MIX DESIGN OF SELF-COMPACTING CONCRETE (SCC) WITH RECYCLED AGGREGATE

MISCHUNGSENTWURF, FRISCH- UND FESTBETONEIGENSCHAFTEN VON SELBSTVERDICHTENDEM BETON (SVB) MIT REZYKLIERTER GESTEINSKÖRNUNG

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SUMMARY

Within a master thesis [1], the development of self-compacting concrete (SCC) was investigated using 100% recycled aggregate (RA). The main motivation of this study lies in addressing the environmental and technical challenges of using recycled aggregates in high-performance concretes such as SCC, which are typically sensitive to variations in aggregate quality, water absorption, and particle shape. The focus lies on evaluating the fresh and hardened concrete properties and optimizing the mix design using the aggregate-packing-test-method (German "Korngemischprüfung (KGP)") [2], originally developed for natural aggregates and here adapted for recycled aggregates of Type I (recycled concrete) and Type II (mixed demolition waste). The results demonstrate that SCC with recycled aggregates can achieve compressive strengths of up to 40 MPa, which is comparable to SCC made with natural aggregates. However, certain adjustments in water content and admixture dosage are required due to the higher porosity and water absorption of the recycled materials. The study highlights the potential of SCC with RA as a sustainable solution for resource-saving construction and post-war reconstruction projects.

ZUSAMMENFASSUNG

Im Rahmen dieser Masterarbeit [1] wurde die Entwicklung von selbstverdichtendem Beton (SVB) unter Verwendung von 100 % rezyklierter Gesteinskörnung (RGK) untersucht. Die Hauptmotivation dieser Studie liegt darin, die ökologischen und technischen Herausforderungen der Verwendung von recycelten Zuschlagstoffen in Hochleistungsbetonen wie SVB anzugehen, die in der Regel empfindlich auf Schwankungen in der Zuschlagstoffqualität, Wasseraufnahme und Partikelform reagieren. Der Schwerpunkt lag auf der Bewertung der Frisch- und Festbetoneigenschaften sowie der Optimierung des Mischungsentwurfs mithilfe der Korngemischprüfung (KGP) [2], einer ursprünglich für natürliche Gesteinskörnungen entwickelten Methode. Die Ergebnisse zeigen, dass SVB mit rezyklierter Gesteinskörnung Druckfestigkeiten von bis zu 40 MPa erreicht kann, was vergleichbar mit SVB aus natürlicher Gesteinskörnung ist. Allerdings sind aufgrund der besonderen Eigenschaften der RGK gewisse Anpassungen im Wassergehalt und in der Dosierung von Zusatzmitteln erforderlich. Die Studie unterstreicht das Potenzial von SVB mit RGK als nachhaltige Lösung für ressourcenschonendes Bauen und Wiederaufbauprojekte nach Kriegseinwirkungen.

1. INTRODUCTION

The increasing scarcity of natural aggregates and the growing volumes of construction and demolition waste highlight the urgent need for sustainable construction materials. The use of recycled aggregates (RA), obtained from demolished concrete and other structures, provides a promising alternative to natural resources [3].

However, incorporating RA in concrete presents several technical challenges, such as higher water absorption, increased porosity, and a greater variability in particle shape and strength compared to natural aggregates. These characteristics can significantly affect the fresh and hardened properties of concrete, particularly in self-compacting concrete (SCC), which is highly sensitive to changes in workability and stability [1].

Nevertheless, due to its high flowability and flowing behavior, SCC remains a particularly suitable material for integrating recycled aggregates provided that the mix design and admixture dosage are carefully optimized to compensate for the specific properties of RA [1].

2. MATERIALS AND METHODS

2.1 Recycled Aggregate Types

Two different types of recycled aggregates were used in this study [4]:

- Type 1: Concrete demolition waste (BA 0/2 and BA 2/16, where BA stands for German “*Betonabbruch*”)

- Type 2: Construction and demolition waste (BS 0/2 and BS 2/16, where BS stands for German “*Bauschutt”*)

The aggregates were obtained from processed demolition waste, cleaned, and graded according to standard specifications.

2.2 Aggregate Testing

Before the mix design, a comprehensive characterization of the recycled aggregates was conducted to evaluate their suitability for SCC production. The following test methods were applied:

- Particle size distribution (sieve analysis) according to DIN EN 933-1 [5], to determine the grading curve and optimize packing density.
- Grain composition, shape and drying behavior in accordance with DIN EN 12620 [6] and DIN EN 933-1 [5], to assess aggregate structure.
- Water absorption according to DIN EN 1097-6 [7], additionally determined by the underwater weighing method.

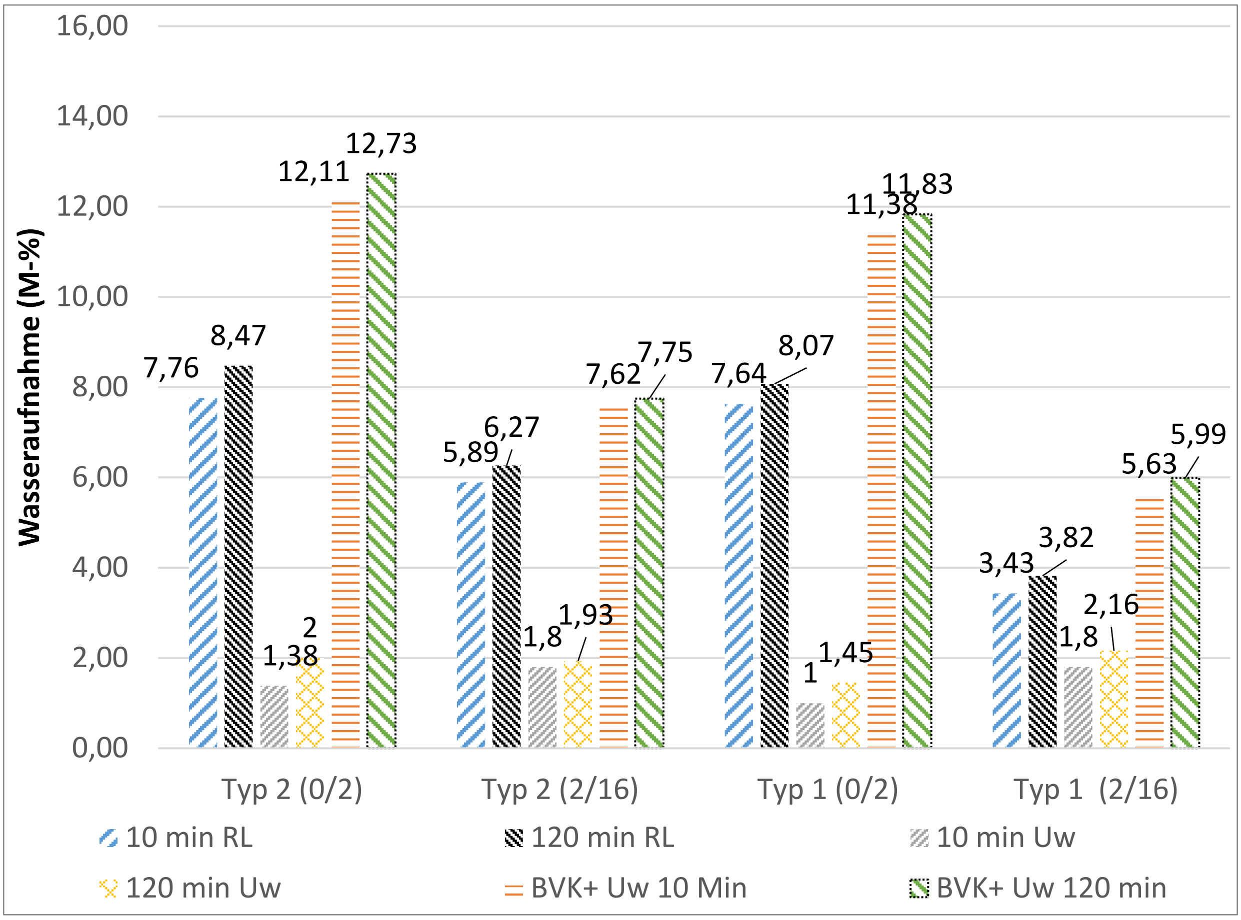

Fig. 1: Water absorption after 10 minutes and 120 minutes according to the guideline (RL: Richtlinie),underwater weighing (Uw), and combined BVK + Uw method [1]

- Oven-dry density was determined separately using the pycnometer method in accordance with DIN EN 1097-6 [7].
- Furthermore, a custom aggregate blend was prepared for subsequent mix design trials.

Significant differences between Type 1 and Type 2 aggregates were observed in terms of water absorption and fines content, as illustrated in Fig. 1, which were crucial for adapting the mix design.

Type 2 aggregates showed notably higher water absorption due to their high brick content and the associated open porosity of the brick particles. In contrast, Type 1 being composed of concrete demolition material—contained fewer capillary pores, resulting in significantly lower water absorption.

In this study, a recycled concrete powder (BAM) was produced from the fine fraction of Type 1 aggregates (concrete demolition material). To characterize the material, its density was determined, and an air jet sieve analysis was performed in accordance with DIN EN 933-10 [8].

The results of the sieve analysis showed that the BAM contains a very high proportion of fine particles, particularly those smaller than 0.125 mm. This indicates that the material is well-suited as a supplementary filler in self-compacting concrete.

2.3 Aggregate-packing-test-method

The aggregate-packing-test-method (German “Korn-Gemisch-Prüfverfahren (KGP“)) developed by Huß [2], was applied and adapted for recycled aggregates. This method focuses on achieving optimal packing density of the aggregate mixture, which directly influences the required paste volume and the resulting concrete properties. Through optimized particle size distribution and correct proportioning of fine and coarse fractions, the KGP ensures minimal voids, reducing binder demand and enhancing stability.

The adaptation of the KGP to recycled aggregates is crucial, as RA exhibits irregular shapes, higher fines content, and significantly higher water absorption than natural aggregates. Proper application of KGP allows for a balanced mix design, compensating for these variations.

2.4 Mix Design and Mixing Procedure

The self-compacting concrete mixes were designed based on the optimized aggregate composition and the corresponding total paste volume determined using the aggregate mix testing method. The water-cement ratio, the water-to-powder ratio (VW/Vm), and the superplasticizer dosage were carefully adjusted to ensure reliable self-compacting behavior.

Several trial mixes were carried out to fine-tune the fresh concrete properties. Due to the high water absorption of the Type 2 aggregates, water and admixtures were added gradually during mixing to compensate for water uptake and to maintain the desired workability throughout the mixing process.

Fig. 2 illustrates the mixing protocol for producing recycled self-compacting concrete (R-SCC). Initially, the 0/16 aggregate is mixed with absorbed moisture and left to rest for 10 minutes before cement, concrete recycling powder (CRP), water, and superplasticizer are added and mixed to form the final R-SCC.

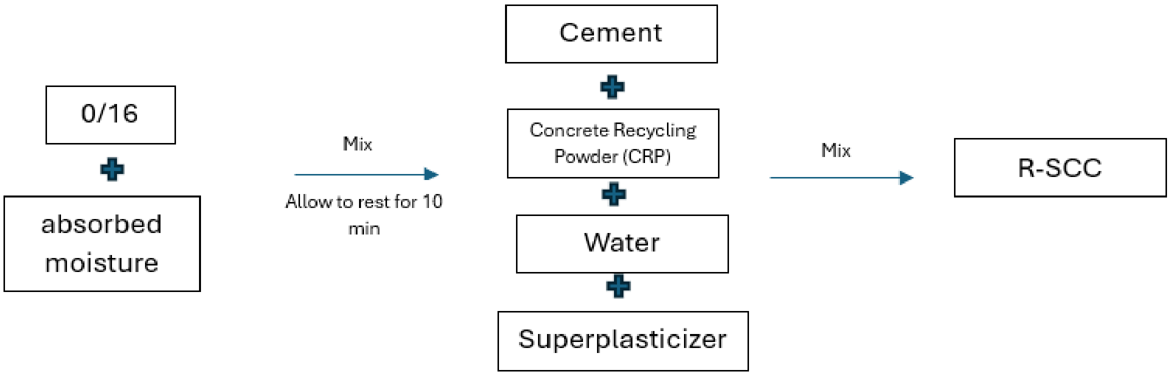

Fig. 2: Mixing Protocol [1]

In Table 1 example mixtures of Type 1 and Type 2 are described.

2.5 Testing Procedures

Fresh concrete tests included:

- Slump flow diameter
- V-funnel flow time
- Air content
- Fresh density

Table 1: Example mixtures of Type 1 and Type 2 [1]

Parameter	**Einheit**	**BA 3**	**BA 4**	**BS 4**	**BS 5**
Total volume	[m^3]	0.02	0.03	0.02	0.03
Paste content nL,is (ACTUAL)	[dm^3/m^3]	511.00	511.00	562.80	562.80
BA 0/2	[%]	32.00	32.00	45.00	45.00
BA 0/2	[kg]	6.38	12.75	7.73	18.98
BA 2/16	[%]	68.00	68.00	55.00	55.00
BA 2/16	[kg]	13.65	27.30	9.49	
Bulk density of aggregate mix	[kg/dm^3]	2.60	2.60	2.51	2.51
Average water absorption	[M.-%]	4.78	4.70	6.76	6.76
Cement	[kg/m^3]	343.60	343.60	372.50	372.50
Addition material content	[kg/m^3]	348.87	348.87	416.68	416.68
Air content	[Vol.-%]	1.50	1.50	1.50	1.50
Cement density	[kg/dm^3]	3.01	3.01	3.01	3.01
Required water content	[kg/m^3]	223.34	223.34	242.13	242.13
Selected water-cement ratio, w/c	w/z	0.65	0.65	0.65	0.65
Water-powder ratio		0.82	0.82	0.79	0.79
FM ACE 430	M.-% v. CEM	2.00	2.00	2.25	2.50
FM ACE 430 dosage	[g]	103.60	207.20	125.90	279.00
Required aggregate content	[dm^3/m^3]	512.81	512.81	458.24	458.24
VCEM/VAdditive		0.85	0.85	0.77	0.77
Additive (CRP)	[kg]	5.23	10.47	6.25	12.50
Cement	[kg]	5.15	10.31	5.59	11.18
Water	[kg]	3.25	6.49	3.51	6.98
Target fresh concrete mass	[kg]	33.76	67.53	32.69	65.38
1st Slump flow w/o blocking ring	[mm]	780.00	765.00	675.00	980.00
1st flow time	[s]	5.00	3.30	5.00	2.90
2nd Slump flow w/ blocking ring	[mm]	740.00	745.00	545.00	970.00
2nd T500 flow time	[s]	6.90	4.00	7.00	3.00
Post dosage	[%]	0.50	0.50	0.75	0.25
3rd Slump flow w/ blocking ring	[mm]	825.00	700.00	900.00	880.00
3rd T500 flow time	[s]	3.90	3.30	3.90	3.10
Air content (fresh concrete)	[Vol.-%]	1.30	2.40	0.20	1.20
Fresh concrete temperature	[°C]	21.90	21.60	21.70	21.00

Hardened concrete tests included:

- Compressive strength (150 mm cubes according to DIN EN 12390-3 [9])

Additionally, cut sections of the hardened specimens were visually inspected to evaluate possible sedimentation and the uniformity of aggregate distribution.

3. RESULTS AND DISCUSSION

3.1 *Fresh Concrete Properties*

The incorporation of recycled aggregates significantly influences fresh concrete behavior. The higher water absorption of Type 2 aggregates led to lower initial workability, which was compensated by water and superplasticizer adjustments.

As shown in Fig. 3, the recycled aggregate mixtures (Type 2) exhibited slightly higher sedimentation compared to Type 1, yet maintained overall stability without visible segregation.

Despite exceeding the standard sedimentation limits (according to DIN EN 1045-2 [10]) in some mixes, no visible segregation or aggregate settlement was observed in the cut specimens. The recycled aggregates provided internal stability due to their higher fines content, rough texture, and better interlocking.

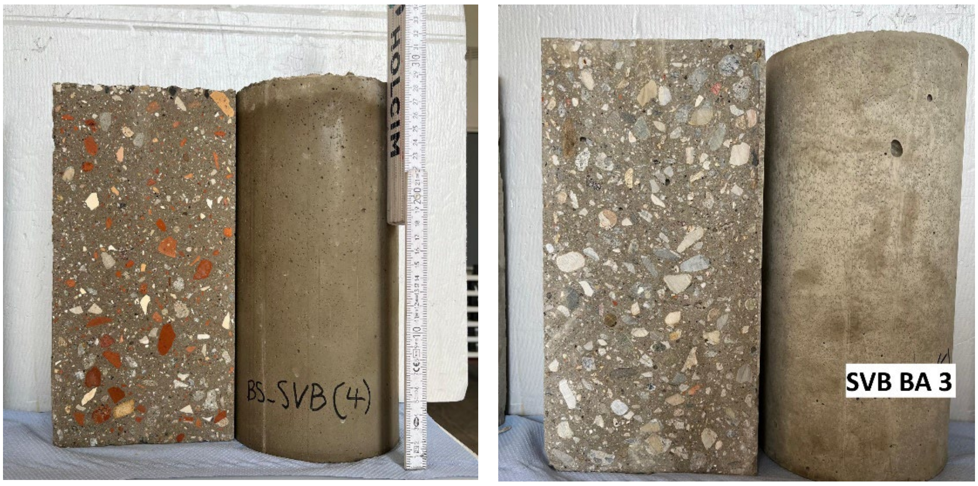

Fig. 3: Sedimentation tendency in the cylinder of mix BS 4 (Type 2) and BA 3 (Type 1) [1]

These observations suggest that existing standards for slump flow and flow time may not fully capture the behavior of SCC with recycled aggregates.

3.2 *Hardened Concrete Properties*

The compressive strength results demonstrated very good mechanical performance of SCC with 100% recycled aggregates. Corrected compressive strengths ranged between approximately 35 MPa and 41 MPa, depending on aggregate type and mix composition. Notably, some mixtures with Type 2 aggregates reached the highest strength levels, indicating that proper mix design can successfully compensate for the challenges associated with recycled aggregate properties.

The achieved compressive strength corresponds to strength classes C30/37 to C35/45 according to DIN EN 206-1 [11], confirming the suitability of these SCC mixes for structural applications.

3.3 Importance of KGP and Paste Thickness

The KGP method [2] proved essential in developing a well-balanced aggregate skeleton, minimizing void content, and ensuring uniform aggregate distribution. In combination with the controlled paste layer thickness, this approach ensured sufficient coating of aggregates while preventing segregation or excessive paste demand. Proper paste thickness is particularly critical with recycled aggregates due to their rough and porous surface, which can otherwise lead to instability or excessive binder consumption.

4. CONCLUSION AND OUTLOOK

This study demonstrates the feasibility of producing high-quality self-compacting concrete using 100% recycled aggregates. By applying the aggregate mix testing method and carefully adjusting the paste content and admixture dosage, both fresh and hardened concrete properties met the requirements for structural applications.

However, the research also highlights that existing normative evaluation criteria, especially those concerning workability classifications such as slump flow limits, may require revision for SCC incorporating recycled aggregates.

A distinctive feature of this study is the production of recycled concrete powder (BAM), which was specifically made from the fine fraction of Type 1 recycled concrete aggregates (concrete demolition material). This self-produced powder was used as a supplementary material in the SCC mixtures, replacing conventional fillers such as limestone powder or fly ash.

By combining 100% recycled aggregates with a recycled fine powder, the resulting concrete qualifies as a fully recycled SCC, referred to in this study as “RC-SCC Plus.”

Future studies should focus on extensive testing with a broader range of recycled aggregate sources and compositions to establish more representative threshold values for fresh concrete performance parameters. In addition, long-term durability aspects such as freeze-thaw resistance and chloride penetration should be investigated to further validate the practical applicability of SCC with recycled aggregates, particularly for sustainable construction and post-war reconstruction projects.

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