OVERVIEW OF SELECTED RECYCLABLE MATERIALS FROM CONSTRUCTION AND DEMOLITION WASTE

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Abstract: *Construction and demolition (C&D) waste represents one of the largest sources of waste globally, with a significant impact on the environment. By recycling this waste, the process of transforming discarded materials into sustainable resources, reduces the consumption of natural resources and CO_2 emissions. Compared to reuse, recycling involves processing materials such as concrete, brick, tiles, and glass, and transforming them into aggregates, filler materials, or supplementary cementitious materials (SCM) for further use in construction sector. This paper explores the potential of recycling C&D waste through the analysis of suitable materials for processing, their properties, and applications. In addition, legal frameworks and regulations in Serbia and worldwide is reviewed in order to compare recycling rates and challenges in implementing sustainable solutions. The findings show that the building industry should practice recycling, as it has a positive impact on the world and contributes to sustainability.*

Keywords: *sustainable building materials, concrete, brick, tile, glass*

1. INTRODUCTION:

The problem of waste generation, including waste from construction, renovation, and demolition of buildings and infrastructure, is a global issue. According to European Union legislation [1], construction and demolition (C&D) waste includes materials generated during the construction, renovation, reconstruction, demolition, or dismantling of buildings and infrastructure. These materials may include concrete, bricks, wood, metals, glass, plastic, gypsum, soil, asphalt, and other materials. Managing this waste involves activities such as separate collection, sorting, transportation, storage, preparation for reuse, recycling, and/or disposal, thereby reducing the negative environmental impact and promoting sustainability through effective resource management.
The European Union adopted the Waste Framework Directive [2], which provides basic guidelines for managing all types of waste, including C&D waste. This directive emphasizes the importance of reducing waste generation, reuse, recycling, and other forms of waste recovery, as well as proper disposal when recycling is not possible. The EU has also adopted a Waste Catalogue [3] that classifies different types of waste, including C&D waste, for easier identification and management.
In Serbia, the management of construction waste is regulated by laws and subordinate regulations that align with European standards. For example, the Regulation on the Method and Procedure for Managing Construction and Demolition Waste [4] stipulates obligations related to collection, sorting, transportation, and storage of this waste, as well as the requirement to create a waste management plan for certain categories of buildings.
Worldwide development projects are being undertaken to expand and improve urban infrastructure facilities, which result in around 30% to 40% of C&D waste in the total waste generation [5]. In Europe, C&D waste accounting for 25-30% of total generated waste [6]. Consequently, the construction industry contributes significantly both to environmental degradation and to the consumption and depletion of natural resources [7, 8]. According to the European environment State of the Environment Report 2020 report [9], although European policies have helped to improve the environment in recent decades [10], Europe is making insufficient progress, and the environmental outlook for the next decade is not encouraging. Waste management practices also need to be improved. Despite being the least favourable option in terms of environmental impact and risks to human health, landfills are still broadly used as waste disposal sites for Municipal

Solid Waste in Europe [11]. Construction waste is generated from works carried out on buildings from the foundation upwards, as well as civil engineering works such as the construction of roads, railways, canals, dams, sports and recreation facilities, ports, airports, etc. The composition of construction waste depends on the type of construction work and the used techniques. Construction waste is classified based on its content and composition according to the European Waste Catalogue [3]. It is divided into five main categories [6]:

- Soil waste (including sand, clay, stones, mud, etc.), typically produced from excavation activities before construction begins. This waste can sometimes be mixed with organic plant materials.
- Packaging waste from construction materials, such as wooden pallets, plastic, and cardboard, although less common in construction activities.
- Residual construction materials, which include both natural stone (concrete, ceramics, aggregates, and their mixtures) and non-stone materials (steel, iron, aluminum, copper, glass, wood, plastic, asphalt, etc.), are generally more uniform in construction projects.
- Hazardous waste, such as contaminated soil and excavated materials, and substances with potentially dangerous properties. This includes flammable concrete additives, adhesives (flammable, toxic, or irritating), tar emulsions (toxic, carcinogenic), asbestos-containing materials in breathable forms (toxic, carcinogenic), wood treated with pesticides or fungicides (toxic, ecotoxic, flammable), coatings with halogenated flame retardants (ecotoxic, toxic, carcinogenic), equipment containing Polychlorinated Biphenyls (PCBs) (ecotoxic, carcinogenic), mercury-based lighting (toxic, ecotoxic), systems with Chlorofluorocarbons (CFCs), gypsum components (potential sources of sulfides in landfills, toxic, flammable), containers for hazardous substances (solvents, paints, adhesives, etc.), and packaging contaminated with hazardous materials.
- Other waste, such as organic materials [12-13].

2. C&D Waste Recycling Challenge

The reduction as will as recycling of C&D waste is critical for society and plays a significant role in promoting sustainable development. Initially, the concerns regarding C&D waste and environmental sustainability were mostly addressed by local governments. However, as the issue grows, it now presents potential risks to both regional and global development [14]. Due to the rapid urbanization around the world, finding economically viable and sustainable solutions for reducing and recycling C&D waste is essential to address the growing conflict between waste accumulation and environmental protection [15].

Although recycling has become more common in the construction industry, the challenge remains in precisely defining the quality of recycling. This is important for comparing different technologies and materials. In non-scientific discussions, terms like remanufacturing, downcycling, upcycling, and even direct reuse are often used interchangeably as forms of recycling, depending on the sector in which they are applied [16].

Recycling is the most extensively studied strategy, focusing on the post-use phase of buildings, with the goal of effectively applying materials. Its purpose is to transform C&D waste into new products that can be reused in the construction industry or other sectors. By preventing the environmentally damaging or costly disposal of potentially useful materials, recycling also helps to reduce the demand for new, raw resources [17]. Recycling involves the on-site sorting of materials and their further reprocessing to convert them into new products.

The costs related to managing and recycling C&D waste for producing value-added products can be significant, as it involves processes such as material screening and reprocessing. This imposes a heavy financial strain on companies focused on C&D waste management, pushing them to ensure profitability [18]. Concrete, specifically for the production of recycled concrete aggregates, is the most commonly recycled material in the construction and demolition industries. The updated Waste Framework Directive [2] introduced the end-of-waste (EoW) criteria to facilitate recycling and turn waste into valuable resources. EoW criteria outline conditions under which waste ceases to be classified as waste and can be treated as a marketable product. If waste, after being processed, has a useful purpose, is in demand, meets technical standards for similar raw materials, and does not pose risks to health or the environment, it can be deemed to have reached EoW status [19].

It is also important to distinguish between reuse and recycling.

1. Reuse - direct use of the same material or product without changing its shape or composition.
   Examples:
   - Using old bricks for new construction without crushing them.
   - Reusing wooden beams or metal elements from demolished buildings.
   - Using old doors or windows in new buildings.
2. Recycling - the process of reprocessing materials into a new product, often involving physical or chemical changes.
   Examples:
   - Using old bricks for new construction with crushing them.
   - Crushing concrete to produce recycled aggregates.

- Melting steel from demolished structures and using it in new steel constructions.
- Recycling plastic pipes into new plastic products.

The annual generation of C&D waste varies significantly across countries such as China, the United States, India, France, Germany, UK, Netherlands, Italy, Austria, Brasil, Spain, etc. While the United States recycles about 75% of its 600 million tons of C&D waste [20], China recycles less than 40%, and India recycles only 1% [21]. To protect the environment and conserve natural resources, appropriate waste management techniques for C&D waste are essential. Figure 1 shows the countries with the highest C&D waste generation in milion tons.

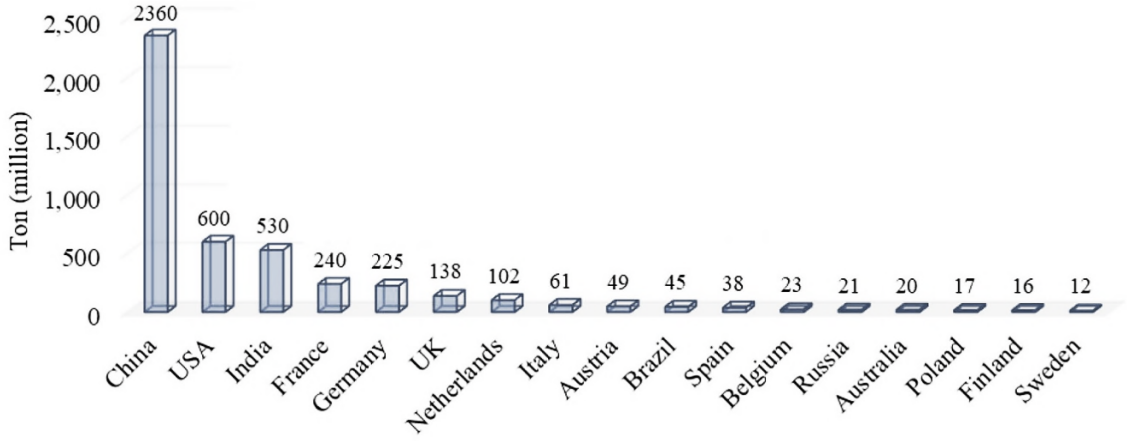


Figure 1: Countries with highest C&D waste generation in million tons [22]

According to the Waste Management Program in the Republic of Serbia for the period 2022-2031 ("Official Gazette of RS", number 30/18) [23], construction waste is classified in the Waste Catalogue [12] under group 17. Non-hazardous C&D waste includes: concrete, soil, brick, glass, stone, plastic, tiles, ceramics, copper, bronze, brass, iron, steel, insulation materials, gypsum, wood, mixed waste, etc. Hazardous C&D waste includes: construction and insulation materials containing asbestos, sealants containing PCBs, glazes containing PCBs, waste from construction and demolition containing mercury, and other C&D waste containing hazardous substances, etc. The majority of C&D waste is disposed of or, more commonly, mixed with municipal waste at local unsanitary landfills.

The estimated composition of C&D waste is as follows [23]:

1. Excavation soil, 75%;
2. C&D waste (ceramics, concrete, iron, steel, plastic waste), 15-25%;
3. Waste asphalt and concrete, 5-10%.

Recycling of C&D waste depends on source separation. Any mixed collection increases the level of contamination and reduces recycling possibilities. Available statistics do not provide realistic potential quantities of C&D waste in the Republic of Serbia. According to data from the Statistical Office of the Republic of Serbia, in 2020, 729,000 tons of C&D waste were generated in Serbia (Statistical Yearbook of the Republic of Serbia, 2021) [24]. However, when compared to the amounts of C&D waste generated in EU countries, the quantities are significantly higher. Taking into account Serbia's GDP (Gross Domestic Product), the potential of 1.6 million tons (upper limit of 3.6 million tons) seems most likely. These amounts, presented in Table 1, were calculated based on assumptions considering total construction turnover, total investments in building construction, GDP of the construction sector, construction activity of contractors in Serbia, and the area of demolished apartments (Municipalities and Regions in the Republic of Serbia for 2020, 2021) [23,25]:

Table 1: Construction Sector in the Republic of Serbia – Statistical Overview of Key Indicators [23]

Indicator	Value
Share of construction in GDP	5.70%
Number of employees in the construction sector in the Republic of Serbia	105,671
Issued construction permits in the Republic of Serbia	22,625
Total investment in construction projects	471,639,883 RSD
Completed buildings and total area	1,961,112 m²
Demolished buildings and total area	129,599 m²

3. Global and Local Regulations on C&D Waste Management

In the Republic of Serbia, there is currently no practice of separate collection of C&D waste, nor is there a recycling scheme for this type of waste. Only small amounts of C&D waste are recycled, and asphalt is recycled in minimal quantities (less than 1,000 tons in 2018) [23]. Although there is a general legal obligation for waste producers to collect separately and sort waste according to future treatment, this provision is not in effect due to the absence of a bylaw. As a result, mainly high-value waste such as metals is recycled, while other potentially recyclable materials are disposed of in landfills or, more often, end up in illegal dumping sites. There are no quality standards for treated C&D waste. The key indicator for the recycling rate of C&D waste, in relation to the specific goal of increasing recycling rates for special waste streams and more efficient resource use, is that the target value (2031) compared to the baseline (2020) should be 40 times higher [23]. Globally, the management of C&D waste is regulated by various laws and directives depending on the region and country. Some of the most important legal frameworks are:

European Union (EU)

- Waste Framework Directive (WFD) 2008/98/EC - Establishes a waste hierarchy and requires EU member states to recycle at least 70% of construction waste by 2020.
- End-of-Waste Criteria (EoW) - Defines the criteria under which construction waste ceases to be waste and becomes a resource.
- Landfill Directive 1999/31/EC - Limits the disposal of construction waste in landfills and promotes recycling.

United States (USA)

- Resource Conservation and Recovery Act (RCRA, 1976) - The primary law regulating waste management, including construction waste.
- EPA Guidelines on C&D Waste Management - The U.S. Environmental Protection Agency (EPA) provides guidelines for recycling and reducing construction waste.
- Green Building Standards (LEED, WELL, etc.) - Standards such as LEED encourage the use of recycled materials and responsible waste management in the construction industry.

China

- Circular Economy Promotion Law (2009) - A law that promotes recycling and reduction of construction waste.
- Construction Waste Management Regulations - Regulations in major cities (e.g., Beijing, Shanghai) governing the disposal and recycling of construction waste.

Australia

- National Waste Policy (2018) - Aims for 80% of construction waste to be recycled by 2030.
- State-Level Regulations - Each Australian state has its own regulations for managing construction waste (e.g., New South Wales Waste Levy).

Japan

- Construction Material Recycling Law (2000) - Requires contractors to separate and recycle concrete, wood, asphalt, and other materials.

All these laws and regulations share a common goal – reducing construction waste and increasing recycling through circular economy strategies.

In the Republic of Serbia, the management of C&D waste is regulated through several key legal acts:

- Waste Management Law - This law defines waste types and classification, waste management planning, responsibilities, and obligations of entities involved in waste management, including special waste streams such as construction and demolition waste [26].
- Regulation on the Manner and Procedure of Managing Construction and Demolition Waste - This regulation prescribes activities and measures for managing waste generated during construction and demolition, including separate collection, sorting, transport, storage, preparation for reuse, and disposal of construction waste [27].
- Rulebook on the Arrangement, Management, Disposal, and Landfilling of Construction Waste during Works Execution - This rulebook introduces the obligation to develop a construction waste management plan for projects of specific categories, defines the responsibilities of waste owners and contractors, and establishes procedures for extracting useful components from buildings before the start of work [28].

These regulations together form the legal framework for responsible and efficient management of C&D waste in Serbia, with the aim of protecting the environment and promoting recycling and reuse of materials.

4. Applications of Recycled C&D waste in Construction Sector

Recycled materials are becoming an essential component in the sustainable construction industry. In this review, the most commonly used recycled materials and their application are analyzed. These materials are used as aggregates, fillers, or

supplementary cementitious materials (SCMs), i.e. materials that partially replace cement in cement-based composites, as shown in Table 2.

Table 2: Application of Recycled C&D Waste Materials in Construction Sector and Relevant Literature Review

Material	Use of C&D Waste as Material	Literature Review
1. Concrete	Recycled Aggregate: Coarse and fine aggregates obtained by crushing old concrete replace natural aggregates. Filler: Finer parts of recycled concrete are used as fillers in concrete and mortars. SCM: Crushed concrete powder can replace cement in concrete mixes to reduce CO_2 emissions.	Zhang et al. [29] investigate the properties and processing of mixed recycled concrete aggregates to improve sustainability and reduce the ecological footprint in the construction industry. Oliveira et al. [30] use of recycled concrete powder as SCM in cement mortars. The results showed that there is potential for reducing binder consumption by 9% and carbon emissions by 8% for mortars at age of 91 days. Xiao et al. [31] presented a method for preparing foamed lightweight soils using alkaline-activated recycled concrete powder from prefabricated buildings.
2. Bricks	Recycled Aggregate: Crushed bricks replace natural sand or gravel in concrete mixes.. SCM: Ground brick replaces cement in concrete, improving durability and reducing CO_2 emissions.	Mohan et al. [32] conclude that crushed brick powder, which mainly consists of silica and alumina, exhibits pozzolanic properties when processed at specific temperatures, leading to increased hydration and improved strength and durability of concrete. Wong et al. [33] summarize the potential use of waste brick as a binder and aggregate substitute in concrete.
3. Tiles	Recycled Aggregate: Crushing ceramic tiles provides aggregates for concrete. Filler: Tile powder improves density and rheological properties of concrete.	Paul et al. [34] investigated the use of waste ceramic tiles as a partial replacement for natural coarse aggregate in concrete. Otunyo and Arinze [35] investigated the partial replacement of fine aggregate with crushed waste ceramic tiles in concrete and found that the highest compressive and flexural strength was achieved at a 40% replacement level. Malik et al. [36] explored the use of crushed ceramic tiles as an alternative construction material to address the increasing demand for construction materials and environmental degradation.
4. Glass	Recycled Aggregate: Crushed glass replaces sand in concrete, reducing natural resource consumption and improving aesthetics. Filler: Ground glass improves surface finish and reduces concrete permeability. SCM: Glass powder can partially replace cement, reducing CO_2 emissions.	Boukhelf et al. [37] investigated the use of glass powder as a SCM in concrete, showing improved mechanical properties and reduced cement consumption. Khan et al. [38] reviewed the use of waste glass as SCM and fine aggregate, finding improved durability with 10–40% cement replacement, despite a slight strength reduction.
5. Stone	Recycled Aggregate: Crushed natural stone is used as a replacement for natural aggregate, providing excellent strength and durability to concrete. Filler: Stone dust (rock dust) can serve as filler that improves the density and compactness of concrete, reduces porosity, and increases wear resistance.	Dobiszewska et al. [39] studied the use of stone dust from various sources as a substitute for fine aggregate in cement composites, showing improved workability and increased mechanical properties.

Recycled construction materials from C&D waste have a wide application in the construction sector. Concrete is most commonly used by crushing old concrete and using it as coarse or fine aggregate, replacing natural aggregates. Its finer particles serve as fillers in concrete and mortars, while ground concrete powder can be used as a substitute for cement to reduce carbon dioxide emissions. Studies, such as those by Zhang et al. [29], focus on improving sustainability through the processing of mix recycled concrete aggregates. Oliveira et al. [30] examined the use of recycled concrete powder as SCM in cement mortars, that showed a promising alternative for the production of environment-friendly cement, while Xiao et al. [31] develop methods for producing lightweight foamed materials using recycled concrete powder.

Similarly, crushed bricks are used as a substitute for sand or gravel, and when finely ground, they can replace cement in concrete mixtures, improving durability and reducing CO_2 emissions. Mohan et al. [32] conclude that brick powder, rich in silica and aluminum, has pozzolanic properties when thermally processed, contributing to better hydration and strength of the concrete. Wong et al. [33] also confirm the potential of using waste bricks as a replacement for aggregate and binder.

Ceramic tiles, when recycled, are mainly used as aggregate in concrete but also as fillers that improve the density and rheological properties of the mix. Studies show that replacing natural aggregate with ceramic waste up to a certain level can result in increased strength. Paul [34], Otunyo and Arinze [35], and Malik [36], along with their colleagues, investigate various aspects of ceramic tile application and highlight their potential as a sustainable material in construction sector.

Glass also has multiple applications – crushed glass is used as a substitute for sand, reducing the use of natural resources, improving the appearance and finishing of concrete, while in powder form, it can reduce permeability and partially replace cement. Boukhelf [37] and Khan [38] et al. show that the use of glass powder can improve the mechanical properties and durability of concrete, although a slight reduction in strength is observed at higher substitution levels.

Finally, natural stone is mainly used as aggregate, but also as a filler in the form of stone dust. This material provides excellent strength and durability of concrete. The study by Dobiszewska et al. [39] confirms that stone dust improves the workability and mechanical properties of concrete composites.

This review shows that various recycled materials from C&D waste, such as concrete, bricks, tiles, glass, and stone, can successfully be used as partial replacement of materials from natural resources, with additional benefits in terms of emission reduction and improvements in durability and sustainability of obtained construction materials.

5. CONCLUSION

The study on the recycling of C&D waste highlights its significant role in improving sustainability within the construction industry, which is one of the largest contributors to environmental degradation. Given that construction and demolition activities generate a large portion of global waste, it is important to adopt more sustainable practices. Recycling C&D waste reduces material costs, protects natural resources, and addresses waste management issues.

Recycling of C&D waste materials such as concrete, bricks, tiles, glass, and stone reduces dependence on natural raw materials, thereby decreasing the environmental impact of resource extraction, production, and CO_2 emissions. Additionally, recycling helps conserve land, water, and energy, which are often overused in traditional construction processes.

On a global scale, the recycling of C&D waste is not equally developed. For example, the United States manages to recycle about 75% of its generated waste, while countries like India and China have much lower recycling rates, at only 1% and below 40%, respectively. These differences highlight the need for localized solutions that consider economic capabilities and infrastructure.

In Europe, C&D waste accounts for 25-30% of total waste, and progress in recycling varies across countries. While developed nations achieve good results with support from legislative frameworks, challenges remain in areas such as regulatory enforcement, infrastructure development, and industry involvement.

Serbia, as a country in transition, faces its own unique set of challenges when it comes to managing C&D waste. Despite generating approximately 729,000 tons of C&D waste in 2020, the country recycling rate remains low, and a more comprehensive strategy is required to tackle the growing waste issue.

The Waste Management Program in Serbia (2022-2031) sets ambitious goals for waste reduction and recycling but achieving these targets will require significant investment in waste management infrastructure, public education, and capacity building.

Ultimately, the recycling of C&D waste holds the potential to play a crucial role in transforming the construction industry into a more sustainable and resource-efficient sector. Beyond reducing waste and conserving resources, it could contribute to the creation of green jobs, reduce carbon footprints, and foster a more circular economy that benefits not only the construction industry but society at large.

This study shows that concrete, bricks, tiles, glass, and stone can be successfully used in construction sector as SCMs, fillers, or aggregates in certain quantities.

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