Implications of the circular economy for cultural heritage protection in smart cities

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Abstract
The following objectives are addressed in the paper: identification of indoor and outdoor environmental factors in some monuments, practical ways and solutions for recovery and recycling of construction materials from demolition. Preliminary studies: this paper is based on the author's expertise in the field of conservation and restoration of stucco, facades decoration or stone substrates, pollutants identification, mechanisms of degradation and conservation of important Romanian monuments from the architectural heritage. Also, the work is based on the author's expertise in the field of Archaeometry and Restoration and Heritage Regeneration, with implications in the Study of Materials for Architecture. Approach: cultural heritage buildings occupy an unique niche in the urban landscape, and their protection and preservation is a matter of particular interest for a smart city. The microclimate and the present pollutants (tourists, oil lamps, candles, urban pollution) contribute to the building degradation. In this context, the concept of circular economy encourages the restoration and reuse of cultural heritage monuments, which represent a valuable resource in developing the tourist offer and promoting a smart city. Results: the paper will present the identification of indoor and outdoor environmental factors in some monuments such as SOx, NOx, chlorides, pH, RH, T, in monuments: Corvin Castle, Hunedoara, Roman mosaic, Constanta, Basarabi-Murfatlar Churches, Adamclisi Monument, Constanta, and ways to recover and recycle construction materials from demolition: ceramics (brick, marble), plastic waste (polyurethane) and wood waste (eg sawdust). Implications: the solutions presented will address the present challenges for reusing construction and demolition waste, promoting local business opportunities for the transition to a circular economy and developing a smart city. Value: the paper has a high level of originality and will present examples of ecological materials and technologies for the conservation/consolidation of buildings with waste materials resulting from construction and demolition.

Keywords: circular economy, pollutants, sustainability, waste recycling, smart city.

1. Introduction

1.1. General aspects. Definitions and legislation

According to the Europeana White Paper on smart cities, "cultural heritage defines the identity of our communities, contributes to social cohesion and enhances innovation and tourism (Europeana 2015)" [1, 2, 3]. In the same context, the "Agenda 2030 for sustainable development of the General Assembly of the United Nations", approved in 2015 by the UN member countries, promoted the "Sustainable Cities" model, which involves reducing the negative environmental impact on cities by 2030, granting special attention to the management and recycling of generated waste [4, 5, 6, 7]. Sustainable and smart cities assume, through technological innovation, the replacement of a «linear economy" with a «circular economy", in which waste is incorporated into the production processes of new products and/or materials (in order to achieve the objective of "zero waste") [8].

In every city, construction and demolition waste (DCW) represents a serious environmental pollution problem, due to its inadequate management and low rates of recycling or utilization. Globally, 25-30% of the total solid waste worldwide, equivalent to 3 trillion tons per year, is the result of waste from the construction industry. Every year, in Europe, approximately 750 million tons of C&D waste are generated, representing approximately 32.6% of the total waste resulting from: households and industry [9].

Without a doubt, the massive amounts of waste resulting from human activities imply a decision-making management in an intelligent city. And the new concepts of linear, recycling and circular economy compete in the strategy and decision-making management of these cities.

Nowadays, many cities around the world are faced with abandoned heritage buildings. These buildings are mainly located in central urban areas and are in continuous decay due to the action of several external factors. The regeneration and rehabilitation of these buildings is not always a point of interest, as it involves high costs. Because they ensure the continuity of traditions and shared values, heritage buildings have become an important resource in urban regeneration and evolution. Saving industrial heritage buildings brings cultural, social and ecological benefits as avoiding demolition allows them to save resources and energy as well as avoid pollution.

The objective of this work consists in:

- Studying the state of conservation and chemical-physical degradation of historical buildings, evaluating environmental conditions, different historical know-how (manner) and/or previous restoration;
- Digital reconsidering of the monuments or historical buildings;
- Providing indications regarding the properties of waste materials resulting from construction and demolition, the creation and use of new compositions of recycled aggregate materials, compatibility and availability for maintenance and restoration interventions;
- The establishment of correct investigation and intervention procedures that are based on solutions with historical, artistic and documentary relevance, to use the interdisciplinary skills of laboratories capable of providing technical and scientific answers to the complex problems of restoring and preserving the surfaces of monuments.

1.2. Classification

Regarding DCDs, they can be classified into two categories: usable and non-usable waste. If the unusable waste is that contaminated with hazardous waste, which imposes specific environmental regulations, in the category of usable waste within concrete, ceramics, clay bricks, masonry, and mortar waste, glass, polyethylene terephthalate (PET), polyurethane from household appliances, tires, waste concrete, agricultural waste, silica cloud, fly ash, etc., can be used in concrete production to reduce the disposal of large volumes of DCD by substituting aggregates [9] used for fine aggregates and rudeness. DCDs are classified from A to D according to the Brazilian standard NBR 15113 [10] as follows:

- Class A: mortar, concrete and ceramic components (eg bricks, blocks, tiles, and coatings);
- Class B: plastics, paper, cardboard, metals, glass and wood;
- Class C: plaster-based residues;
- Class D: hazardous waste such as asbestos, tars and paints, heavy metals (chromium, lead, mercury), varnishes, paints, adhesives, polyvinyl chloride, solvents, polychlorinated biphenyl compounds, various types of resins used for preservation, flame retardant, waterproofing etc.

In the same context, the adoption of the circular economy emerged as a promising strategy to reduce the negative environmental impact of DCD [11].

2. Waste from construction and demolition activities within the circular economy

2.1. Circularity of construction materials

The main contributor to the circular economy in the construction sector is the recovery, reuse and recycling of CDW. The recovery, reuse and recycling of DCD are essential components of the circular economy in the construction sector.

The linear economy involves the following stages: production, sorting, use, disposal. The recycling economy implies: production, sorting, use (with recycling) and then disposal. The circular economy involves the assembly of both types of economy above, as follows: production, sorting, use through recycling and/or return, reuse, reuse. Building components should be selected according to their circularity potential, following the hierarchy of the 3Rs (reduce, reuse, recycle) of the circular economy [12, 13].

Paper waste is the most common waste encountered in most spheres of activity and is an important source of cellulose fibers. It is found in different forms (writing paper, wrapping paper, newspapers, magazines, catalogs, postal waste, boxes or other packaging made of plain and corrugated cardboard from cosmetics, household appliances, drinks, including TetraPak packaging, etc.), paper occupies approximately 41% of the total household waste that we produce today. Through the recycling process, each ton of recycled paper can save 17 trees, and it takes a 15-year-old tree to produce 700 paper bags. Paper and cardboard can only be recycled 10 times. By recycling paper, approximately 25% of the amount of electricity and 90% of the amount of water (300 l) needed to produce 1 kg of white paper are saved. Also, the toxic chlorine required for the production of white paper is eliminated [14].

Plastic waste: By recycling each ton of recycled plastic, between 700 and 800 kg of crude oil is saved. The toxicity of plastic can be found both after burning, resulting in substances that cause lung diseases, or because the ink used to print the bags contains cadmium, a very toxic metal, released into the air when the bags burn. A single plastic bottle through recycling leads to saving energy for the operation of a 60W light bulb for 6 hours.

According to the latest reports, in 2017, demand for plastics in Europe in 2016 was 49.9 MTn, 3.1% higher than in 2014. Of this demand, 7.5% is polyurethane, implying a annual demand of 3.78 MTn in 2017. Of the 2.62 MTn of polyurethane foam (PU), approximately 27% of waste is generated (700,400 Tn), of which, 31.1% is recycled (220,000 Tn), 41 .3% is incinerated (294,278 Tn) and the remaining 27.3% is taken to the landfill (193,120 Tn). The industrial sectors responsible for these quantities are: construction and demolition (24.5%); automotive (19.5%), refrigeration (21.3%) and other sectors (34.7%).
Several works are known in which polyurethane foam waste, combined with pitch binders, are used as dry aggregates in various cements or gypsum matrices. In cement mortars, PU as recycled aggregates provides excellent durability, and is able to reduce the amount of sand in cement mortars by replacing sand in the proportion of 13-33%, 25-50% or even 25-100% [15, 16, 17, 18, 19, 20].

Wood waste: Wood waste represents a set of products and materials whose origin can be found in all stages of the wood industry, from logging to the manufacture of finished products. The main sources of wood waste are:

- From forestry operations: bark, sawdust, thin wood;
- From the wood processing industry (cutting, carpentry, furniture factories, parquet): chips, sawdust, scraps;
- Waste: construction site wood, railway sleepers, pallets, formwork wood.

Wood waste is classified by European rules as ordinary waste, not presenting a dangerous or toxic nature for the environment. In Romania, according to HG 856/5.10.2002 (MOF 659), wood waste is classified according to origin:

- Waste from agriculture, forestry, hunting and fishing, from food preparation and processing;
- Waste from wood processing and the production of tiles and furniture, pulp, paper and cardboard.

Depending on the condition in which the wood waste is found, it can be:

- Wood in its natural state – bark, sawdust;
- Wood residues – results from carpentry, construction, planing sawdust;
- Used wood – beams, windows, treated wood pallets – railway sleepers, PVC.

Wood waste is classified as follows in 3 types of waste:

- Non-impregnated waste: such as wood processing waste: dust, sawdust, sawdust (61% of the total generated);
- Weakly impregnated waste: they were treated with non-hazardous products such as wooden beams, solid furniture, chipboard and PAF waste. This waste can be used for combustion (28%);
- Highly impregnated waste: telephone poles treated with creosote or copper, sawdust that has served to absorb a hazardous product, etc. This waste cannot be used for combustion and goes to the landfill or another specialized center (11%) [21].

Glass waste: Glass needs 1 million years to break down into small pieces. Recycling glass reduces manufacturing pollution by 75% and air pollution by 14-20%. Recycling a glass jar saves enough energy to power a 100W light bulb for 4 hours. Recycling one ton of glass saves 1.2 tons of raw materials (soda, sand, feldspar) and 25% of energy [22]. The glass is 100% recyclable, its recovery saving an important volume of energy resources.

Marble and ceramic waste can also be processed into fine particles or aggregates to replace some of the natural aggregates used in concrete production. The use of marble, ceramics and recycled tiles in concrete can help improve the mechanical properties (compressive strength, flexural strength and abrasion resistance) and durability of concrete, while reducing permeability and water absorption [23]. The use of marble, and recycled ceramics in concrete can help reduce waste generation and conserve natural resources. According to some references [24, 25, 26, 27], the density of concrete containing ceramic waste aggregates decreases linearly as the ceramic concentration increases. At the same time, the depth of penetration of chlorine ions, extremely aggressive, in concrete decreases with the increase in the ceramic content, and the electrical resistance of the concrete increases with the increase in the amount of ceramics, the durability of the concrete increases with the increase in the ceramic percentage.

3. Smart Cultural Heritage and Smart City

The development of the smart city concept in the last two decades has directly contributed to the emergence of the Smart Heritage concept. The "smart" concept has distinguished itself from other visions in which information technology is combined with infrastructure, architecture, everyday activities to address social, economic and environmental issues [28], and in 2018, Yigitcanlar et al. identified three main drivers of smart cities; Community, Politics and Technology [29], to produce productivity, sustainability, accessibility, well-being, viability and governance outcomes. The smart city is becoming a "dominant concept" without a universally accepted definition of a smart city. The definition is different for different people. The concept of Smart City varies from city to city and country to country, depending on the level of development, the desire for change and reform, the resources and aspirations of the city dwellers.

In this context, heritage buildings as distinct entities in smart cities are unique and irreplaceable. Conservation, restoration and rehabilitation of heritage buildings represents in many countries more than 35% of total construction output [30].

The concept of "smart cultural heritage" implies a connection between users of a common digital platform, between the institution and its visitors, between objects/territory and the visitor, and between the real and the virtual world.

Smart heritage connects a physical reality to a virtual reality, but offers a wide range of possibilities to access its representations.

4. Digital solutions. Case studies

4.1. The case of the chalk churches from Basarabi-Murfatlar

Temperature variations and the presence of water are the most aggressive factors affecting this monument, Fig.1, and some measures are required to save this important monument, and virtual digitization could be the first step in this context.

The application of new technologies and the digitization of the Basarabi monument is a preventive measure, helping us to achieve a virtual reconstruction as a model for its preservation, to provide access to the widest possible audience. Laser scanning, 3D modeling, digital scanning and photogrammetry are the most used methods for digitizing cultural heritage, in order to provide 3D models. By means of the laser scanning technique, for this monument it was possible to measure the topographical quantities, the direction of a virtual optical line joining some points on the surface of the monument to a reference point on the measuring device, and the morphological features on the monument, which can be acquired and measured with a very high precision [31]. A mathematical representation of a 3D surface was obtained through the CAD modeling program to create the 3D model of the external projection of the church, Fig. 2. As an alternative, common digital photographs can be used to obtain 2D or 3D coordinates of several photos. In our case, by using 3D photogrammetry, the 3D model of the church envelope was obtained, which should be applied over the church, Fig. 2. a-c. The 3D model created was with an accuracy of 0.72-0.95%.

Fig. 1. The chalk churches of Basarabi-Murfatlar
Source: personal photo

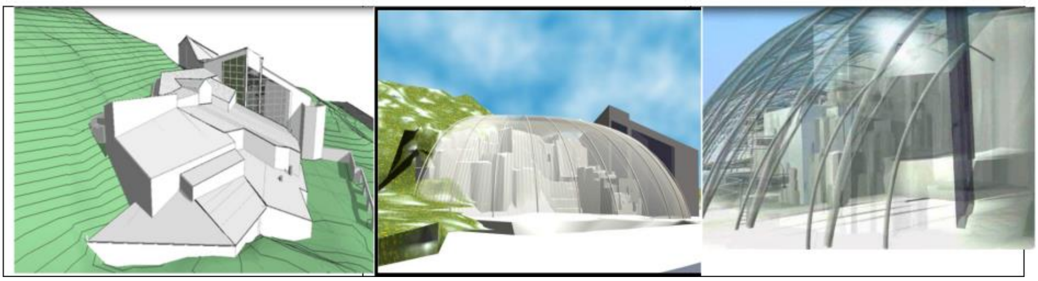


Fig. 2. (a) External digital protection of the monument; (b) Roof protection scheme; (c) The view of the church envelope

4.2. Case study: Adamclisi triumphal monument

A first factor affecting the sustainability of heritage buildings in a smart city is the damage to the surfaces of heritage buildings due to air pollution with effects on limestone or marble facades, stone surface soiling, glass soiling, medieval stained glass damage, metal corrosion and the accumulation of biomass in the urban environment. Internal combustion engines contribute fully to the pollution inside big cities, through high concentrations of sulfur dioxide, carbon dioxide (CO2), ozone (O3). The deposition of pollutants on surfaces depends on the atmospheric concentrations of the pollutants and the climate and microclimate around them. And here we will exemplify the state of pollution in the monuments in Romania, with reference to the triumphal monument from Adamclisi, measurements that were carried out during a research project carried out in the years 2018-2020 [32].

Fig. 3. Adamclisi triumphal monument
Source: personal photo

The concentrations of pollutants sulfur dioxide (SO_2), nitrogen oxides (NOx), nitrogen monoxide (NO), carbon monoxide (CO), ozone (O_3) and the concentration of dust (PM10) measured with specialized sensors are presented in Fig. 4. They vary depending on the season, being more intense in the cold season, when traffic in the area is supposed to be much reduced, and human activities in the area are much reduced.

4.3. Roman Mosaic

Another category of factors is represented by the degradation of building surfaces, caused by physical processes, such as: crystallization of salts in porous walls (stone, brick, plaster, frescoes, murals), deterioration by freeze-thaw cycles in porous materials, sea level rise, swelling-shrinkage of clay minerals in soils affecting the stability of monument foundations, accumulation of biomass (lichens, algae, mosses, fungi) closely related to rain and temperature, depending only on climatic parameters. The degradation phenomenon occurs in a gradual manner and manifests itself differently depending on the materials used in construction. By using high-performance equipment pH meters, digital microscopes with image processing software, pH values, salts, humidity, and organic carbon content caused by ash dust resulting from internal combustion engines were measured, Fig.5. These data were measured and compared for all monuments in the same area: Roman Mosaic, Hippogeus Tomb and Adamclisi Monument, Fig.6.

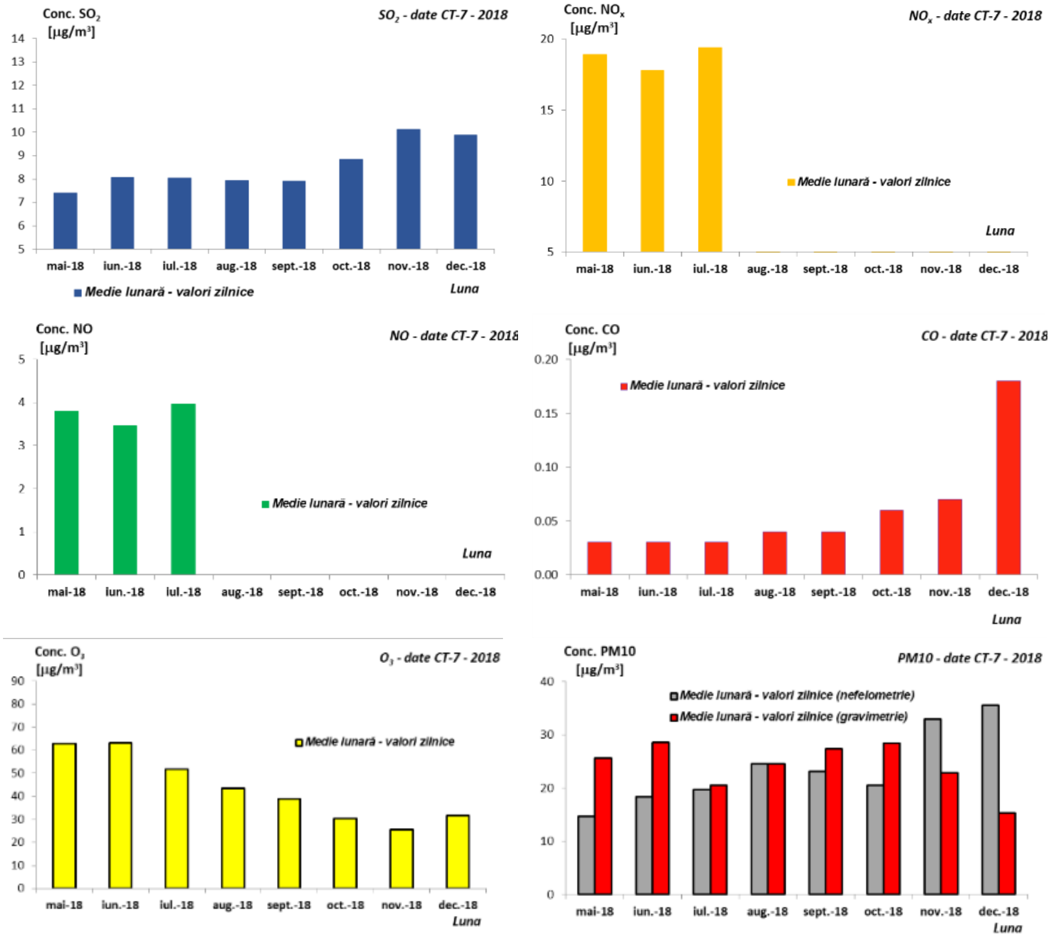


Fig. 4. The level of gaseous pollutants SO_2, NOx, NO, CO, O_3, PM10 in the area of the Adamclisi monument

Fig. 5. Roman mosaic, Constanta
Source: personal photo

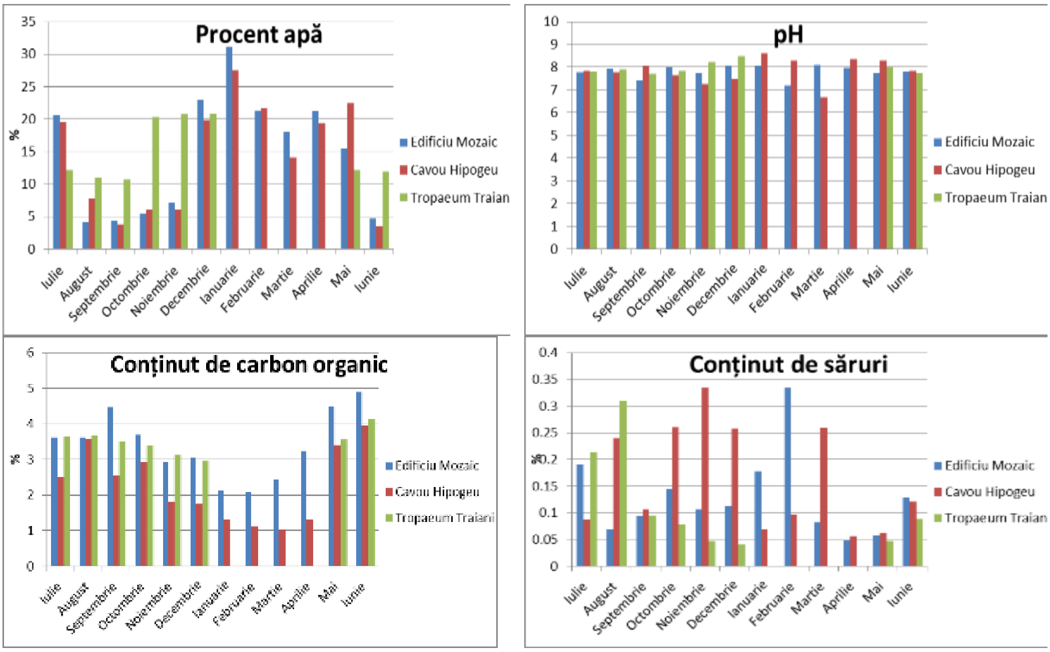


Fig. 6. pH, salts, humidity, and organic carbon content measured by Roman Mosaic, Hippogeus Tomb and Adamclisi Monument

The same trend is visible in this case: increasing pH parameters, organic carbon in spring-summer, and aggressiveness of degradation processes by crystallization of salts and moisture in autumn-winter months [33]. For the use of high-performance equipment pH meters, digital microscopes with image processing software, it was possible to evaluate both degraded areas and the effect of previous restorations on these samples. For the Roman Mosaic, in order to better observe the details of the mosaic samples, 3D simulations in "GIF" format were made using software for editing computer graphics, Fig.7.

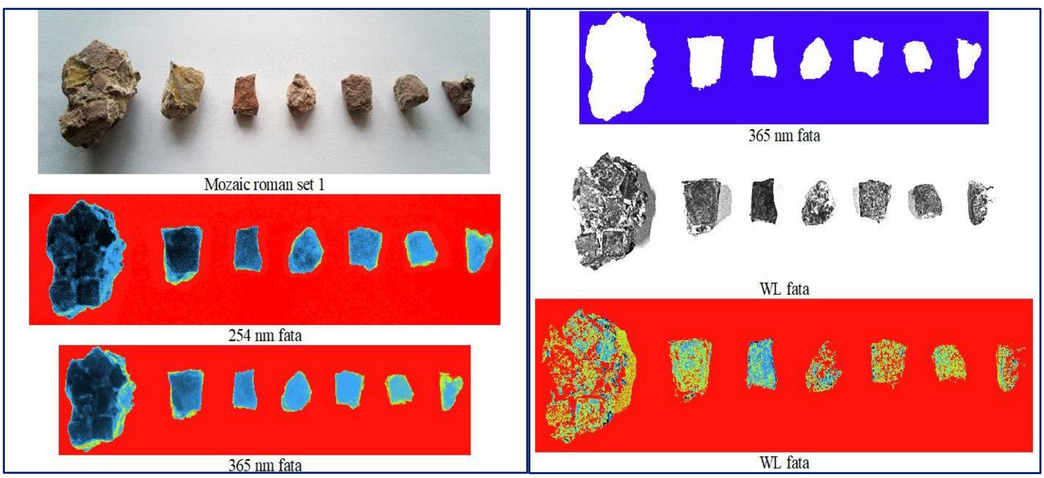


Fig. 7. S3D images for computer graphics editing of mosaic samples.

Cracks and deposits of degradation products can be observed especially when viewed with UV lamps with wavelength 254 nm.

4.4. Case study: Casa Fantaneanu, Slatina

For digital analysis and patrimonial regeneration of stucco and façade decorations, a 3D portable scaner was used Exascan is a portable optical system for data acquisition that captures every detail and provides accurate high-resolution geometries for an accurate representation of the scanned object, Fig. 8. The scanning process is plug&play. It uses the triangulation method to determine its position relative to the part in real time. It is a data acquisition system and at the same time its own positioning system. We exemplify the case of some façade decorations collected by collaborating restuaurators, Fig. 9.

Fig. 8. Exascan Portable 3D System
Source: personal photo

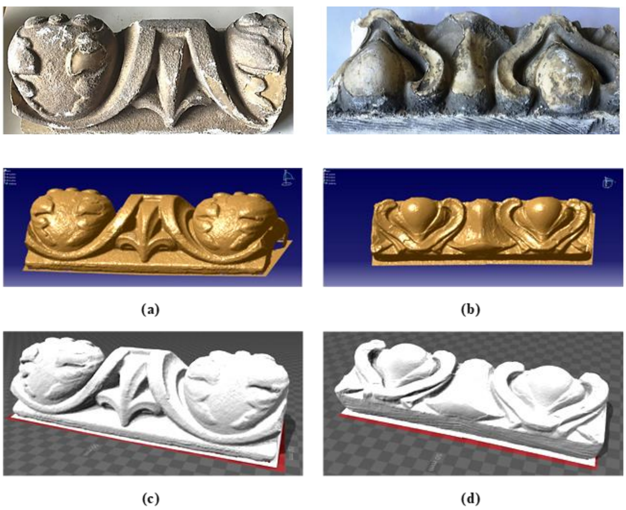


Fig. 9. Digital reconstruction of façade decoration with Exascan portable 3D system

4.5. Corvin Castle

Corvin Castle, also known as Hunyadi Castle in Hunedoara, is the most important Gothic-Renaissance architecture ensemble in Romania, Fig.10. On its site initially functioned an ellipsoidal fortress given to Voicu, the father of John of Hunedoara, on October 18, 1409, by Sigismund of Luxemburg, King of Hungary. The construction of the current Castle started around 1442, by building a new enclosure equipped with rectangular and circular defense towers, when Ioan de Hunedoara occupied the position of voivode of Transylvania. Since 1446, when John Hunyadi became governor regent of the Kingdom of Hungary, a series of civil and religious constructions appear inside the precinct. After the death of John Hunyadi in 1456, numerous Renaissance elements were added to the architecture of the building. The construction stage attributed to Matthias Corvin lasts until 1480, when the castle was recognized as one of the largest and most impressive buildings in Eastern Europe.

Fig. 10. Corvin Castle
Source: personal photo

The general appearance is due to the seventeenth-century constructions and their restoration works from the nineteenth to the twentieth century, some of the latter without reasons of compatibility between the materials used. Today, Corvin Castle is an imposing structure, with tall towers, bastions, an inner courtyard, variously colored roofs and countless windows and balconies adorned with decorative stone elements [34, 35, 36, 37, 38, 39, 40].

Through the methods offered by digitization, and the location of the samples taken, temperature measurements were made at Logia Matia, Fig. 11, 12.

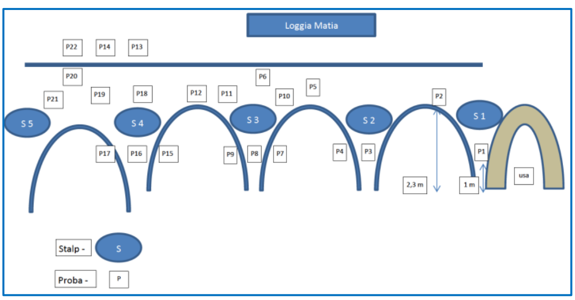


Fig. 11. Location of temperature measurements, Logia Matia

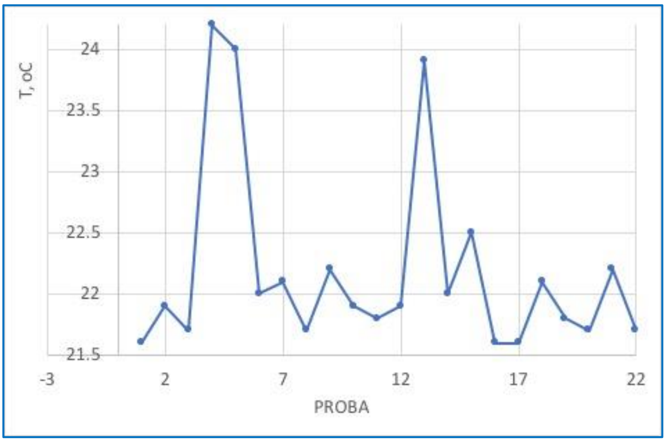
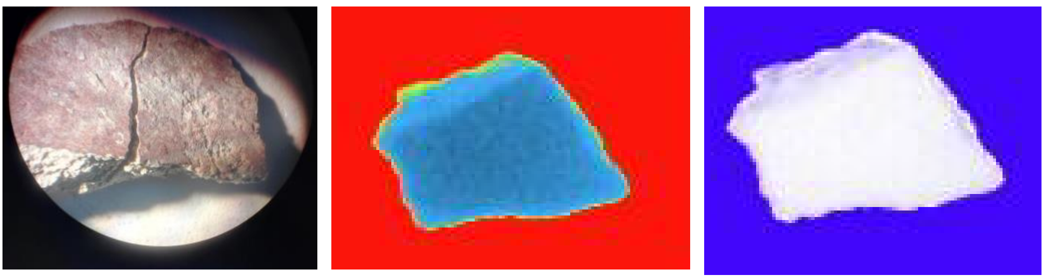


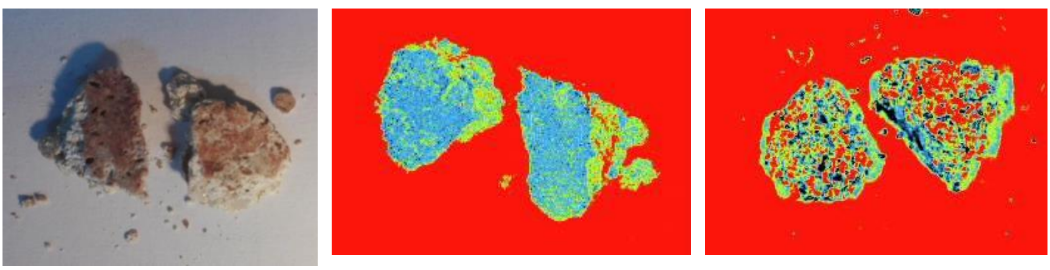
Fig. 12. Graph of temperature variations

The lowest temperatures were measured at the outer pillars of Logia Matia.

In this case, too, 3D simulations were made in the "GIF" format using software for editing computer graphics, especially on the red pigments present on the traces of the picture left on the poles. At 254 nm we can observe the presence of several layers of paint, proof being the multiple interventions at the level of this monument, Fig.13.



P33 P 33_WL_2 P 33_WL_3



P31 P 31_4 UV 365 nm P31_VERSO_2 UV 254 nm

Fig. 13. 3D images for computer graphics editing of Logia Matia samples

5. Use of the aggregat's recycled concrete

Most of the waste produced by the demolished structures was disposed of by throwing it away as filler. The dumping of waste on land causes a lack of landfills in urban areas. Therefore, it is necessary to start recycling and reusing demolition concrete waste to save the environment, costs and energy. The use of recycled aggregates from construction and demolition waste has a prospective application in construction as an alternative to natural aggregates [41].

Many old buildings, concrete pavements, bridges and other structures have exceeded their age and limit of use due to structural damage beyond repair and need to be demolished. The structures, even suitable for use, are being demolished because they do not serve the needs of the current scenario. The structures are turned into debris resulting from natural disasters such as earthquake, cyclone and floods, etc. New construction is necessary for better economic growth [42].

Recycled concrete aggregates (RCA) contain not only the original aggregates, but also hydrated cement paste. The recycling of aggregates can take place either at the site of the materials, with the help of crushers, or the materials can be transported to a central recycling facility where large stocks can accumulate. Recycled aggregates from these central recycling facilities undergo a number of processes to ensure high quality [43].

Various processes involve, crushing, pre-sizing, sorting, sieving and removing contaminants. Then to start with clean, quality aggregates, to easily meet design criteria and finally get a quality product that will go into end use. Further cleaning is also done to ensure that the recycled concrete product does not contain dirt, clay, wood, plastic and organic materials. This is done by floating water, manual choice, air separators and electromagnetic separators.

Brick rubble has been used since antiquity in construction. Thus, in Vitruvius' work on architecture, published in 13 BC, we find in book VII, chapter 4, the following: “In the plaster for the wet foundation, instead of sand, crumbs of burnt bricks will be used, so that this part of the plaster is not damaged by moisture”. In the research carried out by Prof. Steopoe on mortar samples from Sarmisegetuza, it was found that mortars in pavements or lower parts of walls contained as aggregate a mixture of brick debris and dust. It is reported that brick debris can also be used as aggregates for lightweight concrete, which have good insulating properties [44].

6. Original experimental results

By using various assortments of waste (ceramics, marble, wood – polymer sawdust), specimens were made 5x5x5 cm (Fig.14) subjected to structural, compositional and microscopive analyzes, but also resistance to external factors and mechanics

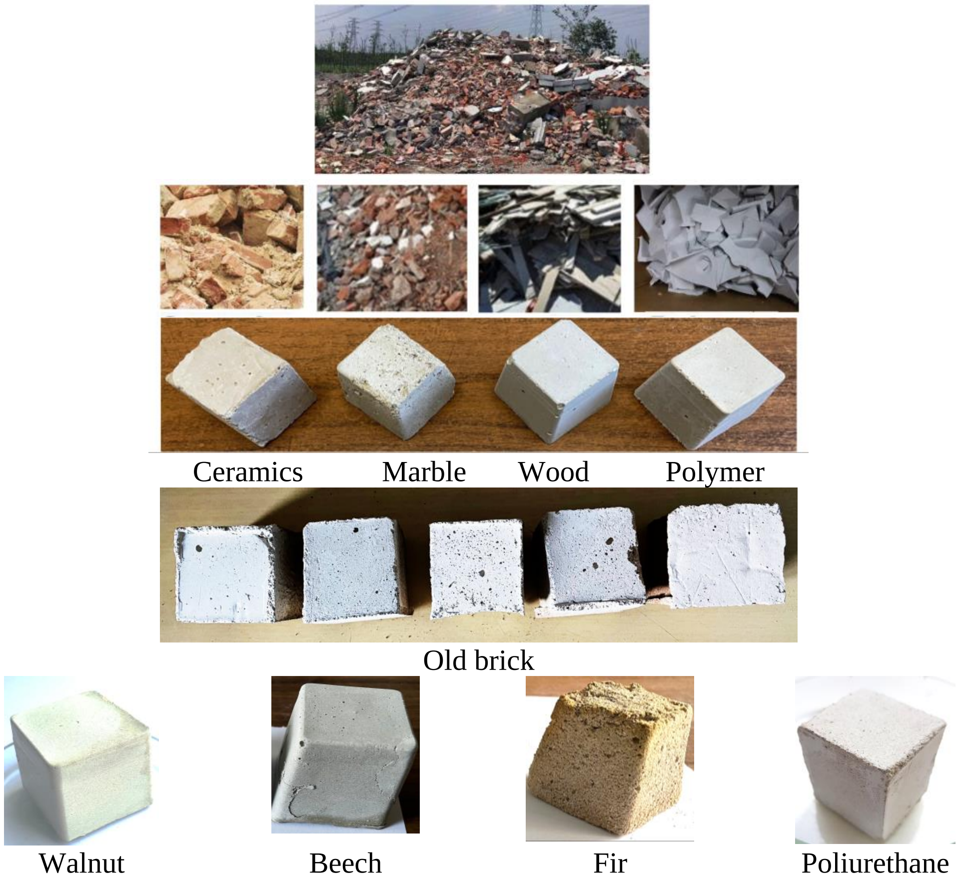


Fig. 14. Specimen samples made with various aggregates

The mechanical strength of polyethane mortar samples is shown in Fig. 15, indicating a mechanical strength close to that of a normal cement [45, 46, 47].

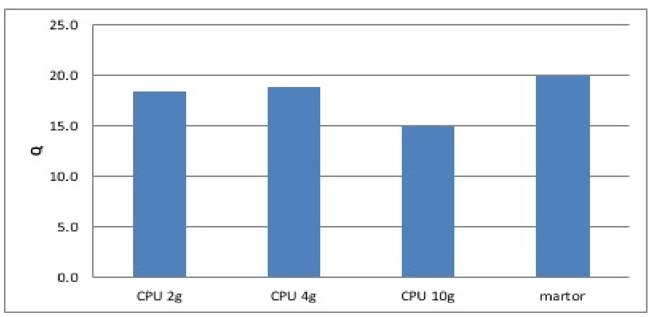


Fig. 15. Variation of mechanical resistance in specimens with polyethane RCA

In the case of old RCA, the pore volume is ten times smaller, making it more compressive and resistant [48, 49]. This could explain the higher mechanical strength (7 MPa) than the initial mechanical strength (5 MPa) after 24 hours. At 28 days, these values became 10 MPa, and after 50 days they became 18 MPa.

6.1. Behaviour of bricks made from recycled materials and their testing
Resistance to repeated freeze-thaw cycles was tested on these specimens, an example being shown on walnut sawdust specimens, Fig. 16.

Inițial After 10 cycles After 20 cycles

Fig. 16. Resistance to repeated freeze-thaw cycles specimens with walnut sawdust

7. Conclusions
Research has shown that coarsely recycled aggregates can be used in concrete up to a compressive strength of 80 N/mm2 and can be used in the range of 20-30% of the mass of aggregates required together with natural aggregates [50].

The acceptability of recycled aggregates is hindered for structural applications due to technical problems associated with them, such as weak interfacial transition areas between cement paste and aggregates, porosity and transverse cracks in demolished concrete, high level of sulfate and chloride content, impurities, cement residues, poor classification and high quality variation.

The broken material is cornered and therefore it is possible to give less workable concrete. However, this disadvantage is counteracted by the use of modern means of vibration, through which good compaction of concrete is achieved.

The aggregate obtained by crushing concrete from demolition is also loaded at the cost of crushing labor. It is therefore necessary that the material is not used alone, but mixed with gravel and gravel sand. As regards the proportion of the mixture and the required dosage, these will be determined by the destination of the concrete and the results obtained in the preliminary tests.

The porosity of a hardened concrete is higher than that of concrete made with ordinary siliceous aggregates, the concrete mixture will therefore require a lot of water to reach the plastic consistency, which will produce a reduction in mechanical resistance and an increase in shrinkage when drying.

Such materials can be used to make lightweight concrete with apparent densities towards the upper limit of the permissible values for this type of concrete made with light aggregates. Possible fields of use for such concretes refer to the realization of masonry blocks, non-loadbearing walls, filling for sandwich walls. Realization of exterior arrangements on the site of the historical monument and realization / rehabilitation /

modernization of related constructions including rehabilitation, modernization of roads / direct access ways, or extension of historical monuments.

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