# Construction and Demolition Wastes as Aggregates for Structural Concrete: the European Project RE$^4$

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**ABSTRACT**: This research deals with the optimization of concrete mixtures, fully based on Construction and Demolition Wastes (CDW) aggregates and Portland cement, suitable for structural applications and developed in the European project RE$^4$ (*REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction*). The objective was to formulate concrete compositions, using 100% of CDW aggregates, in compliance with requirements for industrial production of prefabricated building elements (e.g. beams, columns, foundations, stairs, slabs, panels, partitions). Concretes of strength class C25/30 and C32/40 and suitable consistency have been designed and produced on lab scale. Technical performance (e.g. consistency, compressive strength, density) of concretes have been evaluated according to specific standards and, therefore, their suitability for industrial scaling up has been assessed. At this stage of the Project, selected concretes formulations are used for industrial production of prefabricated elements, intended for installation on real-scale demo-buildings located in different European climatic regions.

## 1 INTRODUCTION

Construction and Demolition Waste (CDW) is one of the heaviest and most voluminous waste streams generated in the EU. It accounts for approximately 25% - 30% of all wastes generated in the EU and consists of numerous materials (e.g. concrete, bricks, wood, glass, metals, plastics) many of which can be recycled. CDW, for their large volume and high potential for re-use and recycling, has been identified as a priority target in the EU. According to Waste Framework Directive (2008/98/EC) the challenges for Member States is to achieve, by 2020, the target of 70% of non-hazardous CDW for reuse, recycling and recovery. However, despite its potential, the level of CDW recycling and recovery varies greatly (between less than 10% and over 90%) across the EU, due to the differences in building traditions or local economic activities [*http://ec.europa.eu/environment/waste/construction_demolition.htm*].

Technology for separation and recovery of CDW is well established, readily accessible and in general inexpensive. Although many countries have gone to great lengths to treat high amounts of CDW in recycling plants and reintroduce them into the construction cycle, many others still embrace landfilling as the main solution to dispose these materials, thereby leading to other environmental concerns [*De Brito et al., 2016*]. Moreover, recovered materials are often confined to low-grade applications (filling materials), precluding the exploitation of the high technical and economic potential value of such materials [*Del Rio Merino et al., 2009*]. There is, however, a market for aggregates derived from CDW in roads, pavements, drainage, geotechnical applications as well as studies focusing on the suitability of CDW aggregates for concrete production [*Cardoso et al., 2016; Ossa et al., 2016; Silva et al., 2014; McNeil et al., 2013; Behera et al., 2014*]. The use of recycled aggregates (RA), as a replacement of natural aggregates (NA), in construction applications (e.g. unbound and cement-treated layers, road pavements, mortars, concretes) can be considered one of the most effective approaches for recycling CDW and, at the same time, to face problems resulting from extraction of natural resources and construction/demolition activities having severe impacts on the environment [*De Brito et al., 2016*]. According to some studies [*Akhatar et al., 2018*], CDW derived aggregates are of inferior quality and it is suggested their utilization in

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concrete in the range 30% - 50% to achieve the strength equivalent to concrete based on NA. In spite of the proven technical feasibility of RA for structural concrete, there are various barriers that still prevent their wider production. One of the main barriers deals with the quality and the high variability of these materials. Indeed, the use of RA in the production of structural concrete is considered as a realistic alternative to NA, assuming that the materials are of high quality. Another barrier concerns the standards. Even though some existing standards and specifications allow the use of RA in concrete production, most either have very restricting limitations or convey a vague concept of the potential behavior of RA-based concrete. Many barriers still remain mostly due to economic reasons [*De Brito et al., 2016, Akhatar et al., 2018*].

In this scenario, further research is still necessary (e.g. improvement of CDW treatment technologies, validation of CDW use in practical applications) to endorse the common adoption of CDW aggregates in the construction industry, thus contributing to its sustainability while promoting materials recycling. Bearing this in mind, the challenge of the European project $RE^4$ [*http://www.re4.eu/*] (currently in progress, duration 2016-2020) is to develop prefabricated energy-efficient buildings based on components and elements containing up to 65% of conventional and non-conventional CDW-derived materials and structures (e.g. mineral fractions, ceramics, wood, plastics, timber). $RE^4$, coordinated by CETMA and involving 12 partners with complementary competences, covers interconnected research and industrial activities also considering their perspectives for the market uptake. $RE^4$ work plan, as strategic steps, includes: an innovative system for CDW recovery (improved separation and robotic sorting techniques for high-quality CDW); optimization of CDW-based building materials (e.g. concretes for structural and non-structural applications), usable for industrial production of prefabricated solutions (e.g. components, elements); assessment of technical performance (materials and building elements level); evaluation of environmental aspects and certification issues to allow the market acceptance and, finally, the application of $RE^4$ prefabricated solutions for new and refurbished demo-buildings. This paper, specifically, reports on innovative structural concretes consisting of 100% CDW-derived aggregates and ordinary cement, developed for $RE^4$ by CETMA labs and usable for industrial production of prefabricated building elements (e.g. beams, columns, foundations, stairs, slabs, panels, partitions).

## 2 MATERIALS AND METHODS

### 2.1 Materials

Materials used for concretes developed in this study include: normal-weight aggregates from Construction and Demolition Wastes (CDW), ordinary Portland cement (CEM I 42.5 R) as binder and a super-fluidifying additive (MasterGlenium Sky 828, BASF). CDW-derived aggregates consist in mixed mineral fractions (concretes, mortars, bricks, tiles, glass) and have been provided by CDE Global (a company responsible for CDW recovery, separation and sorting in $RE^4$ project). The aggregates, coming from different CDW recycling sites (South and North Europe) to take into consideration a certain variability in the composition, were provided in different sizes (0-2 mm, 2-8 mm, 8-16 mm and 0-4 mm, 4-10 mm and 10-20 mm) suitable for concretes and shown in *Figure 1*.

*(a)* *(b)* *(c)*

*Figure 1. CDW-derived mineral aggregates - fine (a), medium (b) and coarse (c) size.*

## 2.2 Methods

The physical characterization of mineral CDW aggregates was performed according to standards generally used for natural aggregates (sand, gravel and crushed rocks). Aggregates have been tested in terms of grading [*UNI EN 933-1*], particle density and water absorption [*UNI EN 1097-6*]. Some preliminary tests on mortars have been performed to assess the compatibility of CDW aggregates with cement. Working on these evaluations and aggregates properties (e.g. size distribution, $\rho_{ssd}$ (kg/m$^3$) - density in saturated conditions with the surface dry, $WA_{24h}$ (%) - water absorption after 24 h), concretes have been designed according to standard procedures (volumetric method which allows the calculation of the mix recipe for 1 m$^3$ of concrete). The specific aim of the experimental work was to formulate optimized concretes using large amounts of CDW aggregates and suitable for industrial production of prefabricated building elements (e.g. beams, columns, foundations, stairs, slabs, panels, partitions). *Table 1* reports target requirements prescribed by industrial producers, while *Table 2* reports concrete formulations as designed.

*Table 1. Industrial requirements for RE$^4$ prefabricated concrete elements.*

| Concrete type | Consistency class (Workability)* | Strength class** | Cement |
|---|---|---|---|
| *Vibrated* | *S2/S3 (50-150 mm)* | *C25/30* | *CEM I 42.5 N-R* |
| *Vibrated* | *S2 (50-90 mm)* | *C32/40* | *CEM I 42.5 N-R* |

* workability window 30 min
** compressive strength evaluated on cubes at 28 days of curing

*Table 2. Design of RE$^4$ concretes based on CDW aggregates.*

| Concrete ID | Aggregate type | Cement Dosage (kg/m$^3$) | Water/ Cement | Additive content (%) | Air content (%) |
|---|---|---|---|---|---|
| *Mix 1* | *S-EU CDW (100%)* | *390* | *0.42* | *0.9* | *20.0* |
| *Mix 2* | *S-EU CDW (100%)* | *390* | *0.42* | *1.0* | *20.0* |
| *Mix 3* | *S-EU CDW (100%)* | *400* | *0.41* | *1.0* | *20.0* |
| *Mix 4* | *S-EU CDW (100%)* | *400* | *0.41* | *1.3* | *20.0* |
| *Mix 5* | *N-EU CDW (a) (100%)* | *390* | *0.42* | *0.6* | *20.0* |
| *Mix 6* | *N-EU CDW (a) (100%)* | *390* | *0.42* | *0.8* | *20.0* |
| *Mix 7* | *N-EU CDW (a) (100%)* | *390* | *0.37* | *0.7* | *20.0* |
| *Mix 8* | *N-EU CDW (b) (100%)* | *400* | *0.57* | *0.0* | *20.0* |
| *Mix 9* | *N-EU CDW (b) (100%)* | *400* | *0.48* | *0.5* | *20.0* |
| *Mix 10* | *N-EU CDW (b) (100%)* | *400* | *0.48* | *0.8* | *20.0* |

The approach consisted in the gradual optimization of the design parameters targeting the requirements for C25/30 and C32/40 concretes. In total 10 concretes have been designed and then produced, 4 mixes with 100% CDW aggregates for South Europe (size 0-2 mm, 2-8 mm, 8-16 mm) and 6 mixes with 100% CDW aggregates from North Europe (3 mixes using batch (a) with size 0-2 mm, 2-8 mm, 8-16 mm and other 3 mixes using batch (b) with size 0-4 mm, 4-10 mm, 10-20 mm). In these mixes, cement dosages 390 $kg/m^3$ and 400 $kg/m^3$ have been set, water to cement ratio ranged from 0.37 to 0.57 while additive content from 0.0 % (no additive) to 1.3 %. In order to fully understand how different design parameters (e.g. typology of aggregate, cement dosage, water to cement ratio, additive content) affect concrete performance, in each test only one parameter was changed with respect to the previous one.

Concerning concretes production, a similar procedure used for conventional ones has been followed. The aggregates, stored in normal lab conditions, are placed in the mixer (coarse, medium and then fine aggregate), combined with the cement and mixed. Half part of the total water (cement hydration water and aggregate water allowance, calculated from saturation water and moisture content), combined with the additive, is added the solids and mixed. The remaining water is added gradually to the mix while monitoring the specific behaviour of CDW aggregates. Technical properties of the developed concretes have been assessed following standards used for conventional concretes; these include slump evaluation (15 min, 30 min) [*UNI EN 12350-2*], air content (30 min) [*UNI EN 12350-7*], fresh density [*UNI EN 12350-6*], hardened density [*UNI EN 12390-7*] and compressive strength [*UNI EN 12390-3*] at different curing stages (3, 7, 28 days). Concrete samples, allocated to mechanical testing, have been casted and compacted by a vibrating table; samples have been demoulded the day after the casting and stored in an aging tank. Some steps of the experimental work on concretes are shown in *Figure 2*.

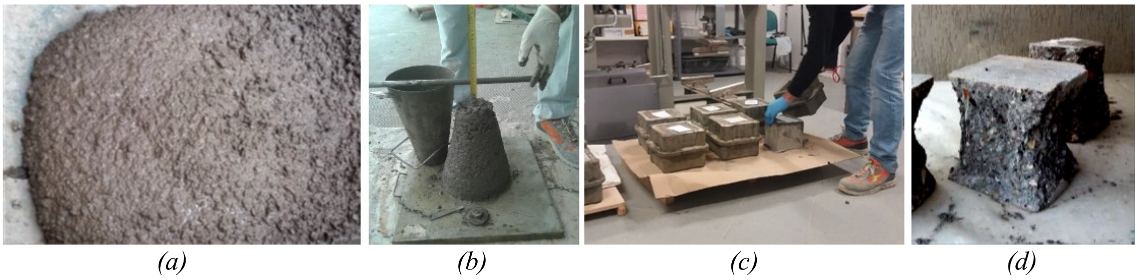


*Figure 2. Fresh CDW-based concrete (a), slump test (b), cubes demoulding (c) and cubes after compression test (d).*

## 3 RESULTS AND DISCUSSION

### 3.1 Aggregates properties

*Table 3* reports the properties (used for concrete mix design purposes) evaluated on CDW aggregates provided for this experimental work. As mentioned, for a more comprehensive study, three different batches of CDW aggregates with different quality, composition and size have been tested. One batch came from South Europe (S-EU) and available in size 0-2 mm, 2-8 mm and 8-16 mm; other two batches were from North Europe (N-EU) and available in size 0-2 mm, 2-8 mm and 8-16 mm (batch (a)) and 0-4 mm, 4-10 mm and 10-20 mm (batch (b)). Comparing S-EU with N-EU aggregates, overall the latter resulted in slightly higher density and water absorption values consistent with natural aggregates ($\rho_{ssd}$ ~ 2.600 $kg/m^3$; $WA_{24h}$ ~ 2,0%). However, it has to be observed that this kind of tests are based on manual operations; this means that the properties can be somehow over-estimated or under-estimated and might be not exactly accurate.

*Table 3. Properties of RE[4] CDW aggregates used for concretes development.*

| Aggregate ID | Material type | Source | Size | Particle density - $\rho_{ssd}$ (kg/m³) | Water absorption – $WA_{24h}$ (%) |
|---|---|---|---|---|---|
| *S-EU 0-2 mm* | *CDW (mineral fraction)* | *S-EU* | *0-2 mm* | *2.276* | *6,5* |
| *S-EU 2-8 mm* | *CDW (mineral fraction)* | *S-EU* | *2-8 mm* | *2.330* | *1,7* |
| *S-EU 8-16 mm* | *CDW (mineral fraction)* | *S-EU* | *8-16 mm* | *2.484* | *1,9* |
| *N-EU (a) 0-2 mm* | *CDW (mineral fraction)* | *N-EU* | *0-2 mm* | *2.271* | *7,9* |
| *N-EU (a) 2-8 mm* | *CDW (mineral fraction)* | *N-EU* | *2-8 mm* | *2.594* | *3,5* |
| *N-EU (a) 8-16 mm* | *CDW (mineral fraction)* | *N-EU* | *8-16 mm* | *2.532* | *3,7* |
| *N-EU (b) 0-4 mm* | *CDW (mineral fraction)* | *N-EU* | *0-4 mm* | *2.550* | *3,2* |
| *N-EU (b) 4-10 mm* | *CDW (mineral fraction)* | *N-EU* | *4-10 mm* | *2.500* | *5,5* |
| *N-EU (b) 10-20 mm* | *CDW (mineral fraction)* | *N-EU* | *10-20 mm* | *2.510* | *4,6* |

### 3.2 Concretes performance

*Table 4* reports the fresh properties evaluated for the developed concretes. Comparing S-EU and N-EU aggregates effect on the concretes performance, overall the latter resulted in slightly higher density on the fresh state (on average 2.039 kg/m³ for S-EU and, respectively, 2.292 kg/m³ and 2.231 kg/m³ for N-EU) and this is consistent with the density of the aggregate used. Referring to consistency of the concretes this is for the three batches of CDW, respectively, in the range S1/S3, S1/S4 and S1/S2. Observing data of air content, the trend shows a reduced air entrapped when aggregates from N-EU are used. In addition to these results it has to be observed that, overall, the quality of concretes based on aggregates from N-EU is certainly preferable (compact mixes, no segregation or separation phenomena). Based on these evaluations, the aggregates sorted from N-EU sites seem more promising in terms of impact on concrete performance.

*Table 4. Properties of RE[4] concretes based on CDW aggregates (fresh state).*

| Concrete ID | Fresh density (kg/m³) | Consistency class | | Air measured (%) |
|---|---|---|---|---|
| | 30 min | 15 min | 30 min | 30 min |
| *Mix 1* | *2.107* | *S2* | *S1* | *12,0* |
| *Mix 2* | *2.022* | *S2* | *S2* | *17,0* |
| *Mix 3* | *2.017* | *S1* | *S2* | *18,0* |
| *Mix 4* | *2.009* | *S2* | *S3* | *15,0* |
| *Mix 5* | *2.321* | *S1* | *S2* | *3,6* |
| *Mix 6* | *2.235* | *S3* | *S2* | *7,4* |
| *Mix 7* | *2.321* | *S3* | *S4* | *3,5* |
| *Mix 8* | *2.214* | *S2* | *S2* | - |
| *Mix 9* | *2.265* | *S1* | *S1* | - |
| *Mix 10* | *2.215* | *S2* | *S2* | - |

Table 5 reports the hardened properties evaluated for the developed concretes. Comparing S-EU and N-EU aggregates effect on the concrete performance, for density values on the hardened state a similar trend than in the fresh state was observed (on average 2.045 kg/m$^3$ for S-EU and, respectively, 2.281 kg/m$^3$ and 2.219 kg/m$^3$ for N-EU at 28 days curing). Note that density reduction with curing days is very limited; this is consistent with the low consistency measured that is, in almost all the cases, in S1 and S2 class. Referring to compressive strength of concretes, the general trend shows that there is an improvement of this performance going from S-EU aggregates to N-EU aggregates (on average 33.3 MPa for S-EU and, respectively, 38.9 MPa and 42.2 MPa for N-EU at 28 days curing). In addition to these results it has to be observed that, as for the fresh state, also for the hardened state the quality of concretes based on aggregates from N-EU is certainly preferable (compact concrete cubes observed after mechanical testing). Based on these evaluations, the aggregates sorted from N-EU sites seem more promising in terms of impact on concrete performance.

*Table 5. Properties of RE[4] concretes based on CDW aggregates (hardened state).*

| Concrete ID | Hardened density (kg/m$^3$) | | | Compressive strength (MPa) | | |
|---|---|---|---|---|---|---|
| | 3 dd | 7 dd | 28dd | 3 dd | 7 dd | 28dd |
| *Mix 1* | *2.092* | *2.080* | *2.120* | *26,8* | *29,9* | *37,9* |
| *Mix 2* | *2.009* | *1.997* | *2.049* | *22,3* | *27,6* | *33,1* |
| *Mix 3* | *2.004* | *2.025* | *2.004* | *24,6* | *28,9* | *31,2* |
| *Mix 4* | *1.999* | *2.002* | *2.007* | *25,4* | *25,5* | *31,1* |
| *Mix 5* | *2.240* | *2.232* | *2.256* | *32,6* | *32,0* | *36,0* |
| *Mix 6* | *2.225* | *2.243* | *2.247* | *28,4* | *26,6* | *36,8* |
| *Mix 7* | *2.307* | *2.294* | *2.339* | *34,0* | *37,3* | *44,0* |
| *Mix 8* | *2.197* | *2.206* | *2.204* | *25,9* | *33,2* | *37,8* |
| *Mix 9* | *2.249* | *2.239* | *2.241* | *37,1* | *40,1* | *44,4* |
| *Mix 10* | *2.200* | *2.198* | *2.212* | *34,3* | *40,8* | *44,3* |

For a meaningful comparison, Figure 3 and Figure 4 show results - in terms, respectively, of workability and mechanical performance - obtained for all the concretes produced in this study, also including the target performance required for their industrial implementation. As target performance, workability classes S2/S3 and S2 and resistance classes C25/30 and C32/40 have been prescribed. Mix 4 and Mix 6 meet the S2/S3 target, while Mix 2, Mix 8 and Mix 10 meet the S2 target. These workability performance have to be also correlated with the resistance targets. Mix 1-Mix 6 and Mix 8 meet the C25/30 target, while Mix 7, Mix 9 and Mix 10 meet the C32/40 target. Comparing all the results, it can be concluded that Mix 6 (slump S3-S2, 36.8 MPa, ~ 2.250 kg/m$^3$) fully complies with the requirements of C25/30 concrete while Mix 10 (slump S2-S2, 44.3 MPa, ~ 2.210 kg/m$^3$) fully complies with the requirements of C32/40 concrete.

It has to be observed that all the concretes developed in this study incorporate 100% of CDW aggregates (fine, medium and coarse fractions) and are suitable for structural applications. Even if, according to [*NTC, 2018*], for structural concretes it is allowed the use of natural, artificial or recycled aggregates (provided their compliance with [*UNI EN 12620*] or [*UNI EN 13055*]) there are some limitations for recycled ones. These limitations in fact, reasonably for safety reasons, fix some thresholds in the use of recycled aggregates which quality is not always predictable. Indeed, only the use of coarse recycled aggregates is allowed for structural concretes and with specific dosage limitations. According to Table 11.2.III of [*NTC, 2018*], up to 100 % of aggregate from buildings demolitions can be used for C8/10 concrete; lower dosages of recycled aggregates (≤ 5

%, ≤ 15 %, ≤ 30%, ≤ 60%) are recommended, depending on the recycled material origin (concrete, reinforced concrete, prefabricated concrete) and the expected resistance class for the final concrete (> C45/55, ≤ C45/55, ≤ C30/37 and ≤ C20/25).

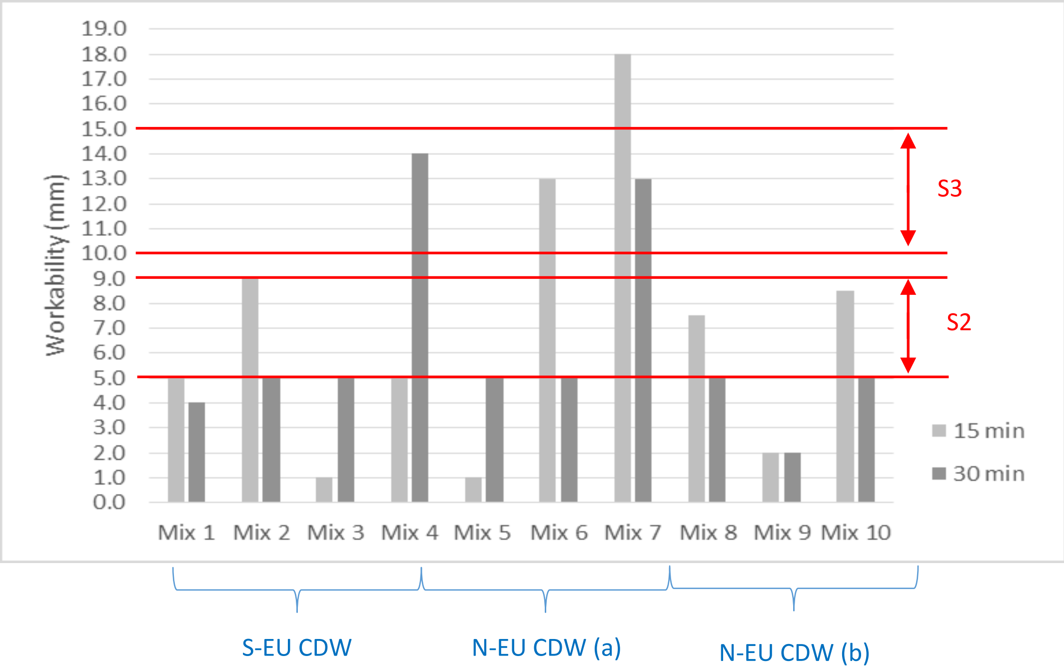


*Figure 3. RE[4] concretes:*
*workability performance compared with industrial prescriptions.*

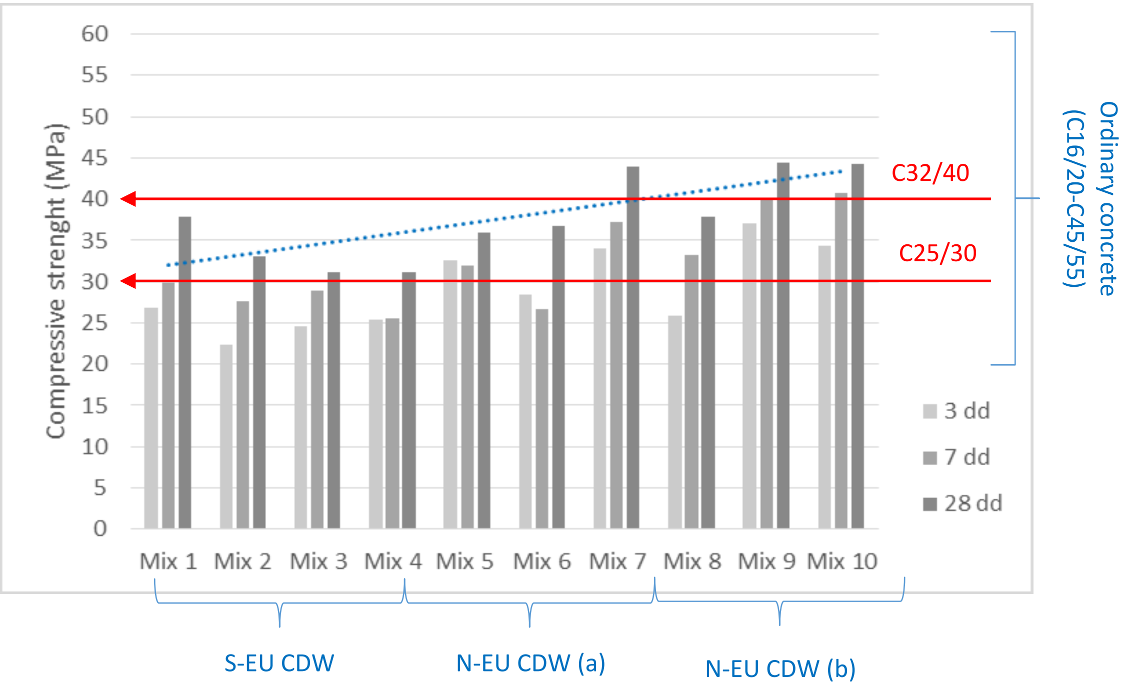


*Figure 4. RE[4] concretes: mechanical performance compared with industrial prescriptions.*

### 3.3 Perspectives for CDW aggregates use in concretes

The successful results achieved in this study - 100% CDW aggregates incorporated in structural concretes of resistance class C25/30 and C32/40 - are reasonably related to the high quality of the aggregates used (improved separation system). This confirms how this is a crucial parameter for the performance of a concrete. The properties of concretes are primarily dependent on properties and quality of the aggregates used, regardless these are natural or recycled. The quality of CDW aggregates used in concretes should always be assessed, on a case-by-case basis, taking into account the end-use applications (low-quality recycled aggregates for low-grade applications and high-quality recycled aggregates for high-grade applications). Following this approach, one of the main issues in using recycled aggregates in concretes can be addressed; this deals with the production of concretes with predictable performance. To this aim, for this kind of aggregates, the definition of quality classes have been proposed and these can be correlated with the performance of the resulting concretes [*De Brito et al., 2016*]. Referring to CDW aggregates investigated in this study, in terms of resistance class, all the concretes resulted in the range of ordinary concrete (C16/20-C45/55) even if with some variations (compactness, concrete quality) among different batches analysed.

The lack of confidence in the quality of CDW, along with an uncertainty about the potential risks for workers using CDW, reduces and restricts their demand that thereby inhibits the development of CDW management and recycling infrastructure in the EU. In this regard, "*EU Construction & Demolition Waste Management Protocol*" [*EU CDW Management*] proposes some actions to reaching the Waste Framework Directive target of 70% of CDW recycled by 2020, thus stimulating EU's transition towards a circular economy. It is clarified how improved waste identification, separation and collection at source are at the start of the CDW management process. This requires good quality pre-demolition audits and waste management plans, elimination of hazardous waste, separation of materials that hamper recycling as well as selective demolitions, dismantling and appropriate on-site operations. It is also observed how successful CDW waste management can only take place if the appropriate policy and framework conditions are in place. Key areas for public actions include an appropriate regulatory framework, enforcement, public procurement and incentives as well as awareness, public perception and acceptance. A proper management of CDW and recycled materials – which, based on the volume, is the largest waste stream in the EU and represents one third of all waste produced - can have major benefits in terms of sustainability and it can, also, provide benefits for the recycling industry and the EU construction sector, as it boosts demand for CDW recycled materials.

## 4 CONCLUSIONS

This study deals with the development of sustainable concrete formulations, combining mineral aggregates from Construction and Demolition Wastes (CDW) and ordinary cement, suitable for prefabricated building solutions and usable for structural applications (e.g. beams, columns, foundations, stairs, slabs, panels, partitions). The concretes have been developed in the European project $RE^4$ (currently in progress, duration 2016-2020), which ambition consists in development of buildings based on prefabricated elements and components incorporating up to 65% of CDW, thereby contributing to reach the Waste Framework Directive target of 70% of CDW recycled by 2020.

Starting from specific requirements, prescribed for industrial production, in terms of strength class and consistency class different concretes formulations have been designed and tested. Different batches of CDW aggregates, sorted from different European sites and therefore with a certain variability in the composition, have been investigated. CDW aggregates have been produced through an innovative separation system aiming at the improvement of their quality. Based on the study carried out, two concrete formulations suitable for industrial production of structural elements have been optimized. Specifically, a concrete compliant with the requirements of C25/30 class (consistence class S3-S2, density ~ 2.250 kg/m$^3$, compressive strength 36.8 MPa) and a concrete compliant with the requirements of C32/40 class (consistence class S2-S2, density ~ 2.210 kg/m$^3$, compressive strength 44.3 MPa) have been optimized. Concretes produced in this study incorporate 100% of CDW aggregates (fine, medium, coarse) and are suitable for structural applications. This can be regarded as a successful result especially considering that, according to regulations in the field, these aggregate dosages are allowed only for non-structural applications (coarse aggregates from building demolitions (rubbles)), while for structural applications aggregates (coarse aggregates from different concretes) dosages ranges from ≤ 15 % to ≤ 60%, depending of the resistance class of the final concrete. These results are reasonably related to the high quality of CDW aggregates used, thus confirming how this is a crucial parameter for the performance of a concrete.

At this stage of RE$^4$ project, selected concretes formulations are used for industrial production of prefabricated building elements. These elements, after performance validation, will be used for real-scale demo-buildings (new and refurbished) located in different European climatic regions.

## ACKNOWLEDGMENTS

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UNI EN 12350-6 "Testing fresh concrete. Density".

UNI EN 12390-7 "Testing hardened concrete. Density of hardened concrete".

UNI EN 12390-3 "Testing hardened concrete. Compressive strength of test specimens".

UNI EN 12620 "Aggregates for concrete".

UNI EN 13055 "Lightweight aggregates".