WASTE AND ROBOTS

AN OPPORTUNITY FOR THE FUTURE OF LOW-CARBON FOOTPRINT BUILDINGS

How can bricks and concrete
from CDW help reduce the
carbon footprint of buildings
through the aid of
robotic fabrication?

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ABSTRACT

Waste derived from constructions and demolitions creates an opportunity to lower the carbon footprint of buildings. As bricks and concrete make up two of the most common construction materials world-wide, once the buildings they are built into, reach their end life, a large portion of the waste becomes available for reuse, rich in properties such as compressive strength and mass. If this waste is placed back into buildings, their carbon footprint can be massively reduced, while saving up on having to extract new raw and natural resources.

In an effort to reduce the amount of construction and demolition waste (CDW) derived from the future generation of buildings, innovation and technologies are necessary. In the past several decades, robotic applications have made a great impact in many industries. Thanks to its efficiency, automated processes and flexibility of use, robotics has proven to be successful in manufacturing and assembly processes which can now be customized for architectural practices like the digital fabrication of new structures with the potential of implementation of new materials . If robotic manufacturing has the potential of upcycling CDW in the construction process, then buildings can have a smaller environmental footprint. Further research into experimenting with this waste material implemented into 3D printing with a 6DOF robot arm is necessary.

Key words:
Upcycling, Waste material, CDW, Low-Carbon Buildings, 3D Printing, AMoC, Robotic fabrication

1. INTRODUCTION

The majority of the existing buildings have not been designed for disassembly and reuse (Soustsos et al., 2017). This means that once the structure of a building has reached its end of life, it has to be demolished. Construction waste is then the result of this action. The built environment makes up for almost 40% of all CO2 emissions of which 11% come from its embodied energy (Architecture2030, 2021) and is responsible for up to 30% of all landfill waste in Europe (Soustsos et al., 2017). The latter derives from construction and demolition waste (CDW). Bricks and concrete are the two most common building materials in constructions world-wide. In the Netherlands alone, 33 Mton of new concrete (roughly 15 billion m3) is produced yearly causing massive emissions, while 12 Mton concrete is demolished and turned into waste - or in a more contemporary perspective, becomes available as a new material to be used in the same industry (Villoria Saez & Osmani, 2019).

According to Eberhardt et al. (2020), a circular economy is a regenerative system where waste and emissions are minimized by limiting, increasing service life and closing loops of materials. A linear building process proposes discarding waste into landfills, meanwhile a circular building economy promotes several approaches, one of which is recycling waste (Mylonas, 2021).

Although CDW is the largest waste stream in the EU, and the average recovery rate for EU27 is below 50% (Soustsos et al., 2017), already in 2016, the Netherlands surpassed the 2020 goal with a recovery target of CDW of 70% setting an example for countries around the globe (Villoria Saez & Osmani, 2019; European Environmental Agency, 2022). Upcycling processes seek to transform waste into new materials increasing in quality or environmental value with the aim to reduce the amount of raw and natural resources extracted (Martin, Parsapour, 2012). Using raw materials to manufacture new building materials is a conservative mind-set.

In an effort to reduce the amount of CDW derived from the future generation of buildings, innovation and technologies are necessary (Soustsos et al., 2017). In the past several decades, robotic applications have made a great impact in many industries. Thanks to its efficiency, automated processes and flexibility of use, robotics has proven to be successful in manufacturing and assembly processes which can now be customized for architectural practices like the digital fabrication of new structures with the potential of implementation of new materials (Bos et al. 2016). If robotic manufacturing has the potential of upcycling CDW in the construction process, then buildings can have a smaller environmental footprint.

The research question is:

How can bricks and concrete from CDW help reduce the carbon footprint of buildings through the aid of robotic fabrication?

2. THEORETICAL FRAMEWORK

In a time where sustainability is crucial for our future generations, architecture and engineering must play a significant role in the built environment to reduce the negative impacts already made and make sure damages are reverted and buildings are future-proof. Moving into an era where an increasing amount of buildings are surging due to the demand for urban growth, the main concept of this project is born through the idea of making use of this abundance of materials, that have been considered to have reached the end of their useful life cycles, and to create a new material by upgrading its current state (found in the landfills) while adopting the existing embedded CO2 and finally taking advantage of its physical properties. Fundamental questions for this research are: What happens currently to the waste and what negative impacts does it create? What new material can derive from the waste? What important attributes does it offer? How can it be used for buildings? How can it be applied through robotic applications? Which robotic application?

It is important to dive into analyzing these two main materials, bricks and concrete, to further understand their composition, where they derive from and their potential in terms of physical and mechanical properties and potential in new designs and their impact when integrated in a circular economy.

2.1 Construction and Demolition Waste (CDW)

Some challenges that come with recycling CDW are that the exact source of CDW is oftentimes either completely unknown or it is known but the history behind it isn't, combining concrete of various grades, ages and compositions (Mylonas, 2021). In order to also achieve a local circular economy, it is therefore important to consider using the CDW of a donor building nearby, where the mechanical and chemical properties can be tested and known prior to reuse. However a common practice in the Netherlands is that the re-use of CDW is generally correlated to backfilling and re-use in low-grade implementations, such as under roads, doubting the competence of recycling in the building industry (Eerland, 2022). There's also an emerging need to create a common protocol for utilization of CDW recycling due to inconsistent standards varying per company, city and country (Krysinski, 2017).

Bricks and concrete from CDW (Fig. 01)

Crushing waste into fractions is an common method used in the Netherlands, a process which transforms larger portions into, for example, coarse (CRCA, CRBA) and fine (fRCA, fRBA) recycled concrete and brick aggregates respectively. Coarse aggregates are those in the particle distribution size of 4-64mm, while fine aggregates are smaller and range between 0-4mm (The Constructor, 2022).

2.2 Concrete and Recycled Concrete Aggregate (RCA)

More than 4 billion tonnes of cement is produced each year, which represents around 8% of global Co2 emissions (Lehne & Preston, 2018). Unfortunately, the amount of concrete needed depends on and is attributed largely to: urban growth. The demand for this is attributed to the need for new homes, but also for new infrastructure, construction of roads, dams, water supply, sanitation, energy services, among others (Deloitte, 2017).

This material is not only polluting once it closes its linear cycle and is in disuse, but also, as pointed out by Ovacen, "concrete is responsible for 9% of industrial water withdrawals worldwide" (Ovacen, 2020). This impact contributes to droughts and water stress, in addition to its high energy consumption.

Concrete is probably still one of the most used materials in construction and urban planning due to its characteristics, but there are decisions that can be taken to reduce its negative impact through its value chain. As stated in the report "A sustainable future for the European cement and concrete industry" by the European Climate Foundation, cutting-edge technologies can be used to reduce the impact of concrete, in addition to efficient use, recycling and structural optimization. The report shows that if in the future all the stages of the value chain are considered, it is possible to reduce up to 80% of CO2 emissions, compared to the 1990 figures, being achievable by 2050. (Favier et al., 2018)

There is a challenge in the market, where the cost of alternatives to recycling are considerably low. When looking at recycled concrete, the use of fRCA may make the prices become higher than regular concrete products, however the performance might also be at a higher-end. Usually when fRCA is integrated in a mix, the amount of cement increases significantly in order to balance out and control the quality of the material. Although this might contribute to sparing the consumption of natural raw resources, this contradicts the efforts towards a more sustainable outcome, as the carbon footprint and energy consumption derived from the cement poured into the composition can well be increased (Mylonas, 2021). This can also potentially be the case with fRBAs.

2.3 Bricks and Recycled Brick Aggregate (RBA)

Brick belongs to the family of ceramics or fired clay products. It is defined as a rectangular prism that has the quality of being able to be handled with one hand. Its raw material is clay, which in a dry state has an earthy appearance and when fired up not only changes its solid state but also changes its color due to the minerals found in it, which provides a durable color that never decreases (Brick Industry, 2006). It is used mainly in the construction of walls, arches, vaults, domes and many other structures (Bueno de la Cuesta, 2018). Some of the main brick types are perforated bricks, solid bricks, tiles or manual bricks, flat bricks, hollow bricks and facing bricks.

The life cycle of a brick consists of 4 main stages, which allow us to evaluate the impacts and environmental load, which are production phase, transport and commissioning phase, use and maintenance phase and the end of the useful life cycle. (Díaz Rubio, 2011).

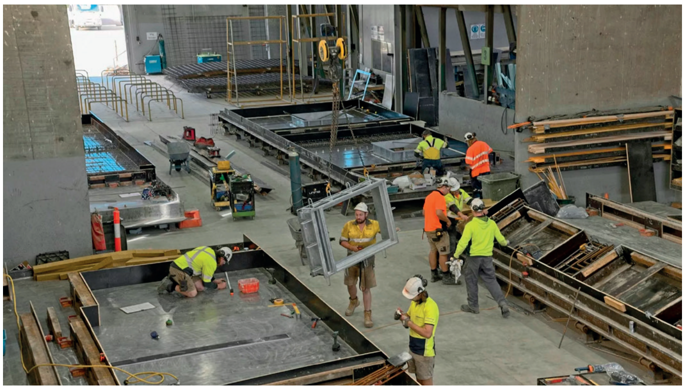
Like most building elements found in our buildings, bricks also leave a carbon footprint. It produces 23.2kg of CO2/m2 brickwork, derived mainly from process emissions and direct emissions from fuel combustion (Manley, 2016). To put it in context, compared to roughly a 30% contribution to CO2 emissions in the construction sector, brick is responsible for nearly 20% of the total emissions.

The compressive strength and absorption of bricks differ between the clay used, the manufacturing method and the firing temperature (GOBRICK). This means that once bricks become waste, it is very probable that they create different physical effects in a same composition of materials in a mix when using different types of bricks.

2.4 Production and Technology in Construction

There are several types of production of concrete and bricks around the world. The following production processes are most commonly found:

In-citu: concrete (Fig. 02)

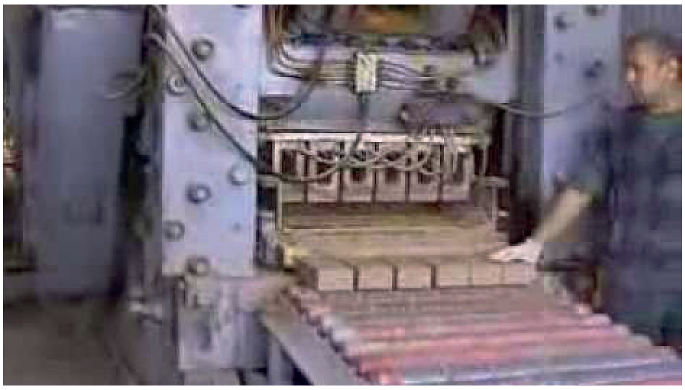


Precast: concrete (Fig. 03)

Extruded: concrete (Fig. 04)

Extruded: brick (Fig. 05)

Molded: brick (Fig. 06)



Dry-pressed: brick (Fig. 07)

In most of these processes, the machinery is tailored to the production of the product, limiting the flexibility of production the materials can offer. In other words, if an upgrade of the process/ end-product is developed, it would potentially either require to make modifications in the machine itself or even have the machine replaced. Also, in most of these processes, there is much labor required to load and unload, maneuver and intervene in the process. For instance, the assembly of the molds and placement of the reinforcement for in-situ casting involve physically demanding labor (Bos et al., 2016). In contrast, robotic applications may present more flexible solutions and be less labor intensive.

2.5 Potential Robotic Applications in Upcycling of Waste

Using raw materials to manufacture new building materials is a conservative mind-set. As mentioned before, current building processes and procedures that deal with (virgin) concrete and bricks are significantly labor, cost and time intensive. Robotic processes have the potential to increase not only the efficiency of production, leading to reduction of costs and time, but also the accuracy in which the processes are executed. Digital fabrication through robotics can provide the tools to become a fully integral part of the construction process. There are several robotic applications being implemented in many manufacturing processes for construction elements, such as the unloading of brick after firing (Brick Industry, 2006). The aim of the project is to combine this technology to aid the process of upcycling brick and concrete waste into a new building element in order to reduce the environmental impact of constructions. So, which robotic applications can help in this specific process of building with this CDW? There are a number of robotic applications suitable to become part of the upcycling process of CDW into building components, from sorting to manufacturing to assembly. For this project, different robot applications were taken into consideration for assessment in the theoretical process of upcycling CDW.

There are different types of existing robotic processes involved in manufacturing and assembly. The most common are: (Aushermann, 2019)

- **Articulated robots (4-7 Degrees of Freedom)**
- **Cartesian/gantry robots**
- **Selective Compliance Articulated Robot Arm (SCARA)**
- **Delta robots**

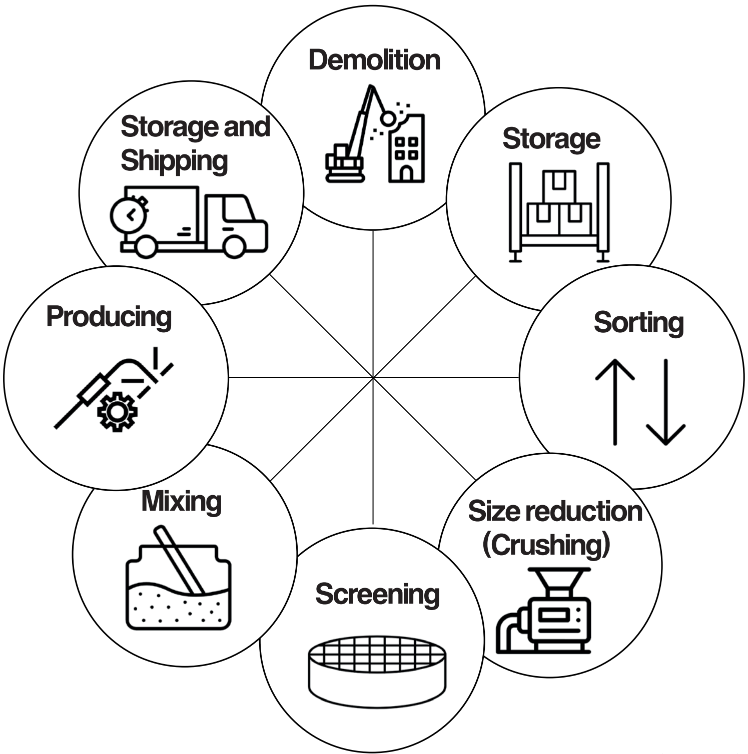
Articulated robot (Fig. 08)

Cartesian robot (Fig. 09)

SCARA (Fig. 10)

Delta Robot (Fig. 11)

In order to assess which robot is most suitable, it is crucial to know which are the most important steps in the process of upcycling concrete and brick waste. Something like the following would be the order of such a process:



(Fig. 12)

An assumption was made for the types of robot that have the potential to support the following processes due to their characteristics and main use:

- Storage > →
Articulated robot, Cartesian robot, SCARA

- Sorting >
Articulated robot, SCARA, Delta robot

- Producing/ Manufacturing >
Articulated robots, Cartesian robots, Delta robot

- Storage and Shipping > →
Articulated robot, Cartesian robot, SCARA

The production and manufacturing phase of the process is where the design can make the most impact. An articulated robot of 6DOF was chosen for this stage of the process due to its high level of flexibility of use and availability at the faculty of Architecture. The following are some of the possible applications and examples this robot can offer for the manufacturing of the upcycled brick and concrete waste.

- 3D Printing:
- 3D Printed Mold or Eggshell Mold
- Smart Dynamic Casting
- Mesh Mold
- CNC Milling
- CNC or Hot-wire-cut Formworks
- Ball Pressing
- Rammed Earth Technique
- Spray
- Sand-cast
- Planar/Non-.Planar Filament on Membrane Formwork
- Jamming: Coreless Filament Winding
- Extruded Printing
- Assembly of Parts

2.6 6 Degrees of Freedom applications for construction

A set of criteria was laid out in order to get a better overview of which robotic application was capable of fabricating a set of common building elements needed in buildings. This is mainly based on assumptions and should be looked into more deeply to gain better and more accurate results.

The following chart shows the potential each application has when fabricating with the UBCW:

The chosen robotic application for the manufacturing stage of the process in upcycling this waste is the Additive Manufacturing of Concrete process with an articulated robot arm, mainly due to the availability of the end effector needed, which matched the with one of the highest resulting criteria.

	3D Printing	3D-Printed Mold or Eggshell Mold	Smart Dynamic Casting	Mesh Mold	CNC Milling	CNC or Hot-Wire-Cut Formworks	Ball Pressing	Rammed-Earth Technique	Spray	Sand-Cast	Planar/Non-Planar Filament on Membrane Formwork	Jamming: Coreless Filament Winding	Extruded Printing	Assembly of Parts
Structural walls	x	x	x	x		x		x						
Partition walls	x	x	x	x		x	x			x			x	
Wall finish		x			x	x	x	x	x	x	x		x	
Columns	x	x	x	x		x		x						
Beams	x	x	x	x		x		x						
Floor Slabs	x	x	x	x		x								
Floor finish		x				x			x					
Roofs	x	x	x	x		x								
Ceilings		x	x		x	x	x		x		x		x	
Window frames	x													
Doors	x	x	x			x								

(Fig. 13)

🟩 Most Criteria Fulfilling

🟩 Second Most Criteria Fulfilling

🟦 Personal Preference

🟦 Second Personal Preference

3. METHODOLOGICAL FRAMEWORK

3.1 Experimental Research

Through the research method of "experimentation", brick- and concrete waste from demolitions were the main materials looked into and the medium with which the (theoretical) fabrication process occurred was through the use of Additive Manufacturing of Concrete with an articulated robot arm with 6DOF.

- So far, until my P4, I haven't been able to experiment with the articulated robot arm with 6DOF, however if there is enough time, I intend to have some sort of experiment by P5, therefore, this part remains theoretical for now. -

Brick waste was rescued from demolition and transformation projects broken down with the use of a jaw crusher, separated in specific sizes of aggregates by means of a mechanical sieve and sorted by physical appearance (color). Concrete waste on the other hand was provided by a third party in charge of separating construction waste and filtering the resulting aggregate sizes. In a conventional process, the material is cleaned of foreign components, such as metals, wood, plastics, soil and the like. This third party then crushes down the bricks into a certain granulate size and processes the concrete granulate into sand, gravel and cement stone powder. The sand and gravel have an 80% clean surface. This makes them suitable for use as an aggregate for new concrete. The cement stone powder is a filler, which can best be compared to limestone flour. This filler is suitable for use in the concrete industry for the production of self-compacting concrete (Insert, 2018). Recycled mineral aggregate may present a number of contaminations which can limit its use in structural concrete (4). For the sake of the research goal, the chemical composition was not taken into account, it is therefore assumed the CDW used is not contaminated.

These waste materials were stored and divided into buckets, ready to be used in the experimentation phase in search for the right material balance between both and to be mixed as a material usable by the robot. The material underwent iterative sampling and analyses, in order to achieve a more comprehensive overview of the potential these two materials can provide when combined. The architectural expression was explored by looking at the color and texture of the mixes. To arrive at a usable material for the building of components, the samples that came out of the following series of experiments, were tested on the basis of one key aspect: compressive strength, in order to determine if it is capable of carrying loads.

If there is more time after the P4, the goal is to look into more aspects of this material and undergo a series of experiments through the use of robotic arms.

(Fig. 14)

3.2 Material Sampling

The aim with sampling of materials is to explore the mix of materials in search of unique architectural expressions as well as to determine the correct mix for Additive Manufacturing of Concrete (AMoC). The following first 3 steps are the procedure taken for both goals of sampling. The next steps diverge into two different processes.

(Fig. 15)

Step 1:

Harvest waste-bricks from demolition sites. Select the bricks by hue and only if found in larger batches of up to 4-5 bricks in order to use the same properties of that brick type and be able to perform any experiments on them. As the concrete-waste is provided by a third party and already sorted into a particle distribution size of 0-4mm, this was to be used in further steps.

(Fig. 16)

Step 2:

Crush the bricks using a jaw crusher (provided by the faculty of Civil Engineering at TU Delft). Sort by color into buckets. The crushing should be performed to reduce the fraction size of the brick to <32mm.

(Fig. 17)

Step 3:

Sort by particle size distribution. By means of a mechanical sieve (provided by the faculty of Civil Engineering at TU Delft), the goal is to sort the fractions of the aggregate into 3 categories: (0-2mm) , (2-4mm) and (4-16mm).

a) Exploration of Architectural Expression:

(Fig. 18)

Step 4a:

In a plastic rubber mold used to bake, a series of experiments were made to begin to understand how the two materials react when mixed together. Varying in quantities and ratios of brick, concrete, cement and water.

(Fig. 19)

Step 5a:

In custom-made molds, the samples were made with the intention of understanding possible applications in terms of building components, such as walls, facade elements, tiles, etc.

(Fig. 20)

Step 6a:

In a further attempt to find out the different expressions this new material might provide, a sample was taken out from the core of a small cylinder to see how the aggregates look like on the inside.

b) Determining of CDW Concrete Mix for AMoC:

(Fig. 21)

(Fig. 22)

Step 4b:

Define the specifications. As for the binder, Portland CEM III was used as cement, as it is the most commonly used in practice. The concrete mixtures were designed with the aim to obtain an environmental class of XC3 and a compressive strength grade of C25/30, as they are widely used in the industry. Examples that provide these classes were compared with to provide an indication of water:cement ratios. Then it is important to determine the aggregate amount and the particle size distribution to be used in the mix.

(Fig. 23)

(Fig. 24)

Step 5b:

Create four different mixes to be analyzed. To reach this step, the amount of liters that fits in the desired mold needs to be translated from volume to weight. A mold of 150x150x150mm was used because of its standard dimensions for compression testing. The mold holds 3.375 liters of volume. A typical water:cement ratio is between 0,3 and 0,6. The particle size distribution for the 4 samples was kept at 0-4mm. The following four mixes were then created:

M1: 10% Cement, 85% Aggregates (50-50% brick-concrete), 5% Water

M2: 20% Cement, 70% Aggregates (50-50% brick-concrete), 10% Water

M3: 30% Cement, 65% Aggregates (50-50% brick-concrete), 10% Water

M4: 20% Cement, 70% Aggregates (25-75% brick-concrete), 10% Water

(Fig. 25)

Step 6b:

Add grease to the mold before pouring the mix. Once the mix sets inside, use an industrial vibrator to get all the air pockets out of the mix. Let the mix set and dry for 7 days before testing (minimum drying time for testing). Once 7 days is up, use a pressure gun in the bottom socket of the mold to release the sample from the mold.

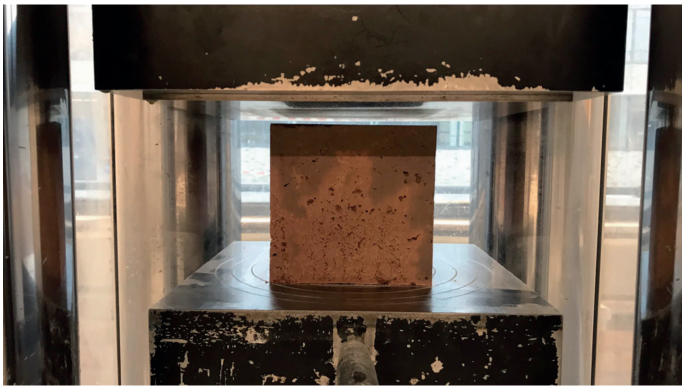
3.3 Material Testing

The results of the compression tests in the 4 samples conclude that the material has the potential to be used in the building sector. The following results of the samples:

(Fig. 26)

M1:

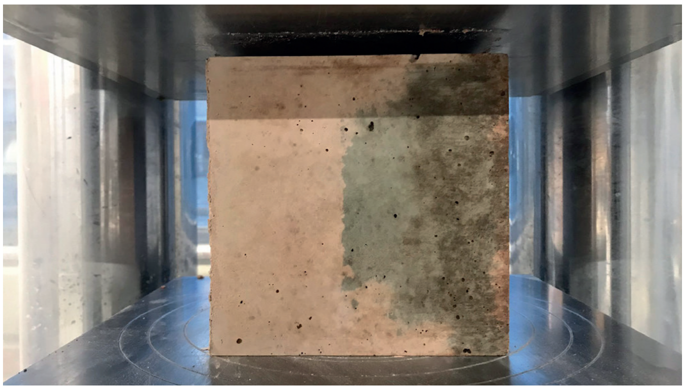
Inconclusive. Sample exploded in the compression machine before it could register a strength score. This is due to the lack of binding material in the mix. 5% of water is also very low for the full mix.



(Fig. 27)

M2:

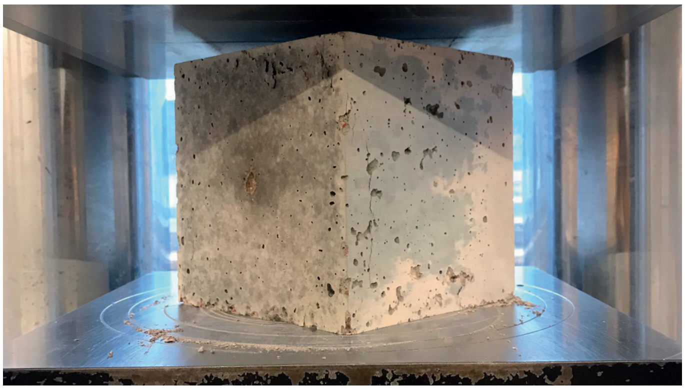
The average result of 3 samples made was: 228kN // 10.13Mpa. This result is too low for structural purposes. However it could be interesting to see what other possibilities it could be used for. Perhaps the porosity tests lead to a good facade material. To be further explored.



(Fig. 28)

M3:

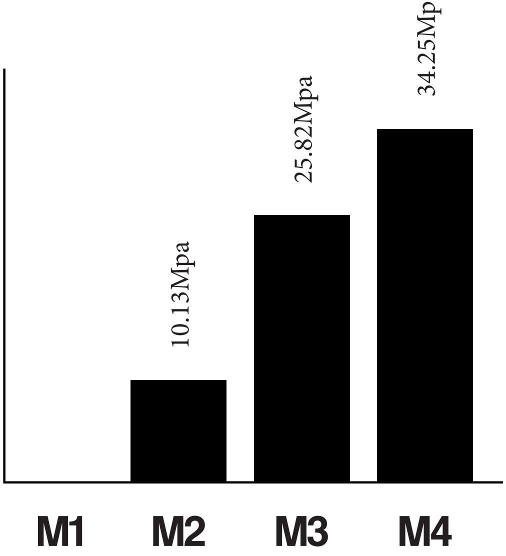
The average result of 3 samples made was: 581 kN // 25.82Mpa. This result is close to the aimed strength grade. However, the increase in cement is not desirable, as one of the main goals is to reduce CO2 emissions.



(Fig. 29)

M4:

The average result of 3 samples made was: 770kN // 34.25Mpa. This leaves the sample to surpass the strength class of C25/30. This mix, in contrast to the other mixes, did use more concrete aggregates than bricks, leading to the conclusion that brick is weaker in terms of compression when used in such small fraction sizes.



(Fig. 30)

3.4 6 Degrees of Freedom Concrete Printing

This sub-chapter of the research presents a theoretical approach to implement this material in construction through an AMoC process with a 6DOF articulated robotic arm. The AMoC, also known as 3D Concrete Printing (3DCP), is suitable for the manufacturing of building elements due to the cementitious character of the upcycled brick and concrete waste. With this application and material, and due to its fluid state before setting, the potential for fabricating free-form load bearing structures emerges (Bos et al., 2016).

Not only the form can be designed and optimized, but also its texture. The robot arm has an end effector called a print head or nozzle, where the content is extruded through and then layered on top of to create the desired outcome. The direction and velocity of the extruded content varies, giving different effects in terms of quantity of printed material and the quality of it (Bos et al., 2016). In the design, some attempts to create a design with this material have been carried out, however more research is necessary to understand what the boundary conditions are in this process and how to effectively extrude and 3D print with this material. Some questions to be further researched could be: How much time does it take for the material to bind once extruded? What is the shrinkage % of this material? What is the right composition and temperature for this extruded material not to crack? How effectively does this material bind to its adjacent layering?

When analyzing the particle size distribution and comparing with standard 3DCP mixes, the size must be even more specific in the range of 0-2mm instead of 0-4mm as tested previously. Sample mix M4 was inserted in different manual extruders with a nozzle diameter that matched that of the nozzle from the extruder available at the faculty of Architecture, however, the fraction was too large for the content to pass through and effectively be extruded. In order to be able to extrude this material, it is recommended to decrease the particle size distribution and test the compression strength once again to determine what suits best as a load bearing character.

3.5 Prototyping (materials + robotics)

In further attempts to reach the results desired in terms of digital fabrication, the final material would have to be experimented on and put to test through thte execution of prototypes caried out through AMoC. As the research shows much potential in the material, other tests such as viscosity, permeability and elastic modulus would have to be looked into in order to improve on the printiability of the material. Printing tests with different nozzle sizes, nozzle angles and layer heights would have to be studied to reach a more controlled result.

4. CONCLUSION

The built environment makes up for almost 40% of all CO2 emissions of which 11% come from its embodied energy (Architecture2030, 2021) and is responsible for up to 30% of all landfill waste in Europe (Soustsos et al., 2017). The latter derives from construction and demolition waste (CDW). In the Netherlands alone, 33 Mton of new concrete (roughly 15 billion m3) is produced every year while 12 Mton concrete is demolished and turned into waste - or in other words, becomes available as a new material to be used in the same industry (Villoria Saez & Osmani, 2019).

Waste derived from constructions and demolitions creates an opportunity to lower the carbon footprint of buildings. As bricks and concrete make up two of the most common construction materials world-wide, once the buildings they are built into, reach their end life, a large portion of the waste becomes available for reuse, rich in properties such as compressive strength and mass. If this waste is placed back into buildings, their carbon footprint can be massively reduced, while saving up on having to extract new raw and natural resources.

The architectural expression that this waste can provide when combined into one homogeneous material is limitless. The gamma of colors that the different bricks provide as pigmentation and the texture it gains through different molding and casting shows how creative one can get in order to reach different results. The compression strength results from the concrete mixes show that the integration of this waste at regulatory levels is possible. However, it is necessary to look into these mixes through other rounds of experimentation such as elastic modulus, durability, porosity, water absorption and viscosity, in order to have a fuller overview of the material and how it reacts or if it has any side effects through time. There seems to be much potential for CDW to be implemented as a building material through the use of robotic fabrication such as 3DCP with a 6DOF robot arm. This technology provides a wide range of flexibility and precision to production. In order for this waste to be 3D printed, new tests are necessary to evaluate which composition or mix is the most adequate, if at all. Some of these tests may be extrusion, binding, shrinkage, printable composition, temperature, cracking and layering. Perhaps a series of experiments with different fraction sizes of the recycled aggregates is also necessary for the implementation of 3DCP. Ultimately, the advantages of using a 6DOF with this material compared to other robots has not been realized in this report. This would be interesting to look into, as well as exploring the possibilities of the material through the application of a 6DOF.

5. DESIGN

The project tackles a transformation and extension of a building where the process from demolition-to-manufacturing-to-assembly is the outcome of the research by design.

With the ambition to stimulate urban growth and revitalize the North part of the city Apeldoorn, the large brownfield Zwitsal undergoes a phased transformation in the next 18 years. Many buildings are demolished to increase the value of the land and new buildings erect in their place. The concrete and bricks of the demolished buildings are downcycled for other more basic purposes, dismissing the potential of their properties. New buildings mean new materials, meaning more embodied carbon.

A new approach needs to be proposed in order to push for local circular economies. A series of buildings pertinent to the former factory are demolished; they become waste. With the ambition to create a circular economy at a local scale, the goal of the design is to design the transformation of three existing buildings through the upcycling of the demolition waste. The material outcome of the mix between concrete and bricks harvested from the selected donor buildings are used to create new modular building components through the implementation of robotic fabrication processes found on site, in order to create adaptive and flexible buildings for the future. The design tries to stimulate sustainable lifestyles and cater the needs of the new users of the plot while connecting the district together.

The idea, next to designing the extension and transformation of the above-mentioned building, is to design a prototype made of brick- and concrete-waste through robotic manufacturing, in order to provide insight to new ways of integrating this unwanted robust material back into the built environment!

(Fig. 31)

6. LITERATURE

Al Rashid, A., Khan, S. A., G. Al-Ghamdi, S., & Koç, M. (2020). Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. Automation in Construction, 118, 103268. https://doi.org/10.1016/j.autcon.2020.103268

Architecture2030.org, "New buildings ¬ Embodied carbon," [Online]. Available: https://architecture2030.org/new¬buildings¬embodied/

Ausherman, N. (2019, November 15). 4 types of robots every manufacturer should know. NIST. Retrieved May 6, 2022, from https://www.nist.gov/blogs/manufacturing-innovation-blog/4-types-robots-every-manufacturer-should-know

Banjad Pečur, I., Bagarić, M., Milovanović, B., & Carević, I. (2017). (rep.). Construction and demolition waste as a resource for sustainable, very low energy buildings.

Bekkering, J., Ahmed, Z., Kuit, B., & Biffi, A. (2020). (rep.). Architectonic Explorations of the Possibilities of 3D Concrete Printing: The Historic Building Fragment as Inspiration for New Applications with 3D Concrete Printing in Architecture.

Bos, F. P., Ahmed, Z. Y., Wolfs, R. J. M., & Salet, T. A. M. (2017). (rep.). 3D Printing Concrete with Reinforcement.
Bos, F. P., Kruger, P. J., Lucas, S. S., & van Zijl, G. P. A. G. (2021). Juxtaposing fresh material characterisation methods for buildability assessment of 3D printable cementitious mortars. Cement and Concrete Composites, 120, 104024. https://doi.org/10.1016/j.cemconcomp.2021.104024

Bos, F., Ahmed, Z., RomeroRodriguez, C., & Chaves-Figueiredo, S. (2019). (rep.). 3D Concrete Printing for Structural Applications.

Bos, F.P., Wolfs, R.J.M., Ahmed, Z.Y., & Salet,T.A.M. (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping, 11(3), 209-225. https://doi.org/10.1080/17452759.2016.1209867

Bru, K., Touzé , S., & Parvaz, D. B. (2017). (rep.). Development of an innovative process for the up-cycling of concrete waste.

Carvajal Ordonez, N., Conijn, L., Hanse, C., Huang, Y., & Ruiz Carvajal, F. (2020). (rep.). ¡Open construction! Envisioning a network for construction circularity in an urbanizing landscape in the province of South Holland.
Deloitte, 2017. Resource Efficient Use of Mixed Wastes https://ec.europa.eu/environment/system/files/2021-01/resource_efficient_uses_mixed_waste_Final_Report.pdf

Dick Eerland, 2022. Interview on Construction and Demolition waste in the Netherlands
European Environmental Agency, "No Title," [Online]. Available: https://www.eea.europa.eu/themes/waste/waste¬management/construction¬and¬demolition¬waste¬challenges

Gebremariam, A. T., Di Maio, F., Vahidi, A., & Rem, P. (2020). Innovative Technologies for recycling end-of-life concrete waste in the built environment. Resources, Conservation and Recycling, 163, 104911. https://doi.org/10.1016/j.resconrec.2020.104911

Gebremariam, A. T., Vahidi, A., Di Maio, F., Moreno-Juez, J., Vegas-Ramiro, I., Łagosz, A., Mróz, R., & Rem, P. (2021). Comprehensive study on the most sustainable concrete design made of recycled concrete, glass and mineral wool from C&D wastes. Construction and Building Materials, 273, 121697. https://doi.org/10.1016/j.conbuildmat.2020.121697

Hermawan, Marzuki, P. F., Abduh, M., & Driejana, R. (2015). Identification of source factors of carbon dioxide (CO2) emissions in concreting of reinforced concrete. Procedia Engineering, 125, 692–698. https://doi.org/10.1016/j.proeng.2015.11.107

Keijzer, E., Verstraeten-Jochemsen, J., Yu, V., van Leeuwen, S., Visschedijk, A., & de Vos-Effting, S. (2017). (rep.). Bottom-up policy support: Using a construction materials model to identify and quick scan circular opportunities.
Koutamanis, A., van Reijn, B., & van Bueren, E. (2018). Urban Mining and buildings: A review of possibilities and limitations. Resources, Conservation and Recycling, 138, 32–39. https://doi.org/10.1016/j.resconrec.2018.06.024
Krysinski, D. (2017). (rep.). Circular construction and demolition waste? Barriers and opportunities for creating circular business models in the EU C&DW sector.

Le Guen, L., Ferro, G., & Cazacliu, B. (2017). (rep.). It is possible to economically upcycle recycled aggregates.

Leonora Charlotte Malabi Eberhardt , Morten Birkved & Harpa Birgisdot¬tir. (2020). Building design and construction strategies for a circular economy, Architectural Engineering and Design Management
Manley, D. (2016). (rep.). BRICK Sustainability Report.

Martin M., Parsapour A.. (2012). Upcycling wastes with biogas production: An exergy and economic analysis, Fourth International Symposium on Energy from Biomass and Waste, Venice, Italy. (Martin, Parsapour, 2012):
Martins, I. M., Ulsen, C., Kahn, H., Landmann, M., & Müller, A. (2017). (rep.). Characterization of filler fraction from the production of recycled sand from construction and demolition waste.

Mechtcherine, V., Bos, F. P., Perrot, A., da Silva, W. R. L., Nerella, V. N., Fataei, S., Wolfs, R. J. M., Sonebi, M., & Roussel, N. (2020). Extrusion-based additive manufacturing with cement-based materials – production steps, processes, and their underlying physics: A Review. Cement and Concrete Research, 132, 106037. https://doi.org/10.1016/j.cemconres.2020.106037

Medina, C., Sáez del Bosque, I. F., Matías, A., Cantero, B., Plaza, P., Velardo, P., Asensio, E., Frías, M., & Sánchez de Rojas, M. I. (2017). (rep.). Recycled aggregate in civil works and building construction.

Menna, C., Mata-Falcón, J., Bos, F. P., Vantyghem, G., Ferrara, L., Asprone, D., Salet, T., & Kaufmann, W. (2020). Opportunities and challenges for structural engineering of digitally fabricated concrete. Cement and Concrete Research, 133, 106079. https://doi.org/10.1016/j.cemconres.2020.106079

Menna, C., Mata-Falcón, J., Bos, F. P., Vantyghem, G., Ferrara, L., Asprone, D., Salet, T., & Kaufmann, W. (2020). Opportunities and challenges for structural engineering of digitally fabricated concrete. Cement and Concrete Research, 133, 106079. https://doi.org/10.1016/j.cemconres.2020.106079

Mylonas, A. (2021). (rep.). Experimental investigation of concrete mixtures incorporating recycled concrete aggregates.

P. Villoria Sáez and M. Osmani. (2019). “A diagnosis of construction and demolition waste generation and recovery practice in the European Union,” J. Clean. Prod., vol. 241, 2019, doi: 10.1016/j.jclepro.2019.118400

Soutsos , M., Grigoriadis, K., Vinai, R., Lando, R., & Zerbi, T. (2017). (rep.). Indexing and sorting robot based on hyperspectral and reflectance information for CDW recycling. © 2017 TU Delft Library.

Špak, M., Kozlovská, M., Struková, Z., & Bašková, R. (2016). Comparison of conventional and advanced concrete technologies in terms of construction efficiency. Advances in Materials Science and Engineering, 2016, 1–6. https://doi.org/10.1155/2016/1903729

Sung, K. (2015). (rep.). A Review on Upcycling: Current Body of Literature, Knowledge Gaps and a Way Forward.

The Brick Industry Association. (2006). (rep.). Manufacturing of Brick .

The Constructor, [Online]. Available: https://theconstructor.org/building/classification-of-aggregates-size-shape/12339/

Torgal, F. P., Ding, Y., Colangelo, F., Tuladhar, R., & Koutamanis, A. (2020). Advances in construction and Demolition Waste Recycling: Management, processing and environmental assessment. Woodhead Publishing.
Ulsen, C., Kahn, H., Antoniassi, J. L., & Martins, I. (2017). (rep.). Production of low porosity recycled sand from construction and demolition waste .

Wahlström, M., Hradil, P., & Arevalillo, A. (2017). (rep.). Waste audit – securing good quality raw material from construction and demolition waste.

Zhang, C., Hu, M., Di Maio, F., Sprecher, B., Yang, X., & Tukker, A. (2022). An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Science of The Total Environment, 803, 149892. https://doi.org/10.1016/j.scitotenv.2021.149892

Zhang, C., Hu, M., Dong, L., Gebremariam, A., Miranda-Xicotencatl, B., Di Maio, F., & Tukker, A. (2019). Eco-efficiency assessment of technological innovations in high-grade concrete recycling. Resources, Conservation and Recycling, 149, 649–663. https://doi.org/10.1016/j.resconrec.2019.06.023

Images

Fig 01: Bricks and concrete from CDW

Fig 02: Author’s own image

Fig 03: Precast - Industrial. (n.d.). Duggans. photograph. Retrieved from https://www.duggans.com.au/precast/precast-industrial/.

Fig 04: Elematic Oyj. (n.d.). Business Finland. photograph. Retrieved from https://www.businessfinland.fi/en/companies/e/elematic-oyj.

Fig 05: Steele brick and block making machines - heavy clay. J.C. Steele & Sons. (2020, October 16). Retrieved May 7, 2022, from https://www.jcsteele.com/industries/clay-products/

Fig 06: Brick Slip Manufacturing Moulding and Drying. (2016). Retrieved from https://www.youtube.com/watch?v=ct2x8O93ziE

Fig 07: (n.d.). Retrieved from https://i.pinimg.com/originals/01/4c/8a/014c8aa580e610e76d79dc5b-81b52e32.jpg

Fig 08: Articulated robot with Gripper Systems. (n.d.). Retrieved May 7, 2022, from https://www.moellers.com/en/products/palletizer/detail/show/articulated-robot-with-gripper-systems/

Fig 09: Reis robotics bridge gantry with 2 robots - expo21xx.com news. EXPO21XXcom NEWS Reis Robotics equips bridge gantry with 2 robots Comments. (n.d.). Retrieved May 7, 2022, from https://www.expo21xx.com/news/reis-bridge-gantry-robots/

Fig 10: Mohan, A. M. (2021, August 23). New Scara Robots for Packaging Applications. Packaging World. Retrieved May 7, 2022, from https://www.packworld.com/machinery/robotics/article/21578515/new-scara-robots-for-packaging-applications

Fig 11: Bosch Delta Robot. (2022). Retrieved from https://www.happysplanet.top/ProductDetail.aspx?iid=106720138&pr=43.88

Fig 12: Upcycling process. Author’s own image

Fig 13: Different types of robotic applications capable of fabricating certain building elements. Author’s own image

Fig 14: Author’s own image

Fig 15: Author’s own image

Fig 16: Author’s own image

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Fig 26: Author’s own image

Fig 27: Author’s own image

Fig 28: Author’s own image

Fig 29: Author’s own image

Fig 30: Compression strength test resluts in a Bar Chart. Author’s own image

Fig 31: Author’s own image