The Next Generation Ecological Self Compacting Concrete with Glass Waste Powder as a Cement Component in Concrete and Recycled Concrete Aggregates

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ABSTRACT: In the present study the performance characteristics (workability, compressive strength, frost resistance, permeability and temperature of hydration) of the ecological self compacting concrete with reduced cement content and with the next generation recycled concrete aggregates which are obtained from crashed concrete specimens with cement substitution at level of 30% with waste glass powder were investigated. Waste glass as powder ground to certain fineness accelerates beneficial chemical reactions in concrete offers desired chemical composition and reactivity for enhancing the chemical stability and durability of concrete.

1 INTRODUCTION

Sustainable development attempts to meet the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). There has never been so much interest in the ecological impact of buildings as there is today. Buildings are one of the heaviest consumers of natural resources and account for a significant portion of the greenhouse gas emissions that affect climate change (Jodidio, 2009). Concrete has a long history starting used by the Romans for many of their great roads, buildings and aqueducts and becoming the most widely used construction material nowadays. Except for the steel used for modern skyscrapers, no other material has so personified the industrial - era built environment as has concrete - with artists and musicians assailing the twentieth century capitalist city as a “concrete jungle”. One might justifiably expect that the evolving green building movement would, at very least, have to come to terms with - and redefine the use of - this omnipresent material (Milani, 2005). Concrete being as a primary material in construction industry also is one of the most consuming landfills waste materials. The disposal of the construction and demolition waste is becoming increasingly difficult and expensive and also environmental concerns are increasingly limiting the option of landfilling such waste. The cement industry is one of the top two manufacturing industry sources of carbon dioxide emissions, in itself generating about 8 percent of the world’s CO_2 emissions (Mehta, 1998b). There are also other problems, notably in dust generation (in cement production and transport), water pollution (in the ready-mix concrete industry) and great energy consumption (for example, cement production takes 3.2 - 6.3 gigajoules for every ton of cement (van Oss, 2003)). Emissions from cement production include sulfur dioxide (SO_2) and nitrous ox-

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ides (NO_x). And in the mid-nineties, it was estimated that concrete represented 67 percent by weight and 53 percent by volume of construction and demolition (C&D) waste, with only 5% being recycled (Demkin, 1998). Ecological solutions for concrete problems involve changes in production. But perhaps the most influential decisions are those of building designers and developers in selecting materials. They can affect what and how things are produced. There are four main strategies for the green building movement: first, finding *alternatives to concrete*; second, when its use is appropriate, *designing to use less* of it; third, *using more ecological concrete* that contains substantially less Portland cement; and lastly, finding ways to *recycle C&D concrete*, and designing concrete materials for reuse (Milani, 2005). As it was said by architect William McDonough in his oft-cited quote"We should recycle, but it is not the first thing we should do, it is the last. Redesign first, then reduce, and finally recycle if there is no alternative" (Thorpe, 1999). Sustainable and ecological methods for production of construction materials are required. From an economical point of view, if only the traditional costs are taken into account, recycled aggregate concrete with glass waste could be less attractive than natural-aggregate concrete. However, if the eco-balanced costs are considered, the exact opposite would be valid (Moriconi, 2007).

2 EXPERIMENTAL PROGRAM

2.1 Materials and Methods

An experimental study was carried out to investigate the effects on the mechanical properties (compressive strength), durability (frost resistance) and physical properties (workability, permeability and hydration temperature) of concrete with partial substitution of cement with waste glass and recycled concrete aggregates.
The experimental programme was divided in two parts. In the first part (Series I) were produced 5 concrete mixtures. Three of them were with partial substitution of cement with waste glass (30%) – glass cullet chips obtained from the crashed bottles (green, amber and flint colours) which were collected from the local glass bottle return point. The bottles were manually crashed into chips in the laboratory, then chips were washed, dried and ground for 30 minutes into powder in laboratory planetary ball mill Retsch PM400 (with rotation speed 300 min^{-1}). The chemical composition and fineness are shown in the Table 1. Particle size distribution of obtained powders is shown in Figure 1. Other two mixtures were: one concrete mixture with partial substitution of cement with steel slag powder (SSP) (30%) and another control concrete mixture.
The obtained concrete specimens at the age of 28 days were crashed manually (see Figure 2) in the second part of experimental programme (Series II) and recycled concrete aggregates were obtained, which were used for production of SCC concrete with natural gravel substitution at level 100% and partial natural sand substitution at level of 25%. Obtained recycled concrete aggregates were cleaned and sieved into fractions in laboratory. Two size fractions were sorted 0.3/2.5 and 4/8mm.
Ordinary Portland cement CEM I 42.5N from "Kunda Nordic" (Estonia) was applied as a binding agent. Cement conforms to the standard LVS EN 197-1:2012. Natural local aggregates gravel (4/8mm) and coarse and fine sands (0/1mm and 0.3/2.5mm), which conform to the standard LVS EN 12620+A1:2009 L were used for the mixture preparation. Sikament 56 polycarboxylates based plasticizer, silica fume Elkem 971U and nanosilica were used for SCC concrete mixtures.

Table 1. The chemical composition of glass cullet, silica fume and cement.

Bulk oxide, %mass	Glass cullet			**SF**	**SSP**	**PC**
	Flint	**Green**	**Amber**			
CaO	11.300	10.930	8.890	0.66	27.50	62.03
Al_2O_3	1.340	1.530	1.420	0.09	4.62	5.22
SiO_2	69.610	67.800	69.260	98.60	20.05	17.93
K_2O	0.562	0.550	0.507	0.20	0.07	1.76
Na_2O	11.208	11.092	11.436	0.21	0.49	0.20
Fe_2O_3	0.080	0.360	0.430	0.01	17.15	2.97
MnO	0.008	0.018	0.018	0.01	5.83	0.14
MgO	0.462	1.584	3.078	0.10	8.91	4.06
TiO_2	0.028	0.062	0.052	0.00	0.44	0.36
SO_3	0.126	0.036	0.012	0.04	0.23	3.76
P_2O_5	0.021	0.023	0.026	0.04	0.40	0.44
Fineness, m^2/kg	502	463	542	792	521	378

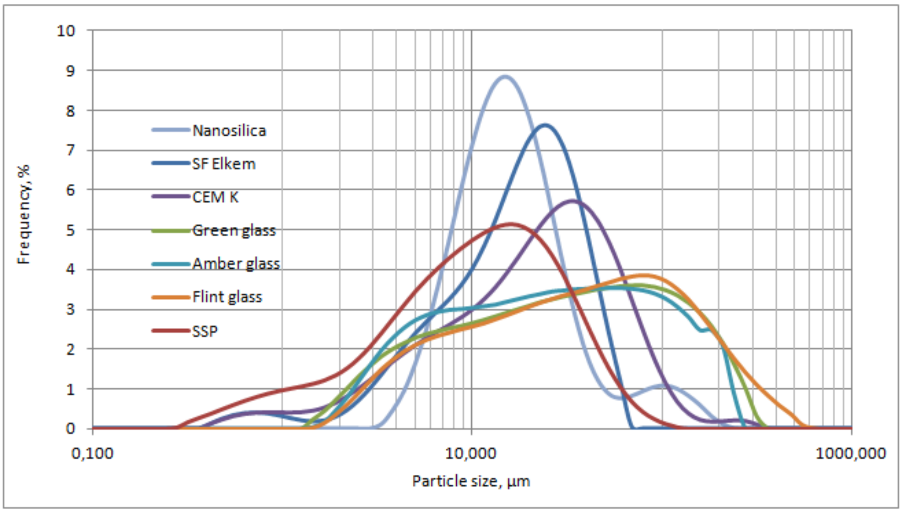


Figure 1. Particle size distribution [µm].

Figure 2. The manual obtaining process of recycled concrete aggregates.

2.2 Concrete mixture composition

Series I - control mixture with no glass cullet substitution (named CTRL1); three with glass cullet powder ground for 30 minutes substitution (named A30 (amber cullet), G30

(green cullet), F30 (flint cullet)) and mixture with steel slag powder substitution (SSP30). Cement was substituted with glass powder at level 30%; the natural aggregates were kept constant, water amount was constant.
Series II – a total of 6 different SCC concrete mixtures were prepared. One of them was a control mixture with natural aggregates and no glass cullet substitution (named CTRL2), which was obtained after optimal design for SCC concrete mixtures was determined. Other 5 concrete mixtures had cement substitution with amber cullet glass powder at level 20%; natural aggregates (gravel) were substituted at level 100% and sand was substituted at level of 25%, water amount, coarse and fine aggregates varied. Concrete mixtures 1-4 had RCA with glass powder and mixture 5 had RCA with SSP. Amber glass cullet powder was chosen for cement substitution at level of 20% due to it has finer particles and gives better results for the compressive strength. Details for different mixtures are shown in Table 2.

Tabella 1. Concrete mixture compositions [kg/m3].

Mixture type	W/C ratio	Portland cement CEM I 42.5 N	Gravel 4/8 mm	RCA coarse 4/8mm	Natural sand 0.3/2.5 mm	RCA fine 0.3/2.5mm	Quartz sand 0/1.0mm	Glass waste powder /SSP	Plasti-cizer	Silica Fume/ Nano SF	Wa-ter
CTRL 1	**0.49**	**410**	**1000**	**0**	**650**	**0**	**120**	**0**	**0**	**0**	**200**
A30/ G30/ F30/ SSP30	0.49	287	1000	0	650	0	120	123	0	0	200
CTRL 2	**0.37**	**500**	**580**	**0**	**580**	**0**	**290**	**0**	**10**	**90/5**	**219**
1	0.47	400	0	550	374	124	333	100	10	50/10	235
2	0.43	400	0	550	425	124	333	100	10	50/5	215
3	0.34	400	0	653	435	145	218	100	10	50/5	190
4	0.37	400	0	580	435	145	290	100	10	90/5	219
5	0.37	400	0	580	435	145	290	100	10	90/5	219

2.3 Concrete mixing and curing

All concrete mixtures were mixed in a power-driven rotary mixer with a moving bottom (but with no blades or paddles). The capacity of mixtures was mostly 21 litres. The mixing procedure was the following:

- ✓ Mixing of the dry ingredients for 120 s;
- ✓ Adding 70% of the total water with/without plasticizer and mixing for 60 s;
- ✓ Adding the rest of the water and mixing for 60 s.

As soon as the mixing was finished, Abram slump/Flow slump test was carried out for each mixture in accordance with LVS EN 12350-2:2009. The results are shown in the Table 3. Specimens were cast in 150x150x150 and 100x100x100 mm plastic or steel moulds, which conform to standard LVS EN 12390-1:2009 and covered with polyethylene wrap. After 24 – 48 hours specimens were removed from moulds and cured in water (with temperature +20±2°C) for 28 days and then were placed in a curing chamber (with air temperature +20±2°C and relative humidity ≥95%) until the tests were carried out.

2.4 Test methods

Mechanical properties – compressive strength

Compressive strength of concrete specimens was determined at the age of 7, 28, 56 and 112 days for concrete mixtures in accordance with LVS EN 206-1:2001 /A2:2008 L standard. To evaluate the hardened concrete properties compressive strength test was carried out. Before the test, the specimens were dried in an oven for 20 min in 50ºC temperature. The testing was done according to LVS EN 12390-3:2009. Compression testing machine with the accuracy of ±1% was used; the rate of loading was 0.7 MPa/s. Compressive strength test was conducted up to 112 days. Three specimens per mixture for each age were prepared and the mean compressive strength value was calculated.

Physical properties - permeability and hydration temperature

The durability of concrete is significantly affected by its permeability. Permeability is defined as the property that governs the rate of flow of a fluid into a porous solid. Permeability test (Figure 3, left) was carried out in the accordance with standard LVS EN 12390-8:2009, which allows determine concrete water tightness exposing hardened concrete surface to water under pressure of 500 ± 50 kPa within 72 hours. Afterwards the concrete cubes at the age of 28 days with dimensions 150x150x150mm were split into two parts and depth of water penetration was measured.

Figure 3. Equipment to measure permeability (left) and hydration temperature inside of concrete mixtures (right).

Equipment to measure hydration temperature inside of concrete mixtures (Kara, 2013) was used: concrete mixtures were cast in demountable 100x100x100 mm plywood moulds with a thermocouple (connected to a data transmitting device) copper tube located in the center of one face of each mould. Four moulds all together were placed into one plywood box with 50mm insulation layer of Finnfoam (Figure 3, right). The temperature was continuously monitored at least up to 90 h after production at ambient air temperature 20 ± 1°C.

Durability - frost resistance test

The standardized method of an estimation of frost resistance of concrete is characterized by number of cycles of freezing and thawing of specimens under standard conditions of test without essential strength decrease. The frost resistance tests were carried out in accordance with GOST 10060.0-95, GOST 10060.1-95, GOST 10060.2-95 and GOST 26134-84. Accelerated frost test method was used and strength losses in the specimens were measured recording the ultrasonic velocity changes. Concrete specimens which were subjected to frost tests had prismatic shape with internal dimensions of 60x60x180 mm (see Figure 4). The specimen's shortest dimensions were chosen so that to obtain the lowest possible freeze through depth. The specimen's length of 180 mm was selected so that the specimen's ultrasonic velocity could be tested by the tester "UK-1401" and low-frequency ultrasonic flaw detector "A1220 Monolith" (Lencis and Linkevica, 2013). Three specimens per each mixture were prepared.

Figure 4. Produced prismatic shape concrete specimens for frost resistance test.

So that throughout the test to record the ultrasonic velocity in the same places, the specimens were marked with measuring points – 4 points forming two diagonals on two opposite long sides of the specimens and 1 centre point on each short side (see Figure 5). One diagonal length is 15 cm, which is a tuner base at the same time (distance between the contact elements) for portable tester "UK-1401". For the most accurate results, the ultrasonic velocity of each diagonal was measured 3 times. The concrete specimens were saturated in 5% salt-water at a temperature of 20 ± 2 °C during the first 3 days. Ultrasonic velocity and mass measurements were performed after concrete specimens were saturated with salt-water and before freezing / thawing cycle. Specimens freezing was carried out in accordance with GOST 10060.1-95 in the climatic chamber ILKA KTK-800 (VEB Maschinenfabrik Nema Netzschkau, 1988) (see Figure 5) in the temperature -20 ± 0.5 °C.

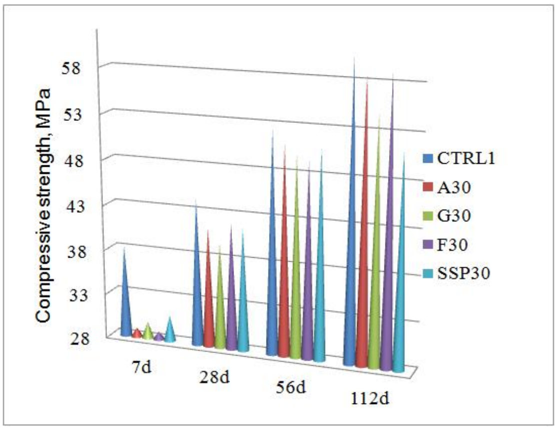
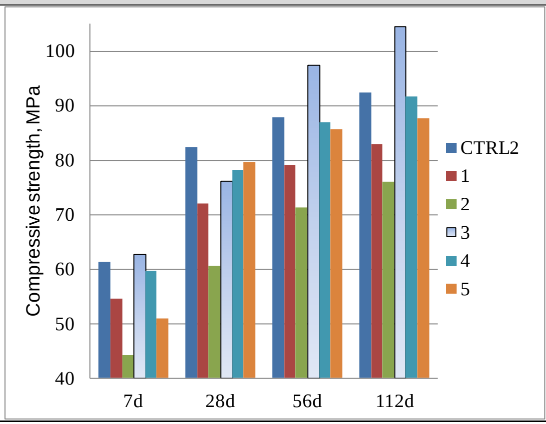
Figure 5. Concrete specimens in the climatic chamber ILKA KTK-800.

According to (Lencis and Linkevica, 2013) the minimum time required for the specimen gets frozen in the freezer (White Westinghouse FC10VMEW1) is 1h 45min and thawing of the specimen in salt-water (20 ± 2 °C) requires in turn a minimum of 1h. Due to that freezing velocity of ILKA KTK-800 is greater than of the freezer the optimal time for cycling during the day time was chosen 1h 30min for both freezing and thawing processes in the present study. Within twenty-four hours was possible to handle 2.5 or 3.5 cycles: 0.5 cycles during the night time when specimens were located in the freezer with temperature -20 °C and 2 or 3 cycles during the day time using climatic chamber which allows obtain -20 °C temperature within 7 min. After a certain number of cycles were fixed ultrasonic velocity and mass changes of the specimens. If the ultrasonic velocity changes didn't exceed 5% and weight changes didn't exceed 3%, it is considered that the specimen has passed number of cycles and frost resistance tests to be continued.

3 RESULTS AND DISCUSSION

The experimental programme results are summarized in Table 3 and Figure 6.

Table 2. Mechanical, physical and thermal properties of concrete mixtures.

Series I Mixture type	**Slump, mm**	**Compressive strength development**	**Hydration temperature, °C**	**The depth of penetration, mm**	**Frost resistance class**
CTRL1	0		30.6	13	F200
A30	45		29.9	20	F100
G30	35		29.9	15	F100
F30	35		30.9	20	F100
SSP30	50		------	20	F200
Series II Mixture type	**Slump flow diameter, mm**	**Compressive strength development**	**Hydration temperature, °C**	**The depth of penetration, mm**	**Frost resistance class**
CTRL2	630		-------	12	F200
1	>700		-------	10	F50
2	690		34.0	10	F150
3	580		36.1	7	F200
4	640		33.6	11	F200
5	680		32.6	4	F100

Mechanical properties – compressive strength

Series I- the compressive strength of the control concrete is seen to be greater than of concretes with cement substitution with glass waste powder and steel slag powder at all ages. In this series the highest obtained result was for the mixture with flint glass waste powder with developed strength of 42 MPa and 59 MPa at the age of 28 days and 112 days accordingly that is for 5.1% and 2.25% less in comparison to the control mixture.
In this series cement substitution with amber waste glass and SSP has shown the best workability in comparison to control mixture, therefore amber glass waste powder with

its finer mean particle size 4.133- 24.863μm was chosen for cement substitution in SCC concrete in Series II.

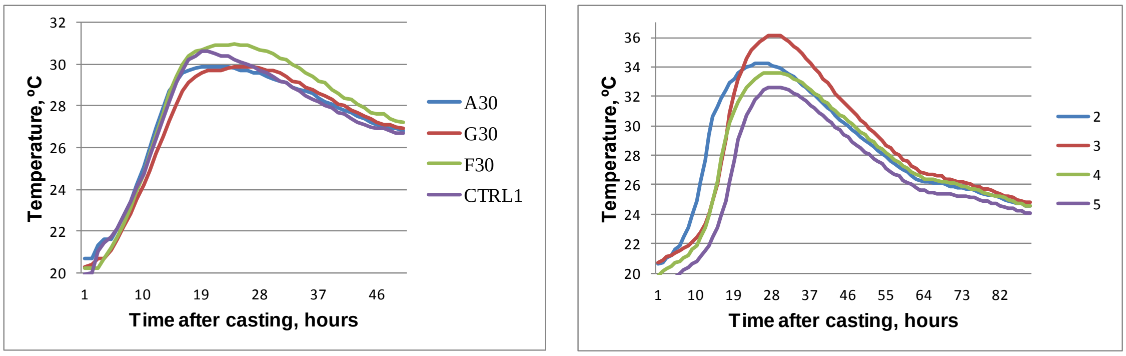


Figure 6. Relationship between temperature and time during hydration for concrete mixture.

The water/binder and coarse/fine aggregates ratio varied in the Series II in order to obtain the best workability of the mixture. In this series the highest obtained result with lowest w/b ratio 0.34 was for the mixture with glass waste recycled concrete aggregates (mixture 3) with compressive strength of 76 MPa (28 days) and 104 MPa (112 days). The best obtained workability was for the mixtures 4 and 5, and mixture 4 with glass waste recycled concrete aggregates showed higher compressive strength in comparison to the mixture with SSP recycled concrete aggregates and lower for 5.1% (28 days) and 0.8% (112 days) in comparison to control mixture. However, the workability of the mixture 3 could be improved by additional amount of plasticizer.

Figure 7. Flow test of the mixture 4.

Physical properties - permeability and hydration temperature

Observing the experimental data in the Table 3 it can be noted that the use of glass waste powder and SSP worsen the water tightness of the concrete along with the negative effect produced by the recycled concrete aggregates in the case of Series I experiments. And it can be noted that the use of glass waste powder and SSP enhance the water tightness of the concrete with addition of plasticizer, silica fume and nanosilica in the SCC mixtures counterbalancing the negative effect produced by the recycled concrete aggregates. Figure 6 (left) illustrates the relationship between temperature and time during the first 50 hours of hydration for A30, G30, F30 and CTRL1. It can be seen that hydration temperature peaks took place within 19-24h after casting; significant difference in peak values in comparison to all mixtures shown at this figure was only for F30 mixture with peak temperature of 30.9°C which is almost equal to CTRL1. Figure 6 (right) illustrates the relationship between temperature and time during the first 89 hours of hydration for mixtures 2, 3, 4, and 5. The peak value of the temperature within the mixture 3 with w/b=0.34 took place approximately 27 h after casting with value of 36.1ºC. The generated temperatures during hydration process of mixture 5 made with SSP RCA were lower in comparison to the mixture 4 with glass waste RCA with values of 32.6ºC and 33.6ºC correspondingly.

Durability - frost resistance test

Mineral admixtures in frost-resistant concrete especially with the large water requirements are undesirable. At the same time, it can be seen that concrete with non-large maintenance of steel slag or glass waste powders (in case of SCC concrete mixtures) may be satisfactory for frost-resistant, and even more if to add in concrete an entrained air. During the frost resistant test the measurements were taken after the 8th, 13th, 20th, 30th, 45th, 60th cycles. The results show that all mixtures belong to 1st or 2nd class: 1 class – non-large frost resistance (F=50 to 150) and 2 class - large frost resistance (F =150 to 300). Series I showed that addition of glass waste powder decrease the frost resistance and Series II showed that by proper mixture composition selection and application of glass waste powder and recycled aggregates the frost resistance can be significantly improved.

4 CONCLUSIONS

The aim of this study was to see how the substitution of Portland cement with glass waste and SSP influences on concrete properties and the most important if the quality of recycled aggregates obtained from such concrete improves or worsen the performance of concrete itself. The next generation ecological self compacting concrete with glass waste powder (as a cement component in concrete) and recycled concrete aggregates (obtained from the concrete waste which already contains glass powder) supposed to be future type of concrete which has reasonable performance in comparison to concrete with natural aggregates, especially considering the limit of natural aggregates and daily grown amount of wastes. Replacing normal aggregates with recycled ones generally leads to a worsening of the concrete performance. However, optimizing concrete mixtures with regard to cement content and recycled aggregates amount is one of the most important factors in the design of ecological concrete. The following conclusions can be summarised by analysing tests performed on the specimens: a significant increase of workability, lower or equal compressive strength, lower permeability, lower hydration temperature, lower or equal frost resistance. The addition of glass waste in the mixtures enhances the mechanical properties and durability performance of the concrete, thus mitigating the worsening effects of RCAs and therefore should be considered for further investigation for the production of more sustainable structural concretes.

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