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Recycled concrete and mixed rubble as aggregates:

influence of variations in composition on the concrete properties

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Abstract

The recycling of concrete, bricks and masonry rubble as concrete aggregates is an important way to contribute to a sustainable material flow. However, there are still various uncertainties limiting the widespread use of recycled aggregate concrete (RC). The fluctuations in the composition of commercial grade recycled aggregates (RA) and their influence on the properties of fresh and hardened concrete are of particular concern regarding the use of RC. In this project, variations in the composition of RA were studied over a period of several weeks. Concrete mixtures were then produced with these aggregates in order to evaluate the resulting variations in concrete properties. Although the high variability in aggregate composition causes corresponding variations in concrete properties, the results obtained demonstrate that RA is suited for a wide variety of applications in the building industry.

Keywords: Petrography, Recycling concrete; Mixed recycled aggregate, Durability

1. Introduction

Decreasing natural resources of sand and gravel and increasing problems with waste management support recycling of the accumulating waste materials. If the vision of a sustainable material flow is to be realized, the amount of recycled waste has to be increased. The building industry in particular is a major consumer of materials and at the same time a major producer of waste. One possibility is to recycle and reuse inorganic building waste as concrete aggregates. However, the composition of these aggregates can vary substantially and their properties have a significant influence on the properties of the concrete [6,19,20,31]. However, the majority of previous studies have been focused on the mechanical properties of recycled aggregate concrete (RC) produced in laboratories [1,13,21,28,31,41]. Only little work has been carried out dealing with the fluctuations in the composition of commercial grade recycled aggregates (RA) in time and the consequences on the properties of the fresh and hardened RC. Furthermore, few data are available about the durability aspects of RC [23,25,26,34,43]. This lack of knowledge is an important factor limiting the widespread use of RC.

In this project, the influence of fluctuations in the composition of RA on concrete quality and the improvement of concrete quality by a partial replacement of RA with primary natural aggregate (PNA) were investigated. Five samples of mixed recycled aggregate (MRA) containing crushed concrete, bricks and tiles were taken and analyzed within a period of several weeks. Four concrete mixtures were produced with the aggregates sampled. Furthermore, four additional concrete mixtures with a partial replacement of RA with natural gravel were made. Compressive strength, bending tensile strength, E-modulus, gas permeability, shrinkage and creep, oxygen permeability (OP) and chloride conductivity were determined and compared to the properties of conventional concrete (CC). The aggregates used were processed in a recycling plant and the mixtures were produced in a concrete plant.

2. Materials and methods

2.1 Materials

The material arriving in the recycling plant was stored either on the pile "concrete" or on the pile "mixed rubble". The material from each pile was crushed with an impact mill. At the same time, reinforcement steel was removed with a magnet and lightweight material, such as wood and paper, were removed with a strong air current generated by a fan. Afterwards, the crushed concrete was sieved into four different fractions (0-4 mm, 4-8 mm, 8-16 mm and 16-32 mm) and stored in silos. On the other hand mixed rubble < 16 mm was discarded after the first crushing. The fraction >16 mm was crushed a second time and handled in the same manner as crushed concrete. The aggregates were not washed, but their surface moisture was measured by a sensor before using them in production of concrete. The concrete was produced in a double-shaft compulsory batch mixer with a capacity of up to 3 m^3.

The different components present in the aggregates were defined as follows:

(1) Secondary Gravel (SG), which consists of natural aggregates with less than 20 % of their surfaces covered with cement paste;

(2) Concrete, which consists of crushed concrete or SG with more than 20 % of their surfaces covered with cement;

(3) Brick, and

(4) Tile

Using this definition RA can be divided into recycled concrete aggregate (RCA) and MRA according to BUWAL [4]. RCA is made of at least 95 % SG and concrete and less than 2 % brick and tiles. MRA contains at least 97 % SG, concrete, brick and tiles. Over a period of four months, five MRA-samples (RA 0–RA 4 without PNS) were taken randomly in the recycling plant and analyzed according to European standard pr EN 933-11 [29] in order to determine the fluctuations in the petrography of commercial grade MRA (RA 0-4 / Fig. 3). For the analysis, only the fractions 8-16 and 16-32 mm were used, according to Swiss Standard SIA 162/4 [35]. Particle density and water absorption were measured according to European standard EN 1097-6 [11] and loose bulk density and volume of voids according to European standard EN 1097-3 [10]. Additionally, four different aggregates were designed using various amounts of either primary natural sand (PNS) or primary natural sand and gravel defined as PNA and RCA and MRA (RA 5-8 / Table 1). The relative proportions of the different types of aggregates were identical in each fraction (0-4 mm, 4-8 mm, 8-16 mm, 16-32 mm).

Table 1 Relative amounts per weight of different classes of aggregates.

aggregate	RCA 0-32 mm [%]	MRA 0-32 mm [%]	PNS 0-2 mm [%]	PNA 0-32 mm [%]
RA 0	-	80	20	-
RA 1	-	85	15	-
RA 2	-	85	15	-
RA 3	-	80	20	-
RA 4	-	90	10	-
RA 5	90	-	-	10
RA 6	-	60	-	40
RA 7	30	30	-	40
RA 8	-	25	-	75

2.2 *Mix design*

Four concrete mixtures (RC 1-4, Table 2) were produced with RA 1-4 (Table 1) in order to determine the influence of the fluctuations in the composition of RA on the concrete properties. Furthermore, four concrete mixtures (RC 5-8) were produced with RA 5-8 in order to improve the concrete quality by a partial replacement of RA with PNA. Mixtures RC 1-3 were produced with CEM II/A-LL 42.5 N and a low CaO fly ash binder. For the other mixtures, no additional fly ash was used. A commercial polycarboxylate type superplasticizer (SP) was used for all mixtures in order to reduce the water to binder ratio (w/b). The addition of water was adjusted for each mixture individually in order to reach the targeted workability: flow values of 350 – 480 mm and compactability 1.04 – 1.25 (paragraph methods).

Table 2 Concrete mixtures.

concrete type		RC 1	RC 2	RC 3	RC 4	RC 5	RC 6	RC 7	RC 8
aggregate type		RA 1	RA 2	RA 3	RA 4	RA 5	RA 6	RA 7	RA 8
aggregate	[kg/m^3]	1762	1778	1771	1710	1920	1920	1886	1931
cement	[kg/m^3]	325	350	350	325	300	325	325	300
fly ash	[kg/m^3]	20	100	100	-	-	-	-	-
superplasticizer	[kg/m^3]	3.45	4.5	4.5	3.25	3.0	3.25	3.25	3.0
total water	[kg/m^3]	175	222	221	195	123	144	123	132

Methods

The grain size distribution of RA 0-4 was determined according to EN 933-2 [9] on samples directly taken from the silos. On the other hand, the grain size distribution of the RA 5-8 was determined by taking a sample of the fresh concrete and washing it on a 0.25 mm sieve. The material was dried in the laboratory and sieved according to EN 933-2 [9] (Fig. 1 and 2).

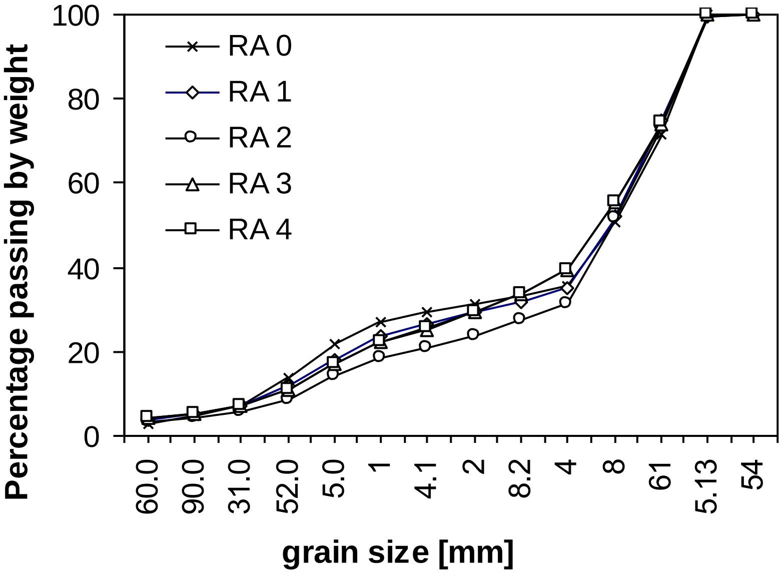

Fig. 1: Grain size distribution of mixtures RA 0-4.

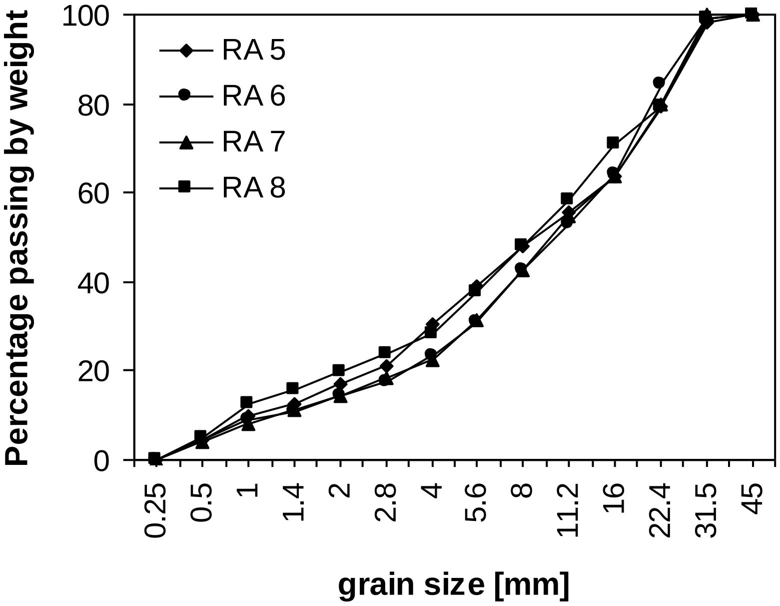

Fig. 2: Grain size distribution of mixtures RA 5-8.

The total water content of the concrete mixtures was measured according to Swiss Standard SN 262/1 [36] by heat drying a sample of fresh concrete until the mass stays constant. Compactability and flow of the mixtures were measured according to EN 12350-4 [38] and EN 12350-5 [39], respectively. The intended flow values were 350 – 480 mm (flow class F2 and F3 according to EN 206-1 [8]) and the intended compactability 1.04 – 1.25 (C2 and C3 according to EN 206-1 [8]). Air void content and bulk density were measured according to EN 12350-6 [12]. Fresh concrete properties were measured at the plant immediately after production and in the laboratory after a transport time of approximately 30 minutes. Specimens used to measure the properties of the hardened concrete were made in the lab.

Compressive strength, bending tensile strength and E-modulus were measured on 120 mm x 120 mm x 360 mm concrete prisms after curing at 20°C and 90 % relative humidity for 28 days. For each mixture, six values were determined for compressive strength, three for tensile bending strength and three for E-Modulus. Shrinkage and creep rate were determined at a temperature of 20°C and relative humidity of 70 % on two prisms (120 mm x 120 mm x 360 mm) during 91 days according to the Swiss standard [37]. A load of 10 MPa was applied to the samples for the creep measurements at the age of 28 days.

The oxygen permeability and chloride conductivity of RC 5-8 were measured on cores taken from separately produced cubes with a diameter of 68 mm and a height of 25 mm according to [2] and [3]. Three specimens were measured per mixture. The oxygen permeability test is based on the decrease of the applied pressure gradient due to oxygen passing through the samples (preconditioned at 50 °C for seven days). The values for oxygen permeability are presented as negative logarithmic values, the oxygen permeability index (OPI). The chloride conductivity is measured after a vacuum saturation of the samples with 5M NaCl solution.

3. Results and discussion

3.1 Composition of RA

The commercial grade aggregates RA 0-4 show a high variability in composition (Fig. 3). The content of brick and tiles in the samples varied between 10 % and 25 %, the content of concrete between approximately 25 % and 50 %. This variability is present as well in aggregates RA 5-8. As a result, for instance, RA 7 contains a higher amount of crushed concrete in petrographic terms than RA 5 despite the much higher percentage of RCA in RA 5.

The number of samples analyzed does not permit a statistical evaluation of variability. However, it is obvious that significant variations can be expected in the petrography of RA over time. This is a direct result of the great compositional diversity of the demolished buildings.

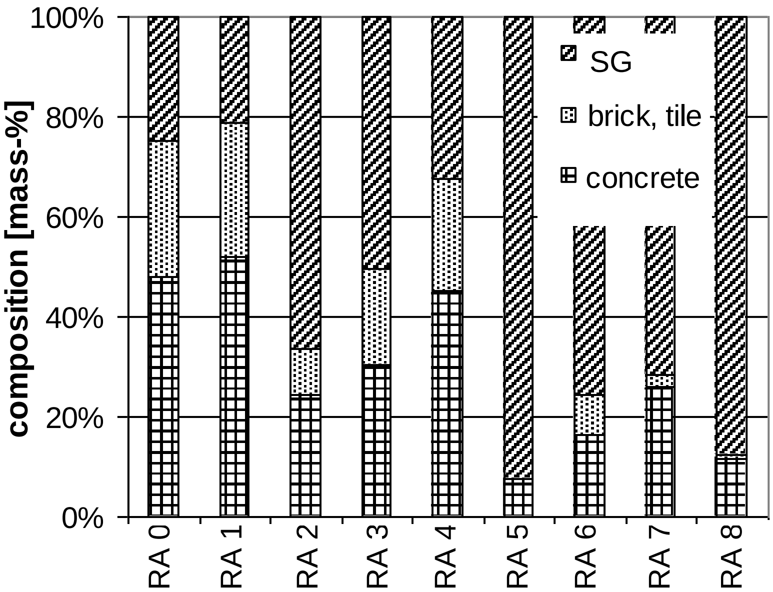

Fig. 3: Fluctuations in the composition of RA 0-8.

3.2 Particle density, water absorption and volume of voids

There is a clear difference in particle density and water absorption between RA 0-4 and RA 5-8; the later show higher density and lower absorption (Fig. 4). However, there are only small differences between the aggregates with respect to loose bulk density and volume of voids.

The observed differences in particle density and water absorption are directly related to the composition of the aggregates; a high proportion of bricks, tiles and concrete causes a low particle density and high water absorption due to the high porosity of these materials. Microstructural analysis [24] showed that extending the crushing process (using a jaw crusher, impact crusher and mechanical grinding) efficiently increases the physical performance of the concrete aggregate by reducing the content of porous components like cement paste. The volume of voids of RA is higher than the one of PNA that is in the range of 24-29 % for a similar sieve curve (Appendix: Table: 4). The higher values for crushed aggregates are due to the shape and roughness of the particles. Consequently, a higher volume of paste is needed to produce a concrete with good workability.

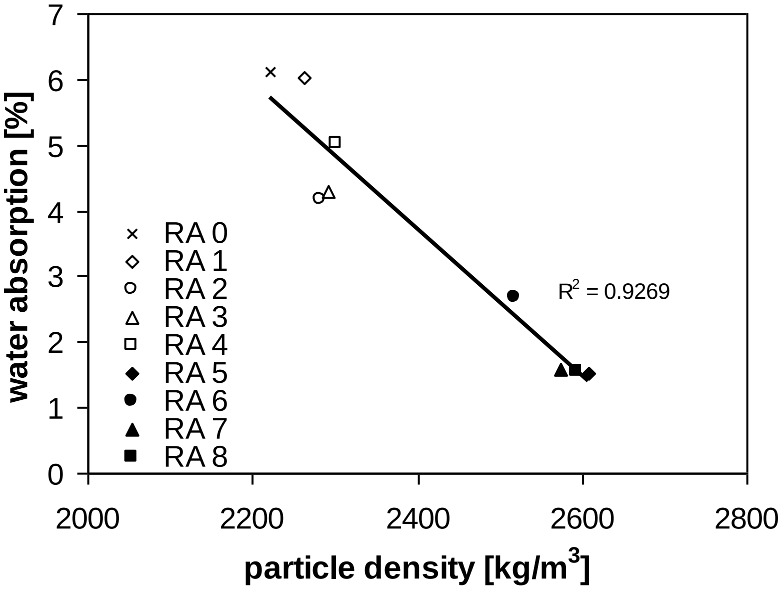

Fig. 4: Water absorption versus particle density of RA 0-8.

Properties of fresh concrete

The slump flow measured at the concrete plant meets the intended flow classes F2 and F3 (Table 3) for the mixtures RC 1- 4. This applies as well after the transport of 30 minutes as there was only a slight loss of workability. Mixtures RC 5 - 8 show slightly lower flow values. The air void content stays constant.

The high porosity of the RA has a considerable influence on concrete production. In comparison to natural aggregates, the water demand to reach a good workability is increased, resulting in a significantly higher w/b. The results obtained show that the water demand increases with an increasing content of bricks, tiles and concrete in the aggregate due to the high porosity present in these materials. This is confirmed among other things by [42].

Table 3 Properties of the mixtures used.

	RC 1	RC 2	RC 3	RC 4	RC 5	RC 6	RC 7	RC 8
slump flow [1] [cm]	44	51	43	54	33	33	36	33
slump flow [2] [cm]	39	48	40	42	30	30	33	31
compactability [1]	1.09	1.03	1.08	1.04	1.10	1.16	1.09	1.13
fresh bulk density [1] [kg/m^3]	2162	2129	2140	2161	2376	2338	2396	2429
air void content [1] [vol-%]	3.3	3.8	3.8	3.0	1.7	1.7	1.2	1.2
air void content [2] [vol-%]	-	-	-	3.8	1.6	1.8	1.5	1.3

total water [l/m³]	247	245	263	282	191	200	172	166
w/b	0.78	0.66	0.71	0.87	0.64	0.62	0.53	0.55

[1] directly after production

[2] after 30 minutes

3.3 Properties of hardened concrete

The properties of the hardened concrete are shown in the Table 4

Table 4 Properties of the various mixtures.

	Compressive strength 28 days [MPa]	Bending tensile strength 28 days [MPa]	E-Modulus 28 days [MPa]	Shrinkage 91 days [‰]	Creep 91 days [‰]	Permeability coefficient 28 days [10^{-16} m^2]	Chloride conductivity 28 days [mS/cm]
RC 1	33.2	4.3	21450	-0.35	-1.15		
RC 2	35.6	4.8	23400	-0.42	-0.84		
RC 3	34.6	5.0	22550	-0.4	-0.66		
RC 4	37.3	5.1	20700	-0.39	-0.80		
RC 5	45.4	4.4	32433	-0.38	-0.49	10.14	1.24
RC 6	54.3	5.9	30667	-0.44	-0.38	10.26	1.41
RC 7	54.4	6.4	33333	-0.43	-0.41	10.44	1.22
RC 8	53.4	6.0	34800	-0.39	-0.33	10.26	1.08

3.3.1 Compressive strength

The compressive strengths of RC 1-8 show a correlation with the w/b (Fig. 5). However, compared to the Eq.1 for CC determined in [18]

$$fc = 100 - 110 \bullet w/b \qquad (1)$$

the values are higher at a corresponding w/b. This is an effect of the water absorption of the porous aggregate during mixing. The water in the aggregates is not available for cement hydration causing a relatively dense paste in relation to the w/b present. The water used to calculate the w/b of the studied mixtures was determined by drying. As a consequence, the total water present in the mixtures including the part absorbed by the aggregates is reflected in the w/b. Compressive strength decreases with an increasing content of crushed concrete, bricks and tiles in the aggregate. This is mainly a consequence of the higher w/b needed to reach the targeted flow value, due to the water absorption of the aggregates as discussed in chapter 3.4.2. The relatively low strength of RA may have an effect on compressive strength as well, but it can not be quantified with the present results. An advantage of the high water absorption of the RA is the potential for internal curing, improving concrete quality. When the w/b is low, the strength of the concrete is governed by the effect of old interfacial transition zones in the RA [32]. When the w/b is high, the concrete strength is influenced by the quality of the new interfacial transition zone between the RA and paste. In general, the high surface roughness of RA leads to a good bond between cement paste and aggregates, as microstructural investigations confirm [27].

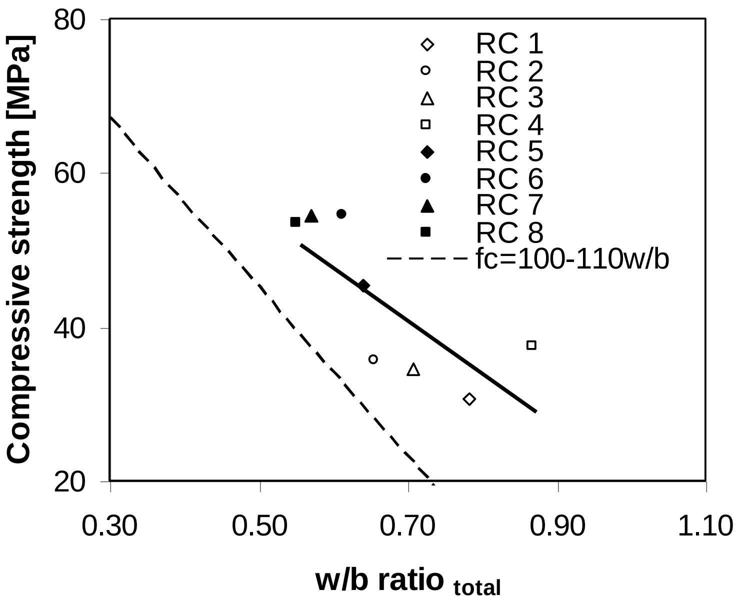

Fig. 5: Compressive strength at 28 days versus w/b.

3.3.2 Bending tensile strength

The bending tensile strength increases with increasing compressive strength (Fig. 6).

There is no significant difference in the relation between the compressive strength and bending tensile strength of RC in comparison with CC, based on the range for CC given in [14]. This correlation indicates that the bond between paste and aggregate in RC is comparable to the one in CC, confirmed by [21]. A qualitative analysis of the fracture zone of the tested specimens shows that the majority of brick and tile particles present are fractured. Obviously, their strength than that of the hardened paste or they even represent a weak point mechanically. Consequently, the amount of brick and tile particles may be a limiting factor on the strength achievable.

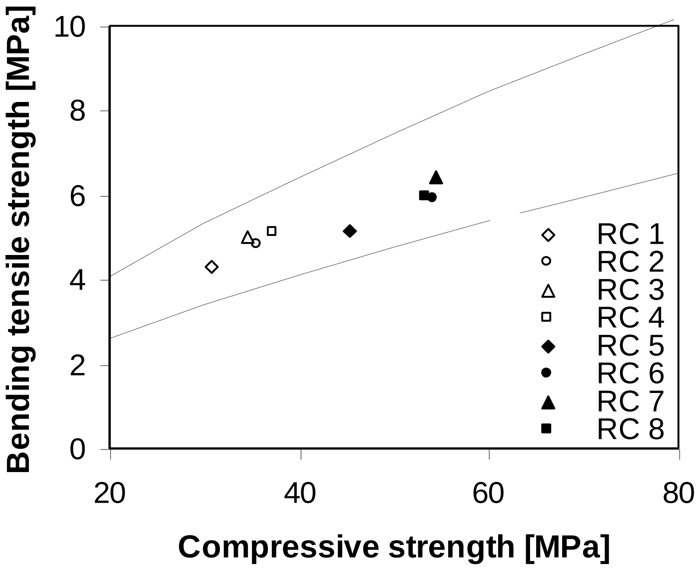

Fig. 6: Bending tensile strength versus compressive strength (area between dotted lines for CC given in [14]).

3.3.3 E-modulus

The E-modulus of RC 1- 8 decreases with the content of RA, in general, and with the content of crushed concrete, bricks and tiles, in particular (Fig. 7).

The E-modulus is significantly lower at a given compressive strength than the one of CC as specified in [40]

$$E = k_{CC} \bullet \sqrt[3]{fc}$$ with k_{CC} = 11000 for NA from Swiss midland (2)

The relationship between compressive strength and E-modulus of the mixtures studied can be expressed by Eq. 3 for mixtures RC 1-4 and by Eq. 4 for mixtures RC 5-8:

$$E = k_{RC1-4} \bullet \sqrt[3]{fc}$$ with $k_{RC1-4} \approx 6800$ (3)

$$E = k_{RC5-8} \bullet \sqrt[3]{fc}$$ with $k_{RC5-8} \approx 9000$ (4)

On the one hand, this relatively low E-modulus of RC is a result of the higher volume of paste compared to CC. On the other hand, the low E-modulus of the RA itself has a strong influence as well [15,16,30]. As an example, the E-modulus of concrete produced with 70 % of the aggregate consisting of bricks is 55 % lower than the one of CC at an identical compressive strength [22]. Concrete with 100 % crushed concrete as coarse aggregate and natural sand shows an E-modulus up to 30 % lower than the one of CC at identical compressive strength [17].

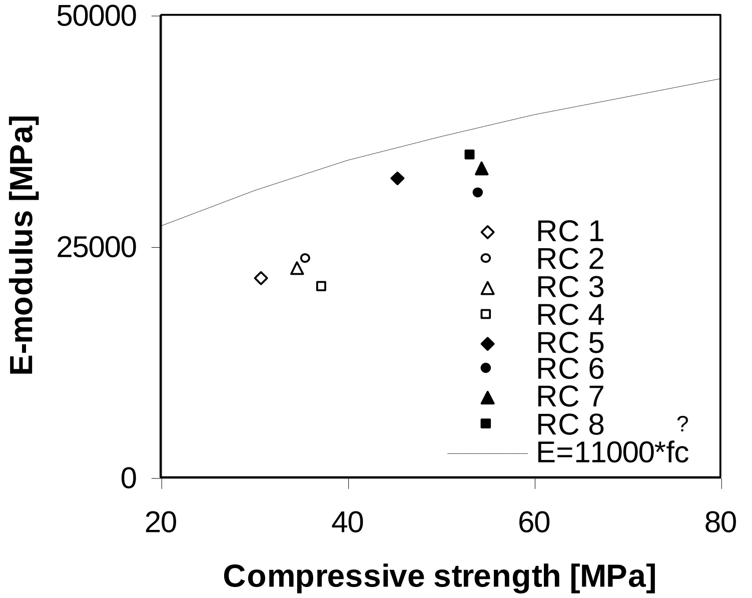

Fig. 7: E-modulus versus compressive strength, both at 28 days (dotted line for CC according to [14]).

3.3.4 Drying shrinkage

After 7 days, mixtures RC 1-8 show a similar shrinkage range as that observed for CC (Fig. 8). However, the shrinkage of RC is significantly higher at the age of 91 days (Fig 9).

The difference in shrinkage between ages of 7 and 91 days can be attributed to the brick and tiles in the RA. Due to the water absorbed during mixing these particles are able to swell during the first few days after production. In this period, concrete with a content of bricks of 70 % can even expand [22]. However, this effect is reversed with time, due to the ongoing drying of the concrete by hydration reactions. Therefore, RC shows a higher shrinkage than CC at higher ages due to its higher volume of paste and higher water content. The degree of this effect may not only be dependent on the petrography of the aggregate (content of bricks and tiles) but on the amount of water present in the aggregate before mixing. If the aggregates already contain a high amount of water before mixing, there will be no subsequent expansion of brick and tile particles. In such cases, the long term drying shrinkage of RC containing bricks and tiles can be increased substantially [5,33]. Damaging effects on transition zone and microcrackings can be the result decreasing the concrete durability.

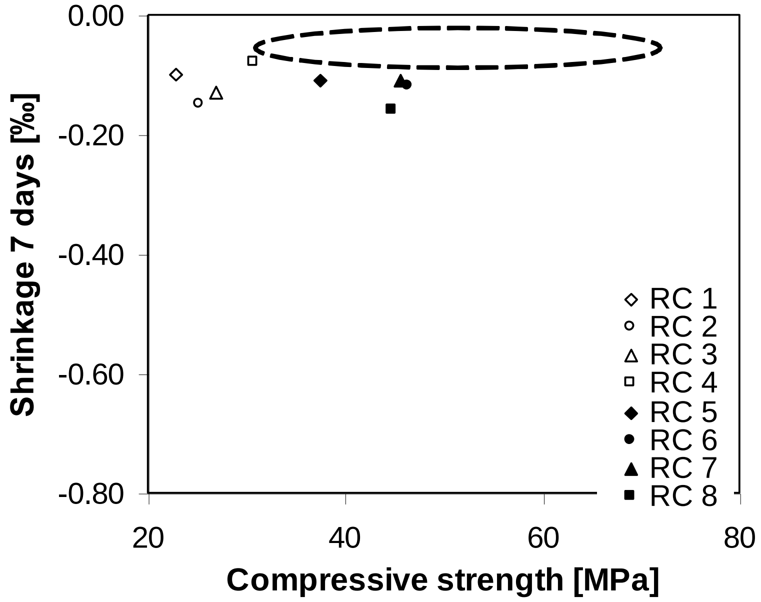

Fig. 8: Shrinkage at 7 days versus compressive strength (encircled area: typical range for CC in Switzerland).

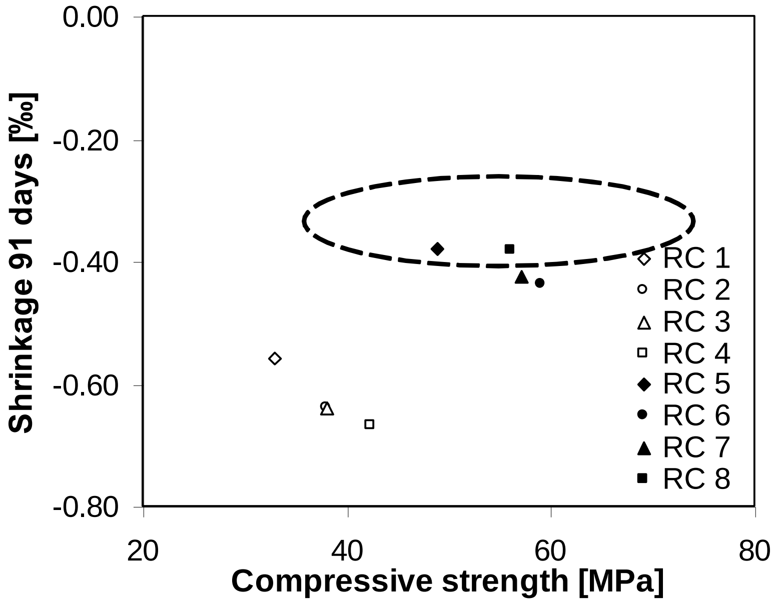

Fig. 9: Shrinkage at 91 days versus compressive strength (encircled area: typical range for CC in Switzerland).

3.3.5 Creep

The creep rates of mixtures RC 1-4 are significantly higher than those of RC 5-8 (Fig. 10).

The amount of low strength particles in the aggregate like bricks and tiles seems to increase creep. This agrees with the low E-Modulus of RC 1-4. However, RC 5-8 nearly reaches values typical for CC.

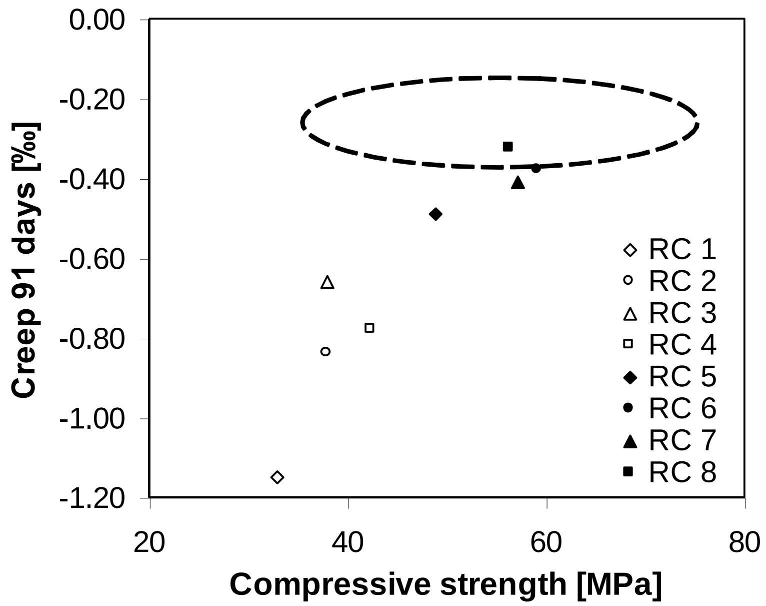

Fig. 10: Creep at 91 days versus compressive strength (encircled area: typical range for CC in Switzerland).

3.3.6 *Chloride conductivity*

The chloride conductivity of mixtures RC 5-8 is higher in comparison to CC with the same compressive strength(Fig. 11). Furthermore, chloride conductivity tends to increase with increasing content of porous aggregates. Consequently, RC 8, containing only 25 % RA, shows the lowest chloride conductivity. Moreover, with an increasing content of brick in the mix (RC 6), the chloride conductivity increases.

There are two reasons possible for the relatively high values of chloride conductivity. On the one hand, the higher values could be related to the cement used. The curve for CC was established with concrete produced with CEM I 42.5 N; CEM II/A-LL 42.5 N was used for RC 5-8. On the other hand, the differences could be attributed to the aggregates. Natural aggregates are very dense and have a low porosity. Therefore, they do not add to the conductivity of the cement paste. However, RA might increase chloride conductivity due to their high porosity. This is indicated as well in the study of Conçalvez et al [7].

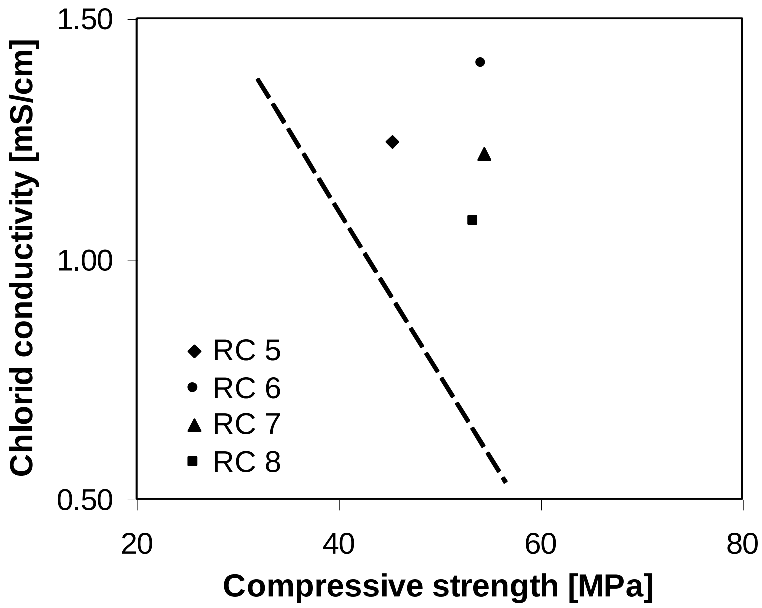

Fig. 11: Chloride conductivity versus compressive strength (dotted line for CC produced with CEM I 42.5 in Switzerland).

OPI

The values for OPI increase with increasing compressive strength (Fig. 12). RC shows the same relation between compressive strength and oxygen permeability as CC. OPI decreases with an increasing proportion of RA in the concrete. Therefore, RC 5, containing the highest amount of RA (90 %) exhibits the lowest oxygen permeability.

The low oxygen permeability (high values of OPI) measured contradicts the results of [5], where considerably higher values were obtained for RC. However, there seem to be no significant differences between RC and CC when a cement content of 350 kg/m^3 is used [7].

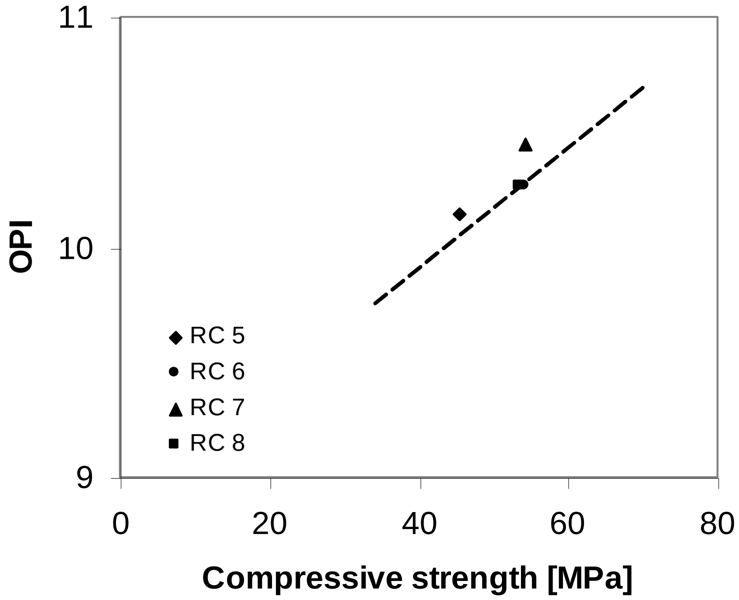

Fig. 12: OPI versus compressive strength (dotted line for CC produced with CEM I 42.5 in Switzerland).

4. Conclusions

- RA show a great variability in their composition reflecting the source of the building waste.

- The density of RA is considerably lower and water absorption is higher than those of natural sand and gravel. The values for these two properties vary with the composition of the aggregate. Due to their high porosity, the amount of bricks and tiles considerably influences these properties.

- A relatively high amount of water is needed in concrete production to reach a good workability due to the high water absorption of RA, if the aggregate is not pre-soaked. Depending on the composition of the

RA and the degree of water absorption before mixing, the amount of water added in the mixing process has to be adjusted accordingly.

- As a relatively large part of the water present in the concrete is absorbed by RA, the compressive strength of RC is higher at an identical w/b compared to the one of CC.
- The strength of RA, as well as the higher volume of paste needed, influence the properties of the hardened concrete. Generally, concrete made with RA displays a lower E-modulus, a higher shrinkage and higher creep rate than CC at a comparable compressive strength. Bending tensile strength, oxygen permeability and chloride conductivity show a similar relation to compressive strength as CC.

- RC is suitable for a wide range of applications in concrete construction as shown by the present results. However, its special properties have to be taken into account by the design of structures, concrete production, casting and curing in order to optimize performance.

- RC should be considered more extensively in international and national standards in order to exploit its potential. This is an important prerequisite towards a sustainable material flow.

5. Acknowledgements

We would like to thank the project partners Amt für Hochbauten der Stadt Zürich, BBL, Eberhard Bau AG, HASTAG and ARV for the financial support of the project. Furthermore, we would like to express our gratitude to our colleague Kurt Pfeiffer for producing a substantial part of the data used for this study.

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7. Appendix

Table 5 Properties of commercial grade mixed recycled aggregates (RA 0-4) and mixtures of RA and PNA for construction-RC (RA 5-8).

properties	RA 0-32 mm								
	RA 0	RA 1	RA 2	RA 3	RA 4	RA 5	RA 6	RA 7	RA 8
particle density on an oven-dried basis [kg/m^3]	2221	2263	2283	2292	2301	2609	2518	2584	2594
water absorption [%]	6.13	6.02	4.16	4.30	5.02	1.52	2.68	1.58	1.55
loose bulk density [kg/m^3]	1547	1460	1534	1478	1518	1702	1665	1612	1759
volume of voids [%]	34.8	36.4	36.6	36.6	36.5	35.7	36.5	38.0	33.2