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Durability of Concrete with Recycled Aggregate

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ABSTRACT
A demand for a more sustainable use of resources entails that recycled aggregate material need to be used in advanced applications, as in concrete. Even if regulations and standards permit the use of recycled aggregate in concrete, the amount used for this application in many countries is negligible. This caution of the potential users is partly due to the uncertainty about how recycled aggregate, from construction and demolition waste and from washed excavation masses, influence the durability of concrete, such as alkali-silica resistance (ASR), frost resistance and carbonation. Choosing a binder that mitigate damaging alkali silica reactions is an effective means to diminish the risk for damage, even with alkali-reactive recycled aggregate. However, the alkali content of crushed concrete used as aggregate must be considered. No negative effect of recycled aggregate on the carbonation of concrete was observed. The uncertainty about the influence of aggregate porosity on the frost resistance of concrete, about adequate concrete test methods, about aggregate test criteria, and about the correlation between aggregate and concrete test methods need to be settled, before porous recycled aggregate like construction and demolition waste (CDW) can be used in more demanding exposure classes with respect to frost.

Key words: Recycled aggregate, CDW, durability, alkali silica reactions, carbonation, frost resistance

1. INTRODUCTION

1.1 General

A sustainable and responsible utilization of natural resources is a question of high priority for many actors, from individual enterprises and branches, via authorities and governments up to the EU level. Several studies on recycled aggregate for concrete have been carried out, for example the Mistra project Constructivate and the EU project RE[4] (www.re4.eu). However, most of these have been focused on mechanical and fresh concrete properties, and not on long time durability aspects. As regards construction and demolition waste (CDW) the degree of recycling is at present low in Sweden, and recycled CDW is mainly used in low grade applications, for example as fillings (down-cycling). A demand for a more sustainable use of resources entails that recycled aggregate material need to be used in more advanced applications, as in concrete. Another potential source for recycled aggregate is excavated materials which can be washed to extract recycled aggregate. Such facilities exist in Sweden. Even if regulations and standards allow the use of recycled aggregate in concrete, the amount used for this application in Sweden is negligible. The caution of the potential users is partly due to the uncertainty about how recycled aggregate, such as CDW or washed excavated materials, influence the durability of the concrete.

To untangle some of the uncertainties regarding the influence of recycled aggregate on the durability of concrete, two related projects have been carried out: one focused on the influence of recycled aggregate from washed excavated materials [1], in the following called WEM, and the other one on aggregate recycled from CDW [2].

Both projects included characterization of the recycled aggregate, to relate to the requirements on recycled aggregate for use in concrete expressed in SS-EN 12620 [3]. This characterization also included the sensibility to alkali silica reaction and frost attack of the aggregate. The durability tests on concrete with recycled aggregate were mainly carried out on concrete with replacement levels (recycled aggregate/total aggregate content) corresponding to the recommendations in the European concrete standard, SS-EN 206 [4], with some additional compositions. The compositions and the tests were primarily selected to be suitable for concrete to be used outdoors in buildings, not for use in the more demanding environments that civil engineering works are subjected to.

1.2 Requirements on recycled aggregate for concrete

As a basis, the requirements on any kind of aggregate for concrete as stated in SS-EN 12620 are also valid for recycled aggregate. Some of these do not cause any need for special caution when recycled aggregate is used, for instance particle size distribution and chemical requirements. However, some properties may need special attention since there are tangible differences between the performance of recycled aggregate and the aggregates normally used in concrete production, in Sweden usually crushed granite type rocks and natural gravel deposits. Two such properties are the water absorption and the frost resistance. Since the source of recycled aggregate normally is not as well defined as the source for crushed rock or gravel from specific deposits some chemical requirements of the recycled aggregate also need special attention, for example the content of chlorides and sulphur containing compounds. There are also a couple of requirements which apply only to recycled aggregate, classification of the constituents of coarse recycled aggregate and water-soluble sulphate content. As regards the alkali silica reactivity (ASR) of aggregate, SS-EN 12620 states the following "*When required the alkali silica reactivity of aggregates shall be assessed in accordance with the provisions valid in the place of use and the results declared*". In Sweden, the assessment of the risk of damages caused by ASR with aggregate is based on petrographic analysis and expansion testing with methods elaborated by RILEM and Nordtest.

In the two projects, the characterisation of aggregate properties focused on water absorption and densities, content of chlorides and sulphur containing compounds, constituents of the coarse aggregate, ASR and frost resistance.

1.3 Requirements related to the use of recycled aggregate in concrete.

According to SS-EN 206 [4], it is always permissible to replace up to 5 % of natural aggregate with reclaimed aggregate, i.e. recycled aggregate obtained by washing fresh concrete or crushing hardened but not used concrete from the producer's own production. For the use of recycled coarse aggregate from external sources SS-EN 206 only gives recommendations. There is a proposed classification in two quality classes, the higher Type A and the lower Type B, based on the proportions of constituents in the recycled aggregate. The recommendations on how much of the coarse aggregate in concrete that can be replaced with recycled aggregate depend on the aggregate quality class and the intended exposure class the new concrete will be subjected to. The highest replacement level recommended is 50 % of the coarse aggregate fraction, but this is only in exposure class X0, i.e. where there is no risk for corrosion or chemical attack. For the most challenging exposure classes, XD2-XD3, XS1-XS3, XF2-XF4 and XA2-XA3, the recommendation is: "*Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30 %.*" The maximum replacement level in the intermediate exposure classes is 30 % for Type A recycled aggregate. As regards the use of fine fractions (≤ 4 mm) of recycled aggregate in concrete nothing is said in SS-EN 206. The recommendations in SS-EN 206 are made mandatory with only minor adjustments in the Swedish application standard to SS-EN 206, SS 137003 [5].

Regarding tests of durability of concrete with recycled aggregate, they were in both projects focused on carbonation resistance, frost resistance and resistance against damaging ASR.

2. CHARACTERIZAION OF AGGREGATE PROPERTIES

2.1 Materials

WEM: Aggregate recycled from washed excavated materials
The source of the recycled aggregate from washed excavated materials was two different wet-washing plants (Malmö and Sundsvall) with different catchment areas and thereby different geographical and geological conditions. These facilities receive uncontaminated as well as contaminated excavated masses originating from local civil engineering projects. The local conditions and the kind of operations that have been performed in the vicinity of the facilities will be reflected in the properties of the resulting aggregate The washing procedure makes it possible to remove contaminations from the sand and gravel fractions. Due to the geological conditions around the Malmö plant, it can be anticipated that the treated material predominantly consists of gneiss, limestone, slate, siltstone, sandstone and flint. Based on the industrial background, remnants of limestone, slag and burnt clay materials may occur.

Table 1 – Test methods used for aggregate characterization

Property	Method	Performed on
Water absorption and particle density	SS-EN 1097-6 [6]	WEM: 48 batches, 12 coarse and 12 fine fractions from Malmö and Sundsvall, respectively CDW: 2 batches, which were separated into 2 coarse and 2 fine fractions
Composition	SS-EN 933-11 [7]	
Water and acid soluble sulphate and chloride, total sulphur	SS-EN 1744-1 [8]	
Petrographic analysis	RILEM AAR-1[9]	WEM: 12 batches; 3 coarse and 3 fine fractions from Malmö and from Sundsvall respectively CDW: 2 batches, which were separated into 2 coarse and 2 fine fractions
ASR resistance	RILEM AAR-2 [10] & NT Build 295 [11]	
Salt-frost resistance	SS-EN 1367-6[12]	WEM: 6 baches (only the coarse fraction) CDW: 2 batches (only the coarse fraction)
Frost resistance	SS-EN 1367-1 [13]	WEM. 1 batch (only the coarse fraction) CDW: 1 batch (only the coarse fraction)

The material from the Sundsvall plant may primarily consist of granites, migmatite, and meta-greywacke, due to the local geological conditions. Due to the industrial history of Sundsvall, it is anticipated that the material may contain smaller amounts of slag and burnt clay materials. At each facility, twelve composite samples of coarse aggregate and twelve composite samples of fine aggregate were taken over a period of several months, summing up to 48 samples on which some aggregate properties were analysed, to study the variation over time. Thereafter, twelve of these samples were selected for additional aggregate characterisation

CDW: Aggregate recycled from construction and demolition waste
The CDW was obtained from one waste facility and consisted of mineral materials such as concrete, rock, mortar, bricks, light-weight concrete coming from demolished structures. Two batches were taken at different occasions. They were crushed in two steps, first to a maximum size of 100 mm and then to a maximum size of 30 mm, and then sieved to fractions 0/8 and 8/16 (two of each).

2.2 Methods

Test methods used for aggregate characterization are given in Table 1.

3 CONCRETE DURABILITY TESTS

3.1 Materials

Constituents
In the WEM series, only one binder combination was used: 68.5 % CEM I 52,5 R (from Heidelberg Materials Cement Sweden) and 31.5 % GGBS conforming to SS-EN 15167-1 [14] (Merit from SWECEM). In the CDW series, the same binder as in the WEM series was used, but also a sulphate resistant, low alkali CEM II/A-V 42,5 N (from Heidelberg Materials, Sweden). A superplasticizer (Viscocrete 1030) was used to obtain a slump between 160 and 200 mm and an air entraining agent (AEA) with the trade name Master Air 105 was used to increase the air content where air entrainment was needed.

The source of the fine and course crushed natural aggregate was the same granite quarry. The water absorption of the natural aggregate was 0.7 % and the oven-dried density 2.65 g/cm^3. It had been tested with regard to alkali-silica reactivity with RILEM-AAR2, but since it did not contain any fast-reacting components it had not been tested with NT Build 295. The natural aggregate fractions were used in a reference mix without recycled aggregate, and in combination with recycled aggregate

In the WEM series one batch with fine aggregate and one with coarse aggregate were selected to represent the recycled aggregate from Malmö and similarly two batches were selected from the Sundsvall materials.

Concrete compositions
The same basic concrete composition was used in both series. The binder content was 400.4 kg per m^3 concrete in the mixes without AEA. When AEA was added the binder content became slightly lower. A water-to-binder ratio of 0.48 was chosen, which in Sweden is commonly used in concrete for external parts of buildings. In most mixes with recycled aggregate 30 % of the coarse aggregate fraction (≥ 4 mm) was recycled aggregate. However, in some mixes also 30 % of the fine fraction was recycled aggregate. In the RE[4] project [15], it was suggested that the

coarse recycled aggregate replacement level should be doubled. In the CDW series, a mix with 60 % recycled aggregate of the coarse fraction was therefore included.

According to [5] no AEA should be used in the ASR test. However, to achieve adequate frost resistance, AEA is necessary. Therefore, in all specimens with WEM except the ones intended for the ASR test, AEA was used with the intention to reach 4.5 % air. In the specimens with CDW, the AEA was only used in the specimens intended for frost testing. The main parameters of the mixes can be seen in Table 2. In the following M and S stand for WEM from Malmö and Sundsvall respectively, and indexes $_F$ and $_S$ signify coarse and fine fractions.

Table 2 – Main parameters of the concrete mixes

	Replacement level recycled aggregate (%)		Recycled aggregate	Binder	AEA
	Fine fraction	Coarse fraction			
Ref	0	0	-----	CEM I+GGBS	With and without
0/20M	0	20	M_C	CEM I+GGBS	With and without
0/30M	0	30	M_C	CEM I+GGBS	With and without
30/30M	30	30	M_F & M_C	CEM I+GGBS	With and without
0/20S	0	20	S_C	CEM I+GGBS	With and without
0/30S	0	30	S_c	CEM I+GGBS	With and without
30/30S	30	30	S_F & S_C	CEM I+GGBS	With and without
0/30C	0	30	CDW_C	CEM I+GGBS	With and without
30/30C	30	30	CDW_C & CDW_F	CEM I+GGBS	Without
0/60C	0	60	CDW_C	CEM I+GGBS	Without
0/30CF	0	30	CDW_C	CEM II/A-V	With and without

In addition to the durability parameters, the fresh properties and the compressive strength evolution of the mixes were also measured. When the differing air contents of the mixes were adjusted for, the influence of coarse recycled aggregate replacement on the fresh properties and the compressive strength was only marginal on all concrete mixes. The average 28 day strength of all mixes with GGBS in which coarse recycled aggregate was used was 44,4 MPa, with a standard deviation of 2.3 MPa compared to 45.2 MPa for the mix without recycled aggregate. However, replacement of 30 % of the fine aggregate in addition to replacement of the coarse aggregate lowered the compressive strength level with maximum 5 % with the WEM and with maximum 15 % with the CDW. See [1] and [2] for more details. It became obvious that one detail that need to be properly addressed in the casting routines is how to consider the higher porosity and water absorption of especially the recycled CDW aggregate. If this is not done properly, it can lead to a wrong water-to-cement ratio of the mix and that the measured air content in the fresh concrete AEA is misleading, since it may include air in aggregate pores. The best way to ensure mistakes caused by the relatively high porosity is to ensure that all pores in the aggregate are water filled when put into the mixer.

3.2 Methods

The methods used for determining the concrete durability are shown in Table 3.

Table 3 – Test methods used for concrete durability properties

Property	Method	Performed on
ASR resistance	RILEM AAR-11 [16]	WEM: 7 mixes without AEA CDW: 2 mixes without AEA
Salt-frost resistance	CEN/TS 12390-9 slab method with salt [17]	WEM: ----- CDW: 2 mixes with AEA
Frost resistance	CEN/TS 12390-9 slab method without salt [17]	WEM: 7 mixes with AEA CDW: ------
Carbonation	SS-EN 12390-12 [18]	WEM:7 mixes with AEA CDW: 4 mixes without AEA

4. RESULTS AND COMMENTS – CHARACTERIZATION OF AGGREGATES

4.1 Water absorption and densities

The average measured water absorption and different particle densities of the materials are given in Table 4.

Three of the WEM fractions have water absorption and oven dried particle densities like typical crystalline Swedish natural aggregates. Of the WEM, only the coarse fraction from Malmö has a water absorption which differs significantly from what is experienced with ordinary Swedish natural aggregate, probably due to presence of sedimentary, porous rock types. As anticipated, all the CDW fractions have water absorption much higher than for common crystalline aggregates. This is also manifested in a lower oven dried particle density. All the other fractions of WEM have water absorption and oven dried particle densities like ordinary Swedish natural aggregate. However, the apparent density is at about the same level for all materials, which indicates that all aggregate pores are open pores accessible to water.

Based on all the tests carried out (48 WEM and 4 CDW) it was shown that the variation of these properties between batches taken at different occasions was marginal.

Table 4 – Water absorption and particle densities of the recycled aggregate

Origin and fraction	Particle density (g/cm^3)			Water absorption (%)
	Apparent, ρ_a	Oven dried, ρ_{rd}	Surface dry, water saturated, ρ_{ssd}	
WEM M_F	2.66	2.64	2.65	0.3
WEM S_F	2.68	2.65	2.66	0.4
WEM M_C	2.68	2.48	2.56	3.0
WEM S_C	2.69	2.64	2.66	0.7
CDW_F	2.72	2.40	2.52	4.0
CDW_C	2.65	2.34	2.46	5.0

4.2 Constituents of coarse recycled aggregate

The constituents shall be divided into the following categories according to SS-EN 12620 [3].

- Rc Concrete, concrete products, mortar, concrete masonry units
- Ru Unbound aggregate, natural stone, hydraulically bound aggregate
- Rb Clay masonry units (i.e. bricks and tiles), calcium silicate masonry units, aerated non-floating concrete
- Ra Bituminous materials
- FL Floating material (in volume)
- X Other:
    - Cohesive (i.e. clay and soil)
    - Miscellaneous: metals (ferrous and non-ferrous),
    - Non-floating wood, plastic and rubber
    - Gypsum plaster
- Rg Glass

Particles of the different constituents are separated from each other according to SS-EN 933-11 [7] and weighed, except for the floating material which is measured by volume. The results of this process are shown in Table 5 for the coarse fractions used in the concretes. In this table, the Swedish requirements for the different quality types of recycled aggregate are also given. As can be seen, according to total amount of concrete and unbound stone (Rcu), all three materials fulfil the requirement for Type A recycled aggregate. Unfortunately, the requirement on glass plus other materials (Rg+X) is not achieved, but it should be mentioned that most of the particles under Rg+X were different types of slag, which according to new recommendations should be allocated to Ru.

Table 5 – Constituents of the materials

	Ru	Rc	Rcu	Rb	Ra	Rg+X	V_{FL}
			Weight fraction (%)				cm^3/kg
			Measured amount of constituents				
WEM M_C	95.0	1.1	**96.1**	1.2	0.2	2.3	0
WEM S_C	96.7	1.1	**97.8**	0.7	0.3	1.2	0
CDWC	20.8	76.7	**97.5**	2.5	0	<0.1	1.4
			Requirements according to SS 137003 [5] for use in concrete				
Type A			**≥ 95**	≤ 10	≤ 1	≤ 1	≤ 2
Type B			**≥ 70**	≤ 30	≤ 5	≤ 2	≤ 2

4.3 Water soluble chlorides and sulphate

The contents of water-soluble chlorides and sulphate of the materials are given in Table 6.

Table 6: – Content of water-soluble chlorides and sulphates

	Water soluble chloride (% by mass)	Water soluble sulphate (% by mass)
WEM M_F	< 0.001	0.23
WEM M_C	< 0.001	0.04
WEM S_F	0.002	0.01
WEM S_C	< 0.001	0.002
CDW_F	0.002	0.037
CDW_C	< 0.001	0.011

Regarding the content of water-soluble chloride, no limit value exists, but the value shall be declared so that it can be considered by the concrete producer. The measured value is very low for all materials. The limit value recommended in SS-EN 206 for water soluble sulphate in recycled aggregate is ≤ 0.2 %. All materials except the WEM fine fraction from Malmö fulfil this requirement. The water-soluble sulphate content is lower in the WEM from Sundsvall than in the WEM from Malmö. The CDW values are in the range between the two WEM sources.

4.4 Petrographic analysis

The petrographic analysis was carried out both ocularly (unaided eye) and on thin sections in microscope. In this paper only a short summary of the findings is given.

At least 35 % of the WEM from Malmö was granite, amphibolite, diabase, and free mineral grains of quartz and feldspar. Around 20 % of the coarse fraction was limestone, marble or calcite, and around 15 % was sandstone. In the fine fraction the values of these were lower. The materials also contained flint. The industrial remnants were scarce, but small amounts of concrete, bituminous material and slag were also seen.

Of the WEM from Sundsvall at least 75 % was granite, amphibolite, diabase, and free mineral grains of quartz and feldspars. The second largest proportion found was porphyritic metavolcanic rocks, mylonite and cataclasite. Other minerals and rocks were only found in small quantities. Also in this case the industrial remnants were scarce, with small amounts of slag, concrete, and bituminous material.

The CDW was dominated by concrete and brick (over 75 %). There were also smaller amounts of bituminous materials. Around 20 % consisted of non-bound stone and the vast majority of this was granite, feldspar, and quartz. In the coarse fraction, also a small amount, 1 %, of flint could be found.

4.5 ASR-tests

The expansion during tests with RILEM AAR-2 [10] and NT Build 292 [11] with the recycled aggregates are shown in Figure 1.

RILEM AAR-2 is in Sweden used to qualify aggregate as non-reactive regarding ASR when there are no fast-reacting components, like flint, in the material. When the aggregate incorporates fast-reacting components, NT Build 292 should be used for testing. The limit expansion value under which the aggregate is considered innocuous and can be used in concrete without restrictions is for the RILEM method 0.25 % after 28 days and for the NT Build method 0.1 % after 140 days. These limits are also marked in Figure 1. The coarse fraction of the WEM from Malmö is considered alkali reactive regardless of what method is used. The CDW material is considered innocuous irrespective of which method is used. But both WEM fractions from Sundsvall and the fine WEM fraction from Malmö is considered innocuous when tested with NT Build 295 and alkali reactive when tested with RILEM AAR-2.

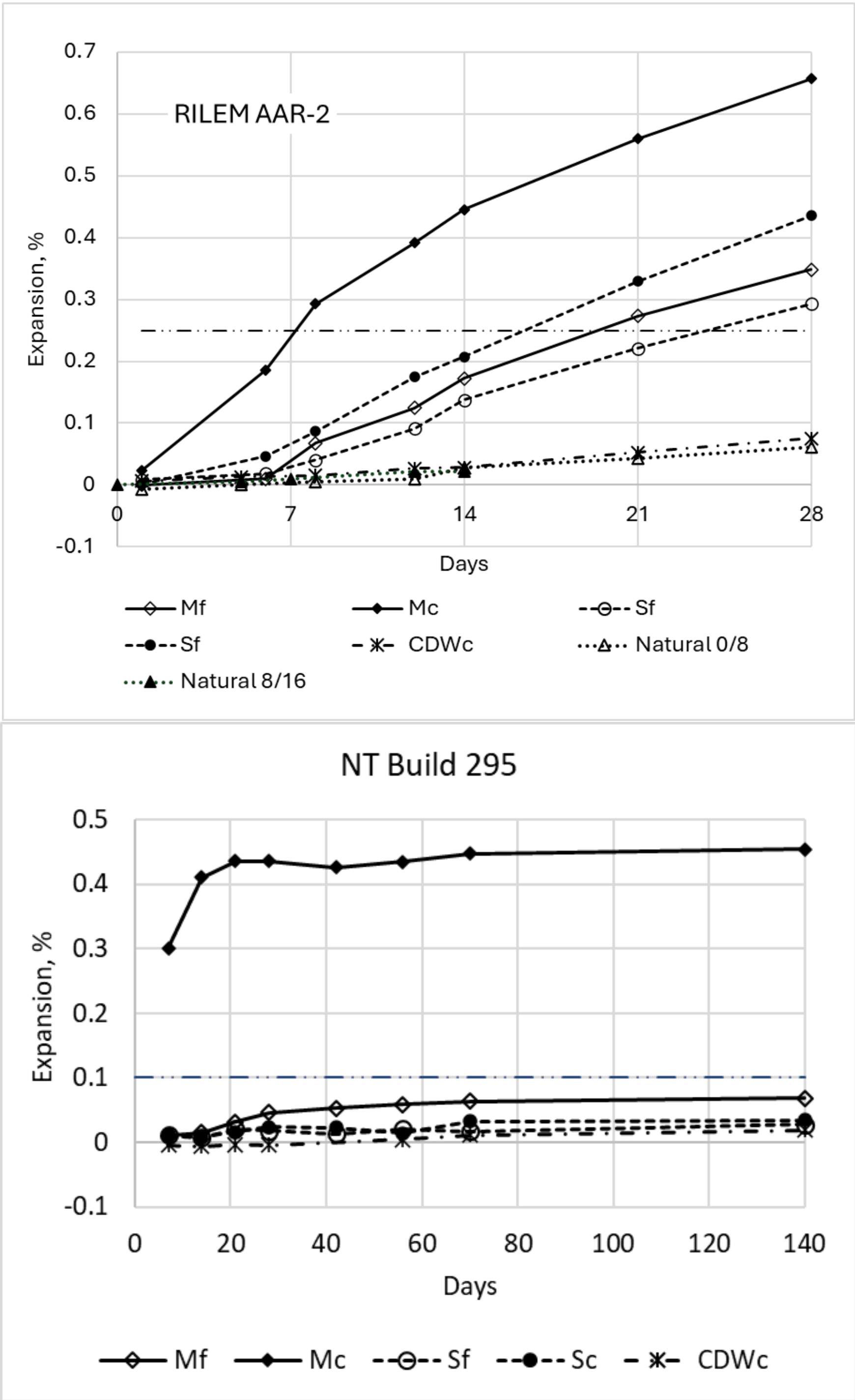

Figure 1 – Expansion of the recycled materials used in concrete during testing with RILEM AAR-2 (top) and NT Build 295 (bottom). Tests with RILEM AAR-2 with the natural aggregate is also included in the top figure.

4.6 Frost resistance of the coarse aggregate

To evaluate the frost resistance of coarse aggregate, the first step is to check its water absorption. If the water absorption is <1.0 %, the aggregate is considered frost resistant. Of the recycled aggregates in this study, only the coarse aggregate from Sundsvall fulfils this requirement. If the water absorption is higher, the frost resistance can be tested in water or in salt solution, depending on what kind of exposure environment the concrete will be submitted to. In Sweden, testing in water is used for exposure classes XF1 and XF3, and testing in salt solution for XF2. The test values are given in Table 7, together with the water absorption and Swedish limit values according to [6]. However, it must be pointed out that these limit values are not based on experience and might have been chosen with a large safety margin. As can be seen in Table 7, the WEM from Malmö and the CDW have much higher test results both when tested with salt and without. However, the WEM from Sundsvall fulfils the requirement when tested without salt but has slightly higher value than the Swedish limit for XF2.

Table 7: Water absorption, and freeze-thaw results of the recycled aggregate.

Designation	Water absorption (%)	Freeze-thaw in water (%)	Freeze-thaw in salt solution (%)
WEM M_C	3.0	3.8	9.1
WEM S_C	0.7	0.7	2.5
CDW_C	5.0	5	37
Limit value (no test needed)	*1.0*		
Limit test value for XF1/XF3 [6]		*2.0/1.0*	----
Limit test value for XF2 [6]		----	*2.0*

5. RESULTS AND COMMENTS – CONCRETE DURABILITY TESTS

5.1 ASR

The results from the tests with RILEM AAR-11 on samples of the concrete mixes with 30 % of the coarse aggregate replaced with recycled aggregate (both WEM and CDW) are shown in Figure 2 and with the other replacement levels in Figure 3 (only WEM). In both figures the results from the reference without recycled aggregate are also included.

In all mixes with WEM and in one ASR-tested mix with CDW, a binder (CEM I + GGBS) was used that in the future will be likely to replace pure Portland cement (CEM I) in concrete for buildings due to its lower carbon footprint. This binder is also known to mitigate damaging effects of ASR. In the other CDW mix a low-alkali CEM II/A-V which includes around 16 % fly as was used. Both the low alkali level and the incorporation of fly ash of this cement contribute to diminish the risk for damaging ASR. Due to this selection of binder, the expansions due to ASR in the concrete test are at a low level, well below the upper limit valid in Sweden for all mixes, even when using recycled aggregate that based on the aggregate test was considered highly alkali reactive. Some tendencies may though be distinguished. When the CDW aggregate is used, the expansion is faster and marginally higher than with both WEM aggregate types, even if these show much higher reactivity when tested with RILEM AAR-2 (see Figure 1). Replacing some of the fine aggregate with recycled aggregate also leads to a somewhat faster expansion initially but does not seem to increase the final expansion.

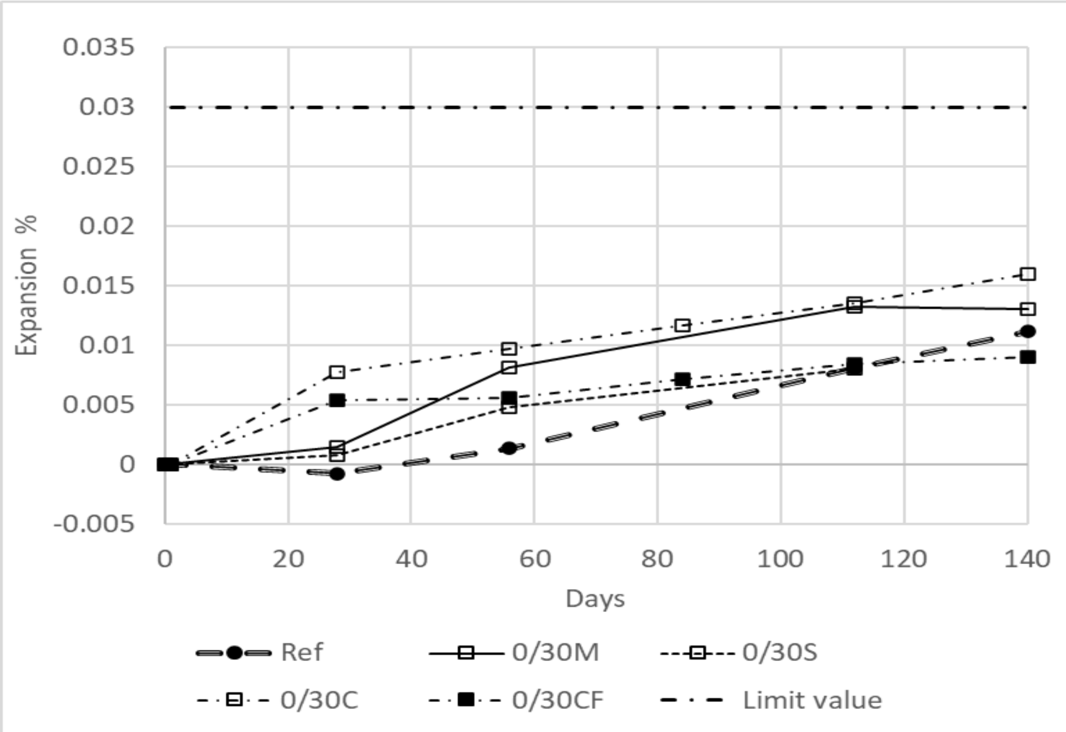

Figure 2 – Expansion measured according to RILEM AAR-11 for concrete mixes with 30 % of the coarse aggregate being recycled aggregate plus the reference mix without recycled aggregate. Limit value according to [6].

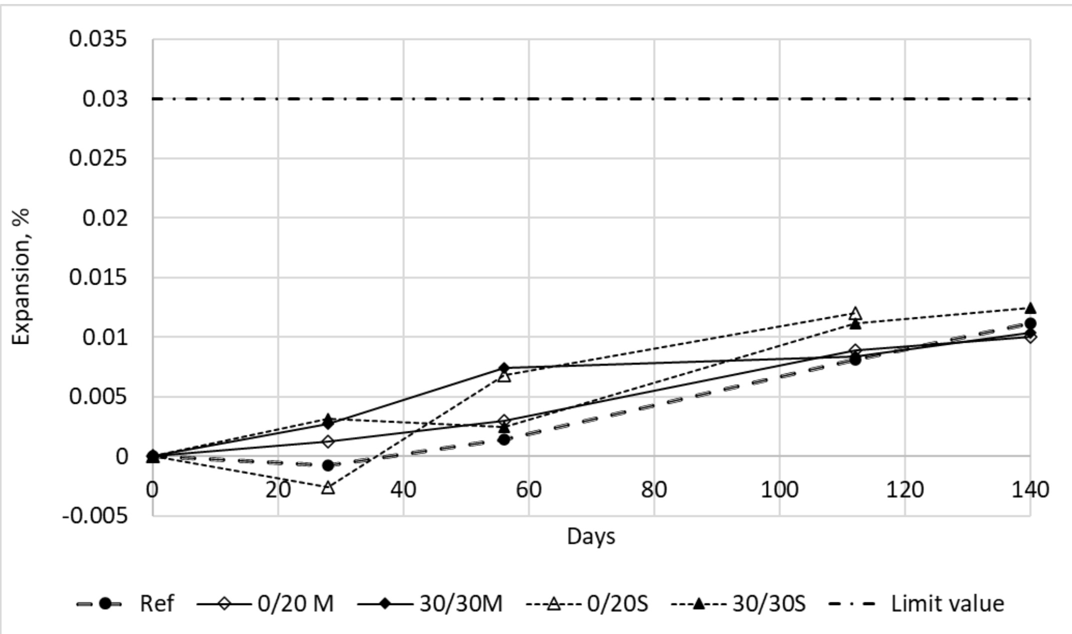

Figure 3 – Expansion measured according to RILEM AAR-11 for concrete mixes with 20 % of the coarse aggregate, 30 % of both coarse and fine aggregate being replaced with recycled aggregate plus the reference mix without recycled aggregate. Limit value according to [6].

5.2 Carbonation

Carbonation depth when exposed to 3 % CO_2 atmosphere during 70 days for the concrete mixes with WEM and the CDW mixes are shown in Figure 4. As can be seen, recycled aggregate does not affect the carbonation resistance negatively, since all tested mixes with recycled aggregate exhibits lower carbonation depths than the reference.

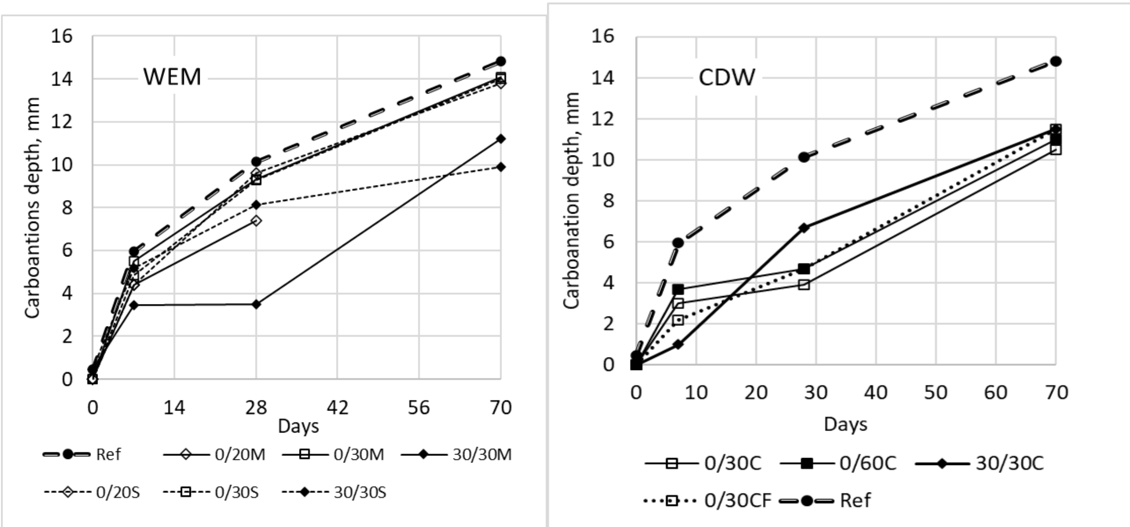

Figure 4– Carbonation depth of the concrete mixes with WEM aggregate and with CDW aggregate plus the reference without recycled aggregate.

5.3 Frost resistance

Scaling while exposed to water without salt of the mixes with WEM and AEA plus the reference without recycled aggregate are given in Figure 5. The measured air content of the mixes is also given in the figure.

For exposure class XF3, the frost resistance can in Sweden be based on either fulfilment of a requirement on air content or on testing according to SS-EN 12390-9 (the slab method without salt). All the mixes with WEM from Sundsvall have comparable scaling resistance to the reference without recycled aggregate. The WEM from Malmö causes a somewhat higher scaling, especially when both fine and coarse recycled aggregate are included. This is likely due to the higher porosity and water absorption of the aggregate from Malmö. However, all mixes have a very good scaling resistance when exposed to only water and would be accepted for use in exposure class XF3 if the frost resistance is verified by testing.

Scaling of the air entrained mixes with CDW while exposed to water with salt are given in Figure 6. The two mixes, which have the same aggregate composition but different binders, show very similar salt-frost scaling. Despite the bad result of the CDW in the aggregate salt-frost tests (see Table 5), these mixes would in Sweden be accepted for use in exposure class XF2, where acceptable salt-frost resistance is required. However, it should be noticed that the water-to-binder ratio (0.48) of these mixes is higher than the maximum allowed for this exposure class in Sweden (0.45). For XF2, testing with this method is not mandatory. Normally the frost resistance is based on an adequate amount of air pores obtained with an AEA giving a satisfactory air void distribution. The mixes would not be accepted for use in XF4 in Sweden, where testing with this method is mandatory and good salt-frost resistance is required.

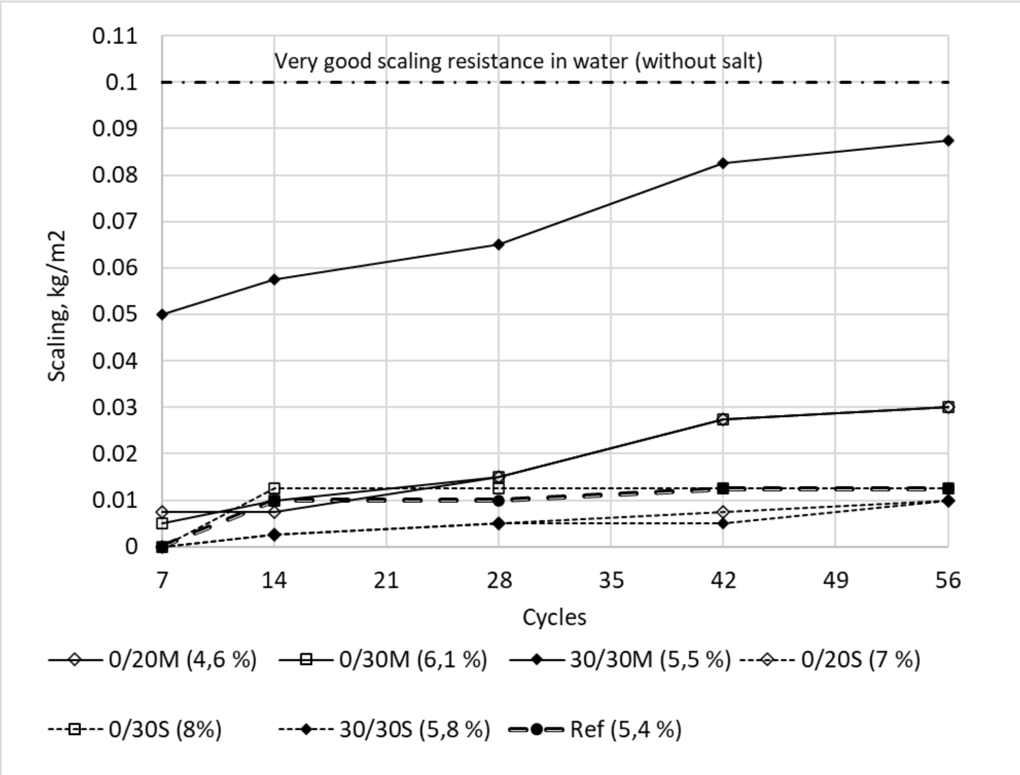

Figure 5 – Scaling of the mixes with WEM plus the reference without recycled aggregate when exposed to water without salt. AEA was used and the measured air content of the mixes are given in parenthesis. Classification limit value according to [19].

All mixes have a very good scaling resistance when exposed to only water and would be accepted for use in exposure class XF3 if the frost resistance is verified by testing.

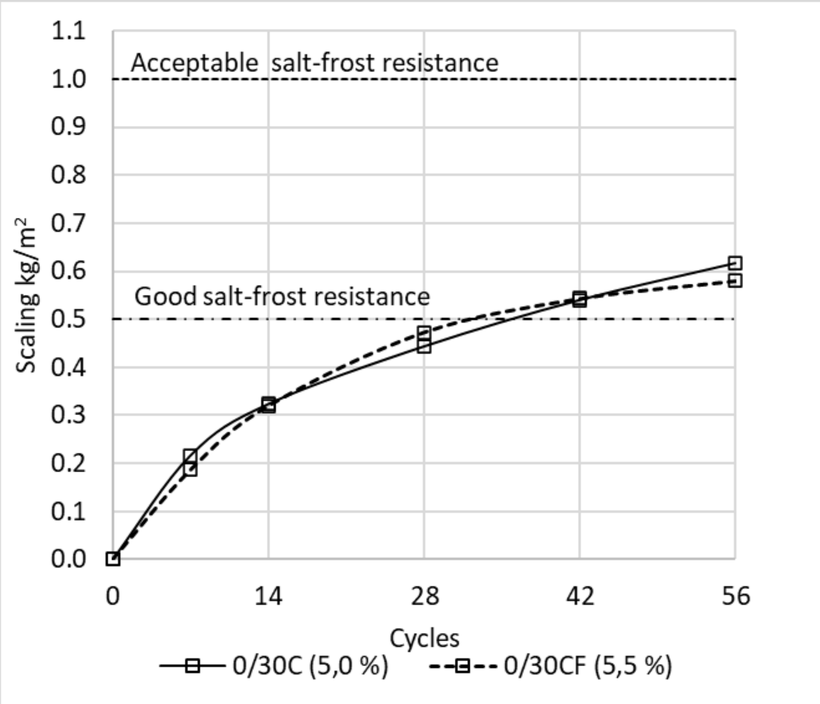

Figure 6 – Scaling of the two mixes with CDW recycled aggregate when exposed to salt solution. AEA was used and the measured air content of the mixes are given in parenthesis. Classification limits according to [19]

6. DISCUSSION

6.1 Problems with the aggregate characterization methods.

The method used to determine the water absorption, SS-EN 1097–6 [6], gives when used on fine fractions of recycled aggregate very uncertain results, which should be thoroughly studied so that the method could be modified.

The method to classify the constituents of coarse aggregate, SS-EN 933–11 [7] is subjective, and the result depends on the operator. The method is carried out by visual assessing and sorting particles by hand in the different component categories. It is especially difficult to correctly categorize unknown fabricated materials visually. It is not specified how different types of slag should be categorized. All types of slag that occurred has therefore been categorized as “other” (X). Particles which have traces of cement mortar or bitumen have been categorized as concrete (Rc) and bituminous (Ra) respectively. This has led to that the mass of concrete and bituminous materials is overestimated. Recommendations on how to categorize two-component particles is needed.

Correlation between results from the methods used for characterizing the frost resistance of aggregate (SS-EN 1367-1), the salt-frost resistance of the aggregate (SS-EN 1367-6) and frost resistance of concrete in which the aggregate is used is lacking. This is a problem for aggregate with a water absorption larger than 1 %, such as CDW, where the frost resistance is based on testing. Therefore, too restrictive limiting values for the aggregate tests may have been chosen.

Studies to correlate the aggregate tests with the performance of the aggregate when used in concrete need to be performed to establish relevant limit values.

The two methods to determine the ASR reactivity of the aggregate lead to different classifications as regards ASR- reactivity. Under which circumstances the respective method gives results that reflect the ASR behaviour of the aggregate when used in concrete in real structures should be clarified.

6.2 Influence of recycled aggregate on ASR of concrete

The ASR reactivity of the recycled aggregate when tested with RILEM AAR-2 gives one ranking of the different types; The coarse WEM aggregate from Malmö is the most reactive one, thereafter comes the coarse aggregate from Sundsvall, the fine aggregate from Malmö and the fine aggregate from Sundsvall, all with reactivities higher than the limit value for being innocuous. The CDW aggregate is well below this limit. Measured with NT Build 295, which in Sweden is used on aggregate containing fast-reactive components, the coarse aggregate from Malmö is the only one that will be classified as alkali-reactive. All the other aggregate types are well below the limit value for being innocuous. Of these, the fine fraction from Malmö is the most reactive and the CDW aggregate the least reactive.

Binders that mitigate the risk for damaging ASR expansion were used in the concrete tests, and this was enough to keep the expansion below the limit value when all these aggregates were used in concrete and tested with RILEM AAR-11 [16]. But why was the influence of the differing types of aggregate so diverging in that case? The WEM aggregate from Malmö gives a slightly higher expansion than the WEM aggregate from Sundsvall, which is logical when compared to the ASR tests on the aggregate. But the non-reactive CDW aggregate gave a faster and slightly higher expansion than the WEM aggregates. This is probably due to the origin of the aggregate. The WEM consist to more than 90 % of unbound stone, while the dominating source of the CDW is concrete. Concrete may contain up to 6 kg alkali per m^3 concrete from the cement. 318 kg CDW per m^3 concrete was used in the concretes subjected to the ASR test, which corresponds to a volume of 0.12 m^3. This may increase the alkali level of the new concrete with 0.12×6= 0.72 kg per m^3 concrete. This should be added to the alkali content coming from the binder of the new concrete.

6.3 Influence of recycled aggregate on the carbonation resistance of concrete

A major difference between the two series is that the WEM mixes exposed to carbonation were air entrained, while the CDW mixes were without air entrainment. Air entrainment will increase the carbonation depth if the water to binder ratio is kept constant, which is the case here. From the series with WEM it can though be deduced that all the mixes with recycled aggregate have smaller carbonation depth than the reference mix without. The largest reduction of the carbonation depth occurs when also some of the fine aggregate is replaced with recycled WEM aggregate.

The generally lower carbonation depths of the CDW specimens compared to the reference may thus partly be due to the AEA. However, the larger porosity of the CDW aggregate may also increase the intrusion of the CO_2 molecules into the concrete. Therefore, one may conclude that replacing natural aggregate with recycled aggregate will not increase the carbonation, neither with WEM nor CDW aggregates.

6.4 Influence of recycled aggregate on frost resistance of concrete

Concrete frost damages may be due to different mechanisms. Scaling of concrete from the surface when the concrete is subjected to repeated freezing and thawing is a mechanism that is predominant when a concrete is exposed to salt solutions. The 9 % expansion that occurs when water in the concrete pores is freezing may also cause internal damages in the concrete. There exist also several other possible degradation mechanisms. However, common to all mechanism, freeze-thaw damages only occur when the concrete has a high degree of water saturation when freezing occurs.

The main method to prevent frost damages is to provide the concrete with small air-filled pores well distributed in the concrete with the help of AEA, which serves as expansion vessels. The normal method to ascertain that there are enough air pores is by requiring a certain air content, which is measured on the fresh concrete. This is easily achieved, and the air pore volume can be measured with satisfying certainty when the aggregate is almost free of voids, like Swedish natural aggregate. But if the aggregate is porous, the aggregate porosity may influence the reading of the instrument for measuring air content, if the pores in the aggregate particles are not water filled when the measuring takes place. Air in the accessible aggregate pores will not provide any protection against the expansion when the water is freezing [20]. Most of these pores will act in the same way as capillary pores in the new paste. To prevent overestimation of the air-entrained pore volume, the pores in the aggregate must be water filled when the measuring takes place. This is most easily achieved by prewetting the aggregate before mixing. This was a lesson learnt from the CDW project, where prewetting was not used. A mixing procedure considering the porosity of the aggregate may also prevent this problem. Another negative effect, if there is still some air in the aggregate pores in the fresh concrete, is that the intended effective water-to-binder ratio is not obtained.

The method used to determine the frost-resistance of concrete in this project was primarily elaborated to determine the salt-frost resistance of a concrete a Portland cement as only binder. The method has been used in Sweden for more than two decades for structures exposed to de-icing salt or to a marine environment (exposure class XF4), resulting in and increased frost durability of such structures compared to what was the case of older structures. In this project, the intended application of concrete with recycled aggregate was for building structures, i.e. a concrete which may have a high degree of water saturation but without salt (exposure class XF3) or a concrete with moderate water saturation only exposed to salt spray (exposure class XF2). The method can also be used without salt, but whether freeze-thaw scaling in water really reflects the decisive frost resistance in XF3 environments can be questioned. Inner degradation due to water expansion during freezing may be a more relevant degradation mechanism, and this has not been measured in this project. Whether scaling in presence of salt occurs when the concrete is not water saturated (as in XF2) can also be questioned.

Testing of salt-frost scaling of the concrete was only performed on two concrete mixes with CDW. The CDW performed badly when tested with the salt-frost test method for aggregate. However, the salt-frost resistance of the concrete in which it was used was not bad. According to Swedish rules [5] these concrete mixes could be used in XF2 and were not far from passing the test criteria for XF4, even though the water-to-binder ratio was slightly higher than the limit for XF2 and XF4.

On the concrete with WEM, which had much better frost resistance than the CDW based on the aggregate testing, only frost-scaling without salt was performed. The WEM from Sundsvall passed the criteria for use in concrete and showed scaling at the same level as for natural aggregate in the concrete frost test. The WEM from Malmö, which had higher water absorption, gave a somewhat increased scaling. However, both resulted in concrete with a very good frost resistance and pass the criteria for XF3.

The uncertainties about

- how the results of the method used to test the frost resistance on the aggregate is related to the frost resistance of concrete,
- appropriate limiting values of the aggregate test,
- the influence of the porosity of recycled aggregate on the concrete frost-resistance, and
- the influence of air in aggregate pores on the measured air content

indicate that these are questions that really need to be scrutinized before porous recycled aggregate, like CDW, can be used in more demanding exposure classes with regard to frost, like XF3 and XF4.

To this is added the uncertainty about appropriate test methods for XF2 and XF3. In that case lively discussions are ongoing among frost experts in Europe and research projects with the aim to formulate adequate requirements and select appropriate test methods for primarily XF2 and XF3 have been initiated.

6. CONCLUSIONS

- The method to characterize the constituents of coarse recycled aggregate is subjective and need to be further elaborated. There are uncertainties on how some materials should be categorized and how particles containing different materials should be categorized.
- The two methods used to determine the ASR reactivity of the aggregate in these projects lead to different classifications. It must be made clear which of the methods to use when, or under which circumstances both should be performed.
- Using a binder that is known to mitigate the risk for alkali silica reactions made it possible to obtain a concrete which showed very limited ASR expansion also when recycled aggregate which had shown high reactivity in the aggregate test were used.
- Use of recycled aggregate of CDW or WEM does not influence the carbonation resistance negatively.
- When using recycled CDW aggregate which contains crushed concrete or mortar, the alkali content of the CDW aggregate originating from the cement in the original concrete or mortar, must be taken into consideration.
- Even though more porous recycled aggregate showed bad frost resistance in the aggregate test, the frost resistance of the concrete with these aggregates were not particularly bad.
- However, the uncertainty about the influence of aggregate porosity on the frost resistance of concrete, appropriate concrete test methods for different exposures, adequate aggregate test criteria, and the correlation between aggregate and concrete test methods indicate that these uncertainties need to be settled before porous recycled aggregate like CDW can be used in more demanding exposure classes with respect to frost, like XF3 and XF4.

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