

Article

Use of Waste Building Materials in Architecture and Urban Planning—A Review of Selected Examples

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Abstract: Modern environmental protection standards have a direct impact on the construction and shaping of public space. Designers are increasingly reaching for materials produced via recycling technologies. Waste materials are more readily adopted and used in urban planning and architecture. Current projects in this area are being increasingly designed to meet the requirements of the circular economy, which is facilitated by the reuse of once-used components. The aim of the study is to review research papers in the Scopus database (bibliometric analysis) and other selected materials applied in construction, which are recycled and used again in various ways in the construction of subsequent buildings. The results show various application possibilities of recycled materials in construction. The study draws attention to the fact that the use of recycled materials in modern construction is becoming more and more effective, which may contribute to increasing the share of the circular economy in the implementation process related to this subject.

Keywords: architecture; urban planning; waste building materials; recycling; environmental protection; environmental impact assessment



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1. Introduction

Modern times have brought challenges of increasing environmental degradation. Like never before, environmental issues have become a leading issue in the field of human activities related to climate change, air pollution and the use of natural resources. The industrial revolution enabled the mechanized production of materials and their manufacture on a mass scale. This process continues to this day. It determines the way we design, make and end the lives of both everyday products and buildings. So far, the environmental costs associated with natural raw materials, the energy required in the process of their creation, and the waste associated with their production have not been an important factor in these processes; what has mattered is significant growth, meeting the demand for these materials and the profit from their production [1].

Such a production model operating for decades has led to environmental degradation in many areas of the globe, through the contamination of water, soils, and air. Moreover, the construction sector has a significant impact on environmental costs; this part of human activity contributes almost 36% to the generated waste [2]. This waste is most often in the form of demolition debris. The problem, in addition to the composition of this waste, is its volume, and therefore problems associated with its storage.

Construction-related activities exploit natural resources and use considerable energy inputs to produce materials, at the same time discharging the by-products of these processes into the soil, water and atmosphere. The energy inputs required to transport heavy and voluminous building components are also quite significant [3].

The whole process starts at the stage of obtaining raw materials, often at a considerable distance from the final place of incorporation, which involves the energy costs of extraction and transport. With growing cities, the demand for new buildings is constantly increasing. These processes cannot be stopped or slowed down. We are at the point where new technologies need to be developed that allow materials once used to be reused in new buildings, or as raw material for processing [4].

In order to level the problems associated with the increasing amounts of construction waste, measures are being taken at the governmental, national and regional levels in the entire European Community [5], as well as in global markets [6]. These aim to regulate materials' management activities that would be sustainable and contribute to the reduction in greenhouse gas emissions [7]. This includes materials from the demolition of facilities as well as those generated during the construction process [8]. Importantly, these measures cannot be introduced immediately; they are spread over years and these changes most often begin with public buildings [9].

Guidelines on how to deal with building materials from demolition are included in the European Parliament regulations. In these documents, it is stated that EU member states should aim to promote preparations for the reuse of materials in their markets [10]. While doing so, the member states should enforce separate waste collection systems to enable the separation of hazardous materials for disposal, and facilitate the sorting of the construction and demolition waste into different categories: wood, mineral fractions (concrete, bricks, tiles, ceramics, stones), metals, glass, plastics and gypsum [11].

The subdivision of the different groups of materials that are not classified as hazardous is included in the decisions of the European Council. The main group comprises construction and demolition waste. The first subgroup includes concrete, bricks, tiles and ceramic materials, and mixed waste of concrete, brick rubble and other ceramic waste, as well as fixtures. Mixed waste should not contain hazardous substances. Another subgroup consists of wood, glass and plastics. The last part contains metal components, including metal alloys such as copper, bronze, brass, aluminium, lead, zinc, iron, steel, tin, metal mixtures and cables that do not contain hazardous substances [12].

The above construction materials placed on the market should take into account their recyclability for the sustainable use of natural resources. Under this legislation, emphasis is placed on the use of recycled materials in newly constructed buildings [10].

Initiatives to recover some of the materials created during the construction and end-of-life stages of a building are also emerging independently of government legislation. The two leading solutions operating globally are LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) certifications. The certification of an investment is graded on the basis of points that are awarded for, e.g., achieving an appropriate percentage of recycling or waste recovery for the investment [13]. These measures should, in the first instance, correspond to the 3Rs principle: reducing the use of materials in the first place, followed by the reuse of once-used materials, and, as the last item, the recycling of building materials [14].

Measures related to the sustainable management of construction materials, in addition to establishing the principles mentioned above, should also include supporting companies and the economy by making the data available, digitizing construction processes, promoting the circular economy through design, and changing consumption patterns to create a market for waste and recycled materials [9]. These elements are part of the broader initiative of the 17 UN Sustainable Development Goals to move towards a circular economy in many fields of human activity, including sustainable architecture [15].

The most favourable solution is to reuse once-used materials in their entirety for the construction of new buildings. This bypasses the extraction and processing of raw materials. The financial and environmental costs incurred are limited to those of dismantling, transporting and building on a new site (this ideal situation is depicted in Figure 1). The second-best approach is the processing of materials from building demolition in addition to new materials [16]. An additional cost is related to the process of shredding or re-melting

the material. An important factor in each of these cases is the costs associated with the recovery of the materials, and therefore their competitiveness with new materials. If the use of recycled materials could be introduced on a large scale, it should be cost-competitive and provide a high quality of use and aesthetics [17]. Another significant barrier to the marketing of recycled materials is the issue of regulation related to their processing and production. A major obstacle is related to obtaining recycled materials that are homogeneous in their properties and composition. These materials may additionally be contaminated with undesirable substances introduced intentionally or unintentionally at the production stage, and also contaminated by external influences acting on the material, which will later be a source of raw material for CDW materials. This issue is addressed by the concept of a circular economy, which involves the widest possible reuse of materials created as part of the recycling process [18]. By processing waste through chemical processes, new building materials or components of their mixtures are created [19]. The skilful use of these components often allows for the reinforcement, and development of better technical properties, of the base materials. This is the case with the addition of glass dust (GP) to cement and concrete mixtures, as well as in the use of wood residues in the structural systems of new buildings [20,21]. The situation is similar in the cases of metal and concrete, where residues of these materials are transformed into fragments of concrete or re-melted into other metal elements. The circular economy is extremely relevant to conservation and climate actions [22]. Research on the reuse of recycled materials in architecture and construction is part of a broader scientific trend related to wide-ranging environmental and climate protection goals [23]. The economic factors associated with the recovery of materials from waste should also be considered [24]. These relate to cost-saving and the shortening of the assembly and realization process during construction [25]. Knowledge related to the reuse of recycled materials in construction requires constant publicity aimed at the construction industry and the target users of such solutions, because it allows for greater savings of resources and energy, and is environmentally friendly. The described review of the possibilities of using specific types of materials is in line with the assumptions of the circular economy, which is a strategy that allows for greater environmental and climate protection; therefore, research related to the topic should be promoted and gain public awareness.

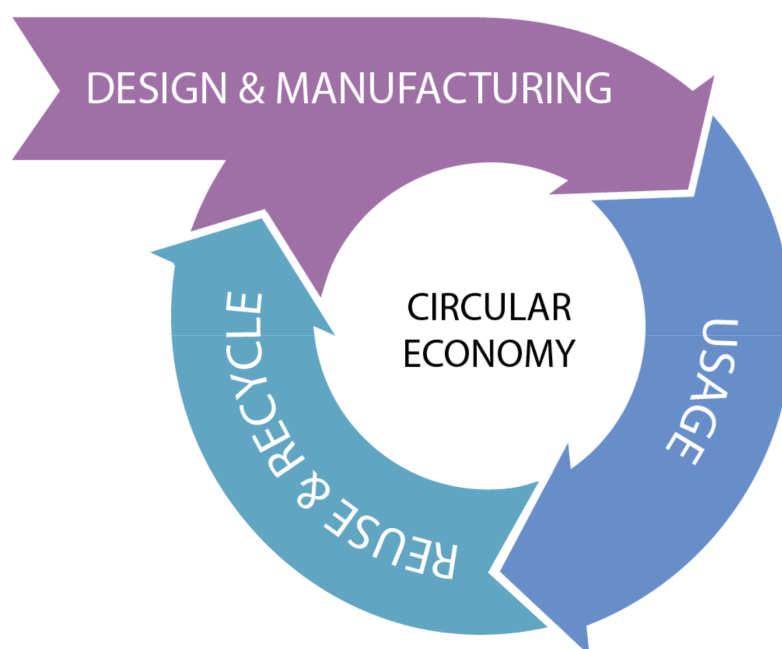


Figure 1. Circular flow of materials in the circular economy in the building life-cycle phases.

This study presents different types of recycled materials used in construction related to urban planning and architectural design. It shows the specificities of metal, ceramic, concrete, plastic and wood as elements that, after being processed, become components of subsequent mixtures used in construction. In addition, detailed solutions for the application of recycled materials in specific construction, execution and finishing problems are discussed. A compilation of guidelines and possible pathways for dealing with building materials at the end of their life-cycle is posed as the main objective of the study.

2. Materials and Methods

This paper is a review of the recycling of building materials in the context of architectural design. Therefore, it addresses the issue of the circular economy (CE) [26–29]. The main research goal was to draw attention to the diversity of the use of selected recycled materials in construction, architecture and urban planning, which are metals, wood, ceramics, plastic, stone and glass. These materials are recognized as the most relevant during preliminary studies on recycled materials used in architecture and urban design.

The review was carried out through a bibliometric analysis and selected project reviews. After (1) identifying the research goal, we (2) identified relevant studies, (3) selected studies based on particular aspects, and (4) collected, summarized, and reported the results [30,31].

(I) The bibliometric analyses were carried out to trace the intellectual structure of the research field [32,33]. The bibliometric analyses were performed using Scopus. The scope of the review of research papers was limited to the last 5 years, in order to present the most current state of research. Therefore, the study was limited to works published between 2014 and 2022 in all English-language articles, in the following subject areas: Engineering, Materials Science, Environmental Science, and Energy. The literature dataset from the Scopus search string was built as follows:

- For metal materials—TITLE-ABS-KEY (“recycled” AND “metal” AND “architecture” OR “urban design”). A total of 79 papers based on this Scopus search were found;
- For wood materials—TITLE-ABS-KEY (“recycled” AND “wood” AND “architecture” OR “urban design”). A total of 37 papers based on this Scopus search were found;
- For ceramics materials—TITLE-ABS-KEY (“recycled” AND “ceramics” AND “architecture” OR “urban design”). A total of 18 papers based on this Scopus search were found;
- For plastic materials—TITLE-ABS-KEY (“recycled” AND “plastic” AND “architecture” OR “urban design”). A total of 72 papers based on this Scopus search were found;
- For stone materials—TITLE-ABS-KEY (“recycled” AND “stone” AND “architecture” OR “urban design”). A total of 17 papers based on this Scopus search were found;
- For glass materials—TITLE-ABS-KEY (“recycled” AND “glass” AND “architecture” OR “urban design”). A total of 49 papers based on this Scopus search were found.

The above literature dataset represents a departure point for choosing a study that focuses on selected aspects of the use of wood, plastic, concrete, glass, ceramics and metal related to construction and architecture. In the case of wood, attention was paid to the process of using recycled wood in the construction of new architectural objects and to the use of recycled materials obtained in this way in architectural constructions. The discussion presents examples of such solutions. Describing the use of recycled plastic, the focus was on architectural and artistic elements used in public spaces. The discussion focused on the use of plastic in concrete mixes. Recycled concrete was described in terms of the general possibilities of use in construction and architecture, and the discussion referred to the use of this material in chemical mixtures used in construction. When describing glass, the general aspects of applications in construction were discussed, and the discussion focused on the use of this material in cement and concrete mixes. When analyzing the use of recycled ceramics, attention was paid to original solutions in architecture and interior design, and the discussion referred to the use of this material in the re-production of building materials. When examining the use of recycled metal, the focus was on its modes

of use in the construction process, and the discussion referred to the use of this element in chemical mixtures used in construction.

(II) A project review was carried out to supplement the data acquired during the bibliometric analysis. The scope of the review concerned architectural and urban projects completed around the world between 2010 and 2022. Project documentations published by their authors were studied.

Subsequently, a discussion of the results was carried out. The materials studied were compared. Recommendations were then worked on and are included in the conclusions.

3. Results

3.1. Wood

Wood has a wide range of applications in modern construction, including the possibility of replacing energy-intensive and potentially harmful building materials [34,35]. At the same time, increasing the use of wood materials in the construction industry will directly reduce and limit the CO₂ produced during the building process. There is no doubt that this will have an impact on improving the environment and air quality [36]. Wood is environmentally friendly and, following sustainable forest management, can be continuously renewable [36].

Wood material deposited in landfills represents significant potential for closed-loop reuse in the construction industry [28]. Its main sources are in the construction sector, municipal solid waste, and the wood processing industry (Figure 2). The construction industry generates a huge amount of wood construction waste resulting from (i) new constructions, (ii) the renovation and upgrading of existing stocks, and (iii) building demolition [37]. According to the Construction and Demolition Recycling Association (CDRA), wood accounts for at least 20–30% of all construction and demolition waste (CDW) [38]. The proportion of CDW wood waste varies according to the country of generation. It is estimated to be 26.7% in Germany [38], 10–16% in Brazil [39], and 6–7% in the United States [40].



Figure 2. The process of using recycled wood in the construction technology.

Recycled wood is easy to sort and does not require complex processing. Recycled CDW wood waste can be classified into three categories: (i) Untreated Wood Waste, (ii) Engineered Wood Waste (EWW), and (iii) Preservative-Treated or Painted Wood Waste. Untreated timber and construction wood waste, depending on its softness, can also be used, e.g., as softwood for the production of packaging or pallets, and as hardwood for the production of window frames or furniture. Structural timber can often also be directly reused in the construction industry, e.g., for finishing or as a building material. Treated and painted wood waste can be used for OSB, MDF, chipboard, or plywood production [41,42]. Non-recyclable wood, on the other hand, can be used in the energy industry as a biomass fuel.

Wood waste that is not recovered through recycling is disposed of and stored, mainly in landfills or by incineration [43,44].

Wood material offers potential value to industry—its use also responds to the growing need for environmentally friendly products [45]. The construction industry is seeing an increasing number of building projects that use wood directly collected from the demolition process. This solution is particularly popular in sustainable buildings, as it is also addressed in green building certification programs [46]. Unfortunately, it represents a small proportion of the market for building materials; according to a UK study, around 10–15% of the timber used in new construction is recycled [38].

3.2. Plastic

The scientific research on the use of plastic waste offers many solutions at the level of architecture and urban planning. In the literature, we can find studies on how to conduct biodegradation processes [47] to reduce the amount of landfilled plastic waste, but also recycling solutions through which the material can be reused.

Recycling researchers study aspects of building materials' reuse in architecture over centuries of tradition. When considering what is known as container architecture, the phenomenon of reusing stone, wood, columns, paper, or plastic is cited as beneficial from economic and environmental perspectives [48].

When analyzing scientific reports on the secondary use of plastic, it can be concluded that plastic waste is used as a substance in many fields. In contemporary visual art, sometimes referred to as post-art, examples include the works of the famous Polish artists Tadeusz Kantor and Władysław Hasior. Like many other fields, contemporary architecture is also looking for new means of expression. Epochal changes are directing forms to pick up anti-aesthetic tendencies. Approaches exposing flaws, traces of wear and tear, old age and deformations are being clarified. In architecture, anti-aesthetics is also expressed through the use of waste as a building material [49].

The trend promoting the use of plastic waste in architecture emerged in the 1970s as a form of rebellion of the art world against poverty and economic stratification, and the consequent isolation of the poorest groups of society from the stream of consumerism. Tomasz Wagner [50], in addition to an interesting classification of phenomena related to the use of waste in architecture and art, cited after Marek Krajewski [51], gives examples of the use of once-used materials as consciously reused structural materials. He classifies plastic packaging in the group of recycled materials used as physical building blocks.

This historical perspective, which opens up horizons for the understanding of consumerism and the overproduction of plastic waste, points to the need for in-depth reflection not only on poverty, and social and economic stratification, but also on the growing problem of littering. Further questions arise, addressing the consideration of ecology and the reuse of plastic as a substance that is almost completely resistant to biological degradation. As the amount of plastic waste is of particular concern for the environment, attempts are being made to develop policies to manage this waste so that recycling processes reuse these materials, including via their application in architecture [52].

Researchers have found uses for plastic waste in the production of the most common traditional building material in architecture, i.e., bricks. They report that the production of bricks from plastic waste is an alternative to their traditional manufacture, and that this production is the most economical and environmentally friendly solution in the construction industry [53].

Another aspect involves the construction of buildings using waste PET bottles as a construction material standing in for standard bricks. Researchers' attention is being drawn to the issue of difficult biodegradation, with the reuse of non-degradable materials becoming the most environmentally friendly solution. Researchers point to the speed of the process, as it does not require the curing time that traditional bricks do, as well as energy savings, the lack of carbon dioxide emissions produced in the firing process of traditional bricks, and the low weight of the material coupled with its greater strength. At

the same time, they emphasize the energy efficiency associated with heat retention inside the buildings [54] (Figure 3).



Figure 3. PET bottles used as flowerpots in a public space in Zurich. Source: authors' photograph.

Another aspect related to the reuse of plastics for house construction refers to economic values. The problem of poverty is highlighted and linked with the reuse of PET bottles, with the advantages cited as accessibility, economy, environmental protection via reducing excessive litter, and also thermal and acoustic insulation [55].

An alternative use of plastic waste for reuse as fuel materials is also being considered. It may be possible to generate energy from plastic waste to heat homes using the pyrolysis process [56]. Another aspect of plastic reuse in architecture and urban planning is road construction [57]. The research results emphasize the fact of moisture absorption, reduced rutting and pothole formation, and the overall improved durability of roads covered with a layer of recycled plastic [58]. Examples of the use of recycled plastic waste are numerous, from art (as an expression of dissent), through the latest thermal energy technologies, to architecture and construction. Architectural uses of plastic waste include insulation materials, window frames, roofing, noise barriers, playground and sports surface coverings, landscaping elements, decking boards, installation pipes and ducts, etc. [59].

Analyses of the literature on the subject lead to the conclusion that any possibility of reusing plastic is ecologically and economically legitimate. From an architectural and urban planning perspective, it seems to fit into the holistic design trend, taking into account environmental aspects through the use of secondary building materials. A reorientation of views, inclined to see rubbish as a raw material, is becoming a necessity [60], as cited in [59].

3.3. Concrete

Concrete is the building material contributing the greatest carbon footprint; its production has a large environmental impact. It is used in construction on a large scale, most often in building construction [61–63] (Figure 4). Research is being conducted on the reuse of aggregates from recycled concrete, but this may generate technological problems related to the change of its chemical properties, durability and strength. Traditional concrete production uses cement, water, sand and aggregates. The last two elements can be recovered from concrete waste, replacing natural materials. However, recycled concrete does not have exactly the same properties as classic concrete; a decrease in elasticity and greater shrinkage are observed [64]. Despite this, it is assumed that recycled aggregates can be used in the concrete production process. However, this should be preceded by a series of tests, not only of the aggregate itself, but also of the final material obtained [62,63]. For this reason, recycled concrete is most often used in non-structural elements. However, in recent years, new recycling methods aimed at improving the secondary properties of concrete have emerged, e.g., by impregnating the aggregate with cement slurry or oil. Another method is to remove the cement mortar from the surface of the recycled aggregate by mechanical abrasion, the additional annealing of the rubble, or the gravitational classification of the aggregates due to their density [63,65–67]. An alternative method is to add superplasticizers to the recycled aggregates, which improve the mechanical properties of concrete [68].



Figure 4. Recycled concrete—construction of a multi-family house, designer A. Starzyk (author’s photography).

Recycling reduces the consumption of raw materials for the production of concrete, minimizes waste, and reduces water consumption by up to 30%, which translates into investment returns.

The concrete recycling phases include [64,66–68]:

- I. The crushing of rubble—concrete rubble → primary crushing → secondary grains;
- II. Refining—thermal and mechanical treatment;
- III. Products—(i) coarse fractions ($d \geq 4 \text{ mm}$) (aggregate for high-quality concrete), (ii) fine fractions ($d < 4 \text{ mm}$) (active additive for cement composites, component in the cement production process, active ingredient for autoclave).

In addition to material salvage, the recycling of larger and smaller overall elements derived from demolition or modernization processes is distinguished [69,70]. Building recycling is also distinguished, i.e., the adaptation of entire individual buildings to new functional needs. Buildings made of reinforced concrete, i.e., a material consisting of concrete reinforced with steel bars, belong to the group of buildings contribute greatly to recycling.

3.4. Glass

Glass is an isotropic material with a disordered internal structure, the characteristics of which depend mainly on how it is smelted. The basic raw materials for its production include quartz sand, sodium carbonate and calcium carbonate. In modern construction, glass is used in many ways, the central one of which is to become an element of window structures and façade glazing. It is used as well to make walls, roofs and floors, for which reinforced, flat rolled or tempered glass are used. The material is characterized by the great diversity of its properties [71]. Glass is an inert material that can be repeatedly processed without changing its chemical properties [72]. It can take on different textures, shades and degrees of transparency, as well as different values of thermal resistance and mechanical strength. Such a wide range of characteristics allows us to determine its optimal application in regions with different needs, and climatic and social conditions. To achieve this, it is important to analyze and compare the methods of manufacturing the material and the biometric properties obtained [71].

Waste glass can be reused many times due to the high mouldability of this material. Recycling to make new glass products reduces the amount of raw materials and energy required in the furnace. The vast majority of glass waste consists of material from different sources, which can consequently lead to chemical incompatibility in the recycling process. For this reason, the costly separation of glass waste into appropriate types and colors is necessary. Unsorted glass of an inert nature inevitably ends up in landfills [73]. Due to its chemical properties and chemical composition, among the various municipal solid wastes, glass can be considered as the most suitable substitute for cement and sand [74]. Glass waste is a by-product of the silica-based industry. It consists of about 70% silicon oxides and has pozzolanic properties [75]. This allows it to be used as an alternative to cement, sand or aggregates. Glass waste can be subdivided into glass powder and glass sludge, the latter being produced during the glass grinding process [76].

Post-consumer glass waste is usually part of household waste, or is collected at designated collection sites for reuse. It is the job of environmental authorities to divert post-consumer glass into economically viable glass product streams instead of landfills. Glass can be produced in forms such as container glass, bulb glass, flat glass, or CRT glass. Each form of this material has a limited life in a given form. Once it has completed its designated function, it should be recycled to avoid being placed in landfills [72].

Glass waste can be reused in the construction industry in many ways. The reuses of cullet can include as aggregate for road construction, asphalt, aggregate for concrete, glass tiles and bricks, wall panels, fiberglass insulation, and fiberglass or hydraulic cement [77]. In concrete, glass can be used as coarse and fine aggregate, and in powder form [76] (Figure 5), as an inert aggregate filler or supplementary cementitious material by replacing a certain percentage by weight of cement with it [78]. Recycled glass waste in the form of powder can be used to increase the mechanical parameters of stabilized soil [79]. E-glass waste obtained from electronic-grade glass scrap is also used in cement mixes to improve its properties [80].



Figure 5. Glass recycling process. Source: istockphoto.

3.5. Ceramics

Recent decades have seen significant industrialization and economic development, increasing the quality of life for urban and rural residents. However, it should not be forgotten that any production system produces by-products and wastes that can affect the environment. These can occur at any stage of the construction facility's operations, from construction, through operation and changes, to the death of the building and the need to demolish it. Natural materials used in the construction processes, such as ceramics, contribute to the possibility of reuse only with negligible processing during the production phase. Unfortunately, using them in their natural state in most cases is impossible or uneconomical. As a result, in recent years, there has been growing public concern about the problem of waste management in general, and industrial waste and waste from the construction industry in particular. Among others, the forerunners in the search for a means of recycling ceramic materials were Kats and Kvyatkovskaya, who, as early as 1972, looked for the possibility of reusing ceramic materials [81]. However, it was not until after 2000 that directions toward a circular economy and waste recycling became apparent, mainly due to the development of certifications such as LEED and BREAM [82,83] (Figure 6).

The use of ceramics as building materials requires thermal treatment, through which ceramics achieve a significant load-bearing capacity, but also, depending on the treatment, acoustic and thermal insulation. Their reuse is, therefore, a complex process, based typically on the local use of demolition materials that have similar technological properties and have had similar mechanical treatments to those of the material. The reuse of ceramic materials is possible after cleaning them of mortar, especially when renovating historical buildings. Pure brick materials can be reused in powder form as aggregates for concrete [84,85] and mortar [86,87], and for lime-silicate bricks. The reuse of ceramics is also seen in non-construction-related sectors, such as using red "flour" in tennis court clay surfaces or as unique absorbent substrates for plants. A particular use of recycled ceramics as construction and finishing material is seen in the unique designs of the architect Fernando Menis. He uses a technology that combines crushed red brick and concrete, called Picado. In his design of the Jordanki concert hall in Toruń, Poland, he took advantage of the excellent acoustic properties of crushed red demolition brick, thanks to the considerable roughness of the brick left in its natural state.



Figure 6. An example of using recycled ceramics in a building.

3.6. Metals

Metal products are widely used in the construction industry as homogeneous materials and components of other products [88]. The use of metal products is subject to high environmental costs associated with the extraction of ore and the manufacture of materials, which in turn is linked with the high energy intensity of these processes. This translates into the rather high price of the end product relative to other material groups. The popularity of the use of metal products is influenced by their wide application. This includes steel construction elements, reinforcements in reinforced concrete elements, mechanical fasteners, parts of other products such as doors and windows, and installation elements such as pipes, electric cables, façade and finishing materials (Figure 7). Metal products can be divided into two groups. The first includes ferrous metals, which mostly have a structural function in the construction sector. The second category comprises non-ferrous metals such as copper, zinc and aluminum for the manufacture of installation components, doors, windows and cladding materials.

Both ferrous and non-ferrous metals are desirable demolition materials. Due to their value and reusability, they are most often recycled almost entirely and used as a remelting material. The percentage of the total amount of waste that construction and demolition work generates is estimated at 2.5 to 4.0 [89]. Metal products are recovered and recycled in [90].

The ways in which metals are obtained vary depending on the elements from which they are extracted. These range from large elements from the demolition of steel structures, elements of reinforcement obtained from the crushing of reinforced concrete and the dismantling of installations such as installation pipes, to cables for electrical installations. They include the dismantling of wall elements with aluminum window frame inserts in PVC windows, door frames, and the façade cladding elements of both ventilated wall systems and sandwich panels [91]. At the dismantling stage, it is crucial to plan demolition activities in such a sequence that waste can be separated according to recoverability, and prioritized for use [92].



Figure 7. Reinforcing bars made of recycled metal. Source: author's photo.

Metals have a high potential for re-use in the construction industry. The first group, which is most obvious, comprises steel elements, which are used repeatedly in the construction of buildings, such as excavation protection elements, i.e., sheet piling elements, scaffolding, and site infrastructure, usually in the form of steel building containers. Similar features are seen in structures designed to be converted or relocated, such as marquee building systems, most often in the form of halls erected as temporary structures. Such buildings are simple to erect, durable, and, most importantly, can be converted or relocated for a new function. For these conditions to be met, such buildings must be made of simple elements that are durable, and easy to assemble and transport. Today, only steel elements can meet these requirements. Columns, steel girders and truss elements have the same function. These structures can be successfully used for newly erected buildings. This can be done either by relocating the entire structural system or by adapting these elements for new construction [93].

Interior architecture also offers opportunities for the recovery of metal materials. These can include, e.g., drywall systems based on the steel profiles of standardized sizes for partition walls and suspended ceilings. These systems allow a certain degree of reuse of demolition materials [94].

Metal components are also mechanical connection systems that can be successfully reused. Their standardized dimensions and parameters allow them to be used in new buildings. Metal installation components also have some potential for reuse as, e.g., equipment of standardized sizes and parameters, such as heating system components (radiators, copper pipes) and building electrical equipment [95].

Some potential for steel recovery in construction is represented by the reinforcement of reinforced concrete elements [89]. Steel recovery, in this case involving the crushing of concrete, is fraught with considerable energy expenditure. For most of elements, steel will usually only be suitable for remelting after recovery; from some of the crushed materials, we are able to recover reinforcing rods that can be used to build new structures.

Another group of metal elements includes all the kinds of façades or roof claddings. Here, of course, it is possible to recover the material to be used as a remelting material, but in some cases, particularly if these claddings are in reasonably good condition, they can be used successfully in new buildings. These include sandwich panels, which can be used as façades on new buildings, metal cassette cladding and roof cladding such as roofing sheets, and titanium zinc sheets [95]. As a rule, these types of acquired materials are used to cover buildings with a secondary function, e.g., outbuildings or warehouses. This trend can also

be seen in poorer areas of the world, where corrugated sheet metal and steel elements are used for housing in slum areas due to their properties, as well as their easy transport and application.

A final group of metal products desirable for secondary use includes materials that represent high aesthetic or historical value. This is a narrow group of metal components, reused mainly as decorative elements.

4. Discussion

The study draws attention to the general applications of selected materials once again in construction, which is enabled by recycling and is of great importance when applying the circular economy concept. The discussion presents specific solutions and details of the use of the materials listed in the results of the construction process.

The recycled materials used in construction are associated with large savings, as well as activities related to resilience and activities related to promoting the reuse of waste in accordance with the circular economy [96–99]. There are many examples of test cases around the world, and the resulting indications have been included in the local law, taking into account these types of materials as preferred in the implementation of new architectural structures [100–103]. An example here is given in British research, which has shown that in the case of recycling wood waste from construction and demolition, the use of site panellized modular timber frame systems saves up to 50% of the carbon and 35% of the energy compared to the traditional methods and materials used in housing construction [104,105]. The use of wooden materials brings great benefits when designing tall architectural structures. In such cases, the replacement of concrete with wood is often undertaken in the construction [106]. An example of such solutions is the eight-storey building in Stadthause, where a wooden core was formed modeled on concrete solutions [107]. A similar strategy was adopted in the design of the 42-storey building by the architectural firm Skidmore, Owings and Merrill, which proposed a wooden version of a common system typical in the construction of very tall concrete buildings. It uses a central core connected to the shear walls near the outer edges of the building by means of rigid connecting beams [108]. Another example of applying solutions using recycling wood waste from construction and demolition is the proposal of alternative construction systems using the specificities of this material. An example of this is the use of a frame around the building's perimeter, instead of an interior core, which can load all elements with uniform tension and compression. This solution was implemented using glued timber in a 14-storey building in Treet in Bergen, Norway [109]. Recycling wood waste from construction and demolition can be used in the following types of construction solutions: Laminated Veneer Lumber (LVL), Structural Forneer Lumber (SVL), and, above all, Cross-Laminated Timber (CLT), where wooden panels made of at least three layers of softwood lumber are stacked on top of each other at right angles and glued together. The CLT systems used in structures allow for the most effective use of wood in high-rise buildings. An example of the use of this technology is the said building in Norway [104,109].

There are many plastics with different applications on the market. However, only some plastics can be recycled, and these fall under the category of thermoplastics, e.g., PET (polyethylene terephthalate), HDPE (high-density polyethylene), LDPE (low-density polyethylene), PVC (polyvinyl chloride), PP (polypropylene), and PS (polystyrene). Non-recyclable plastics belong to the category of thermosetting plastics and synthetic fibers, e.g., multilayer and laminated plastics, Teflon, PUF (polyurethane foam), bakelite, polycarbonate, melamine, and nylon [110]. In construction, plastic waste (SPW) from polyethylene terephthalate (PET) and moulding sand (FS) is most often used to build green production bricks [111]. PET obtained from drinking water bottles is used as a sand substitute in concrete moulding. In turn, plastic waste combined with rubber waste is used to reinforce rubber and concrete [112,113]. Generally, adding recycled plastic waste to building materials increases their compressive strength, but at the same time reduces strength parameters [114–116].

In research on the use of recycled materials, researchers often point to the use of concrete in construction [117]. Different solutions are used here; one includes demountable shear connection systems for composite steel concrete beams, which are taken out of service after disassembly and then reused as a solution to achieve a more sustainable steel concrete composite construction in full compliance with the principles of the circular economy [118]. Demountable steel–concrete beams made of precast concrete slabs and steel beams connected by pre-tensioned friction grip bolts (HSFG) are used here. A number of studies also describe the strength properties associated with the use of composite materials containing recycled concrete, indicating that composite performance combines and optimizes the structural properties of the two most used and influential building materials, i.e., steel and concrete [119–123]. In addition, recycled concrete is being tested for reuse as an aggregate, with attention paid to the economic and environmental benefits of such solutions [124]. First of all, the use of secondary aggregates has an impact on the reduction in hazards posed by the mining industry, which is important to nature and climate protection. The greatest challenge for researchers is to develop a type of aggregate that would be fully workable and smooth [125,126]. Another application of recycled concrete is road construction and asphalt mixtures [127]. It is generally assumed that asphalt concrete (AC) is a heterogeneous material, which basically consists of various substituents: asphalt cement, natural or artificial aggregate, mineral filler, additives and air voids. Among the various components, aggregate constitutes the largest part of the pavement mix, and it therefore plays an important role and has a significant impact on the engineering properties of the asphalt mix, hence the importance of using RCA (recycled concrete aggregates) in the production of this material [128].

Recycled glass is mainly used as part of cement and concrete mixes. Recent studies have indicated that it can have a serious impact on the specific technical properties of these materials. An example may be the recently popular UHP self-compacting concrete, wherein using a mixture of glass powder (GP) and lime powder (LP) results in 20% higher compressive, tensile and bending strengths of the material [129]. Structural elements of buildings made of high-strength concrete are usually heavily reinforced. A small spacing of steel bars can lead to defects after concrete pouring. If high-strength concrete is used, it becomes self-compacting, which eliminates the problem of concrete nesting, and thus the production of a building from high-strength concrete with dense reinforcements is simpler. When using this type of material, concrete based on GP and LP fills the mould completely under its own weight. An additional advantage is the lower cost and reduced wear of the machines used for compacting the mixture [130]. Worth noting is the role of recycled glass in soil stabilization, which is important to foundations used in construction [131].

Ceramic waste is used in the form of aggregates, cement substitutes, components of remanufactured ceramic elements, and as decorative materials used in the design of floors in urban spaces [132,133]. The reuse of this type of materials is also extremely important with regard to ecology and the size of storage areas [134]. The reuse of ceramic waste through the demolition process reduces its total volume, which is an advantage in terms of environmental protection and economy [84]. Dust and aggregates generated as a result of the recycling process require lower transport costs, and facilitate logistics related to the storage and use of this material for construction purposes. Research is underway on the use of ceramic dust as a substitute for cement in concrete mixes—recycled ceramic mortars (CeRM) and ceramic waste powder (CWP)—which would allow for a greater use of recycled materials [135,136]. Research on the reuse of ceramic dust (85%) in the production of ceramic roof tiles has brought interesting results. This was achieved in the form of significant reductions in the energy needed for baking (temperature lower by 200 degrees compared to baking using natural materials) [133]. Recycled ceramic elements also pose specific aesthetic solutions in urban and architectural space. In addition to floors, these are often unique elements of external walls and can be used in the surfaces inside the building, examples of which include the Madrid-Barajas Airport, Spain, or the implementations of the architectural team SITE [137,138].

An important element related to the reuse of recycled elements in construction is the well-chosen method related to properly conducted selective recycling, which has a large impact on the implementation of circular economy concepts in construction. Such action is of great importance for life-cycle assessments (LCA), and the construction and demolition (C&D) of waste [139–142]. In the case of recovering metal components, this is particularly important, because the specific selection method has a direct impact on the quantity and quality of the recovered material. An important element affecting the recovery of metal materials from the façade and their reuse is the method of coating them with zinc, which directly affects the quality and processing time of materials [143,144]. However, it is worth paying attention to the profits: despite the longer time required for material recovery, research shows that as much as 95% (based on the example of recycling steel façade materials) of metal elements can be recovered and reused [145]. Metal waste can also be used in the production of self-compacting concrete, similar to GP. Its production in the form of slag results in concrete with better chloride ion penetration resistance and water penetration under pressure resistance, and although this technology involves additional production time, the concrete obtained in this way has a greater and, above all, longer-lasting climate resistance, which is an advantage of this solution [146–149].

Residues of materials used in construction can cause far-reaching environmental damage, which is why it is so important to be able to recycle and reuse them (Table 1). When these types of materials are used in the groups described in the study, the results point to several recommendations related to applications and future research on this topic. These recommendations are as follows:

- Essentially, in the case of recycling wood waste from construction and demolition, the technology of their production and connection is indicated. In the first case, attention is paid to the welding of wood using the high-frequency oscillation or linear friction of adjacent wooden surfaces as a replacement for wet glues. This joining method is being studied for moment joints in softwood structures. Another element is the use of higher-strength fiber-reinforced wood in construction in order to obtain more resilient wooden structures with a better stiffness and strength-to-weight ratio;
- Recycled plastic waste is still relatively rarely used in construction. Its use requires further in-depth quantitative and qualitative research. Considering the huge amounts of plastic in the environment, it would be worth expanding on the possibilities of the widest use of recycled plastic in mixtures that are components of building materials;
- In the case of using recycled concrete in construction, attention should be paid to issues related to the reuse of reinforced concrete elements. In addition, it would be advisable to develop research in relation to modern composite materials that show preferential technical properties and could be more widely used in construction. Another element is recycled aggregates, which would require additional research on the introduction of an optimized amount of RCAs (recycled concrete aggregates) into the concrete mix as a partial replacement of NCA (natural concrete aggregates). Their application seems the most efficient and promising strategy for a more sustainable construction and concrete industry. On the other hand it is known that aggregates significantly affect both the fresh and hardened properties of concrete, and especially its durability in an aggressive environment. RCAs, due to the attached layer of mortar on the primary aggregate, have a lower density and lower strength, and higher crushing value and water absorption compared to NCA;
- Recycled glass has a wide range of applications as a material reinforcing the parameters of cement and concrete mixes. It can even be used as a substitute for cement. Currently, research is underway on the wider use of GP as a component of building materials. The potential of using recycled glass as a finishing material in building interiors is also worth noting;
- Recycled ceramics are also used in the interior finishing of buildings, and work well as external cladding used in architectural projects. Like GP, this material can also be used

- as a powder to reinforce the concrete mix. Due to the large storage volumes of ceramics, their recycling is highly recommended and should be developed in further research;
- Recycled metal waste can be melted, depending on the mix, into new building materials, or after burning, it can be used in the form of slag as a component of building material mixes. As is the case of other materials indicated in this study, further research is needed on the use of recycled metal in construction.

Table 1. Risks, possibilities and advantages of the recycling and reuse of building material types.

Type of Material	Risks Related to Building Material Remainers	Possibilities and Advantages Related to the Reuse of Recycled Material
Wood	<ul style="list-style-type: none"> Lingering in landfills, which may cause harmful putrefactive processes when stored improperly. Loss of valuable biological material. 	<ul style="list-style-type: none"> Glued wood from recycled waste as a component of high-strength structures. Creation of new mixed materials with higher strength properties.
Plastic	<ul style="list-style-type: none"> Generation of additional waste, occupying a large area of land. Risk of additional soil and air contamination during long-term storage. 	<ul style="list-style-type: none"> After recycling—as a component of concrete and rubber used in construction. In production of “green bricks”.
Concrete	<ul style="list-style-type: none"> Waste that uses large amount of space. With improper storage, there is a risk of additional soil contamination. 	<ul style="list-style-type: none"> With proper disassembly—the possibility of reusing the elements. After recycling—a component of concrete and asphalt mixes.
Glass	<ul style="list-style-type: none"> Waste that poses a potential risk of physical damage during the organization of people’s work in storage and deposition. Increased fire hazard during storage (lens effect). 	<ul style="list-style-type: none"> Recycled glass can be a component of cement and concrete mixes. Special properties of “glass powder” (GP) when connecting concrete with steel construction elements.
Ceramics	<ul style="list-style-type: none"> A very large storage area for this type of construction waste. Waste that poses a potential risk of physical damage during the organization of people’s work in storage and deposition. 	<ul style="list-style-type: none"> Reuse as fine aggregate and as a substitute for cement in concrete mixes. Covering material on façades and internal walls. Flooring material inside buildings and in urban spaces.
Metal	<ul style="list-style-type: none"> Long-term storage poses a risk to the environment due to chemical decomposition, which can be a threat to soil and climate. 	<ul style="list-style-type: none"> Due to the specificity of the material, a large percentage can be transformed into reused building elements. Self-compacting concrete ingredient.

5. Conclusions

The examples of using recycled materials in construction, presented in the article, are in line with the principles of the circular economy. Increasingly, the policy related to the use of this type of materials is based on global and local legal regulations. The use of recycled elements in construction, despite the undoubted benefits associated with their use, must be carried out according to strictly defined rules. An important element is the process of obtaining the material, and assessing its cost in relation to the general economic situation.

Equally important are the methods of sourcing the materials; they should be based on processes that minimize the negative impact of such activities on the environment. The use of recycled materials in construction works pro-ecologically and contributes to the protection of natural resources. It is also worth noting that the use of this type of elements is associated with many benefits, such as energy and raw material savings, lower costs, less waste and shorter construction times when using such solutions.

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