DURABILITY PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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Abstract

Recycled aggregates have evolved towards a worthy alternative for natural aggregates. Therefore more applications with added value should be found for these kind of recycled aggregates that usually end up in low grade applications. This is the case for recycled concrete aggregates, recycled brick aggregates and mixed recycled aggregates which can find their wide use in building construction process where environmental influence on their durability and load bearing demands in use are considerably lower than for other applications. Energy efficiency, sustainable construction and the use of recycled resources together with renewable energy sources are becoming priorities of contemporary construction process.

ECO-SANDWICH is a ventilated prefabricated wall panel utilising recycled CDW and mineral wool produced using innovative and sustainable Ecose® technology for reduction of primary energy consumption in building stock. The inner (load bearing) layer of the ECO-SANDWICH is made of recycled concrete aggregates while the outer façade layer is made of recycled brick aggregates. In order to achieve the best ecology-to-quality ratio considering materials, appropriate selections should be made. Concrete mix proportioning is optimized in order to maximise usage of recycled CDW without the reduction of mechanical and durability properties. In the paper are shown results of testing mechanical and durability properties of the concrete mixtures produced with different amounts and different types of the recycled aggregate.

1. INTRODUCTION

Construction and demolition waste (CDW) has been identified by the EC as a priority stream because of the large amounts that are generated and the high potential for re-use and recycling embodied in these materials. Indeed, a proper management would lead to an effective and efficient use of natural resources and the mitigation of the environmental impacts to the planet. The Waste Framework Directive (WFD) requires Member States (MS) to take any necessary measures to achieve a minimum target of 70% (by weight) of CDW by 2020 for preparation for re-use, recycling and other material recovery, including backfilling operations using non-hazardous CDW to substitute other materials [1]. Although the recycling rate is high in some EU

countries, the use of recycled aggregate is confined to low-grade applications, such as unbound road base, fill and hardcore [2-5]. There are many unsolved problems encountered in controlling the quality of recycled aggregate concrete (RAC), which include low compressive strength, wide variability of quality, high drying shrinkage, large creep and low elastic modulus, applications of recycled aggregate concrete are hampered [4-6]. In order to make recycled aggregate competitive to natural aggregate and to close the building materials cycle by recycling C&D waste in high technical applications, it is necessary to increase its market value through properties, application possibilities and price. One of the possible applications of recycled aggregate in concrete is in industry of prefabricated elements. Hereafter will be shown application of RAC in innovative wall panel system called ECO-SANDWICH [7, 8].

The ECO-SANDWICH wall system is prefabricated wall panel with integrated core insulation allowing very low energy design and retrofit of buildings. It consists of two precast concrete layers interconnected through stainless steel lattice girders, Figure 1. The inner (load bearing) layer of the ECO-SANDWICH is made of recycled concrete aggregates while the outer façade layer is made of recycled brick aggregates.

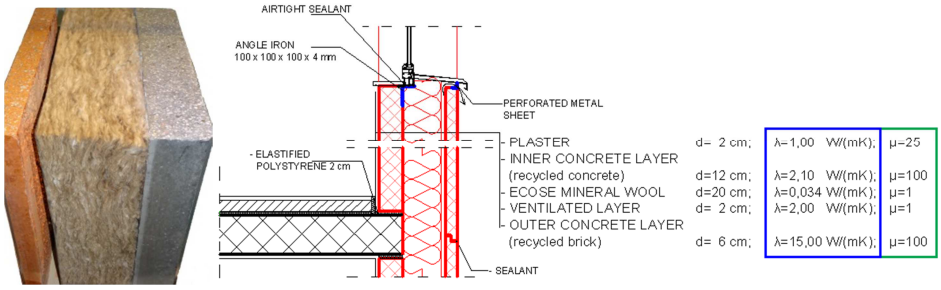

Figure 1: ECO-SANDWICH wall system

The ECO-SANDWICH has a vast potential to substantially improve energy performance of the deteriorating building stock thus facilitating a move towards reaching the EU's 20-20-20 goals by 2020. The ECO-SANDWICH helps to follow waste hierarchy by using recycled CDW and recycled materials used in the production of Ecose® based mineral wool. Being harmonized with both Energy Performance of Building Directive - EPBD (2002-91-EC), its Recast EPBD II (2010-31-EU) and EU Waste Framework Directive (2008/98/EC), the ECO-SANDWICH wall system is expected to facilitate the implementation of both legislations by providing a market for recycled CDW and by substantially improving the energy balance of the existing as well as new buildings. In order to maximise usage of recycled CDW without the reduction of mechanical and durability properties, concrete mixtures need to be optimized.

2. EXPERIMENTAL PART

For laboratory testing, 6 concrete mixtures were prepared on which a thorough analysis of mechanical and durability properties was performed (Table 1). The aim of testing was to optimize concrete mixtures for ECO-SANDWICH wall panel.

In the mixtures, proportions of the recycled aggregate of 40 %, 50 % and 60 % were varied. All concrete mixtures were produced with cement CEM II A/S 42.5 R. As aggregate, it was used natural sand of the nominal size 0-4 mm from two sources: river sand and crushed aggregate and recycled concrete (RB) and brick (RO) aggregates 4-8 mm and 8-16 mm. For

concrete mixtures with 40 % of recycled aggregate it was also used natural crushed aggregate 4-8 mm. Recycled concrete aggregate was produced by crushing laboratory specimens, while recycled brick was produced by crushing waste brick. Except aggregate, proportion of other components was the same in all mixtures: 400 kg of cement, w/c =0.42 and air entraining plasticizer MELCRET SPA 0.7 % per weight of cement.

Table 1: Testing program

Property	**Test method**	**Specimen dimension (cm)**	**Age (days)**	**No of specimens**					
				Recycled concrete			**Recycled brick**		
				RB40	**RB50**	**RB60**	**RO40**	**RO50**	**RO60**
COMPRESSIVE STRENGTH	HRN EN 12390-3:2009	15x15x15	1	3	3	3	3	3	3
			3	3	-	3	3	-	-
			7	3	-	3	3	-	3
			28	3	3	3	3	3	3
MODULUS OF ELASTICITY	HRN U.M1.025	15x30	1	3	3	3	-	3	-
			3	3	3	3	3	3	3
			7	-	-	-	-	-	-
			28	3	3	3	3	3	3
BENDING STRENGTH	HRN EN 12390-5:2009	10x10x40 (50)	1	-	3	-	-	3	-
			3	3	-	3	3	-	3
			28	3	3	3	3	3	3
CAPILLARY ABSORPTION	HRN EN 13057:2003	Φ10x20	28	2	1	1	2	1	2
CHLORIDE MIGRATION	NT BUILD 492	Φ10x20	28	2	1	1	2	1	2
FREEZE-THAW RESISTANCE	HRN CEN/TR 15177:2006	10x10x40	28	3	3	3	3	3	3
FREEZE-THAW RESISTANCE - SCALING	HRN CEN/TS 12390-9:2006	15x15x15	28	4	-	4	4	-	4
WATER PERMEABILITY	HRN EN 12390-8:2009	15x15x15	28	-	3	-	1	3	-
GAS PERMEABILITY	HRN EN 993-4:2008	Φ10x20	28	-	1	-	-	1	-
RAPID AIR	HRN EN 480-11:2005	15x15x15	28	1	1	-	1	1	-

3. RESULTS OF TESTING

3.1 Results of testing fresh concrete

Results of testing fresh concrete are shown in the Table 2. Slump values of all mixtures, except RB50 can be classified into S3 consistency class (100-150 mm). Concrete with 40 % and 60 % recycled brick were produced in concrete plant in the winter period, while concrete mixtures with 50 % recycled brick were produced in laboratory conditions. That resulted with lower fresh concrete temperatures for the mixtures with 40 and 60 % recycled brick.

Table 2: Properties of the fresh concrete

Concrete mixture	Slump (mm)	Air temperature (°C)	Concrete temperature (°C)	Density (kg/dm^3)	Air content (%)
RB40	150	20	17.2	2.23	7.2
RB50	70	17.1	18.8	2.33	4.2
RB60	140	20	17.8	2.22	7.7
RO40	140	6.8	7.5	2.12	5.0
RO50	100	20	23.1	2.13	7.2
RO60	120	6.8	8.3	2.21	4.4

3.2 Mechanical properties

Compressive strength was tested according to HRN EN 12390-3:2009 on the cubes 15x15x15 cm after 1, 3, 7 and 28 days. Specimens with 50 % of recycled aggregate were tested after 1 and 28 days. Results of testing are shown in the Table 2. From the results of testing, it can be seen that concrete with 50 % recycled concrete (RB50) has the largest compressive strength in the age of 1 day, as well as the in age of 28 days which is obviously caused by smaller air content (4.2 %). In general, concrete produced with recycled concrete has higher compressive strength than concrete with recycled brick.

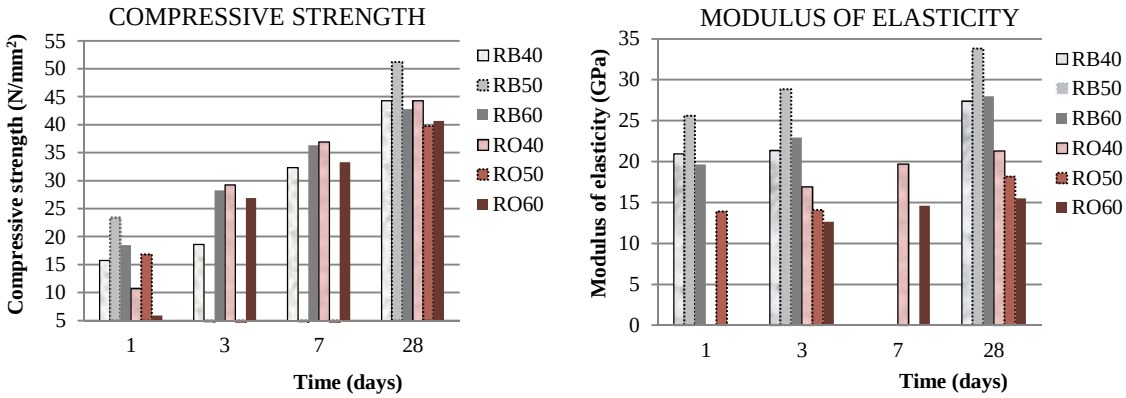

Figure 2: Mechanical properties of concrete

The largest values of modulus of elasticity have specimens with 50 % recycled concrete in the age of 1, 3 and 28 days, which is in accordance with the results of testing compressive strength. Values of modulus of elasticity of the concrete with recycled brick are considerably smaller. After 28 days, three point bending strengths of all concrete types were between 5.2

and 6.4 MPa. The largest bending strength of 6.4 MPa was obtained for concrete with 50 % recycled concrete.

3.3 Durability properties

Relevant durability properties for prefabricated concrete wall elements are resistance to freezing and thawing and capillary absorption. These elements should satisfy requirements for XF1 exposure class. Moreover, by this research program, the intention was also to analyse other relevant properties of recycled aggregate concrete such as resistant to freezing and thawing with de-icing salts, waterpermeability, gaspermeability and chloride migration.

Testing of capillary absorption was carried out on the series of three specimens in the age of 28 days, in duration of 24 hours and obtained results are shown in the Figure 3a. RO60 has middle capillary absorption and is of middle quality. Other concrete types with recycled concrete and recycled brick have large absorption.

Testing of the freeze-thaw resistance – scaling was carried out on the concrete specimens with recycled brick and recycled concrete with proportions of 40 % and 60 %. Specimens were tested 56 cycles. Cumulative scaled material per test area was on all tested specimens less than 0.5 kg/m^2. From the results obtained (Figure 3b), it can be concluded that concrete with aggregate from recycled brick and recycled concrete are resistant to freezing and thawing with de-icing salts and that concrete satisfy requirements for XF2 (28 cycles) and XF4 (56 cycles) exposure classes. When comparing specimens produced with recycled concrete and recycled brick, it can be seen that concrete with recycled brick has larger value of the scaled material per test area. The largest value of scaling was observed for concrete with 60 % recycled brick. Based on the results of testing freeze-thaw resistance after 28 cycles, it can be concluded that all concrete types satisfy requirements for XF1 exposure class. Moreover, concrete types with 40 and 60 % of recycled aggregate that were tested 56 cycles satisfy XF3 exposure class as well.

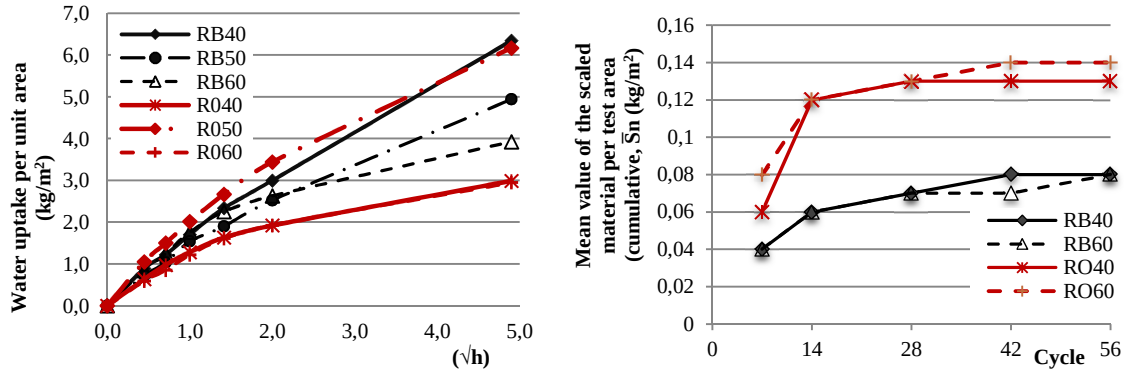

Figure 3: Results of testing a) capillary absorption; b) freeze-thaw resistance - scaling

Waterpermeability was tested on concrete types: RB50, RO40 and RO50. Evaluation of the results is based on average value of water penetration determined according to HRN EN 12390-8:2009. The largest water penetration depth was observed on the specimen with 50 % recycled brick. Concrete with 40 % recycled brick has almost equal waterpermeability as concrete with 50 % of recycled concrete. Difference between those two concrete types is

negligible. According to the results shown in the Table 3, concrete RB50 and RO40 can be classified into waterpermeability class 3 and concrete RO50 into class 2.

Gaspermeability was tested on concrete mixtures RB50 and RO50 according to HRN EN 993-4:2008. According to criteria recommended in [9], it can be concluded that both concrete types are of middle quality. Regarding chloride migration coefficients determined according to NT BUILD 492 (Table 3) and recommended criteria [9], it can be seen that all specimens have poor resistance to chloride penetration except RB50 that has the lowest chloride migration coefficient and can be classified as middle resistant. According to the results of Rapid Air test (HRN EN 480-11:2005), it can be concluded that all specimens satisfy requirements, because their specific surface is larger than 25 mm^{-1}, and spacing factor is less than 0.2 mm.

Table 3: Results of testing waterpermeability, gas permeability, chloride migration and Rapid Air test

Concrete mixture	Average water penetration depth (mm)	Coefficient of gas permeability (m^2)	Chloride migration coefficients Dnssm (m^2/s)	Rapid Air test		
				Air content (%)	Specific surface (mm^{-1})	Spacing factor (mm)
RB40	-	-	49.92×10^{-12}	8.27	35.34	0.104
RB50	14.17	14.44×10^{-17}	11.15×10^{-12}	5.74	29.90	0.159
RB60	-	-	30.67×10^{-12}	-	-	-
RO40	14.05	-	21.01×10^{-12}	10.59	38.42	0.075
RO50	23.78	8.83×10^{-17}	16.66×10^{-12}	10.55	26.13	0.114
RO60	-	-	21.21×10^{-12}	-	-	-

4. ANALYSIS

When comparing results of testing concrete produced in similar conditions, it can be concluded that increase of the recycled brick amount from 40 % to 60 % decreases compressive strength for approximately 10 %. For recycled concrete, there is a similar trend for 28-day compressive strength, but concrete with 60 % recycled aggregate has had faster strength development. For aggregate obtained from recycled concrete, it is however very important interfacial transition zone and composition of the old concrete. When observing results of testing concrete with 50 % recycled aggregate, influence of the air content on the results of testing compressive strength is obvious. Concrete with 50 % of recycled concrete aggregates has the lowest air content and consequently the highest compressive strength. Concrete with 50 % recycled brick has higher air content than concrete with 40 % and 60 % recycled brick and that causes smaller compressive strength. Obviously, crucial influence on the results of testing compressive strength and other concrete properties has preparation of the concrete mixtures and amount of the chemical admixture. The highest modulus of elasticity in the age of 3 and 28 days has concrete with 50 % recycled concrete, the same as it has the highest compressive strength. In general, concrete with recycled brick has lower values of modulus of elasticity. By increasing amount of recycled brick, modulus of elasticity decreases. Values of bending strength are approximately the same for all concrete mixtures. The highest value was obtained for concrete with 50 recycled concrete, as for compressive strength. Regarding durability properties, it can be concluded that all concrete types, with

recycled concrete and recycled brick, satisfy requirements for class exposures XF1, XF2, XF3 and XF4. Higher coefficient of gas permeability had concrete produced with recycled concrete. Based on the results of testing, it can be concluded that resistance to chloride penetration is unsatisfactory and that tested concrete types would not be suitable for structural elements in marine environment or it should be additionally protected. All results of testing are shown in Table 4.

Table 4: Results of testing concrete with recycled aggregate

Property	Concrete mixture					
	Recycled concrete			Recycled brick		
	RB40	RB50	RB60	RO40	RO50	RO60
CONSISTENCY, slump (mm)	S3	S2	S3	S3	S3	S3
COMPRESSIVE STRENGTH, 28 days (N/mm^2)	44.3	51.2	42.8	44.3	39.7	40.7
MODULUS OF ELASTICITY, 28 days (GPa)	27.4	33.8	28.0	21.3	18.2	15.5
BENDING STRENGTH, 28 days (N/mm^2)	5.8	6.4	5.4	5.8	5.9	5.2
COEFFICIENT OF CAPILLARY ABSORPTION ($kg/m^2\sqrt{h}$)	1.31	1.09	1.92	0.49	1.12	0.50
CHLORIDE MIGRATION COEFFICIENT Dnssm (m^2/s)	49.92×10^{-12}	11.15×10^{-12}	30.67×10^{-12}	21.01×10^{-12}	16.66×10^{-12}	21.21×10^{-12}
FREEZE-THAW RESISTANCE (%) 28 cycles (max. 25 % for XF1) 56 cycles (max. 15 % for XF3)	 0.2 1.0	 1.8 *	 0 1.3	 7.2 4.5	 6.0 *	 6.5 5.4
FREEZE-THAW RESISTANCE - SCALING (kg/m^2) 28 cycles ($\leq 0.5 kg/m^2$ for XF1) 56 cycles ($\leq 0.5 kg/m^2$ for XF3)	 0.07 0.08	-	 0.07 0.08	 0.13 0.13	-	 0.13 0.14
AVERAGE WATER PENETRATION DEPTH (mm) Class 1 max. 50 mm Class 2 max. 30 mm Class 3 max 15 mm	-	14	-	14	24	-
COEFFICIENT OF GAS PERMEABILITY (m^2)	-	14.44×10^{-17}	-	-	8.83×10^{-17}	-
RAPID AIR TEST, SPACING FACTOR (mm) (<0.2 mm) SPECIFIC SURFACE (mm^{-1}) (>25 mm^{-1})	0.104 35.34	0.159 29.90	-	0.075 38.42	0.114 26.13	-

*Not measured

5. CONCLUSION

The quality of recycled aggregate directly depends on the quality and composition of C&D waste. Composition and quality of construction and demolition waste have influence on the

quality of recycled aggregate produced from waste. Most studies recommend a limit of 30 % of recycled aggregate. By this investigation, it was shown that both, recycled brick and recycled concrete can be successfully used for high-grade application even in amount of 60 % of recycled aggregate. For specific purpose, it is however necessary to carry out a preliminary testing of the relevant concrete properties to make decision on optimum recycled concrete amount. With this research, it was shown that recycled aggregate concrete satisfies requirements for freeze-thaw resistance and can be successfully applied in outer concrete elements. However, certain precaution is necessary if using recycled aggregate in harsh environment. In these cases, it is recommended to use smaller amount of recycled aggregate and to prove by testing that concrete satisfy prescribed requirements.

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