Evaluation of optimal replacement of natural aggregates by recycled concrete aggregates to achieve sufficient durability

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ABSTRACT
The use of recycled concrete aggregate (RCA) is one way to reduce the depletion of raw materials for the production of concrete. In this article RCA was tested and evaluated. Concrete with 10 to 30 % of overall RCA was examined in terms of its durability performance, particularly capillary suction and shrinkage. Capillary suction testing showed that RCA has better or identical results to the reference mixture. Concrete with a high proportion of RCA had reduced durability, even with reduced durability the concrete maintains all the requirements of the Norwegian Standard. RCA as partial replacement in smaller quantities shows good properties.

Key words: Concrete, RCA, Recycling, Durability, Mix Design, Testing, Particle Shape, Flakiness Index, Grading, Water Absorption, Density, Slump, Air, Compressive Strength, E-modulus, Capillary Absorption, Shrinkage.

1. INTRODUCTION

Implementation of recycling of material and a circular economy approach can significantly reduce the extraction of natural aggregates (NA) and the deposition of construction and demolition waste (C&DW) in landfills [1]. One of the objectives of the EU Member States is to recycle at least 70% of CDW by weight [2]. Concrete is the most used building material worldwide, and concrete constitute approximately 70% of its volume [3]. recycled concrete aggregate (RCA) can replace a certain amount of natural aggregates (NA), while concrete will still perform as required [4, 5].

The composition of the material varies in origin and quality [6]. The relationship between the materials and their composition significantly affects the concrete in both fresh and hardened conditions [7]. Usually, the amount of aggregate is between 65-80% of the final volume of concrete and it is natural that the properties of the aggregate affect the quality of the concrete [8]. The material composition and material documentation must be declared in accordance with the requirements of NS-EN 12620. For bonded use in concrete, NS-EN 206 classifies recycled aggregates into quality groups referring to the minimum content of mineral material. Moreover, NS-EN-206 allows that 30% of coarse aggregate in fraction 4-32 can be replaced by RCA. Up to 10% of NA can be replaced by RCA in fa fraction 0-4 mm. This assumes type AN with strength class C25/30 and durability X0. Higher values can be used as long as this is specified, and the material properties of the concrete have been declared [9].

Therefore, the original value this paper contributes to the body of knowledge in this area is provided by the experimental research results that prove the evaluation of optimal replacement of natural aggregates by recycled concrete aggregates to achieve sufficient durability performance, particularly capillary absorption, and shrinkage of recycled concrete. The performance of concrete with RCA was compared to reference concrete with NA.

2. METHODS

Laboratory research has been used as a method in a comparative case study [10]. The laboratory tests include two mixtures with recycled material, as well as a reference mixture. One mix according to requirements in NS-EN 206 and one recipe with increased RCA amount. Mix within NS-EN 206 contains 5% fine RCA and 20% coarse RCA, in total 10% of RCA (RCA10). Mix with increased RCA contains 20% of fine RCA and 60% of coarse RCA, in total 30% of RCA (RCA30). All mixes contain 62% fine aggregate and 38% coarse aggregate. All mixtures are based on the same recipe, where the cement content is kept constant. The thesis is limited to the production of C30/37; X0, XC1-4, XF1 concrete with associated requirements. The properties of the RCA were determined and declared in accordance with Norwegian Standards NS-EN 12620 and concrete with RCA according to NS-EN 206 [8].

Program of testing geometrical and physical properties consisted of tests: (i) Flakiness, (ii) abrasion test Los Angeles by NS-EN 1097-2:2020, (iii) material graining by NS-EN 933-2: 2020, (iv) particle size distribution by NS-EN 933-1:2012 and (v) aggregate density and water absorption by NS-EN 1097-6:2013. The density, slump, consistency, and air content was tested on fresh concrete. Then, to specify the mechanical properties of hardened concrete, the following test program was performed: (i) compressive strength on cubes of size 100×100×100 mm by NS-EN 12390-3:2019, (ii) stiffness/elasticity modulus by BS-EN 12390-13, (iii) shrinkage by NS-EN 12390-16:2019 as well as (iv) capillary suction by procedure 426 in Handbook R210.

3. RESULTS AND DISCUSSION

3.1 Aggregate

In Table 1 the overall values and categories for NA and RCA are shown. The aggregates were only dry sieved before testing and mixing. The grain size of the RCA varies from 0-22 mm. The grains have a homogeneous appearance and consist mainly of cubic to cubiclong grains, with a rough surface and a rounded shape. Most grains have a tight-fitting coating on the grain surface.

Table 1 – Overall properties values for both natural (NA) and recycled aggregate (RCA).

Aggregates	NA 0/8 Raabakkan, NA 8/22 Austvika		RCA 0/8, RCA 8/22	
	Results	Category	Results	Category
Flakiness	-	FI_{15}	6.58	FI_{15}
Particle grading	-	$G_{NG}90$, $G_C90/15$	-	$G_{NG}90$, $G_C90/15$
Fines amount	1.8%	f3,f1.5	2.95%, 0.72%	f3, f1.5
Density saturated surface dry	2700 kg/m^3 2770 kg/m^3	Normal	2300 kg/m^3 2590 kg/m^3	Normal
LA-value	-	LA_{25}	30.5	LA_{35}

The tight coating on the aggregate will increase the amount of fines in the mixtures, it will have increased the porosity of the grains, which gives the concrete poorer adhesion between the cement paste and the aggregate. The higher water absorption indicates that the aggregate is not resistant to freeze-thaw attacks without further testing. LA value indicates that the aggregate has adequate resistance to crushing. Particle size distribution of the different mixes is well graded.

3.3 Fresh and hardened concrete properties

Fresh concrete results are within requirements according to slump class S4 with values from 200 to 230 mm. Density of fresh concrete was measured from 2370 to 2470 kg/m^3. The air content reached values between 1.6 and 3.8%. w/b ratio was measured from 0.44 to 0.50. Hardened concrete compressive strength shows that all RAC mixtures meet the requirements for a C30/37 concrete, see Table 2.

Table 2 – Compressive strength and elasticity-module values for different mixes of RAC.

Mixture	Day 3		Day 28		Day 90	
	Compressive Strength [MPa]	E-mod. Ec [GPa]	Compressive Strength [MPa]	E-mod. Ec [GPa]	Compressive Strength [MPa]	E-mod. Ec [GPa]
RAC 0	34.22	24.19	51.94	28.81	69.37	32.53
RAC 10	31.42	23.96	53.57	28.69	70.38	32.41
RAC 30	30.76	23.04	46.11	27.38	62.90	30.56

RAC30 has 10% weaker values and has mostly to do with the coating and fines of the RCA. Even with the reduced values of RAC30, all the RAC mixes have a compressive strength that is high enough for its class. The e-module of the concrete mixtures has an evenly uniform increase for all the mixtures throughout the hardening process, where the reference mixture and RAC10 have almost equal values. RAC30 has about 5% worse results.

The reference mixture and RAC10 have a correspondingly equal shrinkage of 400×10^{-6} m/m. RAC30 has 20 % higher shrinkage with 500×10^{-6} m/m. The increased shrinkage of RAC30 can be seen in connection with recycled aggregate increased water demand, the coating on the grains and hence increased amounts of capillary pores.

Table 3 – Shrinkage and weight loss for different RAC samples.

		Day 1	Day 7		Day 28		Day 56	
Mixture	Density [kg/m^3]	Weight [g]	Weight [%]	Δl [10^{-6} m/m]	Weight [%]	Δl [10^{-6} m/m]	Weight [%]	Δl [10^{-6} m/m]
RAC0	2444	12323.4	99.04	129.35	98.65	282.16	98.62	373.13
RAC 5/20	2440	12376.5	99.83	169.74	98.39	382.10	98.29	397.72
RAC 20/60	2365	12125.5	99.65	208.19	98.00	485.32	97.85	500.24

From testing of capillary suction, RAC10 shows to perform better than the reference mixture and mixture RAC30 worst. RAC30 had the same absorption rate with the reference mixture in the initial phase, but has more capillary pores, hence the increased porosity. RAC10 may have performed best due to an increased proportion of fines from recycled aggregate + natural aggregate's better grain surface and shape.

Table 4 – Porosity, capillary number and resistance number of different RAC samples.

Mixture	Porosity [%]	Capillary number - k [kg/m$^2\sqrt{s}$]	Resistance number - m [s/m^2]
RAC0	14.64 ± 2.5 %	0.0306	1.96×10^7
RAC 5/20	14.05 ± 2.5 %	0.0254	2.60×10^7
RAC 20/60	16.49 ± 2.5 %	0.0295	2.45×10^7

4. CONCLUSIONS

Concrete with a high proportion of recycled aggregate had reduced durability, even with all the requirements of the Norwegian Standard. From the laboratory research, it was proven that the recycled aggregate geometric and physical requirements are satisfactory.

The equally linear increase of e-module for all the mixtures can be seen in connection with the aggregates used having the same stiffness and the same amount of cement paste.

Even with an increase of 30% RCA for mixture RCA30, the volume change of all concrete mixtures throughout the hardening process is within the normal range of 0.3 ‰ - 1 ‰ corresponding to $300\text{-}1000^{-6}$ m/m. All mixtures also maintain the requirement according to NS-EN 12620 Section 5.7.2: Volume stability - desiccation loss of 750×10^{-6} m/m.

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