Mortar ID	**Fresh mortar**		**Mechanical properties of hardened mortar**								
	Slump [mm]	Density ρ_m [kg/m^3]	Density $\rho_{m, dry}$ [kg/m^3]			Flexural strength R_f [MPa]			Compressive strength R_c [MPa]		
			7 dd	14 dd	28 dd	7 dd	14 dd	28 dd	7 dd	14 dd	28 dd
Mix 13_15%RP	210.0	2008.5	1853.5	1734.4	1734.0	1.0	0.8	0.9	12.5	16.4	18.8
Mix 14_20%RP	220.0	1875.7	1734.4	1718.8	1703.1	0.8	0.8	0.9	12.4	13.5	13.8
Mix 15_30%RP	175.0	1716.8	1554.7	1554.7	1527.3	0.6	0.6	0.7	7.3	8.6	8.7

Table 55: Hygrothermal properties of RP (S-EU) based mortars

Mortar ID	Hygrothermal properties of hardened mortar				
	Density $\rho_{m,\,dry}$ [kg/m^3]	Design thermal conductivity λ [W/m·K]	Specific heat capacity c_p [J/kg·K]	Water vapour resistance factor μ (dry)	μ (wet)
	28 dd	28 dd	28 dd	28 dd	
Mix 13_15%RP	1734.0	0.96	1000	10	6
Mix 14_20%RP	1703.1	0.94	1000	10	6
Mix 15_30%RP	1527.3	0.81	1000	10	6

Table 56: Fresh and hardened properties of WP (S-EU) based mortars

Mortar ID	Fresh mortar		Mechanical properties of hardened mortar								
	Slump [mm]	Density ρ_m [kg/m^3]	Density $\rho_{m,\,dry}$ [kg/m^3]			Flexural strength R_f [MPa]			Compressive strength R_c [MPa]		
			7 dd	14 dd	28 dd	7 dd	14 dd	28 dd	7 dd	14 dd	28 dd
Mix 16_15%WP	167.5	1623.7	1353.5	1380.9	1331.6	0.4	-	0.4	4.9	5.1	4.3
Mix 17_20%WP	150.0	1414.7	1107.4	1113.3	1072.3	0.2	-	0.2	2.1	2.0	2.2
Mix 18_30%WP	155.0	1121.7	955.1	791.0	865.6	-	0.4	0.3	-	-	0.7

Table 57: Hygrothermal properties of WP (S-EU) based mortars

Mortar ID	Hygrothermal properties of hardened mortar				
	Density $\rho_{m, dry}$ [kg/m^3]	Design thermal conductivity λ [W/m·K]	Specific heat capacity c_p [J/kg·K]	Water vapour resistance factor μ (dry)	μ (wet)
	28 dd	28 dd	28 dd	28 dd	
Mix 16_15%WP	1331.6	0.68	1000	10	6
Mix 17_20%WP	1072.3	0.50	1000	10	6
Mix 18_30%WP	865.6	0.35	1000	10	6

Figure 27 Mortars based on RE[4] lightweight fractions, Rigid Plastic and Wood and Plastic from S-EU.

4.4 Lightweight Flakes for Insulating Panels

4.4.1 Introduction

The variability of lightweight flakes for insulating panels is studied on wood flakes, considering, as above mentioned (par. 3.2), two different batches coming from two batches from recycling plants in N-EU (Germany and Norway) and S-EU (France), respectively. The two batches were in very different physical state when received, as it can be seen in Figure 28.

a) S-EU wood scraps

b) N-EU wood scraps

Figure 28: Wood scraps from a) S-EU and b) N-EU recycling centres

The Southern region wood was on arrival almost wet, in big pieces and small quantity (approximately 20 kg). For this reason, it was ground once in CETMA laboratories in a miller with a 20 mm sieve. The resulting material is shown in Figure 29.

Figure 29: Grinded S-EU wood scraps

The variability of the wood is studied with regard to physical variability in terms of variation of density of the produced panels and in thermal properties.

For this reason the material was processed in order to obtain the insulating panels. The process used for this study was not the optimized one, but a first stage process, able to produce 100% wood panels. The steps of the process were:

a. Sieving of the material

b. Soaking of the material
c. Filling of the mould with material and the first compression steps
d. Keeping of the material under pressure and in temperature
e. Cooling to room temperature
f. Demoulding of the panel

4.4.2 Grading –following EN 933-1:2012

For this study, the comparison was made between the 0-4 mm grading class from the southern region,, which was more than 50% in weight of the ground material (as reported in deliverable D4.2) and more suitable for production of insulating panels due to geometric uniformity, and three different grading classes of Northern region material, 0-4 mm sorted by machine; 0 – 4 mm mixed sorted (manually and by machine); 0-8 mm sorted by machine.

The Northern region wood material is characterized by different grading class and less uniformity in shape. Using the material as it arrived, the panel production process failed. For this reason the variability study was carried out on the 0-8 mm sorted by machine material (which correspond to the first useful grading class for which the panel production process worked) and the 0-4 mm grading class. As the material consists of both scraps and fibres (scraps = pieces where all the three dimensions are comparable, fibres = pieces where one dimension is predominant with respect to the other) two different sorting methods were used for the 0 – 4 mm grading class. The first was the automatic sorting method, where the material was sorted by means of a sieving machine and the material remaining in the sieve with a mesh equal or less than 4 mm was collected. The second method was an automatic sorting of the material with the addition of manually sorted fibres from the material resulting from the sieves with bigger meshes.

4.4.3 Water absorption

After the sieving, which is previously described, the soaking step was realized starting from completely dry material in order to evaluate the physical variability of the materials. The different materials were soaked in at least five small batches and the weight of each of batch was recorded during a certain time period (Figure 30). This procedure was carried out to establish the time it took until the water absorption of the different classes of materials under discussion was completed.

Figure 30: Absorption characterisation of 0-4 mm mixed sourced N-EU material

Such data were necessary in order to establish a common minimum time period for the soaking step, as it is essential for the success and optimization of the production process. In Figure 31 the different materials are shown after the soaking step. The weight average increases of the different classes of materials are given in

Table 58 as function of time period for soaking.

a) S-EU wood scraps

b) N-EU wood scraps (0/4 mm sorted by machine)

c) N-EU wood scraps and fibres(0/4 mm mixed siewed)

d) N-EU wood scraps and fibres (0/8 mm sorted by machine)

Figure 31: Different grading classes of Wood scraps and fibres after soaking

Table 58: Absorption values related to soaking time as percentage of increased weight

Material	24h soaking	4 days soaking	5 days soaking	6 days soaking
S-EU wood				
0-4 mm	**260%**	**259%**	**254%**	**259%**
N-EU wood				
0-4 mm sorted by machine	**182%**	**214%**	**209%**	**212%**
0-4 mm mixed sorted	**176%**	**199%**	**209%**	**210%**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723583

0-8 mm sorted by machine	**160%**	**189%**	**198%**	**197%**

The small variations in the stabilized weight after absorption are probably due to small variations in the draining steps, because of very small amounts of water left in the material.

Once soaked, each grading class material was hence moulded at the same process conditions: temperature of 120° C on both upper and lower plates and pressure of 40 bar of the printing press system circuit. The process lasted for 25 hours each time and the cooling step was made at room temperature. The mould was always filled with the same quantity of soaked material (irrespective of the initial dried weight of the material), i.e. 2 kg.

The following figures show examples of the different wood – based panels.

Figure 32: 0-4 mm S-EU wood panel

Figure 33: 0-4 mm sorted by machine N-EU region wood panel

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Figure 34: 0-4 mm mixed sorted N-EU wood panel

Figure 35: 0-8 mm sorted by machine N-EU wood panel

4.4.4 Density – following EN 323:1993 and Hygrothermal Properties – following EN ISO 10456:2007

Densities of produced panels were calculated using the method reported in the EN 323:1993, without cutting the panels in samples, but using the whole panel volume and weight for the calculation.

The hygrothermal properties were calculated by linear interpolation of the achieved values with the reference values reported in **Section 3.2.3.5.**

Table 59: 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

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S-EU wood					
0-4 mm	246.63	< 0.07	1700	<5	<3
N-EU wood					
0-4 mm sorted by machine	310.85	0.0822	1700	7.03	3.81
0-4 mm mixed sorted	317.90	0.0836	1700	7.26	3.90
0-8 mm sorted by machine	323.55	0.0847	1700	7.45	4.01

From the results reported in Table 60 and considering the water absorption behaviour of different grading class materilas, for lightweight flakes for insulating wood- -based panels the following conclusion on physical variability are reported:

- the absorption capability of the two different batches are different. Southern region wood can absorb more water then the Northern region wood. Morever, among the same batch material (Northern region wood), the grading class of the material influences the absorption capability, being the lower grading class capable of an higher absorption of water;
- the density of the panels, therefore the thermal conductivity, is lower in the panels with higher absorption of water, being the wood completely dried during the moulding process.

Considering these conclusions it is recommended that the wood - based panels are realized with wood scraps and fibres with higher absorption capability and lower grading classes.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Mineral Aggregate N-EU

- Good particle size distribution was observed for 0/2 mm and 2/8 mm size fractions of all 4 N-EU batches. However, when it comes to 8/16 mm fraction, the amount of particles less than 8 mm was quite significant and varied between 14.2% (Batch 4) and 23% (Batch 1).

- All four 8/16 mm size fractions (Batches 1 to 4) contained small quantities of Rb (bricks & tiles), Ra (bitumen), Rg (glass) and X (wood, plastic, rubber and gypsum) inferior/defective particles and hence complied with the requirements of EN 206:2013+A1:2016 [23] and BS 8500-2:2015+A1:2016 [24] for use in structural concrete. A notable exception was Batch 1 in which the amount of Ra (bitumen) was 5.6% as opposed to a limit of 5% set by the above standards. Finally, the amount of Rc (concrete & mortar) particles was very low ranging between 3.7% (Batch 4) and 5.4% (Batch 1). Consequently, all 4 N-EU batches contained high levels of good quality natural aggregate.

- Low water absorption values ranging between 1.1% and 1.8% were recorded for all size fractions (0/2 mm, 2/8 mm & 8/16 mm) of N-EU Batches 2, 3 and 4. The water absorption values of Batch 1 were slightly higher and varied between 2.4% (8/16 mm) and 3% (0/2 mm). Taking into account that the water absorption of virgin aggregate typically varies between 0.5% and 1.5%, the above values indicated good quality recycled aggregate.

- Saturated surface dry density values of all size fractions (0/2 mm, 2/8 mm & 8/16 mm) of all N-EU batches were very close to the ones assumed by BRE [29] for either crushed or uncrushed virgin aggregate.

- All tested size fractions (0/2 mm & 8/16 mm) of all N-EU batches contained very low levels of water-soluble chlorides. Consequently, they complied with the requirements of EN 206:2013+A1:2016 [23] for use in structural concrete.

- All tested size fractions (0/2 mm & 8/16 mm) of all N-EU batches contained very low levels of water-soluble sulfates. Consequently, they complied with the requirements of EN 12620:2002+A1:2008 [30] for use in structural concrete.

- High and stable workability values (180 mm to 210 mm at 15 min and 30 min) of OPC concrete made using N-EU Batch 2, 3 and 4 recycled aggregate were recorded. When it comes to OPC concrete made using N-EU Batch 1 recycled aggregate, lower workability values were recorded (110 mm at 15 min and 90 mm at 30 min). However, these were still adequate when it comes to vibrated OPC concrete.

- The fresh density values of OPC concrete made using N-EU Batch 2, 3 and 4 recycled aggregate were very similar (2360-2370 kg/m^3) and within the range assumed by BRE [29] for normal concrete mixes containing 100% crushed or uncrushed virgin aggregate (2300-2400 kg/m^3). On the other hand, the fresh density of OPC concrete made using N-EU Batch 1 recycled aggregate was 2260 kg/m^3. This was lower by approximately 4.5% when compared to the density of mixes made using Batch 2, 3 and 4 recycled aggregate. The above reduction was mainly due to the higher Rc + Rb + Ra content of Batch 1 (14.6% by mass) as opposed to Batch 2 (10.7% by mass), Batch 3 (7.6% by mass) and Batch 4 (6.7% by mass).

- The hardened density values (oven-dried and water saturated) of OPC concrete made using N-EU Batch 2, 3 and 4 recycled aggregate were very similar. The oven-dried density varied between 2230-2250 kg/m^3, whereas the water saturated density varied between 2380-2390 kg/m^3. When it came to OPC concrete made using N-EU Batch 1 recycled aggregate, lower oven-dried (2120 kg/m^3) and water saturated (2270 kg/m^3) hardened density values were recorded. These were in line with the fresh density values obtained for that mix.

- All 4 OPC concrete mixes made using N-EU Batch 1, 2, 3 and 4 recycled aggregate achieved very similar 28-day compressive strength values ranging between 36-37.5 MPa.

- All 4 mixes made using N-EU Batch 1, 2, 3 and 4 recycled aggregate achieved very similar 28-day tensile strength values ranging between 2.65-3.15 MPa.

5.2 Mineral Aggregate S-EU

- Good particle size distribution was observed in all three 0/2 mm fractions. However, the amount of particles greater than 2 mm was relatively high (9 % by mass) in Batch 1. The size-distribution of 2/8 mm S-EU Batch 1 and 2 was very good. However, Batch 3 deviated heavily with 25% by mass of particles being less than 2 mm. Finally, in all three 8/16 mm size fractions, the amount of particles greater than 16 mm was very low, ranging between 0% and 3%. However, the amount of particles less than 8 mm was relatively high in all fractions ranging from 12% (Batch 1) to 20 wt% (Batch 2).

- S-EU Batch 1 did not comply with the requirements set by EN 206:2013+A1:2016 [23]. It contained too much Rg (glass) and X (wood, plastic, rubber & gypsum) material in order to be classified as a Type B aggregate. It should be noted that most of Rg (glass) of S-EU Batch 1 consisted of void reach industrial slag. In contrast, S-EU Batch 2 contained a high proportion of Ru (unbound aggregate) and Rc (concrete & mortar). In addition, Rb (bricks & tiles) and Ra (bitumen) content was well below the limit for Type B recycled aggregate [23]. However, the high Rg (glass) content (2.6% by mass) was well above the Type B limit of 2% and consequently S-EU Batch 2 also failed to fulfil the requirements of EN 206:2013+A1:2016 [23] for use in structural concrete. However, it should be mentioned that like S-EU Batch 1, most of Rg (glass) fraction of S-EU Batch 2 consisted of void rich industrial slag. Finally, S-EU Batch 3 was the most homogenous and managaged to meet all the requirements for Type A CDW aggregate of EN 206:2013+A1:2016 [23] for use in structural concrete. The total proportion of Rc (concrete & mortar) and Ru (unbounded aggregates) was 97%. The remaining part was made of Rb (bricks & tiles) at 2.6% and Rg (glass) at 0.3% (both below the limit set for Type A recycled aggregate by EN 206:2013+A1:2016 [23]).

- All tested size fractions (0/2 mm & 8/16 mm) of all S-EU batches contained very low levels of water-soluble chlorides. Consequently, they complied with the requirements of EN 206:2013+A1:2016 [23] for use in structural concrete.

- The water-soluble sulfate content (by mass of aggregate) of all size fractions in S-EU Batch 2 and 3 was well below the 0.2% by mass limit set by EN 12620:2002+A1:2008 [30] for use in structural concrete. However, the coarse size fractions of S-EU Batch 1 were close to the limit, whereas the fine size fraction (0/2 mm) of S-EU Batch 1 was significantly above it.

- Stable workability values (60 mm to 75 mm at 15 min and 30 min) of OPC concrete made using S-EU Batch 1, 2 & 3 recycled aggregate were recorded. However, it should be noted that these values were significantly lower compared to N-EU Batch 2, 3 & 4. This is attributed to the significantly lower content of Rc (concrete & mortar) in N-EU coarse size fractions (3.7% to 5.7%) as opposed to S-EU coarse size fractions (10.2% to 69.4%).

- The fresh density values of OPC concrete made using S-EU Batch 1, 2 and 3 recycled aggregate varied between 2090 kg/m^3 (Batch 1) and 2340 kg/m^3 (Batch 2). The above significant difference in fresh density can be attributed to the considerable variation of Rc (concrete & mortar) content (10.2% in Batch 1 and 69.4% in Batch 2).

- The hardened density (water saturated) values of OPC concrete made using S-EU Batches 1, 2 and 3 recycled aggregate were in line with fresh density values and varied between 2150 kg/m^3 and 2410 kg/m^3. The above significant variation in hardened density can be attributed to the considerable variation of Rc (concrete & mortar) content (10.2% in Batch 1 and 69.4% in Batch 2).

- Significant variation in compressive strength results of OPC concrete made using S-EU Batches 1, 2 and 3 recycled aggregate was observed. More specifically, 28 days compressive strength values varied between 34.5 MPa and 53.0 MPa. However, this variation is strongly linked to the combined Ru and Rc content of the coarse aggregate. Such result is supported by the Type A and B assessment of coarse recycled aggregates in EN 206, according to which it is positive to have high Rc and Rc+Ru, and low Rb, Ra and X+Rg.

5.3 Lightweight Aggregates for Insulating Mortars

- Lightweight aggregates - rigid plastic/RP and wood and plastic/WP from N-EU and S-EU source - have been used for the development of mortars and their effect on density and thermal insulating performance evaluated;

- For RP-based mortars no significant differences in terms of density of the final products were observed, in turn thermal conductivity values are comparable (1.04-0.89 W/mK for RP N-EU and 0.96-0.81 W/mK for RP S-EU);

- For WP-based mortars no significant differences in terms of density of the final products were observed, in turn thermal conductivity values are comparable (0.65-0.40 W/mK for WP N-EU and 0.68-0.35 W/mK for RP S-EU).

5.4 Lightweight Flakes for Insulating Panels

- The absorption capability of the two different batches are different. Southern region wood can absorb more water then the Northern region wood. Morever, among the same batch material (Northern region wood), the grading class of the material influences the absorption capability, being the lower grading class capable of an higher absorption of water;

- The density of the panels, therefore the thermal conductivity, is lower in the panels with higher absorption of water.

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