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UTILIZATION OF RECYCLED AGGREGATES IN CONCRETE: CASE STUDY

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ABSTRACT

The increase in carbon emissions is a growing concern for the sustainability in our society, particularly as energy consumption rises, leading to annual CO_2 releases into the environment. The construction sector, responsible for utilizing a significant portion of the Earth's yearly extracted raw materials, significantly contributes to this issue. After the life cycle of a structure, this one is often transformed or demolished for new developments, generating large amounts of construction debris. Most concrete debris is further processed to create recycled aggregates, which are commonly used for road construction or as filling material. Nonetheless, efforts are underway to promote material circularity by reusing these aggregates back into concrete, reducing concrete downcycling and disposal in landfills. Hamburg's "Musterbude" project in 2022 stands as an example of material circularity, showcasing the sustainable use of recycled aggregates in concrete. Seven concrete mixes were formulated; two conforming to German recycled concrete standards with 45% and 35% recycled aggregate replacement. Others, including the so-called "Hamburger Mische," departed from these standards, incorporating varied recycled materials like crushed bricks and 100% mixed C&DW aggregates. The findings provided valuable insights for policymakers, engineers, and researchers, fostering a transition towards a more circular economy in the construction sector while minimizing environmental impact.

1. INTRODUCTION

In recent years, the interest in the utilization of recycled concrete within civil engineering projects has increased with the shift in industry focus driven by mounting concerns over global warming and the carbon footprint associated with construction activities. However, existing DIN standards have imposed strict regulations on the use of recycled aggregates for concrete production. Factors such as aggregate proportions, granulation sizes, exposure areas, and physical properties of recycled concrete are among the key characteristics subject to meticulous standardization and oversight by construction authorities.

1.1 State of the Art

Currently in Germany, two types of recycled concrete are permitted, namely Type I with a 45% volume of recycled aggregates, and Type II with a 35% volume of recycled aggregates, primarily intended for interior exposure. However, the allowable proportions of recycled aggregates decrease significantly for exterior exposure applications. Additionally, according to the standards outlined in DIN 4226-100 (Deutsche Institut für Normung, 2002) particles smaller than 2 mm generated during concrete demolition cannot be reused as recycled material, leading to substantial construction waste. Consequently, a significant portion of recycled concrete is currently used for road construction and filling materials, which can be classified as material downcycling.

To address the limitations in the country surrounding the production and use of recycled concrete, a sample booth called the "Musterbude" was developed in the city of Hamburg. The Musterbude is a small concrete cabin built to showcase different concrete mixes using recycled concrete. This cabin not only demonstrates recycled concrete recipes adhering to existing standards but also explores concrete structures incorporating varying proportions of recycled aggregates outside the standard.

1.2 Objectives

By developing recycled concrete that matches the performance of traditional concrete, the project aims to reduce carbon emissions during production, promote material circularity, and drive innovation in the construction

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sector. By raising awareness among policymakers and the community, the showcase project aims to encourage collaboration and demonstrate the potential of using higher levels of recycled aggregates in different exposure categories. This initiative not only actively promotes circularity in construction, but also plays a key role in waste reduction by significantly reducing the amount of construction waste sent to landfills nationwide.

2. CHALLENGES AND LIMITATIONS

This section evaluates the prevailing challenges associated with acquiring, processing, and establishing the competitiveness of recycled materials in the construction industry, as the demand for sustainable alternatives continues to rise.

2.1 Demolition Preparation and Planning for Future Use

The limitations of recycled concrete extend beyond its usage and encompass the surrounding processes of acquisition, storage, transportation, and distribution. Insights gathered from demolition work in Hamburg revealed that successful concrete recycling requires careful preparation. Emphasizing the prioritization of on-site demolition, crushing, storage, and utilization of recycled concrete minimizes the need for transportation (Purchase, et al., 2021). However, this approach may not always be feasible in construction projects, needing additional collaborative efforts from various stakeholders to process the aggregates and provide temporary storage. Furthermore, it was observed that having a clear plan for the future utilization of crushed concrete before demolition work starts is advantageous to avoid potential delays and penalties (European Commission, 2018).

2.2 Recycled Concrete Price

Price challenges are a real barrier to the widespread adoption of recycled concrete in construction projects. Some of these challenges include obtaining the appropriate type of recycled concrete, which can be more expensive than extracting the raw material due to the process involved in demolition and C&D waste classification, such as metal extraction, ensuring concrete quality standards, and impurity content such as bituminous material. Once the material is collected from the demolition site, it must be transported to a recycling facility to be crushed and stored. This additional step adds cost to the recycled concrete, especially since the supply has not yet reached the level of the raw material (Holcim, 2023), and the recycled aggregate must be stored until enough production is reached and then can be sold and shipped to the new construction site. Therefore, the higher price of recycled concrete together with the potential delays in obtaining the material near future projects to decrease transportation emissions may discourage some stakeholders from completing the transition or seeking the recycled concrete route when it comes to concrete production. This reduces the motivation to adopt a circular economy in construction and the wider adoption of recycled concrete in the industry.

2.3 Production

During the demolition of concrete structures, the concrete scrap is separated from external materials such as steel and plastic to be further crushed and sieved into grain-size categories. Currently, only grain size larger than 2 mm and up to 16 mm is accepted to be reused in concrete based on industry standards for alkaline salt resistance (Memminger-Rieve, 2021), any rubble smaller than 2 mm becomes construction waste. After the separation of concrete, the granulated material is subjected to quality control tests in accordance with the DIN 12620 standard (Deutsche Institut für Normung, 2008). These tests evaluate various parameters, including conductivity, pH levels, and the presence of PAH (Polycyclic Aromatic Hydrocarbons), which are considered problematic due to long-term health effects after exposure (Abdel-Shafy & Mansour, 2016). While asphalt and gypsum may not be ideal, they are still accepted as recycled materials in certain cases, with a maximum allowable content of 1% (Jaawani, Franco, De Luca, Coppola, & Bonati, 2021).

3. MATERIAL AND METHODOLOGY

A total of eight specific recipes were formulated to construct the Musterbude, consisting of seven mixes that incorporated varying proportions of recycled aggregates as a replacement for conventional aggregates, and one mix that served as a reference using solely virgin aggregates for comparison purposes. The primary objective was to implement an environmentally sustainable approach in construction by developing recycled concrete that performs as conventional concrete, thereby minimizing carbon emissions during production and promoting material circularity.

In Figure 1, an aerial picture of the Musterbude is shown. From the building image, the simple design of the structure as well as the properly marked section with its corresponding concrete mixture can be seen. Additionally, two panels on each side of the Musterbude were constructed to further showcase the use and performance of recycled aggregate in concrete.

3.1 Concrete Recipes

This section describes the eight concrete mixes used in the Musterbude. In general, the concrete mixes are as follows: one reference mix using raw aggregates, two (2) Type I RC mixes adhering to German standards and utilizing size 2-16 mm aggregates, one (1) Type II RC mix following German standards with size 2-16 mm aggregates, and four (4) additional mixes incorporating varying proportions of recycled aggregates placed out of the current standards for recycled concrete mixtures.

3.1.1 Reference Concrete (RB- Reference Beton in German)

The reference concrete was developed with the specific intention of serving as a benchmark, not only for assessing the physical properties of the concrete but also for evaluating appearance-related aspects such as surface roughness, porosity, microorganism growth, and other visual characteristics.

FIGURE 1: Musterbude.

3.1.2 Type I Recycled Concrete 2-16 mm 45% (R1 and R8)

The R1 mixture, which was prepared following the guidelines for Type I recycled concrete as per DIN EN 206 and DIN 1045-2, was used in an exterior wall of the Musterbude. On the other hand, the R8 mixture, also following Type I recycled concrete specifications, was applied to an interior wall of the Musterbude.

3.1.3 Type II Recycled Concrete 2-16 mm 35% (R5)

This mix was prepared following the standard for Type II recycled concrete, utilizing coarse granulated aggregates with a size larger than 2 mm. The maximum allowable proportion of recycled aggregates used in this mix was 35% of the total volume of aggregates.

3.1.4 Fine and Coarse Recycled Concrete (R4 Not in the standard)

This particular mix was formulated outside the current standards for recycled concrete due to its composition, which includes 17% of fine aggregates ranging from 0-2 mm in size and 28% of 2-16 mm aggregates. The existing German standard does not currently permit the use of aggregate sizes smaller than 2 mm. However, in the upcoming update of the standards, the inclusion of particles smaller than 2 mm will be allowed.

3.1.5 Recycled Concrete using Bricks (R3 Not in the standard)

This mix was specifically formulated with a 60% by volume of crushed bricks as a replacement for traditional aggregate. Currently, no standards addressing the utilization of brick with such a high content as an aggregate substitute exist.

3.1.6 Recycled Concrete using 100% Mixed C&D Waste as Recycled Aggregates (R6 and R7 Not in the standard)

The unique "Hamburger Mische" mix was specifically designed with the complete replacement of aggregates (0-2 mm and 2-16 mm) using mixed demolition rubble, which includes clinker, brick, sand-lime brick, unbound natural stone grains, and concrete. This mixture does not conform to any standard for recycled concrete. However, it does meet the requirements of DIN 4226-101 (Deutsche Institut für Normung, 2017) concerning the types and regulated dangerous substances in recycled aggregate for concrete.

In Figure 2, the material composition of each concrete mix compared to the reference concrete is shown in a bar chart. In this chart, a clearer visualization of material usage and proportions by volume can be seen in comparison to the reference concrete. The percentage of recycled aggregate used in each mix is also shown including brick, processed recycled aggregate, or mixed construction and demolition waste depending on the mix design.

4. RESULTS

The result of the hardened concrete test is shown in Table 1. In this table, the laboratory results obtained from the density and compressive strength test done on each concrete mix can be seen.

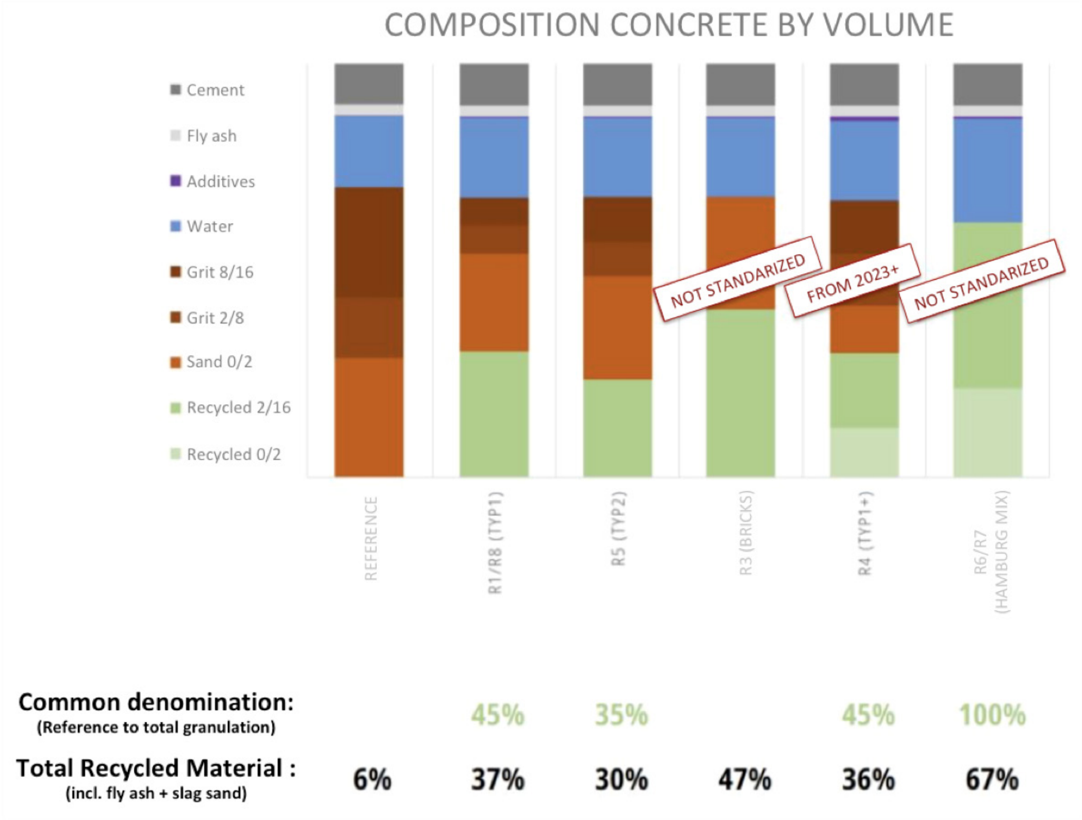

FIGURE 2: Composition of the tested concrete types by volume.

From Table 1, R6 corresponding to the "Hamburger Mishe" concrete has the lowest density and compressive strength values. This is due to the porous nature of the construction rubble used as the aggregate substitution in the mix. The high porosity in the R6 concrete mix increases the w/c ratio, which leads to an overall reduction in the concrete performance. Similarly, R4 shows a significant decrease in strength due to the replacement of sand. This increases the water content, thus, reducing the concrete performance.

5. DISCUSSION

Concrete mixes R1 and R8, both exhibited a notable increase of approximately 29.2% in total water content compared to the reference concrete mix. Moreover, there was a reduction in compressive strength, with the R1 mixture experiencing a decrease of 29.8% and the R8 mixture showing a decrease of 21.7% in compressive strength when compared to the reference concrete mix. In the case of R5, this specific mixture, which was applied to an exterior wall of the Musterbude, demonstrated a significant increase of 35% in total water content and a notable decrease of 32.7% in compressive strength when compared to the reference concrete. All of the previously mentioned concrete mix designs were according to the DIN 4226-100 (Deutsche Institut für Normung, 2002).

Regarding the non-standarized concrete mixes used in this project, the mix R4, applied in an exterior wall of the Musterbude, exhibited a 34.2% increase in total water content and a substantial 45.75% reduction in compressive strength when compared to the reference concrete. Moreover, the mix R3, using 60% of brick as the aggregate

TABLE 1: Hardened concrete tests at 28 days.

Concrete Mix	Density kg/m³	Compressive Strength kg/m²	Description
RB	2335	48,3	Reference Concrete
R1	2200	33,9	Typ1- 2/16 45%
R3	2130	35,6	Brick-2/16 60%
R4	2140	26,2	Type1- 0/2 18% 2/16 27%
R5	2220	32,5	Type2- 2/16 35%
R6	1980	20,8	HH Mische 100% Mix demolition waste
R8	2230	37,8	Type1- 2/16 45%

replacement had an outcome of a 37.9% increase in total water content and a 26.3% reduction in compressive strength when compared to the reference concrete. Despite the absence of current standards, this mix was successfully employed in an exterior wall, providing valuable insights for potential future guidelines regarding the use of high-brick-content mixes in construction practices. Finally, the Hambuger Mische, which consists of a 100% mix of construction and demolition waste as aggregate substitution, was applied in the construction of the floor, side panels, and part of the ceiling of the Musterbude, this mix displayed intriguing characteristics. It showed a significant 48.8% increase in total water content and a 56.9% reduction in compressive strength when compared to the reference concrete. Despite not adhering to recycled concrete standards, its compliance with DIN 4226-101 (Deutsche Institut für Normung, 2017) offers the assurance of safe usage with recycled materials, providing valuable insights for future sustainable construction practices.

It is important to emphasize for the purpose of this investigation that the aggregates used in this project were not prewashed or treated in any way before mixing to prevent excess water absorption, nor the use of chemical admixture to improve concrete performance. Because of this, the water absorption of recycled aggregates is significantly higher than using virgin aggregate due to the high porosity in the recycled concrete as aggregates.

Since the concrete mixes were created as a proof of concept for the use of different proportions of recycled aggregate in concrete, the concrete mixes can be replicated and improved outside the German context.

6. CONCLUSIONS

From the results obtained in this research, it can be concluded that a proportion of aggregates in concrete can be successfully replaced with recycled concrete. However, a series of steps have to take place before the addition of this recycled material in concrete. For example, elemental analysis of the recycled aggregate, especially for heavy metal content, and aggregate pre-washed are essential for good concrete performance.

The successful use of recycled concrete relies on defined and specific concrete property specifications, including exposure category, moisture class, and minimum compressive strength, among others. Additionally, ensuring a continuous flow of recycled concrete as aggregate in the market necessitates early planning for material reuse, involving all relevant stakeholders and concrete production facilities and building a strong standarized supply chain to drive the prices down and increase the demand of this materials.

To fully attain circularity in construction materials after demolition and to prevent the downcycling of concrete in civil engineering projects, further research and investigations are imperative, particularly focusing on increasing the proportion of recycled aggregate in concrete.

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