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INNOVATION IN CONSTRUCTION AND DEMOLITION WASTE SELECTION FOR THE PRODUCTION OF HIGH-QUALITY RECYCLED AGGREGATES

Corrado Gatti [1], Alan Piemonti [2,*], Giovanni Plizzari [2] and Sabrina Sorlini [2]

[1] Gruppo Gatti S.p.A., via IV Novembre 29, 25030 Lograto (BS), Italy
[2] Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Italy

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ABSTRACT

Italian production of construction and demolition waste (CDW) reached about 62 million tons in 2022. Despite the high recovery rate (79.8 percent), most of the treated CDW is stored waiting to be used. In most cases, the recycled aggregates (RAs) resulting from CDW processing turn out to be of low quality and mostly destined for "low-grade" applications (road and railway pavements, civil engineering works, backfills or environmental recoveries). The use of RAs in so-called "high-grade" applications, such as concrete production, is unfortunately limited today by several factors, including the type and origin of RAs, their mechanical properties (often lower than those of natural aggregates) and the potential release of contaminants. In fact, concrete production requires an RA that has similar performance to natural aggregate. This is the main objective of the Life CDW Circle project, co-funded by the European Union and presented in this paper, which aims to achieve total recycling and use of treated CDW, thanks to an innovative sorting technology that allows the separation of different aggregate fractions (aggregates, bricks, tiles, etc.) and the production of RAs with high added value. During the experimental activities, the resulting RAs will be characterized and used for concrete production. After the experimental phase, the project partners will develop appropriate business models, creating an ecosystem with sector stakeholders. The aim of the paper is to provide an overview of CDW and RAs production and use in Italy. In addition, the new Life CDW Circle project structure and objectives will be presented.

1. INTRODUCTION

Construction and demolition waste (CDW) is the most significant special waste flow at the European level, estimated to be more than 800 million tons per year (EUROSTAT). In Italy, hazardous and non-hazardous special waste production reached about 161.5 million tons in 2022. Among these, just over 80 million tons (50 percent) are CDW and excavated soil and rocks. Excluding the latter (about 23 percent), the remaining 62 million tons consist of CDW (ISPRA, 2024).

Through the Directive 2008/98/EC, the European Union imposed, by 2020, a minimum threshold of 70 percent by weight of non-hazardous CDW to be prepared for reuse, recycling or other material recovery, including backfilling operations, to which each Member State had to comply. Depending on construction methodologies, materials used, and demolition techniques, each EU country has CDW that are more or less heterogeneous and composed of different inert fractions, which may facilitate or hinder recovery operations. Before 2020, countries with recovery rates close to 100 percent were the Netherlands (100 percent of CDW destined for recycling operations) and Malta (20 percent of CDW destined for recycling, the remainder for backfilling operations). In contrast, the countries with lower recovery rates were Bulgaria (25 percent) and Slovakia (50 percent), with the portion of non-recovered CDW destined for disposal (Damgaard, 2022). Among these, Italy appears to be one of the most virtuous countries on the European scene, with a recovery rate of about 80 percent, higher than the 70 percent value imposed by Directive 2008/98/EC (ISPRA 2024).

Although the recovery rate in Italy is quite high, most of the CDW that undergo treatment operations are stored waiting to be used. High recovery rates are therefore not indicative of high circularity in materials management. This mainly comes from the origin and nature of CDW, which are closely related to past construction practices and current demolition techniques. In particular, demolition in Italy is mostly non-selective and dependent on various factors

* Corresponding author:
Alan Piemonti
email: a.piemonti001@unibs.it

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such as location and organization of the site, age of the structure, construction materials used, construction type, etc. Thus, demolition occurs in a single stage, in which there is little or no distinction of the different types of materials. CDW entering the treatment plants are therefore heterogeneous, both in terms of form and composition. As a result, the recycled aggregates (RAs) leaving the treatment plants will be low-quality aggregates and not entirely suitable for use in the construction sector. In fact, nowadays, RAs are mostly used in "low-grade" applications (road construction, backfills, and environmental recovery), which still require the respect of certain properties by RAs themselves. Due to the mechanical properties of RAs, which are lower than those of natural aggregates, their use in "high-grade" applications, such as concrete production, is still very limited (Coelho & de Brito, 2011; Silva et al., 2017; Diotti et al., 2020).

In fact, companies operating in concrete production have to face several critical issues related to the use of this type of material in partial or total replacement of natural aggregates, i.e., limited availability of RAs with suitable characteristics for the given application, reduced knowledge of the real potential of the material, and lack of regulatory clarity.

Among the many limitations that affect the use of RAs for the production of concrete, one of the most important is certainly related to their low mechanical properties when compared to those of natural virgin raw materials. With a view to an economy based on circularity and a more efficient use of RAs, the Life CDW Circle project, started in November 2023, co-funded by the European Union and involving 8 partners, aims to produce RAs with high added value from CDW, through the implementation of a new and innovative treatment plant equipped with optical selection technology. Indeed, thanks to the latter, it will be possible to separate the different CDW aggregate fractions (aggregates, bricks, tiles, etc.) and produce high quality RAs suitable for concrete production.

The aim of the paper is therefore to provide an overview of the state of the art of CDW and RAs production and use in Italy. In addition, the new European Life CDW Circle project will be presented, describing its structure, objectives and expected environmental, social and economic benefits.

2. FROM CONSTRUCTION AND DEMOLITION WASTE (CDW) TO RECYCLED AGGREGATES (RAS)

2.1 Origin and merceological composition of CDW

Construction and demolition waste (CDW) come mainly from the following sectors (Reis et al., 2021; Ronchi & Nepi, 2021):

- Demolition: CDW from the demolition of the building heritage, consisting of materials heterogeneous in nature, shape and size (aggregates, bricks, ceramics, concrete, plastics, metals, etc.);
- Construction: CDW from the construction of the building heritage, consisting mostly of "clean" materials (remnants of construction materials, packaging, etc.);
- Maintenance: CDW from renovation and/or maintenance activities of the building heritage, consisting of materials similar to those obtained from demolition but with greater presence of finishing materials;
- CDW from calamitous events (earthquakes, floods, etc.).

According to data from association surveys conducted by ANPAR (National association of producers of recycled aggregates; "Associazione Nazionale Produttori Aggregati Riciclati"), 58 percent of CDW in Italy come from small demolition, renovation and/or maintenance operations of existing buildings. The remaining fraction of CDW comes from construction sites (major demolitions, 22 percent), industrial activities (16 percent) and calamitous events (4 percent) (Ronchi & Nepi, 2021).

The characteristics of CDW in terms of merceological composition and physical, chemical and environmental properties vary depending on the area considered and the construction and demolition techniques. At the local level, and in particular in Lombardy (a region located in Northern Italy) and in accordance with the elaborations of the MUD 2018 ("Modello Unico di Dichiarazione Ambientale") data, 95 percent of CDW is composed of materials classified with the following EWC ("European Waste Catalogue") codes:

- EWC 17.09.04 - "Mixed waste from construction and demolition activities, different from those listed under the codes 17.09.01, 17.09.02, 17.09.03" (about 45%);
- EWC 17.05.04 - "Soils and rocks, different from those listed under the code 17.05.03" (about 26%);
- EWC 17.03.02 - "Bituminous mixtures, different from those listed under the code 17.03.01" (about 8%);
- EWC 17.04.05 - "Iron and steel" (about 6.5 percent);
- EWC 17.01.01 - "Cement" (about 5.5%);
- EWC 17.01.07 - "Mixtures or waste of cement, bricks, tiles and ceramics, different from those listed under the code 17.01.06" (about 3.5%)
- EWC 17.05.08 - "Crushed stone for railway ballast, different from those listed under the code 17.05.07" (about 1.5%).

2.2 Demolition techniques and treatment plants

The demolition procedure must be evaluated case by case and is dependent on several factors such as location and organization of the construction site, age of the structure, materials used during construction, type of construction, size of the intervention, etc. (Silva et al., 2017). As these factors vary, the company can then choose the most congenial demolition technique, specifically:

- Non-selective demolition: it is generally developed in a single phase and there is no distinction between the different fractions that will constitute the CDW. As a result, the CDW entering the treatment and recovery plants will be characterized by strong heterogeneity, both in terms of nature and composition, and the output RAs will be of low quality;
- Selective demolition: it is developed in multiple operational phases and requires more planning and design

(site space, schedules, equipment, labor, etc.). Selective demolition thus allows for an initial sorting of the different components (concrete, paper and cardboard, wood, metals, glass, plastics, ceramics, etc.), even before the CDW enter the treatment plants. Each material is stored in special piles and then allocated to its recovery sector.

In the Italian context, non-selective demolition is unfortunately still widespread, through which very heterogeneous CDW are obtained and, consequently, less performing RAs than natural ones. It is evident how the implementation of selective demolition practices allows to separate homogeneous fractions of materials to be destined to appropriate treatment and recovery operations, increasing their level of recyclability and improving their quality (Silva et al., 2017).

At the regulatory level, the incentive for the implementation of selective demolition practices can be found in section 6-quinquies of Article 205 of Italian Legislative Decree 152/2006 (section added through Legislative Decree 116/2020, which transposes European Directive 2018/851), which states the following (in Italian): "*The Ministry of the Environment and Protection of Land and Sea promotes, after consulting with trade associations, selective demolition, in order to allow the safe removal and treatment of hazardous substances and facilitate the high-quality reuse and recycling of residues from construction and demolition activities through the selective removal of materials, as well as ensuring the establishment of construction and demolition waste selection systems at least for wood, mineral fractions (cement, bricks, tiles and ceramics, stones), metals, glass, plastic and plaster*".

Once demolition has taken place, CDWs are transferred to appropriate treatment plants, which can be divided into two macro-types: stationary plants and mobile plants.

Stationary plants are very complex plants both in terms of technology employed and management; they occupy a rather large area and are generally equipped with several crushing, sorting and screening stations, through which RAs of different grain sizes can be produced. They are powered by electricity, provide high productivity in terms of tons per year, better dust control, and the possibility of creating a local catchment area for demolition companies. On the other hand, the disadvantages include the high initial investment required to install and start up the plant and the high environmental impact values, mainly related to the transport of CDWs from the demolition site to the plant itself.

Mobile plants are generally less complex than stationary plants and have fewer processing stations (usually single crushing and screening); this leads to lower quality RAs output. These types of plants are generally diesel-powered and, compared to stationary, allow somewhat limited productivity in terms of tons per year of CDW processed. However, they can be transported and installed at demolition sites in order to carry out targeted treatment campaigns and are characterized by a lower initial investment. In addition, since the treatment plant is mobile, there is no longer a need for the transport of CDWs from the demolition site to the plant itself; this helps to reduce impacts in terms of emissions (Zhao et al., 2010, Pacheco & de Brito, 2021).

In the Lombardy region (Italy), about 86 percent of CDWs are processed in mobile plants, while the remainder (14 percent) are sent to stationary plants (Borghi et al., 2018). As a result, the RAs leaving these plants are strongly heterogeneous and have highly variable physical, chemical and performance properties.

2.3 Treatment technologies

The treatment processes for CDW to obtain recycled aggregates (RAs) are multiple and vary depending on a number of factors: nature of input materials (CDW), expected and desired quality of output materials (RAs), location of the plant, available technologies, possible presence of contamination elements in the input materials. In general, in a conventional treatment plant for CDW of average quality, the main operational steps can be summarized as follows (Silva et al., 2017, Bressi & Facchin, 2018):

Pre-treatment operations

- CDW input to the plant;
- Preliminary visual inspection of incoming CDW, with the aim of identifying any materials unsuitable for treatment;
- Weighing, acceptance and storage pending subsequent treatment steps;
- Possible manual sorting and preliminary removal of undesired or oversized materials (steel, wood, plastic, paper, glass, etc.);
- Possible preliminary crushing of larger blocks in order to obtain materials with dimensions suitable for treatment. Hydraulic breakers mounted on crawler or wheeled excavators are usually used at this stage.

Treatment operations

- Feeding CDW to the plant;
- Mechanical crushing of CDWs, generally performed by crushers (the most common are jaw, impact and gyratory crushers). The purpose of this stage is to reduce the size of the CDW in order to obtain a predetermined grain size suitable for subsequent treatment stages. Depending on the quality of the RAs to be obtained and the future applications of the same, several crushing stages can be envisaged;
- Deferrization, usually performed by means of self-cleaning magnets, the efficiency of which depends on several factors: distance between magnet and material flow, volume of material in transit, speed of the conveyor belt and angle of positioning of the magnet with respect to the belt itself. They are placed at various strategic points on conveyor belts and are used to separate metals from the rest of the material;
- Separation of the lightweight fractions (bricks, wood, plastic, paper, etc.) from the heavier aggregates by dry, wet or innovative processes;
- Screening, with the aim of performing a size selection of the different fractions, which will be stored in separate piles;
- Verification of the eco-compatibility of the different particle size fractions (usually by performing leaching

tests) and CE marking, in accordance with the relevant technical standards;
- Storage pending placing on the market.

The separation phase of undesired fractions (bricks, wood, plastics, paper, etc.) during treatment operations is crucial for obtaining good quality RAs. Separation technologies that are commercially available and already operational in treatment plants are many and differ from each other depending on the characteristics of the material to be treated (CDW), the organization and potential of the plant, and the desired quality of the output RAs. Separation processes can be divided mainly into (Schnellert & Mueller, 2010):

- Dry separation processes;
- Wet separation processes;
- Innovative separation processes.

2.3.1 Dry separation processes

In turn, dry separation processes can be divided into two different types:

- Density separation processes, which occur in air separators. Here, the separation of light fractions from heavier fractions takes place by means of an air flow that "directs" the lighter fractions into a different output canal than that used for the heavy fractions;
- Separation processes by magnetic or electronic properties, which occur through the use of magnets or electrical conductors capable of producing an electromotive force (separation by electromagnetic induction). An example is the technology using rotor equipped with magnets, which makes it possible to separate non-ferromagnetic metals (rejected by electromagnetic induction) from ferromagnetic metals (attracted by magnets) and non-conducting materials.

2.3.2 Wet separation processes

Wet separation processes take place by exploiting the density gap among the different fractions and the density of the medium used (usually water). The technology adopted varies depending on the organization of the individual treatment plant. Unlike air treatment technologies and to ensure the proper implementation of wet separation, the plant must be equipped with a water and wastewater treatment circuit in order to guarantee recirculation of process water and to limit water consumption. Compared with air separation processes, wet separation processes allow better removal of fine fractions and better control of the particle sizes of the output products, ensuring higher quality of the RAs obtained at the end of the process.

2.3.3 Innovative separation processes

The separation stage of unwanted fractions (bricks, wood, plastics, etc.) during treatment operations is crucial for obtaining good quality RAs. In fact, the aforementioned fractions have lower mechanical performance than the inert fractions and, if not properly separated, would result in reductions in the quality of the RAs exiting the treatment operations. Depending on plant organization, available technologies, and the characteristics of the incoming CDW, air or wet technologies may not be sufficient to ensure proper separation of light fractions from heavier aggregates.

In recent years, studies have focused on the possibility of introducing innovative separation technologies based on optical sorting and/or artificial intelligence (Cirelli Angulo et al., 2013, Dodampegama et al., 2023). Optical separation treatments are already widely used to treat other types of waste (e.g., plastics, glass, etc.) and recent studies have demonstrated their applicability for CDW treatment as well.

The advantages of adopting optical separation technologies are many: improved quality of the RAs exiting the treatment plant, reduction of processes after the separation stage (possible further crushing and screening), and savings in terms of water and energy use (there is no longer a need to introduce wastewater treatment and recycling circuit as for wet separation technologies). On the other hand, disadvantages include high initial investment and maintenance costs (in terms of trained personnel, sensors, databases, possible upgrades, etc.). Depending on whether the technology is more or less advanced, multiple optical sorting stations may then need to be installed to enable the separation of the different fractions, resulting in higher initial and operating costs.

2.4 Recycled Aggregates (RAs)

The treatment plants in Italy are generally equipped with "conventional" technologies, which mainly consist of mechanical crushing, deferrization, simple selection of light and undesirable fractions, and screening; as a result, the output recycled aggregates (RAs) will have rather low quality. Due to the low mechanical properties of RAs and the treatment operations that do not allow their full valorization, they are mostly used as unbound or hydraulically bound material in the road and railway sector, for bituminous mixes and surface treatments of roads and trafficked areas (82 percent) or for backfilling and environmental restoration (11.5 percent). On the other hand, only about 7.2 percent is used for concrete production, with a rather clear division between non-structural (6.8 percent) and structural (0.4 percent) concrete (Ronchi & Nepi, 2021).

As previously mentioned, RAs have lower mechanical properties than natural aggregates commonly used for concrete production. Therefore, the correct evaluation of their characteristics in terms of technical-mechanical performance is a key factor in the proper mixing of concrete with recycled materials. In fact, unlike natural aggregates, RAs consist of the original aggregate to which old cement paste remains "adhered" (in more or less quantity depending on the quality and nature of the treatment processes); due to its poor characteristics, it turns out to be the main responsible for the reduction of the RAs properties, giving the latter greater porosity and water absorption and lower density and resistance to fragmentation (Rémond et al., 2019).

In fact, the above-mentioned aggregate properties are those that most influence the characteristics of both fresh and hardened concrete. Figure 1 shows a schematization of a recycled aggregate, consisting of original aggregate, old adhered mortar and old interfacial transition zone (ITZ) between the two components. Once added to the concrete,

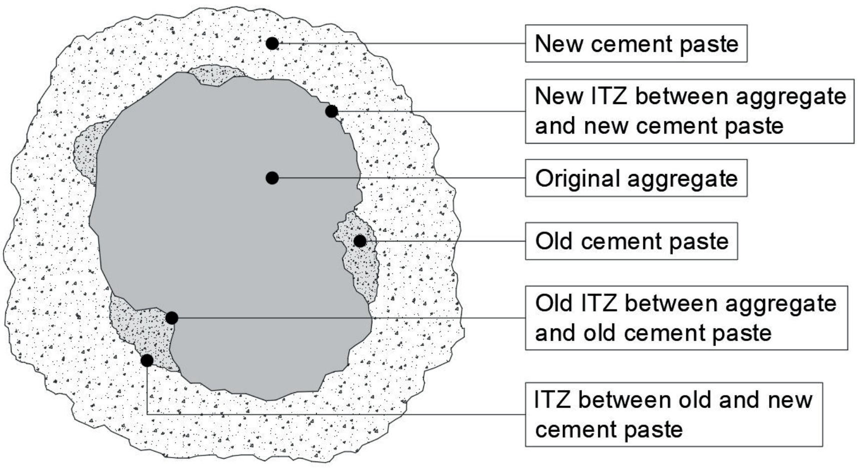

FIGURE 1: Schematization of a RA (original aggregate, old cement paste, old ITZ) once added to concrete (RA, new cement paste, new ITZs between RA and new cement paste and between old and new cement paste).

the new cement paste covers the recycled aggregate, creating a new ITZ.

However, the presence of adhered cement paste does not turn out to be the only factor responsible for the reduction of the properties of RAs; in fact, the treatment processes adopted (particularly the number of crushing steps), the aggregate grain size, the type of original material, and the strength of the parent concrete also contribute to the reduction of the mechanical properties of RAs, as compared to those of natural aggregates.

Table 1 shows the typical intervals of density, water absorption and fragmentation resistance values of RAs compared to natural aggregates (NAs) and, for each of the mentioned properties, highlights the main causes leading to its penalization (Verian et al., 2018, Piccinali et al., 2022).

It can be seen from the table that the specific gravity of RAs is lower than that of natural aggregates. Consequently, concrete produced with RAs will have a lower density than concrete produced with natural aggregates; this difference grows as the substitution percentage between NAs and RAs increases (Caggiano et al., 2012, Verian et al., 2018).

Because of the higher water absorption, great care must be taken both during mix design and during casting, carefully assessing the moisture content of the RAs used; in fact, high values of water absorption cause a faster loss of workability in concrete (Verian et al, 2018).

Finally, reduced resistance to fragmentation of RAs causes a reduction in the compressive strength of concrete (Omary et al, 2016).

3. CONCRETE MADE WITH RECYCLED AGGREGATES (RAS)

3.1 Current Italian regulations

The use of RAs as a replacement for natural aggregates in the production of concrete is provided and regulated by Italian legislation, which, in relation to type and nature of RAs and strength and exposure class of concrete, imposes limit values of substitution percentage. In addition to this, the maximum replacement percentage should also consider the availability of RAs in the area where the construction site will be located, in order to limit transportation costs and thereby reduce related environmental impacts. Table 2 summarizes the main concepts expressed by the different current regulations in Italy regarding the characterization and use of RAs for concrete production.

The Italian Structural Code (NTC 2018) provides Table 11.2.III, which shows the percentages of use of RAs al-

TABLE 1: Comparison among typical intervals of specific gravity, water absorption and resistance to fragmentation (Los Angeles) values of recycled aggregates (RAs) versus natural aggregates (NAs) and main causes leading to their penalization (Verian et al., 2018, Piccinali et al., 2022).

Property	U.M.	NAs	RAs	Causes of penalization
Specific gravity	kg/m^3	2400-2910	1910-2700	• Cement paste adhered on RAs surface • Treatment process (n. of crushing steps) • Type of original material • Strength of parent concrete
Water absorption	%	0.05-5.2	2.70-14.70	• Cement paste adhered on RAs surface • Micro-cracks on RAs surface • RAs size • Type of original material • Strength of parent concrete
Resistance to fragmentation (Los Angeles)	%	11.5-38.9	20.0-51.5	• Cement paste adhered on RAs surface • Cracked particles during treatment processes • RAs water absorption • RAs porosity

TABLE 2: Main provisions contained in current Italian regulations on the characterization and use of recycled aggregates (RAs) for concrete production.

Standard (name)	Brief description	Main provisions
Ministerial Decree January 17, 2018 (Aggiornamento delle "Norme Tecniche per le Costruzioni")	• Definition of principles for the design, execution and testing of constructions	• Suitability of aggregates from recycling processes (according to UNI EN 12620) for structural concrete production • Reference table for the use of RAs for concrete production is Tab. 11.2.III: it shows the allowed percentages in relation to concrete class and RAs origin • Corrections to the empirical formulas of some properties of concrete produced with RAs (tensile strength, elastic modulus)
UNI EN 12620 (Aggregati per calcestruzzo)	• Specification of the properties of aggregates and fillers obtained from the processing of natural, artificial or recycled materials mixed for the production of concrete complying with the requirements of EN 206-1	• Geometrical, physical and chemical requirements of aggregates • Section 5.8, Table 20: shows the constituents of coarse RAs, their description and the different classification categories in relation to the constituent and its percentage content by mass
UNI 8520-2 (Aggregati per calcestruzzo - Istruzioni complementari per l'applicazione della EN 12620 - Parte 2: Requisiti)	• Supplementary instructions for the application in Italy of UNI EN 12620 • Specification of the characteristics of aggregates and fillers, defined and classified in accordance with UNI EN 12620, destined for the manufacture of concretes	• Section 4.2: only certain types of coarse RAs (according to Table 20 of UNI EN 12620) are suitable for concrete production (according to UNI EN 206) • Possibility of using fine RAs and recycled mixes for concrete production, adopting proper precautions • Section 4.5.1, Table 2: allowable limits for fines content in aggregates of different types • Section 4.6, Table 3 (recalling section 5.5 of UNI EN 12620): allowable limits and test methods for the evaluation of density and water absorption of RAs • Table 4: allowable limits and test methodologies for the evaluation of chemical constituents of RAs • Table A.1, Code A: additional requirements and critical issues of different types of RAs
UNI EN 206 (Calcestruzzo - Specificazione, prestazione, produzione e conformità)	• Requirements for: materials, properties of concrete, limitations on concrete composition, delivery of concrete, procedures for production control, criteria and evaluation of compliance • Its application in Italy for structural concrete requires the UNI 11104, which is an integral part of the document	• Recommendations regarding coarse RAs, with diameter ≥ 4 mm • Table E.2: limits for replacement of coarse natural aggregates with coarse RAs, depending on the type of RAs (Type A or Type B) and exposure classes of concrete • Table E.3: recommendations for coarse RAs according to EN 12620 (properties, reference Paragraphs of EN 12620, type of RAs and category)
UNI 11104 (Calcestruzzo: Specificazione, prestazione, produzione e conformità – Specificazioni complementari per l'applicazione della EN 206)	• Supplementary provisions for the application in Italy of UNI EN 206 • It applies to concrete for cast-in-place structures, precast structures and precast structural components for buildings and civil engineering structures	• Use of RAs according to UNI 8520-2 and UNI EN 12620 • Table 4: maximum replacement percentages of coarse natural aggregates with coarse RAs according to the type of RAs (Type A or Type B), strength class and exposure class of concrete

lowed in relation to the concrete strength class and the origin of the RAs themselves. In the mentioned table, the maximum substitution percentage between natural aggregate and mixed coarse RAs (rubble) is 100%, for non-structural concrete of strength class C8/10. As the strength class increases, the allowable substitution percentage decreases and coarse RAs from demolition of concrete only is accepted. NTC 2018 also includes some corrections to the empirical formulas provided for the evaluation of tensile strength and elastic modulus of concrete.

The European Standard for aggregates (UNI EN 12620) specifies, in addition to the properties of natural aggregates, the geometric, physical and chemical requirements that RAs must meet. In Section 5.8, it provides a table in which the constituents of coarse RAs and their description are listed; this table is accompanied by Table 20, in which the different classification categories of coarse RAs are highlighted in relation to the constituents and their mass percentage content (for example, a RA classified as Rc_{90} indicates a RA in which the mass percentage content of Rc (concrete-based constituent) is greater than or equal to 90%).

The Italian Standard for aggregates (UNI 8520-2) includes supplementary instructions for the application in Italy of UNI EN 12620 and only provides for the use of certain types of coarse RAs (classified according to Table 20 of UNI EN 12620) for concrete production. RAs are classified into two types: Type A (higher performance, consisting mostly of concrete and with lower contents of other materials) and Type B (lower performance, consisting of concrete and other lighter masonry- and bituminous-based materials, glass, etc.). The standard also prescribes the possibility of using fine RAs and recycled mixes for concrete production, but only by taking appropriate precautions.

The European Standard for concrete (UNI EN 206) provides recommendations for coarse RAs with diameters larger than 4 mm. Table E.2 shows the limits for the replacement of natural coarse aggregates with coarse RAs in relation to their type (Type A or Type B) and the exposure class of concrete; for more "severe" exposure classes, the allowable replacement percentages decrease, up to a maximum of 30% for Type A RAs and 20% for Type B RAs, reaching a maximum of 50% for exposure class X0 (for both types of RAs. On the other hand, Table E.3 gives some recommendations regarding the properties of coarse RAs, according to EN 12620 (fines content, resistance to fragmentation, bulk density, water absorption, constituents, content of water-soluble sulfates and acid-soluble chloride ions, etc.) and shows the reference paragraphs of EN 12620, the type of RAs (A or B) and the category.

The Italian Standard for concrete (UNI 11104) considers the established practice of concrete use in Italy and is the national application document of UNI EN 206, previously described. Table 4 of UNI 11104 provides maximum replacement percentages of coarse natural aggregates with coarse Ras, depending on the type of RAs (Type A or Type B), strength class and exposure class of concrete. Type B RAs, which are less performing, can only be used in non-structural concrete with strength class C8/10 and in maximum replacement percentage up to 100%. For higher strength classes, the only coarse RAs allowed are Type A, with maximum replacement percentages up to 60% for exposure class X0 and strength class between C12/15 and C20/25. As the strength class increases and for more "severe" exposure classes, the maximum allowable replacement percentages decrease, reaching values of 20% and 30%.

Finally, it is worth mentioning the recent publication of the new Ministerial Decree June 28, 2024, n. 127 (so-called "End of Waste inert waste from CDW" Decree). The latter does not specifically deal with the use of RAs for concrete production, but establishes specific criteria according to which inert waste from construction and demolition activities and others of mineral origin, subjected to recovery operations, cease to be qualified as waste, according to Article 184-ter of Legislative Decree 152/2006. Specifically, in its 9 Articles and 3 Annexes, in addition to recalling the criteria for the End of Waste status, the present Ministerial Decree establishes:

- The categories of waste eligible for the production of RAs, recalling them by EWC codes of the European Waste Catalogue (Annex 1, paragraph (a), Table 1);
- The inspections to be carried out by the treatment and recovery plant operator on incoming waste (Annex 1, paragraph (b));
- The "minimum" treatment process and storage and handling arrangements (Annex 1, paragraph (c));
- The quality requirements of the RAs produced (Annex 1, paragraph (d)). In particular, the Decree specifies the following (paragraph (d.1), in italian): "*Per ogni lotto di aggregato recuperato prodotto è garantito il rispetto di parametri di cui alla Tabella 2 a seconda degli utilizzi cui sono destinati i lotti di aggregato recuperato prodotto previsti dall'Allegato 2 (articolo 4)*". In fact, the Decree provides a list of applications for which the produced RAs may be destined (Annex 2) and the limit concentrations of certain chemical control parameters, depending on the expected use of the batch of RAs under consideration (Annex 1, Table 2);
- The leaching test on the RAs produced (Annex 1, paragraph (d)). In particular, the Decree specifies the following (paragraph (d.2), in italian): "*Ogni lotto di aggregato recuperato prodotto deve essere sottoposto all'esecuzione del test di cessione per valutare il rispetto delle concentrazioni limite dei parametri individuati in Tabella 3. Sono esclusi dal test di cessione i lotti di aggregato recuperato prodotto destinati al confezionamento di calcestruzzi di cui alle NTC 2018 con classe di resistenza maggiore o uguale di C12/15. […] Per la determinazione del test di cessione si applica l'appendice A alla norma Uni 10802 e la metodica prevista dalla norma UNI EN 12457-2*";
- The reference technical standards for the CE marking of RAs (Annex 1, paragraph (e) and Annex 2, Table 5), among which there is also UNI EN 12620 concerning concrete.

Thus, the "End of Waste Decree" just described is a valuable legislative tool for the regulation of the CDW recovery sector and, consequently, for the production of good-quality RAs, so as to promote their marketing and use in accordance with the principles of sustainability and circular economy.

3.2 Properties of concrete with recycled aggregates (RAs)

The properties of concrete produced with partial or total replacement of natural aggregates with RAs turn out to be greatly influenced by the characteristics of the latter. In particular, Table 3 shows the concrete properties that are most affected by the use of RAs (compared with those of concrete produced with NAs) and, in case of penalization, reports the main causes.

It can be seen from Table 3 that the characteristics and nature of RAs significantly influence the properties of the concrete produced with them.

Regarding fresh concrete, a rapid loss of workability occurs, mainly caused by the higher water absorption of RAs and the replacement rate between NAs and RAs themselves (Piccinali et al., 2022). In order to achieve the same or close to the expected workability value, the use of special admixtures (appropriately dosed and provided at the mix design stage) or the pre-saturation of RAs before casting can be adopted (Rashid et al., 2020).

Overall, concrete produced with RAs shows lower mechanical performance than that produced with NAs. As for compressive strength, the value is lower, with a greater reduction in concrete mixtures produced with RAs from concrete alone than in those produced with mixed RAs (Piccinali et al., 2022). An important parameter is certainly the water/cement ratio (w/c); in fact (Thomas et al., 2013, Thomas et al., 2018):

- For low w/c values (< 0.5 approx.), the weaker part of the concrete is represented by the interface between original aggregate and old cement paste, still possibly adhered to the surface of the RA; thus, the final strength of the concrete depends on the type of RAs used (in particular, on the nature and strength of the parent concrete);
- For high w/c values (> 0.6 approx.), the weaker part of the concrete is represented by the interface between

TABLE 3: Properties of concrete with recycled aggregates "RAs" (compared with concrete produced with natural aggregates "NAs"), causes of their possible penalization ("main causes") and main references ("ref.").

Property	Description	Main causes	Ref.
Workability	• Rapid loss of workability • Lower workability as the NA–RA substitution percentage increases	• Water absorption of RAs • Shape and surface area of RAs • NA-RA substitution percentage	• Rashid et al., 2020 • Piccinali et al., 2022
Density	• Lower density • Lower density as the NA–RA substitution percentage increases	• Density of RAs • NA-RA substitution percentage	• Thomas et al., 2013 • Piccinali et al., 2022
Compressive strength	• Lower compressive strength • Lower compressive strength for concretes produced with mixed(*) RAs compared to those produced with RAs from concrete only(**)	• Water absorption of RAs • Strength of original concrete • Presence of cement paste adhered to RAs surface • Water/cement ratio • RAs resistance to fragmentation • Type and quality of RAs • NA-RA substitution percentage	• Thomas et al., 2013 • Thomas et al., 2018 • Piccinali et al., 2022
Tensile strength	• Lower tensile strength • Lower tensile strength for concretes produced with mixed RAs compared to those produced with RAs from concrete only	• Presence of cement paste adhered to RAs surface • Porosity of RAs • Water/cement ratio • Type and quality of RAs • NA-RA substitution percentage	• Thomas et al., 2013 • Eckert & Oliveira, 2017 • Piccinali et al., 2022
Elastic modulus	• Lower elastic modulus • Lower elastic modulus for concretes produced with mixed RAs compared to those produced with RAs from concrete only	• NA-RA substitution percentage • Presence of cement paste adhered to RAs surface • Type and quality of RAs • Water/cement ratio	• Coppola, 1998 • Qasrawi & Marie, 2013 • Geng et al., 2019
Shrinkage	• Higher shrinkage as the NA–RA substitution percentage increases	• Presence of cement paste adhered to RAs surface • Porosity of RAs • Water/cement ratio • Type and quality of RAs • NA-RA substitution percentage	• Eckert & Oliveira, 2017 • Geng et al., 2019 • Rashid et al., 2020
Durability	• Lower resistance to chloride penetration	• NA-RA substitution percentage • Porosity of RAs • Water/cement ratio	• Qasrawi & Marie, 2013 • Yildrim et al., 2015
	• Lower resistance after freeze/thaw cycles	• Water absorption of RAs • Presence of cement paste adhered to RAs surface • Water/cement ratio	• Yildrim et al., 2015 • Guo et al., 2017
	• Higher carbonation depth • Higher carbonation rate	• Water/cement ratio • Concrete compressive strength • NA-RA substitution percentage	• Thomas et al., 2013
Environmental compatibility	• Conflicting results • RAs from concrete only lead to a significant release of total Cr (predominant presence of cement) • RAs from mixed CDW lead to a high release of sulphates (due to ceramic materials and gypsum) • No significant results in terms of contaminants release from test on monolithic concrete with RAs, thanks to the containment function of the cement matrix on RAs itself	• Type and composition of RAs • Presence of cement paste adhered to RAs surface • Size of RAs	• Diotti et al., 2020 • Diotti et al., 2021

(*) *Mixed RAs: RAs composed of aggregates and other materials (ceramics, bricks, cement, etc.)*
(**) *RAs from concrete only: RAs composed mainly of crushed concrete*

new and old cement paste, still possibly adhered to the surface of the RA; thus, the final strength of the concrete is similar regardless of the RAs nature.

Regarding tensile strength, RAs with less cement paste adhered and less porous structure provide better performance. In addition, regardless of the RAs nature, the tensile strength decreases as the w/c ratio and the replacement percentage between NAs and RAs themselves increase (Thomas et al., 2013).

Generally, higher replacement rates also lead to a decrease in the elastic modulus of concrete; this is mainly due to the presence of adhered cement paste and micro-cracks on the surface of RAs, which lead to an increase in their porosity and a decrease in mechanical properties (Geng et al., 2019, Qasrawi & Marie, 2013).

The replacement rate between NAs and RAs also influences the concrete shrinkage; in fact, the higher the replacement rate, the higher will be the shrinkage (Eckert & Oliveira, 2017, Geng et al., 2019). However, the shrinkage phenomenon can be contained by using special admixtures, properly dosed and provided during the mix design phase (Rashid et al., 2020).

Regarding the durability of concrete produced with RAs, few studies are available in the literature and provide sometimes conflicting results. A higher replacement rate between NAs and RAs leads to a lower resistance to chloride penetration, mainly due to the higher porosity of the RAs themselves. In addition, a decrease in w/c ratio may lead to a decrease in chloride penetration (Qasrawi & Marie, 2013, Yildrim et al., 2015).

After freeze-thaw cycles, the strength of concrete produced with RAs is lower than that of conventional concrete, mainly due to the higher water absorption and the presence of adhered cement paste on the surface of RAs (Guo et al., 2017).

For the same w/c ratio, the carbonation rate (expressed in mm/day$^{0.5}$) increases as the replacement rate between Nas and RAs increases. In addition, as the compressive strength increases, the carbonation rate decreases. The main factors governing carbonation rate are alkalinity (which reduces carbonation rate) and concrete permeability (Thomas et al., 2013).

Finally, with regard to environmental compatibility, the factors that most influence the release of contaminants from granular RAs are composition, size, and presence of adhered cement paste. In particular, RAs from concrete-only demolition generally exhibit rather high chromium release, due to the presence of cement, while RAs from mixed and non-selective demolition exhibit rather high sulfate release, mainly due to the presence of ceramic materials and gypsum. Once incorporated into concrete, RAs are covered by the cement paste, which operates a containment function and limits their release (Diotti et al., 2020, Diotti et al., 2021).

4. PRESENTATION AND OBJECTIVES OF THE LIFE CDW CIRCLE PROJECT

It is clear from the previous paragraphs that the possibility of using recycled aggregates (RAs) from the treatment of construction and demolition waste (CDW) for the production of concrete is subject to quite a few critical issues, mostly related to past construction and modern demolition techniques, low quality of the material coming out of treatment plants, lack of regulatory clarity, limited knowledge of the real potential of the materials considered, and absence of a competitive market that can compete with commonly used natural aggregates.

Indeed, proper and conscious use of RAs offers significant economic, environmental and social benefits: reduction in raw material consumption, improvement in waste and resource management, reduction in landfill disposal, reduction in CO_2 emissions, and protection of the landscape.

As already highlighted in Sections 2.3 and 2.4 of this paper, the treatment plants in Italy are equipped with "conventional" technologies, based on mechanical crushing, deferrization, screening and simple separation of light and/or unwanted fractions. The main "problem" is therefore represented by the limited possibility of separation and sorting of aggregates from other weaker fractions (bricks, ceramics, cement, etc.). In fact, the latter are mainly responsible for obtaining very heterogeneous RAs, having low physical, chemical and mechanical properties and low added value; this affects their full possibility of use for concrete production.

In light of this, it is of fundamental importance to implement and develop solutions that are able to provide RAs exiting treatment plants with added value, which is necessary to increase their competitiveness in the market and to make them suitable for use in concrete production. A better and more careful separation of inert fractions from light and undesirable fractions in the sorting step would ensure obtaining RAs with more homogeneous characteristics within the same pile and with definitely higher performance and added value; this turns out to be one of the objectives of the new Life CDW Circle project (whose logo can be seen in Figure 2), started at the beginning of November 2023 with a duration of 42 months (ending April 2027), co-funded by the European Union and consisting of 8 partners.

In fact, the project aims to design and install, at one of the coordinating partner's sites in the province of Brescia (Italy), a new-generation treatment plant that will not only be able to remove metals, plastics, wood, and contaminants from aggregates, but will also be able to sort mineral materials according to texture and color; this will be achieved through the introduction into the treatment flow of an optical sorting stage (the technology for which is provided by one of the project partners), which, through the use of sensors, will allow the sorting of different types of material, ensuring greater stability and uniformity of the individual output fractions.

In addition to the type and performance of the sorting technology, another crucial aspect that must be considered is the economic sustainability of the process, which sees a contrast between the low commercial value of today's RAs and the high installation and maintenance costs of the aforementioned technology; the added value of the output product must therefore guarantee a return on the initial investment and maintenance costs.

The high added-value RAs obtained from the new treatment plant will then undergo technical and environmental characterization in order to assess their suitability for the production of structural and nonstructural concrete.

The technical characterization will be done by evaluating the geometric, physical and chemical properties required by UNI EN 12620 (water absorption, particle and bulk density and particle size distribution). In addition to those of the aggregates, technical, physical and chemical requirements of the brick fraction obtained from the treat-

FIGURE 2: Logos of the Life CDW Circle project and the European Life program.

ment process will also be evaluated, in accordance with UNI EN 13139 (aggregates for mortar).

On the other hand, the environmental suitability of the granular RAs will be assessed by performing leaching tests in accordance with UNI EN 16637-3. In addition to tests on granular aggregates, an assessment of the leaching behavior of monolithic concrete will also be carried out, in accordance with UNI EN 16637-2. Finally, ecotoxicity tests will be carried out on RAs and bricks (granular materials) and concrete (monolithic material) in order to assess possible toxic effects on the environment and human health.

Once the characteristics of high-added value RAs obtained from the innovative process have been analyzed and compared with those of natural aggregates and RAs obtained from a conventional process, C25/30 and C30/37 class concrete mixtures will be designed with the addition of the RAs. Tests will be carried out on these concrete mixtures to assess their properties in the fresh state (workability), in the hardened state (compressive strength, tensile strength, modulus of elasticity, shrinkage) and to investigate their durability (carbon dioxide penetration, chloride penetration, resistance after freeze/thaw cycles and corrosion tests on concrete reinforced with steel bars).

The concrete mixtures with RAs analyzed in this way will first be compared with mixtures produced with natural aggregates and with RAs obtained from conventional treatment processes, and then used for the production and characterization of full-scale structural elements (beams, plates, walls, etc.). The aim of this experimental phase is to evaluate the actual behavior of the produced structural elements and compare them with the same elements made from conventional concrete or concrete with low-quality RAs.

With the results obtained, it will then be possible to optimize the production process, facilitating its replicability to other plants once the project is completed.

Finally, for the entire duration of the project, local (province of Brescia) and regional (Lombardy) surveys will be carried out on the quantitative flows of CDW, their management and treatment methods, and their destination, in order to monitor the state of the art and any further developments in the sector. In addition, part of the activity will be devoted to monitoring and assessing the direct and indirect impacts of the project from the environmental and socio-economic perspectives. In fact, LCA (Life Cycle Assessment) and LCC (Life Cycle Costing) analyses will be carried out, CO_2 emissions will be assessed and monitored, and the KPI (Key Performance Indicator) database will be periodically compiled and updated, a step that is essential to monitor the real impacts of the project both during its lifetime and in subsequent years.

The environmental, social and economic benefits, highlighted above, can thus be related to the Life CDW Circle project by means of the following four macro-categories of benefits, which briefly describe the transition from the current situation (baseline) to the expected results at the end of the project:

- Reduction in raw material consumption: the Life CDW Circle project aims to produce RAs with high added value, suitable for concrete production, helping to reduce the extraction of natural aggregates from quarries;
- Improved waste management: the Life CDW Circle project aims to implement extensive recovery of construction and demolition waste (CDW), helping to reduce the amount of waste to landfill;
- Reduction of CO_2 emissions: the Life CDW Circle project aims to install an innovative treatment plant that operates with low CO_2 emissions;
- Efficient resource management: the Life CDW Circle project aims at the potential market introduction of RAs with high added value, which can be a real competitive factor and be used to replace natural raw materials.

5. CONCLUDING REMARKS

This paper provides a detailed overview of the current situation of recycled aggregates (RAs) management and use in Italy, highlighting benefits and critical issues. An analysis of the literature shows that the use of RAs as a partial replacement of natural aggregate for concrete production is possible and is also provided by current regulations, which give limit percentages depending on the type of RAs and concrete characteristics (strength and exposure). The origin, processing technologies, physical, chemical and performance properties, and possible release of contaminants by RAs are among the main factors to be analyzed and considered for their proper and conscious use for concrete production.

The Life CDW Circle project aims to address the aforementioned critical issues, which limit the use of RAs for concrete production, through the implementation of an innovative treatment plant for obtaining RAs with high added-value and an in-depth characterization of RAs themselves and of concrete produced with them. The project thus represents a novelty on the Italian scenario and aims, once concluded, to be replicable even at other plants both in Italy and abroad, so as to fully embrace the principles of circular economy and of a more conscious and responsible use of resources.

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