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ORIGINAL ARTICLE

Concrete with Recycled Aggregates - Update of the Application Rules in Germany and Outlook

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Abstract

In Germany the use of recycled aggregates is possible within certain limits since the introduction of the DAfStb guideline in 1998. Due to increasing demands of concretes fulfilling requirements regarding sustainability, conservation of resources and avoidance of waste the topic of recycled aggregates has again become the focus of public, economic, and political interest in recent years. Although the results of the BMBF research project "R-Beton" have led to positive changes with respect to the regulation gap in environmentally relevant characteristics several certain barriers still prevent the broad use of recycled aggregates in the German concrete market. In the forthcoming DIN 1045, regulations will be created which, particularly in concrete class BK-N in the application range of up to 25 % volume fraction, will permit simple and thus practical use of recycled aggregates. In addition, fine recycled aggregates of type 1 may be used, which was previously not permitted. Here, changes in the regulatory framework of DIN 1045 will be discussed in the sense of a broader use of recycled aggregates in Germany as well as the context of other national regulations. An outlook regarding further need of research is also given.

Keywords

Concrete, Recycled Aggregate, DIN 1045, Regulatory Framework

1 Introduction

In terms of volume, mineral construction waste is the most important material flow in waste management in Germany [1], as well as in many neighbouring countries [2]. The availability of large amounts of mineral construction waste in combination with legislative demands with respect to waste avoidance promote the production of recycled aggregates from construction demolition waste. In addition, the production of recycled aggregates contributes to the conservation of natural resources as well as sustainability goals [3]. In some countries, mineral construction waste is already used in daily practice for concrete production, whereas concrete containing recycled aggregates (R-concrete) is only part of the delivery program in a few ready-mix concrete plants in Germany. Besides the geological and geographical situation, the role played by R-concrete in practice depends on the respective legislation and regulatory situation of a country.

In all European countries there are regulations governing the recycling of mineral construction waste. However, despite the introduction of European harmonized standards like EN 206 or EN 12620, there are sometimes significant differences in the handling of recycled aggregates between the individual countries. These differences are caused by different editions of the regulations, which have been introduced by the building authorities in the individual European countries, as well as by the very different national application documents, additional national guidelines, and other legal requirements.

However, differences between recycled and natural aggregates make further regulations necessary. These include the more inhomogeneous material composition of recycled aggregates, an increased water absorption capacity due to increased porosity, a reduced bulk density and cement residues remaining after processing. These differences have an impact on fresh and hardened concrete properties, which must be considered in the production and design of components made of R-concrete (e.g. [4]-[9]). The forthcoming DIN 1045 replaces the currently valid guideline of the German Committee for Concrete (DAfStb) guideline as the national application document for the use of recycled aggregates in concrete production in Germany. Following, challenges and chances of this regulatory framework are discussed with respect to the possibilities of a broader use of R-concrete in Germany as well as in comparison to the regulatory situation in some other countries.

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2 National regulations still in force in Germany for the use of recycled aggregates in concrete

In Germany, the use of concrete with recycled aggregates is currently still regulated by the guideline of the DAfStb "Concrete according to DIN EN 206-1 and DIN 1045-2 with recycled aggregates according to DIN EN 12620" (edition September 2010) [10]. From the point of view of concrete technology, it still represents the technical status of 1998 when it was first released. Although the guideline was revised in 2004 and 2010, it was only formally adapted to the European standards for concrete (DIN EN 206-1) and aggregates for concrete (DIN EN 12620).

Due to the fact that the DAfStb guideline for the production of concrete with recycled aggregates has hardly been applied in practice, the regulations of the DAfStb guideline were revised in the BMBF joint research project "R-concrete – re-source-conserving concrete - the next generation of material" from 2014 to 2019. Several factors influencing the properties of R-concrete like environmentally relevant characteristics, alkali-silica reaction, replacement rates of natural concrete or the content of recycled fines were considered. In addition, concepts for dimensioning, environmental impact and life cycle assessment were developed [11].

The results achieved led to recognizable positive changes in the sense of a broader application of recycled aggregates. Some of the changes in the regulations have already been implemented and can be applied. For example, the proof of the environmental compatibility of recycled aggregates was again standardized with the publication of DIN 4226-101 (edition August 2017) [12].

However, based on the results from this project the rules regarding the classification of the recycled aggregate with respect to alkali-silica reaction in case of unknown origin depending on the place of use had to be tightened. Before, recycled aggregate was generally classified in alkali sensitivity class E III-S for the whole of Germany if no other evidence permitted a different classification. Due to the risk of alkali-silica reaction if aggregates from the glacial deposit area in northern Germany are recycled and thus used again in construction classification rules were adapted. If proof of alkali sensitivity class E I-S according to the DAfStb guideline "Preventive measures against damaging alkali reactions in concrete (alkali guideline)" [13] is not possible or not carried out, the concrete is now to be classified in alkali sensitivity class E III-O to E III-OF. This regulation was implemented with a correction of the DAfStb guideline in 2019 [14].

Regarding all other changes concerning the use of recycled aggregates, the responsible committees agreed that these should be included in the revision of DIN 1045. For this purpose, the complete DIN 1045 series in the July 2022 draft versions [15] was presented to the expert public. Objections could be submitted until October 10, 2022. The objection meetings were held in January 2023. The series of standards will be published in mid-2023, and the introduction by the building authorities via the Model Administrative Regulation on Technical Building Regulations (MVV TB) [16] is expected at the beginning of 2024.

3 Future regulations according to DIN 1045-2 for the use of recycled aggregates in concrete

3.1 Classification of concrete with recycled aggregates into concrete classes

With the future DIN 1045-2, concretes with recycled aggregates according to DIN EN 12620 (edition July 2008) [17] will be transferred to the new concept of concrete classes (BK, Betonklasse). As before, the superordinate regulations can be found in Section 5.2.3.4 "Recycled aggregates" and all others in the normative Annex E "Output materials", Section E.2 "Regulations for the use of aggregates".

In future, concrete with recycled aggregates will be assigned to the concrete classes BK-N (normal requirements), BK-E (increased requirements) and BK-S (special requirements) as follows:

- Concrete class BK-N: Concrete with coarse recycled aggregates of type 1 and 2 ≤ 25 % by volume replacement with reference to the total amount of aggregates and in compliance with the general requirements for recycled aggregates according to E.2.3.1
- Concrete class BK-E: Concrete with coarse recycled aggregates > 25 % by volume replacement with reference to the total amount of aggregates or moisture class WA and in compliance with the general requirements for recycled aggregates according to E.2.3.1 and the special requirements according to E.2.3.2
- Concrete class BK-S: Concrete with recycled aggregates deviating from BK-N and BK-E.

The use of recycled aggregates for prestressed concrete and lightweight concrete is still not permitted.

3.2 Adaptation to the terminology of DIN EN 12620

DIN EN 12620 deals with the requirements on aggregates for concrete. A distinction is made between geometric, physical, and chemical requirements. The geometric requirements include that all aggregates, with the exception of fillers, must be described by specifying the aggregate size class by means of lower (*d*) and upper (*D*) sieve size using the designation *d/D*. The respective aggregate size class must meet the requirements for grain composition according to EN 12620 and the requirements for aggregate composition according to DIN EN 12620, Section 4.3 "grain composition".

The general requirements for aggregate composition are derived from DIN EN 12620, Table 2, which subdivides aggregates into coarse and fine aggregates, naturally composed aggregates 0/8 and aggregate mixtures. The standard defines fine aggregates as aggregate groups with *D* not greater than 4 mm, where *d* = 0. For coarse aggregates, *D* must not be smaller than 4 mm and *d* must not be smaller than 2 mm. From the requirements for the grain composition according to Table 2 it follows that for coarse aggregates an undersized content of up to 20 % by mass is permissible.

Neither these conceptual specifications nor the requirements for the aggregate composition are considered by the DAfStb guideline "Concrete according to DIN EN 206-1 and DIN 1045-2 with recycled aggregates according to DIN EN 12620", since only recycled aggregates > 2 mm are addressed here. An aggregate with proportions exclusively > 2 mm is neither technically feasible, since all fines ≤ 2 mm would have to be screened off, nor does this comply with the specifications of DIN EN 12620.

For the above reasons, the terminology for recycled aggregates has been adapted to DIN EN 12620. In future, the terms "fine" and "coarse" aggregates will also be used for recycled aggregates.

In this context, extensive changes regarding the standard requirements for recycled aggregates (DAfStb guideline, Table 2, [10]) were also implemented (see Section 3.4, Table 2 of this article).

3.3 Concrete class BK-N

In concrete class BK-N, up to 25 % by volume with reference to the total volume of aggregate of the coarse aggregate ($D \geq 4$ mm, $d \geq 2$ mm) may be replaced by recycled aggregates. This applies to the use of either type 1 or type 2 recycled aggregates. The scope of application applies to all concretes up to compressive strength class C50/60. The terms "normal-strength concrete" and "high-strength concrete" will no longer exist in the new DIN 1045-2. Regarding the moisture classes according to the DAfStb alkali guideline, the scope of application has been limited to WO and WF. The moisture class WA was assigned to the concrete class BK-E.

In addition, fine recycled aggregates may now be used again, as already permitted in the first edition of the DAfStb guideline "Concrete with recycled aggregate" [18]. The possibility of using fine recycled aggregate was an important focus of the BMBF joint research project "R-concrete", in which the options for use in concrete and cement production were investigated. With the introduction of DIN EN 197-6 "Cement - Part 6: Cement with recycled building materials" [19], which is currently available in draft form, it can be assumed that the main mass flows will go into cement production. Nevertheless, regulations have already been created for use in concrete.

In concrete class BK-N, fine recycled aggregates of type 1 may be used if they originate from the production of coarse recycled aggregates of type 1 for which the material composition requirements according to DIN EN 933-11 (edition May 2011) [20] have been verified. The requirements are shown in Table 1. However, the total volume of recycled aggregate must not exceed 25 % by volume and the proportion of fine recycled aggregate in relation to the proportion of coarse recycled aggregate must not be greater than the proportion of total fine aggregate in relation to the proportion of total coarse aggregate.

Fine recycled aggregate type 2 may still not be used, as the necessary scientific evidence is lacking that could allow its application. Studies on the use of fine recycled aggregate type 2 are the subject of current research.

Table 1 Requirements for the material composition of coarse recycled aggregate crowns according to DIN EN 12620:2008-07, 5.8, (corresponds to DIN 1045-2, Table E.18)

Constituents	Category of aggregate Type 1	Type 2
Rc + *Ru*	Rcu_{90}	Rcu_{70}
Rb	Rb_{10-}	Rb_{30-}
Ra	Ra_{1-}	Ra_{1-}
X + *Rg*	XRg_{1-}	XRg_{2-}
FL	FL_{2-}	FL_{2-}

Rc: Concrete, concrete products, mortar, concrete masonry blocks
Ru: Unbound aggregate, natural stone, hydraulically bound aggregate
Rb: Masonry bricks (i.e. masonry blocks and bricks), sand-lime bricks, non-floating aerated concrete
Ra: Bituminous materials
Rg: Glass
X: Other materials: cohesive materials (i.e. clay and soil), miscellaneous other materials: metals (ferrous and non-ferrous), non-floating wood, plastic, rubber, plaster
FL: Floating material in volume

Concretes with recycled aggregates of concrete class BK-N must comply with the general requirements for recycled aggregates according to DIN 1045-2, Section E.2.3.1, see Section 3.4.

Structural members made of concrete with recycled aggregates may be designed according to DIN EN 1992-1-1 (Eurocode 2) [21] under the aforementioned conditions.

In comparison to the regulatory framework of other countries the application rules of recycled aggregates in concrete in class BK-N are similar to those of SIA 2030 “Concrete with recycled aggregates” [22] valid in Switzerland. Here concrete with a maximum replacement rate of natural aggregates of 25 % by mass concrete recycled aggregates (similar to type 1) is considered as normal concrete without further limitations. Different to the rules of DIN 1045-2 is the possibility of the production of normal concrete containing mixed recycled aggregates (similar to type 2) with a maximum replacement rate of 10 % by mass according to SIA 2030. In addition, the use of fine recycled aggregates is encouraged unless technical limitations with no restriction to the type of material.

3.4 General requirements for recycled aggregates

The general requirements for recycled aggregates can be found in DIN 1045-2, Section E.2.3.1 and apply equally to all concrete classes. These concern the requirements for:

- the material composition of type 1 and 2, see Table 1
- the categories that can be used for recycled aggregates (comparable to the previous requirements for recycled aggregates)
- the water absorption
- the resistance to alkali-silica reaction
- the impact on soil and groundwater

Regarding the requirements for the material composition of the recycled aggregate, there have been no changes compared to the previous regulations. These correspond to the requirements specified in DIN 4226-101. In the European concrete standard EN 206 (edition June 2021)

[23], informative Annex E defines Types A and B. These are not congruent with the national specifications.

Table 2 Usable categories for recycled aggregates according to DIN EN 12620:2008-07, (corresponds to DIN 1045-2, Table E.19)

Property	Section in DIN EN 12620	Category of aggregate Type 1 Type 2
Particle size distribution from …		
narrow-graded coarse aggregate	4.3.2	$G_C85/20$
wide-graded coarse aggregate	4.3.2	$G_C90/15$
fine aggregate	4.3.2, 4.3.3	G_F85
natural aggregate mixes	4.3.2, 4.3.5	G_A90
Particle shape	4.4	FI_{50} and better respectively SI_{55} and better
Seashell content [a]	4.5	No requirement
Fines from …		
coarse aggregate	4.6	f_4
fine aggregate	4.6	f_3 [e]
natural aggregate mixes	4.6	f_3 [e]
Resistance to …		
fragmentation	5.2	No requirement
wear	5.3	No requirement
polishing	5.4.1	No requirement
surface abrasion	5.4.2	No requirement
abrasion by spiked tyres	5.4.3	No requirement
Particle density [b] (oven-dry) ρ_{rd}	5.5	≥ 2.000 kg/m³
Freeze-Thaw resistance [c]	5.7.1	F_2 and better for XF3; F_4 and better for XF1; No requirement for all other exposition classes
Magnesium sulfate resistance	5.7.1	No requirement
Shrinkage due to drying	5.7.2	No requirement
Chlorides [d]	6.2	Chlorid content ≤ 0,15 % by mass for concrete without reinforcement or other embedded metal
Acid-soluble chloride	6.2	≤ 0,04 % by mass
Acid-soluble sulfate	6.3.1	$AS_{0,8}$ and better
Total sulfur	6.3.2	≤ 1 % by mass
Water-soluble sulfate	6.3.3	$SS_{0,2}$
Constituents that change the setting and hardening behaviour of concrete	6.4.1	Passed
Lightweight organic impurities of coarse aggregate and natural aggregate mixes	6.4.1 und annex G.4	≤ 0,1 % by mass
Lightweight organic impurities of fine aggregate	6.4.1 und annex G.4	≤ 0,5 % by mass
Resistance to alkali-silica reaction	DAfStb alkali-guideline	DIN 1045-2, E.2.3.1.3

a Relevant only for aggregates extracted from the sea.
b Variation range related to the mean value of the particle density declared by the manufacturer: ± 150 kg/m³.
c Alternatively, the freeze-thaw resistance of recycled aggregates can be verified by means of a clay test according to E.2.3.3.1.
d Otherwise, the chloride content of the concrete shall be verified according to 5.2.8.
e As an alternative to the requirements of f_3, these aggregates can be used with a fines content of ≤ 4 % by mass.

As already indicated, some changes have been made to the standard requirements, resulting in a broader scope of application for recycled aggregates. The usable categories for recycled aggregates according to DIN EN 12620 are listed in the future DIN 1045-2 in Table E.19, see Table 2 of this article.

In addition to the supplementary regulations for the fine aggregates with regard to the particle size distribution and the fine fractions, the use of wide-graded coarse aggregates is now also permitted for coarse aggregates. The categories of possible particle size distributions were set equal for types 1 and 2 since it was unclear why a higher oversize content should be permitted for type 2.

Parameters of grain density and water absorption are essential and must be taken into account in concrete production [24]. The particle density (oven-dry) ρ_{rd} must be greater than or equal to 2,000 kg/m³. The variation range of the particle density in relation to the mean value of the particle density declared by the manufacturer must not exceed or fall below 150 kg/m³. Within this range no problems will occur during concrete production. Water absorption is determined for the coarse recycled aggregate after 10 minutes and must not exceed 10 % by mass for type 1 and 15 % by mass for type 2. Extensive studies in [5] show that the usual water absorptions of recycled aggregates after 10 minutes are well below the above-mentioned maximum values. Recycled aggregate of type 1 absorbed on average 74 % of the 24-hour water absorption within the first ten minutes, aggregate of type 2 absorbed on average 78 % under the same boundary conditions.

The requirements for resistance to alkali-silica reaction result from the classification of the recycled aggregate into alkali sensitivity classes according to the DAfStb alkali guideline [13]. This and the tightening since 2019 [14] have already been referred to in Section 2.

Similarly, the topic of environmental compatibility was also addressed in Section 2. Proof can be provided by means of a declaration of performance based on a European Technical Assessment (ETA) or by an assessment of the performance based on DIN 4226-101 in compliance with DIN 4226-102 [25] in a technical documentation with the involvement of a body qualified in accordance with Art. 43 BauPVO [26].

3.5 Concrete class BK-E

Concretes with recycled aggregates > 25 % volumetric exchange of the coarse aggregate (with reference to the total aggregate volume) are assigned to concrete class BK-E, as are concretes with recycled aggregates, which are grouped in moisture class WA and must therefore meet the requirements of the DAfStb alkali guideline.

In addition to the general requirements according to DIN 1045-2, Section E.2.3.1, which were dealt with in the previous section, the special requirements according to Section E.2.3.2 must also be met. The special requirements are dealt with in Section 3.6.

Concrete with recycled aggregate of concrete class BK-E may also be designed in accordance with DIN EN 1992-1-1 (Eurocode 2) [21].

3.6 Special requirements for concrete with recycled aggregates > 25 % by volume content or moisture class WA

Among the special requirements for concrete with recycled aggregates, the already known regulations of the DAfStb guideline "Concrete according to DIN EN 206-1 and DIN 1045-2 with recycled aggregates according to DIN EN 12620" (edition September 2010) [10] were essentially adopted.

Thus, in concrete class BK-E, only coarse recycled aggregates of either type 1 or type 2 according to Table E.18 may be used for the production of concrete. The compressive strength class is limited to C30/37 as before. The principle of the concrete families may be applied to concrete with recycled aggregates separately for types 1 and 2.

Depending on the moisture class and the exposure class, recycled aggregates may be added with maximum proportions given in Table 3. Based on research results obtained [11], some changes could be made in Table 3 compared to [10].

Table 3 Permissible proportions of coarse recycled aggregates, based on the total aggregate (% volume fraction), (corresponds to DIN 1045-2, Table E.21)

Scope of application		Category of aggregate	
Alkali guideline [a]	DIN EN 206 and DIN 1045-2	Type 1	Type 2
WO	Cabonation XC1	≤ 45 [b]	≤ 35
WF	No corrosion risk X0 Carbonation XC1 to XC4 Freeze-thaw attack without de-icing agent XF1 and XF3 Concrete with high water penetration resistance according to DIN 1045-2, 5.5.3	≤ 45	≤ 35
	Chemical attack XA1	≤ 25	≤ 25
WA [c]	XD1 and XD2 XS1 and XS2 XF2 and XF4	≤ 30	≤ 20

a Preventive measures against damaging alkali reactions in concrete (DAfStb alkali guideline) and additional requirements, DIN 1045-2, E.2.3.1.3, (2) and (3).

b Fine recycled aggregates of type 1 ≤ 20 % by volume of the exchangeable recycled aggregate may be used, provided they originate from a production of coarse recycled aggregate type 1 for which the material composition requirements according to DIN EN 933-11 have been verified. The total volume of recycled aggregate must not exceed 45 % by volume. The proportion of fine recycled aggregate in relation to the proportion of coarse recycled aggregate must not be greater than the proportion of total fine aggregate in relation to the proportion of total coarse aggregate.

c Moisture class WA may only be used for recycled aggregate with verified alkali sensitivity class E I-S according to the DAfStb alkali guideline.

d The regulation on chemical attack is covered for XA1 by concrete class BK-N.

For interior components (exposure class XC1 and moisture class WO), a maximum of 45 % by volume of coarse recycled aggregate may still be used, but in future it will also be permitted to use fine aggregate (see footnote b). However, the use of fine recycled aggregate applies only to type 1, analogous to the regulations for concrete class BK-N.

In the application area of moisture class WF, except exposure class XA1, the permissible replacement rates by coarse recycled aggregate were increased by 10 % by volume for type 1 and type 2. Since no investigations on the chemical attack of concrete with recycled aggregates were carried out in the research project, the existing regulations were adopted here.

The line for moisture class WA has been newly included in Table 3 and thus concerns all exposure classes in which alkali is supplied from outside, e.g. by the use of de-icing agents in the form of NaCl. Exposure classes XD3 and XS3 are excluded. For the use of recycled aggregate in moisture class WA, the alkali sensitivity class E I-S according to the DAfStb alkali guideline must be verified. This regulation could be of particular interest if it is certain that aggregate origin is from projects that already met these requirements during construction and therefore appear to be suitable for renewed use. Furthermore, for concrete with recycled aggregates of concrete class BK-E, an extended initial test has to be carried out and additional tests are mandatory during production control of the concrete manufacturer.

Looking at regulations regarding the maximal replacement ratio by recycled aggregates of other countries different concepts are in place. According to SIA 2030 recycled concrete with concrete recycled aggregates (RC-C) is split into two classes, one containing recycled aggregates between 25 % and 50 % by mass, the other between 50 % and 100 % by mass. Similarly, classes of recycled concrete with mixed recycled aggregates (RC-M) are defined by contents between 10 % and 40 % by mass and 40 % and 100 % by mass, respectively. Depending on the concrete class (which is based on the intended use, exposition class and other criterions) the use of RC-C or RC-M is permitted, permitted if the suitability is confirmed by additional tests or prohibited. As the use of fine recycled aggregates is generally allowed concrete with 100 % recycled aggregates can be produced for certain applications.

According to the British standard BS 8500-2 [27] the use of coarse recycled aggregate is permissible for the production of concrete with a maximum strength class of C40/50 and certain exposure classes. Depending on the intended use of the concrete up to 100 % replacement of the coarse aggregate fraction by recycled aggregates is possible.

3.7 Concrete class BK-S

Concrete with recycled aggregates that do not correspond to concrete classes BK-N or BK-E are assigned to concrete class BK-S and therefore must be separately specified.

Usually this concerns the deviation from one or more requirements of BK-N or BK-E. For such cases, the state building regulation provides for object-related approval in individual cases (ZiE, Zustimmung im Einzelfall) and project-related construction approval (vBG, vorhabenbezogene Bauartgenehmigung). This means that concrete compositions deviating from the usual regulations will be examined within the framework of an expert opinion and by the building supervisory authority of the respective state.

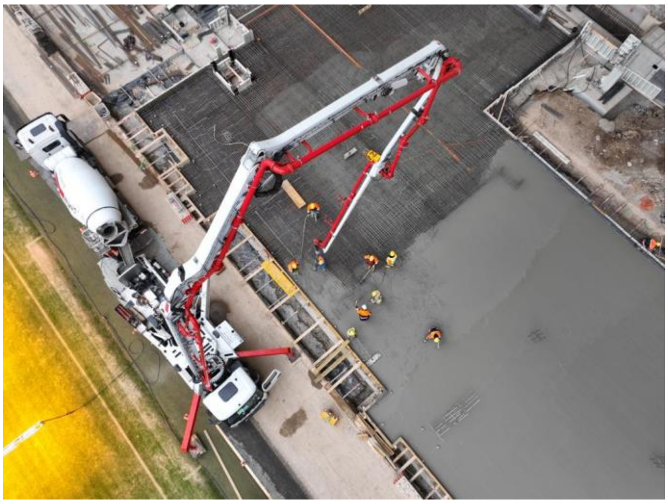

Figure 1 Mercedes-Benz Arena, Stuttgart, demolition of the old main stand and use of the processed material in the construction of the new main stand (during the ongoing operation of the soccer season), Picture: Ed. Züblin AG

A current example is the Mercedes Benz Arena in Stuttgart (see Fig. 1). Here, the main stand was demolished, recycled by a local company, and reused in the construction of the new main stand. All this was handled during the ongoing operation of the Bundesliga matches. In the present case, the concrete composition deviates in numerous points from the specifications of the regulations currently still in force. In this case, a ZiE had to be obtained, which was accompanied by an expert opinion from the authors. With the introduction of the new DIN 1045-2, a ZiE would no longer be necessary, since significant simplifications in the standardization are achieved and thus a wider use of recycled aggregates is possible.

In another case, a ZiE was accompanied for a facade made of concrete with coarse recycled aggregate type 2 with 100 % volume fraction. The facade was developed for Factory 56 of Mercedes-Benz AG in Sindelfingen. In the car factory of the future, Mercedes-Benz is relying consistently and comprehensively on innovative technologies and processes in the production of its vehicles under the keywords "digital, flexible, green". Special requirements were also placed on the concrete with recycled aggregates [28].

Figure 2 First residential building with load-bearing and non-load-bearing interior walls where the aggregate was replaced by 100% recycled aggregate type 3 (abZ/aBG), Picture: Fa. Büscher, Heek

Even more innovative were the goals of Büscher, Heek, namely to be able to use recycled aggregate of type 3, which is not intended for use in concrete according to the regulations. In a longer process and with the support of the authors, it was possible to obtain a general technical approval (abZ, allgemeine bauaufsichtliche Zulassung) and general design approval (aBG, allgemeine Bauartgenehmigung) for load-bearing and non-load-bearing walls, the so-called Büscher wall, from the Deutsches Institut für Bautechnik (DIBt), Berlin [29]. The first practical implementation took place in the context of an apartment building that required only four months from the ground-breaking ceremony to the move-in of the first tenant due to the precast concrete construction method (see Fig. 2).

4 Further research and outlook

Although a broader use of recycled aggregates for concrete production in Germany is possible with the new DIN 1045-2 several applications are still restricted due to a lack of research results. Thus, additional research is necessary to further improve and broaden the application of recycled aggregates in construction. This is particularly important with respect to the conservation of natural resources and high-quality recycling of construction and demolition waste.

For example, the use of recycled aggregate is also conceivable in prestressed precast concrete elements as it is already permitted in Switzerland under certain conditions [22]. Other researchers were also able to show a suitability of concrete with a replacement rate by recycled aggregate up to 20 % without affecting the long-term properties of the prestressed concrete component [30].

In addition to the increased water absorption and porosity, the different grain shape of the recycled aggregate compared to natural aggregate influences the properties of the concrete in its fresh and solid state. Due to the preparation process, an increased angularity as well as flatness and elongation can be observed. Computed tomography (CT) offers the possibility of detailed three-dimensional grain shape analysis of both coarse and fine recycled aggregate [31]. Within the framework of a current DFG research project, the influence of the grain shape of fine recycled aggregates on the workability and strength of mortar and concrete is therefore being investigated at the Department of Materials in Civil Engineering of the RPTU [31]. The aim is to investigate a possible increase in the use of fine recycled aggregates of both type 1 and type 2 in optimized sand compositions.

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